IRRIGATION AND NITROGEN IMPACT ON BERMUDAGRASS YIELD RESPONSE IN THE SOUTHEASTERN COASTAL PLAIN

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ABSTRACT. *In the southeastern region of the U.S., the cattle industry has a critical need for sustainable hay production. Yet this production is threatened by frequent short-term regional drought. This drought threat can be mitigated by properly managed irrigation. In this study on Tifton 85 bermudagrass, irrigation management, nitrogen fertility levels, and harvest interval were evaluated for their impact on hay quality and yield. The experimental treatments were arrayed in a split-plot design with harvest interval as the main treatment; irrigation by nitrogen (N) levels were the subplots. Treatments had four replicates and were repeated for two years. The optimal irrigation rate was set to maintain soil water potentials below -30 kPa. When needed, the full irrigation treatment received a 12.5 mm irrigation application. The reduced irrigation treatments received water at rates of 0%, 33%, and 66% of the full irrigation rate. In addition, each irrigation treatment had nitrogen rates of 168, 336, and 504 kg N ha^{-1}. The irrigation and nitrogen treatments were harvested at four-week or eight-week intervals. Total harvests per year ranged from three to six. Over both years and for all harvests, there was no irrigation-nitrogen interaction for hay yield. Over all harvests, nitrogen significantly increased bermudagrass hay yield, nutrient concentrations, and forage quality. Forage quality was higher for the four-week harvest interval. Throughout the study, forage quality was maintained within desired industry standards. When irrigation was required, it significantly increased hay yield. During these periods, the four-week and eight-week 100% irrigation treatments yielded 612 and 1600 kg ha^{-1} greater, respectively, than the non-irrigated treatments. The four-week harvest interval was more sensitive to irrigation. Additionally, we observed a linear relationship between non-irrigated bermudagrass hay yields and average soil water potential. As soil water was depleted, non-irrigated hay yields decreased 31 kg ha^{-1} per kPa. Timely supplemental irrigation to maintain soil water potentials above -30 kPa can increase bermudagrass yields. Thus, irrigation management should be critically assessed for its potential role in sustaining hay production in the southeastern Coastal Plain.*

Keywords. *Bermudagrass, Forage quality, Irrigation, Irrigation management, Nitrogen.*

In almost all southeastern U.S. states, cattle production ranks in the top ten leading commodities by cash receipts (USDA-ERS, 2011). This cattle production is vital to the regional economy. In this region, the cattle production industry has a critical need for sustainable hay production. Bermudagrass has become a major crop for forage and hay production crop in the southeastern U.S. (Muir et al., 2010; Alderman et al., 2011). However, hay production has been impacted by frequent short-term regional drought. This drought threat can potentially be mitigated by properly managed irrigation.

Bermudagrass is a drought-tolerant forage widely grown in the southeastern U.S. (Burton et al., 1957). In a three-year study, Burton et al. (1987) found that Coastal bermudagrass irrigation increased yields in only two of 23 cuttings. However, in their study, growing season rainfall ranged from 77% to 92% of the long-term average. In Alabama, Doss et al. (1962) found that maintaining adequate water in the soil profile increased Coastal bermudagrass production. In all three years of their study, they observed increasing yields with increasing available soil water. Ashley et al. (1965) reported a small increase in Coastal bermudagrass forage yield with irrigation, but only at high N levels. They also reported increased forage yields with irrigation particularly during low rainfall periods. In the Texas High Plains, Marsalis et al. (2007) investigated irrigated bermudagrass as an alternative to cotton production due to decreasing groundwater levels and water availability in the region. In a two-year study, they observed excellent Tifton 85 forage yields when irrigation was limited to approximately 300 mm year^{-1} and observed rainfall was approximately 190 mm year^{-1}.

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Much of the recent research on irrigated bermudagrass hay production has been in association with land application of wastewater. Most of these research findings focused on bermudagrass nutrient utilization rather than irrigation (Burns et al., 1985; Westerman et al., 1985). Using subsurface drip irrigation for effluent application, Stone et al. (2008) reported a significant increase in bermudagrass hay yields with increased nitrogen rates, but no corresponding significant increase in yields with irrigation. In Brazil, da Fonseca et al. (2007) reported that supplemental irrigation with secondary-treated wastewater could significantly increase bermudagrass hay production. However, their yield responses were dependent on the growing season rainfall intensities.

Most previous research on bermudagrass water use reported that periods of low rainfall or drought can impact production. Stone et al. (2010) reported that climate change and weather extremes were impacting water resources availability in the U.S. and throughout the world. Weather extremes (droughts and flooding) have been occurring with a higher frequency in the central U.S., with a higher percentage of extreme events occurring in the western U.S. and to some extent the eastern U.S. These weather extremes, particularly short-term droughts, have the potential to impact bermudagrass hay production. The expectation of more frequent drought periods provides an incentive to investigate irrigation responses for stable bermudagrass hay production. Additionally, most of the previous research on bermudagrass irrigation was conducted with older cultivars that yielded about 75% of the current cultivars (Burton et al., 1993). Increased forage production with the newer cultivars suggests that reaching the genetic potential for yield may require more aggressive management. The objective of this research is to determine the impact of irrigation, nitrogen, and harvest interval on Tifton 85 bermudagrass hay yield and forage quality.

Materials and Methods

In the spring of 2007, Tifton 85 bermudagrass was sprigged under a 6 ha site-specific center-pivot irrigation system on a relatively uniform Norfolk loamy sand (Typic Kandiudult) near Florence, South Carolina. In 2008 and 2009, an experiment was conducted to determine the impact of irrigation and nitrogen on bermudagrass hay yield and forage quality. Irrigation rate, nitrogen rate, and harvest intervals were evaluated. There were four irrigation treatments (0%, 33%, 66%, and 100% irrigation). For each irrigation, the 100% irrigation treatment received a 12.5 mm application. The other irrigation treatments received a proportional application depth. In addition, each irrigation treatment had nitrogen treatments of 168, 336, and 504 kg N ha^{-1}. The irrigation and nitrogen treatments were harvested at four- or eight-week intervals. The experimental design was a split-plot with harvest interval as main plots and the irrigation by N levels as subplots. The plot size was 20 m wide × 20 m long with four replicates (96 total plots). All treatments remained in the same plots for both years.

Irrigation System

The center-pivot irrigation system had been modified in 1995 to permit variable applications to individual areas as small as 9.1 × 9.1 m. The center-pivot radial length was divided into 13 segments, each 9.1 m in length. In this study, we combined two adjacent segments to obtain an approximately 20 m wide plot. Variable-rate water applications were accomplished by using three manifolds in each segment, each with nozzles sized to deliver 1×, 2×, or 4× of a base application depth at their location along the center-pivot radius. The 12.7 mm irrigation rate we used was achieved when the outer tower was operated at 50% duty cycle. A more detailed description of the water delivery system may be found in Omary et al. (1997) and of the control system in Camp et al. (1998).

Fertilizer Applications

All nitrogen fertilizer was applied via fertigation through the center-pivot system in three annual split applications. In the spring, one-third of the total N per year for each treatment was applied at green-up, with the rest being applied in equal applications after the eight-week harvests. Low, medium, and high rates were 56, 112, and 168 kg N ha^{-1} per application. Total annual N application rates were 168, 336, and 504 kg N ha^{-1}. Phosphorus and K were uniformly applied in granular form across all plots each spring based on soil testing and recommendations of the Clemson University Extension Agricultural Service Laboratory. Fertilizer applied was 56 kg ha^{-1} P_2O_5 and 112 kg ha^{-1} K_2O in 2008, and 56 kg ha^{-1} P_2O_5 and 168 kg ha^{-1} K_2O in 2009.

Variable nitrogen fertilizer rates were applied using the center-pivot irrigation system and injecting UAN 30 into the incoming water stream at the base of the J tube. The UAN injection rate was varied proportionately based on the calculated water flow rate entering the pivot to achieve a constant UAN concentration in the water supplied to the pivot. This was achieved with a four-head, 24 VDC, variable-rate injection pump (model 40320, Ozawa R&D, Inc., Ontario, Ore.). The pump injection rate was controlled by varying the pump speed using a 0-5 VDC signal to the pump controller. The onboard computer controlling the variable-rate center-pivot system calculated the desired injection rate and the proper control voltage setting, and then set the appropriate control voltage for the pump controller. The entire system was run long enough in a non-plot area to achieve 1.5 complete system exchanges and bring the entire pivot volume up to the constant concentration being injected at the beginning of the pivot. The variable N rates on plots were then achieved by applying different water depths of this constant UAN concentration. Nitrogen applications were applied with the minimal water application depths in order to minimize irrigation water applications to non-irrigated plots. For this experiment, all nitrogen was delivered with either 3.6 mm of water at 50% duty cycle or 1.8 mm at 100%. At the end of the nitrogen application, the system was again run in non-plot area to purge the system of nitrogen.

SOIL WATER POTENTIAL MEASUREMENT

Soil water potentials (SWP) were measured in all irrigation treatments and harvest intervals for the high N rate using tensiometers at two depths (0.30 and 0.60 m). Measurements were recorded at least three times each week. The Norfolk loamy sand has a water holding capacity of approximately 2.54 cm in the surface 0.30 m. A SWP value of -30 kPa represents an approximately 50% depletion of the available water holding capacity. Irrigation was initiated when SWP at the 0.30 m depth was below -30 kPa in the 100% irrigation plot with high N. When the SWP decreased below -30 kPa, a 12.5 mm irrigation application was applied to the 100% irrigation treatments. The other irrigation treatments received a proportional application (0%, 33%, and 66% of 12.5 mm). Additionally, if the SWP decreased below -50 kPa, an additional 12.5 mm irrigation was applied if the rainfall forecast was less than 50%.

HARVEST

The bermudagrass hay was harvested at four- and eight-week intervals. In 2008, four-week harvests occurred on 27 May, 24 June, 21 July, 18 August, and 18 September. The eight-week hay harvests were on 24 June, 18 August, and 14 October. There was not a four-week harvest on 14 October because of a lack of growth in those plots. In 2009, the four-week hay harvests were on 22 June, 21 July, 17 August, 14 September, and 19 October. The 2009 eight-week harvests were on 22 June, 17 August, and 19 October. In 2009, the four-week bermudagrass treatments were delayed coming out of dormancy, so we postponed the initial harvest until June 2009 (eight weeks for this interval) to allow the crop to establish. Bermudagrass hay was harvested by cutting with a 3 m wide rotary mower/conditioner at an approximately 8 cm height with a single pass thorough the center of the plots. A length of the windrow 3 m long was then raked onto a small tarp and weighed using a hanging scale (HSDC-100 kg, Cardinal Scale Mfg., Webb City, Mo.). A small subsample was collected for moisture calculations, C and N analysis, and forage quality testing. The rest of the plot was then mowed, dried, raked, baled, and removed from the field. Collected subsamples were weighed on a scale (model 4040, Mettler Toledo, Columbus, Ohio) before and after drying. Samples were dried in an electric oven (Blue M model DC-1406E, SPX, Rochester, N.Y.) at 60°C.

FORAGE QUALITY ANALYSIS

After the bermudagrass subsample was dried, it was ground through a Wiley mill. Total N and carbon were measured using dry combustion and measurement with a Leco 2000 CNS analyzer (Leco Corp., St. Joseph, Mich.). Crude protein (CP) was estimated by multiplying N content by 6.25. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined sequentially at the Agricultural Service Laboratory (Clemson University, Clemson, S.C.). *In vitro* dry matter digestibility was determined using a Daisy incubator (ANKOM Technology, Macedon, N.Y.) as modified by Holden (1999).

STATISTICAL ANALYSES

All data were statistically analyzed in SAS (SAS Institute, Inc., Cary, N.C.) using a mixed model analysis. Each harvest in each year and total hay yield for the year were analyzed separately using the GLIMMIX procedure. Irrigation rate and N level were considered as fixed effects, and replicates were considered random. Using the ESTIMATE command in GLIMMIX, linear, quadratic, and deviation from quadratic effects were tested for irrigation, and linear and deviation from linear effects were tested for N.

RESULTS

HAY YIELDS

In 2008 and 2009, the mean bermudagrass hay yields for the rainfed treatments were 9.2 and 14.4 Mg ha^{-1}, respectively. Initial analysis indicated that the two years were significantly different, so we analyzed years separately. The differences between the years were mostly attributed to the differences in rainfall distribution. In 2008 and 2009, the total rainfall for the growing season was 701 and 522 mm, respectively. However, the rainfall distribution and irrigation applications were different for each growing season (table 1). In 2008, the rainfall occurred during the latter part of the growing season. In 2009, the rainfall occurred during the first part of the growing season. In August and September 2009, the monthly rainfall was below normal, and irrigation was required to meet crop demand. The total water applied was greater in 2008 than in 2009 due to the poor early season rainfall. In 2008, the 100% irrigation treatment received irrigation amounts of 152 mm and 191 mm for the four- and eight-week harvests, respectively. The corresponding 2009 100% irrigation treatments received 89 and 102 mm of irrigation for the four- and eight-week harvests, respectively.

IRRIGATION TREATMENTS

Irrigation generally increased bermudagrass hay yields both annually and across cutting intervals. Irrigation linear-

Table 1. Number of irrigations and rainfall for the 2008 and 2009 bermudagrass hay four- and eight-week harvest intervals over the irrigation treatments.

Harvest	Month 5		Month 6		Month 7		Month 8		Month 9		Month 10		Month Total	
Interval and Year	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)	No. of Irrig.	Rainfall (mm)
Four-week interval														
2008	2[a]	83	3	39	2	133	-	165	0	199	0	-	7	619
2009	-	-	0	251	0	97	-	63	2	29	5	82	7	522
Eight-week interval														
2008	-	-	11	122	-	-	4	299	-	-	0	281	15	701
2009	-	-	0	251	-	-	1	161	-	-	7	111	8	522

[a] The 100% irrigation treatment received 12.5 mm per irrigation. The other irrigation treatments received a percentage of that amount per irrigation.

Table 2. Mean 2008 and 2009 bermudagrass hay yields (kg ha^{-1}) for the four- and eight-week harvest intervals over the irrigation treatments.[a]

Harvest Interval and Year		Irrigation	Month						
			5	6	7	8	9	10	Total
Four-week interval	2008	0%	1552	664	1455	1904	3063	-	8638
		33%	1547	1151	1939	1570	3090	-	9297
		66%	1666	1332	2303	1546	3350	-	9893
		100%	1733	1450	2160	1352	2966	-	9504
		Linear	*	**	**	**	ns		**
		Quadratic	ns	*	ns	ns	ns		**
		Deviation from quadratic	ns	ns	ns	ns	ns		ns
	2009	0%	-	6986	3253	2441	733	1514	14927
		33%	-	6684	3003	2402	886	1734	14708
		66%	-	6328	2985	2605	812	2101	14831
		100%	-	7172	3055	2654	947	2293	16121
		Linear		ns	ns	ns	ns	**	ns
		Quadratic		*	ns	ns	ns	ns	ns
		Deviation from quadratic		ns			ns	ns	ns
Eight-week interval	2008	0%	-	2889	-	2789	-	4171	9755
		33%	-	3327	-	3036	-	4062	10426
		66%	-	3349	-	2749	-	3535	9658
		100%	-	3869	-	2819	-	3783	10446
		Linear		*		ns		ns	ns
		Quadratic		ns		ns		ns	ns
		Deviation from quadratic		ns		ns		ns	ns
	2009	0%	-	6000	-	5103	-	2710	13813
		33%	-	5481	-	5380	-	3248	14109
		66%	-	6188	-	4543	-	3624	14356
		100%	-	5439	-	5173	-	4313	14925
		Linear		ns		ns		**	ns
		Quadratic		ns		ns		ns	ns
		Deviation from quadratic		*		*		ns	ns

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference.

ly increased bermudagrass hay yields in five of ten four-week harvests and in two of six eight-week harvests. In 2008, the overall yearly four-week harvest hay yields were significantly linearly correlated with the irrigation treatments (table 2). Likewise, the individual four-week harvests were also positively linearly correlated with irrigation treatment for all harvest except the August 2008 harvest. The August harvest was negatively correlated to irrigation treatment. During the growth period for this harvest, no irrigation was applied because of plentiful rainfall. Additionally, the plant nitrogen removed in the hay had a similar negative trend, possibly indicating that 165 mm of rainfall during that harvest interval may have leached available N below the root zone.

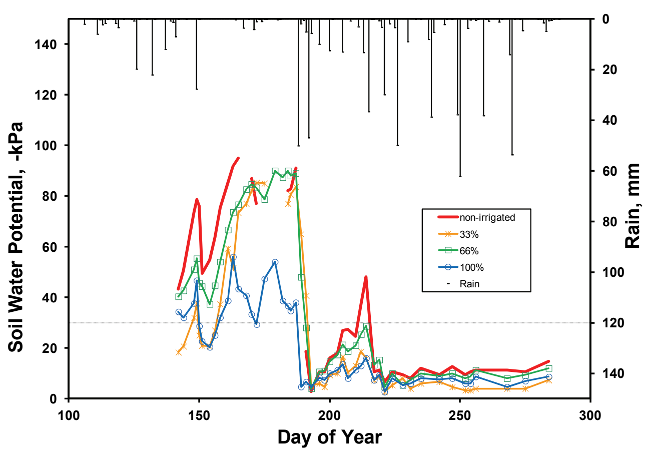

Figure 1. Soil water potentials for the 2008 four-week harvest interval, 30 cm irrigated bermudagrass.

During the first part of the 2008 growing season, rainfall totals were below normal, and irrigation was required to keep soil water levels at an adequate level. This corresponded to the observed low soil water potential values from May to July (DOY 142 to 191; fig. 1). Both the 30 and 60 cm deep soil water potentials followed the same trend (60 cm soil water potential; data not shown). During this time period, the 100% irrigation applications (12.5 mm per application) were generally not large enough to keep the 30 cm deep soil water potential less than -30 kPa, but soil water potential was still greater than -50 kPa and did not trigger the additional 12.5 mm irrigation.

The overall 2008 eight-week hay yields were not correlated to the irrigation treatments. Only in the first eight-week harvest in June 2008 did yield significantly increase with irrigation. Because of sufficient rainfall, the remaining two eight-week harvests were not correlated to irrigation treatments.

In 2009, the overall four- and eight-week hay yields were not correlated to the irrigation treatment. Only the October 2009 four- and eight-week harvests were correlated to irrigation treatment. The 2009 rainfall distribution was at or above normal for most of the early growing season. However in late August and September (DOY 225-272), the rainfall was well below normal. This low rainfall contributed to both the low observed soil water potentials (fig. 2) and the yield response to increasing amounts of irrigation.

Additionally, we plotted yield versus average soil water potential for the harvest period for both harvest intervals and each irrigation treatment across both years (figs. 3 and 4). For the four-week harvest interval, the non-irrigated

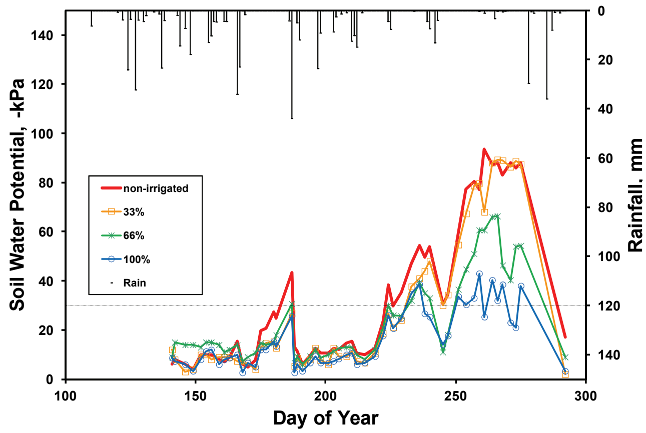

Figure 2. Soil water potentials for the 2009 four-week harvest interval, 30 cm irrigated bermudagrass.

soil water potentials were correlated to yield (r^2 = 0.68; fig. 3), but the irrigated soil water potentials were not (r^2 = 0.33, 0.31, and 0.44 for the 33%, 66%, and 100% treatments, respectively). The eight-week harvest intervals generally had slopes similar to the four-week harvest intervals (fig. 4). The eight-week non-irrigated SWP values were less correlated (r^2 = 0.49) than the four-week results. Interestingly, the non-irrigated four- and eight-week harvest intervals had similar slopes (-30.4 and -31.8 kg ha^{-1} kPa^{-1}, respectively). The eight-week irrigated SWP values had a very poor correlation to yield (r^2 = 0.29, 0.08, and 0.01 for the 33%, 66%, and 100% treatments, respectively), yet the 33% and 66% treatments had slopes similar to the four-week harvest interval. The poor correlations were also expected because the range of SWP values was much smaller and corresponded to the increasing irrigation application depth treatments.

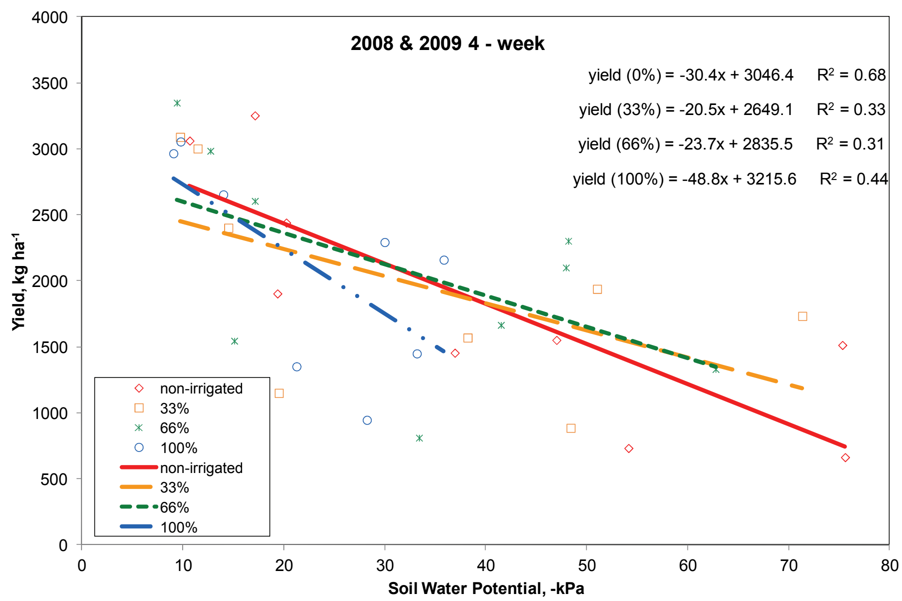

Figure 3. Bermudagrass hay yields as influenced by soil water potential for the four-week harvest intervals.

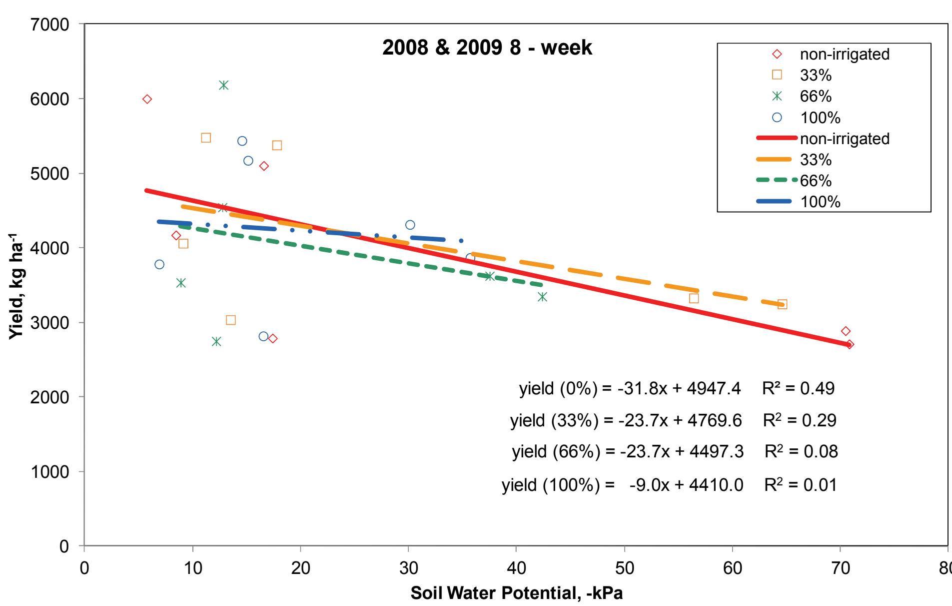

Figure 4. Bermudagrass hay yields as influenced by soil water potentials for the eight-week harvest intervals.

Table 3. Water use efficiency and irrigated water use efficiency for the 2008 and 2009 bermudagrass hay for the four- and eight-week harvest intervals over the irrigation treatments.[a]

Harvest and Year	Irrigation	Water Use Efficiency (kg ha^{-1} mm^{-1}) by Month: 5	6	7	8	9	10	Total	Irrigated Water Use Efficiency (kg ha^{-1} mm^{-1}) by Month: 5	6	7	8	9	10	Total
Four-week interval															
2008	0%	18.7	17.2	10.19	11.5	15.4	-	14.0	-	-	-	-	-	-	-
	33%	17.0	18.0	12.9	9.5	15.6	-	13.9	-0.6	19.5	28.5	-	-	-	13.2
	66%	16.7	15.0	13.8	9.4	16.9	-	13.8	6.7	13.4	24.9	-	-	-	12.4
	100%	16.0	12.6	11.7	8.2	14.9	-	12.3	7.2	10.3	13.8	-	-	-	5.7
2009	0%	-	27.9	33.4	38.5	25.4	18.4	28.6	-	-	-	-	-	-	-
	33%	-	26.7	30.8	37.9	23.8	16.8	26.7	-	-	-	-	19.1	10.5	-7.6
	66%	-	25.3	30.6	41.1	17.8	16.9	25.5	-	-	-	-	4.6	14.0	-1.6
	100%	-	28.6	31.4	41.9	17.4	15.7	26.4	-	-	-	-	8.6	12.2	13.4
Eight-week interval															
2008	0%	-	23.8	-	9.3	-	14.9	13.9	-	-	-		-	-	-
	33%	-	19.9	-	9.6	-	14.5	13.7	-	9.5	-	14.5	-	-	10.7
	66%	-	15.7	-	8.3	-	12.6	11.7	-	5.0	-	-1.2	-	-	-0.8
	100%	-	14.8	-	8.1	-	13.5	11.7	-	7.0	-	0.6	-	-	3.6
2009	0%	-	24.0	-	31.7	-	24.4	26.4	-	-	-	-	-	-	-
	33%	-	21.9	-	32.6	-	23.1	25.4	-	-	-	69.3	-	18.6	8.7
	66%	-	24.7	-	26.9	-	21.3	24.4	-	-	-	-70.0	-	15.5	8.1
	100%	-	21.7	-	29.8	-	21.6	23.9	-	-	-	5.4	-	18.0	10.9

[a] Irrigated water use efficiency was only calculated for those periods when irrigation was applied.

We also calculated the overall water use efficiency (WUE) of the bermudagrass hay crop (table 3). The overall annual four-week harvest interval WUE ranged from 12.3 to 28.6 kg ha^{-1} mm^{-1}, while the eight-week WUE values ranged from 11.7 to 26.4 kg ha^{-1} mm^{-1}. The WUE values were greater in 2009 than in 2008 because of higher 2009 yields. Our WUE values were similar to those reported by Garcia et al. (2008) of 12 to 24 kg ha^{-1} mm^{-1}. Additionally, for those harvest intervals that had irrigation applied, we calculated the irrigated water use efficiency (IWUE). The IWUE was calculated by subtracting the non-irrigated yield from the irrigated hay yield and dividing by the irrigation water applied. The annual IWUE for the four-week harvest interval ranged from -7.6 to 13.4 kg ha^{-1} mm^{-1}, and the annual IWUE for the eight-week harvest interval ranged from -0.8 to 10.9 kg ha^{-1} mm^{-1}. Negative IWUE values occurred during harvest intervals when little irrigation was applied and rainfall would have been sufficient. In the harvest intervals that had a significant increase in yield with irrigation, the IWUE values for the four-week 100% irrigation treatments ranged from 7.2 to 13.8 kg ha^{-1} mm^{-1}, and the IWUE values for the eight-week 100% irrigation treatments were 7.0 and 18 kg ha^{-1} mm^{-1}.

Nitrogen Rates

For both years and over both harvest intervals, the annual hay yields had a significant linear correlation to increasing N rate (table 4). Additionally, the 2008 four-week and 2009 eight-week harvest interval hay yields had significant deviation from the linear trend for increasing N rate. The correlation between increased N rate and yields has been observed in other studies (Burns et al., 1985; Mandebvu et al., 1999; Adeli et al., 2005; da Fonseca et al., 2007; Garcia et al., 2008; Alderman et al., 2011). For the individual four- and eight-week harvest intervals, all had linearly correlated yield increases with increasing N rates. Only the four-week

Table 4. Mean 2008 and 2009 bermudagrass hay yields (kg ha^{-1}) for the four- and eight-week harvest interval over the nitrogen treatments.[a]

Harvest Interval and Year		Nitrogen Applied (kg N ha^{-1})	Month: 5	6	7	8	9	10	Total
Four-week interval	2008	Low (168)	1273	673	1245	1421	1989	-	6601
		Medium (336)	1701	1038	2225	1527	3422	-	9913
		High (504)	1899	1737	2422	1907	3941	-	11842
		Linear	**	**	**	**	**		**
		Deviation from linear	ns	ns	ns	ns	**		*
	2009	Low (168)	-	5579	2330	2026	304	1307	11545
		Medium (336)	-	7023	3200	2373	951	1964	15510
		High (504)	-	7777	3692	3178	1278	2461	18386
		Linear		**	**	**	**	**	**
		Deviation from linear		ns	ns	ns	ns	ns	ns
Eight-week interval	2008	Low (168)	-	2679	-	1969	-	2537	7185
		Medium (336)	-	3300	-	3109	-	4045	10445
		High (504)	-	4097	-	3617	-	5081	12975
		Linear		**		**		**	**
		Deviation from linear		ns		ns		ns	ns
	2009	Low (168)	-	4817	-	3853	-	2172	10843
		Medium (336)	-	6275	-	5275	-	3669	15219
		High (504)	-	6239	-	6022	-	4580	16841
		Linear		**		**		**	**
		Deviation from linear		*		ns		ns	**

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference.

harvest in September 2008 and the eight-week harvest in June 2009 had significant deviations from linear response.

HARVEST INTERVALS

Harvest intervals did not have a significant impact on the annual bermudagrass hay yields. In 2008, the four- and eight-week hay yields were 9.3 and 10.1 Mg ha^{-1}, respectively. In 2009, the four- and eight-week hay yields were 15.1 and 14.3 Mg ha^{-1}, respectively. The most noticeable difference between the harvest intervals was for the June, August, and October harvests. Since nitrogen fertilizer was applied at eight-week intervals, these harvests were typically lower in yield than the May, July, and September harvests, possibly due to lower available N.

More four-week harvests than eight-week harvests had significant yield increases with irrigation. This could be the result of short-term droughts (7 to 20 days). Sheridan et al. (1979) documented that there was a 50% chance of a 20-day drought annually in the southeastern Coastal Plain. A drought of this length would more likely impact a 28-day harvest interval than a 56-day harvest interval. In North Carolina, Stone et al. (2008) reported on the impact of several short-term drought periods on bermudagrass production and found similar trends in hay yields.

HAY NITROGEN REMOVAL

The overall combined bermudagrass hay plant nitrogen concentrations over both years and cutting intervals ranged from 1.70% to 1.72% and were not significantly different when analyzed across irrigation application rates. When analyzed across nitrogen application rates, the plant nitrogen concentrations were significantly different ($p = 0.05$). The plant nitrogen concentrations were 1.9%, 1.7%, and 1.5% for the high, medium, and low nitrogen application rates, respectively. In analyzing the individual harvests, the four-week harvests tended to have higher concentration for the first harvest after nitrogen application (tables 5 and 6) (May, July, and September). However, for the second four-week harvest after nitrogen application (June, August, and October), the plant N concentrations were similar to the eight-week harvest N concentrations. The N application rate treatments almost always had significantly different N concentrations for all individual harvests. The irrigation application rates for the individual harvests did not generally have significantly different plant N concentrations. Typically, only the 0% irrigation treatment had significantly lower plant N concentrations than the other irrigation treatments. For the four-week harvest, the plant N concentration had a significant linear trend with irrigation for the August 2008 harvest, and both linear and quadratic trends occurred in July 2008 and October 2009. The bermudagrass hay N concentrations for this study were lower than those reported by Burns et al. (1985) of 2.2% to 2.9% using lagoon effluent at higher N application rates (338 to 1340 kg ha^{-1}). Stone et al. (2008) reported plant N concentrations ranging from 1.93% to 2.25% for bermudagrass fertilized with treated swine wastewater at N application rates ranging from 280 to 300 kg ha^{-1}.

Table 5. Mean 2008 and 2009 bermudagrass hay plant nitrogen concentration and mass nitrogen removed for the four- and eight-week harvest intervals over the irrigation treatments.[a]

Harvest and Year	Irrigation	Plant Nitrogen (%) by Month 5	6	7	8	9	10	Plant Nitrogen (kg ha^{-1}) by Month 5	6	7	8	9	10	Total
Four-week interval														
2008	0%	1.8	1.5	2.5	1.6	2.3	-	28.7	10.4	38.0	30.0	72.4	-	179.5
	33%	2.0	1.6	2.1	1.6	2.3	-	32.6	19.0	43.1	25.9	72.0	-	192.6
	66%	1.9	1.6	2.2	1.7	2.3	-	32.1	21.9	51.5	26.7	78.7	-	210.9
	100%	1.9	1.6	2.2	1.7	2.2	-	33.4	22.8	47.8	22.6	67.7	-	194.3
	Linear	ns	ns	**	**	ns		ns	**	ns	*	ns		
	Quadratic	ns	*	**	ns	ns		ns	**	ns	ns	ns		
	Deviation from quadratic	**	ns	ns	ns	ns		ns	ns	ns	ns	ns		
2009	0%	-	1.2	2.2	1.9	2.5	1.9	-	85.0	71.3	47.0	19.4	30.5	253.2
	33%	-	1.2	2.2	1.9	2.5	1.8	-	80.3	66.1	47.2	23.8	33.1	250.5
	66%	-	1.2	2.2	1.9	2.6	1.8	-	76.0	68.0	49.9	21.8	38.8	254.5
	100%	-	1.2	2.3	1.9	2.6	1.9	-	88.0	72.0	50.6	25.5	42.9	279.0
	Linear		ns	ns	ns	ns	*		ns	ns	ns	ns	*	
	Quadratic		*	ns	ns	ns	**		ns	ns	ns	ns	ns	
	Deviation from quadratic		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	
Eight-week interval														
2008	0%	-	1.0	-	1.2	-	1.5	-	29.3	-	33.7	-	65.6	128.6
	33%	-	1.2	-	1.2	-	1.6	-	38.8	-	37.2	-	66.4	142.4
	66%	-	1.0	-	1.2	-	1.5	-	33.2	-	36.1	-	55.4	124.7
	100%	-	1.0	-	1.2	-	1.5	-	37.9	-	31.1	-	60.0	129.0
	Linear		ns		ns		ns		ns		ns		ns	
	Quadratic		ns		ns		ns		ns		ns		ns	
	Deviation from quadratic		ns		ns		ns		ns		ns		ns	
2009	0%	-	1.3	-	1.2	-	1.9	-	79.0	-	64.1	-	51.7	194.8
	33%	-	1.3	-	1.2	-	1.6	-	72.2	-	67.4	-	51.9	191.5
	66%	-	1.2	-	1.3	-	1.7	-	76.6	-	58.0	-	62.9	197.5
	100%	-	1.3	-	1.3	-	1.6	-	69.4	-	66.7	-	70.9	207.0
	Linear		ns		ns		**		ns		ns		*	
	Quadratic		ns		ns		*		ns		ns		ns	
	Deviation from quadratic		ns		ns		**		ns		*		ns	

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference.

Table 6. Mean 2008 and 2009 bermudagrass hay plant nitrogen concentration and mass nitrogen removed for the four- and eight-week harvest intervals over the nitrogen treatments.[a]

Harvest and Year	Nitrogen Applied (kg N ha^{-1})	Plant Nitrogen (%) by Month						Plant Nitrogen (kg ha^{-1}) by Month						Total
		5	6	7	8	9	10	5	6	7	8	9	10	
Four-week interval														
2008	Low (168)	1.6	1.5	2.0	1.5	2.0	-	20.4	10.0	25.4	21.7	39.3	-	116.8
	Medium (336)	1.9	1.6	2.3	1.6	2.2	-	32.4	18.0	51.3	24.7	77.1	-	203.5
	High (504)	2.2	1.7	2.4	1.8	2.6	-	42.3	28.9	58.6	34.1	101.7	-	265.6
	Linear	**	ns	ns	**	**		**	**	ns	**	**		
	Deviation from linear	**	**	*	**	**		**	**	*	**	**		
2009	Low (168)	-	1.1	1.9	1.8	2.3	1.7	-	61.6	44.0	36.9	7.4	22.8	172.7
	Medium (336)	-	1.2	2.2	1.9	2.5	1.8	-	85.7	68.3	45.3	23.8	36.1	259.2
	High (504)	-	1.3	2.6	2.0	2.9	2.0	-	99.6	95.7	63.9	36.6	50.0	345.8
	Linear		ns	**	**	**	**		**	**	**	**	**	
	Deviation from linear		**	**	**	**	**		**	**	**	**	**	
Eight-week interval														
2008	Low (168)	-	1.0	-	1.1	-	1.4	-	27.9	-	22.4	-	34.9	85.2
	Medium (336)	-	1.0	-	1.1	-	1.4	-	31.9	-	34.4	-	58.7	125.0
	High (504)	-	1.1	-	1.3	-	1.8	-	44.7	-	47.0	-	91.9	183.6
	Linear		ns		**		**		**		**		**	
	Deviation from linear		ns		**		**		**		**		**	
2009	Low (168)	-	1.1	-	1.2	-	1.6	-	52.5	-	45.1	-	33.7	131.3
	Medium (336)	-	1.2	-	1.2	-	1.6	-	76.1	-	65.3	-	58.2	199.6
	High (504)	-	1.5	-	1.4	-	1.9	-	94.3	-	81.7	-	86.3	262.3
	Linear		**		**		**		**		**		**	
	Deviation from linear		**		**		**		**		**		**	

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference.

At each harvest, the mass N removed in the bermudagrass hay ranged from 10 to 88 kg ha^{-1} and was generally not significantly different across irrigation treatments. Only two harvest dates in 2008 and one in 2009 had significantly different mass N removal rates due to irrigation rate (table 5); these harvest dates corresponded to dates with significant irrigation trends. For the N rate treatments, the mass N removal rates had positive significant trends with increasing N application rate for all harvest except the July 2008 four-week harvest. The overall annual N removal rates across all treatments averaged 196 kg ha^{-1}. The N removal rates ranged from 125 to 279 kg ha^{-1} across the irrigation rate treatments. For the nitrogen application rate treatments, the annual N removal rates ranged from 85 to 346 kg ha^{-1}. Stone et al. (2008) reported similar N mass removal rates for treated swine wastewater ranging from 120 to 261 kg ha^{-1}. In a study with swine effluent N application rates ranging from 200 to 600 kg ha^{-1}, Adeli et al. (2003) reported similar annual N removal rates ranging from 265 to 302 kg ha^{-1}. In a study with much higher swine effluent application rates (338 to 1340 kg ha^{-1}), Burns et al. (1985) reported N removal rates ranging from 338 to 1340 kg ha^{-1}.

Forage Quality

The overall crude protein (CP) concentrations averaged 12.1% for the four-week harvest interval and 8.3% for the eight-week harvest interval. Lower CP concentrations for the eight-week harvest interval were also reported by Mandebvu et al. (1999). They observed that CP concentrations decreased with increasing harvest intervals. For the irrigation application rate treatments, there was little difference among CP concentrations for the individual harvests. Only three of the four-week harvests in 2008 and the final harvest in 2009 (four- and eight-week harvests) had any significant trends in CP concentrations. These trends with irrigation application corresponded to the significant trends in irrigation treatments with yield. The trend during these harvest dates tended to be reduced CP with increasing irrigation application rate. For the N application rate treatments, the CP was highly significant and followed the trend of increasing CP with increasing N application. Woodard and Sollenberger (2011) observed a similar trend of increased CP with increased N application on bermudagrass hay production in the Lower Suwannee River basin in northern Florida.

The mean acid detergent fiber (ADF) concentrations ranged from 26.3% to 35% (tables 7 and 8). Mandebvu et al. (1999) reported similar ADF concentrations in bermudagrass. Our individual harvests had some significant differences. The harvests with significant differences were for the most part after eight weeks of growth (either the eight-week or the second four-week harvest). The first four-week harvest, after N application, was not significant for any harvest date for either the irrigation or N treatments. The overall trend for those harvest dates with significant differences tended to be increasing ADF with increasing N application rate. The trends in ADF with irrigation application are shown in table 7. Several of the harvest dates with significant ADF/irrigation trends corresponded to those with significant irrigation/yield trends.

The mean neutral detergent fiber (NDF) concentrations ranged from 59% to 72.3% (tables 7 and 8). As with the ADF results, significant differences occurred for NDF in individual harvests. Again, the harvests with significant differences were for the most part after eight weeks of growth (either the eight-week or the second four-week harvest intervals). The NDF concentrations tended to decrease with increasing N application rate. As with ADF, the significant NDF/irrigation trends corresponded with significant irrigation/yield trends.

Table 7. Mean 2008 and 2009 bermudagrass hay quality measurements for the four- and eight-week harvest intervals over the irrigation treatments.[a]

Harvest		ADF (%) by Month						NDF (%) by Month						TDN (%) by Month						CP (%) by Month					
and Year	Irrigation	5	6	7	8	9	10	5	6	7	8	9	10	5	6	7	8	9	10	5	6	7	8	9	10
Four-week interval																									
2008	0%	30.0	27.8	28.7	28.8	28.6	-	61.8	64.3	65.1	68.7	64.2	-	67.6	70.2	68.7	69.1	68.9	-	11.4	9.5	15.8	9.8	14.2	-
	33%	30.0	27.9	29.8	28.9	28.5	-	62.1	65.5	67.0	69.2	64.1	-	67.5	70.1	67.7	68.9	69.0	-	12.4	10.0	13.1	10.2	14.1	-
	66%	29.9	28.4	29.7	28.2	28.5	-	62.1	65.5	66.9	68.0	63.2	-	67.7	69.5	67.7	69.6	69.0	-	11.7	10.1	13.6	10.7	14.4	-
	100%	29.9	28.8	29.5	27.8	28.5	-	62.0	66.1	67.8	68.0	63.3	-	67.7	69.1	67.9	70.2	69.0	-	12.0	9.8	13.6	10.6	14.1	-
	Linear	ns	**	ns	**	ns		ns	**	**	*	ns		ns	**	ns	**	ns		ns	ns	**	**	ns	
	Quadratic	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	*	**	ns	ns	
	Dev. quad.	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		**	ns	ns	ns	ns	
2009	0%	-	33.3	29.8	31.5	26.4	29.2	-	66.0	62.3	66.4	59.0	64.3	-	64.4	67.6	65.9	71.2	68.4	-	7.5	13.7	11.8	15.7	12.2
	33%	-	32.9	30.0	32.0	26.8	30.3	-	66.1	63.0	66.2	59.5	64.6	-	64.8	67.4	65.3	70.8	67.2	-	7.4	13.5	12.0	15.9	11.4
	66%	-	32.6	29.4	31.3	26.3	29.4	-	65.8	62.5	66.4	59.3	65.0	-	65.1	68.0	66.2	71.3	68.3	-	7.5	13.8	11.9	16.2	11.3
	100%	-	33.3	30.1	32.0	26.3	29.8	-	66.3	62.8	66.9	59.3	63.9	-	64.3	67.2	65.3	71.2	67.8	-	7.6	14.5	11.8	16.2	11.6
	Linear		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	ns	*
	Quadratic		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		*	ns	ns	ns	**
	Dev. quad.		ns	ns	ns	ns	**		ns	ns	ns	ns	ns		ns	ns	ns	ns	**		ns	ns	ns	ns	ns
Eight-week interval																									
2008	0%	-	31.3	-	34.5	-	32.2	-	66.7	-	71.9	-	67.6	-	66.6	-	63.0	-	65.4	-	6.1	-	7.5	-	9.4
	33%	-	31.8	-	34.6	-	31.6	-	67.3	-	72.4	-	67.2	-	66.0	-	62.8	-	65.9	-	7.2	-	7.4	-	10.0
	66%	-	32.2	-	33.8	-	31.4	-	68.0	-	71.7	-	67.0	-	65.7	-	63.7	-	66.2	-	6.1	-	7.4	-	9.6
	100%	-	32.8	-	33.5	-	31.1	-	68.7	-	71.4	-	66.5	-	65.0	-	64.2	-	66.6	-	5.9	-	7.2	-	9.6
	Linear		**		ns		**		**		ns		**		**		ns		**		ns		ns		ns
	Quadratic		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns
	Dev. quad.		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns
2009	0%	-	31.7	-	34.9	-	31.4	-	63.8	-	67.3	-	64.8	-	66.1	-	62.5	-	66.0	-	8.2	-	7.8	-	11.6
	33%	-	32.0	-	35.0	-	31.5	-	65.3	-	67.4	-	65.0	-	65.7	-	62.4	-	66.0	-	8.1	-	7.8	-	10.0
	66%	-	31.7	-	34.5	-	32.6	-	64.6	-	67.1	-	64.5	-	66.1	-	62.9	-	64.8	-	7.6	-	7.9	-	10.6
	100%	-	31.7	-	33.4	-	32.1	-	64.6	-	66.2	-	65.3	-	66.1	-	64.1	-	65.4	-	8.0	-	8.1	-	10.1
	Linear		ns		*		ns		ns		ns		ns		ns		*		ns		ns		ns		**
	Quadratic		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		*
	Dev. quad.		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		ns		**

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference. ADF = acid detergent fiber, NDF = neutral detergent fiber, TDN = total digestible nutrient, CP = crude protein, and Dev. quad. = deviation from quadratic.

Table 8. Mean 2008 and 2009 bermudagrass hay quality measurements for the four- and eight-week harvest intervals over the irrigation treatments.[a]

Harvest		ADF (%) by Month						NDF (%) by Month						TDN (%) by Month						CP (%) by Month					
and Year	Nitrogen	5	6	7	8	9	10	5	6	7	8	9	10	5	6	7	8	9	10	5	6	7	8	9	10
Four-week interval																									
2008	Low	29.9	28.8	29.1	29.2	28.3	-	62.6	65.4	67.0	69.7	63.5	-	67.8	69.2	68.5	68.7	69.4	-	9.9	9.2	12.8	9.6	12.4	-
	Medium	30.2	27.8	29.3	27.7	28.4	-	62.0	65.2	66.4	67.8	63.8	-	67.4	70.2	68.0	70.2	69.2	-	11.9	10.1	14.4	10.2	14.0	-
	High	29.7	28.1	29.8	28.4	28.9	-	61.5	65.5	66.7	68.0	63.8	-	67.7	69.8	67.4	69.4	68.3	-	13.8	10.4	14.9	11.2	16.1	-
	Linear	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns		ns	ns	ns	*	*		**	ns	ns	**	**	
	Dev. linear	ns	**	ns	**	ns		**	ns	ns	**	ns		ns	**	ns	**	*		**	**	*	**	**	
2009	Low	-	32.7	29.5	30.9	26.6	30.4	-	66.0	62.9	66.2	59.5	64.7	-	65.1	68.2	66.6	71.0	67.2	-	6.8	11.7	11.3	14.4	10.7
	Medium	-	32.8	29.6	31.4	26.3	29.9	-	66.4	62.2	66.2	59.3	64.8	-	64.9	67.8	66.0	71.3	67.7	-	7.6	13.6	11.9	15.7	11.5
	High	-	33.6	30.4	32.7	26.4	28.8	-	65.7	62.8	67.0	59.0	63.8	-	64.0	66.7	64.5	71.0	68.9	-	8.1	16.4	12.5	18.0	12.7
	Linear		ns	ns	**	ns	**		ns	ns	**	ns	**		ns	*	**	ns	**		ns	**	**	**	**
	Dev. linear		ns	ns	**	ns	**		ns	ns		ns	ns		ns	*	**	ns	**		**	**	**	**	**
Eight-week interval																									
2008	Low	-	31.2	-	32.7	-	30.4	-	67.3	-	72.0	-	66.9	-	66.7	-	65.0	-	67.5	-	6.3	-	6.8	-	8.6
	Medium	-	32.0	-	34.6	-	31.9	-	67.7	-	72.3	-	67.3	-	65.9	-	62.9	-	65.8	-	6.0	-	7.1	-	9.0
	High	-	32.8	-	35.0	-	32.5	-	67.9	-	71.4	-	67.0	-	64.9	-	62.3	-	64.9	-	6.7	-	8.1	-	11.2
	Linear		*		ns		ns		ns		ns		ns		*	ns	ns	ns	*		ns		**		**
	Dev. linear		**		**		**		ns		ns		ns		**	ns	*	ns	**		ns		**		**
2009	Low	-	31.7	-	34.7	-	31.7	-	65.0	-	67.9	-	65.3	-	66.1	-	62.8	-	65.9	-	6.8	-	7.3	-	9.8
	Medium	-	32.0	-	35.0	-	32.3	-	64.8	-	67.3	-	65.2	-	65.7	-	62.4	-	65.2	-	7.7	-	7.8	-	10.0
	High	-	31.5	-	33.8	-	31.8	-	63.9	-	65.8	-	64.3	-	66.1	-	63.7	-	65.5	-	9.5	-	8.5	-	11.9
	Linear		ns		ns		ns		*		**		**		ns		ns		ns		**		**		**
	Dev. linear		ns		ns		ns		ns		**		ns		ns		ns		ns		**		**		**

[a] * and ** indicate contrast was significant at $p < 0.10$ and 0.05, respectively; ns indicates no significant difference. ADF = acid detergent fiber, NDF = neutral detergent fiber, TDN = total digestible nutrient, CP = crude protein, and Dev. linear = deviation from linear.

The total digestible nutrient (TDN) concentrations that were significant were generally the same as those significant for ADF and NDF (tables 7 and 8). There was no overall trend in TDN concentrations for the individual harvest dates. The mean TDN concentrations ranged from 62.3% to 71.3%. Like ADF and NDF, the TDN/irrigation treatments with significant trends were also those with significant irrigation/yield trends. Unlike ADF and NDF, the TDN trends tended to be in the opposite direction of the irrigation/yield trends. Our CP, ADF, NDF, and TDN concentrations were similar to those recommended for targeted nutrient concentrations for dairy rations by Texas Agricultural Extension Service (Stokes and Prostko, 1998) and those reported by Mandebvu et al. (1999).

CONCLUSIONS

We conducted a two-year study to investigate the response of bermudagrass hay production to irrigation and nitrogen application rates. In both years, when irrigation was required to maintain soil water potentials greater than -30 kPa, bermudagrass hay yields significantly increased with increasing water application rate. The four-week 100% irrigation treatments increased mean yields by 612 kg ha^{-1} per cutting over the non-irrigated treatment, and the eight-week 100% irrigation treatment increased mean yields by 1600 kg ha^{-1} per cutting. Additionally, for the non-irrigated bermudagrass hay yields, we observed a linear relationship between hay yield and soil water potential.

Non-irrigated hay yields were shown to decrease (-31 kg ha^{-1} kPa^{-1}) as soil water was depleted. For harvest dates with significant irrigation/yield trends, plant N concentration, plant N removal, ADF, NDF, and TDN almost all had significant trends with irrigation application rates. Increasing nitrogen application rates significantly increased bermudagrass hay yield, nutrient concentrations, and forage quality. Both nitrogen and irrigation were found to positively impact bermudagrass hay production. Bermudagrass can benefit from timely supplemental irrigation applications to boost yields and maintain forage quality. Bermudagrass irrigation management to maintain soil water potentials above -30 kPa can increase yields and sustain production levels in the southeastern Coastal Plain.

References

Adeli, A., J. J. Varco, and D. E. Rowe. 2003. Swine effluent irrigation rate and timing effects on bermudagrass growth, nitrogen and phosphorus utilization, and residual soil nitrogen. *J. Environ. Qual.* 32(2): 681-686.

Adeli, A., J. J. Varco, K. R. Sistani, and D. E. Rowe. 2005. Effects of swine lagoon effluent relative to commercial fertilizer applications on warm-season forage nutritive value. *Agron. J.* 97(2): 408-417.

Alderman, P. D., K. J. Boote, and L. E. Sollenberger. 2011. Regrowth dynamics of Tifton 85 bermudagrass as affected by nitrogen fertilization. *Crop Sci.* 51(4): 1716-1726.

Ashley, D. A., O. L. Bennett, B. D. Doss, and C. E. Scarsbrook. 1965. Effect of nitrogen rate and irrigation on yield and residual nitrogen recovery by warm-season grasses. *Agron. J.* 57(4): 370-372.

Burns, J. C., P. W. Westerman, L. D. King, G. A. Cummings, M. R. Overcash, and L. Goode. 1985. Swine lagoon effluent applied to Coastal bermudagrass: I. Forage yield, quality, and element removal. *J. Environ. Qual.* 14(1): 9-14.

Burton, G. W., G. M. Prine, and J. E. Jackson. 1957. Studies of drought tolerance and water use of several southern grasses. *Agron. J.* 49(9): 498-503.

Burton, G. W., J. L. Butler, and R. E. Hellwig. 1987. Effect of supplemental irrigation on the yield of coastal bermudagrass in the southeastern United States. *Agron. J.* 79(3): 423-424.

Burton, G. W., R. N. Gates, and G. M. Hill. 1993. Registration of Tifton 85 bermudagrass. *Crop Sci.* 33(3): 644-645.

Camp, C. R., E. J. Sadler, D. E. Evans, L. J. Usrey, and M. Omary. 1998. Modified center-pivot irrigation system for precision management of water and nutrients. *Applied Eng. in. Agric.* 14(1): 23-31.

da Fonseca, A. F., A. J. Melfi, F. A. Monteiro, C. R. Montes, V. V. d. Almeida, and U. Herpin. 2007. Treated sewage effluent as a source of water and nitrogen for Tifton 85 bermudagrass. *Agric. Water Mgmt.* 87(3): 328-336.

Doss, B. D., O. L. Bennett, D. A. Ashley, and H. A. Weaver. 1962. Soil moisture regime effect on yield and evapotranspiration from warm-season perennial forage species. *Agron. J.* 54(3): 239-242.

Garcia, S. C., W. J. Fulkerson, and S. U. Brookes. 2008. Dry matter production, nutritive value, and efficiency of nutrient utilization of a complementary forage rotation compared to a grass pasture system. *Grass Forage Sci.* 63(3): 284-300.

Holden, L. A. 1999. Comparison of methods of *in vitro* dry matter digestibility for ten feeds. *J. Dairy Sci.* 82(8): 1791-1794.

Mandebvu, P., J. W. West, G. M. Hill, R. N. Gates, R. D. Hatfield, B. G. Mullinix, A. H. Parks, and A. B. Caudle. 1999. Comparison of Tifton 85 and coastal bermudagrasses for yield, nutrient traits, intake, and digestion by growing beef steers. *J. Animal Sci.* 77(6): 1572-1586.

Marsalis, M. A., V. G. Allen, C. P. Brown, and C. J. Green. 2007. Yield and nutritive value of forage bermudagrasses grown using subsurface drip irrigation in the southern High Plains. *Crop Sci.* 47(3): 1246-1254.

Muir, J. P., B. D. Lambert, A. Greenwood, A. Lee, and A. Riojas. 2010. Comparing repeated forage bermudagrass harvest data to single, accumulated bioenergy feedstock harvests. *Bioresour. Tech.* 101(1): 200-206.

Omary, M., C. R. Camp, and E. J. Sadler. 1997. Center-pivot irrigation system modification to provide variable water application depths. *Applied Eng. in. Agric.* 13(2): 235-239.

Sheridan, J. M., W. G. Knisel, T. K. Woody, and L. E. Asmussen. 1979. Seasonal variation in rainfall and rainfall-deficit periods in the southern Coastal Plain and Flatwoods regions of Georgia. Bulletin 243. Athens, Ga.: University of Georgia Agricultural Experiment Station.

Stokes, S. R., and E. Prostko. 1998. Understanding forage quality analysis. College Station, Tex.: Texas agricultural Extension Service, Texas A&M University. Available at: http://lubbock.tamu.edu/files/2011/10/forageanalysis_6.pdf.

Stone, K. C., P. G. Hunt, J. A. Millen, M. H. Johnson, T. A. Matheny, M. B. Vanotti, and J. C. Burns. 2008. Forage subsurface drip irrigation using treated swine wastewater. *Trans. ASABE* 51(2): 433-440.

Stone, K. C., P. G. Hunt, K. B. Cantrell, and K. S. Ro. 2010. The potential impacts of biomass feedstock production on water resource availability. *Bioresour. Tech.* 101(6): 2014-2025.

USDA-ERS. 2011. State fact sheets. Available at: www.ers.usda.gov/StateFacts/. Washington, D.C.: USDA Economics Research Service.

Westerman, P. W., M. R. Overcash, R. O. Evans, L. D. King, J. C. Burns, and G. A. Cummings. 1985. Swine lagoon effluent applied to Coastal bermudagrass: III. Irrigation and rainfall runoff. *J. Environ. Qual.* 14(1): 22-25.

Woodard, K. R., and L. E. Sollenberger. 2011. Broiler litter vs. ammonium nitrate as nitrogen source for bermudagrass hay production: Yield, nutritive value, and nitrate leaching. *Crop Sci.* 51(3): 1342-1352.