ESTABLISHMENT, DROUGHT TOLERANCE AND RECOVERY, AND CANOPY ANALYSIS OF TURFGRASSES IN THE TRANSITION ZONE

by

ANTHONY LEE GOLDSBY

B.S., Kansas State University, 2005
M.S., Kansas State University, 2008

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture, Forestry, and Recreation Resources

College of Agriculture

KANSAS STATE UNIVERSITY
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Abstract

Increasing water scarcity may result in greater irrigation restrictions for turfgrass. Drought tolerance and recovery of Kentucky bluegrasses (*Poa. pratensis* L.) (KBG) were evaluated during and after 88 and 60 day dry downs in 2010 and 2011, respectively, under a rainout shelter. Changes in green coverage were evaluated with digital images. Green coverage declined slowest during dry downs and increased fastest during recoveries in the cultivar ‘Apollo’, indicating it had superior drought tolerance.

Electrolyte leakage, photosynthesis, and leaf water potential were evaluated in 7 KBG cultivars during and after the dry downs. Soil moisture at 5 and 20 cm was measured. There were generally no differences in physiological parameters among cultivars during or after dry down. The highest reduction in soil moisture at 5 and 20 cm was in Apollo, suggesting it had a better developed root system for mining water from the profile during drought.

Weed prevention and turfgrass establishment of ‘Legacy’ buffalograss (*Buchloe dactyloides* [Nutt.] Engelm.) and ‘Chisholm’ zoysiagrass (*Zoysia japonica* Steud.) grown on turf reinforcement mats (TRM) was evaluated. ‘Chisholm’ zoysiagrass stolons grew under the TRM; as such, use of TRM for this cultivar is not practical. Buffalograss had 90% or greater coverage when established on TRM in 2010 and 65% or greater coverage in 2011; coverage was similar to that in oxadiazon-treated plots at the end of each year.

‘Legacy’ buffalograss plugs were established on TRM over plastic for 3 weeks, stored in TRM under tree shade for 7, 14, or 21 days, and evaluated for establishment after storage. In 2010, plugs on mats stored for 7 days had similar coverage to the control, but in 2011 displayed similar coverage to plugs stored on TRM for 14 or 21 day treatments.

Green leaf are index (LAI) is an important indicator of turfgrass performance, but its measurement is time consuming and destructive. Measurements using hyperspectral radiometry were compared with destructive measurements of LAI. Results suggest spectral radiometry has potential to accurately predict LAI. The robustness of prediction models varied over the growing season. Finding one model to predict LAI across and entire growing season still seems unrealistic.

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Acknowledgements

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Finally, I would like to thank my parents for raising me with values that taught me the meaning of hard work and discipline. Your love and guidance are the major reason I am the man I am today.

Dedication

I dedicate this to my wonderful children Emma and Harper. Keep dreaming and reaching for the stars throughout your lives as all things are possible through Jesus Christ.

Chapter 1 - Response of Kentucky Bluegrass Cultivars to Prolonged Drought Stress in the Transition Zone

Abstract

Water restrictions for irrigation may be imposed during drought with little or no regard for effects on the landscape. My objectives were to evaluate responses of Kentucky bluegrass (*Poa pratensis* L.) (KBG) to prolonged drought in the transition zone near Manhattan, KS, USA. Irrigation was withheld from 30 bluegrasses for 88 days in 2010 and 60 days in 2011. Plots were sheltered from rainfall by an automated rainout shelter. Digital images were collected weekly during dry down and recovery to obtain percent green turfgrass coverage. In 2010, plots were completely brown (0% green coverage) by the end of the 88 day dry down. Among cultivars, green coverage declined to 25% by 44.3 to 54.1 days after irrigation (DAI) was withheld. In 2011, plots were less brown (15-30% green cover) by the end of the 60 day dry down because all plots received 39 mm of precipitation after the rainout shelter malfunctioned, green coverage declined to 25% by 39.0 to 57.1 DAI withheld. In both years, green coverage declined slowest in Apollo, Bedazzled, Blue Velvet, Envicta, Midnight II, and Thermal Blue Blaze and fastest in Blue Knight, Cabernet, Kenblue, Limousine, and Touchdown. Recovery of green coverage after dry downs in both years was fastest in Apollo, Award, Baron, Unique, and Moonlight and slowest in Abbey, Bartitia, Nu Destiny, Park, and Touchdown. Given its slower decline in green coverage during dry downs in both years and faster recovery thereafter, Apollo displayed superior drought tolerance. The recuperative ability of all 30 bluegrasses was noteworthy because all entries eventually recovered after prolonged drought.

Introduction

Water scarcity is an increasing challenge to the turfgrass industry and may result in irrigation restrictions being imposed without regard for damage to turfgrass (Beard and Kenna, 2008). For turf managers, thriving in an industry where turf quality is of utmost importance is difficult when water is limiting. Therefore, research investigating turfgrass resistance to drought stress has become increasingly important.

Kentucky bluegrass is the most widely used cool-season turfgrass for lawns, golf courses, athletic fields, and other areas where a dense grass cover is desired (Christians, 2004; Brooks Gould, 2004; Lyman et al., 2007). In the continental U.S., KBG is grown predominantly in the cool-arid/humid regions. However, KBG has a broad range of adaptability that also makes it suitable for use as far south as the transition zone of the U.S. Wide ranges in drought tolerance and water use among KBG cultivars undoubtedly contribute to its adaptability (Shearman, 1986; Ebdon and Petrovic, 1998; Richardson et. al., 2009; Merewitz et al., 2010; Lewis et al., 2012).

Drought resistance in turfgrasses has two primary components: dehydration avoidance and dehydration tolerance (Beard, 1989). For example, a cool-season grass such as tall fescue (*Festuca arundinacea* Schreb.*)* has the ability to avoid dehydration by mining soil moisture from deeper in the profile with an extensive rooting system. Even in KBG, cultivars with greater root mass deeper in the profile (15-45 cm) avoided drought stress better than cultivars with less root mass at those depths (Bonos and Murphy, 1999). In the latter study, soil moisture was depleted more at 15-30 cm in drought-tolerant cultivars than in intolerant cultivars. Nevertheless, the root system in KBG is relatively shallow compared with tall fescue (Christians, 2004). Therefore, in order to survive extended periods of drought, KBG may undergo dormancy (Christians, 2004). Dormancy is associated with dehydration tolerance, not avoidance, and is accompanied by loss of green color in foliage (Beard, 1989). Crowns and rhizomes of KBG can live for several months under drought conditions, which allow for regrowth when water becomes available (Christians, 2004).

A number of studies have screened cool-season grasses for drought tolerance under controlled conditions in greenhouses or growth chambers (Abraham et. al., 2004; Ebdon and Kopp, 2004; Wang et al., 2008). In such studies, lysimeters are typically used, which may restrict soil volumes for root growth, result in higher root temperatures than would be found in ambient soils in the field, and alter physiological properties of turfgrasses (e.g., leaf area, above- and below ground biomass density) (Bremer, 2003), all of which may impact drought resistance. Furthermore, while growth chambers and greenhouses have the advantage of more controlled environments, they may not accurately predict responses of cultivars to the more dynamic, stressful conditions typical in the field.

In other research, drought tolerance among KBG cultivars has been successfully evaluated in the field using broad screening techniques including visual quality, digital image analysis, and physiological measurements (Keeley and Koski, 2001; Richardson et. al., 2008, 2009; Merewitz et. al., 2010). In those studies, irrigation was withheld for approximately 35 days or less, which typically resulted in severe drought stress but with a fraction of the canopies remaining green.

In Texas, seven cultivars of St. Augustinegrass survived 60 days with no irrigation or precipitation, and in one year most of the cultivars were nearly completely dormant by the end of the study (Steinke et al., 2010). That research was in response to a local water municipality requiring a list of turfgrasses with the ability to survive without water for 60 days during summer months. Presumably, similar irrigation restrictions may occur where KBG is grown, but the ability of KBG to survive 60 days without irrigation or precipitation has not been evaluated.

Due to considerable diversity in growth and performance among KBG cultivars, researchers have classified them into phenotypic groups (Murphy et al., 1997; Bonos et al., 2000; Brooks Gould, 2004). Because of relatively quick turnover of commercially-available KBG cultivars, determining the drought tolerance of phenotypic groups may provide a viable alternative for estimating drought tolerance of cultivars not included in any specific study. Keeley and Koski (2001) investigated visual quality and leaf firing during field dry downs of 22 to 33 days in 15 cultivars of KBG representing various KBG phenotypic groups. Those authors reported dehydration avoidance rankings from high to low were Mid-Atlantic > Bellevue > Baron, BVMG, Victa, Merit, and Gnome > Common. Conversely, Richardson et al. (2008) did not find trends in drought tolerance among KBG phenotypic groups, as measured by days to 50% green cover. Beyond the latter studies, few have investigated relative drought tolerance among phenotypic groups of KBG in a field setting.

A fully automated rainout shelter located in the transition zone in northeastern Kansas, USA, offered the ability to compare growth and performance of multiple KBG cultivars in the field while restricting water. The objective of this study was to evaluate percent green coverage, using digital image analysis, of 28 cultivars of KBG and two hybrid bluegrasses (KBG × Texas bluegrass [*Poa arachnifera* Torr.]) during exposure to prolonged drought and during the recovery period after rewatering.

Materials and Methods

Study site and experimental design

This study was conducted from 15 June to 4 Sept. 2010 (88 d), and 1 June to 1 Aug. 2011 (60 d). Turfgrass plots were maintained under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas, USA (39°13’53” N, 96°34’51”

W). The rainout shelter rests north of the plot area but automatically covered the plots as precipitation began and retracted 1 h after cessation of rainfall. The rainout shelter malfunctioned three times, once in the first year of the experiment, and twice during the second year. The first malfunction occurred on 5 July 2010 and allowed approximately 25 mm of precipitation to fall on the study plots. The subsequent malfunctions occurred on 15 July 2011 and 21 July 2011, allowing approximately 7 mm of precipitation and 32 mm, respectively. The soil at the site was a Chase silt loam (fine, smectitic, mesic, Aquertic Argiudoll) with a pH of 6.9. A soil test prior to the study indicated P and K levels were adequate.

Weather data for Manhattan, KS during the study were obtained from Kansas State University weather data library (http://www.ksre.ksu.edu/wdl). Air temperatures during the study were generally greater than the 30-year normal in both years (Figure 1.1). Furthermore, 2011 was generally warmer than 2010. For example, air temperature during the dry down averaged 0.8 ^{o}C greater than normal in 2010 and 2.7 ^{o}C greater than normal in 2011. Daily maximum air temperatures exceeded 35 ^{o}C on 21 days during the 88-day study in 2010 and on 29 days during the 60-day study in 2011 (data not shown).

Ninety plots, consisting of 28 cultivars of Kentucky bluegrass (*Poa pratensis* L.*)* and two hybrid bluegrasses (Table 1.1), were arranged in a randomized complete block design with three replications. The plots, established in Sept. 2006, measured 1.13 by 1.22 m and were bordered with metal edging (10 cm depth). Commercially available cultivars of KBG were selected to include representatives from major phenotypic groups (Murphy et al., 1997; Bonos et al., 2000). Because visual color and quality were of interest in this study, cultivar performance in previous NTEP trials was evaluated to guide in the cultivar selection (National Turfgrass Evaluation

Program, 2001). Additional details about plot establishment and cultivar selection can be found in Lewis et al. (2012).

Plot Maintenance

Plots were maintained at a 7.6 cm mowing height and fertilized with urea (46-0-0), to provide N at 49 kg N ha^{-1} in April, September, and October of each year. Imidacloprid (1-[(6-chloro-3-4 pyridinyl) methyl 3 (2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate) was applied at 0.12 kg a.i. ha^{-1} to control billbug grubs and white grubs (*Cyclocephala lurida* Bland) on 1 May 2010 and 3 May 2011. Azoxystrobin ((methyl(E)-2-{2-[6-(2-cyanpphenoxy) pyrimidin-40yloxy]phenyl}-3 methoxyacrylate)) was applied at 0.61 kg a.i. ha^{-1} on 15 April 2010 and 9 April 2011 for summer patch (*Magnoporthe poae* Landschoot & Jackson) prevention. The herbicides carfentrazone-ethyl (Ethyl α,2-dichloro-5-[4(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl]-4-fluorobenzenepropanoate) (0.03 kg a.i. ha^{-1}) + 2,4-D [2-ethylhexyl ester (2,4 dichlorophenoxyacetic acid] (1.29 kg a.i. ha^{-1}) + Mecoprop-p acid [(+)-R-2-(2-methyl-4 chlorophenoxy)propionic acid] (0.27 kg a.i. ha^{-1}) + dicamba acid (3,6-dichloro-o-anisic acid)(0.08 kg a.i. ha^{-1}) were applied on 6 April 2010, 23 Oct. 2010, and 9 April 2011 for broadleaf weed control. Applications of dithiopyr [S,S'-dimethyl 2-(difluoro-methyl)-4-(2-methylpropyl)-6-(trifluoromethyl)-3,5-pyridin-edicarbothioate] were made at 0.58 kg a.i. ha^{-1} on 6 April 2010 and 9 April 2011 to control annual grassy weeds. Water was applied three times weekly for a total of 25 mm of precipitation per week.

Measurements

The plots were well watered until 15 June 2010 and 1 June 2011. Thereafter, plots were allowed to dry-down for 88 days in 2010 and 60 days in 2011 with no precipitation or irrigation.

Overhead photos of all pots were taken weekly and images were used to calculate percent green turfgrass cover according to the method of Richardson et. al., (2001) and Karcher and Richardson (2005). Images were obtained with a Nikon D3000 (Nikon Co., Tokyo, Japan) digital camera. In 2010, the camera was mounted on a tripod 3.0 m in height with a horizontal arm that was mounted at 90^{o} from vertical and extended 1.0 m away from the tripod center. All images were collected under clear skies at (~1200 CST) to minimize changes in solar zenith angle. In 2011, construction of a camera light box allowed for more flexibility in the time of data collection (Peterson et al., 2011). The light box (51 × 61× 56 cm) was fabricated from 0.16002-cm. thick aluminum. Four compact fluorescent light bulbs (model CF13EL/MICRO/C/865/BL2; color temperature = 6,500K; Sylvania, Danvers, MA) mimicking natural sunlight color temperature (5,500 to 6,500 K) were installed inside the box. The light bulbs are powered by a portable power pack (Duracell Power Pack 600, Duracell, Bethel, CT). The camera was mounted in the center of the box and a sponge surrounding the lens prevented sunlight from entering the light box and provided support for the camera. The images were saved in a JPEG format with a color depth of 16.7 million colors, and an image size of 1280 by 960 pixels. Camera settings included a shutter speed of 1/400 s, aperture of F4.0, and focal length of 26 mm. The images were analyzed with SigmaScan Pro (v. 5.0, SPSS, Chicago, IL). The program selectively identified green pixels (leaves) in the image with the hue range set from 47 to 110 and the saturation set from 0 to 100 (Figure 1.2).

Statistical analysis

Digital image data were analyzed on a date-by-date basis with the MIXED procedure of SAS (SAS Institute, Cary, NC). In cases where the F-test for treatment differences were significant (P=0.05) on a given date, 95% confidence intervals were used for comparison among individual treatment means.

Scatter plots of percent green turf cover versus days after irrigation was withheld (DAIW) during drought stress, and days after irrigation (DAI) was applied during recovery from drought, indicated nonlinear relationships. Furthermore, the data fit very well to a sigmoid variable slope model similar to that described by Karcher et al., (2008). The slope parameter of both models defines how rapidly turf cover changes over time. For the dry-down, more negative values represent steeper slopes of the sigmoid curve. For the recovery, more positive values indicate a quicker change in green cover over time. Briefly, for the dry-down in both years a sum of squares reduction F-test was used to determine if KBG cultivars significantly affected green turf cover during drought stress and the subsequent recovery. The F-test compared the sum of squares from a global model (average of all cultivars for Day_{25} or Day_{75} and slope values) against the cumulative sum of squares from separate models of each cultivar for Day_{25}, Day_{75}, and the slopes. For the dry down periods, a Day_{75} and Day_{25} value was calculated to estimate DAIW until each plot reached 75 % and 25% green cover. For the recovery periods a Day_{75} was calculated to estimate DAI was initiated before each plot reach 75% green cover. After the 2010 dry down, measurements of canopy green cover during the recovery were only obtained for 60 DAI was reapplied. However, most canopy regrowth in the bluegrass entries with the slowest recoveries occurred thereafter, primarily during the next spring prior to the 2011 dry down. Therefore, Days_{75} during the 2010 recovery was extrapolated using the sigmoid models in most cultivars. For 2011, all plots had reached 75% green cover by 45 days after irrigation was returned. Nonlinear regression analysis of the turf percent cover data was performed using GraphPad Prism version 4.0 for Windows (Graphpad Software, San Diego, CA).

Results and Discussion

In 2010, all plots were completely brown (0% green cover) by end of the 88-day dry down (Figure 1.3). At the end of the dry down in 2011 the plots were less brown than in 2010, ranging from 15 to 30% green cover (Figure 1.4). Greater percent green coverage at the end of the 60-day dry down in 2011 was likely a result of 39 mm of total precipitation that inadvertently fell on the plots after the rainout shelter malfunctioned on two occasions, at 44 and 51 DAI withheld.

Bluegrass cultivar significantly affected green turf coverage during both the dry down and subsequent recovery periods in both years of the study (Table 1.2). The sigmoid models used to predict percent green cover provided a good fit of the green cover data, resulting in average coefficient of determination (R^2) values of 0.93 and 0.88 during drought stress in 2010 and 2011, respectively, and 0.57 and 0.86 during recovery after drought in 2010 and 2011, respectively (Tables 1.3 and 1.4).

The weaker goodness of fit of the sigmoid models during recovery from drought stress in 2010 (R^2=0.57) was the result of a slow recovery period that lasted into the spring of 2011, with green turf cover varying considerably among replications of each cultivar (Fig. 1.5). Slower recovery in 2010 was probably caused by the longer dry down period (88 days), which resulted in greater drought stress than during the 60-day dry down in 2011.

In 2010, green coverage was between 93-100% among cultivars at the beginning of the dry down (Fig. 1.6). In contrast, green coverage was lower at the beginning of the dry down in 2011, ranging from 79-98% among cultivars (Fig. 1.7). This was likely an artifact of the slow recovery in 2010, in which some plots had not yet reached full green coverage by the beginning of the dry down in 2011.

In both years, green coverage began to decline quickly in some cultivars after irrigation was withheld (Figure 1.6 and 1.7). Based on predictions from the sigmoid models, the Days_{25} averaged 50.7 in 2010, which was almost two days greater than the average of 48.9 in 2011. However, the range of Days_{25} among cultivars was 44.3 to 54.1 in 2010 (a 9.8-day span), which was narrower than the range of 39.0 to 57.1 days in 2011 (an 18.1-day span) (Table 1.3). The narrower range in Days_{25} in 2010 resulted in fewer differences in Days_{25} among cultivars than in 2011 (Figs. 1.8 and 1.9). The cause of these differences in Days_{25} between years is uncertain. The average air temperature during the first 10-15 days of the dry down was similar between years (Figure 1.1). Thus, it is unlikely that differences in heat stress caused the differences in Days_{25} between years. It is more likely that because some cultivars started with less green coverage in 2011, they declined to 25% faster than in 2010 when they were closer to full coverage.

The cultivars that demonstrated the greatest number of days to reach 25% green cover in both years of the study were: Apollo, Bedazzled, Blue Velvet, Envicta, Midnight II, and Thermal Blue Blaze (Figure 1.7 and 1.8). Apollo consistently ranked in the top ten cultivars, as measured by slowest decline in green coverage, among the cultivars during both years of the study. Previous research has shown good tolerance of cultivars in Compact types (Moonlight and Diva) and Compact America types (Mallard, SR 2284, and Brilliant) for drought tolerance, since those cultivars in their respective groups performed well (Richardson et al., 2008). In our study, Compact America types (Apollo and Bedazzled) showed superior drought tolerance in drydowns of both years. Furthermore, in our study Compact types (Moonlight and Diva) showed contrasting drought tolerance with each cultivar falling into the top ten in one year and then in the middle/bottom of the cultivars in the other year. The cultivars exhibiting the least drought tolerance in both years of the study were: Blue Knight, Cabernet, Kenblue, Kingfisher, Limousine, and Touchdown (Figure 1.8 and 1.9).

Previous research has indicated that KBG hybrids are similar to KBG cultivars in their susceptibility to drought stress (Su et al., 2007, 2008, 2009; Richardson et al., 2008, 2009). In our study, drought tolerance was relatively good in Thermal Blue Blaze but was less consistent in the other hybrid Longhorn. These results support the observations of Richardson et al. (2008), who suggested that hybrids have wide ranges in drought tolerance but no inherent superiority to KBG cultivars.

Predictions from the sigmoid models illustrate the slower post-drought recovery in 2010 (mean Days_{75} = 86.9 days) than in 2011 (mean Days_{75} = 30.5 days) (Table 1.4), which was discussed earlier. Among cultivars, the Days_{75} during recovery averaged almost two months (56 days) more in 2010 than in 2011. The range in Days_{75} during recovery was from 57.8 to 148 days in 2010 and from 20 to 43.7 days in 2011 (Table 1.4). The cultivars with the fastest recovery (i.e., the fewest Days_{75}) during both years were Apollo, Award, Baron, Unique, and Moonlight (Figure 1.10 and 1.11). These results from Apollo and Moonlight support observations by others that indicated cultivars with the best drought tolerance during drought are typically the quickest to recover after drought (Richardson et al., 2008). The cultivars demonstrating the slowest recovery in both years of the study were: Abbey, Bartitia, Nu Destiny, Park, and Touchdown (Figure 1.12 and 1.13). The cultivar Touchdown required the fewest days to reach 25% green coverage in 2010. For 2011, Touchdown was in the top four cultivars which required the fewest days to reach 25% green coverage.

Conclusions

Results from this study illustrate the importance of proper cultivar selection where the possibility exists for long-term drought and subsequent irrigation restrictions. In some cases, there were differences of 18 days among cultivars in the Days_{25} during drought. Furthermore, there were differences of 90 days among cultivars in the Days_{75} after the 2010 dry down. These differences could be significant if KBG cultivars are located in a municipality which during drought may face intermittent or extended periods of irrigation restriction.

Overall, the amazing recuperative ability of KBG from prolonged drought is noteworthy for all cultivars. Apollo demonstrated great drought tolerance and subsequent recovery for both the 2010 and 2011 dry down. Furthermore, it was one of the fastest to recover from drought stress after the return of irrigation. Information from this study could assist cultivar selection for turfgrass managers located in a municipality which may face extended periods of irrigation restriction.

Figures and Tables

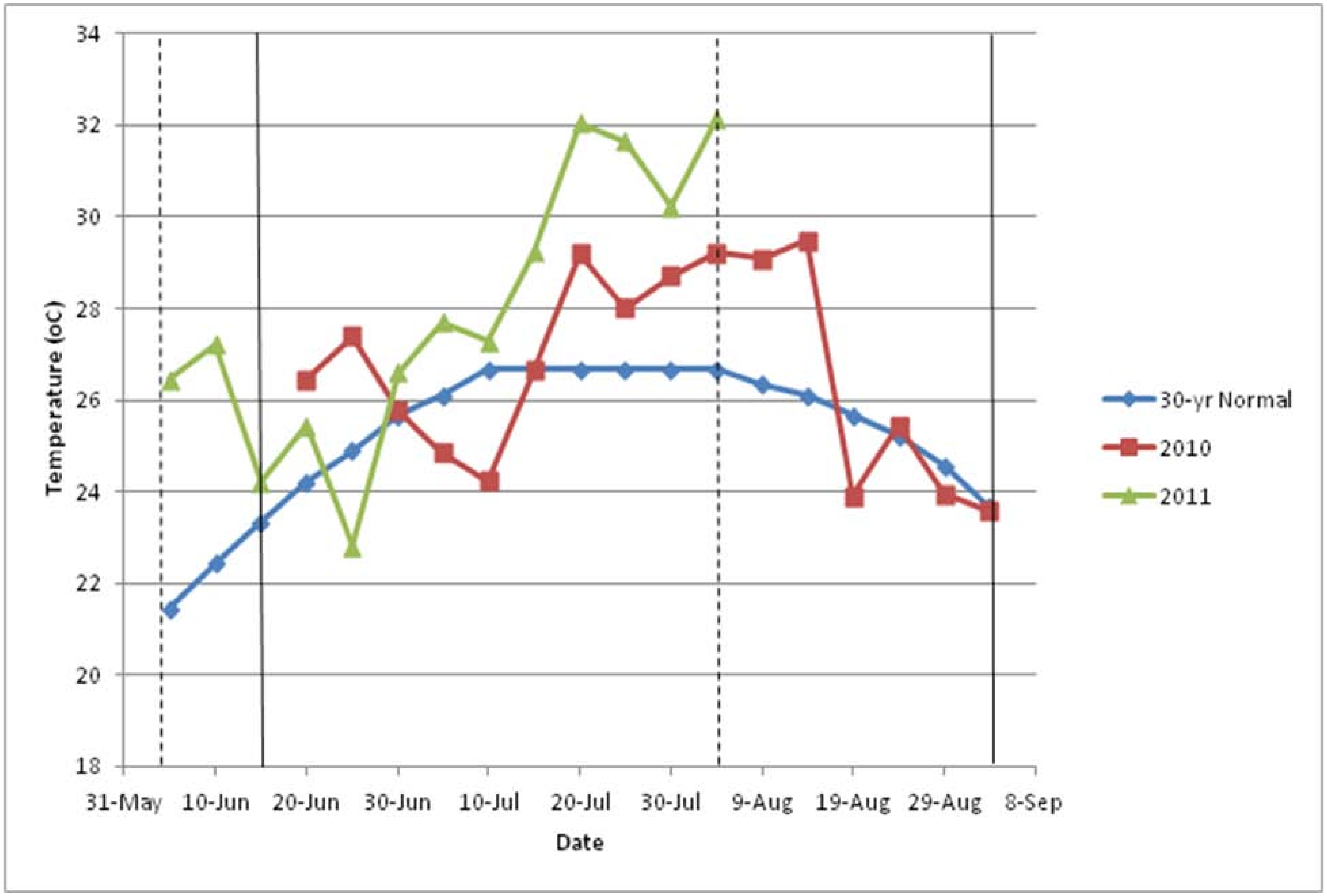

Figure 1.1- Average air temperature during the dry downs in 2010 and 2011. Solid black lines signify the start and cessation of the 2010 dry down. Dashed black lines signify the start and cessation of the 2011 dry down. Markers represent 5 day averages.

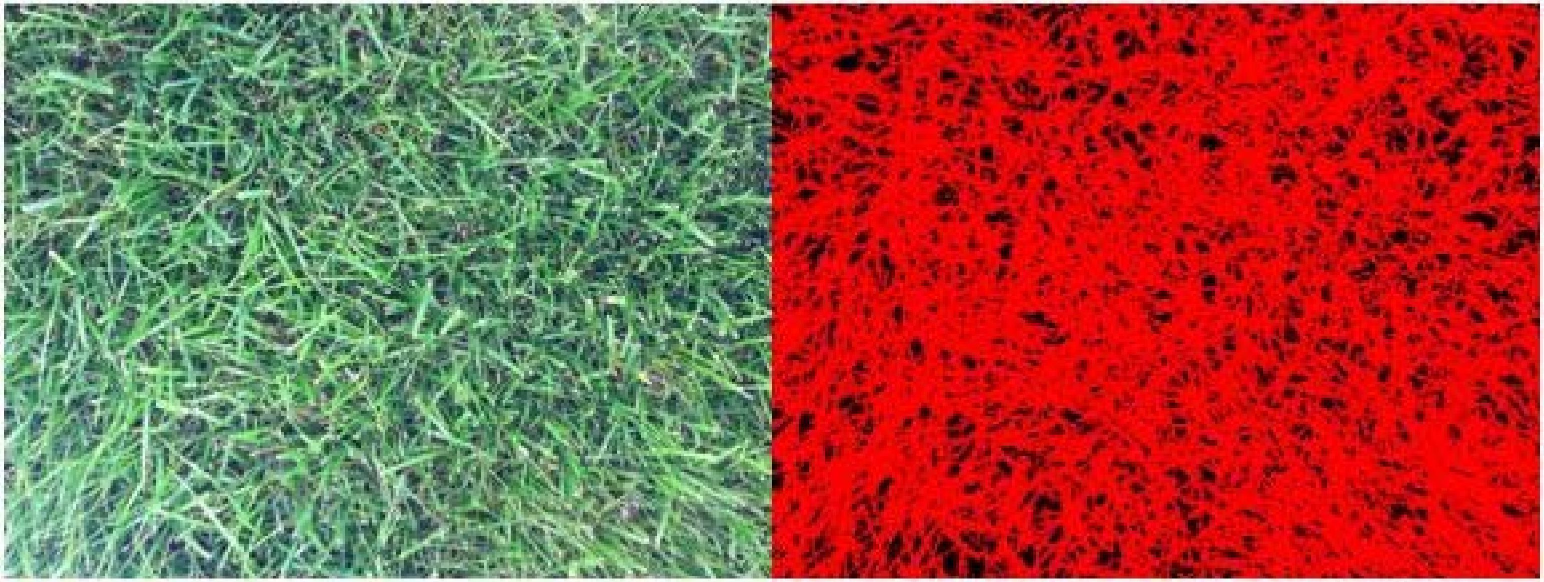

Figure 1.2- Original image (left) followed by the color composite image after being processed with image analysis software (right). The software identifies pixels that fall under preset green hue settings and then highlights them in red.

Figure 1.3- Plots on September 4, 2010, after receiving no irrigation for 88 days.

Figure 1.4- Plots on August 1, 2011, after receiving no irrigation for 60 days.

Figure 1.5- Digital images of all three replicates of the KBG cultivar 'Cabernet' in 2010, at the beginning (26 June) and end (2 Sept.) of the dry down and after 60 days of recovery (5 Nov.).

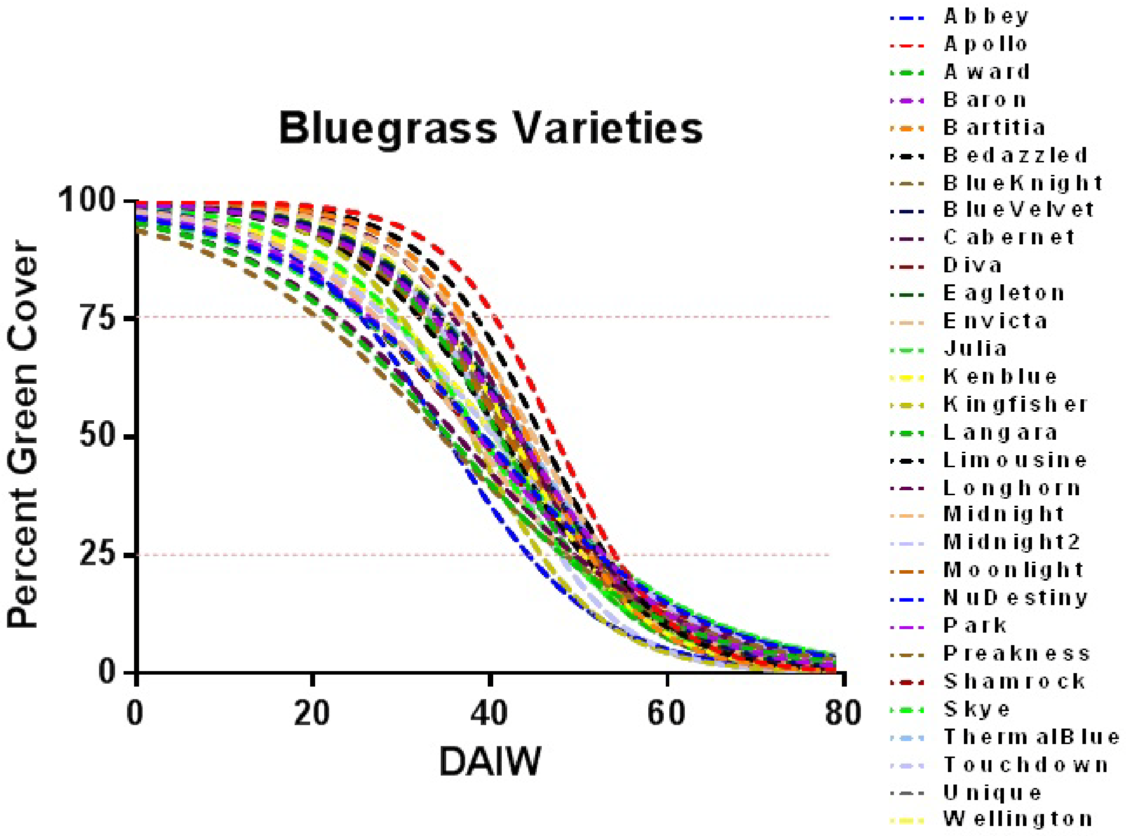

Figure 1.6- Predicted dry-down curves for the 30 bluegrasses in 2010.

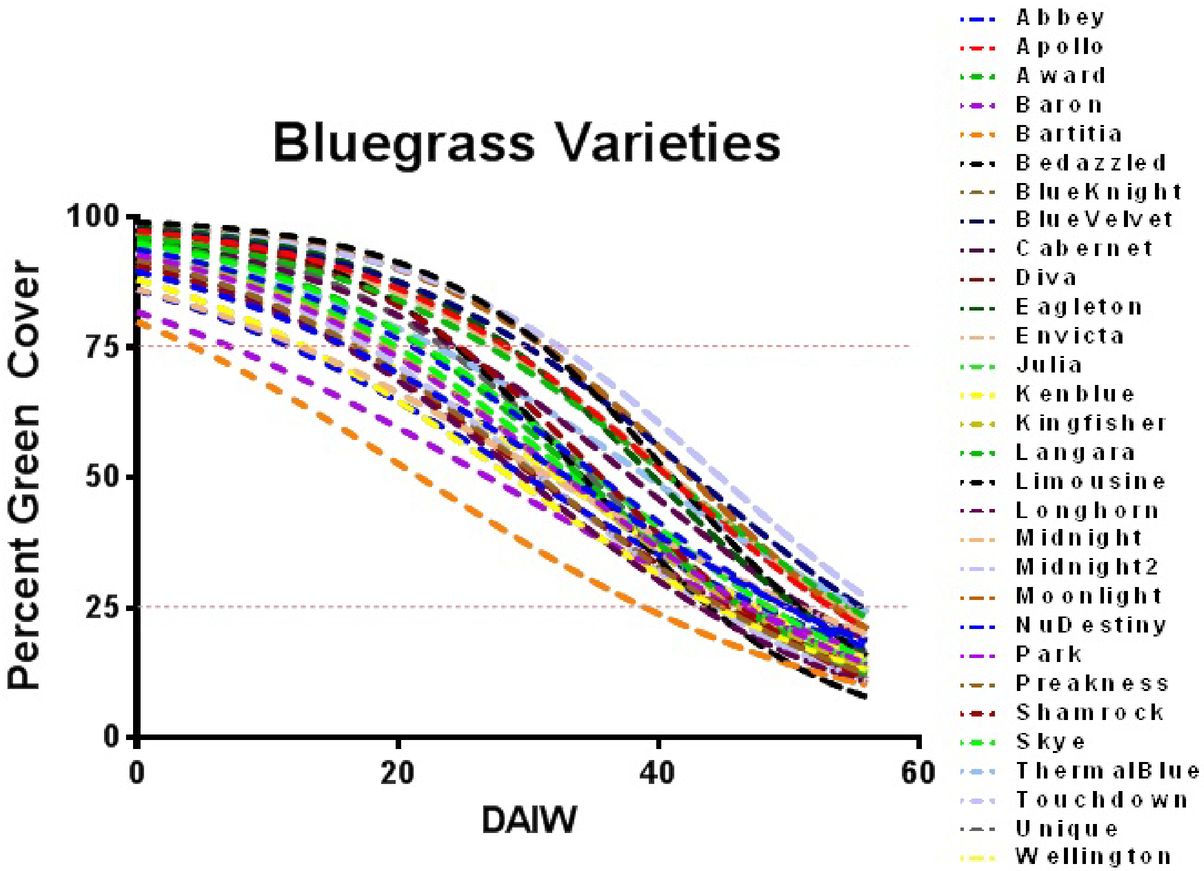

Figure 1.7- Predicted dry-down curves for 30 bluegrasses in 2011.

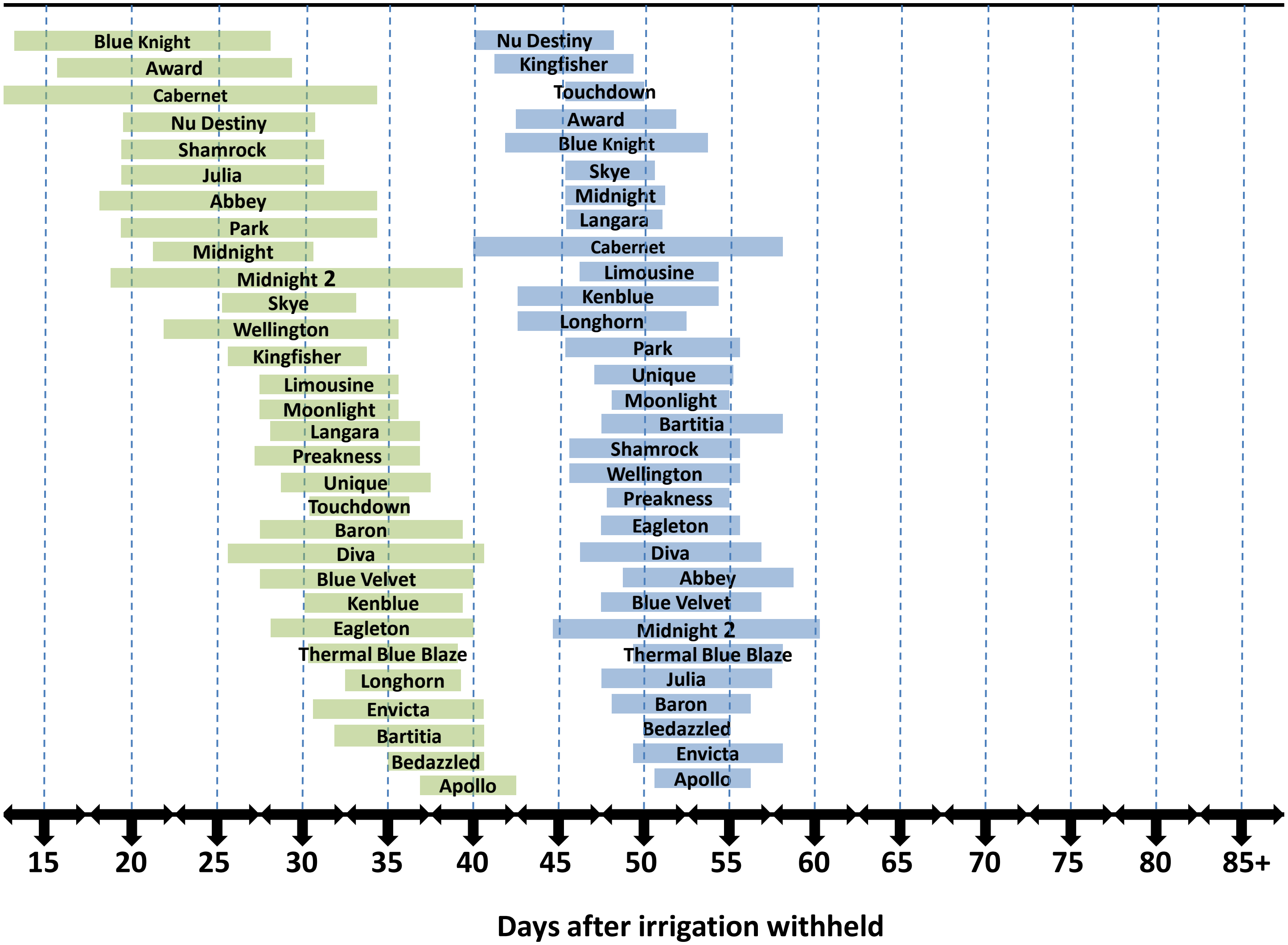

Figure 1.8- The 95% confidence intervals for the number of days after irrigation was withheld until bluegrass cultivars reached 75% and 25% green cover in 2010. Green bars represent days until cultivars reached 75% and blue represent 25% green cover. Cultivars with overlapping bars were not significantly different.

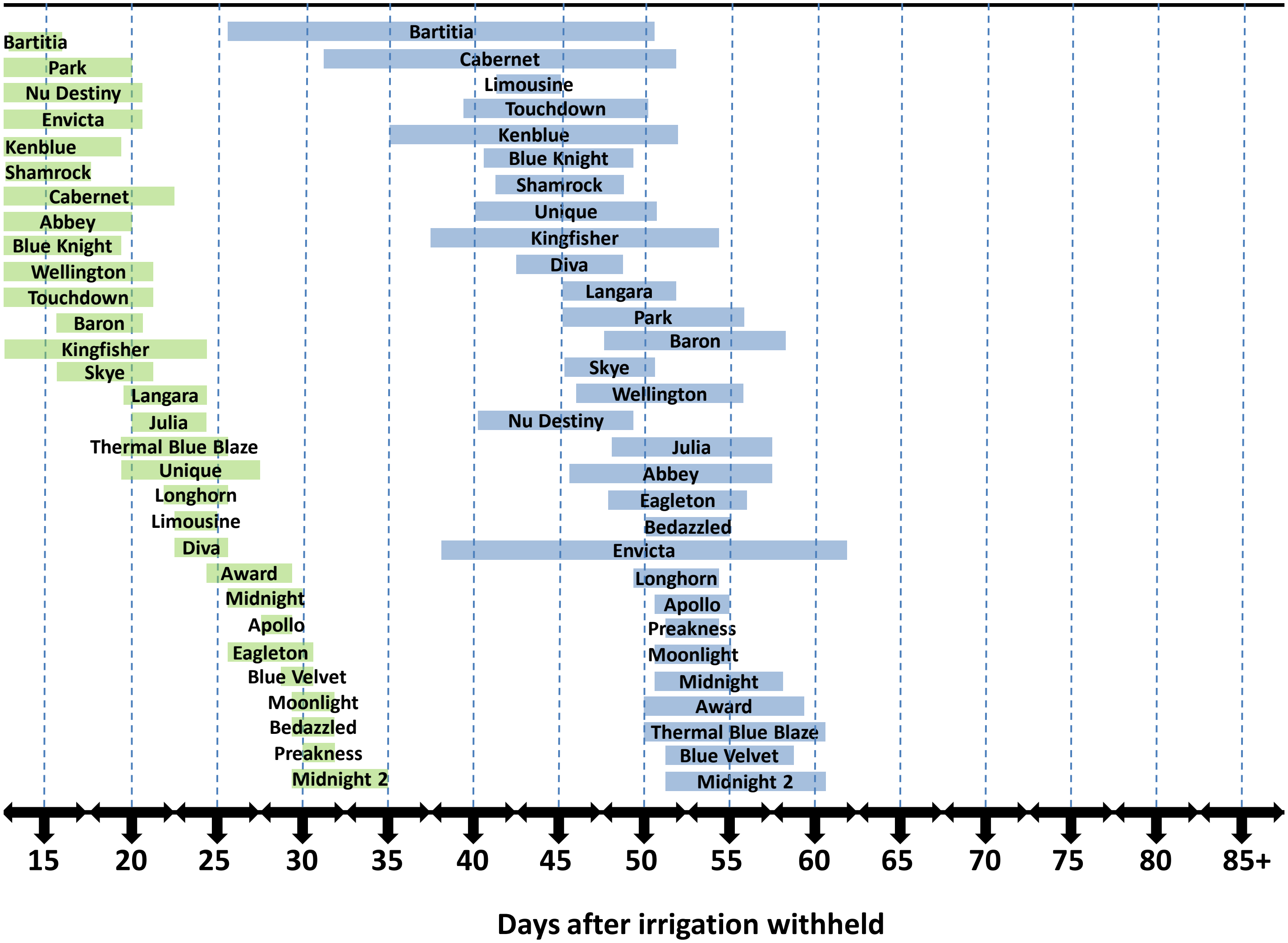

Figure 1.9- The 95% confidence intervals for the number of days after irrigation was withheld until bluegrass cultivars reached 75% and 25% green cover in 2011. Green bars represent days until cultivars reached 75% and blue represent 25% green cover. Cultivars with overlapping bars were not significantly different.

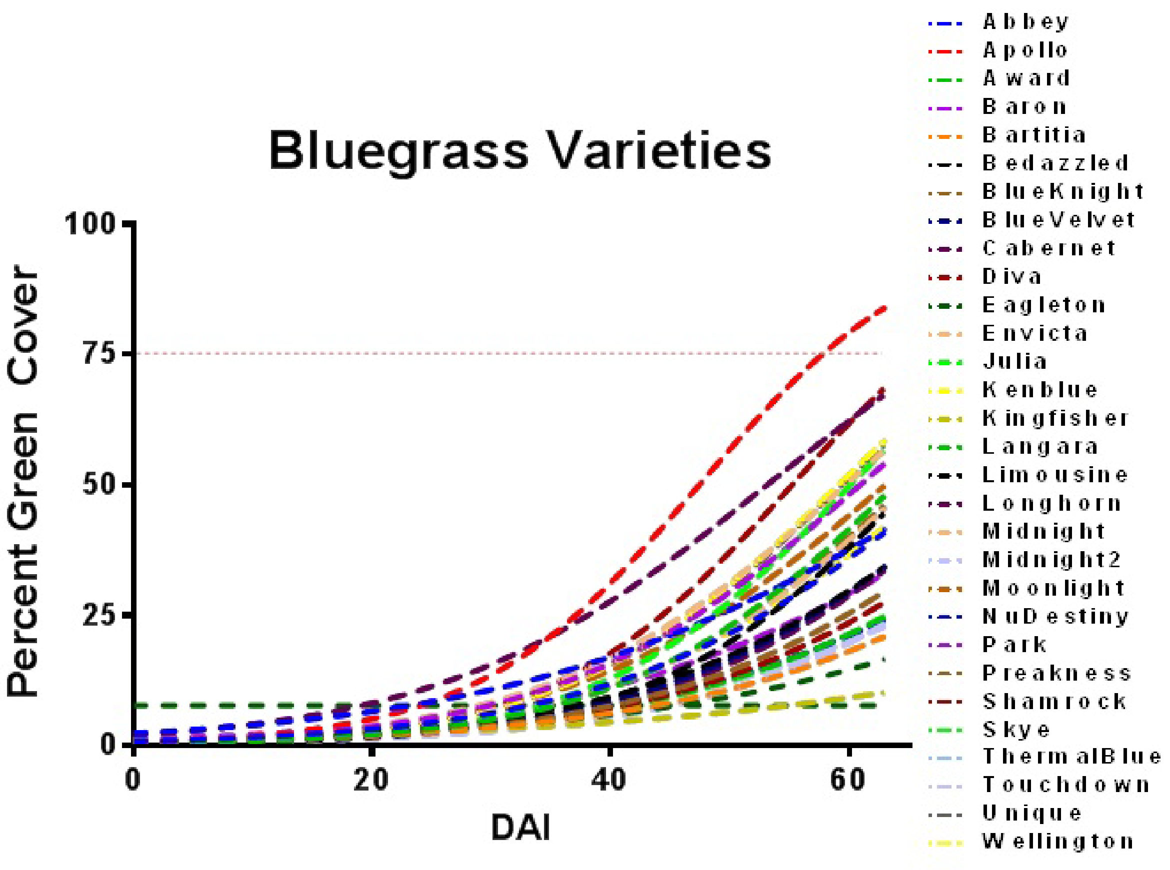

Figure 1.10- Predicted recovery curves for 30 bluegrasses in 2010.

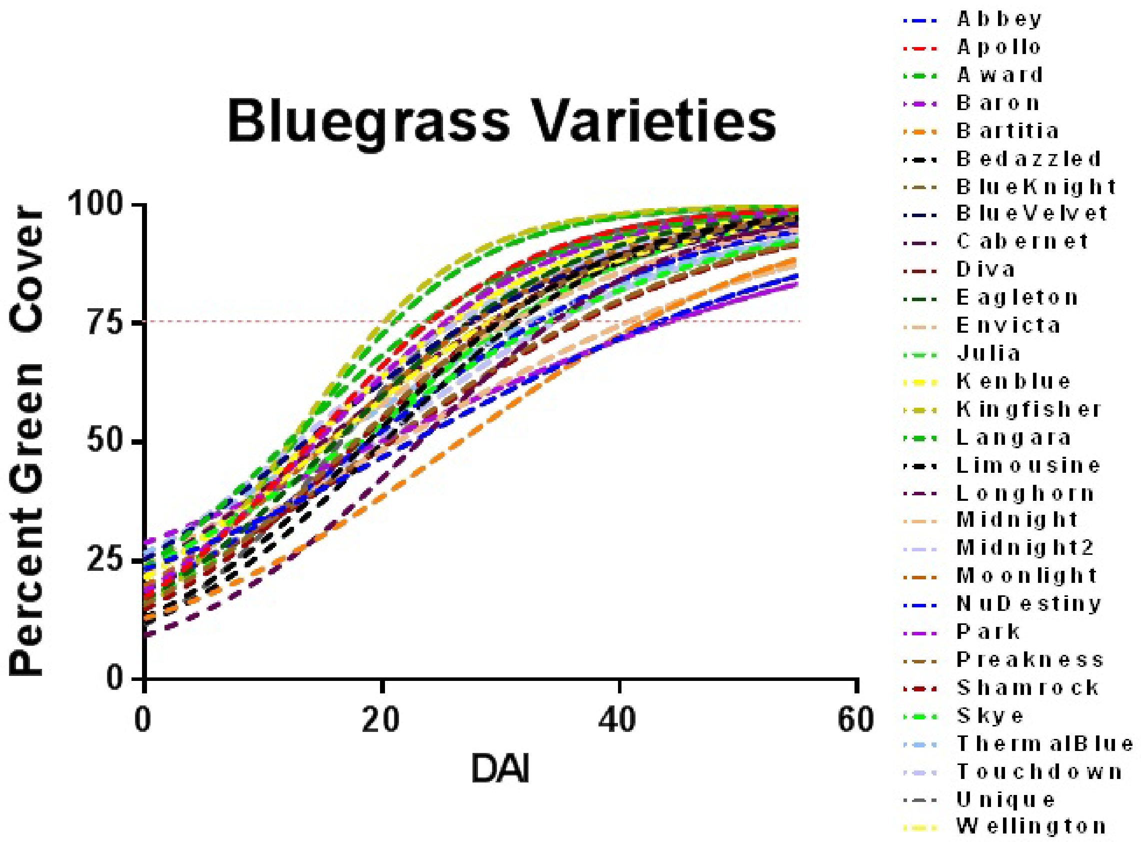

Figure 1.11- Predicted recovery curves for 30 bluegrasses in 2011.

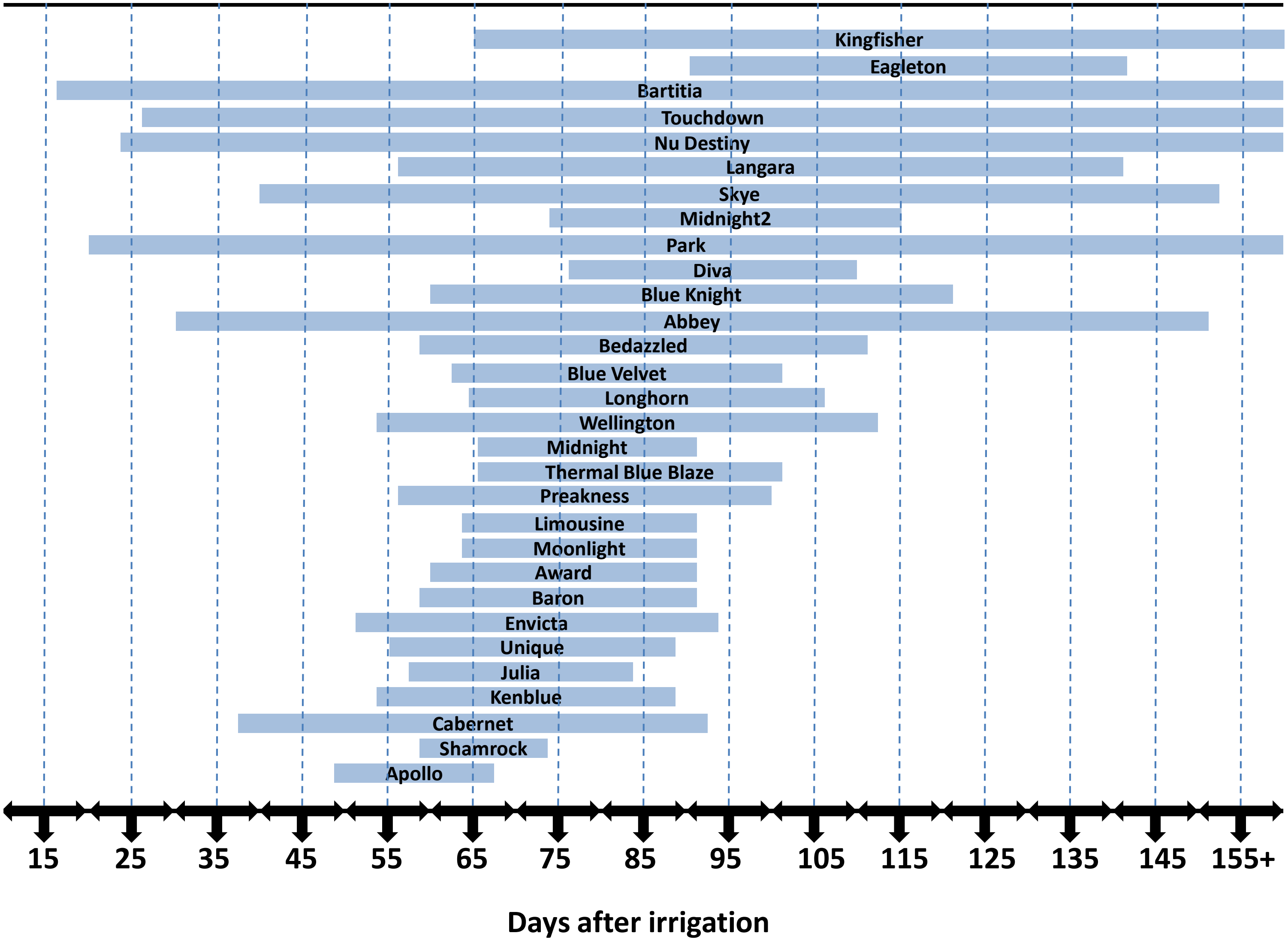

Figure 1.12- The 95% confidence intervals for the number of days after irrigation until bluegrass cultivars reached 75% green cover in 2010. Cultivars with overlapping bars were not significantly different.

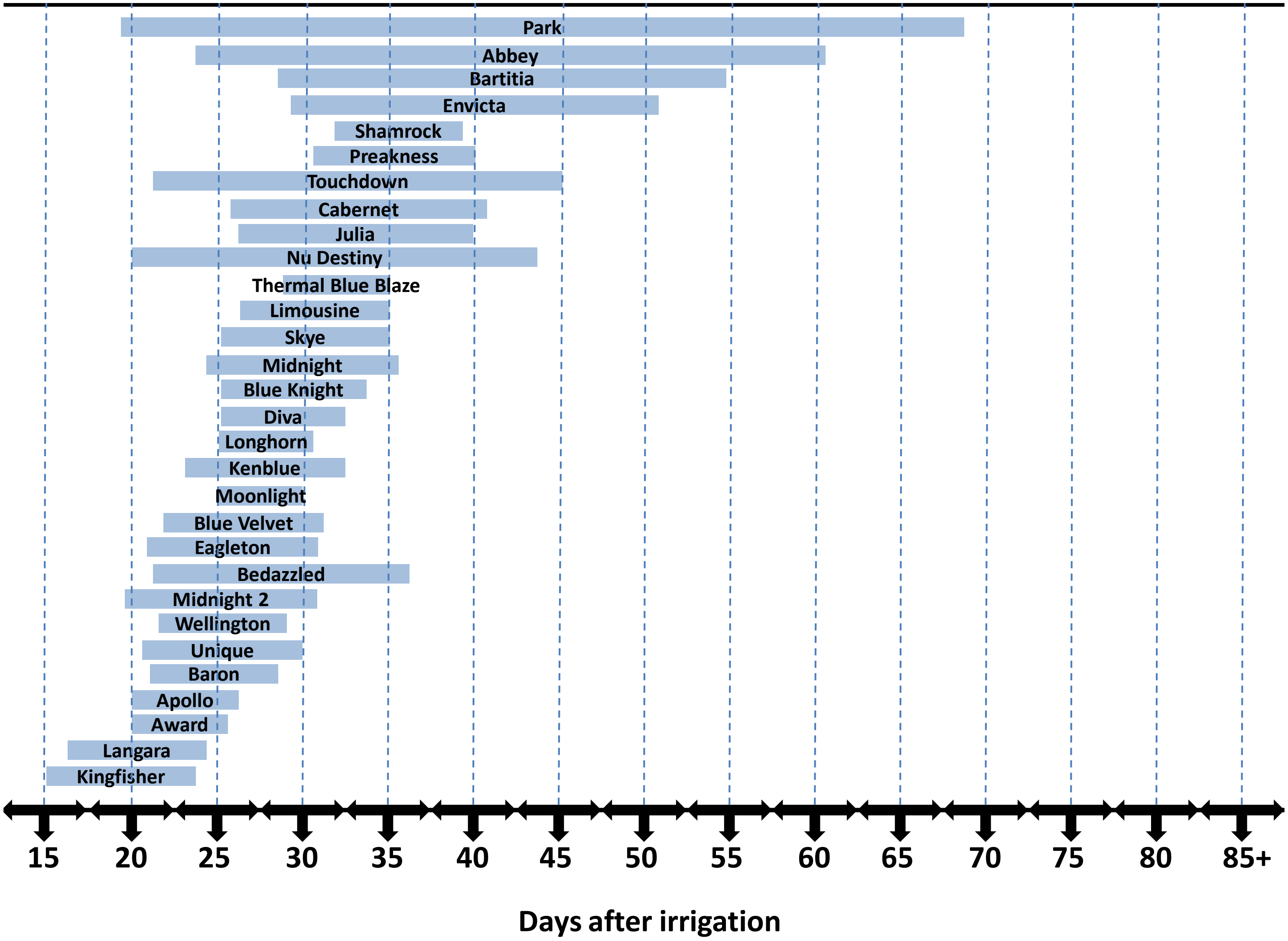

Figure 1.13- The 95% confidence intervals for the number of days after irrigation until bluegrass cultivars recovered in 2011. Cultivars with overlapping bars were not significantly different.

Table 1.1- Phenotypic types and cultivars of Kentucky bluegrass and hybrid bluegrasses.

Group	Cultivar
Common[†]	Kenblue
	Wellington
	Park
Compact	Diva
	Skye
	Moonlight
Compact America	Langara
	Bedazzled
	Apollo
Julia	Julia
Mid-Atlantic	Eagleton
	Preakness
	Cabernet
Compact Midnight	Midnight
	Midnight II
	Blue Velvet
	Nu Destiny
	Award
Shamrock	Shamrock
BVMG	Baron
	Envicta
	Abbey
Aggressive	Limousine
	Touchdown
European‡	Blue Knight
	Bartitia
Texas bluegrass hybrids	Thermal Blue Blaze
	Longhorn

[†] Kentucky bluegrass classification types as described in Bonos et al., 2000.

‡ Blue Knight and Bartitia have since been reclassified as “Other Type” (Brooks Gould, 2004).

Table 1.2- Hypothesis test summaries for bluegrass entry effects on green turf coverage during dry-down and subsequent recovery in 2010 and 2011.

Sums of squares reduction test	**Dry-down 2010**	**Dry-down 2011**	**Recovery 2010**	**Recovery 2011**
Null hypothesis	Shared regression parameters (slope and days$_{25//75}$) for all varieties†			
Alternative hypothesis	Different regression parameters for each variety			
Numerator df	58	58	58	58
Denominator df	480	570	390	570
F value	1.961	7.481	3.138	2.485
P value	<0.0001	<0.0001	<0.0001	<0.0001

† Slope and days$_{25/75}$ values determine percent green turf cover according to the sigmoid variable slope model.

Table 1.3- Statistical parameters for predicting dry-down characteristics of Kentucky bluegrass cultivars. Smaller (more negative) slope values translate to more rapid changes in green cover over time. Days$_{25}$ is the predicted number of days from irrigation withheld for the selected cultivar to reach 25% turfgrass coverage.

Dry down 2010						Dry down 2011					
Cultivar	Slope	SE	Days25	SE	R^2	Cultivar	Slope	SE	Days25	SE	R^2
Apollo	-0.070	0.0108	54.1	1.205	0.96	**Midnight 2**	-0.038	0.003	57.13	2.061	0.93
Envicta	-0.057	0.011	53.17	1.932	0.91	**Blue Velvet**	-0.037	0.001	55.71	0.8872	0.98
Bedazzled	-0.065	0.0074	53.06	0.99	0.97	**Thermal B**	-0.029	0.002	55.49	2.505	0.92
Baron	-0.050	0.0097	52.82	2.172	0.91	**Award**	-0.034	0.003	54.72	2.225	0.93
Julia	-0.035	0.004	52.82	2.231	0.93	**Midnight**	-0.036	0.002	54.24	1.541	0.96
Thermal BB	-0.053	0.0085	52.71	1.692	0.94	**Moonlight**	-0.042	0.002	53.71	1.051	0.98
Midnight 2	-0.039	0.01092	52.47	3.773	0.83	**Preakness**	-0.042	0.001	53.65	0.47	0.99
Blue Velvet	-0.052	0.0116	52.45	2.376	0.9	**Apollo**	-0.038	0.001	53.34	0.955	0.98
Abbey	-0.036	0.0067	52.3	2.812	0.9	**Longhorn**	-0.035	0.001	51.53	1.196	0.97
Diva	-0.052	0.0129	52.22	2.669	0.88	**Envicta**	-0.024	0.005	51	6.036	0.67
Eagleton	-0.054	0.0116	52.2	2.253	0.91	**Bedazzled**	-0.048	0.003	50.91	1.298	0.97
Preakness	-0.05	0.0082	51.87	7.796	0.94	**Eagleton**	-0.043	0.004	50.75	1.86	0.94
Wellington	-0.04	0.0078	51.72	2.354	0.91	**Abbey**	-0.028	0.002	50.02	2.737	0.9
Shamrock	-0.037	0.0055	51.56	2.268	0.93	**Julia**	-0.036	0.002	48.62	1.459	0.96
Bartitia	-0.067	0.01323	51.25	1.78	0.91	**Nu Destiny**	-0.026	0.006	48.13	6.263	0.62
Moonlight	-0.051	0.0068	51.21	1.438	0.96	**Wellington**	-0.031	0.004	47.67	3.727	0.82
Unique	-0.053	0.009	51.21	1.79	0.94	**Skye**	-0.035	0.003	47.14	2.219	0.93
Park	-0.039	0.007	50.84	2.623	0.9	**Baron**	-0.033	0.002	47.05	1.924	0.94
Longhorn	-0.064	0.0069	50.83	1.027	0.97	**Park**	-0.024	0.007	46.71	7.185	0.51
Kenblue	-0.06	0.0088	50.51	1.477	0.95	**Langara**	-0.038	0.003	46.53	2.016	0.93
Limousine	-0.051	0.0082	50.51	1.725	0.94	**Diva**	-0.044	0.002	46.5	1.085	0.98
Cabernet	-0.036	0.0093	49.6	4.13	0.82	**Kingfisher**	-0.034	0.006	46.44	3.811	0.8
Langara	-0.058	0.0093	49.32	1.636	0.95	**Unique**	-0.042	0.005	46.26	2.645	0.9
Midnight	-0.044	0.0055	48.77	1.526	0.96	**Shamrock**	-0.032	0.002	45.46	1.517	0.96
Skye	-0.049	0.0058	48.65	1.324	0.97	**Blue Knight**	-0.033	0.002	44.99	1.505	0.96
Blue Knight	-0.034	0.0055	48.52	2.805	0.9	**Kenblue**	-0.030	0.005	44.61	4.407	0.75
Award	-0.031	0.005	48.2	2.148	0.94	**Touchdown**	-0.036	0.005	44.25	2.851	0.87
Touchdown	-0.067	0.0094	47.88	1.324	0.96	**Limousine**	-0.048	0.002	44.02	0.853	0.98
Kingfisher	-0.06	0.0093	45.78	1.41	0.96	**Cabernet**	-0.035	0.008	43.28	4.955	0.7
Nu Destiny	-0.05	0.0095	44.33	1.987	0.94	**Bartitia**	-0.275	0.007	39.04	6.115	0.56

Table 1.4- Statistical parameters for predicting recovery characteristics of Kentucky bluegrass cultivars. Larger (more positive) slope values translate to more rapid changes in green cover over time. Days$_{75}$ is the predicted number of days from irrigation initiation for the selected cultivar to recover to 75% turfgrass coverage.

Recovery 2010						Recovery 2011					
Cultivar	Slope	SE	Days75	SE	R^2	Cultivar	Slope	SE	Days75	SE	R^2
Apollo	0.046	0.0138	57.76	4.08	0.75	**Kingfisher**	0.0615	0.011	20.06	2.205	0.88
Shamrock	0.043	0.0116	66.13	3.75	0.79	**Langara**	0.0575	0.007	20.9	1.511	0.94
Cabernet	0.031	0.0185	68.15	11.5	0.39	**Award**	0.0421	0.004	23.43	1.532	0.94
Kenblue	0.038	0.0181	71.55	8.23	0.53	**Apollo**	0.048	0.005	23.88	1.476	0.94
Julia	0.041	0.014	71.74	5.92	0.68	**Baron**	0.0445	0.004	25.17	1.517	0.94
Unique	0.038	0.0166	71.92	7.74	0.57	**Unique**	0.0535	0.008	25.41	1.921	0.91
Envicta	0.035	0.0176	73.27	9.81	0.47	**Wellington**	0.0406	0.003	25.71	1.223	0.96
Baron	0.034	0.0135	74.68	7.97	0.61	**Midnight 2**	0.0362	0.006	26.06	3.113	0.83
Award	0.037	0.012	76.57	6.78	0.7	**Bedazzled**	0.043	0.009	26.69	3.176	0.84
Moonlight	0.033	0.009	77.24	6.46	0.74	**Eagleton**	0.0431	0.005	27.12	2.014	0.92
Limousine	0.039	0.0126	77.45	6.44	0.73	**Blue Velvet**	0.347	0.004	27.27	2.03	0.92
Preakness	0.036	0.0164	77.98	9.80	0.55	**Moonlight**	0.039	0.002	27.56	1.129	0.97
Thermal BB	0.035	0.0097	78.42	5.99	0.77	**Kenblue**	0.035	0.004	28.83	2.311	0.9
Midnight	0.035	0.0098	78.55	6.08	0.77	**Longhorn**	0.0345	0.002	28.85	1.38	0.96
Wellington	0.031	0.0167	82.36	13.7	0.47	**Diva**	0.042	0.005	29.3	1.99	0.93
Longhorn	0.033	0.0118	86.04	10.0	0.67	**Blue Knight**	0.04	0.004	29.44	1.713	0.94
Blue Velvet	0.032	0.0126	86.3	11.2	0.62	**Midnight**	0.0319	0.004	30.57	2.587	0.9
Bedazzled	0.03	0.011	87.81	11.8	0.62	**Skye**	0.0386	0.005	30.59	2.207	0.92
Abbey	0.023	0.017	89.85	27.3	0.26	**Limousine**	0.0432	0.005	31.16	1.945	0.94
Blue Knight	0.03	0.013	90.78	14.3	0.56	**Thermal BB**	0.0285	0.002	32.23	1.693	0.96
Diva	0.030	0.0068	92.84	7.68	0.83	**Nu Destiny**	0.034	0.010	32.82	5.576	0.67
Park	0.255	0.0228	93.74	33.9	0.21	**Julia**	0.029	0.004	33.79	3.249	0.86
Midnight 2	0.315	0.0086	94.46	9.92	0.76	**Cabernet**	0.042	0.009	34.22	3.548	0.84
Skye	0.027	0.0180	97.37	25.7	0.36	**Touchdown**	0.032	0.008	34.37	5.367	0.72
Langara	0.273	0.013	98.22	19.4	0.5	**Preakness**	0.03	0.003	36.04	2.247	0.94
Nu Destiny	0.025	0.02	101.4	35.5	0.26	**Shamrock**	0.0302	0.002	36.45	1.507	0.97
Touchdown	0.025	0.0196	102.4	34.9	0.28	**Envicta**	0.0248	0.005	40.35	5.196	0.77
Bartitia	0.026	0.0227	103.2	39.6	0.23	**Bartitia**	0.031	0.008	41.73	6.2	0.72
Eagleton	0.021	0.0042	117.2	11.8	0.84	**Abbey**	0.023	0.007	42.97	8.554	0.57
Kingfisher	0.016	0.0069	148	38.2	0.53	**Park**	0.0199	0.007	43.77	11.37	0.42

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Chapter 2 - Physiological responses of Kentucky Bluegrass Cultivars to Prolonged Drought Stress in the Transition Zone

Abstract

Increasing water scarcity may result in irrigation restrictions being imposed with no regard for damage to turfgrass. My objectives were to evaluate visual performance and physiological parameters during prolonged drought of Kentucky bluegrass (*Poa pratensis* L.) (KBG) cultivars. Irrigation was withheld from six bluegrasses for 88 days in 2010 and seven bluegrasses for 60 days in 2011; cultivars were selected due to their broad range of days to wilt between watering in an earlier study. Plots were protected from rainfall by an automated rainout shelter near Manhattan, KS, in the transition zone of the USA. Visual color and quality, and digital images were collected weekly during the dry downs. Physiological measurements included electrolyte leakage (EL), leaf water potential (Ψ_{leaf}), and photosynthesis. In general, there were no differences in EL, Ψ_{leaf} , and photosynthesis among cultivars during or after each dry down. Apollo consistently demonstrated the greatest drought tolerance as measured by slowest decline to 25% green cover during both years (54.1 and 53.4 days in 2010 and 2011, respectively), perhaps from Apollo's greater ability to mine soil moisture from the profile than the other cultivars. The mean time to decline to 25% green cover for all cultivars was 52.1 days in 2010 and 51.7 days in 2011. All plots recovered from prolonged drought but Apollo rebounded the fastest to75% green cover (57.7 and 23.8 days in 2010 and 2011, respectively; mean of all cultivars=78.9 and 29.7 days in 2010 and 2011, respectively). Overall, all bluegrasses displayed remarkable recovery after prolonged drought stress incurred during both dry downs.

Introduction

Drought tolerance varies widely among Kentucky bluegrass (KBG) cultivars (Ebdon and Petrovic, 1998; Richardson et. al., 2009; Lewis et al., 2012). There are likely a number of underlying physiological mechanisms affecting drought tolerance. Such mechanisms may include plant water potential, cellular membrane stability, and photosynthesis. The maintenance of a favorable status in these mechanisms during drought stress may improve the performance of some cultivars relative to others.

In a greenhouse study, relative water content, electrolyte leakage (EL) (an indicator of cellular membrane stability), and photochemical efficiency were measured in several KBG cultivars and hybrid bluegrasses (KBG × Texas bluegrass [*Poa arachnifera* Torr. × *P*. *pratensis*]) under drought stress (Abraham et. al., 2004). Interestingly, among all the physiological parameters examined in that study, EL was the most sensitive indicator of drought stress. Originally, EL was used for screening new genotypes to predict whole-plant heat tolerance (Marcum, 1998). However, this technique has been used in more recent studies to evaluate turfgrass drought tolerance, as well as the combination of heat and drought stresses (Du et al., 2009; Liu et al., 2007; Su et al., 2007, 2009; Merewitz et. al., 2010; Domenghini et al., 2013).

Leaf water potential has strong effects on cellular growth, which is highly sensitive to drought and responds before stomatal conductance or photosynthesis (Hsiao, 1973). During periods of drought, when water potentials are low, cell expansion becomes limited and growth is reduced (Fry and Huang, 2004). Leaf water potential has successfully been used to evaluate drought tolerance in several cool-season turfgrasses (Huang et al., 1998; Wang and Bughrara, 2008; Domenghini et al., 2013).

Photosynthesis is a fundamental indicator of plant stress and growth (Salisbury and Ross, 1978) and may be used to evaluate relative drought tolerance among turfgrasses (Huang et al., 1997; DaCosta et al., 2004; Huang and Gao 1999; Su et. al., 2007). Researchers evaluating KBG undergoing nine days of soil drying, reported reductions in photosynthesis of approximately 35-45% (DaCosta et al., 2004). Similar reductions in photosynthesis of (~33%) were also reported in KBG undergoing deficit irrigation (Su et. al., 2007).

Although the physiological mechanisms of Ψ_{leaf}, cellular membrane stability (EL), and photosynthesis have been used to evaluate drought tolerance in cool-season turfgrasses, their responses in KBG cultivars exposed to prolonged drought, as described in Chapter 1, have not been evaluated. Therefore, the objectives of this study were to evaluate the responses Ψ_{leaf}, EL, and photosynthesis in KBG cultivars exposed to the 88 and 60 day dry down in 2010 and 2011, respectively. Visual ratings of quality and color as well as measurements of percent green coverage and soil moisture were also collected.

Materials and Methods

Study site and experimental design

This study was conducted from 15 June to 4 Sept. 2010 (88 d), and 1 June to 1 Aug. 2011 (60 d). Turfgrass plots were maintained under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas, USA (39^{o}13’53” N, 96^{o}34’51” W). The rainout shelter rests north of the plot area but automatically covered the plots as precipitation began and retracted 1 h after cessation of rainfall. The rainout shelter malfunctioned three times, once in the first year of the experiment, and twice during the second year. The first malfunction occurred on 5 July 2010 and allowed approximately 25 mm of precipitation to fall on the study plots. The subsequent malfunctions occurred on 15 July 2011 and 21 July 2011, allowing approximately 7 mm and 32 mm of precipitation, respectively, to fall on the plots. The soil at the site was a Chase silt loam (fine, smectitic, mesic, Aquertic

Argiudoll) with a pH of 6.9. A soil test prior to the study indicated P and K levels were adequate.

Weather data for Manhattan, KS during the study were obtained from Kansas State University weather data library (http://www.ksre.ksu.edu/wdl). Air temperatures during the study were generally greater than the 30-year normal in both years (Figure 2.1). Furthermore, 2011 was generally warmer than 2010. For example, air temperature during the dry down averaged 0.8 ^{o}C greater than normal in 2010 and 2.7 ^{o}C greater than normal in 2011. Daily maximum air temperatures exceeded 35 ^{o}C on 21 days during the 88-day study in 2010 and on 29 days during the 60-day study in 2011 (Data not shown).

Because it was not practical in this study to evaluate physiological mechanisms in all 30 of the bluegrasses described in Chapter 1, a subset of six KBG cultivars was selected; an additional cultivar was added in the second year because of its notably superior performance in the first year. The cultivars were selected based on results from a study conducted on these same plots by Lewis et. al. (2012), in which cultivars were ranked by the amount of water applied over the growing season using wilt-based irrigation. Specifically, we selected six cultivars from across a broad range of water requirements in the previous study in order to evaluate physiological mechanisms that may affect drought resistance in KBG cultivars. In both years, cultivars included ‘Wellington’, ‘Abbey’, ‘Bedazzled’, ‘Blue Velvet’, ‘Moonlight’, and ‘Cabernet’. The cultivar ‘Apollo’ was added in the second year (2011) after recovering the quickest among cultivars after the 2010 dry down. Additional details about overall cultivar selection, plot establishment and maintenance, and experimental design can be found in Chapter 1 and Lewis et al. (2012).

Measurements

The plots were well watered until 15 June 2010 and 1 June 2011. Thereafter, plots were allowed to dry-down for 88 days in 2010 and 60 days in 2011, with no precipitation or irrigation. Turfgrass color and quality were recorded on a weekly basis, during the growing season, by the same researcher throughout the study. The rating scale for color was 1 to 9, where 1= brown and 9= dark green. The rating scale for visual quality was also 1 to 9, where 1= brown, dead turfgrass, 6=minimally acceptable for home lawns, and 9= highest quality based on color, density, texture and uniformity (Emmons, 2000).

Digital images of all cultivars were acquired on a weekly basis and were used for calculating percent green turfgrass cover, according to the methods of Richardson et al (2001) and Karcher and Richardson (2005). In 2010, all images were collected under clear sky conditions at (~1200 CST) to minimize changes in solar zenith angle. In 2011, construction of a camera light box allowed for more flexibility in the time of data collection. The images were analyzed with SigmaScan Pro (v. 5.0, SPSS, Chicago, IL). Further details about collection and analysis of digital images can be found in Chapter 1. Visual quality and color ratings, as well as digital images, were collected from all seven cultivars in both years.

Physiological measurements included Ψ_{leaf}, which was collected biweekly, and EL and photosynthesis, which were collected weekly; these measurements were not taken for Apollo in 2010. Leaf water potential and EL were measured at approximately 1100 CST. Measurements of EL and Ψ_{leaf} were obtained from five leaves randomly sampled from each turfgrass plot. Leaves were placed in a Ziploc bag and quickly transported to the lab, where Ψ_{leaf} and EL samples were prepared within one hour of being harvested from the plots. The Ψ_{leaf} was measured with a water potential meter (WP4-T PotentiaMeter, Decagon Devices, Pullman, WA).

The technique used to measure EL was similar to the method of Blum and Ebercon (1981) and Marcum (1998) with modifications. Leaf samples were taken from each plot and placed in a test tube filled with 50 ml of deionized water. Leaf samples were prepared in the following manner: one 2-cm segment was cut out of three leaves taken from the bluegrass samples, exposing six cut ends of equal size within each turfgrass species. Test tubes were shaken on a Titer Plate Shaker (Lab Line Instruments, Melrose Park, IL) for 24 hours to dissolve electrolytes that had adhered to the leaf blade or leaked from cells. An initial measurement of conductivity (C_1) was then measured with an Oakton Conductivity Meter (Model CON510 Series, OAKTON Instruments, Vernon Hills, IL). Thereafter, the test tubes were placed in a 90-100°C water bath for 1 h (Model MSB-1122A-1 Magni-Whirl Temp Water Bath, Blue M Electric, Blue Island, IL) to destroy all cell membranes. Test tubes were shaken for 24 h to extract the remaining electrolytes from the cells and a second conductivity measurement was taken (C_2). The calculation $(C_1/C_2)*100$ was used to determine the percentage of electrolytes that leaked.

Photosynthesis was measured with a custom chamber described by Murphy (2007) and modified for turfgrass by Lewis (2010). Gross photosynthesis (Pg) was calculated from chamber measurements using the method of Bremer and Ham (2005). Briefly, this method involves consecutive measurements with a sunlit and shaded portable photosynthesis chamber, respectively, at each location; shaded measurements were obtained by covering the chamber with an opaque shell that blocked solar radiation from the chamber. Using Eq. [5] and [6] from Bremer and Ham (2005), sunlit measurements were used to determine Pg - (Rc+Rs) and the shaded chamber measurements to determine Rc + Rs, where Rc is canopy respiration and Rs is soil respiration; all values are defined as positive. Gross photosynthesis was calculated using their Eq. [8]: Pg=sunlit chamber + shaded chamber.

Volumetric soil water content (θ_v) was monitored daily at 5 and 20 cm utilizing the dual-probe heat-pulse technique (Campbell et al., 1991; Tarara and Ham, 1997; Song et al., 1998). Sensors were fabricated in the laboratory as described by Basinger et al. (2003) and Bremer (2003). Measurements of θ_v were logged twice daily with a micrologger and accessories (CR10x and three AM16/32 multiplexors, Campbell Scientific, Logan, UT). In 2011, sensors in all plots of ‘Bedazzled’ at 5 cm malfunctioned. In addition, Time Domain Reflectometry (TDR) (Model 6050X1, Soilmoisture, Santa Barbara, CA) rods 50 cm in length were installed in each of the 6 selected cultivars and measurements were collected weekly in 2010. Due to a malfunction of the TDR unit, data (0-50 cm) were not collected during the 2011 dry down.

Statistical analysis

Scatter plots of percent green turf cover versus days after irrigation was withheld (DAIW) during drought stress, and days after irrigation applied (DAI) during recovery from drought, indicated the data fit very well to a sigmoid variable slope model similar to that described by Karcher et al. (2008). Further details about these analyses can be found in Chapter 1. Briefly, for the dry down periods, a Day_{75} and Day_{25} value was calculated to estimate DAI withheld until each plot reached 75 % and 25% green cover, respectively. For the recovery periods a Day_{75} was calculated to estimate DAI was initiated before each plot reached 75% green cover. Nonlinear regression analysis of the turf percent cover data was performed using GraphPad Prism software (v. 4.0, Graphpad, San Diego, CA). Physiological data were analyzed with the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). In cases where the F-test for treatment differences was significant (*P*=0.05), 95% confidence intervals were used for comparison of individual treatment means.

Results and Discussion

Percent green coverage and visual color and quality ratings.

In 2010, all plots were completely brown (0% green cover) by end of the 88-day dry down (Fig. 2.2). At the end of the dry down in 2011 the plots were less brown than in 2010, ranging from 15 to 30% green cover (Fig. 2.3). Greater percent green coverage at the end of the 60-day dry down in 2011 was likely a result of 39 mm of total precipitation that inadvertently fell on the plots after the rainout shelter malfunctions that occurred 44 and 51 days after irrigation (DAI) was withheld.

Bluegrass cultivar significantly affected green turf coverage during both the dry down and subsequent recovery periods in both years of the study (Table 2.1). The sigmoid models used to predict percent green cover provided a good fit of the green cover data, resulting in average coefficient of determination (R^2) values of 0.90 and 0.81 during dry downs in 2010 and 2011, respectively, and 0.42 and 0.81 during the recovery periods in 2010 and 2011, respectively. The weaker goodness of fit of the sigmoid models during recovery from drought stress in 2010 (R^2=0.42) was the result of a slow recovery period that lasted into the spring of 2011, with green turf cover varying considerably among replications of each cultivar. Slower recovery in 2010 was probably caused by the longer dry down period (88 days), which resulted in greater drought stress than during the 60-day dry down in 2011 (Figs. 2.2 and 2.3.).

In 2010, green coverage was between 95-100% among the seven cultivars at the beginning of the dry down (Fig. 2.2). In contrast, green coverage was lower at the beginning of the dry down in 2011, ranging from 85-98% among the seven cultivars (Fig 2.3). This difference was likely the result of the slow recovery in 2010, in which some plots had not yet reached full green coverage by the beginning of the dry down 2011. In both years, green coverage began to decline quickly in some of the cultivars after irrigation was withheld (Figs. 2.2 and 2.3). Based on predictions from the sigmoid models, the Days_{25} averaged 52.1 in 2010, which was just slightly longer than the average of 51.7 days in 2011. However, the range of Days_{25} among the seven cultivars in 2010 was 49.6 to 54.1days (a 4.5-day span), which was narrower than the range of 43.2 to 55.7 days in 2011 (a 12.5-day span). The narrower range in 2010 resulted in fewer differences Days_{25} among the seven cultivars than in 2011. The average air temperature during the first 10-15 days of the dry down was similar between years (Figure 2.1). Thus, it is unlikely that differences in heat stress caused the differences in Days_{25} between years. It is more likely that because some cultivars started with less green coverage in 2011, they declined to 25% faster than in 2010 when they were closer to full coverage.

All seven cultivars recovered to ~85-100% green turfgrass cover after the dry downs in 2010 and 2011. However, complete recovery from the dry down in 2010 was not achieved until the following spring (March 2011) (data not shown). In 2011, all plots had completely recovered by approximately 2 months (~October) after irrigation was returned.

The cultivars that demonstrated the greatest Days_{25} in both years were Apollo and Bedazzled, but the greatest drought tolerance among all cultivars was consistently in Apollo (See Chapter 1). The cultivar exhibiting the least drought tolerance in both years was Cabernet. By contrast, in a study evaluating minimum water requirements of KBG cultivars using wilt-based irrigation in these same plots, Cabernet was a low water user while maintaining high visual quality (Lewis et al., 2012). Although, the methodology of that study differed from the current one, the results suggest Cabernet may tolerate intermittent drought conditions better than prolonged drought experienced in this study.

Based on recovery predictions from the sigmoid models, the Days_{75} averaged 78.9 in 2010, which was longer than the average of 29.7 days in 2011. The average number of days to reach 75% coverage was 49 days longer in 2010 than in 2011. The cultivar that required the fewest days to reach 75% green cover during both years of the study was Apollo (Figs. 2.4 and 2.5). This result is similar to previous research which suggested that cultivars with good drought tolerance during dry down are typically the quickest to recover following drought (Richardson et al., 2008). The cultivar that demonstrated the slowest recovery in both years of the study was Abbey.

Visual color declined during the dry downs in both 2010 and 2011. Analysis of variance indicated significant differences ($P = 0.05$) among the selected cultivars on 3 of 29 sampling dates in 2010 (data not shown). In 2010, visual color ratings were lower in Cabernet at the start of the 60 day dry-down, which suggests a genetic color difference. By 12 and 18 August, or approximately 8 weeks into the dry-down, color ratings in Apollo were highest among cultivars, indicating greater resiliency in Apollo to maintain color during drought. However, in 2011 there were no differences in color ratings among cultivars on any measurement date.

Visual quality declined substantially during the dry downs of both years. In general, visual quality was similar among cultivars as drought effects intensified. In fact, differences in visual quality among cultivars occurred only on three measurement dates in 2010 and never in 2011 (Fig. 2.6). In 2010, reductions in visual quality were evident by five DAI withheld. Overall, the average quality among cultivars decreased from 7.0 on 17 June to 6.1 by 30 June 2010. On 30 June 2010, the visual quality of Apollo and Bedazzled (both are Compact

Americas) were greater than Cabernet, Blue Velvet, and Abbey. One week later (7 July 2010), visual quality was greater in Bedazzled, Apollo and Abbey than in Wellington and Cabernet. On 12 August 2010, visual quality was greatest in Apollo among cultivars. Visual quality data from 2010 are similar to the data previously discussed that was collected by digital image analysis. For both rating methods, cultivars representing the phenotypic group Compact America (i.e. Apollo and Bedazzled) displayed the highest visual quality or percent green turfgrass cover among cultivars. Previous studies have recommended selecting cultivars from this phenotypic group because of their greater drought tolerance (Richardson et al., 2008; Lewis et al., 2012).

Prior to the 2011 dry down visual quality was below acceptable levels. Following the dry down initiation, visual quality began to decline by 22 DAI withheld. On average, visual quality among cultivars decreased from 5.5 on 15 June to 4.8 by 29 June 2011 (Fig. 2.6). Overall, the decrease in visual quality during the dry down was much less severe in 2011 than in 2010, probably because the plots received 39 mm of precipitation when the rainout shelter malfunctioned in 2011. However, data collected by the digital image method showed a steeper decline when compared to visual quality data. The differences between the two methods are possibly related to the more subjective nature of visual ratings. Plots were rated by the same researcher throughout the study, but visual quality was lower when compared with percent green turfgrass coverage data obtained through digital image analysis in 2011 as in 2010.

Soil Water Content

Volumetric soil water content at 5 cm, 20 cm, and in the 0 to 50 cm profile decreased during both dry downs in both years (Figs. 2.7, 2.8, and 2.9). In 2010, θ_v content at 5 cm was similar among cultivars at the beginning of the dry down (33-34%) (Fig. 2.7). During the next

21 days, θ_v declined rapidly but then abruptly increased on 5 July after the plots received 25 mm of precipitation when the rainout shelter malfunctioned. During the next 25 days, θ_v again declined among cultivars before generally leveling off in the final 35 days of the dry down. In 2011, θ_v at 5 cm was also similar among cultivars at the beginning of the dry down (24-26%). Thereafter, θ_v declined rapidly for the first 15 days and began to level off in four cultivars by 15 June; θ_v continued to decline in Blue Velvet and Wellington for an additional 10 days. Volumetric soil water content increased substantially after all plots received 25 mm of precipitation on 21 July, 2011 when the rainout shelter malfunctioned a second time in the study.

In both years, the greatest depletion of soil moisture at 5 cm was in Cabernet and Apollo. By the end of the period of soil moisture depletion in each year, when θ_v at 5 cm leveled off, θ_v had declined in ‘Cabernet’ by 29% in 2010 and 17% in 2011, and in ‘Apollo’ by 22% in 2010 and 16% in 2011. Cabernet belongs to the KBG phenotypic group Mid-Atlantic, whose cultivars are known for having extensive root and rhizome systems and good tolerance and recovery from summer stress (Bonos et al., 2000; Brooks Gould, 2004). Greater depletion of soil moisture at 5 cm by Cabernet in this study supports these reports. Apollo belongs to the KBG phenotypic group Compact America, whose cultivars have been reported as having moderate ability to recover from summer stress (Brooks Gould, 2004). Both Cabernet and Apollo were among the top performing cultivars in a study that ranked minimum water requirements of 28 KBG and two hybrid bluegrasses (Lewis et al., 2012).

In 2010, θ_v at 20 cm was similar among cultivars at the beginning of the experiment (36-38%) (Fig. 2.8). Soil moisture declined rapidly during the first 15 days of the dry down and then abruptly increased after plots inadvertently received 25 mm of precipitation on 5 July. Thereafter, θ_v declined for the next 30 days before generally leveling off. By the end of the entire 88 day dry down, the greatest decline in θ_v among cultivars was in Apollo (23%). In 2011, θ_v at 20 cm was also similar in all cultivars at the beginning of the dry down (30-31%). The θ_v generally declined from 1 June to 2 July. During this 30 day period the greatest reduction in θ_v was in 'Bedazzled' (19%).

In both years the soil was much drier by the end of the dry down at 5 cm than at 20 cm (Figs. 2.7 and 2.8). Presumably, greater root density nearer the surface resulted in greater depletion of soil moisture at 5 cm (Su et al., 2008). At 20 cm, the greatest decline in θ_v was in cultivars from the phenotypic group Compact America (i.e., Apollo and Bedazzled), which indicates that cultivars from that group had a greater ability to mine water from deeper in the profile (20 cm). In a study conducted by (Bonos and Murphy, 1999) soil moisture of drought tolerant cultivars was significantly lower at the 15-30 cm depth compared with intolerant cultivars. These results suggest that Apollo and Bedazzled may be more drought tolerant than the other cultivars. However, cultivar Wellington from the Common type phenotypic group also had large declines in θ_v at the 20 cm profile for both years, but did not display superior drought tolerance.

In 2010, θ_v in the 0-50 cm profile was similar at the beginning of the experiment (38-43%) (Figure 2.9). The fastest decline in θ_v occurred from 6 July to 9 August. During this 33 day period, the greatest reduction in θ_v was in the Common phenotype Wellington (~21%). Interestingly, decreases in θ_v in Wellington were less at 5 cm and greater at 20 cm than most of the other cultivars. This suggests that Wellington may have depleted even greater soil moisture from deeper in the profile, perhaps because of a deeper root system (21-50 cm).

Leaf Water Potential

Leaf water potential began to decline in the first week of the dry down in both years (data not shown). There were differences in Ψ_{leaf} among cultivars on only 8 out of 55 measurement dates during the two-year study (P=0.05), but there were no conclusive trends. In 2010, average Ψ_{leaf} among the six cultivars declined by 52%, from -3.83 MPa to -5.84 MPa, during the first 21 DAI withheld. Overall, the decline in Ψ_{leaf} during this period was the most rapid of the entire dry down in 2010. At the end of this 21-day period, on 5 July, the plots received 25 mm of precipitation after the rainout shelter malfunctioned. After receiving precipitation, Ψ_{leaf} rebounded to an average of -2.01 MPa among the six cultivars on 7 July. However, after the remaining 67 days of the 88 day dry down, Ψ_{leaf} had again declined to -5.98 MPa among the six cultivars, a decrease of nearly two times. For the first 16 days of recovery, average Ψ_{leaf} ranged from -4.62 MPa to -5.58 MPa among the six cultivars. On 27 September 2010 or approximately 23 days into recovery Ψ_{leaf} finally reached an average level of -3.61 MPa which was similar to the cultivars at the beginning of the dry down.

In 2011, average Ψ_{leaf} among cultivars decreased by 1.47 times, from -1.71 MPa to -4.34 MPa, during the first 44 days of the dry down (data not shown). At the end of those 44 days, on 15 July, the plots received 7 mm of precipitation after the rainout shelter malfunctioned. However, Ψ_{leaf} among the cultivars still continued to decline reaching the lowest point of -6.84 MPa on 21 July 2011. On this date 51 DAI, a second rain shelter malfunction occurred and the plots received 32 mm of precipitation. By 26 July 2011 Ψ_{leaf} had rebounded to -1.09 MPa when average across the six cultivars. Overall, in this two-year study Ψ_{leaf} did little towards discerning differences in drought tolerance among KBG cultivars.

Values of Ψ_{leaf} in this study were low at the beginning of the dry down, particularly in 2010 (mean = -3.83 MPa), as well as at the end of the dry down (e.g., range of Ψ_{leaf} from -6 to

-10.8 MPa in 2010). Other studies have reported Ψ_{leaf} from -0.5 to -1.8 under well-watered conditions down to <-4 MPa under conditions of severe drought (Qian and Fry, 1997; Wang et al., 2008; Domenghini et al., 2013). The low values of Ψ_{leaf} in the present study were likely caused by a combination of the severity of the drought and the fact that Ψ_{leaf} was measured at midday rather than under pre-dawn conditions.

Electrolyte Leakage

Electrolyte leakage (EL) was generally similar among the six cultivars during the dry down and recovery periods in both years (Fig.2.10). In addition, there were no substantial increases in EL as the dry down progressed in both years, indicating the effects of drought stress on cellular membrane stability were negligible. Cell membrane leakage of greater than 50% will typically result in tissue death (Dr. C.B. Rajashekar, personal communication). In this study, EL exceeded 50% on only a few occasions in 2010, but typically dropped below the 50% threshold the following sampling period. For 2011, EL never exceed the 50% threshold.

Interestingly, EL increased substantially in Bedazzled, Abbey, and Wellington on 7 Sept. 2010, which was three days into the recovery (i.e, three DAI was reapplied). During this period, the canopy was a mixture of newly emerging leaves and older leaves. In pepper plants (*Capsicum annuum* L.), EL was reportedly greater in mature leaves than in immature leaves on the same plant (Anderson et al., 1990). Therefore, it is possible that early in the recovery period of the present study, differences in EL resulted from the random selection of older leaves in Bedazzled, Blue Velvet, and Cabernet than in the other cultivars. In support of this, EL decreased in Bedazzled, Blue Velvet, and Cabernet by the next measurement date, with no differences in EL among any of the cultivars. This indicates a limitation in using EL to assess drought stress effects in KBG, which typically goes dormant during severe drought. The difficulty is in selecting leaves that are representative of the entire canopy, which consists of many immature and mature leaves.

The results of this study contradict those from a growth chamber study conducted by Abraham et al., (2004), in which EL was a sensitive indicator of drought stress in turfgrass. However, a number of other studies have reported negligible effects of drought stress on EL among turfgrass species (Su et. al., 2007; Merewitz et al., 2010; Domenghini et al., 2013), which is similar to the results from the present study.

Gross Photosynthesis

Photosynthesis decreased substantially in all six KBG cultivars over the course of the 2010 dry down and in all seven cultivars in 2011 (Fig. 2.11). In 2010, differences in Pg among cultivars were only observed on the initial measurement date of 18 June, which was three days after the dry down began. On that day, Pg ranged widely among cultivars from 10.2 to 27.4 μmol m^{-2} s^{-1} and was greater in Bedazzled than in Cabernet, Abbey, and Wellington. Within 12 days, Pg had declined by 50 to 73% among cultivars. By 23 July, which was about 5 weeks into the dry down, Pg was less than 5 μmol m^{-2} s^{-1} in all cultivars and remained so through the end of the 12.6-week dry down. Interestingly, after re-watering plots on 4 Sept. Pg continued to decline and by 20 Sept. was less than 1 μmol m^{-2} s^{-1} in all cultivars; this was approximately 2 weeks after the plots were re-watered, although most of the canopy either remained dormant or was deceased. Overall, Pg declined by >95% in all cultivars from the study initiation through 20 Sept. 2010.

By 26 Oct.2010, Pg had increased but remained 43 to 75% less than at the beginning of the dry down. Previous research has indicated prolonged drought may damage the photosynthetic apparatus of cool-season turfgrass, which may inhibit Pg even after leaf water status returns to normal (Huang et al., 1998). Therefore, the severity of damage to the KBGs during the 88-day drought likely resulted in a slow recovery. On 3 Nov., it was visually evident that most plots had not fully recovered due to patchy green cover in most plots that resulted in low percent green coverage (Figs. 2.2 and 2.3). Lower solar elevation angles in Nov. than in June also reduced photosynthetically active radiation (data not shown), which probably further depressed Pg in Nov.

In 2011, Pg averaged 18 μmol m^{-2} s^{-1} among the seven cultivars at the beginning of the dry down 6 June (Fig. 2.11). By 8 July, Pg had decreased by 24 to 77% among cultivars and was 75 to 133% greater in Apollo than in Wellington, Cabernet, Abbey, and Bedazzled; 8 July was the only day in 2011 where differences in Pg were observed among cultivars. Greater Pg in Apollo, a Compact America phenotype, is similar to the results from two separate 30-day dry downs in an earlier study on these same plots, which also indicated greater Pg in Apollo than in other KBG cultivars (Lewis, 2010); unfortunately, Pg in Apollo was not measured in 2010 in the present study. By 20 July 2011, Pg in all seven cultivars had declined by about 85% from the beginning of the dry down, averaging 2.69 μmol m^{-2} s^{-1} among cultivars.

Optimal temperature range for photosynthesis and plant growth in cool-season grasses is 20-25 ^{o}C (Fry and Huang, 2004). Temperatures exceeded 30 ^{o}C on days during both dry downs in 2010 and 2011. Greater reductions in Pg during the 88-day dry down in 2010, which resulted in a slower recovery, indicated greater severity in drought stress than during the shorter (60-day) dry down in 2011 and subsequent faster recovery. In fact, the recovery period after the 2010 dry down extended into and through the spring of 2011 (data not shown). Nevertheless, plots had recovered to (85-98%) turfgrass coverage by the beginning of the dry down in 2011 (Figs 2.5), indicating a remarkable capacity for recovery by KBG after extended drought.

Conclusions

In summary, all cultivars of KBG recovered from prolonged drought stress which was incurred during both dry downs. One of the most significant factors in distinguishing among the seven cultivars examined came from their ability to extract soil moisture while undergoing irrigation deficit. The KBG cultivars ‘Cabernet’ and ‘Apollo’ showed the highest reduction in volumetric water content from the 5-cm soil profile for both years of the study. However, those two cultivars had contrasting drought tolerance as measured by the amount of days to reach 25% green turfgrass coverage. At 20 cm, the greatest decline in θ_v was in cultivars from the phenotypic group Compact America (i.e., Apollo and Bedazzled), which indicates that cultivars from that group had a greater ability to mine water from deeper in the profile (20 cm). Apollo consistently demonstrated the greatest drought tolerance among the cultivars while Cabernet was the least drought tolerant. The cultivar that required the fewest days to reach 75% green cover during the recovery in both years was Apollo.

With the exception of greater Pg in Apollo late in the dry down of the second year, there were generally no differences in the physiological factors of EL, Ψ_{leaf}, and Pg among cultivars in this study

Figures and Tables

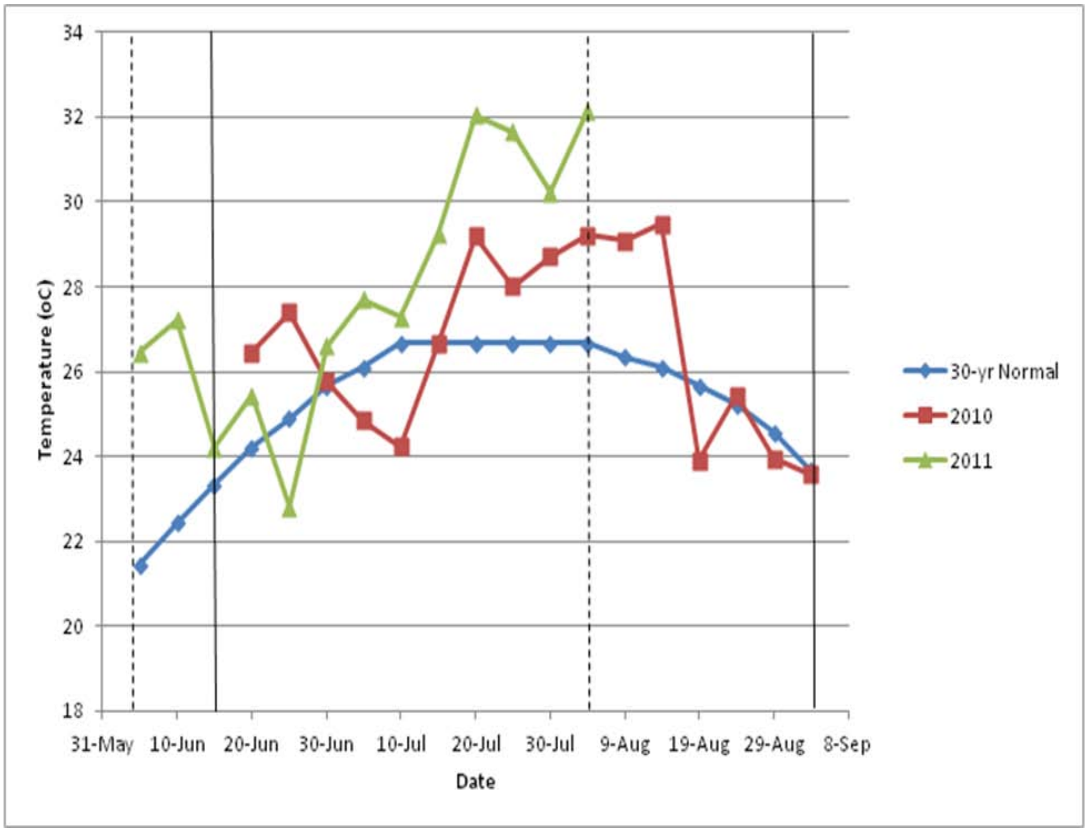

Figure 2.1- Average air temperature during the dry downs in 2010 and 2011. Solid black lines signify the start and cessation of the 2010 dry down. Dashed black lines signify the start and cessation of the 2011 dry down. Markers represent 5 day averages.

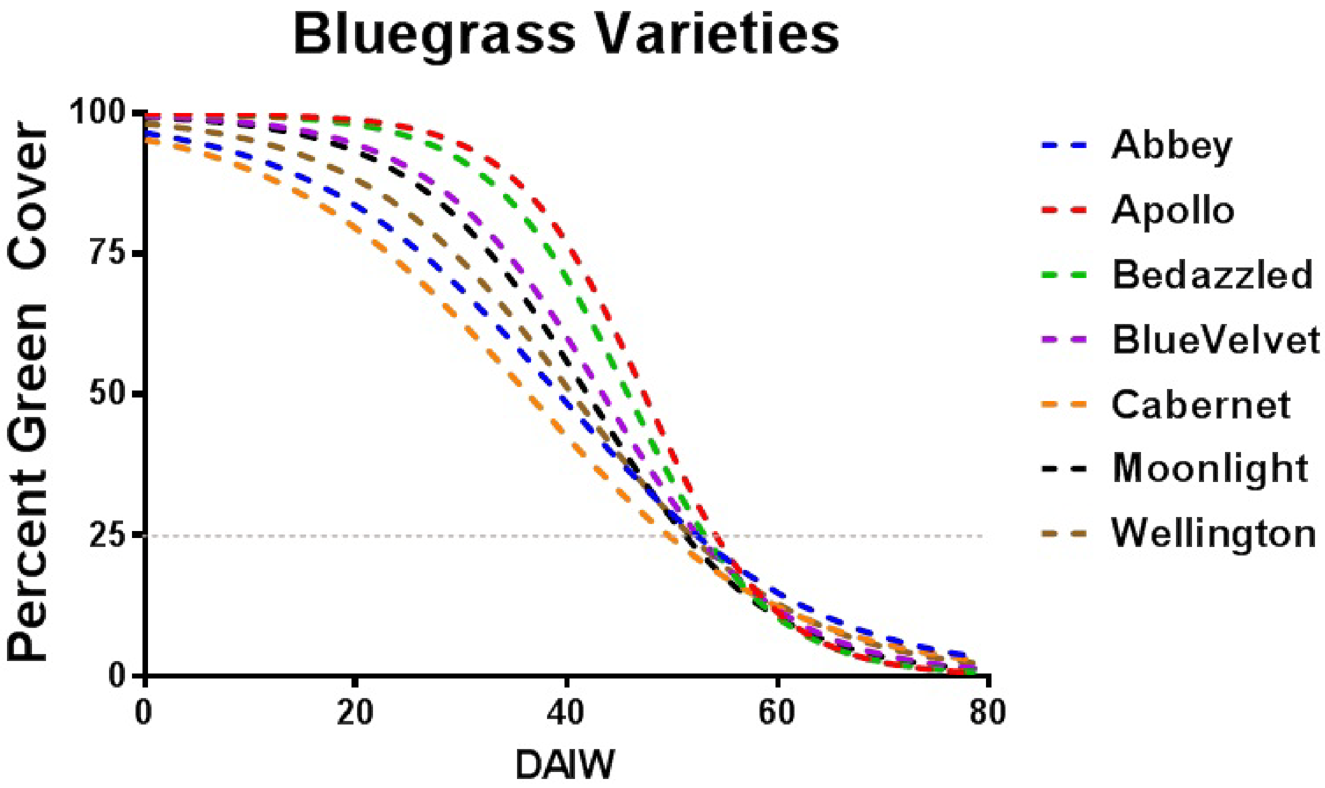

Figure 2.2- Predicted dry-down curves of 7 cultivars of KBG during a 60-day dry down in 2010. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Dashed line indicates DAI$_{25}$.

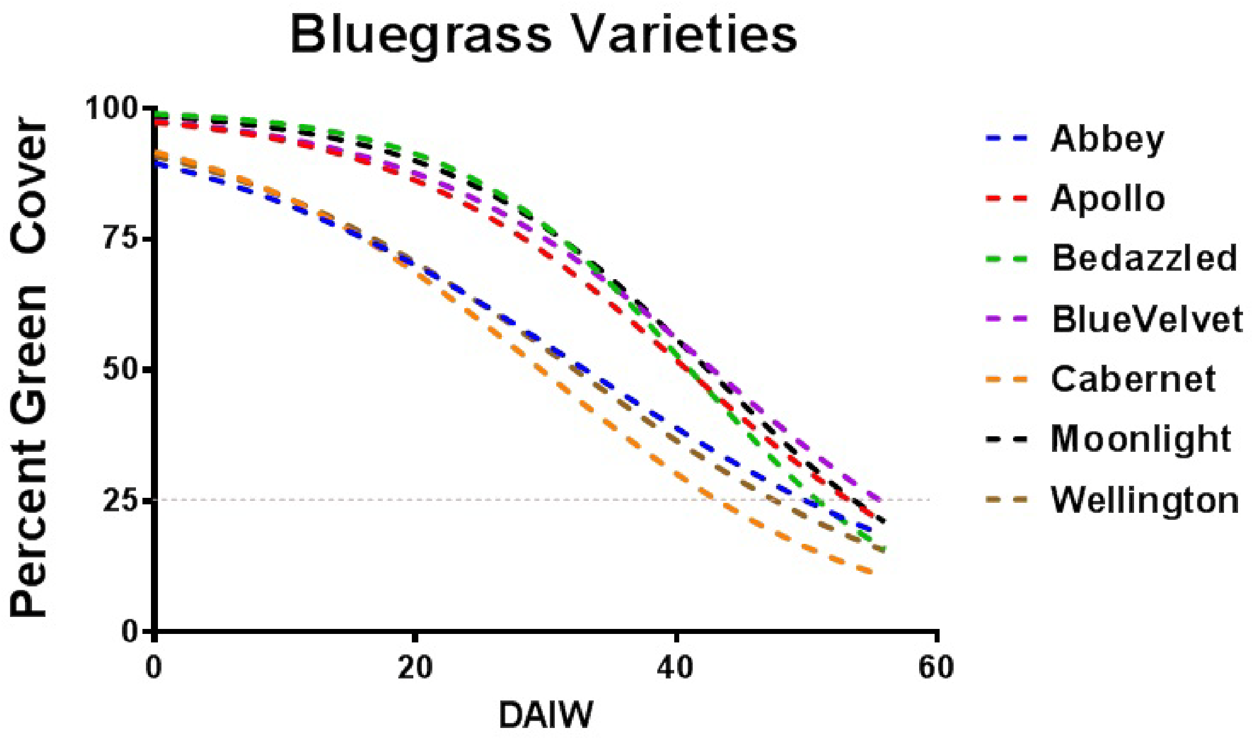

Figure 2.3- Predicted dry-down curves of 7 cultivars of KBG during a 60-day dry down in 2011. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Dashed line indicates DAI_{25}.

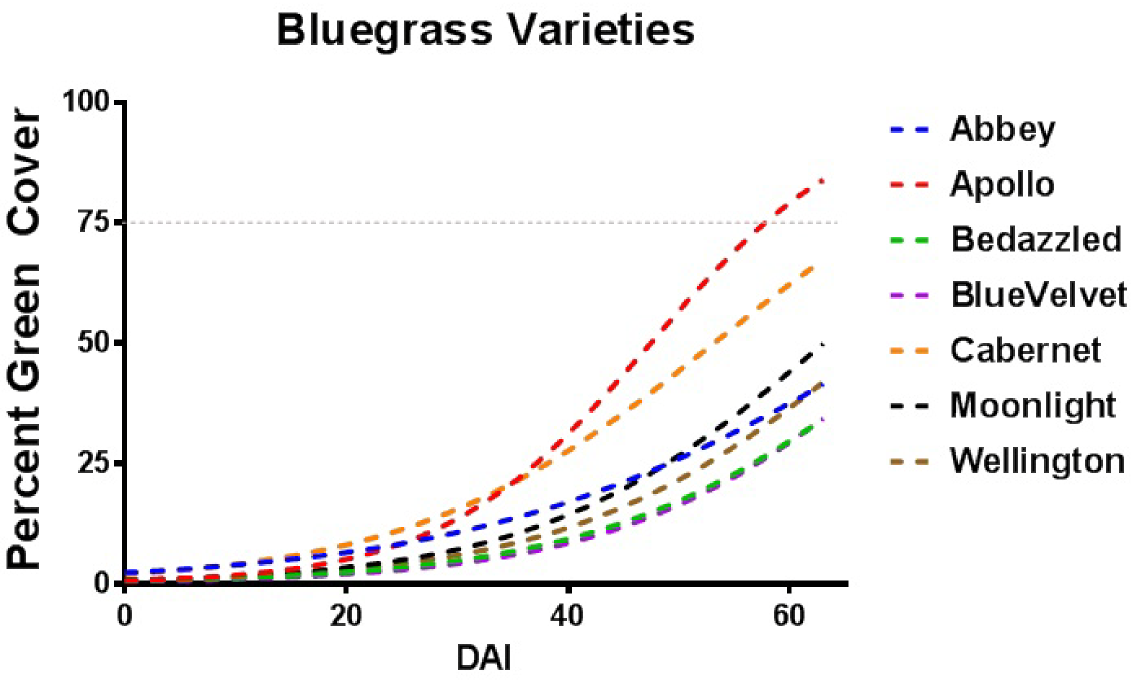

Figure 2.4- Predicted recovery curves of 7 cultivars of KBG following a 60-day dry down in 2010. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Dashed line indicates DAI$_{25}$.

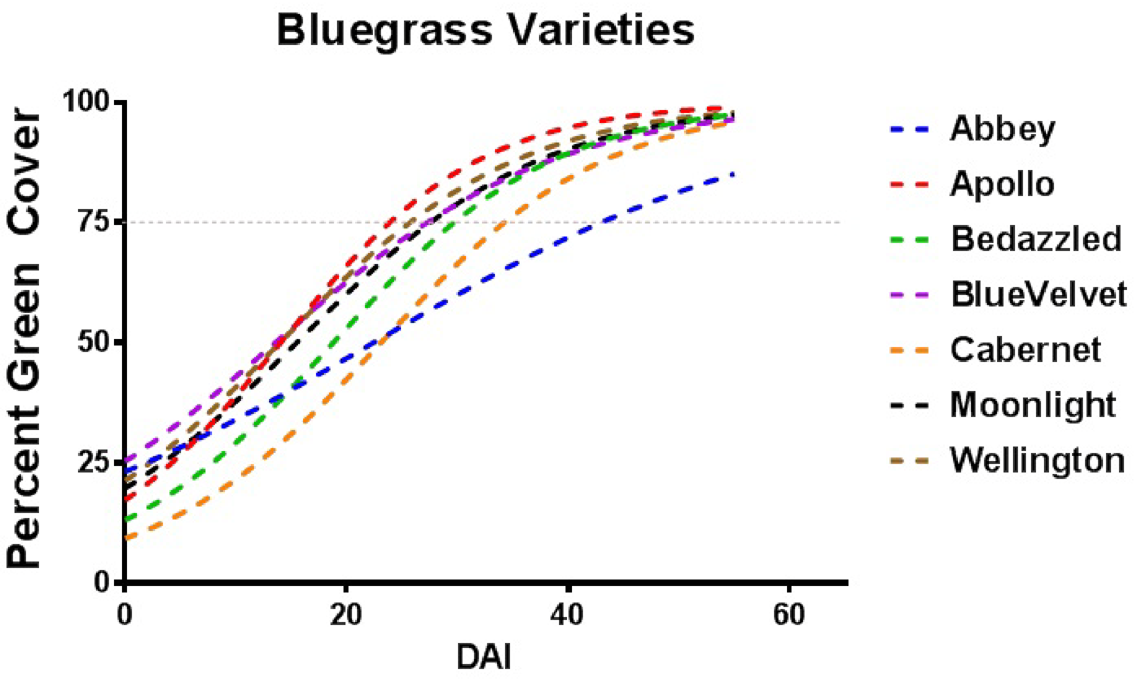

Figure 2.5- Predicted recovery curves of 7 cultivars of KBG following a 60-day dry down in 2011. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Dashed line indicates DAI_{25}.

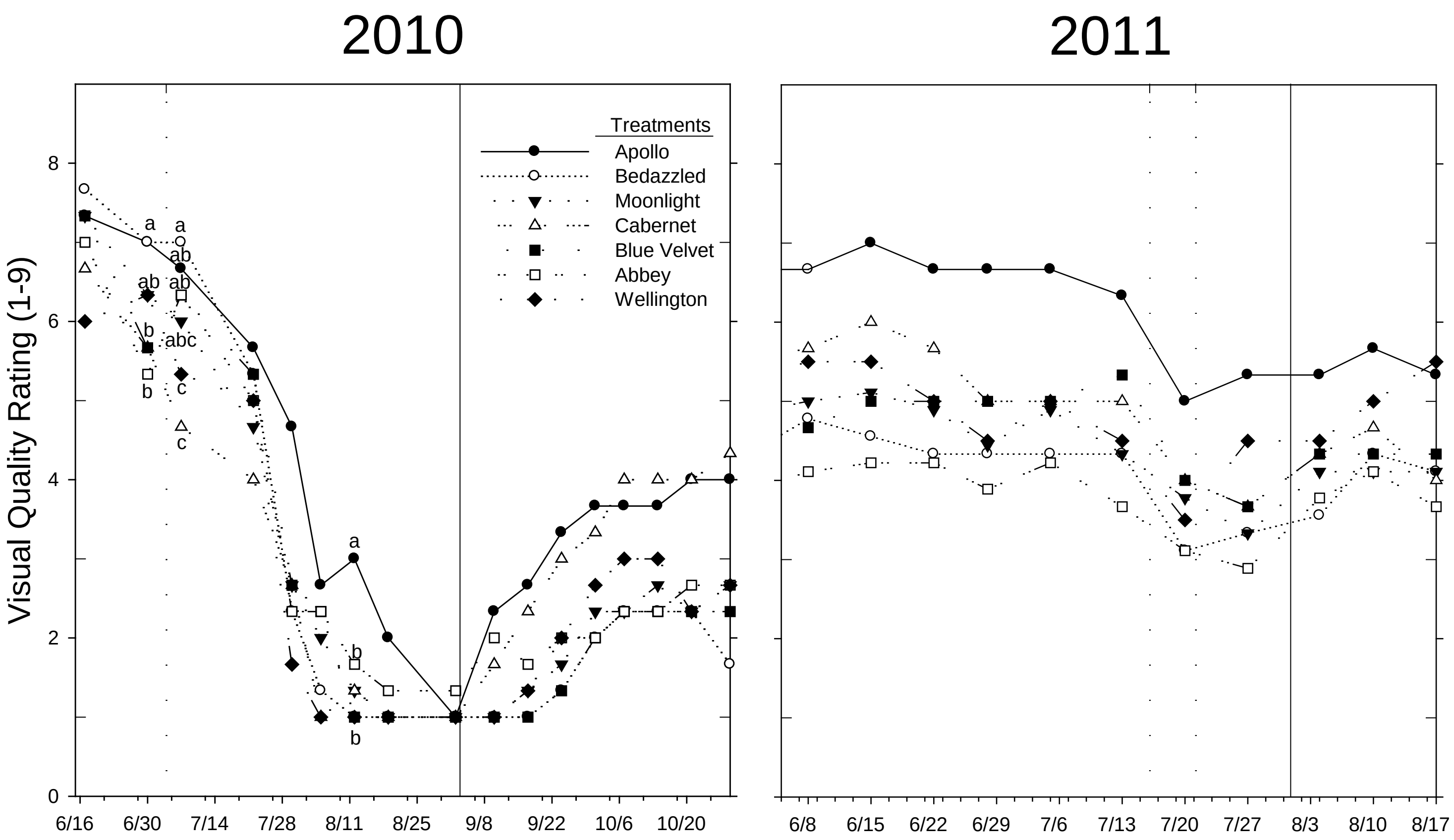

Figure 2.6- Visual quality rating of 7 cultivars of KBG during a 60-day dry down in 2010 and 2011. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Vertical solid black lines in the above graphs indicate the completion of the dry down. Vertical dotted lines in both years indicate rain shelter malfunctions. Means followed by the same letter on a date are not significantly different according to the F-LSD (*P* < 0.05).

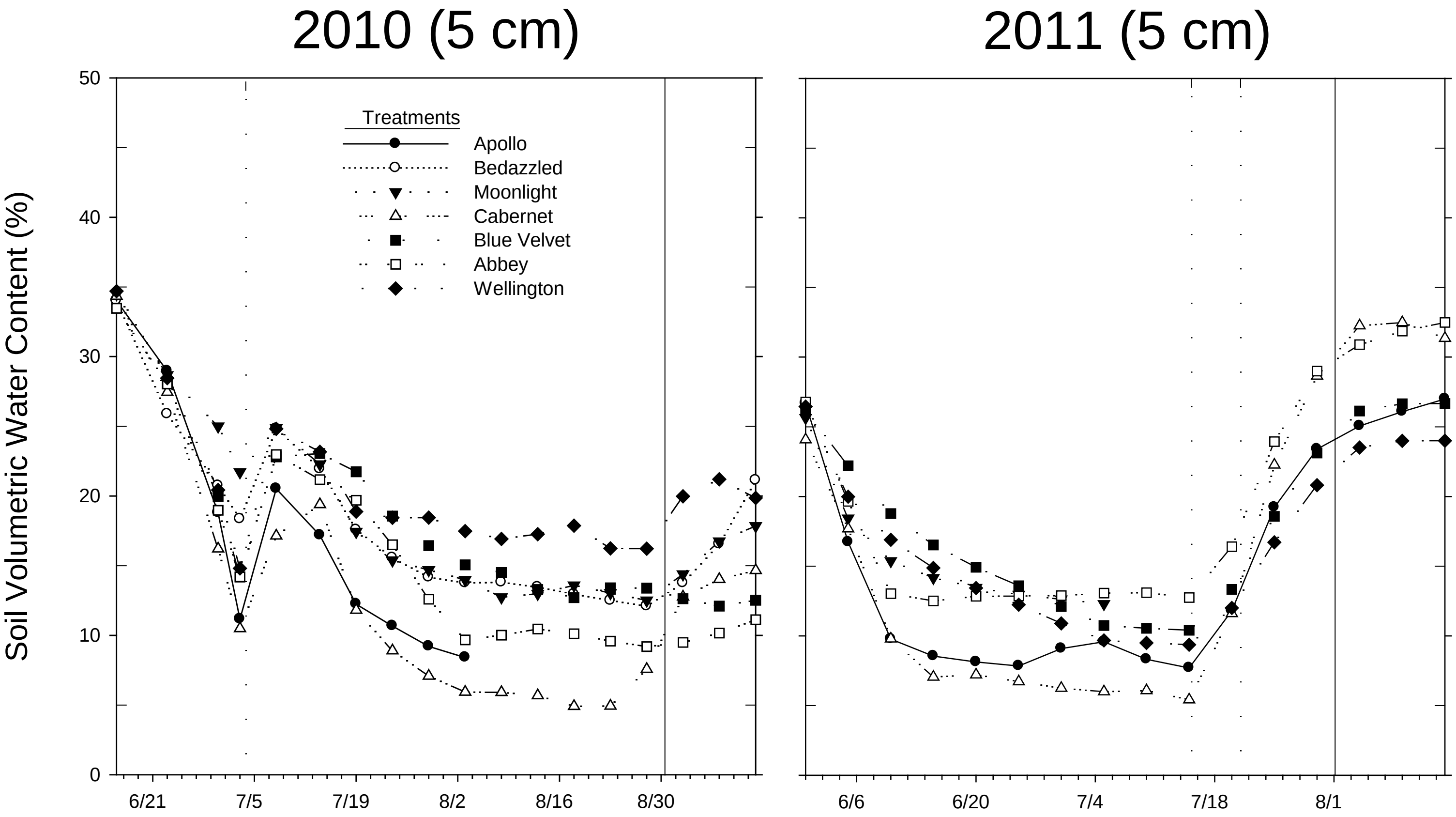

Figure 2.7- Volumetric Water Content (5cm) of 7 cultivars of KBG during a 60-day dry down in 2010 and 2011. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Vertical solid black lines in the above graphs indicate the completion of the dry down. Vertical dotted lines in both years indicate rain shelter malfunctions. Markers represent 5 day averages. In 2011, data were not available in Bedazzled because of sensor failure.

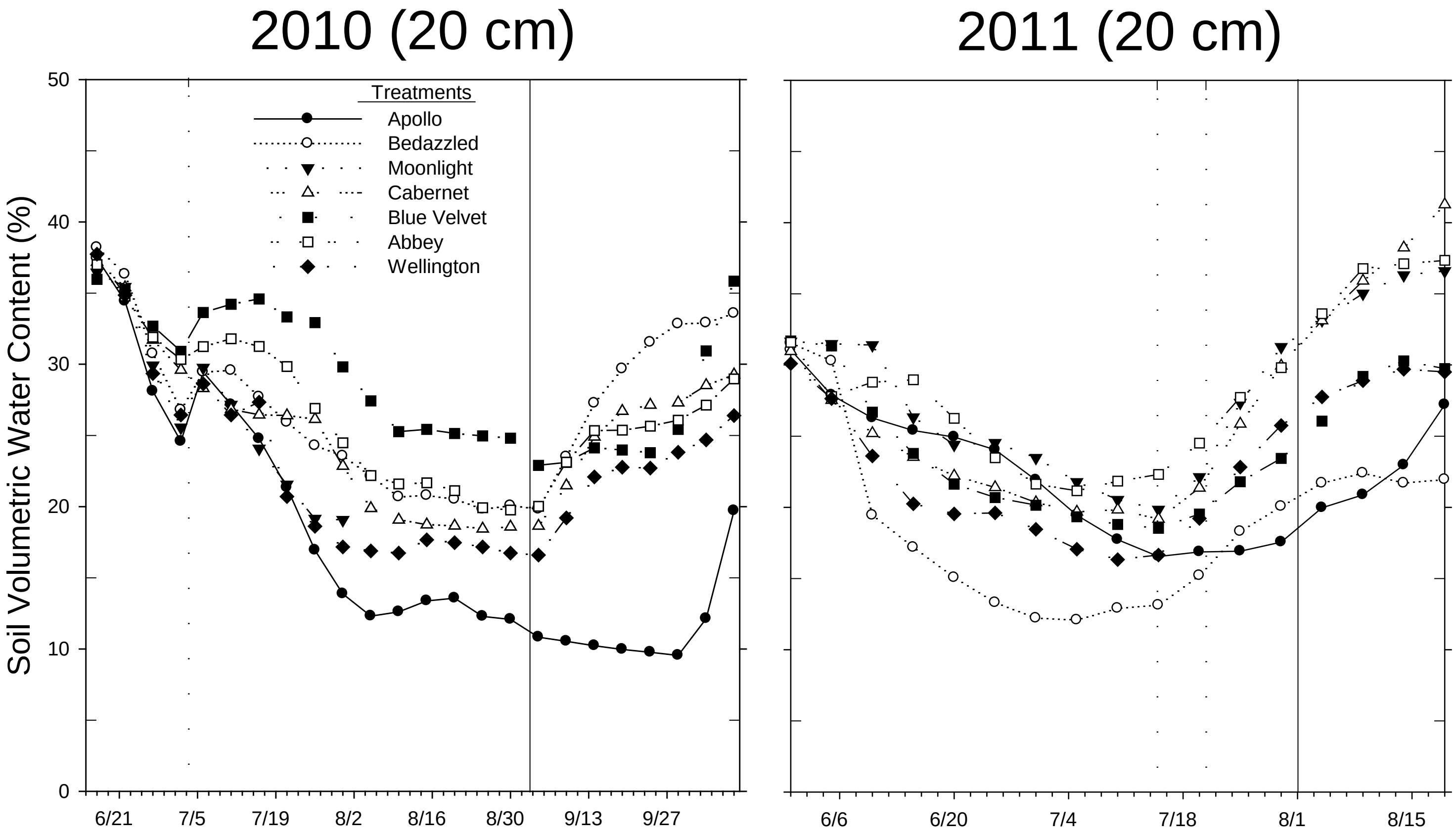

Figure 2.8- Volumetric Water Content (20cm) of 7 cultivars of KBG during a 60-day dry down in 2010 and 2011. Treatments included Apollo; Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Vertical solid black lines in the above graphs indicate the completion of the dry down. Vertical dotted lines in both years indicate rain shelter malfunctions. Markers represent 5 day averages.

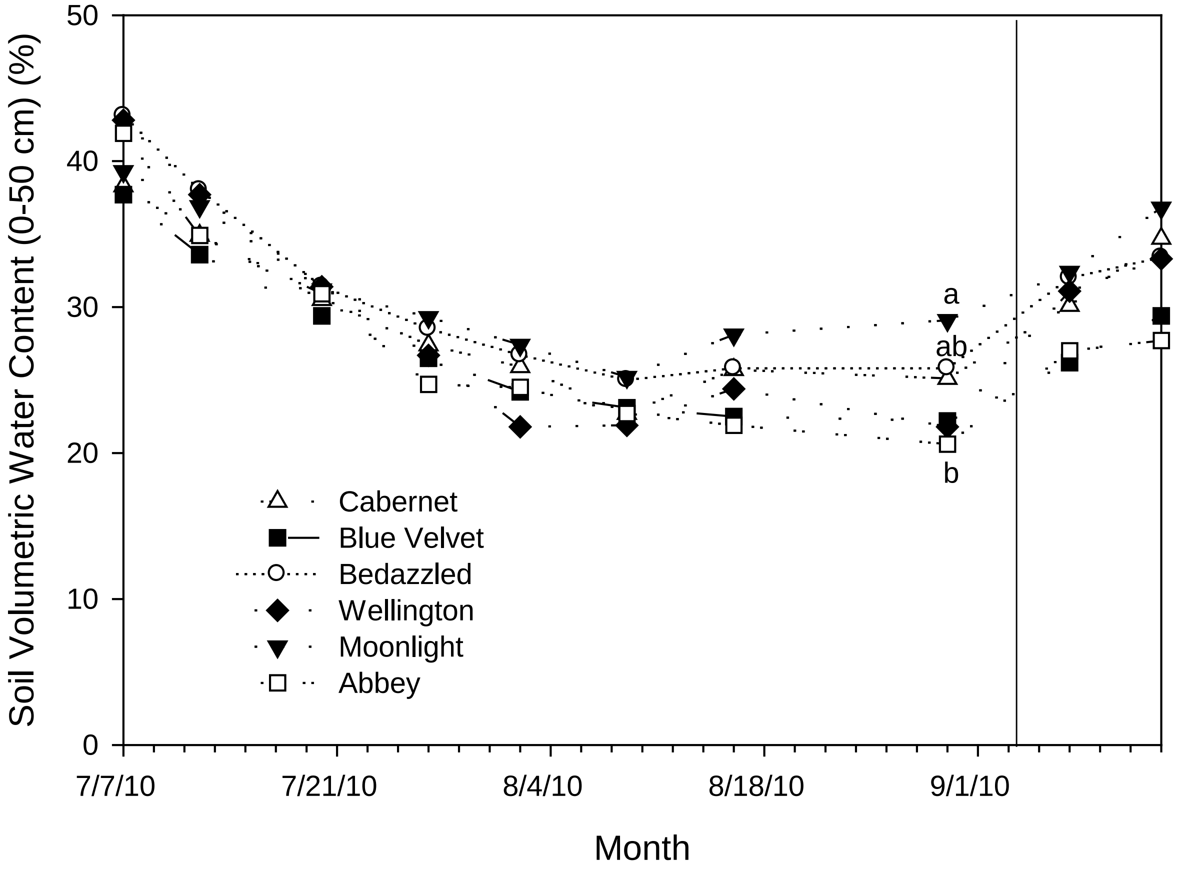

Figure 2.9- Volumetric Water Content (0-50cm) of 6 cultivars of KBG during a 60-day dry down in 2010. Treatments included Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Vertical solid black line in the above graph indicates the completion of the dry down.

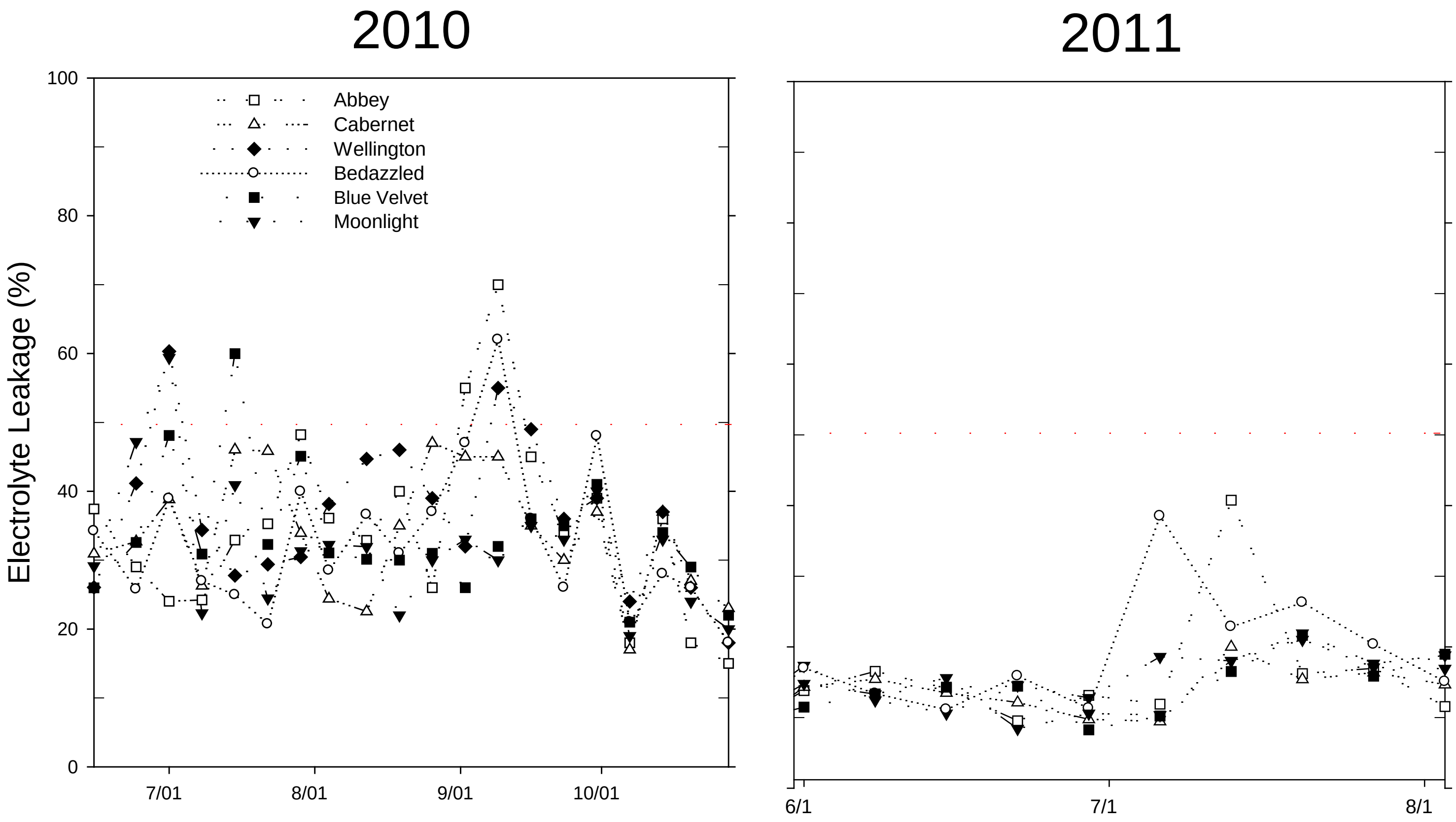

Figure 2.10- Electrolyte Leakage of 6 cultivars of KBG during a 60-day dry down in 2010 and 2011. Treatments included Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Apollo was not included in the data collection for 2010. Red horizontal dashed line indicates level of 50% electrolyte leakage. Means followed by the same letter on a date are not significantly different according to the F-LSD (*P* < 0.05).

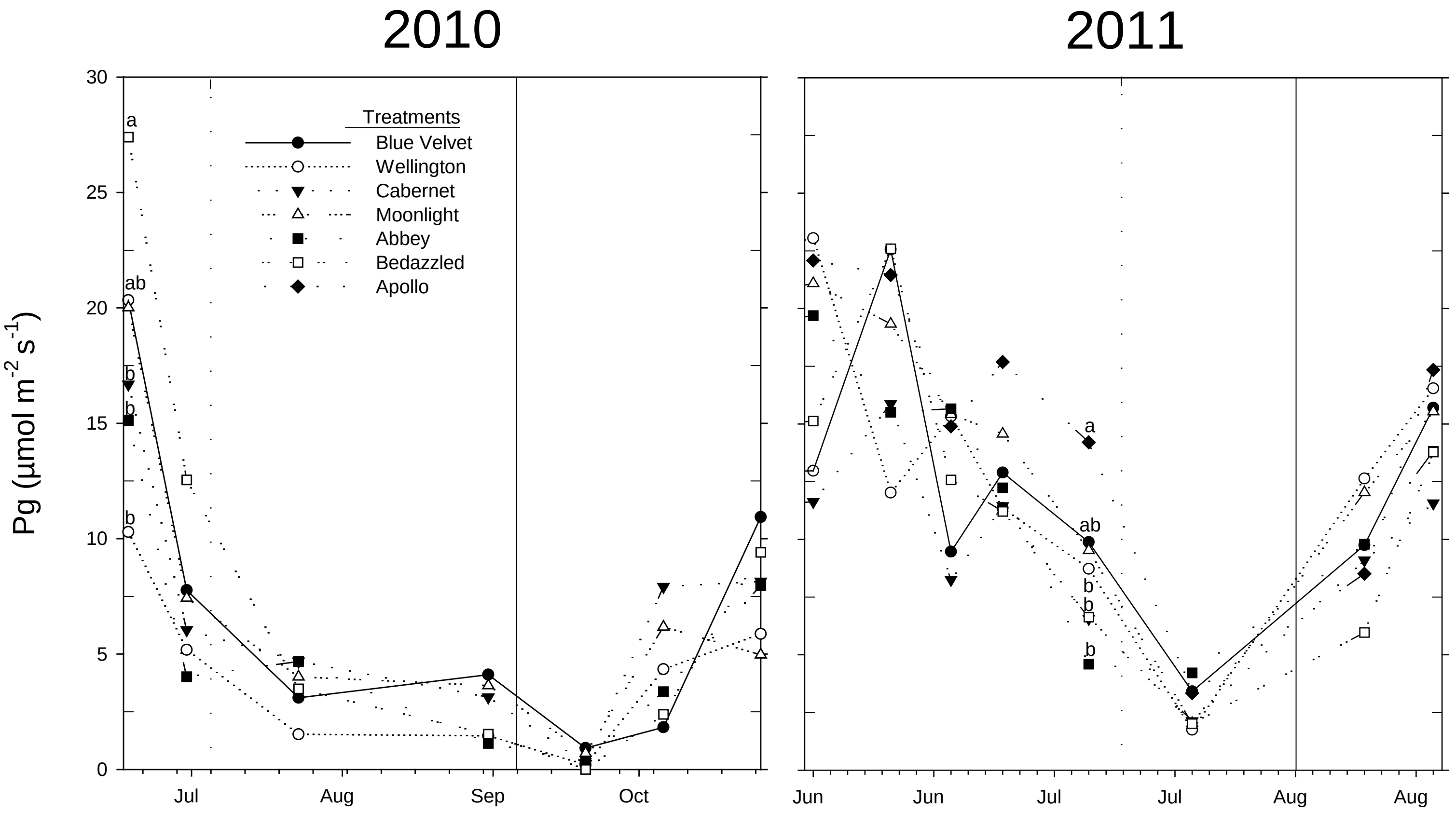

Figure 2.11- Gross Photosynthesis of 7 cultivars of KBG during a 60-day dry down in 2010 and 2011. Treatments included Bedazzled; Moonlight; Cabernet; Blue Velvet; Abbey and Wellington. Apollo was not included in the data collection for 2010. Vertical solid black lines in the above graphs indicate the completion of the dry down. Vertical dotted lines in both years indicate rain shelter malfunctions. Means followed by the same letter on a date are not significantly different according to the F-LSD (*P* < 0.05).

Table 2.1- Hypothesis test summaries for bluegrass entry effects on green turf coverage during dry-down and subsequent recovery in 2010 and 2011.

Sums of squares reduction test	**Dry-down 2010**	**Dry-down 2011**	**Recovery 2010**	**Recovery 2011**
Null hypothesis	Shared regression parameters (slope and days$_{25//75}$) for all varieties[†]			
Alternative hypothesis	Different regression parameters for each variety			
Numerator df	12	12	12	12
Denominator df	112	133	91	91
F value	2.200	7.985	2.705	2.965
P value	0.0161	<0.0001	0.0036	0.0016

[†] Slope and days$_{25/75}$ values determine percent green turf cover according to the sigmoid variable slope model.

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Chapter 3 - Evaluation of Turf Reinforcement Mats and Their Effect on Establishment of Buffalograss and Zoysiagrass

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Abstract

Turf reinforcement mats (TRM) can reduce erosion and prevent weed encroachment during turfgrass establishment. ‘Legacy’ buffalograss (*Buchloe dactyloides* [Nutt.] Engelm.) and ‘Chisholm’ zoysiagrass (*Zoysia japonica* Steud.) were evaluated in separate field studies for establishment when vegetative plugs were 1) planted in TRM; 2) planted in plots which were subsequently treated with oxadiazon; or 3) untreated. Plugs were established on TRM over plastic prior to transplanting to study areas. ‘Chisholm’ zoysiagrass stolons grew under the TRM; as such, use of TRM for this cultivar is not practical. Buffalograss had > 90% coverage when established on TRM in 2010 and > 65% coverage in 2011; coverage was similar to that in oxadiazon-treated plots in each year. Weed levels in plots where TRM (up to 8% weed coverage) were used were generally lower than those where oxadizaon was applied (up to 43% weed coverage); untreated plots (up to 63% weed coverage) generally had higher weed levels than the other treatments. Turf reinforcement mats offer potential for establishment of ‘Legacy’ buffalograss where labor involved in planting individual plugs on site is not available, use of herbicides is not desired, or soil erosion concerns exist.

Introduction

Establishment of warm-season turfgrasses in the transition zone can be an arduous task. Rainfall events can cause significant erosion on new seedbeds or areas established with vegetative plugs. Such erosion increases the transport of sediments into surface waters (U.S. Environmental Protection Agency, 1999). Traditionally, erosion control materials that utilize concrete blocks, rock riprap, and reinforced paving systems have been used in highly erosive areas. While these materials can withstand significant hydraulic forces, they do not provide sediment removal capabilities (U.S. Environmental Protection Agency, 1999).

In addition to erosion, annual weed competition after planting warm-season grasses can impede successful establishment (Fry et al., 1986; Harivandi et al., 1993). Weeds compete with desirable turfgrass species for light, water, and nutrients (Beard, 1973). Pre- and postemergence herbicides have been commonly used to control weeds during establishment, but erosion could still be a concern.

Turf reinforcement mats may provide the landscape manager with a means to prevent erosion and suppress weeds during establishment of warm-season turfgrasses. Turf reinforcement mats are typically manufactured using tightly compressed plant fiber. An example of this is jute, which is extracted from the stems of plants belonging to the genus *Cochorus*. The mat may, or may not, be reinforced with plastic netting and provides a high-strength material that prevents soil erosion (U.S. Environmental Protection Agency, 1999) and germination of weed seeds, or weed seedling survival after germination (Lowe et al., 1999).

Several warm-season turfgrasses have been successfully established for soilless sod using organic fiber mediums composed of kenaf, a fiber-based plant product comparable to the material used in TRM (Rowell and Stout, 1998). Specifically, kenaf-based organic fiber mats provided a suitable medium for sprigging of ‘MS Express’ bermudagrass (*Cynodon* X *magenissii*

Hurc.), common centipedegrass (*Eremochloa ophiuroides* Munro Hack.), and ‘Meyer’ zoysiagrass (*Z. japonica* Steud.) (Hensler et al, 1998).

One advantage to TRM is that vegetative plantings can be established on the mats at the grower’s location prior to installation at the job site. In fact, this has been done commercially with native landscape plants and turfgrass sod (Matt Campbell, personal communication). This is ideal for the landscape manager who may not have the labor to plant individual plugs on site, or for customers who may prefer a non-herbicide approach to weed control and erosion prevention benefits afforded by TRM. Our objective was to evaluate the establishment of ‘Legacy’ buffalograss and ‘Chisholm’ zoysiagrass from vegetative plugs on TRM.

Materials and Methods

Study site and experimental design

Separate experiments were conducted to evaluate establishment of ‘Chisholm’ zoysiagrass and ‘Legacy’ buffalograss from vegetative plugs in 2010 and 2011. ‘Chisholm’ was most recently evaluated as DALZ 0102 zoysiagrass in the 2002 National Turfgrass Evaluation Program Zoysiagrass Test (National Turfgrass Evaluation Program, 2006). Experiments were conducted at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas, USA ($39^{o}13^{'}53$” N, $96^{o}34$’51” W). Soil was a Chase silt loam (fine, smectitic, mesic, Aquertic Argiudoll) with a pH of 6.9.

Treatments for the two experiments were: 1) plugs established in TRM; 2) plugs planted in plots which were subsequently treated with oxadiazon; and 3) untreated. In each experiment, plots measured 3 by 3 m, and were arranged in a randomized complete block design with three replications.

‘Chisholm’ zoysiagrass plugs were initially established from sprigs at the KSU greenhouse; planting was done in March 2010 and 2011. ‘Legacy’ buffalograss plugs were purchased from Todd Valley Farms (Mead, NE) prior to experiments in each year.

Turf Reinforcement Mats

The TRM used in this study were designed and manufactured by StayTurf® (Jimboomba Turf Company, Acacia Ridge, Australia). The original StayTurf® TRM are composed of felted jute fiber manufactured at 650 g m^{-2} with UV resistant plastic netting inserted. Testing conducted at the Texas Department of Transportation Erosion Control Laboratory found StayTurf® acceptable for protection up to 194,013 L min^{-1}, 58 kg m^{-2} shear force, and a velocity of 12.11 m s^{-1} (Matt Campbell, personal communication). The company also offers a similar product without the plastic netting (StayTurf® Soil Saver.), which was the product used herein.

For the TRM treatment, plugs were planted into the mats in an area adjacent to the experiment locations on 10 June 2010 and 1 June 2011, three weeks prior to plugs in other treatments being planted. This was done to mimic the approach a grower would use to establish plugs on the TRM prior to delivery to the job site. A single turfgrass plug was inserted into 2.5-cm diameter slits on 30.5 cm centers on each 3 m x 3 m section of TRM. The TRM rested directly on a layer of 7-mil. black plastic. Irrigation was applied three times daily to deliver up to 2 mm of water in order to ensure mats stayed moist and to prevent turfgrass stress. On 1 July 2010 and 23 June 2011, three weeks after inserting plugs into mats, TRM containing plugs of the respective species were lifted from the plastic and planted in adjacent, separate, zoysiagrass and buffalograss study areas. These were considered the dates planting occurred in field.

At the date of planting each experiment, 5-cm diam. zoysiagrass and buffalograss plugs were also planted on 30.5 cm centers (16 plugs per plot) in untreated plots and plots to be treated with oxadiazon. Oxadiazon was applied at 3.9 kg a.i. ha^{-1} using a hand-held shaker bottle to plots receiving that treatment. All plots were topdressed with 49 kg P ha^{-1} from diammonium phosphate (18-46-0) at the time of planting.

Plot Maintenance

Irrigation was applied as necessary to keep soil at field capacity (~33% volumetric water content) based upon twice weekly measurements at 0 to 20 cm depth with a time domain reflectometer (Soil Moisture Equipment Corporation, Santa Barbara, CA). Each study area was fertilized with N from urea at 49 kg ha-1 on 24 July 2010 and 13 July 2011.

Measurements

Plots were rated visually for percentage turfgrass coverage and weed coverage periodically during each study. Ratings were done visually on a 0 to 100% scale, where 0 = no turf or weed coverage, and 100% = complete turf or weed coverage. Weed species present in the study areas included annual bluegrass (*Poa annua* L.), goosegrass [*Eleusine indica* (L.) Gaertn.], spotted spurge (*Euphorbia maculate* L.), and dandelion (*Taraxacum officinale* Weber ex F.H. Wigg.).

Statistical analysis

Data were subject to analysis of variance using the GLM procedure of SAS (SAS Institute Inc., Cary, NC). Means were separated using Fisher's Protected LSD ($P < 0.05$). Levene's test was used to assess the homogeneity of variances in order to determine if data on turfgrass or weed coverage in each experiment could be pooled for over years ($P < 0.05$) (Levene, 1960).

Results and Discussion

Turfgrass Establishment and Weed Suppression

Zoysiagrass

‘Chisholm’ zoysiagrass established on TRM exhibited lower levels of coverage compared to oxadizaon-treated or untreated plots in 2010 and 2011 (Fig. 3.1). ‘Chisholm’ produced stolons that grew below the TRM. These plugs did not receive photosynthetically active radiation and appeared to be etiolated. This reduced zoysiagrass coverage ratings because stolons were not visible. The use of TRM for establishment of ‘Chisholm’ zoysiagrass from plugs was not practical due to its growth habit. Perhaps there are other zoysiagrass cultivars whose stolons would develop on the surface of the TRM and would be more favorable candidates for establishment on TRM; more investigation is necessary.

Between 17 and 78 DAP 2010, zoysiagrass in the oxadiazon-treated plots exhibited weed coverage (up to 18%), which was lower than untreated (up to 57%), and similar to the TRM treatment (0%) (Fig 3.2). Between 55 DAP and 99 DAP 2011, weed suppression provided by the TRM treatment (0 %) was superior to that provided by oxadiazon (up to 43%), and both were superior to untreated plots during this period (up to 68%). Despite weed suppression in the oxadiazon treatment which was superior to untreated turf on 7 dates in 2010 and 4 dates in 2011, zoysiagrass coverage at the end of the growing season in the oxadiazon treatment was superior to untreated only in 2011 (Fig. 3.1).

Oxadiazon (3.4 kg a.i. ha^{-1}) also increased coverage of ‘Meyer’ zoysiagrass established from sprigs in Maryland (Carroll et al., 1996). This was due, in part, to a 66% reduction in crabgrass cover where oxadiazon was applied compared to untreated plot. Oxadiazon (3.4 kg a.i. ha^{-1}) reduced coverage of annual grasses by 78% to 97% in Maryland, which contributed to increased coverage of ‘Meyer’ zoysiagrass from vegetative plugs and sprigs compared to untreated plots (Fry et al., 1986).

Buffalograss

There was a significant ($P \leq 0.05$) treatment effect on buffalograss coverage on 6 of 24 evaluation dates (Fig. 3.3). Buffalograss treated with oxadiazon or established on TRM had greater coverage than untreated plots at 63 and 111 DAP in 2010. On the other 2 dates in 2010 when differences occurred, buffalograss coverage was greater in oxadizaon–treated plots than untreated plots, but coverage in the TRM treatment was similar to that in untreated plots. Buffalograss coverage was higher in oxadiazon-treated plots and TRM-treated plots than untreated plots at 19 DAP 2011; no differences occurred on other dates. On several occasions in 2011, wind lifted the TRM in one replicate, which dislodged a few of the buffalograss plugs. This ultimately affected the level of coverage observed, and reduced the overall coverage mean observed in the TRM treatment.

Weed coverage in buffalograss planted in TRM (0%) or oxadiazon-treated plots (up to 18%) was lower than that in untreated plots (up to 58%) on most rating dates in 2010 (Fig 3.4). Likewise, weed coverage in buffalograss planted in the TRM treatment (up to 8%) was lower than that in oxadiazon-treated plots (up to 40%) on four dates in 2011. Weed coverage in the oxadiazon treatment did not differ from untreated (up to 63%) at 14, 21, 43, 48 and 100, and 116 DAP 2011. Annual weedy grasses and broadleaves can be controlled in buffalograss using several pre-and postemergence herbicides (McCarty and Colvin, 1992; Fry et al., 1997; Shearman et al., 2004; Goss et al., 2006). Oxadiazon (2.2 kg a.i. ha^{-1}) was also shown to reduce weed competition and enhance buffalograss establishment from plugs in California (Harivandi et al., 1993).

Economic Considerations

Total cost for 'Legacy' buffalograss plugs is approximately \$ 463 USD ha^{-1} if planted on 30.5 cm centers. Purchasing TRM to cover the same one hectare area would cost approximately \$ 220 USD. In contrast, cost of oxadiazon for weed control at the rate used herein would be approximately \$8.61 USD ha^{-1}.   Therefore, high costs associated with TRM may make its use practical only those situations which pose high risks for erosion.

One particular area where buffalograss established in TRM could be useful is on roadside channels along highways where vegetation is desired. Roadside channels play an important role in the highway drainage system as the initial conveyance for runoff (U.S. Department of Transportation and Federal Highway Administration, 2005). Buffalograss has been recognized as an important species for soil stabilization along roadways (Christians, 2007).

Conclusions

Turf reinforcement mats were effective in encouraging successful establishment of 'Legacy' buffalograss from vegetative plugs. However, establishment of 'Chisholm' zoysiagrass with TRM was not successful due to stolon growth beneath the mat. Turfgrass reinforcement mats effectively eliminated all weed competition. Despite higher weed levels in oxadiazon-treated buffalograss, coverage was comparable to plots established using TRM by the end of the season. Turf reinforcement mats may be a suitable technique for vegetative buffalograss plugs where labor involved in planting individual plugs is not available, use of herbicides is not desired, or soil erosion concerns exist.

Figures and Tables

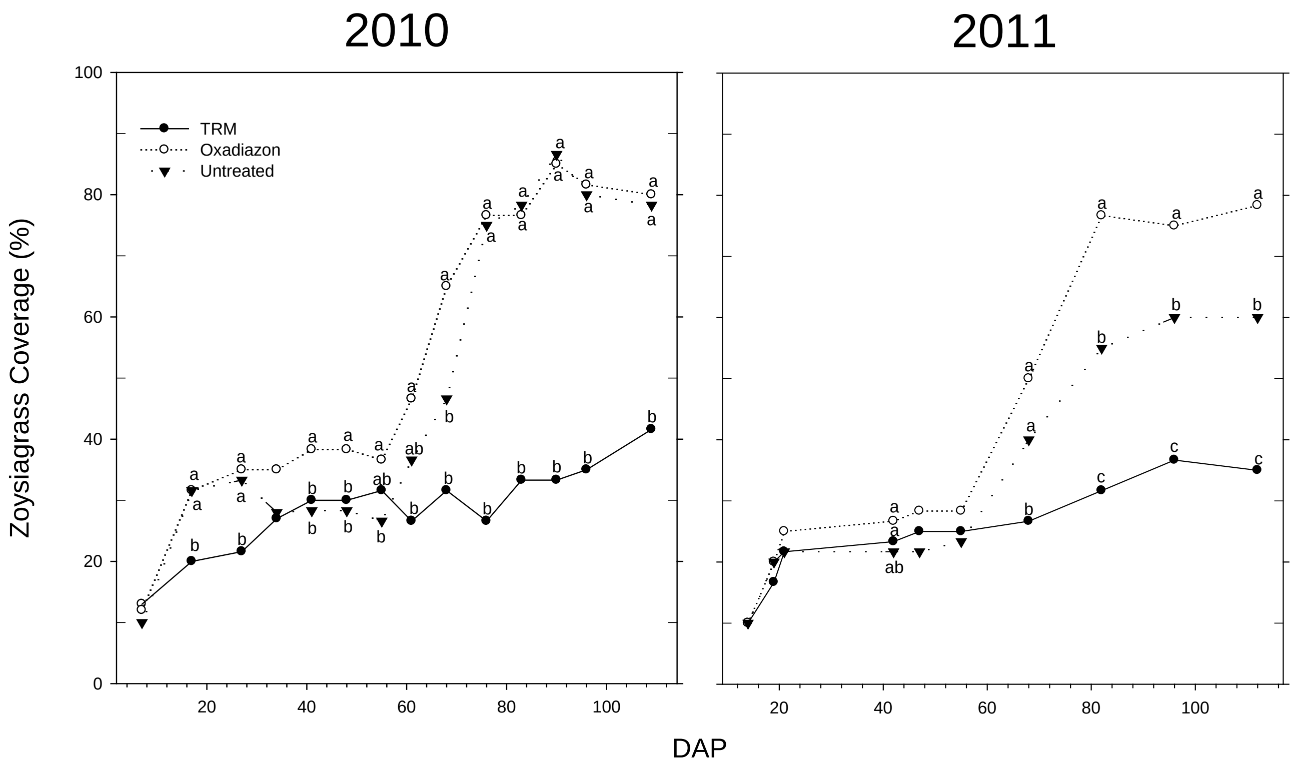

Figure 3.1- Coverage of 'Chisholm' zoysiagrass from vegetative plugs as affected by establishment method at Manhattan, KS in 2010 and 2011. Treatments included planting in turf reinforcement mats (TRM); application of oxadiazon at 3.9 kg a.i. ha^{-1} just after planting; and untreated. Planting was done on 1 July 2010 and 23 June 2011 and subsequent rating dates are referred to as days after planting (DAP). Coverage was rated visually on a 0 to 100% Scale. Means followed by the same letter on a date are not significantly different according to the Fisher's Protected LSD ($P < 0.05$).

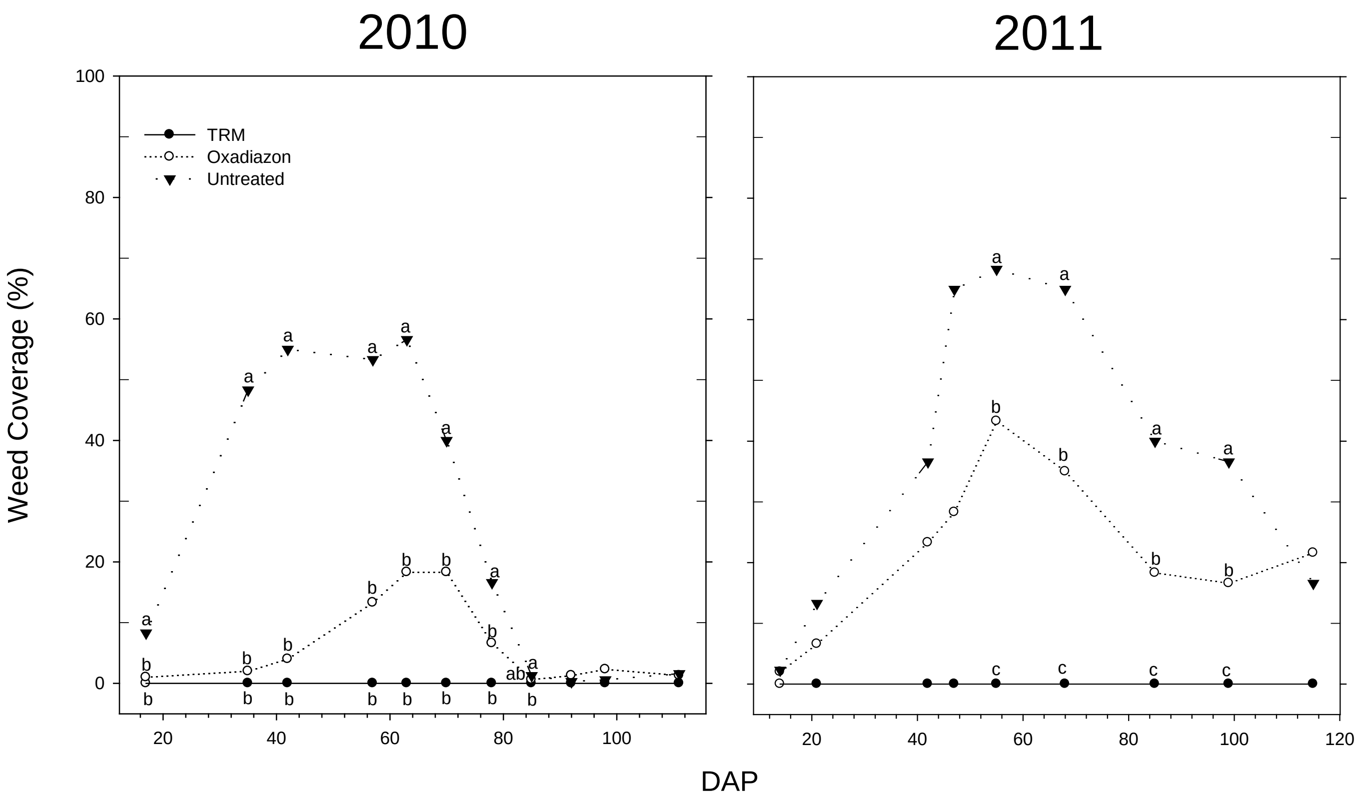

Figure 3.2- Weed coverage in 'Chisholm' plots planted as vegetative plugs as affected by establishment treatment at Manhattan, KS in 2010 and 2011. Treatments included planting in turf reinforcement mats (TRM); application of oxadiazon at 3.9 kg a.i. ha^{-1} just after planting; and untreated. Planting was done on 1 July 2010 and 23 June 2011 and subsequent rating dates are referred to as days after planting (DAP). Coverage was rated visually on a 0 to 100% Scale. Means followed by the same letter on a date are not significantly different according to the Fisher's Protected LSD (P < 0.05).

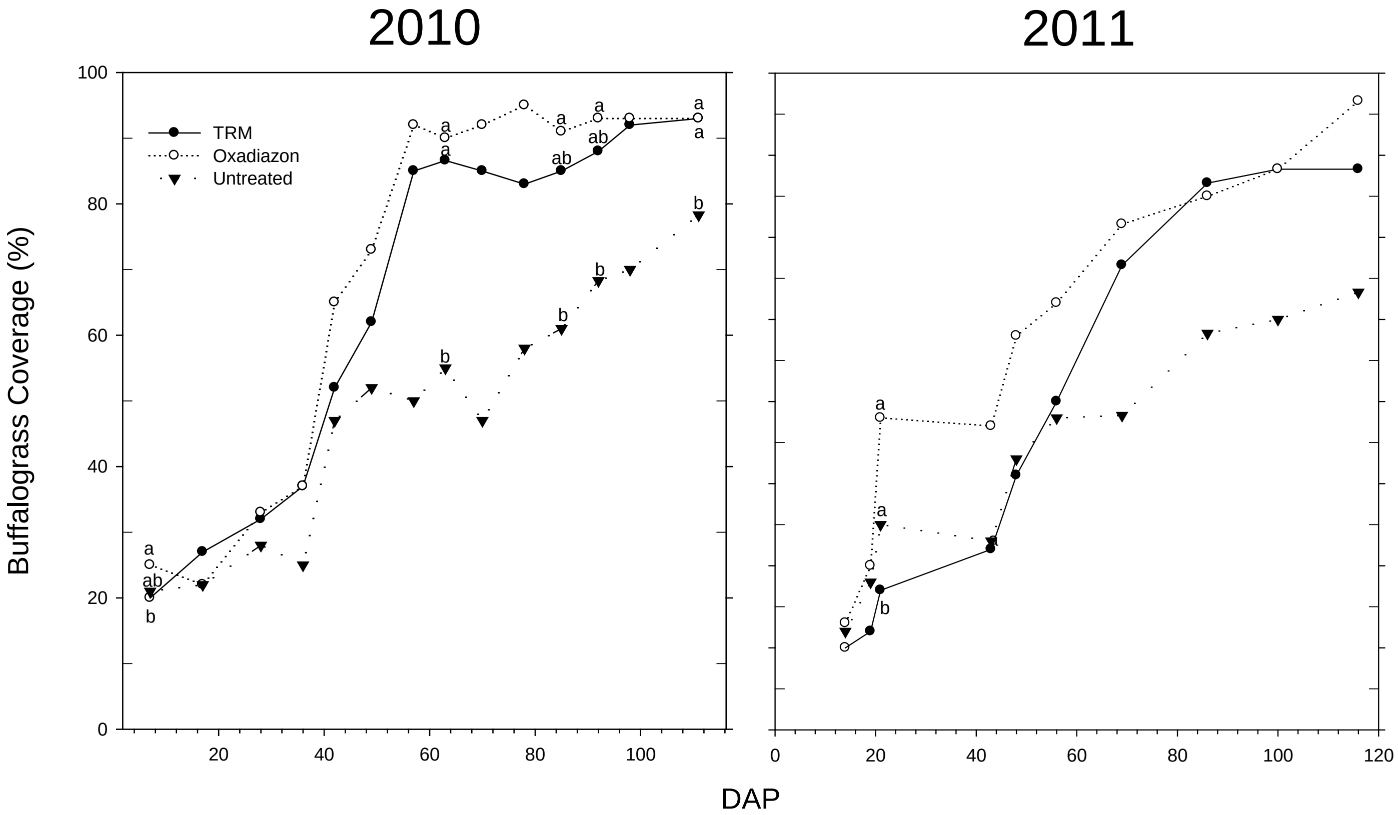

Figure 3.3- Coverage of 'Legacy' buffalograss from vegetative plugs as affected by establishment method at Manhattan, KS in 2010 and 2011. Treatments included planting in turf reinforcement mats (TRM); application of oxadiazon at 3.91 kg a.i. ha^{-1} just after planting; and untreated. Planting was done on 1 July 2010 and 23 June 2011 and subsequent rating dates are referred to as days after planting (DAP). Coverage was rated visually on a 0 to 100% Scale. Means followed by the same letter on a date are not significantly different according to the Fisher's Protected LSD (*P* < 0.05).

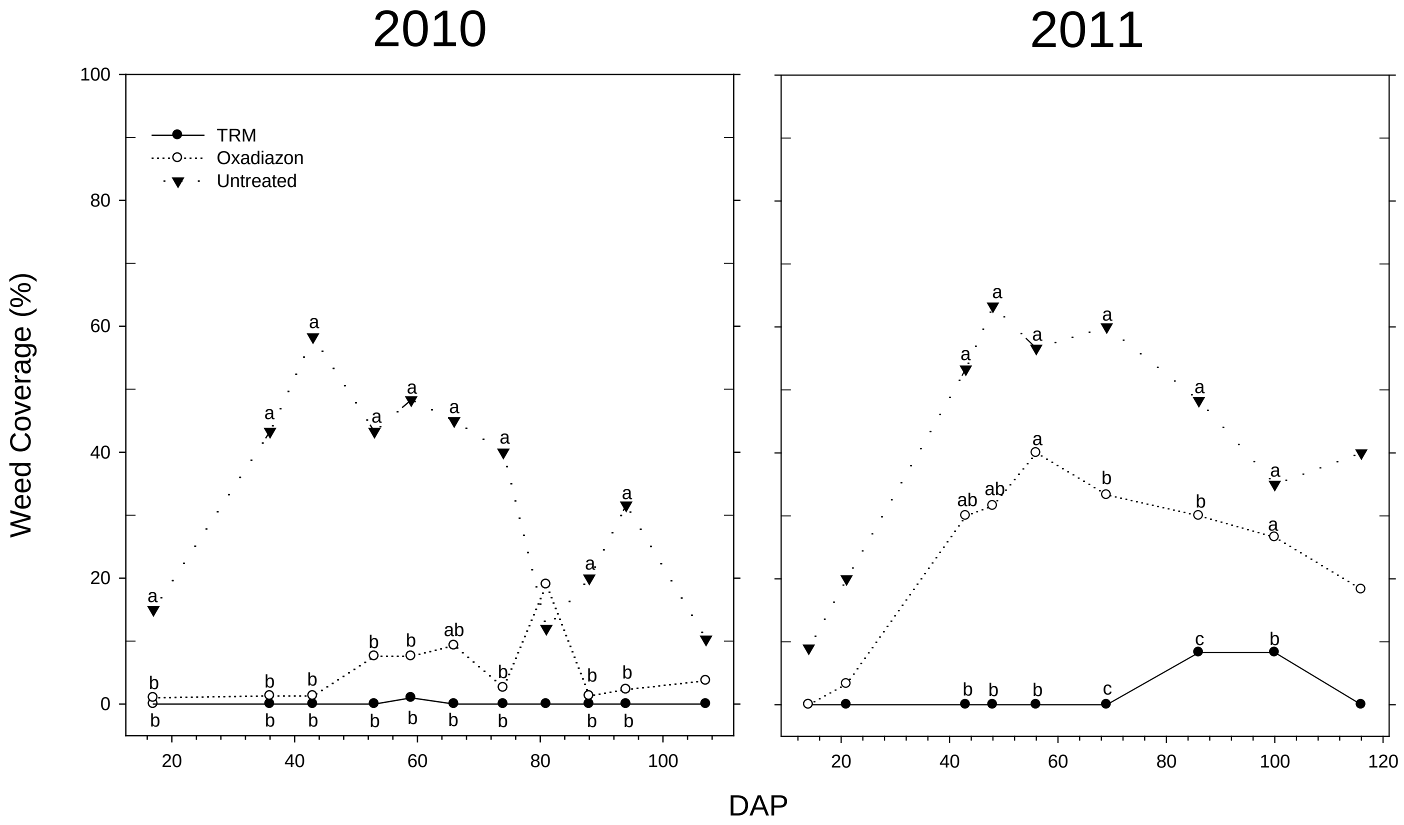

Figure 3.4- Weed coverage in 'Legacy' buffalograss plots planted as vegetative plugs as affected by establishment treatment at Manhattan, KS in 2010 and 2011. Treatments included planting in turf reinforcement mats (TRM); application of oxadiazon at 3.91 kg a.i. ha^{-1} just after planting; and untreated. Planting was done on 1 July 2010 and 23 June 2011 and subsequent rating dates are referred to as days after planting (DAP). Coverage was rated visually on a 0 to 100% Scale. Means followed by the same letter on a date are not significantly different according to the Fisher's Protected LSD (*P* < 0.05).

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Chapter 4 - Establishment of Buffalograss from Vegetative Plugs after Short-term Storage on Turf Reinforcement Mats

Abstract

Turf reinforcement mat (TRM) can reduce erosion and prevent weed encroachment during turfgrass establishment. ‘Legacy’ buffalograss plugs were established on TRM over plastic for 3 weeks, stored in TRM under tree shade for 7, 14, or 21 days, and evaluated for establishment after storage. Average daily temperature inside the rolls during storage in 2011-12 ranged from 19 to 28^{o} C. In 2011, buffalograss coverage was lower for the 14 and 21 day storage treatments than the control or 7 day treatments on 7 of 9 evaluation dates. Buffalograss stored on TRM for 0 or 7 days had similar coverage (75%) by the end of the growing season. Coverage of buffalograss by season’s end when stored on TRM for 14 days was 26%. Coverage of buffalograss after 21 days of storage was (<5 %) by the end of the growing season. In 2012, buffalograss coverage was lower for the buffalograss stored on TRM for 7, 14 and 21 days than that stored for 0 days at 35 and 42 DAP. In comparison to 2011, buffalograss stored for 0 days exhibited significantly higher establishment (81%) by the end of the 2012 growing season in comparison to the 7 day storage treatment (48%). Maximum coverage of buffalograss stored on TRM for 7 days was 27%, whereas that stored for 14 days was (36%) in 2012. Buffalograss planted as vegetative plugs in TRM may be stored for seven days in shaded conditions before planting with minimal impact on coverage by the end of the growing season.

Introduction

Establishing warm-season turfgrasses provides a unique set of challenges to homeowners. Rainfall events can cause significant erosion on new seedbeds or areas established with vegetative plugs. Furthermore, annual weed competition during establishment of warm-season grasses can also impede growth (Fry et al., 1986; Harivandi et al., 1993). Weeds compete with desirable turfgrass species for light, water, and nutrients (Beard, 1973). Annual weedy grasses and broadleaves can be controlled in buffalograss using several pre-and postemergence herbicides (McCarty and Colvin, 1992; Fry et al., 1997; Shearman et al., 2004; Goss et al., 2006). However, these herbicides do not offer any protection from erosion.

Turf reinforcement mat (TRM) combines vegetative growth and synthetic materials to form a high-strength mat and helps prevent soil erosion (U.S. EPA, 1999). Furthermore, TRM has the potential to suppress weeds during buffalograss establishment (Chapter 3). Turf reinforcement mats are typically manufactured using tightly compressed plant fiber such as Jute. Jute is the common name given to the plant fiber which is extracted from the stems of plants belonging to the genus *Cochorus*, family Tiliacea (Rowell and Stout, 1998). The mat may, or may not, be reinforced with plastic netting and provides a high-strength material that prevents soil erosion (U.S. EPA, 1999) and germination of weed seeds, or weed seedling survival after germination (Lowe et al., 1999).

Several warm-season grass species have been successfully established for soilless sod using organic fiber mediums composed of kenaf, a fiber-based plant product comparable to the material used in TRM (Hensler et al, 1998; Rowell and Stout, 1998). Specifically, jute-based TRM was effective for establishment of ‘Legacy’ buffalograss from vegetative plugs (Goldsby and Fry, 2012). In that experiment, buffalograss established in TRM had coverage similar to oxadiazon-treated plots throughout the study. However, weed suppression was superior in plots established with TRM (~8% weed coverage) when compared to those where only oxadiazon was applied (~43% weed coverage).

The use of TRM with buffalograss is ideally suited for areas where labor involved in planting individual plugs is not available, use of herbicides is not desired, or soil erosion concerns exist. Another advantage provided by using TRM is that vegetative plantings can be established on the mats at the grower's location prior to installation at the job site. In fact, this has been previously done with native landscape plants and turfgrass sod (Matt Campbell, personal communication). Similar to traditionally cut sod, the TRM can be divided into sections and rolled up and placed in storage for future installation.

When turfgrass sod is harvested, it is commonly rolled up and stored. However, heat accumulation inside of rolls can cause sod quality to decline and may eventually result in turfgrass death (King, 1970). Research has been conducted evaluating storage effects on common bermudagrass (*Cynodon dactylon* (L.) during summer months in Albany, GA (Maw et al., 1998). The rolls were stored for three weeks in full sun, and temperatures inside the rolls reached 35 ^{o}C, which was 12 ^{o}C above ambient temperature. Four weeks after planting the rolls, 75% of the bermudagrass had fully recovered (Maw et al., 1998). High temperatures can increase the turfgrass carbohydrate reserves expended for respiration, and such carbohydrates are critical for growth and development after the sod is laid (Watschke et al., 1970). After installation, the combined effects of both heat stress coupled with expended carbohydrate reserves may have a detrimental effect on turfgrass establishment.

Although traditional sod and vegetative plugs on TRM can both be harvested and stored prior to planting, there is little information available regarding what impact temporary storage of

TRM may have on establishment. Our objective was to evaluate the establishment of 'Legacy' buffalograss from vegetative plugs on TRM after temporary storage.

Materials and Methods

Study sites and experimental design

Experiments were conducted at the Olathe Horticultural Research Center, Olathe, KS USA (38.897 N latitude, 94.993 W longitude) in 2011 and the Rocky Ford Turfgrass Research Center in Manhattan, KS USA (39.128N latitude, 96.358W longitude) in 2012. The soil at Olathe, KS site was a Kennebec silt loam with a pH of 7.0. The soil at Manhattan was a Chase silt loam (fine, smectitic, mesic, Aquertic Argiudoll) with a pH of 6.9. Weather data for Olathe and Manhattan during the study period were obtained from Kansas State University weather data library (http://www.ksre.ksu.edu/wdl). The mean monthly air temperature during the study period in Olathe in 2011 was: 28.8^{o} C in June; 30.7^{o} C in July; 28.4^{o} C in August and 19.5^{o} C in September. The mean monthly air temperature during the study period in Manhattan 2012 was: 25.7^{o} C in June; 29.9^{o} C in July; 24.6^{o} C in August and 20.3^{o} C in September.

'Legacy' buffalograss plugs were purchased from Todd Valley Farms (Mead, NE) five weeks prior to planting on TRM in 2011 and 2012. Grasses were established as 5-cm diam. vegetative plugs in TRM in Manhattan, KS on 2 June 2011 and 1 June 2012, three weeks prior to being placed in storage. This was done in order to mimic the approach a sod grower would use to establish plugs on the TRM prior storage or immediate delivery at the job site. A single turfgrass plug was inserted into 2.5-cm diameter slits on 25.5 cm centers on each 1 m x 1 m section of TRM. Each 1 by 1 meter mat contained 9 evenly spaced plugs of 'Legacy' buffalograss. The mats rested directly on a layer of 7-mil. black plastic. Irrigation was applied three times daily to deliver 1 to 2 mm of water in order to ensure mats stayed moist and to prevent turfgrass stress.

After the three weeks of establishment on the plastic, the 0 days of storage treatment TRM (control) was removed from the plastic and laid with plugs intact into the study area in Olathe, Kansas on 23 June 2011, and Manhattan, Kansas on 22 June 2012. Mats representing treatments for other storage times were lifted from the full-sun plot in the field, rolled up, and placed under dense shade (~160 µmol $m^{-2}s^{-1}$ or ~80% reduction from full sun PAR) at Manhattan, KS. Mats remained in storage for 7, 14, or 21 days before planting in the field. In Olathe in 2011, planting dates for respective treatments were: 1 July for 7 days of storage; 7 July for 14 days of storage; and 14 July for 21 days of storage. In 2012 at Manhattan, planting dates for respective treatments were: 29 June for 7 days of storage; 6 July for 14 days of storage; and 13 July for 21 days of storage. These were considered the dates planting occurred in field. The four storage times (0, 7, 14, and 21 days) were arranged in a randomized complete block design at each site with four replicates.

In 2011, mats in storage were unrolled every other day and wetted with a fan spray nozzle attached to a garden hose. In 2012, mats in storage were unrolled daily and wetted. Diammonium phosphate (18-46-0) was applied at 49 kg P ha^{-1} to all treatments at their respective time of planting. All plots received an additional 49 kg N ha^{-1} from urea 46-0-0 on 23 August 2011 and 19 August 2012. Irrigation was applied as needed in order to prevent buffalograss stress during establishment.

Turf Reinforcement Mat

The TRM utilized in this study was a product designed and manufactured by StayTurf® (Jimboomba Turf Company, Acacia Ridge, Australia). The original StayTurf® TRM is composed of felted Jute fiber manufactured at 650 g m^{-2} with UV resistant plastic netting inserted. Testing conducted at the Texas Department of Transportation Erosion Control Laboratory found StayTurf® acceptable for protection up to 194,013 L min^{-1}, 58 kg m^{-2} shear force, and a velocity of 12.11 m s^{-1} (Matt Campell, personal communication). The company also offers other products similar to the TRM that excludes the plastic netting (StayTurf Soil Saver). StayTurf Soil Saver was the product used in this evaluation.

Measurements

Turfgrass coverage was rated visually on a weekly basis on a 0 to 100% scale, where 0 = no turf, and 100% = complete turf coverage. Daily average temperature inside the stored rolls was recorded by using Hobo Dataloggers (HOBO Pro v2, Onset Computer Corp., Bourne, MA). Hobo Dataloggers were initially inserted into three randomly selected TRM's. However, the mats containing these dataloggers were designated as the 21-day storage treatments in order to allow for temperature monitoring throughout the entire storage period.

Statistical Analysis

Data were subjected to analysis of variance using the GLM procedure of SAS (SAS Institute Inc., Cary, NC). Means were separated using Fisher's Protected LSD ($P < 0.05$).

Results and Discussion

Average daily temperatures inside the rolls during shade storage in Manhattan, KS 2011-12 ranged from (19-28° C) (Fig. 4.1). In Olathe in 2011, buffalograss coverage was lower for 14 and 21 day storage treatments than the control or 7 day storage treatments beginning at 14 DAP (Fig. 4.2). Buffalograss stored on TRM for 7 days had a similar level of coverage (74%) at the end of the growing season as the control (75%) (Fig. 4.3 and 4.4). Maximum coverage for buffalograss stored on TRM for 14 days before planting was 26% at the end of the growing season (Fig. 4.5). In plots established to buffalograss stored on TRM for 21 days, only one replicate survived and coverage was <5% at the end of the growing season (Fig. 4.6). Lower coverage observed in buffalograss stored on TRM for 14 or 21 days storage treatment may be partially attributed to a lack of photosynthetically active radiation available during storage. During this time buffalograss likely expended non-structural carbohydrates during respiration. Non-structural carbohydrates would be critical for root development and foliar growth after planting (Hull, 1992). Furthermore, buffalograss stored on TRM was at a disadvantage because daylength declined as time progressed, which would favor treatments that were planted in the field earlier. The mean daily solar radiation during the study period in Olathe in 2011 was: 28.3 MJ/m^2 in June; 27.4 MJ/m^2 in July; 24.0 MJ/m^2 in August; 20.6 MJ/m^2 in September and 15.9 MJ/m^2 in October. The mean monthly solar radiation during the study period in Manhattan 2012 was: 24.9 MJ/m^2 in June; 26.6 MJ/m^2 in July; 24.7 MJ/m^2 in August; 20.3 MJ/m^2 in September and 17.5 MJ/m^2 in October. The higher mean monthly solar radiation in June and July would favor treatments that were planted in the field earlier.

Another disadvantage for TRM stored for 14 and 21 days came during the arrival of shorter days and cooler nighttime temperatures during August, September and October. The mean monthly air temperature during the study period in Olathe in 2011 was: 28.8^{o} C in June; 30.7^{o} C in July; 28.4^{o} C in August; 19.5^{o} C in September and 14.5 ^{o} C in October. The mean monthly air temperature during the study period in Manhattan 2012 was: 25.7^{o} C in June; 29.9^{o} C in July; 24.6^{o} C in August; 20.3^{o} C in September and 12.91 ^{o} C in October. The warmer average air temperatures during June, July and August would favor the treatments that were planted earlier in the summer.

In Manhattan in 2012, buffalograss coverage was lower for the 7, 14 and 21 day storage treatments than the control treatments at 35 and 42 DAP, and also at 70 DAP for the 21 day storage treatment (Fig. 4.2). In comparison to 2011, buffalograss planted in the control treatment exhibited significantly higher coverage (81%) by the end of the growing season in comparison to the 7 day storage treatment (48%) (Fig. 4.7 and 4.8). Turfgrass coverage for the control treatment and 7 day storage treatment differed between 2010-11. In 2011, 7 and 14 day storage treatments began to separate from the remaining treatments at approximately 20 DAP. In 2012, the control treatment began to separate from the remaining treatments at approximately 28 DAP. Maximum coverage for buffalograss stored on TRM for 14 days before planting was (36%) (Fig. 4.9), whereas coverage for the 21 day storage treatment was (27%) by the end of the growing season (Fig.4.10).

Coverage of buffalograss stored for 14 or 21 days was higher at the end of the season in 2012 than 2011. As previously discussed, watering frequency of stored rolls was increased from every other day in 2011 to daily in 2012, in order to reduce intermittent drying. This was done in an attempt to decrease buffalograss stress during storage, and possibly increase subsequent establishment following planting. Additionally, following TRM planting in Olathe 2011, water was applied by overhead irrigation as needed to prevent visible stress. During establishment in Manhattan 2012, water was applied almost every day by overhead irrigation controlled by an automatic timer. These differences in watering frequency during both storage and subsequent establishment may have encouraged survival of turf stored for 14 and 21 days.

Average daily temperatures inside the rolls during shade storage in Manhattan, KS 2011-12 ranged from (19-27^{o} C) (Figure 4.1), which were comparable to ambient temperature averages (24-31.5^{o} C). Research done on common bermudagrass sod stored on pallets for three weeks during summer in full sun, found temperatures inside the rolls reached 35 °C, which was 12 °C above ambient temperature (Maw et al., 1998). This was not a major concern in our study due to TRM rolls being stored under shade conditions. However, if rolls are going to be stored or transported under full sun conditions, high internal temperature of sod rolls may be a concern.

Conclusion

In summary, establishing ‘Legacy’ buffalograss on TRM over plastic for three weeks, and then lifting and storing in shade for up to seven days appears feasible. However, further research investigating storage in an artificially cooled environment should be investigated.

Figures and Tables

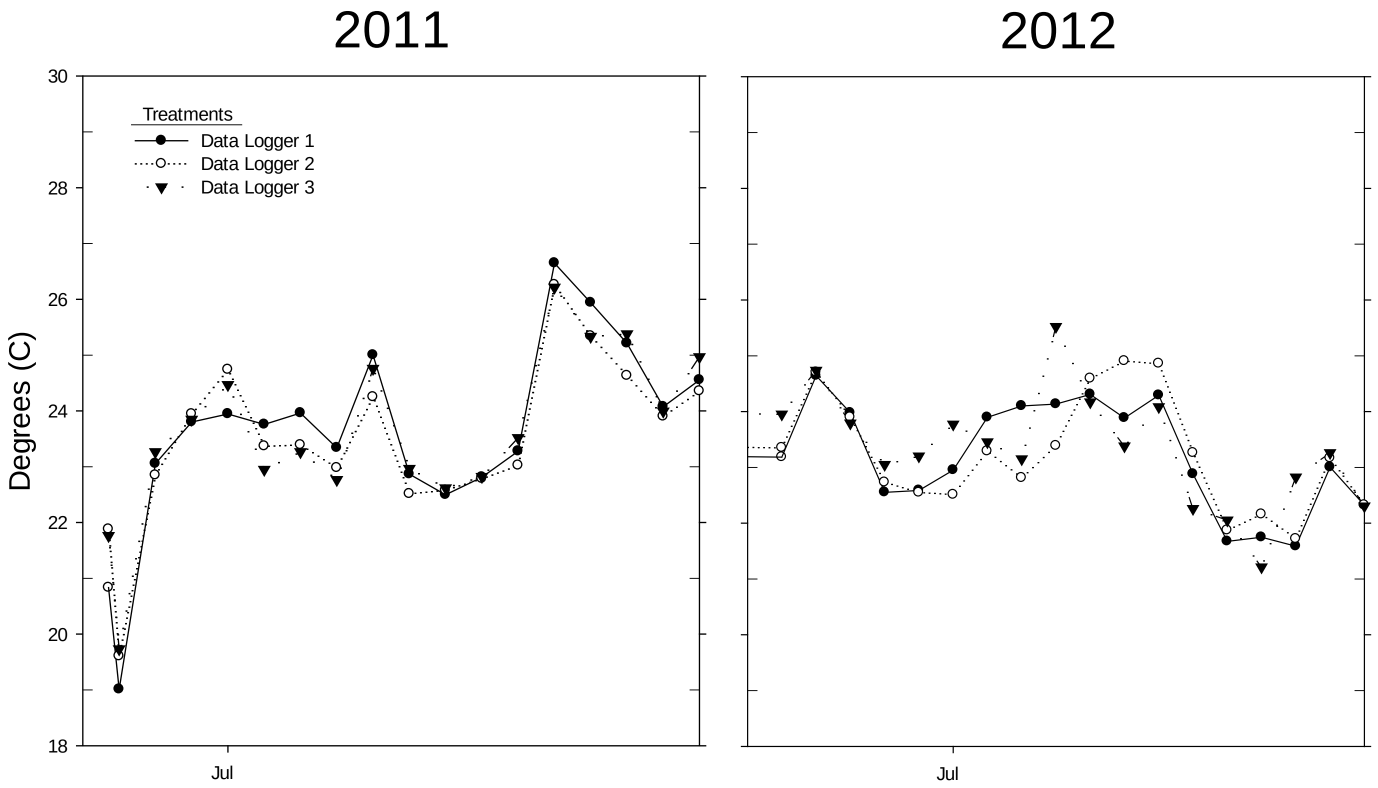

Figure 4.1- Temperature inside TRM containing Legacy buffalograss plugs during storage in Manhattan, KS in 2011and 2012. Data were collected using Hobo dataloggers placed in the 21 day storage treatment.

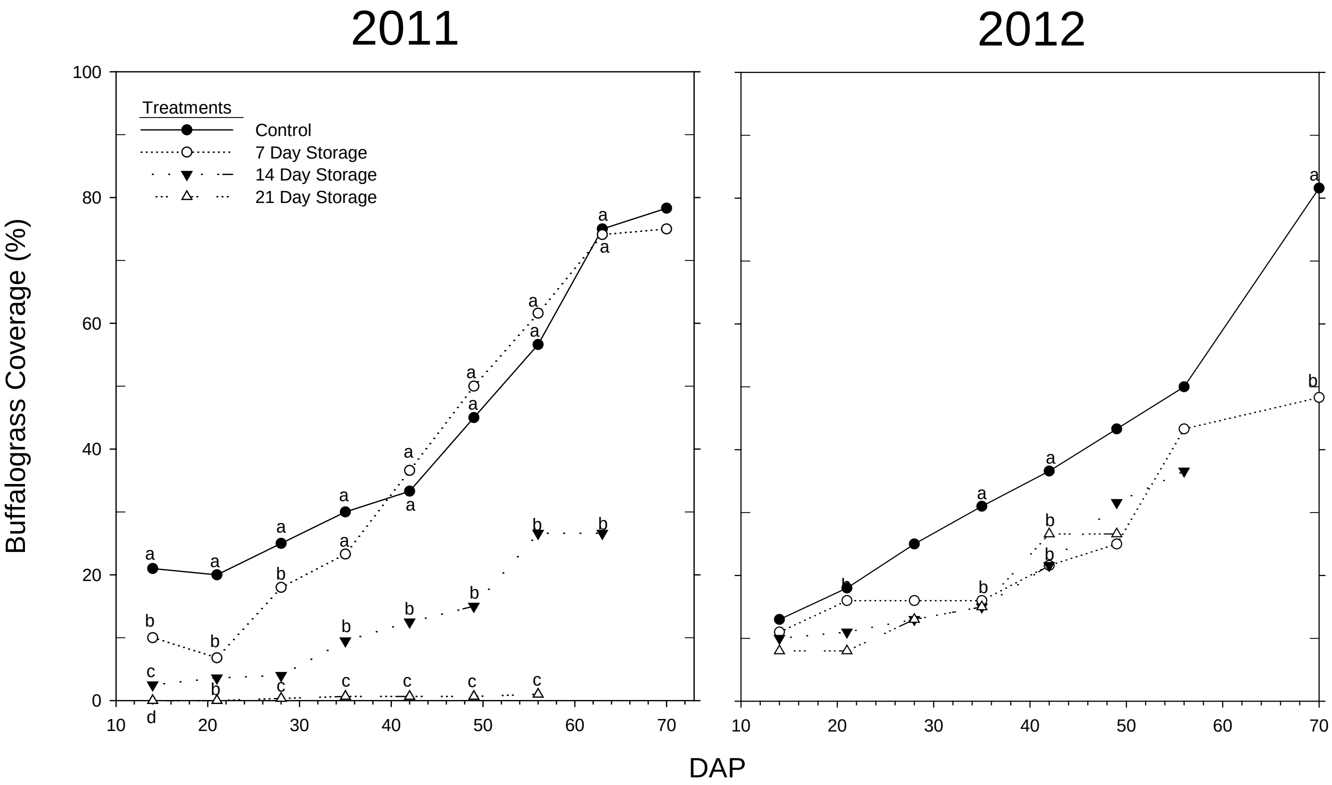

Figure 4.2- Coverage of Legacy buffalograss from vegetative plugs as affected by storage time at Olathe (left) and Manhattan (right), KS in 2010 and 2011. Buffalograss was planted on TRM and established on plastic in full sun for three weeks. Mats were then lifted, rolled, and stored for 7, 14, or 21 days in dense shade before planting. Planting was done following the lapse of the respective storage time and subsequent dates are referred to as days after planting(DAP). Coverage was rated visually on a 0 to 100% Scale. Means followed by the same letter on a date are not significantly different according to the F-LSD (*P* < 0.05).

Figure 4.3- 'Legacy' buffalograss stored on turf reinforcement mat for 0 days prior to planting on 23 June 2011 in Olathe, KS. Photo taken 22 Sept. 2011.

Figure 4.4- 'Legacy' buffalograss stored on turf reinforcement mat for 7 days prior to planting on 1 July 2011 in Olathe, KS. Photo taken 22 Sept. 2011.

Figure 4.5- ‘Legacy’ buffalograss stored on turf reinforcement mat for 14 days prior to planting on 7 July 2011 in Olathe, KS. Photo taken 22 Sept. 2011.

Figure 4.6- ‘Legacy’ buffalograss stored on turf reinforcement mat for 21 days prior to planting on 13 July 2011 in Olathe, KS. Photo taken 22 Sept. 2011.

Figure 4.7- 'Legacy' buffalograss stored on turf reinforcement mat for 0 days prior to planting on 22 June 2012 in Manhattan, KS. Photo taken 19 Sept. 2012.

Figure 4.8- 'Legacy' buffalograss treatment on turf reinforcement for 7 days prior to planting on 29 June 2012in Manhattan, KS. Photo taken 19 Sept. 2012.

Figure 4.9- 'Legacy' buffalograss stored on turf reinforcement mat for 14 days prior to planting on 6 July 2012 in Manhattan, KS. Photo taken 19 Sept. 2012.

Figure 4.10-'Legacy' buffalograss stored on turf reinforcement mat for 21 days prior to planting on 13 July 2012 in Manhattan, KS. Photo taken 19 Sept. 2012.

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Chapter 5 - Utilizing hyperspectral radiometry to predict green leaf area index of Kentucky bluegrass

Abstract

Determining green leaf area index (LAI) is an important method for inferring the photosynthetic capacity of a turfgrass canopy. There are several methods for determining LAI, but typically destructive sampling and scanning of leaves is used. Destructive sampling requires large research plots in order to account for multiple sampling dates over a growing season. Rapid, non-destructive estimation of LAI would be useful for turfgrass researchers and breeders. The objectives of this study were to I) evaluate whether hyperspectral radiometry can be utilized to accurately predict LAI of Kentucky bluegrass (*Poa Pratensis* L.); and II) determine which regions of the spectrum provide the best LAI predictions. For empirical calibration using spectral data we used partial least squares regression (PLSR). In the 2010 growing season, the PLSR method created only one viable model on only one sampling date(24 June 2010) (R^2=0.57). In 2011, viable first iteration PLSR models were created on four of the seven sampling dates. When comparing all first iteration models for 2011, the strongest was for the 17 May (R^2=0.85) sample date. Factor weights were analyzed for the first iteration regression models and a second iteration of models were created. The new models included only regions centered around 600, 690, 761, 960, 1330, 1420 nm (±10 nm). In this study, two of the five first iteration models containing all wavelengths (except water absorption bands) had a higher r-squared value than those second iteration models with selected spectral regions. This suggests for the other three first iteration models the information contained in the remaining (~2250) wavelengths was either redundant or had minimal influence on the model for predicting LAI. Overall, the results of this study suggest that spectral radiometry has the potential to accurately predict LAI. In our study, however, the robustness of the prediction models varied over the course of the growing season. The dynamic canopy of turfgrass accumulates more biomass

during early spring compared to middle and late summer. Therefore, finding one model robust enough to accurately predict LAI from spectra at any point during the growing season still seems unrealistic.

Introduction

Green leaf area index (LAI) is an important indicator of the photosynthetic capacity of a turfgrass canopy. For turfgrass researchers, this can be an important indicator of turfgrass health in studies where turfgrass is exposed to various forms of environmental stress such as drought, heat, etc. Measuring LAI in turfgrasses is typically accomplished by destructive sampling and scanning of green leaves. Unfortunately, destructive sampling is time consuming and requires large research plots in order to accommodate multiple sampling dates over a growing season. Therefore, development of a rapid, non-destructive means to estimate LAI would be a significant advancement for turfgrass researchers and breeders. Recently, canopy reflectance as measured with spectral radiometry has been used as an alternative to destructive sampling to estimate LAI in turfgrass canopies (Trenholm et al., 1999; Fitz-Rodriguez and Choi., 2002; Jiang et al., 2004; Jiang and Carrow, 2007; Merewitz et al., 2010).

In order to extract biophysical or biochemical information from the reflectance spectrum, vegetation indices (VI), defined as simple mathematical relationships between reflectance values at different wavelengths, are calculated (Field et al., 1994). Vegetation indices are typically designed to highlight a particular property of vegetation such as green LAI or biomass, water content, or nutrient status. Specific VIs such as the normalized difference vegetation index ((NDVI, computed as $(R_{\mathrm{NIR}} - R_{\mathrm{RED}})/(R_{\mathrm{NIR}} + R_{\mathrm{RED}})$) and the simple ratio (SR, computed as $R_{\mathrm{NIR}}/R_{\mathrm{RED}}$), where $\mathrm{R}_{\mathrm{NIR}}$ is reflectance in the near-infrared region and $\mathrm{R}_{\mathrm{RED}}$ is reflectance in the red region of the spectrum, have been used to predict photosynthetically active biomass (Rouse et al., 1973; Penuelas et al., 1997a). Higher LAI values correspond with increases in chlorophyll absorption and near infrared (NIR) scattering, which results in decreased red and increased NIR reflectance (Roberts et al., 2012).

Several studies conducted on grassland have reported strong correlations between the amount of green LAI or biomass and VIs (e.g. NDVI) obtained from spectral reflectance data (Mutanga and Skidmore, 2004; Vescova et al., 2004; Lee, 2008; Gianelle et al., 2009; Maskova et al., 2008; Chen et al., 2009; Fan et al., 2009). Vegetation indices such as NDVI have, however been shown to lack sensitivity when applied to crops with high biomass because the spectral response saturates (Baret and Guyot, 1991). For example, NDVI was sensitive to changes in vegetation fraction and LAI only at the beginning of the growing season, when LAI ranged from 0 to 1.2 (Gitelson, 2004).

Leaf pigments and structures greatly influence spectral reflectance characteristics of a turfgrass canopy. For instance, chlorophyll pigments influence the reflectance of wavelengths in the visible portion of the spectrum (400-730 nm) (Jensen, 2007). Specifically, reflectance in the range 680-740 nm is highly correlated with chlorophyll concentrations, with reflectance decreasing as chlorophyll content increases (Gitelson, 2012). Furthermore, leaf structural components, including stomata, nuclei, cell wall constituents, and cytoplasm also contribute to reflectance in the NIR (700-1200 nm) (Gausman, 1977; Jensen, 2007). Water content in plant leaves create strong absorption responses in the middle-infrared wavelengths. (1300-2500 nm) (Jensen, 2007). The “red edge” is an abrupt increase in reflectance in the 680-800 nm region of the reflectance spectrum, caused by chlorophyll absorption in the lower (visible) end and light scattering by intercellular spaces of the spongy mesophyll cells in the upper (NIR) end (Jensen, 2007). This region is used for many vegetation indices due to its strong relationship to chlorophyll content.

In turfgrass studies, VIs have been developed using multispectral and hyperspectral reflectance radiometry (Trenholm et al., 1999; Jiang et al., 2004; Jiang and Carrow, 2005, 2007;

Merewitz et al., 2010). Multispectral radiometry measures the spectral reflectance of plant canopies in approximately eight bands. Those spectral bands are not contiguous and each band interval is broad, normally greater than 25 nm (Liang, 2004). Because multispectral radiometry integrates over wide ranges of wavelengths, it may mask subtle effects of LAI on reflectance in the narrower bands.

Hyperspectral radiometry, however, allows for measurements of spectral reflectance in approximately two thousand narrow wavelengths. The increased spectral resolution of the narrower bandwidths associated with hyperspectral measurements may permit greater spectral sensitivity to subtle variations in the canopy properties. Therefore, if changes in LAI affect canopy reflectance in specific regions of the spectrum, hyperspectral radiometry may detect these effects better than the broader bands associated with multispectral radiometry. For example, reflectance in the green region (500-600 nm) of the spectrum was affected as LAI increased (Ustin et al., 1996). Broadband spectral radiometers such as the Cropscan MSR-16(CropScan, Inc. Rochester, MN) have two 10-25 nm integrated wavelengths located at 509 nm and 559 nm. Therefore, it is possible they may mask subtle effects of LAI on reflectance in the narrower bands in the green portion of the spectrum.

Although direct relationships between LAI and spectral reflectance have been determined for a number of crops (Asrar et al., 1994, Daughtry et al., 1992, Vescovo et al., 2004), few studies have evaluated those relationships in turfgrass. However, a study conducted by Lee (2008) evaluated the relationship of reflectance with green LAI, aboveground biomass, and chlorophyll content in five cool-season and two warm-season turfgrasses. Results of the study indicated correlations between green LAI and reflectance at 507,559, 613, and 706 nm(r^2= 0.30 to 0.40) when data from a number of turfgrass species and mowing heights were pooled.

Furthermore, when the data from the study were analyzed separately by species, stronger correlations between LAI or biomass and reflectance were found in some turfgrass species (r=0.80 to 0.99) (Lee, 2008). However, overall the use of multispectral radiometry has provided mixed results when attempting to accurately predict LAI. We hypothesize that if spectral reflectance is affected by LAI primarily in narrow spectral regions, then hyperspectral radiometry would detect these effects better.

The main objective of this study was to evaluate whether hyperspectral radiometry can be utilized to accurately predict LAI of Kentucky bluegrass. Since the potential relationship between LAI and the reflectance spectra of the canopy is not fully understood, empirical calibration is needed in order to model LAI from raw spectral data.

Therefore, a second objective of this study was to identify bands with the highest influence on spectral models for predicting LAI of Kentucky bluegrass. Because turfgrass properties that affect spectral reflectance, such as biomass density, may vary temporally, measurements were taken on a number of dates throughout the growing season.

Materials and Methods

Study Site and experimental design

Reflectance data were collected on 24 June, 30 July, 28 Sept., and 4 Nov. in 2010. In 2011, data were collected on 28 April, 17 May, 8 June, 30 June, 18 July, 24 Aug., and 28 Sept. Nine plots of Kentucky bluegrass were maintained at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas, USA ($39^{o}13'53''$ N, $96^{o}34'51''$ W). The soil at the site was a Chase silt loam (fine, smectitic, mesic, Aquertic Argiudoll) with a pH of 6.9. A soil test prior to the study indicated P and K levels were adequate. Plots (1.5 m x 1.8 m) were mowed and maintained at three heights, 5, 8.9, and 12.7 centimeters, were arranged in a completely randomized block design with three replications (Figure 5.1). All treatments were fertilized with 49 kg N ha^{-1} on 13 May, 15 September, and 16 November 2010. For 2011, all treatments were fertilized with 49 kg N ha^{-1} on 3 May, 12 September, and 10 November. Irrigation was applied three times weekly for a total of 25 mm of water per week.

Plot Maintenance

Imidacloprid (1-[(6-chloro-3-4 pyridinyl) methyl 3 (2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate) was applied at 0.12 kg a.i. ha^{-1} to control billbug grubs and white grubs (*Cyclocephala lurida* Bland) on 1 May 2010 and 3 May 2011. The herbicides carfentrazone-ethyl (Ethyl α,2-dichloro-5-[4(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl]-4-fluorobenzenepropanoate) (0.03 kg a.i. ha^{-1}) + 2,4-D [2-ethylhexyl ester (2,4 dichlorophenoxyacetic acid] (1.29 kg a.i. ha^{-1}) + Mecoprop-p acid [(+)-R-2-(2-methyl-4 chlorophenoxy)propionic acid] (0.27 kg a.i. ha^{-1}) + dicamba acid (3,6-dichloro-o-anisic acid)(0.08 kg a.i. ha^{-1}) were applied on 6 April 2010, 23 Oct. 2010, and 9 April 2011 for broadleaf weed control. Applications of dithiopyr [S,S'-dimethyl 2-(difluoro-methyl)-4-(2-methylpropyl)-6-(trifluoromethyl)-3,5-pyridin-edicarbothioate] were made at 0.58 kg a.i. ha^{-1} on 6 April 2010 and 9 April 2011 to control annual grassy weeds.

Measurements

Hyperspectral reflectance was measured monthly with a FieldSpec 3 Portable Spectoradiometer (ASD Inc., Boulder, CO) (Figure 5.2). The ASD spectoradiometer has 2150 channels ranging from 350 nm to 2500 nm. Spectral resolution for the instrument is 1.4-nm in the visible spectrum and 10-nm in the middle infrared. For each plot and measurement date, three radiometer scans were obtained and then averaged into a single reading (Figure 5.3). The radiometer measurements were consistently acquired with a nadir viewing angle at 1.2 m above the canopy using an 18 degree field of view adapter that yielded an instantaneous field-of-view of, approximately 0.283 m^2 at turfgrass' surface. Direct measurements of green leaf area index were obtained immediately after collection of radiometer measurements by destructively harvesting two random areas of the turfgrass canopy, each 45.6 cm^2 (7.62-cm diam. PVC ring). Prior, to image analysis brown senesced leaves and debris were sorted from green leaf tissue. Green leaf area was then measured with an image analysis system (WinRHIZO Model 2002a, Regent Instruments, Quebec, Canada).) (Figure 5.4). Thereafter, the leaf samples were dried at 75 ^oC for 48 hours and then weighed to measure total aboveground biomass.

Initially, spectral data were reviewed using (Viewspec Pro, ASD Inc., Boulder, CO) software to ensure that all readings were acceptable. Readings which were blank or contained errant spectral responses were discarded. Next, the portions of the spectrum (<400nm, 1340-1420nm, 1800-1930nm, >2400nm) that are highly influenced by atmospheric attenuation were removed prior to analysis (Pimstein et al., 2011). For empirical calibration using spectral data, approaches such as the use of partial least squares regression (PLSR), are recommended (Beebe and Kowalski, 1987; Martens and Naes, 1991). PLSR is particularly suited for use when there are more predictor variables than response variables, which is quite often the case when using chemometrics techniques. Standard regression is not suited for data sets containing more predictor variables (e.g. 2400 wavelengths) than response variables (9 treatments).

Statistical Analysis

Data were analyzed using the PLSR method contained within GRAMS software (Thermo Fisher Scientific, Hanover Park, IL). The first iteration of PLSR models included all (~2400) spectroradiometer wavelengths measured to build the model. These first iteration models were evaluated on a date-by-date basis to determine which sampling periods yielded viable models. The GRAMS software predicts/recommends the number of factors that should be used for the model. In the case where the software did not recommend any number of factors it was considered not a viable model. Factor weights were analyzed for all the viable first iteration regression models. One of the most powerful pieces of information provided by the PLSR method is in the form of the model "factor weights". This information provides insight into the wavelengths that are having the greatest influence on your prediction model. Regions of the spectrum with the highest factor weights were selected, and a second iteration of PLSR models was created using the selected wavelengths. In this study, the new models included only regions centered around 600, 690, 761, 960, 1330, 1420 nm (±10 nm). These areas were selected due to their high factor weights as determined by studying all the first iteration models.

Results and Discussion

The R-squared critical value for statistical significance for this data set was 0.399. If correlation values are greater than 0.399 or less than -0.399, it can be concluded the odds are less than 5 out of 100 that this is a chance occurrence. All the viable prediction models for this study were found to be statistically significant at ($P < 0.05$). For the 2010 growing season, only one model on one sampling date (24 June) was found to be statistically significant using the PLSR method (R^2=0.57) (Figure 5.5). For 24 June, there were two factors for the first iteration model. Factor one had the highest factor weight (0.039) at wavelength 1119 nm(Figure 1.6). Factor two had the highest factor weight (0.023) at wavelength 706 nm (Figure 5.6). Factor weights from 24 June 2010, in addition to the remaining 2011 sampling periods that yielded viable models, were studied to determine regions in the spectrum that most highly influenced spectral models for predicting LAI. A second model was created that included only selected regions of the spectrum with the highest weights (centered around 600, 690, 761, 960, 1330, 1420 nm ±10 nm). For the 24 June model, the coefficient of determination (R^2=0.46) was lower than the original (Figure 5.5)

For 2011, statistically significant PLSR models were created for four of the seven sampling dates. On the remaining three sampling dates the relationship between reflectance and LAI was so weak that there were no factors suggested and no viable models produced. The first statistically significant model for 2011 was created on 17 May , (R^2=0.85) (Figure 5.7). When comparing all first iteration models across the two year study, this date yielded the strongest prediction model. The 17 May model again was defined by two major factors. Factor one had the highest factor weight (0.043) at wavelength 761 nm (Figure 5.8). For factor two, the highest weight (0.003) was recorded at wavelength 684 nm. Once again, a second model was created for this 17 May sampling date using only selected spectrum regions around (600, 690, 761, 960, 1330, 1420 nm ±10 nm). For the second model, the (R^2=0.83) was slightly lower than the original.

The next date in 2011 that resulted in a statistically significant model was 30 June (R^2=0.73) (Figure 5.9). The 30 June 2011 model only consisted of a single factor. Factor weights for the single factor model were highest (0.04) at 761 nm (Figure 5.10). For the second model, which only included the selected spectral regions (centered around 600, 690, 761, 960, 1330, 1420 nm ±10 nm), the coefficient of determination (R^2=0.86) was higher than the original model (R^2=0.73).

The next statistically significant first iteration model was created on 18 July 2011 (R^2=0.52) (Figure 5.11). Similar to the 30 June model, this 18 July model only consisted of a single factor. Factor weights for the single factor model were highest (0.04) at 761 nm (Figure 5.12). For the second iteration model, the coefficient of determination improved (R^2=0.71) when compared to the original model containing all portions of the spectrum.

The final statistically significant model for the study occurred on 24 August 2011 (R^2=0.79) (Figure 5.13). This model only consisted of a single factor which had the highest weight (0.04) at wavelength 870 nm (Figure 5.14). For the second iteration model, the coefficient of determination once again improved (R^2=0.81) when compared to the first-iteration model, which contained all (~2400) wavelengths measured by the spectralradiometer.

Factor weights for 3 of the 5 first iteration models created in this study were highest around 761 nm. Chlorophyll pigments strongly influence reflectance at wavelengths in the visible portion of the spectrum (400-700 nm) (Jensen, 2007). The peak absorption wavelengths of chlorophyll *a* are 430 nm and 664 nm; peaks for chlorophyll *b* are 460 nm and 647 nm (Larkum, 2003). However, Gitelson and Merzlyak (1994 a and b) found that reflectance in spectral bands located quite far from these main absorption band pigments near 550 nm and 700 nm were closely related to chlorophyll for a wide range of plant species. In the present study, the highest factor weights occurred around 761 nm, which is located in the middle of the red edge and suggests that chlorophyll absorption had a minimal impact on prediction of LAI from spectra. However, factor weights from the models presented in this study suggest the “red edge” where the shift from absorption of visible spectrum by plant pigments to reflectance in the NIR is indeed an important region of the spectrum when attempting to accurately model and predict LAI.

For all the second iteration models we included wavelengths centered around 960, 1330, 1420 nm (±10 nm), which are in the NIR. Leaf structural components, including stomata, nuclei, cell wall constituents, and cytoplasm affect reflectance in the NIR (700-1200nm) (Gausman, 1977; Jensen, 2007). Furthermore, water content in a leaf has strong absorption of middle-infrared wavelengths (1300-2500 nm) (Jensen, 2007). Both the 24 June 2010 and 24 August 2011 models had highest factor weights located at 1119 nm and 870 nm respectively. Therefore, it is reasonable to assume that on both of these dates, leaf structural components of the turfgrass canopy that, affect reflectance in the NIR, were having the greatest influence on LAI prediction models.

We originally hypothesized that if LAI is affected by spectral reflectance primarily in narrow spectral regions, then hyperspectral radiometry would detect these effects better. However, in this study two of five of the first iteration models that contained all (~2400) wavelengths had a greater coefficient of determination than those with selected spectral regions (centered around 600, 690, 761, 960, 1330, 1420 nm, ±10 nm). This suggests for the other three models most of the information contained in the remaining ~2250 wavelengths was either redundant or was having minimal influence on the model for predicting LAI. One of the major advantages in using selected wavelengths over the ~2400 wavelengths of a hyperspectral radiometer is related to the cost associated with construction of such an instrument. If you can find a few wavelengths that explain most of the variation, then a much less expensive instrument can be constructed that will permit more users to use this radiometer as opposed to a more expensive hyperspectral radiometer.

Overall, the results of this study suggest there is promise for using spectral radiometry to predict LAI. In our study however, the robustness of the prediction models varied over the course of the growing season, with measurements on some dates yielding stronger models than others. The dynamic canopy of turfgrass accumulates more biomass during early spring compared to middle and late summer. Therefore, finding one model robust enough to accurately predict LAI from spectra at any point during the growing season still seems unrealistic. Perhaps several models accounting for the change in canopy dynamics which occurs throughout a growing season may be necessary. Since the potential relationship between LAI and the reflectance spectra of the canopy is not fully understood, further research is needed in order to model LAI from raw spectral data. Further research studying canopy reflectance over the course of an entire year on several species of cool-season turfgrass may help to develop more robust models for predicting LAI from spectra.

Conclusions

Results of this study suggest that spectral radiometry has the potential to predict LAI. Five first iteration models were created for the eleven sampling periods during the two year study. However, the accuracy of this method varied over the course of the growing season with some periods yielding much stronger models than others. Perennial cool-season turfgrasses such as Kentucky bluegrass produce large amounts of biomass over the course of a growing season. In addition, there may be additional, poorly understood factors of the turfgrass canopy that change over the course of the growing season (e.g. canopy architecture, internal leaf properties). Therefore, finding one model robust enough to accurately predict LAI from spectra at any point during a growing season still seems unrealistic.

Previous studies by other have reported that the “red edge” (680-800 nm) is strongly affected by chlorophyll concentrations in plants. Factor weights obtained from this data set suggest these regions in the red edge are indeed correlated with LAI. Three of the models in this study had the highest loading occurring at 761 nm which is located in the middle of the red edge.

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Figures and Tables

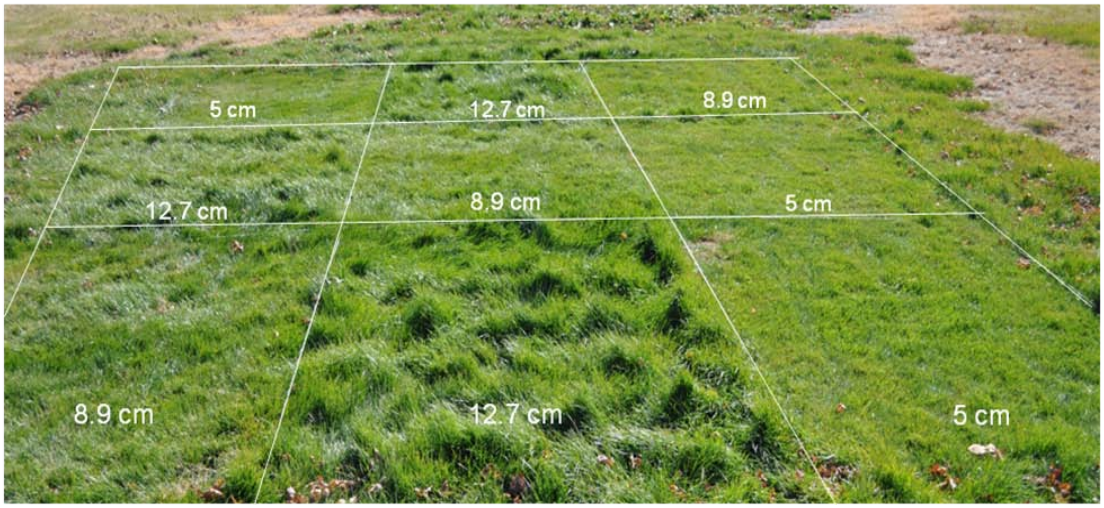

Figure 5.1- Treatments for the study included plots mowed at 5, 8.9, and 12.7 centimeters.

Figure 5.2- Researchers set up and calibrate the spectroradiometers prior to measurements being acquired.

Figure 5.3- Researchers obtaining radiometer readings from the various mowing heights.

Figure 5.4- Image analysis system (WinRHIZO) was used to calculate total leaf area index.

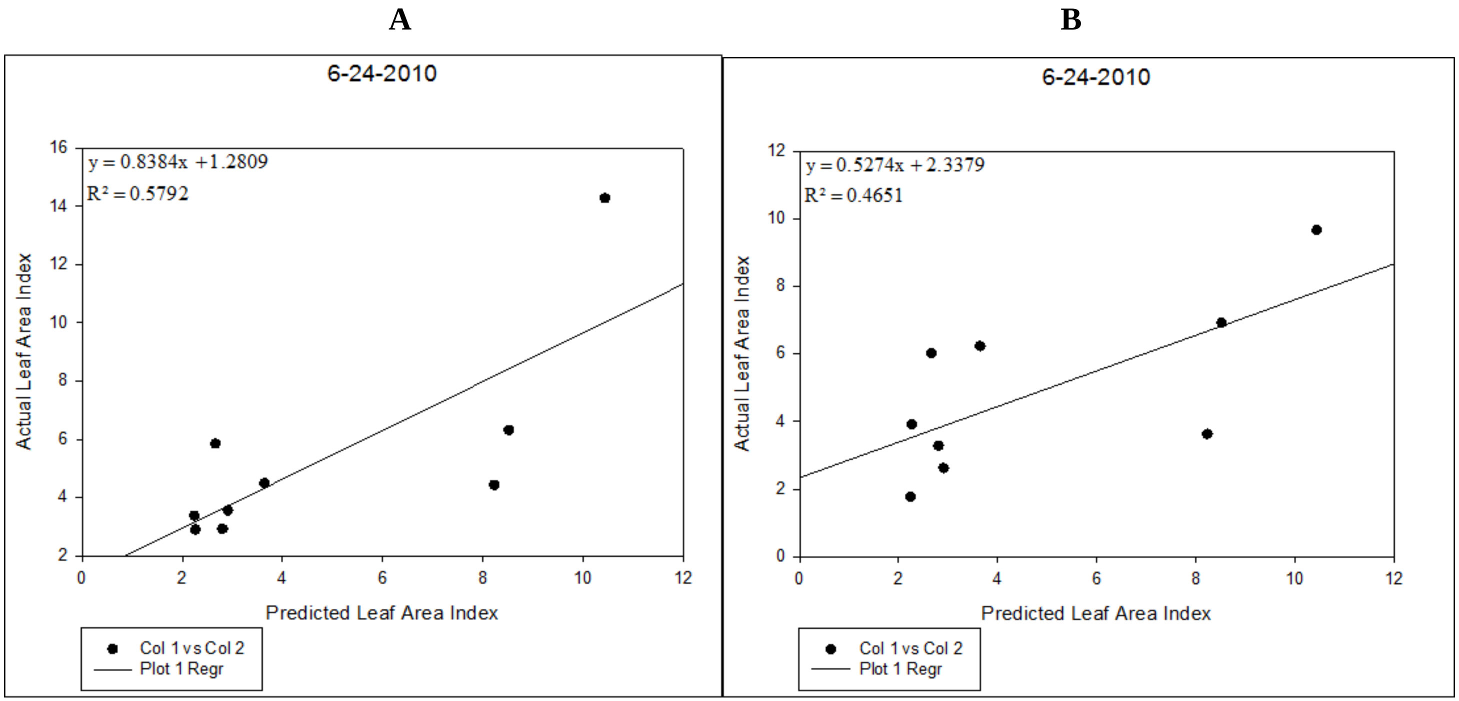

Figure 5.5- Partial Least Square regression models for predicting LAI 2010. Model A includes all 2400 wavelengths measured by the radiometer. Model B includes regions ±10 nm centered around 600, 690, 761, 960, 1330, 1420 nm. These regions were selected from the factor weights from the first iteration models.

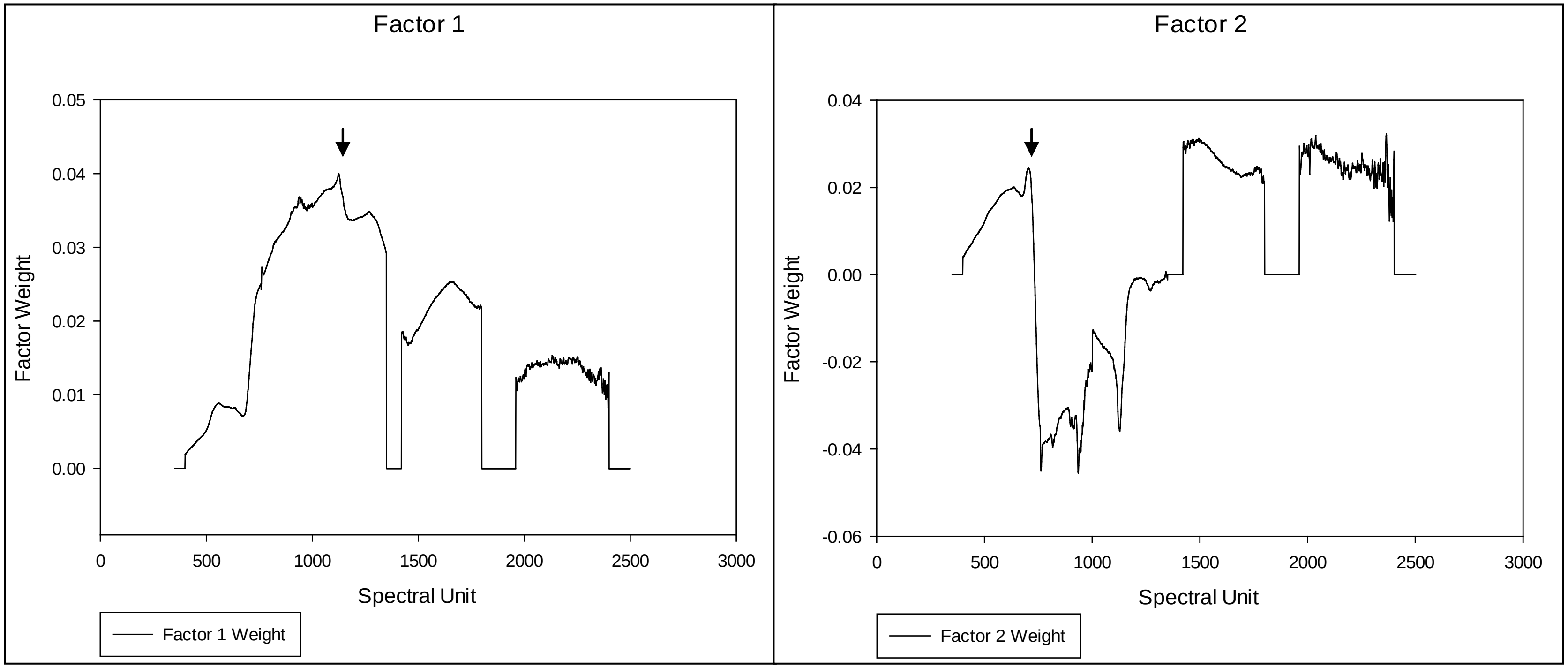

Figure 5.6- Factor weights for 24 June 2010 first model iteration. The graph on the left shows the factor weights of the first factor. The graph on the right shows factor weights of the second factor.

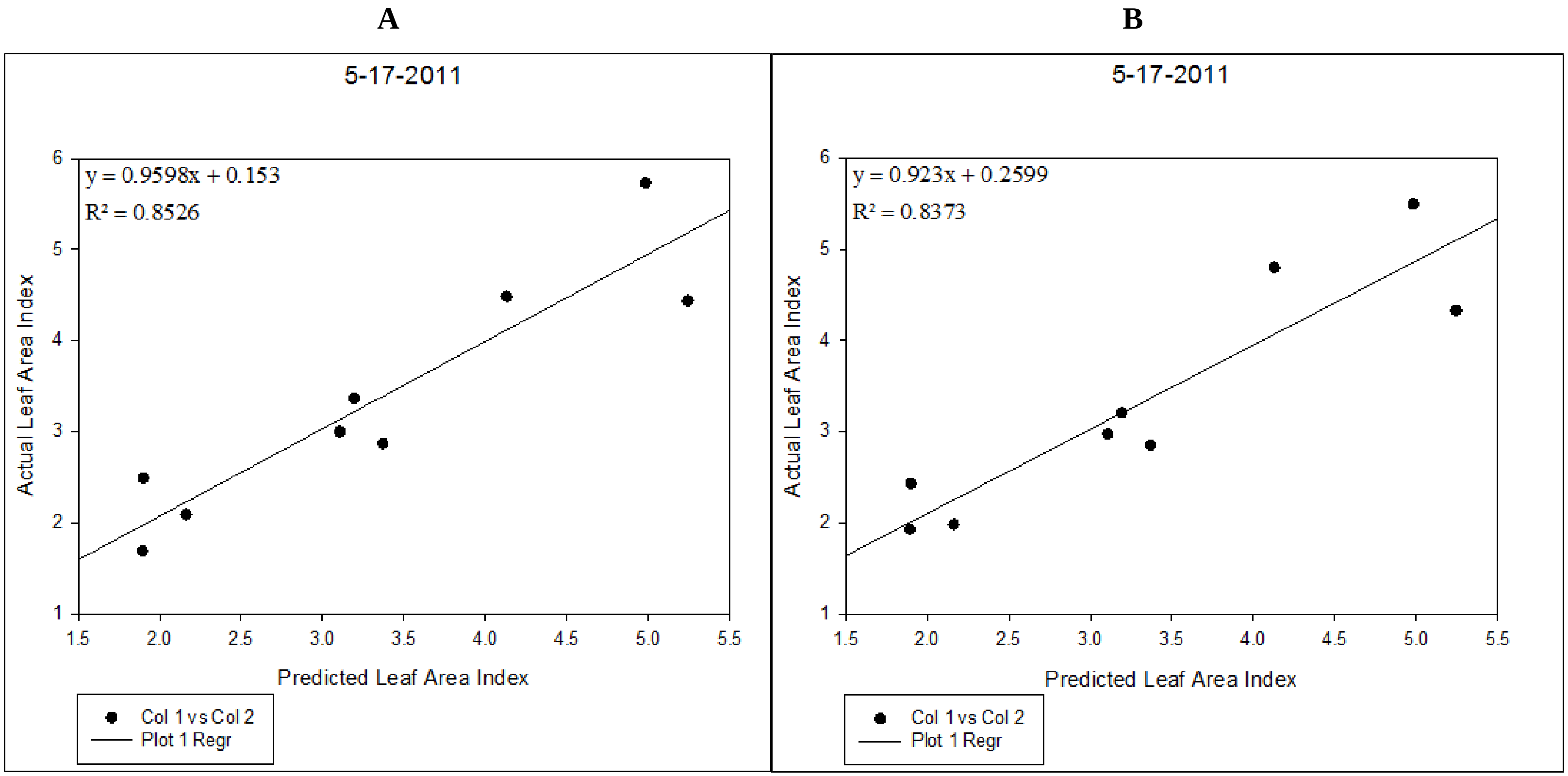

Figure 5.7- Partial Least Square regression models for predicting LAI on 17 May 2011. Model A includes all 2400 wavelengths of measured spectrum. Model B includes regions ±10 nm centered around 600, 690, 761, 960, 1330, 1420 nm. These regions were selected from the factor weight and loadings from the first model.

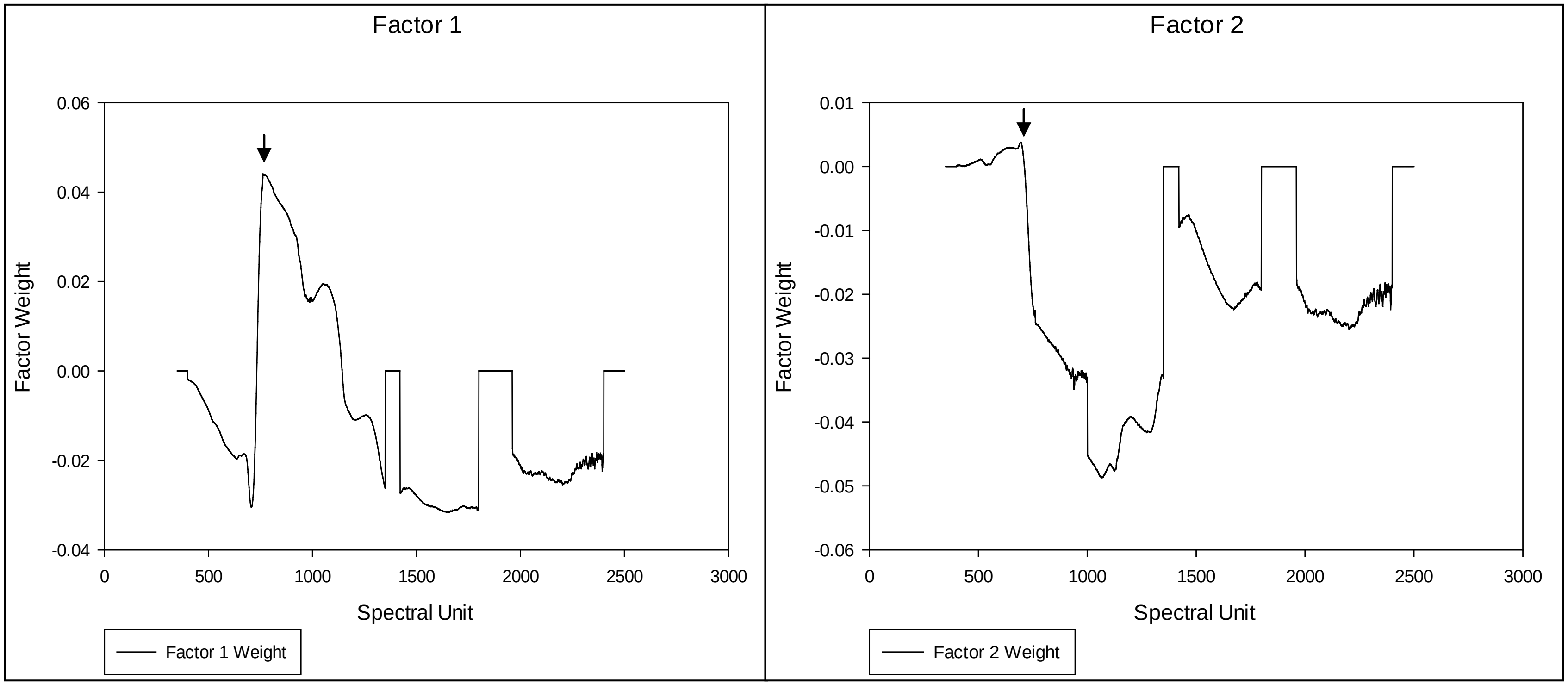

Figure 5.8- Factor weights for 17 May 2011 first model iteration. The graph on the left shows the factor weights of the first factor. The graph on the right shows factor weights of the second factor.

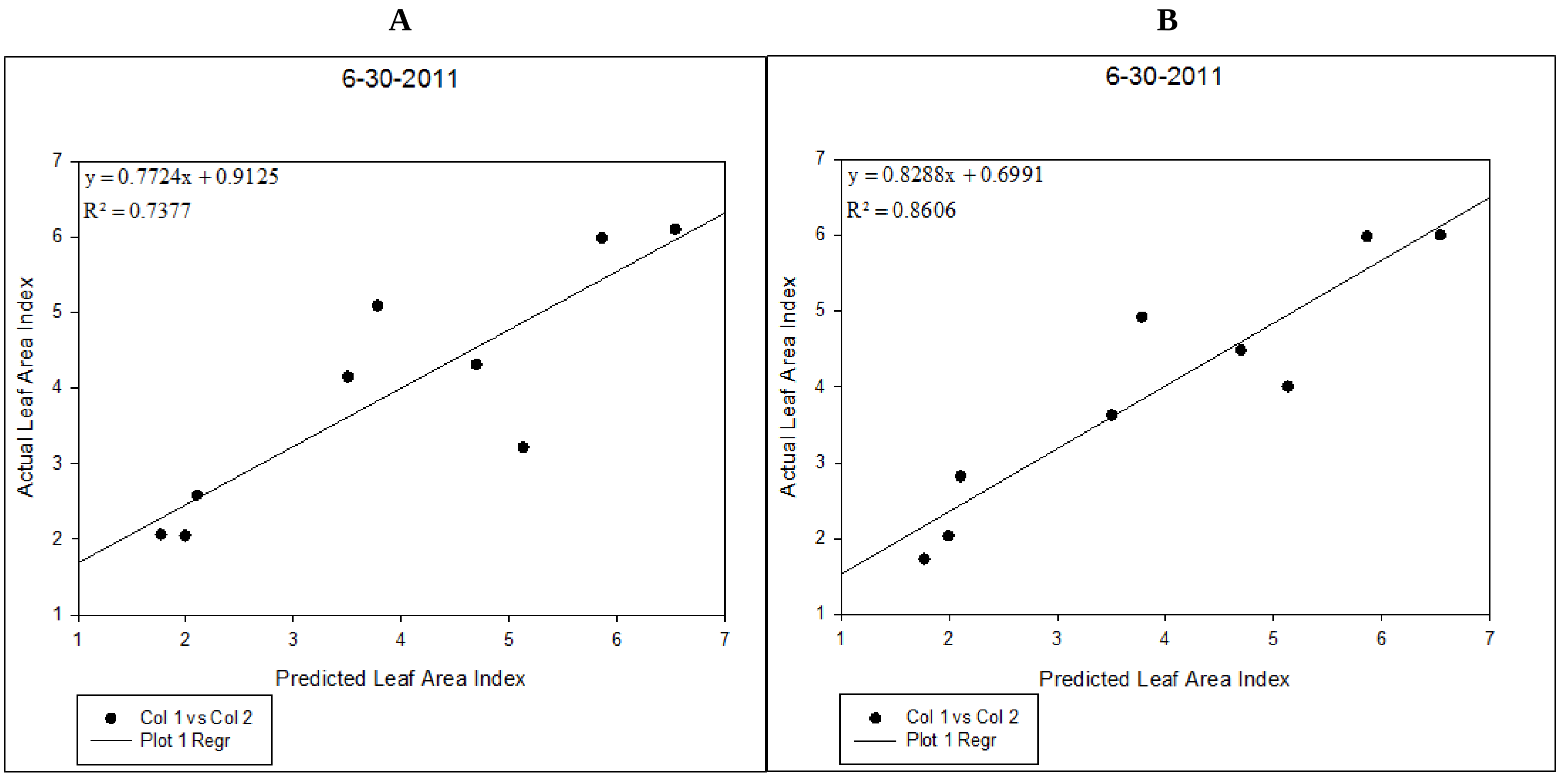

Figure 5.9- Partial Least Square regression models for predicting LAI on June, 30 2011. Model A includes all 2400 wavelengths of measured spectrum. Model B includes regions regions ±10 nm centered around 600, 690, 761, 960, 1330, 1420 nm. These regions were selected from the factor weight and loadings from the first model.

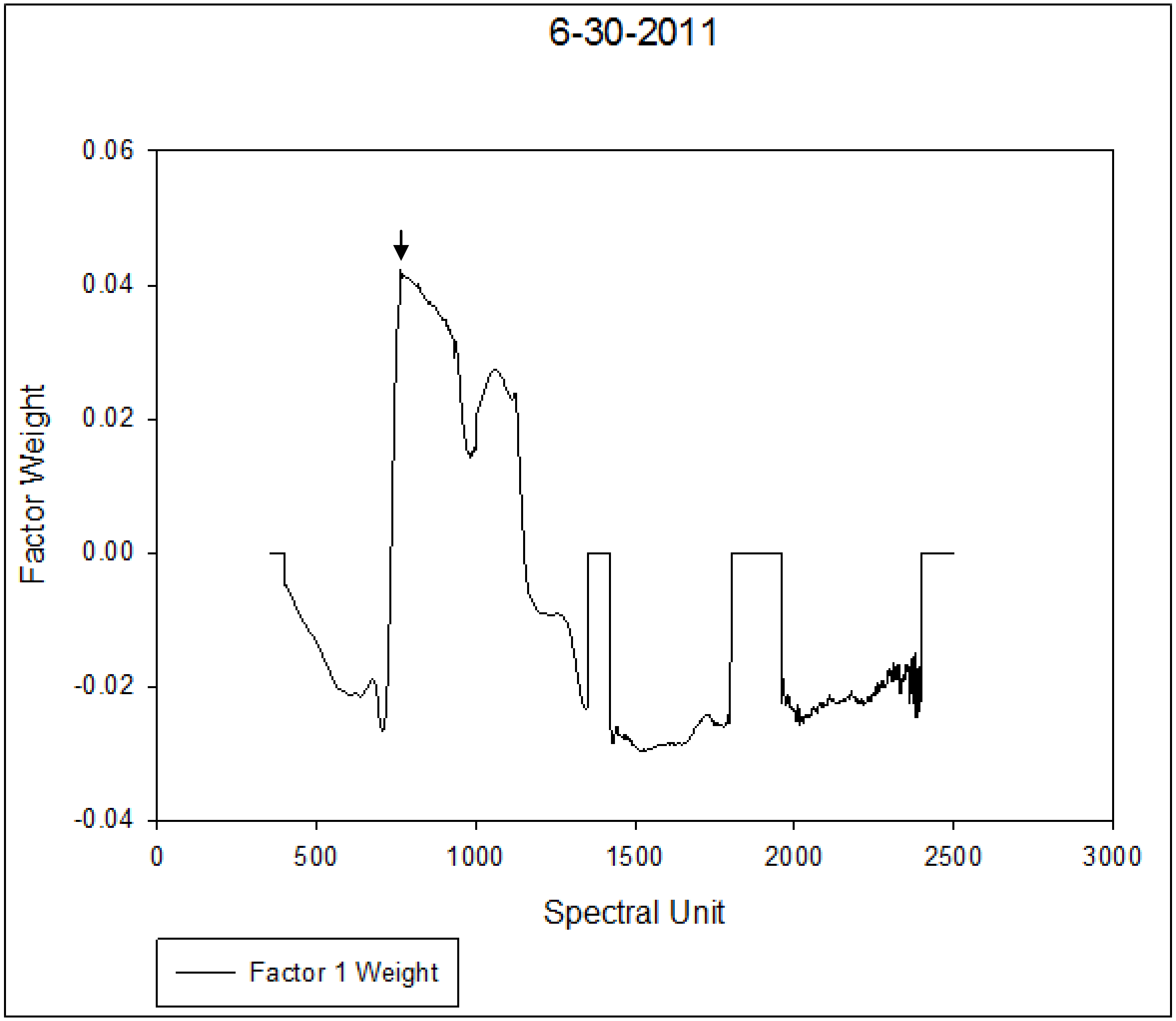

Figure 5.10- Factor weights for 30 June 2011 first model iteration. This graph shows the factor weights of the single factor for this model.

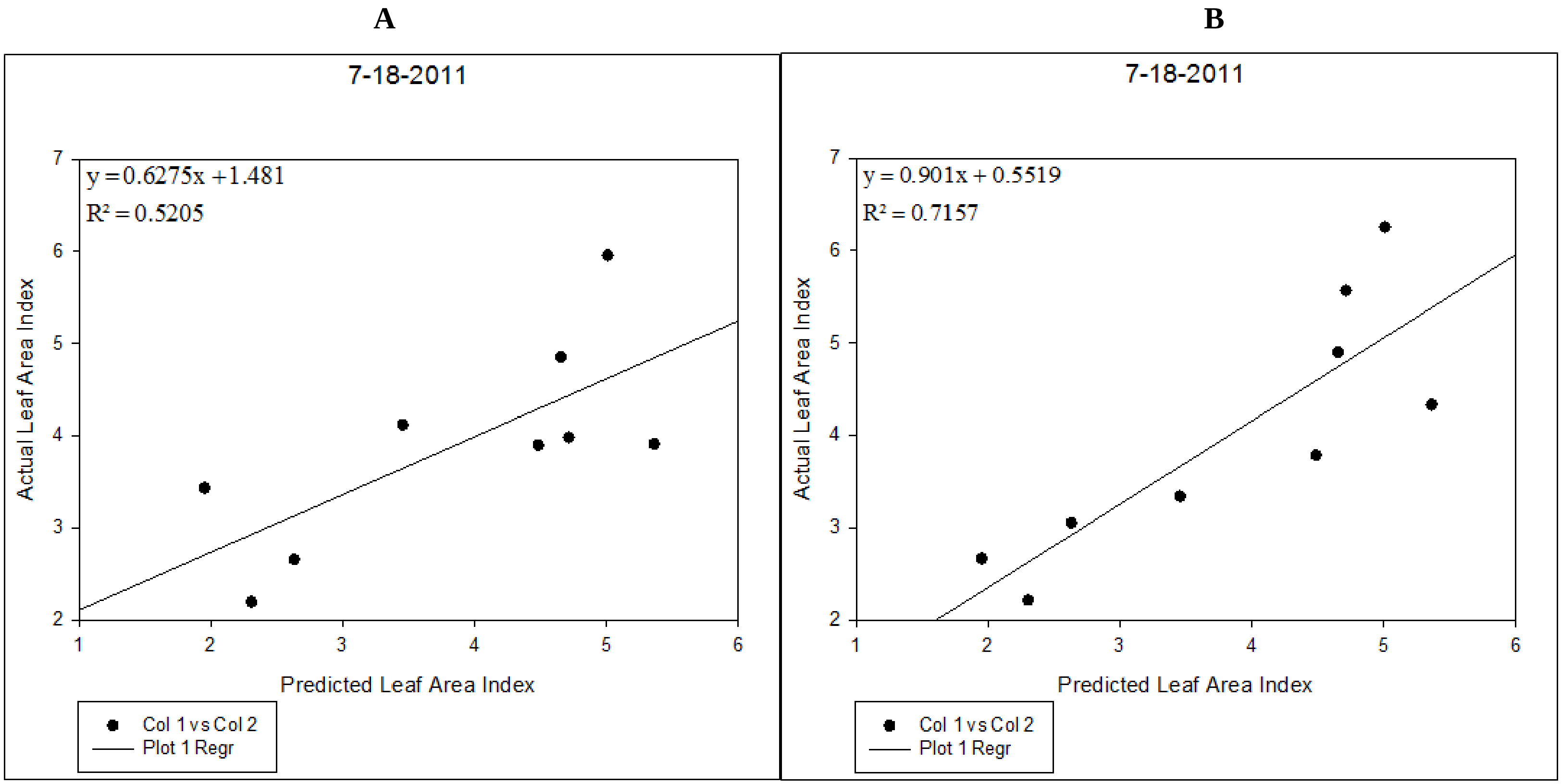

Figure 5.11- Partial Least Square regression models for predicting LAI on 18 July 2011. Model A includes all 2400 wavelengths of measured spectrum. Model B includes regions ±10 nm centered around 600, 690, 761, 960, 1330, 1420 nm. These regions were selected from the factor weight and loadings from the first model.

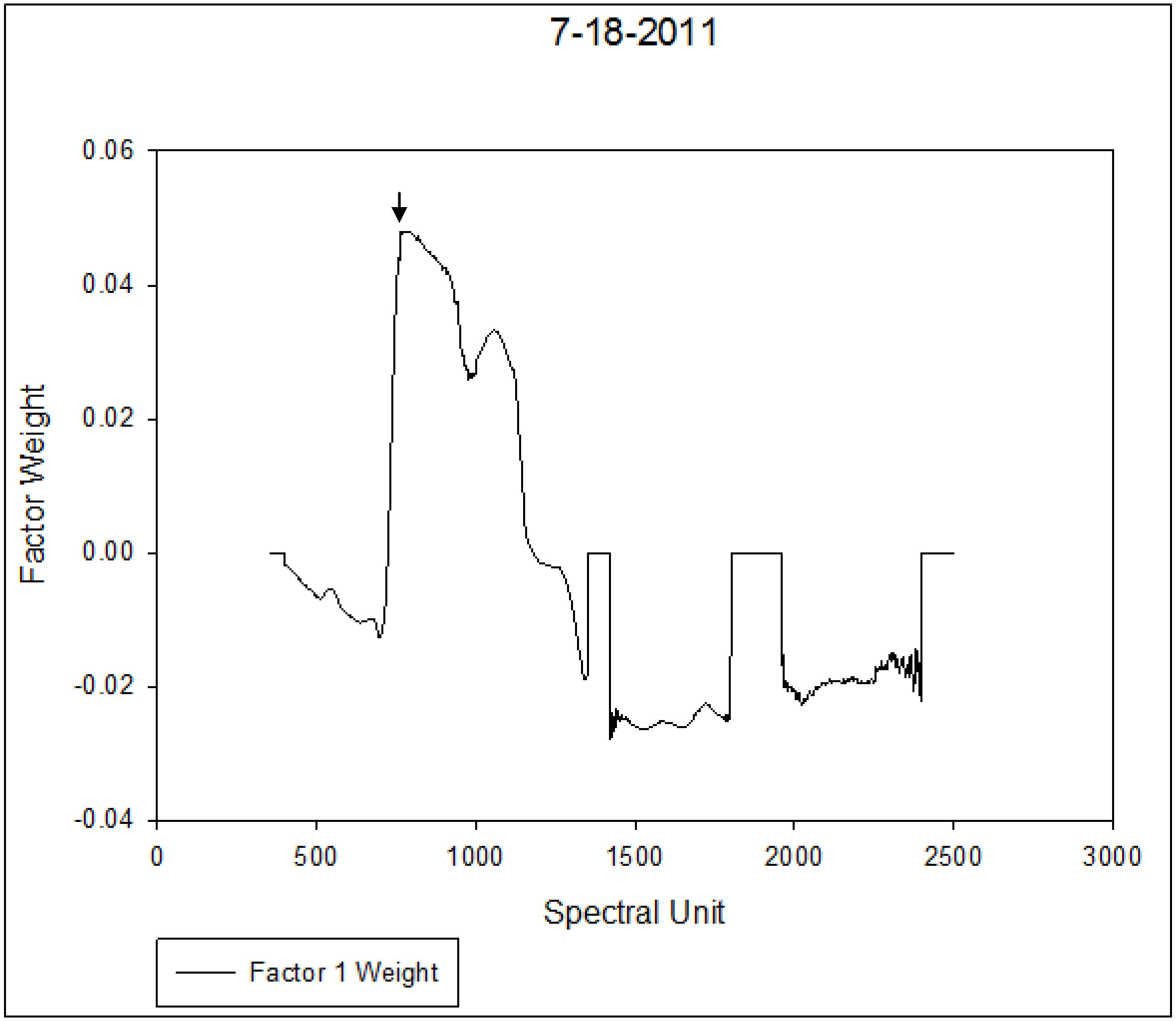

Figure 5.12- Factor weights for 18 July 2011 first model iteration. This graph shows the factor weights of the single factor for this model.

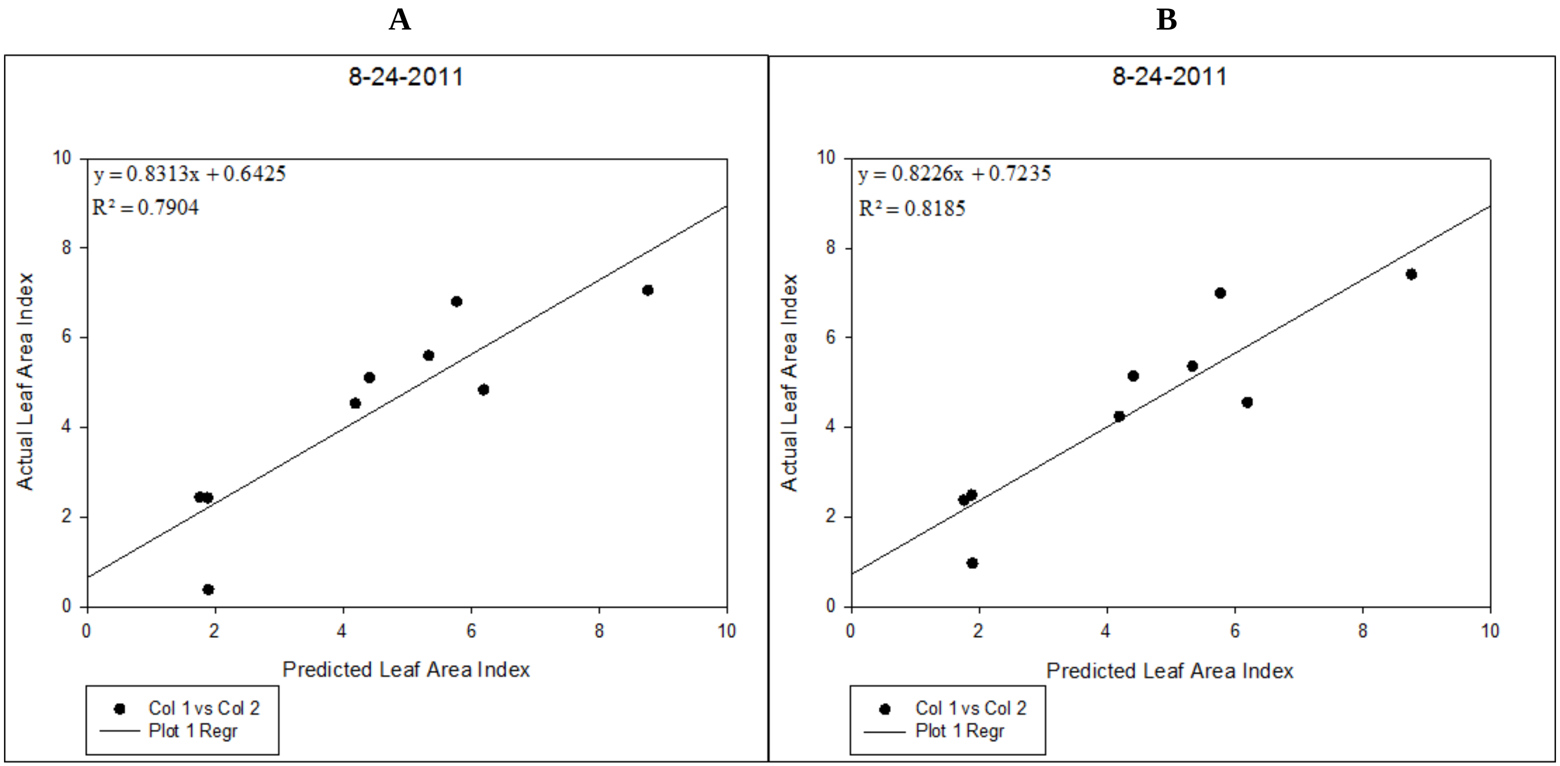

Figure 5.13- Partial Least Square regression models for predicting LAI on August, 24 2011. Model A includes all 2400 wavelengths of measured spectrum. Model B includes regions ±10 nm centered around 600, 690, 761, 960, 1330, 1420 nm. These regions were selected from the factor weight and loadings from the first model.

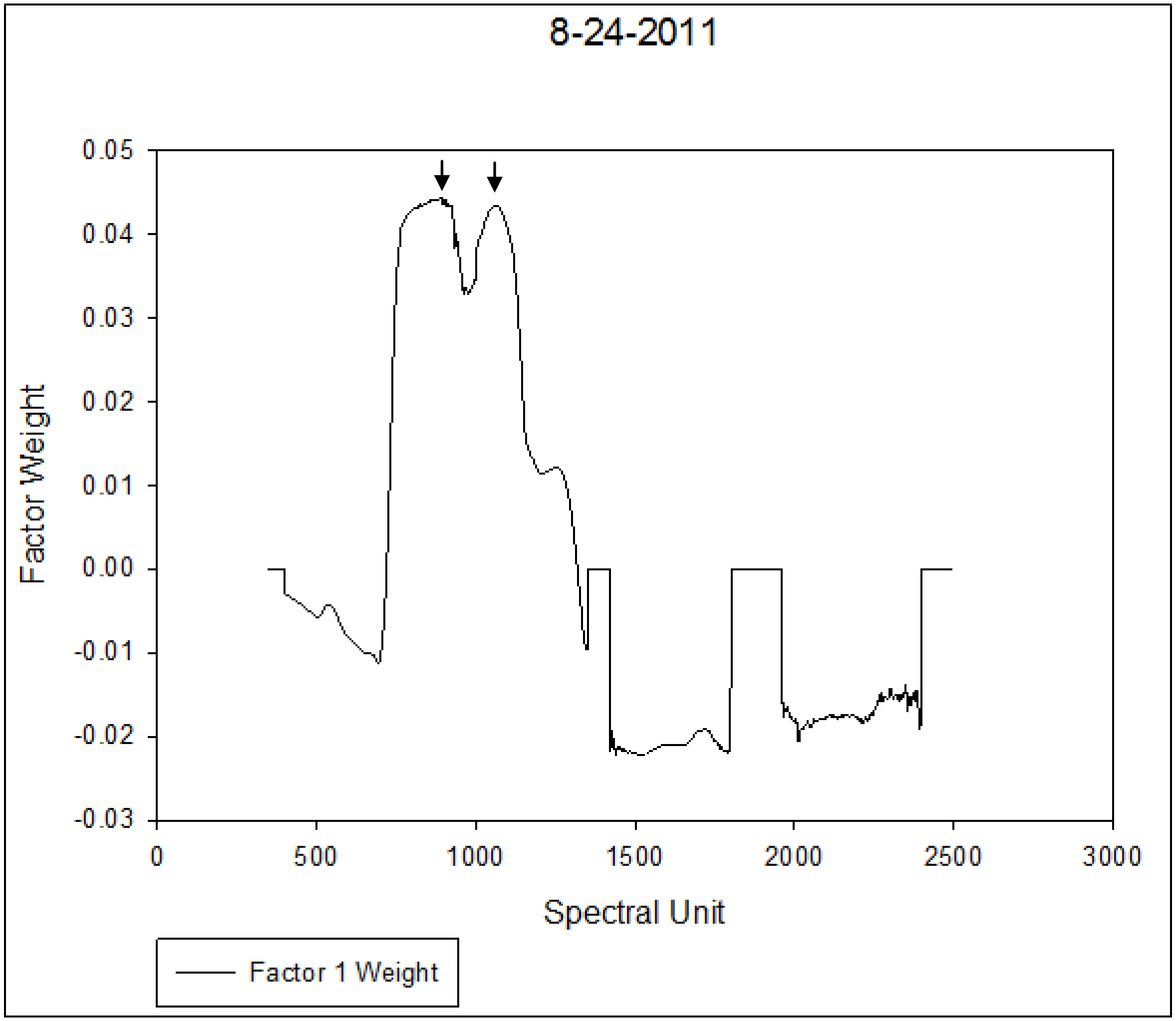

Figure 5.14- Factor weights for 18 July 2011 first model iteration. This graph shows the factor weights of the single factor for this model.

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