

Normalized Difference Vegetative Index Response of Nonirrigated Kentucky Bluegrass and Tall Fescue Lawn Turf Receiving Seaweed Extracts

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Abstract. Turf managers are continually seeking improved grasses, management practices, and products that enhance heat and drought tolerance and reduce supplemental irrigation needs. To this end, products like seaweed extract (SWE) have been extensively studied on short-cut (≤ 12 mm) golf turf and seedlings of various turfgrass species exposed to stress conditions. Few studies, however, have reported SWE effects on mature, higher cut (≥ 38 mm) cool-season turfgrass swards. A 3-year field study (2013–15) was conducted in Connecticut to determine the effect of various SWE treatments on the normalized difference vegetative index (NDVI) response of nonirrigated kentucky bluegrass (*Poa pratensis* L.) and tall fescue (*Festuca arundinacea* Schreb.) turf managed as a lawn and cut at 76.2 mm. Separate experiments for each species were set out as randomized complete block designs with three replicates. Throughout the growing season in each year, various liquid SWEs were applied at a concentration of 9.55 L·ha⁻¹ weekly or 19.1 L·ha⁻¹ biweekly. A nontreated control was included. The study lacked extreme heat stress conditions during the yearly growing seasons, but periodic moisture deficits below normal were present. Within each year, there were no significant SWE effects on the NDVI of either species. The results suggest that there is no improvement in the NDVI by applying SWEs to mature, higher cut cool-season turfgrass lawns under less than extreme heat-stress conditions, water-stress conditions, or both. Because this study was conducted only at one site without extreme stress, further research of SWE applications to established, higher cut cool-season turfgrass lawns should be conducted across different locations and soils to determine the effects of applying SWE to these stands under extreme heat-stress conditions, water-stress conditions, or both.

SWE (extracts of *Ascophyllum* spp. and related macroalgae) applied to horticulturally important plants have been reported to act as biostimulants for root and shoot growth, increase abiotic-stress tolerance, and to act as inducers of plant defenses against pathogens and insect pests (reviewed in Sangha et al., 2014). Turf managers are continually seeking improved grasses, management practices, and products that enhance heat and drought tolerance, and reduce supplemental irrigation needs. To this end, SWE have been extensively studied on creeping bentgrass

(*Agrostis stolonifera* L.) used for low-cut golf putting greens or fairways (with heights of cut from 3 to 4 mm and 10 to 12 mm, respectively) to improve heat, drought stress, salinity, or shade tolerance of established stands or to enhance the establishment and seedling survival of newly seeded bentgrass stands (Table 1). Other studies have investigated turfgrass response to SWEs applied to kentucky bluegrass (*Poa pratensis* L.) or tall fescue (*Festuca arundinacea* Schreb.) seedlings or to sod crops (mowed at 50 mm) of these species before harvest to extend post-harvest shelf life or enhance transplanting establishment and to enhance tolerance to ultraviolet-B radiation (Table 1). Additional studies investigated SWE to enhance seedling emergence and survival or drought stress tolerance of newly established creeping red fescue (*F. rubra* var. *rubra* L.) and perennial ryegrass (*Lolium perenne* L.) stands (Table 1). Most of these studies have reported beneficial effects of SWE applications to enhance the stress tolerance of turfgrasses. However, few studies have evaluated the effect of SWE on established lawn turf.

The Normalized Difference Vegetative Index is commonly used as an indirect, but quantitative, measure of turfgrass green color

and visual quality or appearance, to differentiate species and cultivars, and to determine N fertility treatment effects (Bell et al., 2002, 2004; Bremer et al., 2011a, 2011b; Fitz-Rodríguez and Choi, 2002; Geng et al., 2014; Lee et al., 2011; Stiegler et al., 2005; Trenholm et al., 2001; Xiong et al., 2007). Because abiotic stresses can affect turfgrass color, NDVI has also been used to distinguish treatment differences in response to drought stress (Burgess and Huang, 2014; Fenstermaker-Shaulis et al., 1997; Huang et al., 1998; Jiang and Carrow, 2005; Jiang et al., 2009; Johnsen et al., 2009; Merewitz et al., 2010; Taghvaeian et al., 2013), heat stress (Wang et al., 2013, 2014), and salinity stress (Schiavon et al., 2014) in both cool- and warm-season turfgrasses. In these studies, NDVI was greater in those treatments that provided the most stress tolerance when compared with controls or other less-effective treatments. In general, the results of these studies are consistent and strongly suggest that NDVI can identify turfgrass color changes, quality changes, or both in response to abiotic stress.

Subjective visual estimates of color, quality, or both are generally positively correlated with NDVI (Bell et al., 2009; Bremer et al., 2011a; Fitz-Rodríguez and Choi, 2002; Lee et al., 2011; Leinauer et al., 2014; Schiavon et al., 2014). However, predictive models of visual estimates based on NDVI typically have wide 95% confidence intervals because visual quality can range by several scale units at any given NDVI reading (Bremer et al., 2011a). This is probably due to NDVI being measured on a continuous scale (from 0 to 1) and subjective visual ratings reported on a discrete ordinal scale, usually from 1 to 9. Variability within NDVI measurements is often less than variability within visual estimations (Bremer et al., 2011a; Lee et al., 2011), suggesting that NDVI may be able to identify smaller differences than can be distinguished with subjective visual ratings. In drought-stressed creeping bentgrass, NDVI was able to detect water stress up to 48 h before visual assessments could recognize it (Johnsen et al., 2009). However, in one reported case, NDVI of warm-season turfgrasses under increasing and prolonged soil water deficit was not an effective predictor of drought stress (Cathey et al., 2011).

There is a lack of information on the NDVI response of mature, higher cut cool-season turfgrass lawns in relation to liquid SWE applications in temperate climates under field conditions. This research was conducted to determine the effect of several commercially available SWE products, and one experimental product, on the NDVI response of established and nonirrigated kentucky bluegrass and turf-type tall fescue lawns in southern New England. Our hypothesis was that if SWE was effective in increasing stress tolerance, especially under nonirrigated conditions, greater NDVI readings would be obtained where it was applied.

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Table 1. Summary of studies investigating the effects of seaweed extracts on cool-season turfgrass responses. Mature turf is at least 1 year's growth past seeding.

Species	Variable or effect measured	Study conditions	Reference
Creeping bentgrass (<i>Agrostis stolonifera</i> L.)	Seeding drought stress	Controlled environment	Zhang and Schmidt (2000)
	Mature turf summer stress tolerance	Field	Zhang et al. (2003a)
	Mature turf summer stress tolerance	Field	Xu and Huang (2010)
	Mature turf shade tolerance	Field	Ervin et al. (2004a)
	Mature turf drought resistance	Controlled environment	Zhang and Ervin (2004)
	Mature turf salinity tolerance	Controlled environment	Doak et al. (2005)
	Seeding salinity tolerance	Controlled environment	Koske and Gemma (2005)
	2-month-old turf growth and development	Controlled environment	Hunter and Butler (2005)
	Mature turf growth and development	Field	Butler and Hunter (2007)
	Mature turf microbial communities and turf quality	Field	Mueller and Kussow (2005)
	3-month-old turf heat tolerance	Controlled environment	Zhang and Ervin (2008)
	3-month-old turf heat tolerance	Controlled environment	Zhang et al. (2010)
	Seeding drought stress	Controlled environment	Zhang and Schmidt (1997)
	Seeding growth and development	Controlled environment	Zhang and Schmidt (1999)
Kentucky bluegrass (<i>Poa pratensis</i> L.)	Mature sod transplant survival	Field and controlled environment	Goatley and Schmidt (1990)
	Seeding turf quality and nutrient efficiency	Field	Goatley and Schmidt (1991)
	Mature turf salinity tolerance	Controlled environment	Yan et al. (1993)
	Mature sod recovery from heat stress	Field	Nabati et al. (1994)
		Field grown; heat treatment controlled environment; transplanted back into field	Zhang et al. (2003a)
	Mature turf ultraviolet-B radiation tolerance	Controlled environment	Ervin et al. (2004b)
	Seeding drought stress	Controlled environment	Zhang and Schmidt (2000)
Tall fescue (<i>Festuca arundinacea</i> Schreb.)	Mature sod heat tolerance and transplant quality	Field grown; heat treatment controlled environment; transplanted back into field	Zhang et al. (2003b)
Perennial ryegrass (<i>Lolium perenne</i> L.)	1-month and older turf drought stress	Controlled environment	Yan et al. (1997)
Creeping red fescue (<i>F. rubra</i> var. <i>rubra</i> L.)	Seeding growth and development	Controlled environment	Hunter (2004)
	Seeding emergence and survival	Controlled environment	Button and Noyes (1964)

Materials and Methods

Field experiments were conducted at the University of Connecticut's Department of Plant Science and Landscape Architecture Research and Education Facility, located in Storrs, CT (41°47'N; 72°13'W; elevation 203 m), from July 2013 through Oct. 2015. Separate, but adjacent, field plot experiments were conducted on established stands of kentucky bluegrass (blend of 'Blue Velvet', 'America', 'Granite', and 'Moon Shadow') and tall fescue (blend of 'Crossfire 3', 'Mustang 4', and 'Cayenne'). The stands were seeded on 19 Aug. 2009, on a Paxton fine sandy loam soil (coarse-loamy, mixed, active, mesic Oxyaquic Dystrudepts).

The experiments were set out as randomized complete block designs with three replicates. Individual plot size was 1.8 × 3 m. Treatments consisted of the following liquid SWE treatments: Sea Green Organics (Sea Green Organics LLC, Bridgeport, CT), Ocean Organics Guarantee Organic 0–0–1 and EXP DRX experimental (Ocean Organics, Natural and Organic Fertilizers, Wal-doboro, ME), Neptune's Harvest Seaweed Plant Food 0–0–1 (Neptune's Harvest, Gloucester, MA), and Sarkli/Repêchage Agri-Force Standard and AgriForce 50 (Sarkli/Repêchage Ltd., Secaucus, NJ). The primary ingredient of each product is liquefied *Asco-phyllum nodosum* or a proprietary blend of *A. nodosum* and other seaweeds. EXP DRX and AgriForce50 also had a small amount of other proprietary ingredients, which cannot be disclosed because of confidentiality agreements. A water (well-water source) control treatment was included.

Each SWE was applied weekly at a concentration of 9.55 L·ha⁻¹ or biweekly at a concentration of 19.1 L·ha⁻¹ throughout the growing season. The total monthly application rate for each treatment was 38.2 L·ha⁻¹. Because there was no label information or recommended rates specifically for turfgrass with Sea Green Organics, Ocean Organics EXP DRX, Neptune's Harvest Seaweed Plant Food 0–0–1, or Sarkli/Repêchage AgriForce Standard and AgriForce 50, application rates were selected based on the ranges of recommended label rates for the Ocean Organics Guarantee Organic 0–0–1 (9.55 to 19.2 L·ha⁻¹ every 14 d). The SWE concentrate was diluted in water and applied using a CO₂-pressurized sprayer with a hand-held boom outfitted with flat-fan nozzles calibrated to deliver a total volume of 815 L·ha⁻¹ at 276 kPa. Control plots received the same total volume of water.

Treatments were applied to the same plots each year from 17 July to 21 Nov. 2013, 14 May to 26 Oct. 2014, and 19 May to 1 Oct. 2015. The turf was managed as a lawn and mowed at a 76.2-mm cutting height as needed to avoid scalping throughout the growing season. No irrigation was applied. Across all growing seasons, 49 kg N/ha was applied in May and another 49 kg N/ha was applied in October using urea (45–0–0) as the N source. Annual soil test results of the study area indicated that soil extractable levels of

phosphorus and potassium were sufficient for turf growth throughout the duration of the experiment. Pest control was applied as needed (warm-season annual grass weeds, broadleaf weeds, and white grubs).

Turfgrass color, as indicated by NDVI, was measured with a Spectrum FieldScout CM 1000 NDVI Chlorophyll Meter (Spectrum Technologies, Inc., Aurora, IL) at about weekly or biweekly intervals throughout the application periods. Ten measurements per plot of the turf canopy were taken with the meter between 1000 and 1400 hr on sunny days and averaged per plot. All measurements were taken with the meter facing away from the sun at a height of ≈ 1 m from the turf canopy. NDVI was measured on 11 dates in 2013, 19 dates in 2014, and 12 dates in 2015 for tall fescue and 11 dates in 2015 for kentucky bluegrass.

Because the number of sampling dates was different within each season, NDVI data were analyzed separately by species and year. In each year, NDVI data were analyzed using repeated measures ANOVA with the MIXED procedure of SAS/STAT 14.1 software (SAS Institute Inc., 2015). The blocking effect was considered as random, and sampling date within each year was considered the repeated measure.

Results

Weather conditions. In general, few high air temperature stress periods were present across the 3-year study. Mean maximum monthly temperatures did not exceed 27.5 °C for any month (Table 2). Across the active growing season (April through No-

vember), there were only 4 d where maximum daily temperatures were ≥ 32.2 °C—2 d in July 2013, 1 d in July 2015, and 1 d in Sept. 2015.

Although no prolonged high air temperature periods were recorded across the data collection periods (July–Oct. 2013, May–Oct. 2014 and 2015), there were instances of monthly rainfall deficits (Table 2). Of the 15 months during data collection, 11 months received below-normal rainfall amounts, ranging from slight (5 mm or 4.9% below normal) to extensive (84 mm or 83.4% below normal). On average, months that were in rainfall deficit were 41 mm or 38.3% below normal. The greatest precipitation deficits relative to normal amounts occurred in September (–39 mm) and October (–82 mm) 2013, June (–56 mm) and September (–65 mm) 2014, and May (–84 mm), July (–54 mm), and August (–22 mm) 2015. Overall, 2015 was a relatively dry year as the precipitation total during the May–October data collection period was 101 mm or 16% below normal, with five of the six monthly precipitation totals below normal. In addition, the 6 months before May 2015 had below-normal precipitation (cumulative deficit of –125 mm or 20% below normal).

NDVI. There were no significant differences ($P > 0.05$) for the SWE treatment NDVI means across sampling dates, and there was no treatment \times date interaction effect for kentucky bluegrass or tall fescue in any year (Table 3). The only significant ($P < 0.05$) model effect for NDVI was attributed to sampling date (Table 3). Across the growing season in each year, NDVI varied, with the mean NDVI (pooled across treatments) of

kentucky bluegrass and tall fescue following similar trends across the measurement dates (Fig. 1).

Discussion

Most of the reported research in the literature that investigated the effects of SWE applied to cool-season turfgrasses was conducted under conditions of high stress (heat, drought, and salinity) with young seedlings of various species, or mature low-cut bentgrass golf turf (Table 1). Under these conditions, the previous studies suggested that the application of SWE could result in greater tolerances to stress in many cases.

There are limited data, however, on the reported effects of SWE applied to older, established turfgrass swards managed as higher cut (≥ 38 mm) turf under field conditions. Of the previous studies with mature (>1-year-old stand), higher cut kentucky bluegrass or tall fescue swards receiving SWE, results have been mixed. Application of SWE to kentucky bluegrass sod turf mowed at 38 mm had little effect on post-transplant rooting and sod strength (Goatley and Schmidt, 1991). Whereas, SWE in combination with humic acid enhanced transplant rooting and generally reduced visual stress symptoms of high-heat-stressed kentucky bluegrass and tall fescue sod mowed at 50 mm (Zhang et al., 2003a, 2003b). Because SWE and humic acids were not applied separately in these studies (only in combination), it cannot be determined if the positive turf response to treatment was attributed to the individual SWE or humic acid components or the synergistic effect in combination.

Table 2. Monthly and active growing period April through November temperature and precipitation across the 3-year study period (July 2013 to Oct. 2015) with 30-year normal (Norm, 1981–2010) at Storrs, CT. Data collection periods are shaded.

Month	Temperature minimum (°C)				Temperature maximum (°C)				Precipitation (mm)			
	2013	2014	2015	Norm	2013	2014	2015	Norm	2013	2014	2015	Norm
Jan.	–6.8	–9.9	–9.9	–7.5	1.6	–0.7	–1.7	0.6	54	81	66	96
Feb.	–5.8	–7.9	–14.6	–5.8	1.3	–0.1	–4.6	2.7	91	82	60	85
Mar.	–2.3	–6.8	–5.4	–2.2	4.5	2.6	3.1	6.8	56	117	78	113
Apr.	2.5	2.5	2.9	3.4	13.0	12.4	12.9	13.4	54	108	96	115
May	8.4	8.7	9.6	8.3	19.9	18.6	22.8	19.3	143	133	17	101
June	14.4	13.6	13.1	13.7	24.1	23.1	22.6	23.8	309	58	198	113
July	19.8	16.9	16.4	16.6	27.1	25.4	26.5	26.2	91	111	46	100
Aug.	14.8	14.6	16.0	15.7	23.8	24.0	26.9	25.6	92	83	75	97
Sep.	10.5	11.5	13.6	11.7	20.8	21.7	25.4	21.7	65	39	96	104
Oct.	5.9	7.1	4.7	5.7	16.3	15.2	15.7	15.6	35	150	98	117
Nov.	–0.9	–0.6	3.1	1.5	8.8	7.7	12.3	9.8	97	107	47	116
Dec.	–4.7	–2.0	2.2	–4.2	2.5	4.8	10.6	3.3	86	100	104	107
Month	Deviation (%) from normal				Deviation (%) from normal				Deviation (%) from normal			
	2013	2014	2015		2013	2014	2015		2013	2014	2015	
Jan.	–9.3	31.9	31.9		161.8	–218.2	–381.8		–43.5	–16.4	–31.4	
Feb.	0.4	36.5	152.9		–52.2	–104.1	–269.4		7.4	–3.0	–29.3	
Mar.	3.5	205.0	142.5		–34.1	–61.8	–54.5		–50.6	3.4	–30.9	
Apr.	–26.2	–26.2	–14.8		–3.3	–7.9	–4.1		–52.9	–6.0	–16.8	
May	0.8	4.7	15.3		3.2	–3.5	18.2		41.3	31.5	–83.4	
June	4.9	–0.8	–4.5		1.1	–3.0	–5.1		173.1	–49.1	74.9	
July	19.6	2.0	–1.0		3.6	–3.0	1.3		–9.6	11.2	–53.6	
Aug.	–5.5	–6.7	2.1		–6.9	–6.1	5.2		–4.9	–14.4	–22.3	
Sep.	–10.0	–1.4	16.7		–4.0	0.3	17.2		–37.8	–62.3	–7.8	
Oct.	4.1	25.5	–16.7		4.4	–2.5	0.7		–69.9	28.5	–16.1	
Nov.	–160.0	–140.7	107.4		–10.5	–21.5	24.9		–16.7	–7.7	–59.3	
Dec.	11.3	–52.6	–152.6		–25.0	43.3	218.3		–19.3	–6.4	–2.9	

Table 3. Mean normalized difference vegetative index (NDVI) values for kentucky bluegrass and tall fescue lawn turf receiving seaweed extracts treatments across the growing seasons in 2013, 2014, and 2015 plus *P* values for source effects attributed to treatments, sampling dates, and treatment × date interactions.

			Kentucky bluegrass			Tall fescue		
			2013	2014	2015	2013	2014	2015
Treatment	Rate (L·ha ⁻¹)	Interval (d)	NDVI					
AgriForce 50	9.55	7	0.886	0.888	0.835	0.897	0.877	0.832
	19.1	14	0.879	0.888	0.823	0.894	0.871	0.835
AgriForce standard	9.55	7	0.882	0.890	0.827	0.895	0.866	0.834
	19.1	14	0.879	0.889	0.834	0.892	0.873	0.834
EXPDRX	9.55	7	0.886	0.889	0.834	0.898	0.878	0.840
	19.1	14	0.882	0.888	0.835	0.898	0.873	0.836
Neptune's harvest	9.55	7	0.888	0.890	0.835	0.891	0.873	0.832
	19.1	14	0.886	0.891	0.829	0.894	0.876	0.841
Ocean organics	9.55	7	0.882	0.888	0.833	0.896	0.883	0.829
	19.1	14	0.885	0.889	0.831	0.891	0.873	0.837
Sea green organics	9.55	7	0.886	0.892	0.839	0.893	0.876	0.839
	19.1	14	0.887	0.889	0.842	0.888	0.868	0.836
Control			0.884	0.890	0.845	0.893	0.874	0.837
Source effect			<i>P</i> values					
Treatment			0.1222	0.9953	0.1206	0.4397	0.5651	0.9871
Date			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment × Date			0.9984	0.9999	0.9999	0.9543	0.9989	0.9360

Application of SWE to 1-year-old kentucky bluegrass turf clipped at 50 mm under salinity stress improved rooting and color response compared with the nontreated control (Nabati et al., 1994).

Our results show that no differences in NDVI were obtained by applying SWE to mature (4–6 years old), high-cut (76.2 mm), nonirrigated, moderately fertilized kentucky bluegrass and tall fescue turf managed as lawns at our location in the absence of extreme heat stress, water stress, or both conditions. The absence of high-heat stress in our studies may have precluded finding a beneficial effect of SWE application that has been previously reported for higher cut kentucky bluegrass and tall fescue sod turf (Zhang et al., 2003a, 2003b). However, these previous studies also included humic acid with SWE applications, and therefore, a direct comparison with our studies cannot be made because effects due to the individual products in combination could not be separated.

NDVI was chosen to detect the effects of SWE on turf quality in our study because turf canopy reflectance can be affected by changes in environmental conditions, especially abiotic stress. In general, higher NDVI readings indicate darker green and denser turf, and therefore, less-stressed turfgrass plants. The N fertility regime in our study was selected to remove nutrient deficiencies as a limiting factor for turfgrass color, and pest control measures were applied to maintain optimum turf density and vegetative cover. We assumed that any changes in turfgrass NDVI would, therefore, be related to abiotic stress conditions.

Previous studies have reported significantly higher NDVI readings for treatments that prevent or lessen water stress compared with nontreated controls or treatments that were not as effective (Burgess and Huang, 2014; Fenstermaker-Shaulis et al., 1997; Huang et al., 1998; Jiang and Carrow, 2005; Jiang et al., 2009; Johnsen et al., 2009; Merewitz et al., 2010; Taghvaeian et al., 2013). Other canopy reflectance measure-

ments [ratio of near infrared (935 nm) to red (661 nm)] have shown that seaweed-treated creeping bentgrass had 11% to 27% higher R_{935}/R_{661} ratios than nontreated plots under summer stress conditions (Xu and Huang, 2010).

The lack of significant differences in NDVI response in our study between SWE and control treatments may be attributed, at least in part, to the lack of high air temperature stress conditions at our location across the 2013–15 growing seasons. This 3-year period was unexpectedly free of any extreme heat waves (in the Northeastern United States, this is typically defined by the National Weather Service as three or more consecutive days ≥ 32.2 °C). In our climate, it is not unusual to experience several heat waves in any given summer. However, this was not the case across our study. Typically, when air temperatures reach or exceed 35 °C, cool-season turfgrasses will exhibit signs or symptoms of heat stress (Lyons et al., 2007; Shen et al., 2009; Su et al., 2007).

Although there were few high-temperature stress periods during our study, there were periods when monthly precipitation amounts were lower than normal. This was particularly the case in 2015 when the monthly precipitation totals across the data collection period were well-below normal (–8% to –83%), except for 1 month (Table 2). In addition, the prior 6 months before May 2015 had cumulative total precipitation that was –125 mm in deficit or 20% below normal. Although we cannot conclusively state that water stress was present during these periods (because we did not measure visual wilting symptoms or soil moisture concentrations nor did we have a well-watered control treatment for comparison), NDVI for both species seemed to be strongly affected by the cumulative amount of precipitation received before each measurement (Fig. 1). The trend for both species showed a general pattern of increasing NDVI with higher accumulated precipitation amounts before each measurement and decreasing

NDVI with lower amounts of accumulated precipitation before each measurement.

If water stress-related benefits were to be obtained from SWE applications, it should have been shown with higher NDVI measurements of the SWE-treated plots compared with the nontreated control plot when precipitation amounts were lower than normal. However, we did not find any significant positive SWE effect above the non-treated control for either species at any date in any year (data not shown). Although SWE applications have been reported to enhance water-stress tolerance in short-cut mature bentgrass golf turf or other cool-season turfgrass species during the early seedling stage of development (Xu and Huang, 2010; Yan et al., 1997; Zhang and Schmidt, 1997, 1999, 2000; Zhang and Ervin, 2004), we did not observe this for mature (4 to 6-years old), higher cut kentucky bluegrass and tall fescue turf managed as higher cut lawn at our location under less than extreme heat- and water-stress conditions.

It has been reported that SWE can enhance certain metabolic processes or compounds that promote stress tolerance in turfgrass plants, such as photochemical efficiency, α -tocopherol, superoxide dismutase and catalase activity, CO_2 exchange rates, total carotenoids, anthocyanin, total polar lipid fatty acids and total free sterols, zeatin riboside, and ascorbic acid (Doak et al., 2005; Ervin et al., 2004a, 2004b; Goatley and Schmidt, 1990; Yan et al., 1997; Zhang and Ervin, 2004, 2008; Zhang and Schmidt, 1997, 1999, 2000, 2003a, 2003b, 2003c). It may be possible that these processes or compounds were enhanced, or their concentrations increased within the turfgrass plants in our study in response to SWE application, but we are unable to verify whether this occurred because we did not measure any physiological or biochemical process or metabolites associated with these activities. Because turfgrass color is highly correlated with stress, we are confident that if any meaningful stress-reducing physiological or biochemical processes were enhanced in our study, we

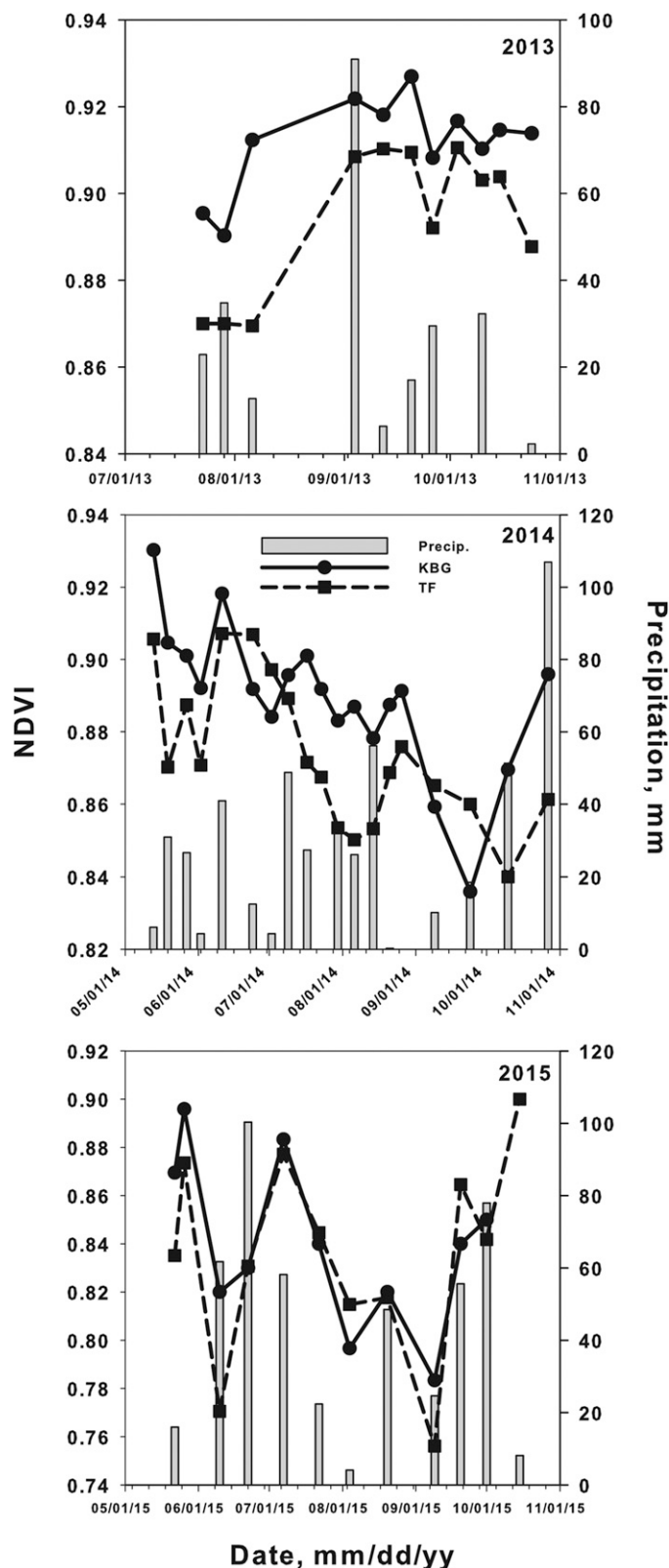


Fig. 1. Mean kentucky bluegrass (KBG) and tall fescue (TF) normalized difference vegetative index (NDVI) values averaged across all treatments for each measurement date (mm/dd/yy) within each year and accumulated precipitation amounts (precip.) between readings. Precipitation amount for the first reading is 10 d before the measurement.

would have detected that through NDVI readings. If any positive physiological changes did occur, they were most likely too small to markedly affect NDVI.

We did not observe any NDVI differences between SWE treatments and the control at the first-spring sampling date in each year before SWE application (data not shown).

This suggests that no residual benefits of SWE applications carried over from the previous fall for mature, higher cut kentucky bluegrass or tall fescue lawn turf in our location.

The only effect on NDVI that we observed in our experiment was the date of measurement. There were significant changes in mean NDVI across all treatments within each growing season, and these seemed to be associated with the accumulated precipitation amounts before each measurement (Fig. 1). Changes in NDVI across the growing season have been previously reported for both cool- and warm-season turfgrasses (Johnsen et al., 2009; Lee et al., 2011; Xiong et al., 2007).

Summary and Conclusions

There was no significant benefit to NDVI of applying SWE to nonirrigated, higher cut mature kentucky bluegrass and tall fescue lawns at our location in the absence of extreme heat-stress conditions, water-stress conditions, or both. In contrast to previous studies on short-cut turf, the lack of any positive response in our study may be attributed to mowing height effects and the lack of extreme stress conditions. With shorter cut turf, grass plants have shallower roots, less photosynthetic leaf area, and are more susceptible to environmental stresses than higher cut turf. In these cases, the effects of supplemental biostimulant products may be more advantageous in shorter cut turf than in higher cut turf, because the grass plants may have a reduced capacity to manufacture stress-protection endogenous hormones in response to the stresses. The higher cut turf in our study most likely had a greater capacity to produce endogenous stress-protecting hormones, resulting in no apparent benefit from the supplemental SWE biostimulants under less than extreme stress conditions, even though there were periods of below normal precipitation.

Because this study was conducted only at one site without extreme stress, further research of SWE applications to established, higher cut cool-season turfgrass lawns should be conducted across different locations and soils to determine the effects of applying SWE to these stands under extreme heat-stress conditions, water-stress conditions, or both.

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