Received: 1 June 2024 | Accepted: 26 February 2025

DOI: 10.1002/csc2.70053

Crop Science

ORIGINAL ARTICLE

Special Section: 2025 International Turfgrass Research Conference

Recovery of five cool-season turfgrasses following long-term ice encasement

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Assigned to Associate Editor Samuel Trachsel.

Funding information
National Institute of Food and Agriculture, Grant/Award Number: 2021-51181-35861; Norges Forskningsråd, Grant/Award Number: 310090

Abstract

Ice encasement is a major concern for turfgrass managers in cold climates; however, there is a lack of data about both which turfgrasses are best suited for survival under these conditions and the reasons behind the superior recovery of some grasses from long-term ice encasement. In this study, we encased golf course putting greens-height field plots of creeping bentgrass (*Agrostis stolonifera* L.), velvet bentgrass (*Agrostis canina* L.), annual bluegrass (*Poa annua* L. var. *reptans* Hausskn.), Chewings fescue (*Festuca*. *rubra* L. ssp. *commutata* Gaudin), and slender creeping red fescue (*F*. *rubra* L. ssp. *littoralis* (G. Mey.) Auquier) with ice for 90–120 days with the inclusion of CO_2, O_2, and temperature sensors at 2.5 and 12.5 cm depth to better understand environmental conditions under ice and factors related to winterkill. Velvet bentgrass had the best overall performance and recovery, while annual bluegrass did not survive. Differences in recovery among turfgrass taxa may have been affected by the length of the ice encasement period, higher CO_2 levels (>40,000 ppm), and lower O_2 values, particularly in the second experimental run. During the recovery period in both years, photochemical efficiency values began increasing 5–10 days before percent green cover, suggesting that visual performance of the turf surface is a lagging indicator of recovery. Overall, recovery from ice encasement was annual bluegrass < Chewings fescue < creeping bentgrass = slender creeping red fescue = velvet bentgrass. These results can guide turfgrass managers in making species selection decisions in areas where long-duration ice encasement is a risk.

Plain Language Summary

Turfgrasses on golf course greens in cold climates can be severely damaged or even die from ice encasement. Little is known about this stress, including why certain grasses can survive longer. As a first step to learn more about this problem, we tested

Abbreviations: Fv/Fm, maximum quantum efficiency of photosystem II; NDVI, normalized difference vegetation index; PAR, photosynthetically active radiation.

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five different turfgrasses for their ability to survive under ice. The study was done during two separate winters in Minnesota under field conditions, resulting in 98 days of ice in 2021–2022 and 112 days of ice cover in 2022–2023. Annual bluegrass died completely during both experimental runs, while Chewings fescue suffered some injury in the first year and did poorly in the second year. Velvet bentgrass was the best grass in both years. Under the longer duration of ice cover in the second year, carbon dioxide levels were very high, while oxygen gas levels slowly declined over the course of the ice encasement period.

1 | INTRODUCTION

With a changing climate, northern latitudes are now more commonly faced with unstable snow cover and formation of ice (Cohen et al., 2018). Long-term duration of ice cover is known to reduce the growth potential of grasses and cause winterkill (Merewitz, 2021). This is an increasing problem on golf course putting greens and results in delayed opening of golf courses and economic loss because of frequent re-establishment (Kvalbein et al., 2017). The effect of ice encasement on turfgrasses has received scant attention by researchers. A lack of new knowledge in this field is concerning, especially in the context of golf greens, which are the most important surfaces on a golf course and necessary for an economically viable, fully functioning operation.

Early work on ice encasement effects on turfgrasses began in the mid-20th century. Beard (1964) found that Toronto creeping bentgrass (*Agrostis stolonifera* L.) could survive under 5.1 cm (2 in.) of ice for at least 51 days in East Lansing, MI. In a follow-up experiment, Beard (1965b) harvested cold-acclimated plugs of creeping bentgrass (Toronto) and annual bluegrass (*Poa annua* L.) from the field and found that creeping bentgrass had far superior survival under multiple ice-formation scenarios, including the most severe treatment of fully encasing the plug in ice: Toronto had 100% survival after 60 days and still had 10% survival after 90 days; conversely, annual bluegrass had no survival after just 15 days. Later, Beard (1965a) found few differences for ice encasement tolerance among creeping bentgrass cultivars available at the time of his study. Together, these studies have been the basis for estimating how long each of these species can survive under ice. Golf course superintendents in cold climates have, for decades, preferred creeping bentgrass to annual bluegrass when ice encasement is a risk; however, due to the competitive ability of annual bluegrass biotypes adapted to greens-height conditions, most golf course budgets likely do not allow for long-term control. Plant breeders have developed perennial-type annual bluegrass cultivars (Bonos & Huff, 2013); however, to our knowledge, there has not been any selection work done by turfgrass breeders specifically for ice encasement tolerance.

More recent work has confirmed Beard's general findings (Beard, 1964, 1965a, 1965b). Tompkins et al. (2004) compared annual bluegrass and creeping bentgrass for response to ice encasement and found that annual bluegrass was killed after 90 days of ice cover in controlled environment conditions, while creeping bentgrass only began to lose hardiness at that point and was able to survive beyond 150 days. Laboratory studies showed that annual bluegrass was more sensitive to anoxia (low O_2, like found under ice) than creeping bentgrass (Castonguay et al., 2009). In a field study in central Norway, Waalen et al. (2017) found that the tolerance to ice encasement of either 98 or 119 days decreased in the order starting with velvet bentgrass (*Agrostis canina* L.) as the most tolerant > creeping bentgrass > Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin), slender creeping red fescue (*F. rubra* L. ssp. *littoralis* (G. Mey.) Auquier) ≥ colonial bentgrass (*Agrostis capillaris* L.) > annual bluegrass.

The concentrations of gases change under ice encasement (Andrews, 1996), with CO_2 increasing and O_2 decreasing. This change can be both directly detrimental to turfgrass survival and indirectly damaging due to causing production of and exposure to other toxic metabolites/volatiles such as ethanol and lactic acid. Castonguay et al. (2009) exposed annual bluegrass to various combinations of CO_2 and O_2 concentrations under low temperature and showed that gas concentration was important for survival. However, we still do not know how CO_2 and O_2 concentrations change over time in the soil of a putting green encased in ice. Such data may be able to help build prediction models for turfgrass mortality and recovery under ice encasement, helping golf course superintendents make better decisions on if/when to remove ice.

When evaluating survival from winter-related damage such as from ice encasement or from direct low-temperature kill, researchers have typically used visual assessment methods. The most common being rating plants as either dead (0) or alive (1), or rating the percentage of surviving tillers on a 1–9 scale to estimate whole plant survival (Hoffman et al., 2012; Hulke et al., 2008). While these methods are simple, the ratings are not always straightforward, and results may vary due

to the person collecting visual data due to interpretation of what is dead or alive. The use of digital image analysis and the evaluation of the amount of green tissue cover in a picture taken of a turfgrass plot could remove interpretation of survival. Additionally, measurements of chlorophyll fluorescence parameters such as the maximum quantum efficiency of photosystem II (i.e., Fv/Fm) could determine the health of survived tissue and distinguish mortality of organs that appear dead to a human eye or ordinary camera. Recent research has used Fv/Fm data to predict mortality in plants exposed to drought (Guadagno et al., 2017; Rico-Cambron et al., 2023) and could be used to evaluate survival from ice encasement.

A better understanding of turfgrass species differences for ice encasement tolerance and recovery would be beneficial for turfgrass managers seeking recommendations for turfgrass stands in climates where long-term ice encasement is a risk. Therefore, we compared five cool-season turfgrass taxa that are used on golf greens in cold climates for survival and recovery from long-term ice encasement under field conditions in Minnesota. Our objective was to identify turfgrasses that can both survive this stress and recover fully to allow for regular functioning of the turf surface. Furthermore, we aimed to measure physiological and environmental parameters to help better understand the mechanisms associated with ice encasement stress responses, and to help develop better methods to assess ice encasement survival and recovery compared to traditional methods.

Core Ideas

- Annual bluegrass did not survive under ice encasement of at least 90 days.
- Velvet bentgrass, slender creeping red fescue, and creeping bentgrass showed good recovery from ice encasement.
- Photochemical efficiency was a good predictor of turfgrass recovery from ice encasement stress.
- Environmental sensing of microenvironments can improve our understanding of ice encasement tolerance.

2 | MATERIALS AND METHODS

2.1 | Experimental design and management

Research plots were established at the University of Minnesota Turfgrass Research, Outreach and Education Center in Falcon Heights, MN (lat: 44.995353, long: −93.185347) on a sand-based, United States Golf Association–specified research green with an original sand layer depth of 30.5 cm. Turfgrass plots of 1 m^2 were arranged as a randomized complete block design with four replications. The experiment was performed during the winter and spring of 2021–2022 and replicated in 2022–2023. Average air temperatures for the first experimental year were −5.6°C, −14.3°C, −11.8°C, −2.0°C, and 3.7°C for December, January, February, March, and April, respectively. For the second year, monthly average temperatures were −9.4°C, −7.1°C, −7.8°C, −3.5°C, and 5.9°C for December, January, February, March, and April, respectively (Minnesota Department of Natural Resources, 2024). Prior to each run, individual plots were seeded (July 17, 2021, and June 7, 2022) with one of the following turfgrass cultivars: Radar Chewings fescue (Mountain View Seeds), Cezanne slender creeping red fescue (DLF Seeds), Luminary creeping bentgrass (Landmark Seed Company), Nordlys velvet bentgrass (Graminor AS), or Two-Putt annual bluegrass (*P. annua* L. var. *reptans* Hausskn) (DLF North America). Chewings fescue and slender creeping red fescue were seeded at 50 g m^{-2}, creeping bentgrass and velvet bentgrass at 7.5 g m^{-2}, and annual bluegrass at 10 g m^{-2}. Cultivars were chosen based on previous use in cold-climate research studies. Single cultivars were used for each species due to space and logistical limitations; in previous studies on turfgrass winter survival, species has been a more important factor than cultivar (Beard, 1965a), so this limitation was considered minor.

During both establishments, starter fertilizer was applied at seeding to provide 10.7 kg N ha^{-1}, 21.3 kg P ha^{-1}, and 13.4 kg K ha^{-1}, and again 2 weeks later to provide 26.9 kg N ha^{-1}, 21.3 kg P ha^{-1}, and 49.1 kg K ha^{-1}. Plots were fertilized again approximately monthly with 4.88 kg N ha^{-1} at each application: 2021 plots were fertilized in late July, late August, and late September; 2022 plots were fertilized in late August and late September. The experimental area was maintained at a 5.6-mm height of cut with a reel mower and top-dressed with United States Golf Association specification sand every 2 weeks. Fungicides were applied for preventative disease control. In 2021, for the first experiment, granular mefenoxam was applied once at 0.38 kg ai ha^{-1} after seeding. In 2022, for the second replication of the experiment, granular mefenoxam was applied once at 0.38 kg ai ha^{-1} after seeding and then weekly during establishment for a total of four applications. In 2022, a liquid application of mefenoxam (0.763 kg ai ha^{-1}) was made on July 14 for further pythium disease (*Pythium aphanidermatum*) prevention, and a combination of fluazinam (0.81 kg ai ha^{-1}) and azoxystrobin (0.32 kg ai ha^{-1}) was applied on September 14 to prevent anthracnose (*Colletotrichum cereale*). Fungicides were applied for snow mold (*Microdochium nivale*; *Typhula* spp.) prevention for the first experiment on November 3, 2021, using a combination of fluazinam (0.809 kg ai ha^{-1}), thiophanate methyl (4.29 kg ai ha^{-1}), tebuconazole (0.82 kg ai ha^{-1}), and iprodione (3.05 kg ai ha^{-1}) and for the second replication of the experiment on November 11, 2022, using a combination of

fluazinam (0.81 kg ai ha^{-1}), thiophanate methyl (3.43 kg ai ha^{-1}), tebuconazole (0.82 kg ai ha^{-1}), and iprodione (3.43 kg ai ha^{-1}). Weed pressure was very low and did not require control measures.

2.2 | Sensor installation and ice encasement

Plots were subjected to ice encasement and monitored through winter and spring recovery. Prior to ice development, custom solar-powered sensor nodes, v2.0.5.B systems as described in Runck et al. (2024), were installed near the plot area, with individual sensors for measuring environmental variables buried in the soil. In the first trial (2021 seeding), sensor nodes were installed to monitor two blocks (repetitions) of the ice-encased plots, and two additional sensor nodes monitored the area outside of the plot area (creeping bentgrass maintained at the same height as the experimental area and not encased in ice). For the trial seeded in 2022, a sensor node was installed to monitor a single block of the ice-encased plots, and a second sensor outside of the ice-encased plot area monitored conditions in the single replication of plots that served as a control without ice encasement. Environmental parameters could not be monitored in additional blocks due to sensor availability. Each node regularly measured rootzone O_2 concentration, CO_2 concentration (Schulz et al., 2024), and temperature. All sensor measurements were recorded at two depths: 2.5 and 12.5 cm.

Each block (replication) was 1 m × 5 m and consisted of five individual 1-m^2 plots. Aluminum barriers were created with multiple 15.2 cm by 3 m lengths of aluminum sheet and used to prevent water movement during ice formation and melt. The barrier was installed around each block in late fall to a depth of 5 cm below the soil surface and was placed such that there was a 50 cm distance between the edge of the block and the aluminum barrier. Water was initially sprayed over the plots to create a thin layer of ice and prevent it from percolating through the soil. Over a 2-week period, further additions of water were added multiple times each day, allowing each to freeze before more was added, until each block was covered by 10.2 cm of ice. In 2021, the soil had frozen prior to the ice-formation process. In 2022, the plot area was covered with snow that had fallen earlier in the winter and late fall; snow was removed from the plots designated for ice encasement to allow for the soil to freeze but was left on the control plots and surrounding areas (a single replication of control plots was present only during the second run of the study). In both years of the trial, snow was removed from the ice-encased plots throughout the study, and water was periodically added to the surface to maintain ice depth. The ice remained over the plots for at least 90 days and was then allowed to melt naturally. Ice formation (10.2-cm ice depth) for the first experiment began on December 16, 2021, and complete ice melt was reached on March 25, 2022, for a total of 98 days of ice encasement. Ice formation for the second experiment began on December 19, 2022, and reached complete ice melt on April 10, 2023, for a total of 112 days of ice encasement. There was no ice formation on any of the areas surrounding the ice-encased plot area including the control plots that were present during the 2022–2023 winter.

2.3 | Data collection

In addition to the environmental data recorded by the sensor nodes, turfgrass responses were collected after ice melt each year. To measure physiological plant stress, a mobile chlorophyll fluorescence imaging system (IMAGING-PAM M-Series Maxi Version; Heinz Walz Co.) with a zoom and focus adjustable lens was used to collect data on the maximum quantum efficiency of photosystem II (Fv/Fm; variable fluorescence to maximal fluorescence; photochemical efficiency) and photosynthetically active radiation (PAR) absorptivity data on an area that was approximately 10 cm × 13 cm (absorptivity = 1 – [red light remission/near-infrared light remission]). Plots were dark-adapted for 5–18 min using blackout cloth drapery as previous research has indicated that 15 min is a good length of time to dark adapt for measuring Fv/Fm (Kalaji et al., 2014). Based on our experience measuring Fv/Fm in turfgrass systems, dark adaptation times between 5 and 30 min results in no significant change in Fv/Fm data, and dark adaption in our study was achieved in 5 min.

Next, LED intensity and gain were adjusted in Walz ImagingWin software so that steady-state fluorescence (F_t) was between 0.16 and 0.18 prior to capturing maximum fluorescence (Fm) data. One sample per plot was taken 2, 3, 4, and 10 days after complete ice melt and weekly for the following 5 weeks. In 2022, data were collected at 7:00 a.m., 11:00 a.m., and 6:00 p.m. to determine optimum sampling time, but an analysis of photochemical efficiency and absorptivity showed no significant main or interactive effect among sampling times, so 11:00 a.m. was chosen for convenience and used in the analyses for both years (Table S1).

A digital image of each plot was taken weekly for at least 7 weeks beginning on Day 2 after ice melt. Images were taken with a digital camera (RX1000 III; Sony Corp.) set at a 1/30-s shutter speed, F6.3 aperture, 200 ISO, and 5500 k white balance atop a custom 60.3 cm × 90.8 cm × 64.8 cm LED light box emitting 90 μmol m^{-2} s^{-1}. Images were later uploaded to Turf Analyzer 1.0.4 (Green Research Services, LLC) to determine percent green cover.

2.4 | Statistical analysis

Our analysis was designed to understand the effect of our experimental design on observed outcomes (green cover,

Fv/Fm, and absorptivity) as well as to test how species recover and respond to ice encasement. All statistics were conducted using the program R version 4.3.1 "Beagle Scouts" (R Core Team, 2023). Green coverage, plant absorptivity, and photochemical efficiency were all proportion data bounded from 0 to 1 and were modeled using a generalized linear model (Warton & Hui, 2011) with the *glm* function with family set to binomial using a logit transformation. Annual bluegrass completely died under the ice in both years, and data for that species were not analyzed. Model selection was guided by reducing the AIC value, which penalizes additional variables in the model, but we still included repetition and year in the model since they were experimental features. Explanatory variables included in the final model were repetition, year, days after melt, species, and species-by-year interaction. Model estimates are shown compared to Replication 1, year 2022, Chewings fescue (this comparator was selected by default based on numerical and alphabetical categorical variables). Model summary estimates are reported exponentiated. The deviance table reports ANOVA information for each generalized linear model using a chi-squared option to calculate p values. The McFadden pseudo-R^2 values were calculated with reference to Pampel (2021). Prediction curves were developed from the results of each model using the *predict* function; since repetition was not significant, model prediction curves showed only one repetition for each dependent variable. Residuals and assumptions were assessed visually; we found some heteroscedasticity in percent green cover, with greater variability at larger values of percent cover. Dispersion was tested in each model, and we found no significant effect of dispersion. Statistical differences among specific species interactions were determined from the generalized linear models using the *emmeans* function in the emmeans package with no p value adjustment (Lenth, 2024).

3 | RESULTS AND DISCUSSION

3.1 | Ice encasement environment

Field-based ice encasement studies are difficult to replicate from year to year since this stress is very dependent on temperature and other environmental factors. We successfully encased the plot area in ice in both years; however, we were not able to match ice encasement durations. To address this limitation, we monitored O_2 and CO_2 concentrations under the ice throughout the study period for both years using environmental sensing nodes (Figure 1 and Figure S1). Snow cover prior to ice encasement in 2022 likely contributed to higher soil temperatures, which appears to have affected CO_2 and O_2 levels, possibly due to microbial respiration (Clein & Schimel, 1995; Rochette et al., 2006). In both years, CO_2 levels rapidly rose during ice encasement, and in 2023 reached the maximum our sensors could detect (40,000 ppm) (Table S2); extended durations of high levels of CO_2 (above 40,000 ppm) have also been reported in ice-encased forest soils in northern Finland (Martz et al., 2016). Oxygen did not decline much during the first year of the study but showed a steadier decline throughout the study period in 2023. In 2022, there was a failure of O_2 sensing during a period when the shallower sensors were under water (not under ice); these data are not shown. We recorded higher O_2 values at the deeper sensor placement depth (12.5 cm) compared to the shallower depth (2.5 cm), while soil temperature was similar at each of the two sensor depths (Figure 1; Table S2).

3.2 | Turfgrass performance

We quantified turfgrass performance by calculating the percentage of each plot that had green cover at a given data collection time point. In both years, there were clear differences between species, with a wider range of responses in 2023 (Table 1; Figure 2). Since the number of days under ice cover was different between years and we found differences in percent green cover for some species, we kept the interaction of year and species in the model. In 2022, creeping bentgrass green cover at 43 days after ice melt was statistically comparable to velvet bentgrass and slender creeping red fescue. When analyzed over the entire 2023 recovery period, velvet bentgrass had the highest percent green cover and was similar to slender creeping red fescue ($p = 0.37$) (Figure 2). In 2023, creeping bentgrass percent green cover at 49 days after melt was 33%, which was only significantly lower than velvet bentgrass at 69% ($p < 0.01$). The only species that died in both years was annual bluegrass. No damage occurred for any species in 2023 in the single replication of ice-free plots (Figure S2).

Castonguay et al. (2009) manipulated gas levels of both O_2 and CO_2 at high and low levels in all combinations and surmised that the primary driver of damage in an ice encasement–like environment was low O_2, but also found that the combination of low O_2 and high CO_2 was the most damaging. Anoxic conditions under ice cause plants and microbes to switch to anaerobic respiration, producing compounds such as CO_2, ethanol, lactic acid, formic acid, and butyric acid; CO_2 is considered to be the most toxic product of anaerobic respiration and a major contributor of cellular damage during anoxia (Andrews, 1996). The very high levels of CO_2 in our study, combined with a steady decline in O_2, appear to have affected annual bluegrass much more than the other grasses. Injury to creeping bentgrass and slender creeping red fescue in 2023, after both species were unaffected by ice encasement the previous year, was possibly only present because O_2 levels fell well below 2%. Our study did not monitor gases under



FIGURE 1 Environmental data from sensors that were under ice in both testing years. O_2 is shown as percentage, CO_2 in parts per million, and soil temperature in degrees Celsius. The O_2 sensors placed at 2.54 cm in the first winter of the study malfunctioned, and data are not reported. CO_2 sensors reached maximum reading of 40,000 ppm in 2023. Vertical red solid lines are the ice-out dates, and vertical black dashed lines are 40 days after melting in each experimental year.

TABLE 1 Modeled summary results for the three response variables of percent green cover, photochemical efficiency (Fv/Fm), and absorptivity based on each explanatory variable. Model was a generalized linear model with response variable as a function of repetition, year, days after melt, species, and species-by-year interaction.

	Green cover		Fv/Fm		Absorptivity	
	Effect	***p* value**	**Effect**	***p* value**	**Effect**	***p* value**
(Intercept)	−	***	−	***	−	**
Rep 2	−		−		−	
Rep 3	+		+		+	
Rep 4	−		+		+	
Year (2023)	+		−		−	
Days after melt	+	***	+	***	+	*
Creeping bentgrass	+	***	+		+	
Slender crp. fescue	+	**	+		+	
Velvet bentgrass	+	**	+		+	**
Year (2023) by creeping bentgrass	−		+		+	
Year (2023) by slender crp. fescue	+		+		+	
Year (2023) by velvet bentgrass	+		+		+	

Note: Estimates are compared to an intercept of Replication 1, 2022, Chewings fescue. Estimates larger than 1 indicate a positive change shown as +, and estimates less than 1 indicate a negative change shown as −.

Abbreviation: Rep, repetition; slender crp. fescue = slender creeping red fescue.

*, **, ***denote significance at the 0.10, 0.05, and 0.01 probability level.

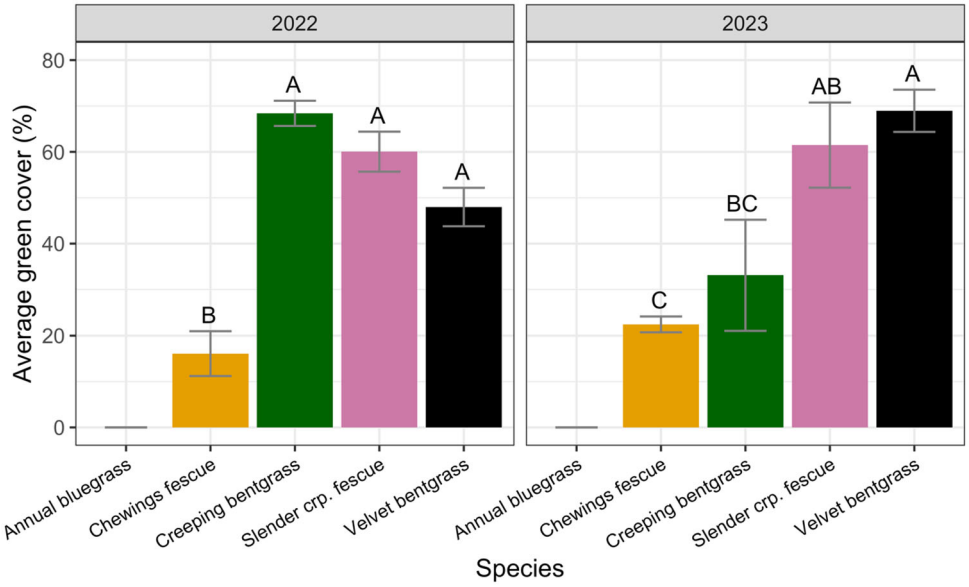


FIGURE 2 Average percent green cover 49 days after melting in 2022 (98 days of ice cover) and 43 days after melting in 2023 (112 days of ice cover). Letters show statistical comparisons within a year. Annual bluegrass completely died and was not modeled. Slender crp. fescue refers to slender creeping red fescue.

all ice-encased plots and, therefore, may not fully represent the ice-encased turf environment; however, the consistency of plant response we found between blocks (replicates) suggests that these microenvironments were quite similar.

In both years, velvet bentgrass and slender creeping red fescue performed in the top statistical group for all parameters. Chewings fescue had less green cover after ice melt in 2022 than all species except for annual bluegrass, while in 2023, it had less green cover than both slender creeping red fescue and velvet bentgrass. These results differed somewhat from those of Waalen et al. (2017) who showed that slender creeping red fescue had poorer ice encasement tolerance than velvet bentgrass. The two studies had some similarities (ice cover duration, same slender creeping red fescue cultivar), but differences in environmental parameters in Norway compared to our study in Minnesota may have had a greater effect on the slender creeping red fescue than other grasses; this warrants further exploration and suggests that the microenvironments under which ice forms are critical to understanding plant response.

3.3 | Plant physiological responses

Each response variable was modeled as a function of replication, year, days after melting, species, and species-by-year interaction (Tables 1 and 2). Velvet bentgrass had greater PAR absorptivity than Chewings fescue but was similar to creeping bentgrass and slender creeping red fescue in 2022, while in 2023, velvet bentgrass was greater than all three other species. PAR absorptivity has a linear relationship with normalized difference vegetation index (NDVI) data especially when soil and other background data are excluded from NDVI, but PAR absorptivity is a better estimator of potential plant growth (Asrar et al., 1992). These data indicate recovery of vegetative tissues in plots after ice encasement and that species such as velvet bentgrass recover green tissue at a faster rate than Chewings fescue.

Photochemical efficiency was similar among turfgrass species in 2022, though in 2023, velvet bentgrass was greater than Chewings fescue, and velvet bentgrass was similar to creeping bentgrass and slender creeping red fescue. When the 2 years were combined, creeping bentgrass photochemical efficiency was greater than Chewings fescue ($p = 0.049$).

Photochemical efficiency values were increasing about 5–10 days prior to percent green cover increases (Figure 3). This suggests that we may be able to predict potential turfgrass recovery through the measurement of fluorescence parameters. Chlorophyll fluorescence parameters such as Fv/Fm are widely used to monitor both biotic and abiotic stress non-invasively over time (Gorbe & Calatayud, 2012; Murchie & Lawson, 2013). Declines in dark adapted Fv/Fm (0.00–1.0) from the theoretical maximum of 0.84 indicate stress, with further reduction in Fv/Fm values connected to severity, potential mortality, and poor recovery. We monitored Fv/Fm to assess mortality and recovery following ice encasement, and results show that while some plots may have appeared dead following ice melt (no green cover), Fv/Fm signals indicated turfgrass plants were alive with potential for recovery. While these data do not directly indicate the survival of crowns on plants, increases in Fv/Fm over time as demonstrated in Figure 3 indirectly indicate whole plant survival of

TABLE 2 Deviance table showing the relative benefit or variance explained of each modeled explanatory variable for each response variable. The model was a generalized linear model with response variable as a function of repetition, year, days after melting, species, and species-by-year interaction. The null value represents the individual model degrees of freedom and total deviance.

	Green cover			Fv/Fm			Absorptivity		
	df	Deviance	*p* value	*df*	Deviance	*p* value	*df*	Deviance	*p* value
Null	367	229		319	55		318	32	
Rep	3	1	0.90	3	0	0.95	3	0	0.96
Year	1	19	<0.0001	1	5	0.03	1	4	0.04
Days after melt	1	147	<0.0001	1	28	<0.0001	1	3	0.09
Species	3	23	<0.0001	3	9	0.03	3	17	<0.001
Year × Species	3	9	0.04	3	2	0.65	3	2	0.66

Note: Remaining deviances for green cover, Fv/Fm, and absorptivity are 31, 10, and 6, respectively, and McFadden pseudo-R^2 values for each model are 0.86, 0.81, and 0.82.

Abbreviation: Rep, repetition.

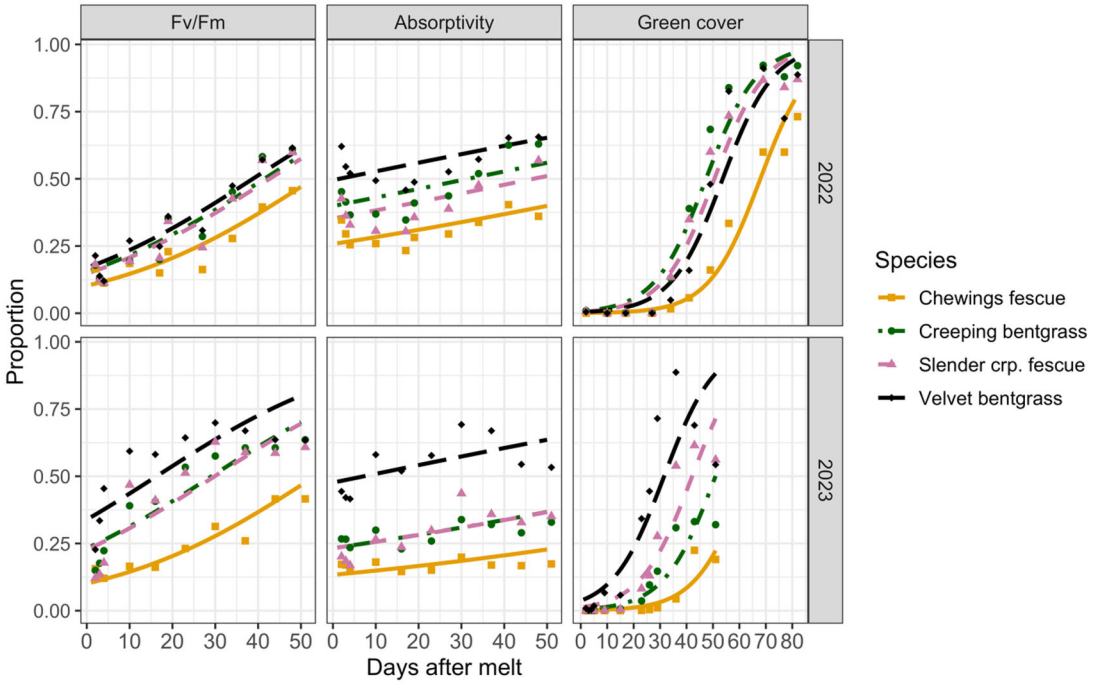


FIGURE 3 Modeled prediction curves (lines) and averaged observed data (points) of each species within both sampling years. Three response variables are shown of photochemical efficiency (Fv/Fm), absorptivity, and percent green cover.

the species that were assessed. Similarly, the rate and magnitude of the increase in Fv/Fm over time provide insight into the health and status of the turfgrasses as they recover from winter. For example, species such as creeping bentgrass that had a relatively higher Fv/Fm directly following ice encasement exhibited a faster rate of recovery and higher Fv/Fm and green cover at the conclusion of the experiment compared to Chewings fescue that had very low Fv/Fm after ice encasement. That rate of recovery may be directly connected to damage sustained during ice encasement.

While Fv/Fm increased over time, indicating survival and recovery, these data were still relatively low compared to healthy plants. The low Fv/Fm values may be due to low-temperature-induced photoinhibition and being exposed to high-intensity light following ice melt. Similar observations have been made in Scots pine (*Pinus sylvestris*) where Fv/Fm was quite low following winter damage yet slowly recovered; trees exhibited Fv/Fm values that were higher and recovered faster when shaded (Ottander & Öquist, 1991). The use of Fv/Fm will benefit turfgrass researchers studying winter stresses. Technological advances would, however, be needed for wider use of this photochemical efficiency measurement by turfgrass managers since current approaches would be too expensive.

Chlorophyll fluorescence parameters have also been used to predict recovery from drought stress before irrigation is

returned in *Arabidopsis* (Rico-Cambron et al., 2023) and to predict grafting success in melons (Calatayud et al., 2013) when a threshold is developed and defined. Because Fv/Fm showed a faster increase over time compared to green cover, future research may be able to develop more refined thresholds that indicate not only turfgrass survival but also estimate the percentage of visual recovery. It is typical to evaluate mortality and recovery by harvesting samples and bringing them indoors to grow. This can take quite a bit of time and requires destructive sampling; a better approach may be to use Fv/Fm to predict recovery several days to a week prior to any striking changes in growth.

Photochemical efficiency correlated better with percent green cover (0.77) than with absorptivity (0.55). The correlation between percent green cover and absorptivity was 0.40. It is not surprising that the correlation between Fv/Fm and absorptivity is low, as leaves can absorb light that does not result in photochemistry but instead leads to non-photochemical quenching or photoinhibition (Murchie & Lawson, 2013). For example, average absorptivity was greater in 2022 (0.43) than in 2023 (0.30) ($p = 0.02$), and Fv/Fm was different between years with an average of 0.28 in 2022 and 0.39 in 2023 ($p = 0.06$) (Figure 3). Leaves were absorbing similar amounts of light in both years, but due to other environmental conditions such as low air temperature and high light intensity, they were likely experiencing higher photoinhibition with a subsequent drop in Fv/Fm. Days after melting had a lower relative impact on absorptivity than we would have expected especially when compared to photochemical efficiency and green cover (Table 2). This could be related to an individual species' unique absorptivity such as due to leaf color and other traits such as trichomes that affect light absorption and remission.

3.4 | Recommendations and future directions

In cold-climate regions where pesticide inputs are more restricted, such as the Nordic countries, the use of pure creeping bentgrass stands is a potential risk since there are no documented instances of creeping bentgrass cultivars being resistant to snow mold pathogens (Gregos et al., 2011). Therefore, turfgrass managers in those regions must rely on other species as important components of turfgrass stands. Our results suggest that slender creeping red fescue is likely a good option for these situations, and Chewings fescues should be acceptable if the ice encasement period is not prolonged well beyond 100 days. To reduce risk of ice encasement injury while balancing other turfgrass performance needs on a golf course, managers should consider mixtures of slender creeping red fescue, Chewings fescue, and creeping bentgrass (Hesselsøe et al., 2022). Our results also clearly reinforce that annual bluegrass populations should be reduced whenever possible on greens in cold climates; while this can be an economically challenging undertaking, allowing mixed stands that include annual bluegrass (when well less than 50% of the stand) to be exposed to regular winter conditions (i.e., not covering greens surfaces) should help reduce populations over time. Our conclusions are based on single cultivars of each taxon; screening of a wider set of cultivars for some of these species could help identify better options for turfgrass managers to use, although there is not strong evidence for intraspecific variation for ice encasement tolerance in the species we studied.

Gendjar and Merewitz (2023) studied soil moisture effects on ice encasement survival and found that when soil water content was at 8% prior to 40 days of ice encasement, recovery of the plant, as measured by green tissue, was over 70% higher than when soil moisture was at either 12% or 16% soil water content prior to the ice encasement. This difference not only points to a possible management strategy for turfgrass managers aiming to reduce ice encasement injury risk, but it also suggests that the environmental conditions under which ice forms may be critical to turf survival. Understanding these environments will be important if turfgrass researchers are to find solutions for reducing the risk of this important stress.

A future experiment, which includes different durations of ice cover in the experimental design, could analyze the number of ice days as a factored variable, days after melt or growing degree days, and species as a three-way interaction to identify if there is a significant recovery adjustment for species among different levels of ice treatments over time. The number of ice days is likely a proxy for environmental variables such as O_2 and CO_2, which we hypothesize would likely give more accurate prediction of survivability than the number of ice days since environmental measurements are accounting for thermal and atmospheric properties within the soil. Tompkins et al. (2004) offered that ice removal could begin at 45 days of encasement for annual bluegrass and might not be needed for creeping bentgrass; however, our results, along with communications from superintendents in northern latitudes, suggest even creeping bentgrass can succumb to ice encasement stress under the right combination of environmental factors.

We were able to monitor environmental conditions under ice and use a variety of methods to assess recovery after a long ice encasement period. This study identified grasses best suited for surviving this stress and should help practitioners in cold climates make informed turfgrass species choices for golf greens. Our study was not designed to answer several important questions. At what level does CO_2 become too high for annual bluegrass survival? How many days can annual bluegrass survive at the highest CO_2 levels? Above what CO_2:O_2 ratio does creeping bentgrass get damaged or die? Each of these questions will require a dependable environmental monitoring approach so that the mechanisms underlying plant

responses can be discovered and leveraged to develop new management strategies and improved cultivars to reduce ice encasement for turfgrass managers in cold climates.

AUTHOR CONTRIBUTIONS

Eric Watkins: Conceptualization; funding acquisition; project administration; writing—original draft; writing—review and editing. **Dominic P. Petrella**: Conceptualization; methodology; writing—original draft; writing—review and editing. **Trygve Aamlid**: Conceptualization; funding acquisition; methodology; writing—original draft; writing—review and editing. **Dominic C. Christensen**: Data curation; formal analysis; methodology; writing—original draft; writing—review and editing. **Sigridur Dalmannsdottir**: Investigation; methodology; writing—original draft; writing—review and editing. **Andrew P. Hollman**: Conceptualization; data curation; investigation; methodology; writing—original draft; writing—review and editing. **Gary Deters**: Investigation; methodology; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

This research was supported by the Scandinavian Turfgrass and Environment Research Foundation and Research Council of Norway's grant no. 310090 to the Norwegian Golf Federation's project ICE-BREAKER. Partial support was also provided through the USDA National Institute of Food and Agriculture Specialty Crop Research Initiative under award no. 2021-51181-35861.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Watkins, E., Petrella, D. P., Aamlid, T., Christensen, D. C., Dalmannsdottir, S., Hollman, A. P., & Deters, G. (2025). Recovery of five cool-season turfgrasses following long-term ice encasement. *Crop Science*, *65*, e70053. https://doi.org/10.1002/csc2.70053