Research Reports

Low-dose Application of Nonionic Alkyl Terminated Block Copolymer Surfactant Enhances Turfgrass Seed Germination and Plant Growth

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Summary. **Rapid seed germination and vigorous seedling growth are desired when establishing turfgrass lawns from seed. Low-dose concentrations of nonionic, block copolymer surfactants can have a direct effect on plant physiological functions and growth. The objectives were to determine if a low-dose application of a nonionic alkyl ended block copolymer surfactant applied directly to the seed, within a film coating, would 1) influence speed, synchrony, and final germination percentage (FGP), and 2) enhance seedling emergence and the speed of turfgrass establishment under deficit irrigation. Tests were performed with tall fescue (*Schedonorus arundinaceus*) and perennial ryegrass (*Lolium perenne*). Surfactant was applied directly to the seed using a rotary seedcoater at 0.1% by weight of seed. In the first experiment, germination was compared between seeds with a surfactant film coating (SFC) and untreated seeds in growth chambers at three different constant temperatures (10, 20, and 30 °C). For both species, the SFC decreased the time for seed germination, and improved germination synchrony, with the greatest treatment response at 10 and 30 °C compared with untreated seed. Application of a SFC did not influence FGP. In the second experiment, untreated and treated seed were compared in a grow-room study, with pots watered weekly to 70% of field capacity (FC). Perennial ryegrass density, cover, and aboveground biomass from the SFC were ≈47%, 48%, and 46% greater than untreated seed, respectively. Tall fescue density, cover, and aboveground biomass from the SFC seeds were ≈22%, 23%, and 28% greater than untreated seed, respectively. Overall these studies demonstrate that SFC can promote seed germination and also enhance turfgrass establishment under deficit irrigation.**

Less than optimal establishment of new turfgrass lawns from seed is often the result of slow and nonuniform germination and emergence because of poor environmental growing conditions (Christians, 1998; Frelich et al., 1973; Perry, 1980). Nonoptimal temperatures for germination and drought are two common abiotic factors that can limit turfgrass establishment from seed (Bewley and Black, 1994; Larsen and Bibby, 2005). Apart from natural drought, turfgrass establishment is also affected by the lack of water imposed by deficit irrigation, which is being implemented in many places worldwide (Fereres and Soriano, 2007). Where the environment limits stand establishment, seeding success may be improved by applying a seedcoating before sowing that will enhance speed, uniformity, and overall germination rate of the seed (Gregg and Billups, 2010; Schiavon et al., 2013). Products are commonly applied to seed, with materials added at various concentrations from thin films, to coatings that weigh as much as, or even several fold the weight of the seed (Gregg and Billups, 2010; Taylor and Harman, 1990). Treatments applied in the coating may include macro- and micronutrients, plant growth regulators, protection products, growth stimulants, inoculants, and specialized polymers (Halmer, 2008; Scott, 1989).

Madsen et al. (2010, 2013, 2014), have shown that coating seeds with a nonionic alkyl ended block copolymer based on C_1–C_4 alkyl ethers of methyl oxirane–oxirane copolymers was effective at improving seedling emergence and plant growth in water repellent soils. This surfactant chemistry was patented by Kostka and Schuermann (2008) and is distributed under the trade name SET-4001 (Aquatrols Corporation of America, Paulsboro, NJ). The seed coating formulation is designed to use the seed as a carrier for the soil surfactant. After planting, precipitation leaches the surfactant from the seed into the soil where it absorbs onto soil particles and ameliorates water repellency within the seeds' microsite (Madsen et al., 2012). With hydrologic function restored around the seed, soil water infiltration, percolation, and retention is improved, which enhances seed germination and plant survival (Moore et al., 2010). Through this coating technology, the soil surfactant is applied to the seed at relatively high-loading rates (i.e., ≥ 10% by weight of the seed) after first applying a barrier coating or jacket to the seed to control phytotoxicity during storage and seed germination (Madsen et al., 2010, 2013, 2014).

In addition to a soil treatment, nonionic surfactants can have a direct effect on plant physiological functions with results varying with surfactant chemistry and application rate (Khatun et al., 1993). Low concentrations of nonionic, block copolymer surfactants can be beneficial for stimulating tissue growth and enhancing cell viability in plant tissue culture media (Anthony et al., 1994; Khatun et al., 1993, 2003). For example, Khatun et al. (2003) showed that a 0.1% and 0.5%

solution of nonionic surfactant promoted shoot regeneration of kenaf (*Hibiscus cannabinus*). Brutovská et al. (1994) found a 0.001% solution of nonionic surfactant increased growth of st. john's wort (*Hypericum perforatum*) by 40%. Nonionic surfactants have also been shown to benefit recovery of cryopreserved plant cells by enhancing viability and increasing biomass production (Lowe et al., 2001).

Given the positive responses observed in the aforementioned studies, it was hypothesized that a nonionic surfactant applied directly to turfgrass seed would enhance germination and subsequent plant establishment. This hypothesis was tested by applying a low-dose application of surfactant, within a film coating, directly onto turfgrass seed for the purpose of 1) evaluating germination speed, uniformity, and FGP under different constant temperatures and 2) assessing seedling emergence and plant growth under deficit irrigation.

Materials and methods

Research was performed in the laboratories at the Eastern Oregon Agricultural Research Center, Burns, OR. Two separate experiments were conducted, with the first evaluating the influence of a SFC treatment on seed germination, and the second to determine SFC treatment's effect on seedling emergence and plant growth. Turfgrass species used in the study were seeds from the same lot of 'LS 1200' tall fescue and 'LS 2300' perennial ryegrass obtained from Lewis Seed Co. (Shed, OR).

Germination experiment

In Expt. 1, seed treated with a SFC was compared with untreated seed (control). Seeds were coated in a 14-inch rotary seedcoater (RP14DB; BraceWorks Automation and Electric, Lloydminster, Saskatchewan, Canada). Materials and application rates used to treat seeds with SFC included 1) surfactant (SET-4001) applied at 0.1% weight of product to weight of seed (w/w), 2) polyvinyl alcohol binder (Selvol-205; Sekisui Specialty Chemicals America, Dallas, TX), delivered to the seed at 0.8% w/w, and 3) diatomaceous earth (MN-47; EnviroTech Soil Solutions, Oregon City, OR) applied at 11% w/w (Table 1). The polyvinyl alcohol binder was prepared with an 8% solid content and was used as a carrier for applying surfactant. Before coating, the polyvinyl alcohol binder and surfactant were mixed together and the liquid mixture of polyvinyl alcohol binder and surfactant was applied directly to the seed. Immediately following the application of the mixture, a dusting of diatomaceous earth was added to keep the seeds from clumping together and absorbing excess liquid. Treated seeds were immediately dried with a forced-air dryer (BraceWorks Automation and Electric) at 43 °C for ≈5 min.

Seed treatments (i.e., coated and the control) were evaluated in environmental growth chambers at three different constant temperatures (10, 20, and 30 ± 0.5 °C) with a 12-h light/dark cycle. At each temperature, seed treatments for each species were arranged in 10 randomized complete blocks. For each replicate of each treatment, 25 seeds were placed in 15-cm petri dishes on top of a single layer of blue blotter paper (Anchor Paper Co., St. Paul, MN). Before adding seed, each blotter paper was submerged in deionized water and then held in the air for ≈5 s until it had stopped dripping. This procedure moistened each blotter paper with ≈4.4 g of water. The blotter paper's moisture was maintained at about this level by moistening with distilled water every 1 to 2 d. Seed germination was counted daily for 19 d. Seeds were considered to have germinated when the radicle extended at least 0.5 mm beyond the seedcoat. Petri dishes were rotated on different shelves in the growth chamber, throughout the experiment.

From daily germination counts, mean germination time (MGT) was determined according to the following equation:

$$\mathrm{MGT} = \frac{\sum Dn}{\sum n}$$

where n is equal to the number of seeds that germinated, and D is equal to the number of days counted from the beginning of germination. Time to reach 10%, 50%, and 90% germination (T_{10}, T_{50}, and T_{90}) was calculated as follows:

$$\mathrm{T} = \left[\left(\frac{t_a - t_b}{n_a - n_b}\right)(N - n_b)\right] + t_b$$

where T is equal to time (days) to subpopulation germination, t_a is equal to the incubation day when subpopulation germination was reached, t_b is equal to the incubation day before subpopulation germination was reached, n_a is equal to the number of germinated seeds on day that subpopulation germination was reached, n_b is equal to the number of germinated seeds on day before subpopulation germination was reached, and N is equal to the number of germinated seeds equal to 10%, 50%, or 90% of the total population. Germination synchrony was estimated by subtracting T_{10} from T_{90} (i.e., $T_{90} - T_{10}$). FGP was calculated as the ratio of the number of seeds germinated to the total number of seeds sown and was expressed as percentage.

All data from the randomized complete block design experiment were subjected to analysis of variance SAS Proc Mixed (version 9.3; SAS Institute, Cary, NC). Effects tested were seed treatment, turfgrass species since both were tested at same time in same experiment, temperature, and their interactions, and therefore block was considered a random factor. Means between seed treatments within a temperature were separated with by LSMEANS procedure in SAS. The resultant probability values were adjusted using a

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.1	bar	MPa	10
0.0929	ft^2	m^2	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
28.3495	oz	g	0.0353
305.1517	oz/ft^2	$g \cdot m^{-2}$	0.0033
1.7300	$oz/inch^3$	$g \cdot cm^{-3}$	0.5780
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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Bonferroni post hoc test, and statistical significance was determined at $P \leq 0.05$. In the text and figures, means are reported with their associated standard error.

Seedling emergence and plant growth experiment

Experimental design. Research was conducted at the Eastern Oregon Agricultural Research Center's grow-room facilities (Burns, OR). Temperature in the grow room was kept at 22 ± 3.0 °C. A dehumidifier operated to keep relative humidity levels ≤ 50%. Research trials were conducted on 8 × 4-ft laboratory benches that had a 12-h dark/light cycle of 632 $W \cdot m^{-2}$ of fluorescent lighting. Fine sandy textured soil (91% sand, 5% silt, and 4% clay) was collected for the evaluation from a site 10.93 miles south of Burns, OR (lat. 43°21′23′′N, long. 119°01′5′′W). At this location, the soil is classified as fine sand, mixed, frigid Xeric Haplocambids. Soil pH was 7.2, and organic matter content was 0.25% [U.S. Department of Agriculture (USDA), 2014]. Volumetric soil water content at –1.5 MPa (permanent wilting point) is equal to 7.0% (USDA, 2014). Soil was packed into square 18-cm-wide by 18-cm-deep plastic pots to produce a bulk density of 1.4 $g \cdot cm^{-3}$.

Table 1. Seedcoating batch formulation applied separately to tall fescue and perennial ryegrass seed, for surfactant film treatment.

Product	Coating wt (g)[z]
Seed	200.0
Polyvinyl alcohol binder	22.0
Surfactant	0.20
Diatomaceous earth	22.0
Total	244.0

[z]1 g = 0.0353 oz.

Seeds of each of the test species were either left uncoated (control) or treated with a SFC treatment as previously described. Tall fescue and perennial ryegrass were sown at a rate of 30 $g \cdot m^{-2}$, at a depth of 0.5 cm. The study was installed in a randomized-complete block design with eight replicates (pots) per treatment on 29 Aug. and ran through 28 Oct. 2013 (60 d).

After seeding, pots were watered to 70% of FC (30% volumetric soil water content). The amount of water held at FC was determined by the "container capacity" method (Cassel and Nielsen, 1986) on three replicate pots that were not included in the seeding experiment. To determine FC, pots were placed in a tub that was filled with water up to 1 cm above the height of the soil. After water had saturated from the bottom of the pot to the soil surface, the pots were removed from the tub, allowed to drain for 48 h, and weighed. Soil in the pots was then dried at 65 °C for 48 h in a soil oven. Field capacity of individual pots was determined by subtracting the oven-dry soil weight from the weight of the soil after draining for 48 h. Measurements for FC were averaged across pots.

Over the course of the study, pots were individually rewatered once a week with the amount of water required to bring the soil to 70% of FC. Water-soluble 12N–37.4P–8.3K fertilizer (Super Start Plus®; Plant Marvel Laboratories, Chicago Heights, IL) was added to the irrigation water at 2.0 $g \cdot m^{-2}$ at 14 d after seeding (DAS).

Measurements. Before each watering, pot weight was recorded for determining volumetric soil water content by dividing weight of water retained by volume of soil. Plant density was estimated weekly by counting the number of live seedlings within a 5 × 18-cm frame, which was placed in the center of the pot. Density measurements were recorded weekly over the course of the study until values became relatively stable. The last density measurements were recorded 38 DAS. Plant cover was visually estimated over the entire pot 24, 38, and 60 DAS. Aboveground biomass was harvested 60 DAS and weighed after oven-drying at 65 °C for 72 h. No clipping of the grasses occurred during the 60-d establishment period.

Data analysis. Data were analyzed in SAS (version 9.3). A repeated measures mixed model was used for analysis of soil water content, plant density, and cover. Fixed effects in the

Table 2. Effect of surfactant film coating (SFC) on four germination parameters, time to 50% germination (T_{50}), mean germination time (MGT), difference between time to 90% and 10% germination ($T_{90}-T_{10}$), and final germination percentage (FGP), under three different incubation temperatures (10, 20, and 30 °C) and two turfgrass species (perennial ryegrass and tall fescue).

Treatment	Incubation temp (°C)[z]	T_{50} (d)	MGT (d)	$T_{90}-T_{10}$ (d)	FGP (%)
		(mean ± SE)			
Perennial ryegrass					
Control	10	9.5 ± 0.12*	10.7 ± 0.13*	12.5 ± 0.13*	87.2 ± 1.5
SFC	10	8.7 ± 0.09	9.6 ± 0.14	10.2 ± 0.27	89.6 ± 1.4
Control	20	4.2 ± 0.04*	5.1 ± 0.07*	4.9 ± 0.06	92.8 ± 2.6
SFC	20	3.8 ± 0.04	4.6 ± 0.06	4.6 ± 0.06	90.8 ± 2.7
Control	30	3.2 ± 0.15*	3.9 ± 0.16*	4.1 ± 0.21	92.4 ± 2
SFC	30	2.4 ± 0.13	3.3 ± 0.15	3.7 ± 0.21	90 ± 1.9
Tall fescue					
Control	10	11 ± 0.25*	12.4 ± 0.3*	12.5 ± 0.33	80 ± 1.7
SFC	10	9.6 ± 0.25	11.1 ± 0.3	10.7 ± 0.35	85.3 ± 1.5
Control	20	4.6 ± 0.01*	5.8 ± 0.07*	5.4 ± 0.02*	98 ± 0.9
SFC	20	4.4 ± 0.01	5.1 ± 0.06	4.8 ± 0.02	97.6 ± 1.1
Control	30	4.9 ± 0.06*	6.5 ± 0.11*	7.4 ± 0.16*	91 ± 1.6
SFC	30	4.3 ± 0.06	5.2 ± 0.09	5.1 ± 0.16	94.4 ± 1.7

[z](1.8 × °C) + 32 = °F.
*Significant difference between control and SFC by Bonferroni post hoc test at $P \leq 0.05$.

model included species, seed treatment, day of measurement, and their interactions, and therefore blocks were considered a random factor. The correlations among the repeated measures were modeled with a first order, autoregressive, moving average covariance structure. Significant interactions and/or main effects were identified and the corresponding means and confidence intervals were computed. When significant main or interactive effects were found, mean values were separated using the LSMEANS procedure, the resultant probability values were adjusted using a Bonferroni post hoc test, and statistical significance was determined at $P \leq 0.05$.

Results

GERMINATION EXPERIMENT. For T_{50}, there was a three-way interaction between species, treatment, and temperature ($F = 3.2$, $P < 0.044$). Generally, SFC treatment had the greatest influence relative to the control at 10 and 30 °C (Table 2). Specifically, at 10 and 30 °C SFC treatment decreased T_{50} by ≈1 d, whereas at 20 °C, T_{50} was only decreased by 0.38 and 0.19 d for perennial ryegrass and tall fescue, respectively.

The SFC treatment also had a significant effect on MGT ($F = 91.7$, $P < 0.001$). At 10 and 30 °C, SFC treatment in general decreased MGT by over 1 d, whereas at 20 °C MGT was decreased by just over 0.5 d. There was a significant three-way interaction for $T_{90} - T_{10}$ between species, treatment, and temperature ($F = 8.7$, $P < 0.001$). For tall fescue the difference between mean $T_{90} - T_{10}$ treatment values was not significant at 10 °C, but seed treated with a SFC did decrease $T_{90} - T_{10}$ at 20 and 30 °C (Table 2). Tall fescue seed with a SFC had mean $T_{90} - T_{10}$ values ≈2 d less than the control. For perennial ryegrass, $T_{90} - T_{10}$ at 10 °C was decreased by 2.3 d (Table 2). There was no significant difference found between mean $T_{90} - T_{10}$ treatment values for perennial ryegrass at 20 and 30 °C.

There was a significant two-way interaction between species and temperature for FGP ($F = 9.0$, $P < 0.001$); for almost all treatments, FGP was near 90%. One exception was found for tall fescue at 10 °C, where FGP of the control was 80.0%, whereas the SFC treatment was 85.3%. Minimal treatment effect by a SFC on FGP ($F = 0.3$, $P = 0.590$) was expected for the species tested in the study, which inherently have high germination rates (Christians, 1998).

SEEDLING EMERGENCE AND PLANT GROWTH EXPERIMENT. Sandy soil and the weekly watering regimen produced a less than suitable environment for seed germination and plant growth. Over a 7-d period, soil water content ranged from ≈30% at the time of rewatering to 10% just before watering. There was no statistical difference in soil water content between soils with treated and untreated seeds [$F = 36.24$, $P = 0.105$ (Fig. 1)].

The SFC produced significantly higher plant densities ($F = 61.96$, $P < 0.001$). A significant two-way interaction was found between treatment and DAS for plant density ($F = 5.86$, $P < 0.001$), with species also being a significant factor ($F = 61.96$, $P < 0.001$). On day 10, pots planted with seed with a SFC treatment had 54.8% more tall fescue and 21.5% more perennial ryegrass seedling emergence compared with the controls (Fig. 2). Over the course of the experiment both treatments experienced a decline in plant density, which is most likely because of seedlings desiccating in-between watering periods and intra-sward competition. Despite competition for limited moisture resources, plant density from the SFC treatment remained significantly higher over the course of the study (Fig. 2). Plant density began to stabilize between 24 and 31 DAS. Final plant density measurements made at 38 DAS showed the SFC treatment was 22.1% and 47.1% higher than the control for tall fescue and perennial ryegrass, respectively.

Significant single factors for cover included species ($F = 30.99$, $P <$

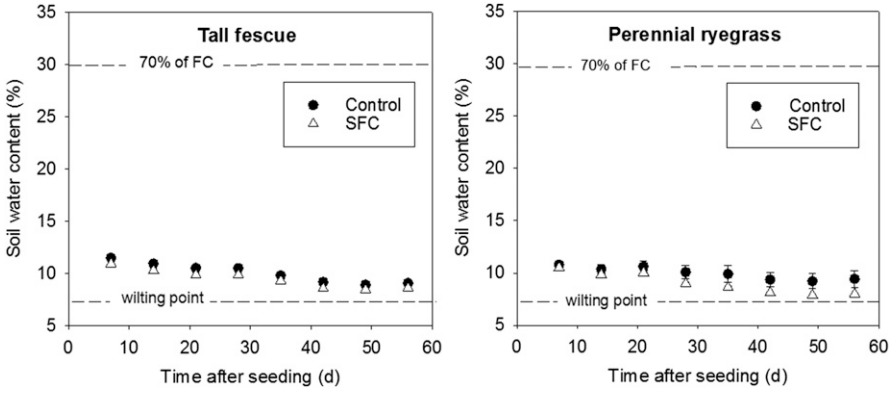

Fig. 1. Volumetric soil water content (mean ± SE) before weekly watering's for pots planted with uncoated seeds (control) and seed receiving a surfactant film coating (SFC) for tall fescue and perennial ryegrass. Note, pots were watered weekly to 70% of field capacity (FC).

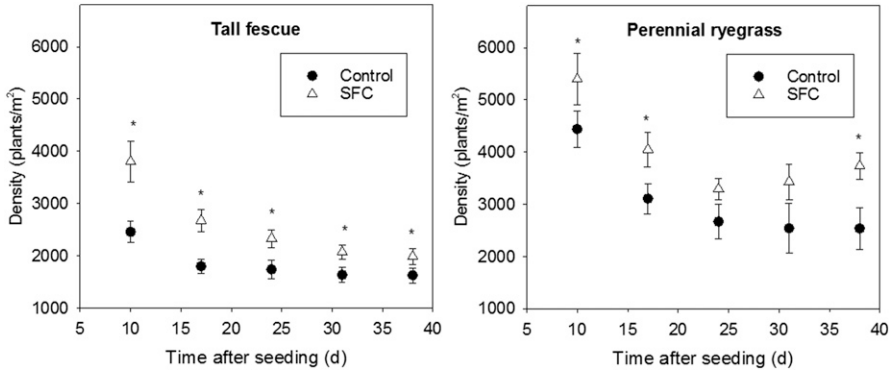

Fig. 2. Turfgrass density (mean ± SE) from uncoated seeds (control) and seed receiving a surfactant film coating (SFC) for tall fescue and perennial ryegrass. *Denotes significant difference between control and SFC by Bonferroni post hoc test at individual sampling dates ($P \leq 0.05$); 1 plant/m² = 0.0929 plant/ft².

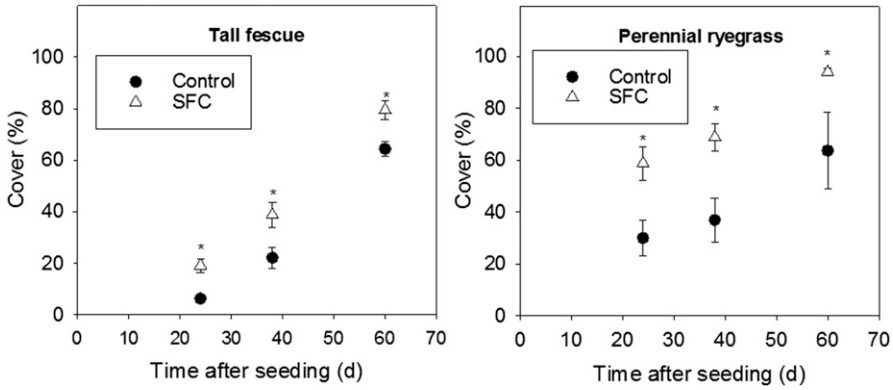

Fig. 3. Turfgrass cover (mean ± SE) from uncoated seeds (control) and seeds receiving a surfactant film coating (SFC) for tall fescue and perennial ryegrass. *Denotes significant difference between control and SFC by Bonferroni post hoc test at individual sampling dates ($P \leq 0.05$).

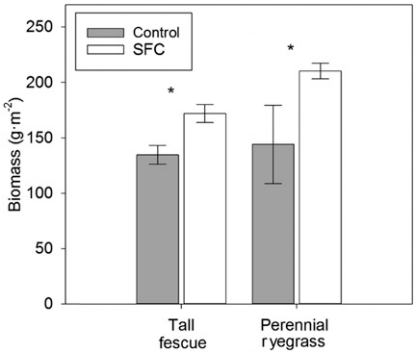

Fig. 4. Final aboveground biomass (mean ± SE) produced from uncoated seeds (control) and seeds receiving a surfactant film coating (SFC) for tall fescue and perennial ryegrass. *Denotes significant difference between control and SFC by Bonferroni post hoc test for individual species ($P \leq 0.05$); 1 g·m^{-2} = 0.0033 oz/ft^2.

0.001), treatment (F = 38.24, $P < 0.001$), and DAS (F = 58.34, $P < 0.001$). An increase in plant cover was exhibited from pots seeded with a SFC treatment. On day 24, newly emerged seedlings from a SFC treatment had cover values 3-fold and 2-fold higher than the control for tall fescue and perennial ryegrass, respectively (Fig. 3). At the conclusion of the study (60 DAS), plant cover of the SFC treatment was 1.25-fold and 1.5-fold higher than the control for tall fescue and perennial ryegrass, respectively. Interestingly, perennial ryegrass not only showed higher plant-density and cover values on average but variability between pots was far less in pots sown with a SFC treatment (Fig. 3). The SFC treatment also improved turfgrass aboveground biomass (F = 38.24, $P < 0.001$). At the conclusion of the study, perennial ryegrass and tall fescue with a SFC treatment had aboveground biomass that was 1.5- and 1.2-fold higher than the control, respectively (Fig. 4).

Discussion

This is the first study to demonstrate that a low-dose application of nonionic surfactant applied directly to seed as a component of a seed treatment was effective at increasing seed germination rate and synchrony. Interestingly, a SFC was most effective at improving germination at suboptimal (10 °C) and supra-optimal (30 °C) germination temperatures for cool-season turfgrass in Expt. 1. These results may indicate that a SFC treatment could have particular utility in extending the window turfgrass can be planted during the year. It can be advantageous to plant turfgrass seeds during periods of the year that are not optimal for seed germination such as early spring. Although temperatures are not always optimal for seed germination during this time, earlier seeding dates allow plants the time required to establish and have the capability to survive through the dormant winter season (Richardson et al., 2004; Schiavon et al., 2015; Shaver et al., 2006).

Expt. 1 also provides justification for the evaluation of a SFC treatment to other species and growing environments. As an example, many row crops are commonly seeded in soils having temperatures below optimal for seed germination (Bedi and Basra, 1993; Hassell et al., 2003). Suboptimal soil temperatures causes slow and nonuniform seedling emergence, which subsequently results in nonuniform plant sizes, harvest dates, poor crop quality, and low yields (Bedi and Basra, 1993).

Faster germination provided by the SFC treatment should also decrease the period soil needs to be maintained at elevated soil-water contents to allow for seed germination. In Expt. 2, greater germination velocity and improved germination synchrony were the contributing factors for SFC treatment producing higher plant densities, cover, and aboveground biomass. Also in Expt. 2, water regimes produced suitable soil water conditions for seed germination directly after watering. However, by the time the next watering occurred soil water content had declined to near wilting point. Thus, where water availability decreased overtime, seeds with faster germination times had a higher probability of completing germination and emergence processes under favorable soil moisture conditions.

Faster germination produced by a SFC treatment would also improve plant growth and survival by allowing the seedlings to grow deeper root systems to better use moisture resources from a rapidly drying wetting front (Nicotra et al., 2002). In addition to improved seed germination shown in Expt. 1, Expt. 2 demonstrates that a SFC treatment can enhance emergence and plant growth under a less than optimal irrigation regimen. Soil surfactants represent a new emerging technology for dealing with deficit irrigation. Chaichi et al. (2015) demonstrated that the application of a nonionic surfactant in irrigation water, improved field corn (*Zea mays*) water use efficiency and yield under deficit irrigation. Economic evaluations from Chaichi et al. (2015) showed that if a surfactant was applied the same profit could be obtained with 40% less water. Our findings that a SFC treatment can contribute to the improvement of seedling emergence and plant growth under deficit irrigation implies that this technology may help to lower

the amount and frequency of water needed for establishing turfgrass from seed. Irrigation water for urban landscapes is becoming increasingly limited (Huang, 2008), and expanding populations in need of water often draw on resources that are also in demand for crop production and maintenance of environmental and anthropogenic systems (Gleick, 2000). Hence, SFC treatment's ability to improve turfgrass establishment under deficit irrigation should help to conserve limited water supplies and enhance urban landscapes by lowering water requirements for establishing new turfgrass (Beard and Green, 1994).

It is unclear if a low-dose application of nonionic surfactant applied directly to seed will improve seed germination and plant growth under suitable temperature and soil moisture conditions. It is possible, however, that a low-dose application of nonionic surfactant applied directly to seed will improve uptake of other seed treatments. Research efforts to regenerate whole plants has suggested that nonionic surfactants may influence shoot regeneration frequency by increasing the permeability of the plasma membrane to growth regulators and/or nutrients by creating transient increases in membrane fluidity (Grant and Hammatt, 2000; Lowe et al., 1994). It may be plausible that seed absorption of various biostimulants such as plant growth regulators, fungicides, and fertilizers could be improved by adding a nonionic surfactant within the seed treatment formulation. Future research is needed to determine how a low-dose seed application of surfactant responds with and in comparison with other seed treatments in laboratory and field trials for improving seed germination under stress conditions.

Literature cited

Anthony, P., M.R. Davey, J.B. Power, C. Washington, and K.C. Lowe. 1994. Image analysis assessments of perfluorocarbon and surfactant enhanced protoplast division. Plant Cell Tissue Organ Cult. 38:39–43.

Beard, J.B. and R.L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 9:452–460.

Bedi, S. and A.S. Basra. 1993. Chilling injury in germinating seeds: Basic mechanisms and agricultural implications. Seed Sci. Res. 3:219–229.

Bewley, J.D. and M. Black. 1994. Seeds: Physiology of development and germination. 2nd ed. Plenum Press, New York, NY.

Brutovská, R., E. Čellárová, and M.R. Davey. 1994. Stimulation of multiple shoot regeneration from reedling leaves of *Hypericum perforatum* L. by Pluronic F-68. Acta Biotechnol. 14:347–353.

Cassel, D. and D. Nielsen. 1986. Field capacity and available water capacity, p. 901–926. In: A. Klute (ed.). Methods of soil analysis, Part 1. 2nd ed. Soil Sci. Soc. Amer., Madison, WI.

Chaichi, M.R., P. Nurre, J. Salven, and M. Rostamza. 2015. Surfactant application on yield and irrigation water use efficiency in corn under limited irrigation. Crop Sci. 55:386–393.

Christians, N. 1998. Fundamentals of turfgrass management. Ann Arbor Press, Chelsea, MI.

Fereres, E. and M.A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. J. Expt. Bot. 58:147–159.

Frelich, J.R., E.H. Jensen, and R.O. Gifford. 1973. Effect of crust rigidity and osmotic potential on emergence of six grass species. Agron. J. 65:26–29.

Gleick, P.H. 2000. The changing water paradigm—A look at twenty-first century water resources development. Water Intl. 25:127–138.

Grant, N.J. and N. Hammatt. 2000. Adventitious shoot development from wild cherry (*Prunus avium* L.) leaves. New For. 20:287–295.

Gregg, B.R. and G.L. Billups. 2010. Seed conditioning. Vol. 2. Technology—Part A. Science Publishers, Enfield, NH.

Halmer, P. 2008. Seed technology and seed enhancement. Acta Hort. 771:17–26.

Hassell, R.L., R.J. Dufault, and T.L. Phillips. 2003. Low-temperature germination response of su, se, and sh_2 sweet corn cultivars. HortTechnology 13:136–141.

Huang, B. 2008. Turfgrass water requirements and factors affecting water usage, p. 193–205. In: J.B. Beard and M.P. Kenna (eds.). Water quality and quantity issues for turfgrass in urban landscapes. Council Agr. Sci. Technol. Spec. Publ. No. 27.

Khatun, A., M.R. Davey, J.B. Power, and K.C. Lowe. 1993. Stimulation of shoot regeneration from jute cotyledons cultured with non-ionic surfactants and relationship to physico-chemical properties. Plant Cell Rpt. 13:49–53.

Khatun, A., N. Zabun, M. Shirin, K. Chandan, and B. Shahna. 2003. An efficient protocol for plant regeneration from the cotyledons of kenaf (*Hibiscus cannabinus* L). Biotechnology. 2:86–93.

Kostka, S.J. and G. Schuermann. 2008. Enhancing plant productivity by improving the plant growth medium environment with alkyl ethers of methyl oxirane-oxirane copolymer surfactants. U.S. Patent No. 7,399,730. U.S. Patent Trademark Office, Washington, DC.

Larsen, S.U. and B.M. Bibby. 2005. Differences in thermal time requirement for germination of three turfgrass species. Crop Sci. 45:2030–2037.

Lowe, K.C., P. Anthony, M.R. Davey, and J.B. Power. 2001. Beneficial effects of Pluronic F-68 and artificial oxygen carriers of the post-thaw recovery of cryopreserved plant cells. Artif. Cells Blood Substit. Immobil. Biotechnol. 29:297–316.

Lowe, K.C., M.R. Davey, L. Laouar, A. Khatun, R.C.S. Ribeiro, J.B. Power, and B.J. Mulligan. 1994. Surfactant stimulation of growth in cultured plant cells, tissues and organs, p. 234–244. In: P.J. Lumsden, J.R. Nicholas, and W.J. Davies (eds.). Physiology, growth and development of plants in culture. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Madsen, M.D., D.L. Zvirzdin, B.A. Roundy, and S.J. Kostka. 2014. Improving reseeding success after catastrophic wildfire with surfactant seed coating technology, p. 44–48. In: S. Carmine (ed.). Pesticide formulation and delivery systems. Vol. 33. Sustainability: Contributions from formulation technology. ASTM Intl., West Conshohocken, PA.

Madsen, M.D., S.J. Kostka, A. Hulet, B.E. Mackey, M.A. Harrison, and M.F. McMillan. 2013. Surfactant seed coating—A strategy to improve turfgrass establishment on water repellent soils. Proc. 10th Intl. Symp. Adjuvants for Agrochemicals. Foz do Iguaçu, Brazil. p. 205–210.

Madsen, M.D., S.J. Kostka, A.L. Inouye, and D.L. Zvirzdin. 2012. Post-fire restoration of soil hydrology and wildland vegetation using surfactant seed coating technology. Rangeland Ecol. Mgt. 65: 253–259.

Madsen, M.D., S.L. Petersen, and A.G. Taylor. 2010. Seed coating compositions

and methods for applying soil surfactants to water-repellent soil. U.S. Patent Appl. No. 20,100,267,554. U.S. Patent Trademark Office, Washington, DC.

Moore, D., S.J. Kostka, T.J. Boerth, M. Franklin, C.J. Ritsema, and L.W. Dekker. 2010. The effect of soil surfactants on soil hydrological behavior, plant growth environment, irrigation efficiency, and water conservation. J. Hydrol. Hydromechanics 58:142–148.

Nicotra, A.B., N. Babicka, and M. Westoby. 2002. Seedling root anatomy and morphology: An examination of ecological differentiation with rainfall using phylogenetically independent contrasts. Oecologia 130:136–145.

Perry, D.A. 1980. Seed vigour and seedling establishment. Adv. Res. Technol. Seeds 5:25–40.

Richardson, M.D., D.E. Karcher, P. Berger, and J.W. Boyd. 2004. Utilizing improved seeded bermudagrasses on transition-zone sports fields. Acta Hort. 661:369–374.

Schiavon, M., B. Leinauer, M. Serena, R. Sallenave, and B. Maier. 2013. Establishing tall fescue and kentucky bluegrass using subsurface irrigation and saline water. Agron. J. 105:183–190.

Schiavon, M., M. Serena, B. Leinauer, R. Sallenave, and J.H. Baird. 2015. Seeding date and irrigation system effects on establishment of warm-season turfgrasses. Agron. J. 107:880–886.

Scott, J.M. 1989. Seed coatings and treatments and their effects on plant establishment. Adv. Agron. 42:43–83.

Shaver, B.R., M.D. Richardson, J.H. McCalla, D.E. Karcher, and P.J. Berger. 2006. Dormant seeding bermudagrass cultivars in a transition-zone environment. Crop Sci. 46:1787–1792.

Taylor, A.G. and G.E. Harman. 1990. Concepts and technologies of selected seed treatments. Annu. Rev. Phytopathol. 28:321–339.

U.S. Department of Agriculture. 2014. Web soil survey. 5 Aug. 2014. <http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx/>.