CHAPTER 3

USING REMOTE SENSING TECHNIQUES TO ASSESS DROUGHT AND SALINITY STRESS IN HYBRID BLUEGRASS UNDER FIELD CONDITIONS

ABSTRACT

Frequent monitoring of stress levels in turfgrass is key to maintaining healthy turfgrass stands. Current methods used to monitor turfgrass for drought and salinity stress can be time consuming and expensive. This study was conducted to determine if data obtained from digital image analysis and spectroradiometry could accurately detect drought and salinity stress in hybrid bluegrass. Furthermore, our objective was to determine if there were strong correlations between these data and visual ratings, relative water content (RWC), and leaf osmolality. The field studies were conducted in 2006 on hybrid bluegrass [*Poa arachnifera* (Torr.) x *pratensis* (L.)] cv. Reveille at the turfgrass research site near New Mexico State University's golf course. Increasing drought levels decreased relative water content (RWC), increased osmolality, decreased visual ratings, percent green cover, and Normalized Difference Vegetation Index (NDVI). Spectral reflectance ratios (e.g. K and NDVI) calculated from spectral reflectance data correlated moderate to high with visual ratings and percent green cover. Our results suggest that hue can be used to distinguish between drought and salinity stress. Both digital image analysis and spectral reflectance effectively detected drought and salinity stress and may have applications in turfgrass management as rapid

and quantitative methods that could potentially replace traditional qualitative visual measures or time consuming soil or plant tissue tests.

Abbreviations: □ET_O, reference evapotranspiration; IR, irrigation amounts; *Kc*, crop factor; NDVI, Normalized Difference Vegetation Index; D1, drought experiment replication 1; D2, drought experiment replication 2; S1, salinity experiment replication 1; S2 salinity experiment replication 2; SAR, sodium adsorption ratio; RWC, relative water content.

INTRODUCTION

In the arid southwest USA turfgrass water requirements exceed amounts provided by natural rainfall during most of the growing season and irrigation is required to maintain adequate turfgrass quality. As a result, up to 50% of the total urban water consumption in the summer can be for landscape irrigation (Kjelgren et al, 2000). However, human population growth and urban development in the Southwest has already become a source of increasing stress on water supplies. In order to preserve potable water for human consumption, municipalities have implemented water conservation strategies for landscape irrigation. The use of potable water for turf irrigation has either been restricted or completely eliminated. Both approaches can have negative impacts on turf quality. If potable water can no longer be used for irrigation, recycled (reclaimed, sewage-effluent), saline groundwater, or brackish surface water have been offered as irrigation alternatives. These types of water usually contain high concentrations of salts, and turfgrass irrigated with such waters can become salinity stressed, leading to a reduction in turf quality (Qian and Mecham, 2005). Thus both strategies, the application of limited potable water or poor quality saline water, can be detrimental to turf stands by causing either drought or salinity stress, and require improved management strategies to minimize plant stress and maintain high quality turf.

The use of remote sensing technology has been suggested by researchers and turf managers as a potential tool to monitor turf areas and to detect stress (Fenstermaker-Shaulis et al., 1997, Hutto et al., 2006, Trenholm et al., 1999). Ikemura (2007a and 2007b) has provided a detailed literature review on the current status of using remote sensing technology to quantify turf quality and to detect various biotic stresses. Most studies have used Normalized Difference Vegetation Index (NDVI) to measure reflectance of two wavelengths to determine plant density and/or stresses. However these devices, from which use ratios of reflectance can be calculated, are not capable of distinguishing one type of stress from another stress. The plant leaf has a low reflectance of incident energy in the visible (400-700 nm) range due to chlorophyll absorption, a relatively high reflectance in the near infrared region due to internal leaf scattering and no absorption, and a relatively low reflectance in the infrared range beyond 1300 nm due to strong absorption by water (Knipling, 1970). Researchers have investigated many other spectral reflectance ratios in evaluating plant leaf and canopy relations such as nitrogen index (Blackmer et al., 1996), normalized difference water index (Gao, 1996), plant water index (Penuelas et al., 1997), optimized soil-adjusted vegetation index (Rougean and Breon, 1995), photochemical reflectance index (Gamon et al., 1997), stress 1 and 2 (Trenholm et al., 1999) to name a few.

In our previous studies (Ikemura, 2007a, 2007b), standardized measurements of turf stress using digital image analysis and spectroradiometry provided information on the corresponding drought or salinity status of the turfgrass under greenhouse conditions. Numerous studies, including those of Huang et al. (1998), Bell et al. (2002a, 2002b), and Hutto et al. (2006) have also reported that spectroradiometry successfully quantified the canopy characteristics resulting from drought stress on turfgrass. However, no attempt has been made to use these techniques to distinguish between drought and salinity stress.

In this study, we conducted a study to determine if digital image analysis and spectroradiometry could be effectively used to detect, quantify, and distinguish drought and salinity stress in turfgrasses under natural field conditions. The first objective of this study was to assess the efficacy of digital image analysis and spectroradiometry in detecting drought and salinity stress in hybrid bluegrass [*Poa arachnifera* (Torr.) x *pratensis* (L.)] cv. Reveille subjected to five levels of drought or two levels of salinity. The second objective was to determine if the remote sensing technology could be used to distinguish between drought and salinity stress.

MATERIALS AND METHODS

Drought and Salinity Experimental Area

The field study was conducted in 2006 at a turfgrass research site next to New Mexico State University's golf course in Las Cruces, NM. The soil consisted of a sandy skeletal mixed thermic typic Torriorthent. Drought and salinity experiments were conducted on established 2m x 2m plots of hybrid bluegrass. Measurements for both experiments were taken from a 50 cm x 50 cm area in the center of each plot. The first drought experiment (D1) was conducted from May 20 to 26 and the second (D2) from November 1 to 15. Data for the first and second salinity experiments (S1 and S2) were collected on April 30 and November 5, respectively. Turfgrass was maintained at a 4.0 cm height using a rotary mower, and nutrients and pest control were applied as needed.

Drought Treatment

Five different levels of water deficit were imposed by applying varying amounts of irrigation water to mimic a range in drought stress. The different amounts of irrigation water used were calculated based on reference evapotranspiration (ET_O) rates. A modified Penman-Monteith equation (Allen et al., 1998) was used to estimate ET_O rates from the plots. ET_O (mm) was calculated from climate data that was downloaded from New Mexico State University's climate center web page (http://weather.nmsu.edu). The weather station used to collect the relevant climate data was located on the golf course, approximately 300 m north of the research site. An ET_O adjustment factor, also called crop factor (K_C), was used to calculate the irrigation amounts (IR) for the different drought treatments. K_C values of 20, 40, 60, 80, and 100% were applied. The IR applied for the drought treatments were calculated using the following formula:

$$\text{IR (mm)} = \text{ET}_\text{O} \text{ (mm)} * K_C \qquad (1)$$

Prior to the onset of the drought experiments, the plots were irrigated fully. Once the drought experiment started, general irrigation was withheld from the plots, and treatment irrigation was applied manually every other day. Treatments were replicated four times and arranged as a completely randomized design.

Salinity Treatment

The salinity treatments were applied using irrigation water of 2 salinity levels. Control plots were irrigated with water of 0.6 dS m^{-1} (SAR = 1.6) (potable), and treatment plots received water of 4.0 dS m^{-1} (SAR = 10.5). Control and salinity plots were irrigated by means of sprinklers every other day at 100% ET_O and at 120% ET_O, respectively. Treatments were replicated three times and arranged as a completely randomized design.

At the end of both salinity experiments soil samples were collected from the top 10 cm of the rootzone from within the test plots and analyzed for electrical conductivity (dS m^{-1}), Sodium Adsorption Ratio (SAR), and pH. All measurements were taken in a saturated paste extract.

Stress Evaluations for Drought and Salinity Experiments

At the end of each experiment, all plots were visually rated for turf quality on a scale of 1 to 9 with 1 corresponding to brown, dead turf and 6 reflecting the minimum acceptable quality. A rating of 9 indicated an optimal quality. Digital image data and spectroradiometry data were collected as described by Ikemura (2007a).

Percent green cover and hue were determined from the digital images using a computer macro developed and described by Karcher and Richardson (2005). Spectral reflectance data were obtained using the spectroradiometer and were then used to calculate spectral reflectance ratios listed in Table 3-1. After visual ratings were taken and spectral reflectance and digital image data were collected, the turf was clipped with scissors, and the clippings were collected to determine RWC and osmolality as described in Ikemura (2007a).

Statistical Analysis

To test the effect of stress on the quantitative and qualitative response data collected, percent green cover, NDVI, RWC, osmolality, and visual ratings were subjected to analysis of variance using SAS Proc Mixed (SAS Institute, Inc., 2002) followed by means separation using Fisher's LSD test at the 0.05 probability level. Pearson's correlation coefficients were calculated and examined to determine the degree of association between data obtained from digital image analysis and spectral ratios obtained from spectroradiometer data and the other response variables.

RESULTS AND DISCUSSION

Analysis of variance indicated significant interactions between drought treatments and experiments (D1 and D2) (Table 3-2). There were also significant interactions between salinity treatments and replicate experiments (S1, S2), but only for RWC and osmolality. Therefore data are presented separately for each experiment.

Salinity experiments

RWC, osmolality, visual rating, percent green cover, and NDVI for both drought and salinity experiments agreed with our findings from the green house experiments (Ikemura 2007a, Ikemura, 2007b). As salinity stress increased during S1, RWC, visual ratings, percent green cover, and NDVI decreased and osmolality increased (Table 3-4). Results were similar in S2 for visual ratings, percent green cover and NDVI. All three response variables in treated plots were significantly different than those of control plots. Osmolality and RWC in salt stressed plots were not significantly different from controls. This can be explained because of heavy rainfall during fall of 2006 which leached salts out of the rootzone and lowered salinity levels in the soil compared to levels measured in S1 (Table 3-3). Based on the lower salinity levels in the soil after S2, we would have expected the treatment plots to show less stress than the treated plots from S1. However, percent green cover and NDVI indicated similar levels of stress after S2 than after S1 despite lower soil salinity levels. Therefore percent green cover and NDVI may not be effective at distinguishing between degrees of salinity stress under field conditions. Additional stresses such as higher temperatures may also influence the susceptibility of turfgrass to salt stress, thereby influencing NDVI and percent green cover. Despite the lower rootzone salinity levels after S2, quality ratings of treated plots were higher in S1 than S2 (Table 3-4) but ratings on both sets of plots were below the acceptable threshold of

6.

Drought experiments

RWC, visual rating, percent green cover, and NDVI decreased as drought stress increased. Osmolarity increased as drought stress increased. All response variables differed significantly between the 20% ETo treatment (highest level of drought stress) and the 40% ETo treatment (second highest level of drought stress), but not between the 40% ETo and the 60% ETo treatment.

Results for D2 were similar, with one notable difference. All response variables with the exception of RWC did not differ significantly between 20% ETo treatments and 40% ETo treatments. Although the trends were the same for D2 and D1, plots subjected to the highest drought level (20% ETo) were not as stressed during D2 as during D1. In fact, all reponse variables except RWC were significantly different between the two experiments at 20% ETo (Figure 3-1).

In order to examine the degree of association between plant response variables and spectral reflectance ratios (Table 3-1), Pearson's correlation coefficients were calculated. Correlation data for drought experiments (D1 and D2) and salinity experiments (S1 and S2) are presented in Tables 3-5 to 3-9. Associations were considered either moderate ($0.5 < r < 0.8$) or strong ($r > 0.8$) (Devore and Peck, 1986). For D1, RWC, osmolality, and visual rating correlated moderately to strongly with all the reflectance ratios (Table 3-5). For D2 the correlation coefficients were lower and in some cases not significant (Table 3-6).

Visual ratings at 20% ETo did not differ between D1 and D2 (Figure 3-1), however, percent green cover was significantly higher in 20% ETo plots for D2 than for D1. NDVI was also significantly lower in the 20% ETo plots for D1 than for D2, indicating that plots were more stressed during D1 than D2 at the same drought level. It therefore appears that visual ratings did not reflect the differences in stress as well as percent green cover and NDVI. The higher percent green cover values might be due to dead turfgrass tissue which still retained chlorophyll, however because of the similar hue values for each of the plants, the software for percent green cover could not separate the dead tissue from the living tissue. NDVI readings were also affected by the dead tissue which retained the green color.

For salinity S1 and S2 the correlations between RWC and other plant response variables and spectral indices were not significant (Tables 3-7 and 3-8). Correlations between osmolality and all other plant response variables were also not significant for S2 (Table 3-8). For S1 osmolality was significantly correlated with visual rating, percent green cover, and NDVI (Table 3-7). Significant correlations in both salinity experiments were only observed between visual ratings and percent green cover and between visual ratings and 7 reflectance ratios including NDVI and IR/R (Tables 3-7 and 3-8). The lack of significant correlation between RWC and reflectance ratios and between osmolality and calculated ratios could be partly due to only 2 salinity treatments and the lack of significant differences between the control and the salinity treatment (for S2). However, the most likely reason is that RWC and osmolality measurements can only be made on live tissue. This means that situations could occur whereby the majority of the stand is severely stressed with an abundance of dead tissue but live blades are selected for the purpose of measuring RWC and osmolality. In such a case the correlation between RWC and visual rating or percent green cover would be understandably low. Schlemmer et al. (2005) collected spectral reflectances on single corn leaves to exclude any background reflectance from the soil. He also did not observe any correlation between spectral ratios and RWC at the leaf level. This might suggest that any significant correlation between spectral ratios and RWC or osmolality was the result of background reflectance (e.g. algae or soil surface).

Visual ratings correlated moderately to strongly with most of the parameters. Other researchers also observed high correlations between visual ratings and NDVI (Huang et al., 1998; Trenholm et al., 1999; Bell et al., 2002b). In our study, K correlated better to visual rating than NDVI did. Other parameters CI, percent green cover, IR/R, MTVI, RN, ST1, ST2, and YCAR correlated highly with NDVI (data not presented).

Unlike other crops, turfgrass blades are narrow and small. Because of that, single leaf measurements are not possible on turf as they are with other plants. Spectral reflectance data from previous turf studies were collected by placing the sensor a few meters above the turf canopy. (Bell et al., 2002a; Bell et al., 2002b; Jiang et al., 2004; Hutto et al., 2006; Kruse et al., 2006; Trenholm et al., 1999). Under such conditions one would expect that the reflectance data obtained would include healthy turf blades, stressed turf blades, and bare soil. In other words, reflectance data give a true representative assessment of the overall turf stand, whereas RWC and osmolality only focus on the healthy component of the overall stand. Haboudane et al. (2002, 2004) also stated that NDVI reflects the entire stand's state and is affected by soil background, canopy shadows, illumination, atmospheric conditions, and leaf chlorophyll concentration. In our study, we collected spectral reflectance 0.19 m above the turf canopy, and correlations between percent green cover and most of the calculated ratios were high, confirming that spectral reflectance gives a representative picture of the condition of the entire stand. The strongest correlations across all experiments were between percent green cover and K, MTVI and NDVI and between percent green cover and visual ratings (Table 3-9).

Hue in salinity treated turfgrass changed from green to yellow (Ikemura, 2007b). In contrast, hue of drought stressed turfgrass hue changed either from green to yellow to then brown or from green to darker green to then bluish green (Ikemura, 2007a). Figure 3-2 shows hue data points plotted against visual ratings for salinity and drought stressed bluegrass. A visual rating of 5 or lower indicates stressed plants. Most data points for the drought stressed grasses were clustered together between

200° and 360° hue. Conversely, all data points for salinity stressed grasses fell to the left of 80° hue. This suggests that drought and salinity stress can be distinguished from each other using digital image analysis over a narrow hue range.

CONCLUSIONS

Our data suggest that digital image analysis and spectral radiometry have potential applications in turfgrass management by providing rapid, inexpensive, and quantitative tools to monitor drought and salt stress. Percent green cover, which is measured using digital imagery, correlated well with several spectral reflectance ratios and both assessed turfgrass stands equally well. Our results suggest that hue can be used to distinguish between drought and salinity stress. This information can be valuable to turf managers as it allows them to determine the correct remediation measures. Digital cameras are less expensive and more readily available than spectroradiometers and are therefore more likely to be used by turf managers in the future. More research is needed to evaluate the ability of spectral radiometry and digital image analysis to distinguish drought and salt stresses from other forms of stress, such as heat stress, insect damage and/or disease damage.

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TABLES AND FIGURES

Table 3-1. The spectral reflectance ratios to be evaluated and their definitions.

Spectral reflectance ratios	Definitions
CI	chlorophyll based difference index, (850 nm-710 nm)/(850 nm-680 nm), (Datt, 1999)
IR/R	leaf area index, 935 nm/661 nm, (Trenholm et al., 1999)
K	the ratio of fluorescence peaks, 690 nm/730 nm, (Methy et al., 1994)
MCARI1	modified chlorophyll absorption in reflectance index, 1.2*[2.5*(800 nm -670 nm)-1.3*(800 nm-550 nm), (Haboudane et al., 2004)
MTVI1	modified triangular vegetation index, 1.2*[1.2*(800 nm-550 nm)-2.5*(670 nm-550 nm)], (Haboudane et al., 2004)
NDVI	normalized difference vegetation index, (935 nm-661 nm)/(935 nm+661 nm), (Trenholm et al., 1999)
NDWI	normalized difference water index, (860 nm-1240 nm)/(860 nm+1240 nm), (Gao, 1996)
OCAR	orange/red chlorophyll absorption ratio, 630 nm/680 nm (Schlemmer et al., 2005)
OSAVI	optimized soil-adjusted vegetation index, (1+0.16)*(800 nm-670nm)/(800 nm+670 nm+0.16), (Rondeaux et al., 1996)
PRI	photochemical reflectance index, (531 nm-570 nm)/(531 nm+570 nm), (Gamon et al., 1997)
RDVI	renormalized difference vegetatin index, (800 nm-670 nm)/√(800 nm+670), (Rougean and Breon, 1995)
RN	nitrogen index, (550 nm-600 nm)/(800 nm-900 nm), (Blackmer et al., 1996)
SRWI	simple ratio water index, 850 nm/1240 nm, (Zarco-Tejada et al., 2003)
ST1	stress 1, 706 nm/760 nm, (Trenholm et al., 1999)
ST2	stress 2, 706 nm/813 nm, (Trenholm et al., 1999)
WBI	water band index, 970 nm/900 nm, (Penuelas et al., 1994)
WMI	water moisture index, (1600 nm/820 nm), (Hunt and Rock, 1989)
YCAR	yellow/red chlorophyll absorption ratio, 600 nm/680 nm (Schlemmer et al., 2005)

Table 3-2. Analysis of variance, testing the main effects and interactions of experiment replications (Rep), drought and salinity treatments (Trt) on relative water content (RWC), osmolality, visual rating, percent green cover, and NDVI for drought and salinity experiments.

Experiment	Source	RWC (%)	Osmolality (mmol kg^{-1})	Visual rating	Percent green cover (%)	NDVI
Drought	Rep	NS‡	NS	*	NS	NS
	Trt	***	***	***	***	***
	Rep*Trt	*	*	**	***	***
Salinity	Rep	*	NS	NS	NS	NS
	Trt	NS	*	***	**	***
	Rep*Trt	*	*	NS	NS	NS

*, **, *** Significant F test at the 0.05, 0.01, and 0.001 level of probability, respectively

‡ NS Not significant at the 0.05 probability level

Table 3-3. Electrical conductivity (EC) (dS m^{-1}), Sodium Adsorption Ratio (SAR), and pH of rootzones at the end of salinity experiments 1 (S1) and 2 (S2) and of irrigation water used in both experiments. Measurements were taken in a saturated paste extract collected from control plots (irrigated with potable water) and from plots irrigated with saline ground water.

Media	Treatments	Experiment	EC (dS m^{-1})	SAR	pH
Rootzone	Control	S1	1.0	3.5	7.8
	Saline	S1	4.0	20.2	8.1
	Control	S2	1.2	2.6	7.6
	Saline	S2	2.1	12.4	8.2
Irrigation water	Control		0.6	1.6	7.2
	Saline		4.0	10.5	8.0

Table 3-4. Mean (± SE) relative water content (RWC), osmolality, visual rating, percent green cover, and NDVI of untreated (control) and saline irrigated hybrid bluegrass in experiments 1 (S1) and 2 (S2). Control plots were irrigated with potable water (0.6 dS m^{-1}) and treatment plots received saline ground water (4.0 dS m^{-1}).

	Experiment							
	S1				S2			
	Control		Treatment		Control		Treatment	
RWC (%)	87.4	± 2.7	79.5	± 1.9	88.1	± 2.6	92.3	± 2.0
Osmolality (mmol kg^{-1})	689	± 24	1178	± 117	843	± 56	859	± 73
Visual rating	8.7	± 0.3	5.0	± 0.6	7.7	± 0.3	3.3	± 0.7
Percent green cover (%)	92.8	± 4.0	57.7	± 14.1	83.2	± 1.4	58.9	± 8.9
NDVI	0.86	± 0.02	0.65	± 0.01	0.85	± 0.01	0.72	± 0.04

Table 3-5. Pearson's correlation coefficients for relative water content (RWC), osmolality, visual rating, and spectral reflectance ratios calculated from Table 1 for drought experiment 1 (D1).

	RWC (%)		Osmolality (mmol kg^{-1})		Visual rating	
Osmolality	-0.93	***				
Visual rating	0.90	***	-0.81	***		
Percent green cover	0.94	***	-0.90	***	0.95	***
CI	0.94	***	-0.87	***	0.94	***
IR/R	0.89	***	-0.76	***	0.94	***
K	-0.96	***	0.90	***	-0.95	***
MCARI	0.90	***	-0.79	***	0.93	***
MTVI	0.92	***	-0.79	***	0.95	***
NDVI	0.96	***	-0.91	***	0.94	***
NDWI	0.92	***	-0.84	***	0.95	***
OCAR	0.91	***	-0.78	***	0.95	***
OSAVI	-0.76	***	0.69	**	-0.75	**
PRI	0.90	***	-0.82	***	0.90	***
RDVI	-0.73	**	0.65	**	-0.72	**
RN	0.91	***	-0.83	***	0.93	***
SRWI	0.92	***	-0.83	***	0.95	***
ST1	-0.95	***	0.87	***	-0.94	***
ST2	-0.95	***	0.87	***	-0.93	***
WBI	-0.91	***	0.84	***	-0.95	***
WMI	-0.91	***	0.87	***	-0.92	***
YCAR	0.90	***	-0.77	***	0.95	***

* ** *** Correlations significant at the 0.05, 0.01, and <0.0001 level of probability.

Table 3-6. Pearson's correlation coefficients for relative water content (RWC), osmolality, visual rating, and spectral reflectance ratios calculated from Table 1 for drought experiment 2 (D2).

	RWC		Osmolality (mmol kg^{-1})		Visual rating	
Osmolality	-0.56	*				
Visual rating	0.85	***	-0.58	**		
Percent green cover	0.70	**	-0.62	**	0.83	***
CI	0.35	NS	-0.44	NS	0.51	*
IR	0.63	**	-0.52	*	0.77	***
K	-0.72	**	0.57	**	-0.83	***
MCARI	0.68	**	-0.49	*	0.76	***
MTVI	0.49	*	-0.64	**	0.63	**
NDVI	0.64	**	-0.53	*	0.77	***
NDWI	0.58	**	-0.70	**	0.67	**
OCAR	0.57	**	-0.34	NS	0.75	**
OSAVI	0.03	NS	-0.11	NS	-0.14	NS
PRI	0.39	NS	0.17	NS	0.24	NS
RDVI	0.06	NS	-0.12	NS	-0.09	NS
RN	0.78	***	-0.53	*	0.80	***
SRWI	0.57	**	-0.68	**	0.67	**
ST1	-0.30	NS	0.44	NS	-0.46	*
ST2	-0.29	NS	0.42	NS	-0.44	NS
WBI	-0.58	**	0.69	**	-0.69	**
WMI	-0.64	**	0.72	**	-0.73	**
YCAR	0.63	**	-0.38	NS	0.82	***

* ** *** Correlations significant at the 0.05, 0.01, and <0.0001 level of probability.

Table 3-7. Pearson's correlation coefficients for relative water content (RWC), osmolality, visual rating, and spectral reflectance ratios calculated from Table 1 for salinity experiment 1 (S1).

	RWC (%)		Osmolality (mmol kg^{-1})		Visual rating	
Osmolality	-0.64	NS				
Visual rating	0.69	NS	-0.95	**		
Percent green cover	0.68	NS	-0.87	*	0.84	*
CI	0.65	NS	-0.88	*	0.92	**
IR/R	0.59	NS	-0.88	*	0.95	**
K	-0.73	NS	0.94	**	-0.96	***
MCARI	0.50	NS	-0.66	NS	0.51	NS
MTVI	0.65	NS	-0.89	*	0.89	**
NDVI	0.70	NS	-0.93	**	0.96	***
NDWI	0.52	NS	-0.71	NS	0.88	*
OCAR	0.61	NS	-0.75	NS	0.72	NS
OSAVI	-0.09	NS	-0.23	NS	0.51	NS
PRI	-0.15	NS	0.18	NS	-0.31	NS
RDVI	0.00	NS	-0.36	NS	0.61	NS
RN	0.71	NS	-0.89	*	0.71	NS
SRWI	0.50	NS	-0.70	NS	0.87	*
ST1	-0.64	NS	0.88	*	-0.90	**
ST2	-0.64	NS	0.87	*	-0.90	**
WBI	-0.59	NS	0.82	*	-0.93	**
WMI	-0.59	NS	0.84	*	-0.94	**
YCAR	0.63	NS	-0.83	*	0.82	*

* ** *** Correlations significant at the 0.05, 0.01, and <0.0001 level of probability.

Table 3-8. Pearson's correlation coefficients for relative water content (RWC), osmolality, visual rating, and spectral reflectance ratios calculated from Table 1 for salinity experiment 2 (S2).

	RWC (%)		Osmolality (mmol kg^{-1})		Visual rating	
Osmolality	0.43	NS				
Visual rating	-0.53	NS	-0.34	NS		
Percent green cover	-0.58	NS	-0.50	NS	0.93	**
CI	-0.53	NS	-0.44	NS	0.98	**
IR/R	-0.45	NS	-0.29	NS	0.97	**
K	0.58	NS	0.41	NS	-0.97	**
MCARI	-0.59	NS	-0.58	NS	0.72	NS
MTVI	-0.52	NS	-0.48	NS	0.96	**
NDVI	-0.56	NS	-0.43	NS	0.96	**
NDWI	0.02	NS	0.09	NS	0.61	NS
OCAR	-0.40	NS	-0.19	NS	0.68	NS
OSAVI	-0.26	NS	-0.63	NS	-0.44	NS
PRI	0.13	NS	0.33	NS	0.64	NS
RDVI	-0.51	NS	-0.81	NS	-0.11	NS
RN	-0.60	NS	-0.60	NS	0.81	*
SRWI	0.03	NS	0.08	NS	0.60	NS
ST1	0.54	NS	0.43	NS	-0.99	**
ST2	0.53	NS	0.45	NS	-0.98	**
WBI	0.25	NS	0.27	NS	-0.73	NS
WMI	0.16	NS	0.11	NS	-0.80	NS
YCAR	-0.47	NS	-0.13	NS	0.82	*

* ** *** Correlations significant at the 0.05, 0.01, and <0.0001 level of probability.

Table 3-9. Pearson's correlation coefficients for percent green cover, and spectral reflectance ratios calculated from Table 1 for drought experiments 1 (D1) and 2 (D2), and salinity experiments 1 (S1) and 2 (S2).

	Percent green cover (%)							
	D1		D2		S1		S2	
Visual rating	0.95	***	0.83	***	0.84	*	0.93	**
CI	0.97	***	0.78	***	0.72	NS	0.98	**
IR/R	0.90	***	0.90	***	0.80	NS	0.93	**
K	-0.99	***	-0.95	***	-0.88	*	-0.99	**
MCARI	0.94	***	0.74	**	0.88	*	0.92	**
MTVI	0.94	***	0.82	***	0.91	*	0.98	**
NDVI	0.98	***	0.92	***	0.84	*	0.99	***
NDWI	0.98	***	0.82	***	0.77	NS	0.49	NS
OCAR	0.92	***	0.70	**	0.95	**	0.77	NS
OSAVI	-0.70	**	-0.09	NS	0.11	NS	-0.26	NS
PRI	0.91	***	-0.03	NS	0.17	NS	0.47	NS
RDVI	-0.67	**	-0.05	NS	0.25	NS	0.07	NS
RN	0.96	***	0.78	***	0.94	**	0.97	**
SRWI	0.97	***	0.81	***	0.76	NS	0.49	NS
ST1	-0.98	***	-0.76	***	-0.70	NS	-0.97	**
ST2	-0.97	***	-0.74	**	-0.68	NS	-0.97	**
WBI	-0.97	***	-0.84	***	-0.83	*	-0.75	NS
WMI	-0.98	***	-0.83	***	-0.85	*	-0.70	NS
YCAR	0.91	***	0.78	***	0.95	**	0.88	*

* ** *** Correlations significant at the 0.05, 0.01, and <0.0001 level of probability.

Figure 3-1. Response of relative water content (RWC), osmolality, visual rating, percent green cover, and NDVI in hybrid bluegrass to 4 drought treatments (bars represent standard errors) during 2 drought experiments.

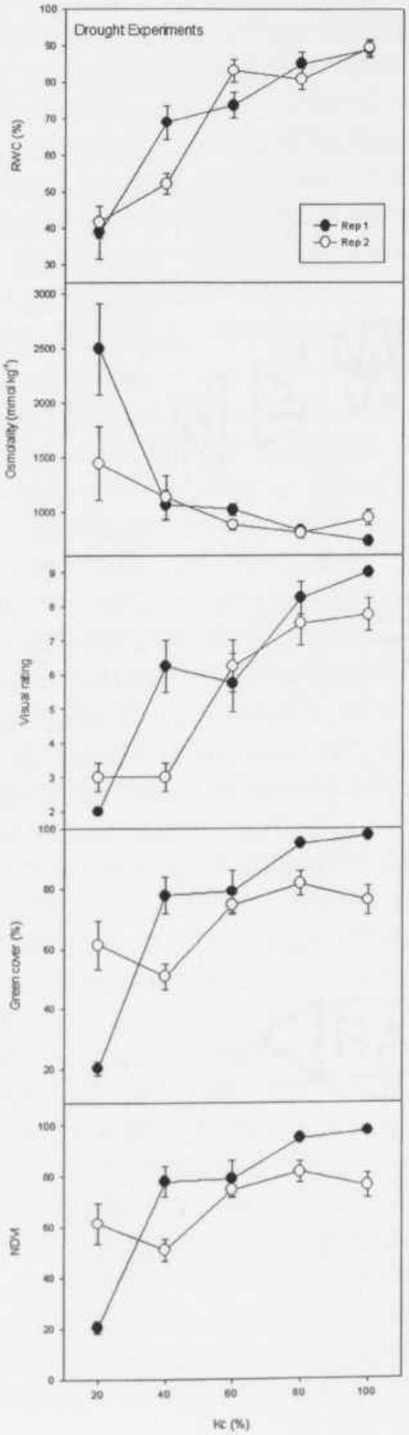

Figure 3-2. Scatter plot of visual ratings and corresponding hue values for all drought (D1 and D2) and salinity (S1 and S2) experiments.