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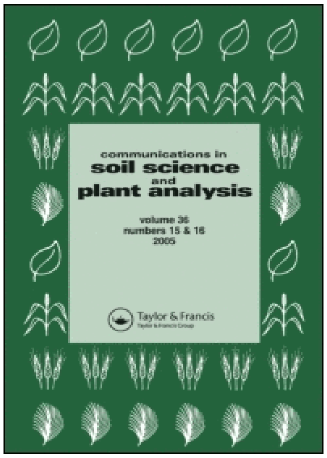

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Use of In-Season Reflectance for Predicting Yield Potential in Bermudagrass

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Abstract: Spatial variability of soil nutrients is known to exist at distances of less than 1 m. Recently, an on-the-go system for application of nitrogen (N) fertilizer based on spectral measurements known as in-season estimated yield (INSEY) improved N use efficiency (NUE) by as much as 17% in winter wheat. Six trials were conducted in 2001, 2002, and 2003 at Ardmore and Burneyville, OK, with an objective to develop an index similar to INSEY for use in predicting yield potential in bermudagrass (*Cynodon dactylon* L.) that can be used for adjusting fertilizer N rates. Initial results indicate that 55% of variation in predicted bermudagrass forage yield was explained by a Bermudagrass–INSEY (B-INSEY) index and 54% of the variation in forage N uptake was explained using the normalized difference vegetative index (NDVI). The remaining challenge is to develop appropriate N fertilizer rates based on this information and apply these rates using on-the-go technology.

Keywords: Bermudagrass, in-season estimated yield (INSEY), normalized difference vegetation index (NDVI), NUE, spectral indices

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INTRODUCTION

During the past few decades, the largest increase in the use of agricultural inputs has been fertilizer N (Johnston 2000). Because many plant nutrients are nonrenewable and depleting rapidly, efficient use of applied fertilizers is important in these times of high production costs and environmental concern. Currently, N-use efficiency for worldwide cereal production is estimated to be 33% (Raun and Johnson 1999) and for forage production, around 45%. The general production practice is to apply most of the N based on a yield goal early in the spring. Johnson (1991) suggested that in order to take the advantage of the above-average growing conditions in dryland agriculture, it is better to set the yield goal above that of average yields. Yield goal is the "yield per acre you hope to grow," clearly indicating the risk the farmer is taking when he calculates the amount of fertilizer for the crop before production (Dahnke et al. 1988). Usually, fertilizer rates are defined by a specified yield goal, taking into account available soil N (Raun et al. 2001).

Osborne et al. (1999) reported that though yield increased with increasing rates of N fertilizer, N-fertilizer recovery levels in bermudagrass were greatest (85%) at N rates less than 224 kg N ha^{-1}, and recovery was less than 20% when 1344 kg N ha^{-1} was applied. Mathias, Bennett, and Lundberg (1978) reported that bermudagrass yields and N concentration increased, whereas percent recovery decreased with rising N applications up to 448 kg N ha^{-1}.

The presence of spatial variability in agricultural landscapes is an issue demanding careful consideration for efficient use of fertilizers. One approach to increase fertilizer-use efficiency is variable rate technology (VRT). Carr et al. (1991) investigated economic efficiency of uniform fertilizer rates for the whole field versus variable rates for dryland wheat in accordance with soil units that had different crop yield potential. They showed positive returns of \$53.57–58.10 kg^{-1} when optimum treatments for a specific soil were applied rather than uniform rates for the whole field. Although soil units and satellite images distinguish field elements by nutrient availability, their separation is rather poor (coarse scale), which results in low efficiency of variable versus uniform application.

Nitrogen-use efficiency is also complicated by cropland spatial variability that is known to exist at resolutions smaller than 1 m^2 (Solie et al. 1996; Raun et al. 1998). Raun et al. (1998) and Solie et al. (1999) reported that variability exists in 0.3-m by 0.3-m bermudagrass plots with regard to the availability of nutrients. The same work reported that variable fertilizer treatment of crops, where each field element is treated separately, can be an effective alternative to the existing uniform fertilizer application practices. Nitrogen fertilizer requirements depend on the potential N uptake by the crop and are related to the overall yield potential. Potential yield is the yield that can be produced on a specific soil under specific weather conditions, and that changes with time (Raun et al. 2001).

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Cabrera and Kissel (1988) made fertilizer N recommendations based on N mineralized from organic matter. According to Rodriguez and Miller (2000), there was a positive linear relationship between total Kjeldahl nitrogen (TKN) and near-infrared reflectance spectroscopy (NIRS). Spectral radiance measurements were evaluated by Sembiring et al. (1998) to identify optimum wavelengths for dual detection of N and P status in bermudagrass when 0, 112, 224, and 336 kg N ha^{-1} and 0, 29, or 58 kg P ha^{-1} were applied in a factorial arrangement of treatments. Biomass, N uptake, P uptake, and N concentration could be predicted using 695/405 nm, with 435 nm as a covariate. Taylor et al. (1998) reported that correlation of forage yield and N removal with red, near infrared (NIR), and normalized difference vegetative index (NDVI) were best with maximum forage production; however, when forage production levels were low, correlation decreased dramatically for the red wavelength compared with NIR and NDVI.

Crawford, Kennedy, and Johnson (1961) reported that the stage of growth, level of N fertilization, plant part, and light intensity all influenced NO_3-N concentration, whereas cultivar, source, time, and method of placement had no effect in forages. Kincheloe (1994) reported that field practices should be site specific and the areas within the field should be categorized to be best management practices (BMP). He defined BMPs as those practices that have been tested in research and proven on farmers' fields as most effective in terms of input efficiency, production potential, and environmental protection.

In-season knowledge of potential yield might be the key to successful variable rate fertilizer applications. Raun et al. (2001) demonstrated that the estimated yield (EY) index was a good predictor of grain yield over a wide range of environmental conditions in winter wheat. Raun et al. (2002) later refined this index, where only one NDVI reading is taken postdormancy, divided by only those days where growing degree days are positive $GDD > 0$ (including this environmental factor eliminates the days where growth is not possible) from planting to the date of sensing, and named it in-season estimate of yield (INSEY). The same work showed that yield potential based on midseason estimates increased NUE by 15% when compared to the uniform rates, and this was attributed to collecting readings from each 1 m^2 and fertilizing each 1 m^2, recognizing that the spatial variability exists at 1-m^2 resolutions and that the potential yield of each 1 m^2 is different.

The objective of this study is to develop an index similar to INSEY for wheat for use in predicting forage yield potential in bermudagrass, which can later be used for adjusting fertilizer N.

MATERIALS AND METHODS

Two field experiments with minimum fertilization located at Burneyville (Minco silt loam, coarse-silty, mixed, superactive, thermic Udic Haplustolls) and Ardmore (Wilson silt loam, fine, smectitic, thermic oxyaquic Vertic

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Haplustalfs), Oklahoma, were initiated in April 2001. These were previously established pastures with "Midland" bermudagrass. The experiments were laid out in a randomized complete block design with eight treatments and three replications. The plots received urea-N rates of 0, 56, 112, 168, and 224 kg N ha^{-1} broadcast applied early in the spring at the time of breaking dormancy (last week of March to first week of April).

Plot sizes were 3.04 m − 6.08 m with 3.04-m alleys. Phosphorus (P) and potassium (K) were broadcast applied as per soil-test recommendations at both sites at the initiation of the experiment. During early March of each year, a mix of LoVol 6, Pendimax, was used to control weeds. Initial soil-test data and dates of activities are reported in Tables 1 and 2, respectively.

Sensor readings were collected for 3 years at both locations at the time of harvest for each cutting and during in-season growth for most cuttings. In-season readings were collected following at least 10–14 days of active growth (around 3 inches of height). Spectral reflectance measurements during 2001 from the bermudagrass canopy was measured using a handheld sensor that was developed at Oklahoma State University, which included two upward- and two downward-looking photodiode sensors that collected readings in two bands, red (671 ± 6 nm) and near infrared (780 ± 6 nm) bandwidths during 2001 (Stone et al. 1996b). The reflectance sensor employed photodiode detectors with inference filters. One pair of filters (up-looking) received incoming light from the sun, and the other pair (down-looking) received light reflected by vegetation and/or soil surface. The instrument used a built-in 16-bit A/D converter that converted the signals from all four photodiode sensors simultaneously. The ratio of readings from down-looking to up-looking photodiodes allowed the elimination of fluctuation among readings due to differences in atmospheric conditions and shadows. During 2002 and 2003, sensor readings were taken using a GreenSeeker® handheld optical sensor (NTech Industries, Inc.) to measure crop reflectance and calculate the NDVI. This sensor is an active sensor (which means it has its own self-contained illumination in the both red [$650 + 10$ nm full-width half magnitude] and NIR [$77 + 15$ nm]). When held at a distance of approximately 60 cm to 100 cm above the crop, it senses an area of 60 cm × 10 cm.

Table 1. Initial surface (0–15 cm) soil chemical characteristics and classification at Ardmore and Burneyville, OK

Location	pH[a]	NH_4-N[b] (mg kg^{-1})	NO_3-N[b] (mg kg^{-1})	P[c] (mg kg^{-1})	K[c] (mg kg^{-1})
Ardmore	5.2	9.4	1.5	56	225
Burneyville	5.7	10.5	2.6	30	187

[a]pH: 1:1 soil–water.
[b]NH_4-N and NO_3-N: 2 M KCl extraction.
[c]P and K: Mehlich III extraction.

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Table 2. Dates for field activities carried out at Ardmore and Burneyville, OK, during the 2001–2003 cropping seasons

	Ardmore			Burneyville		
Field activity	2001	2002	2003	2001	2002	2003
Dormancy fertilization	Mar. 23	Apr. 10	Apr. 3	Mar. 23	Apr. 10	Apr. 3
1st sensor reading	May 22	May 15	May 8	May 22	May 15	May 8
1st harvest	Jun. 20	May 15	Jun. 19	Jun. 20	May 15	Jun. 19
2nd sensing	Jun. 20	Jun. 04	Jun.19	Jun. 20	Jun. 4	Jun. 19
3rd sensing	Jul. 10	Jul. 12	Aug. 1	Jul. 10	Jul. 12	Aug. 1
2nd harvest	Aug. 10	Oct. 02	Oct. 27	Aug. 10	Jul. 12	Sep. 3
4th sensing	Aug. 10	Aug. 09	Sep. 3	Aug. 10	Aug. 9	Sep. 3
5th sensing	Oct. 2	—	Oct. 27	Oct. 2	—	Oct. 27
Final harvest	Oct. 2	—	—	Oct. 2	Oct. 2	Oct. 27

This device measures reflectance, which is the fraction of emitted light in the sensed area that is returned to the sensor (Raun et al. 2005). NDVI is calculated based on the following formula:

$$\mathrm{NDVI} = \frac{(\mathrm{NIRref}/\mathrm{NIRinc}) - (\mathrm{REDref}/\mathrm{REDinc})}{(\mathrm{NIRref}/\mathrm{NIRinc}) + (\mathrm{REDref}/\mathrm{REDinc})}$$

where NDVI is as defined above; $\mathrm{NIR}_{\mathrm{ref}}$ and $\mathrm{NIR}_{\mathrm{inc}}$ are reflected and incident NIR light, respectively; and REDref and REDinc are reflected and incident red light, respectively.

When the bermudagrass was at or near morphological stage of 41 to 49 (anthesis) as defined by West (1990), the forage was harvested. Caution was taken to collect harvest data prior to anthesis because the grass turns a pale color after this stage and there are increased chances of underestimating N uptake, thus altering the N content in the grass. Forage was harvested in the center of each plot using a John Deere (GT 262) lawn mower, with a cutting width of 96.52 cm and a forage collection device attached. Forage samples were weighed for fresh weight and subsampled for moisture content at the time of harvest. The samples were then dried for 48 h in a forced air oven at 70°C and ground to pass a 0.125-mm (120-mesh) sieve.

The total forage N content was analyzed using a Carlo-Erba (Milan, Italy) NA-1500 dry-combustion analyzer (Schepers, Francis, and Thompson 1989). Early-season plant N uptake was determined by multiplying dry-matter yield by the total N concentration determined from dry combustion. The difference method (N removed in the check plot subtracted from the N removed in the

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fertilized plot divided by the amount of fertilizer N applied) was used to determine NUE.

Data was analyzed using Microsoft Excel and SAS (SAS 2001). Growing degree days were calculated by subtracting the base temperature from the daily average minimum and maximum temperatures (Table 3). The minimum temperature at which a plant can grow is called the base temperature (Eastin and Sullivan 1984), which for bermudagrass is 10°C:

$$\mathrm{B-INSEY} = \frac{\mathrm{NDVI}}{\sum \mathrm{GDD}},$$

$$\mathrm{GDD} = \frac{\mathrm{TEMPmax} + \mathrm{TEMPmin}}{2} - 10^{\circ}\mathrm{C}$$

where B-INSEY is in-season estimate of Bermudagrass forage yield.

At each trial, an N-rich strip (N applied at a rate when N would not be limiting through out the growth cycle) was established, and 336 kg N ha^{-1} was applied at the time of breaking of dormancy, followed by 224 kg N ha^{-1} applied after every harvest until September.

RESULTS AND DISCUSSION

Individual Year

In 2001, NDVI measurements collected at the time of harvest at Burneyville and Ardmore (three and two harvests, respectively) were

Table 3. Cropping period, GDD, and GDD > 0 data used at Ardmore and Burneyville

Location	Year	Cutting	Cropping period (days)[a]	GDD > 0[b]	ΣGDD[c]
Ardmore	2001	1	66	38	686
	2002	2	57	19	374
	2003	1	65	23	437
Burneyville	2001	1	66	38	903
	2001	2	51	20	591
	2002	2	57	19	394
	2003	1	65	23	432
	2003	2	75	43	1377

[a]Cropping period: The time between the two harvests.

[b]GDD > 0: The number of days where growing degree days are positive for the period between previous harvest-breaking dormancy and the sensing date.

[c]ΣGDD: Cumulative GDD from previous harvest/breaking dormancy until sensing date.

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highly correlated with forage N uptake (Figure 1). This demonstrates that the amount of N present in forage can be predicted using NDVI at the time of sensing, which is consistent with early work by Stone et al. (1996a), who showed that NDVI was highly correlated with wheat forage N uptake. Further, the sensor readings taken 15–20 days after breaking dormancy and after the first cutting when the grass was around 7–9 cm high were adjusted for cumulative GDD to determine the B-INSEY index. This index was significantly and positively correlated with forage yield (Figure 2). However, it should be noted that this 2001 database was not robust.

The relationship between NDVI and forage N uptake in 2002 is reported in Figure 3. It should again be noted that these NDVI readings were collected on the same day that harvest data was collected. For this year, the relationship between NDVI and forage N uptake at Ardmore behaved in a different manner because of a high weed infestation but still had the same trend, only lower yields (data not shown). The first cutting came up very early, so it was not possible to correlate B-INSEY with forage yield using the first cutting. B-INSEY was correlated with the second harvest, and 38% of the variation in bermudagrass forage yield was explained (Figure 4).

In 2003, the relationship between NDVI and forge N uptake was strong ($R^2 = 0.65$) for data over all site years except the first cutting at Ardmore (Figure 5). Similar to Ardmore in 2002, the first cutting data set behaved a little differently than the others, having a lower correlation. Using data from only the first cutting, B-INSEY was highly correlated with forage yield ($R^2 = 0.92$, data not shown).

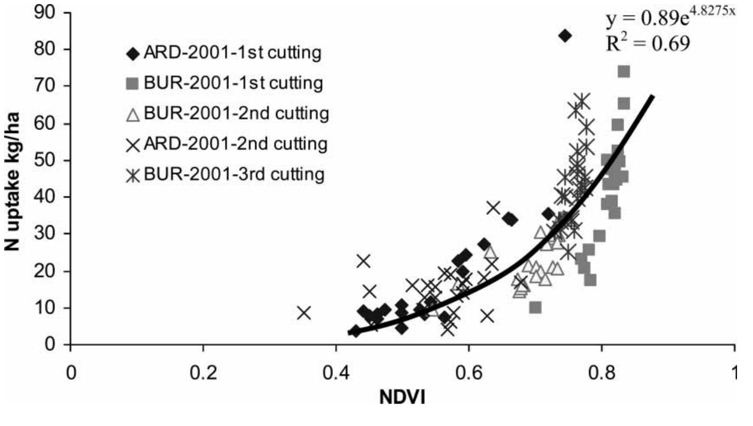

Figure 1. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001 at Burneyville and Ardmore, OK.

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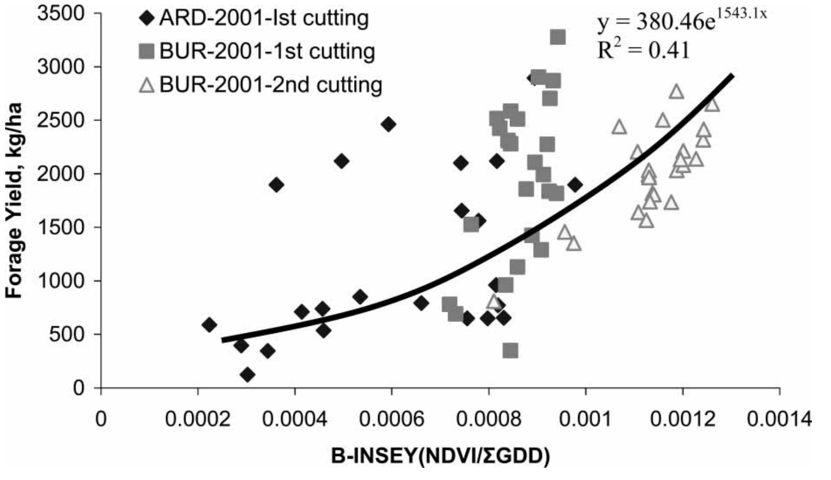

Figure 2. Relationship between forage yield and B-INSEY in 2001 at Burneyville and Ardmore, OK.

Combined Site Years

Over sites and years, these trials demonstrate that spectral reflectance measurements taken midseason (B-INSEY with forage yield across seven site years between harvests) coupled with cumulative GDD can be used for predicting the forage yield in bermudagrass ($R^2 = 0.55$, Figure 6). This tells us that we can predict forage yield potential for each harvest when we sense inseason. Nitrogen forage uptake with NDVI also showed a positive

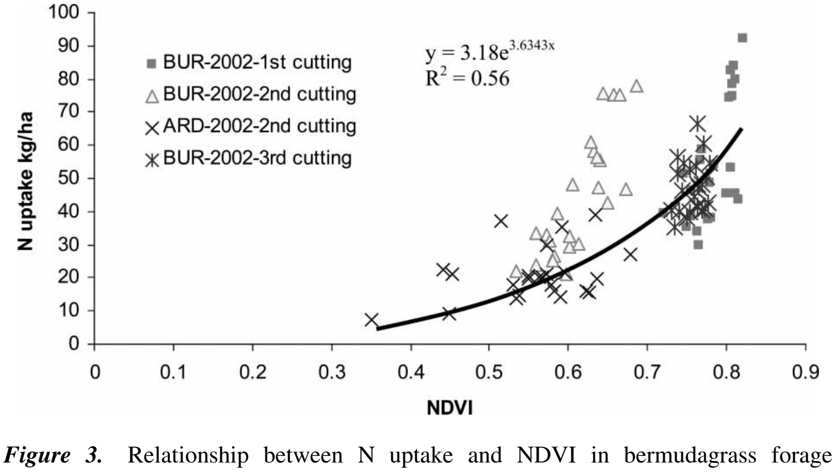

Figure 3. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2002 at Burneyville and Ardmore, OK.

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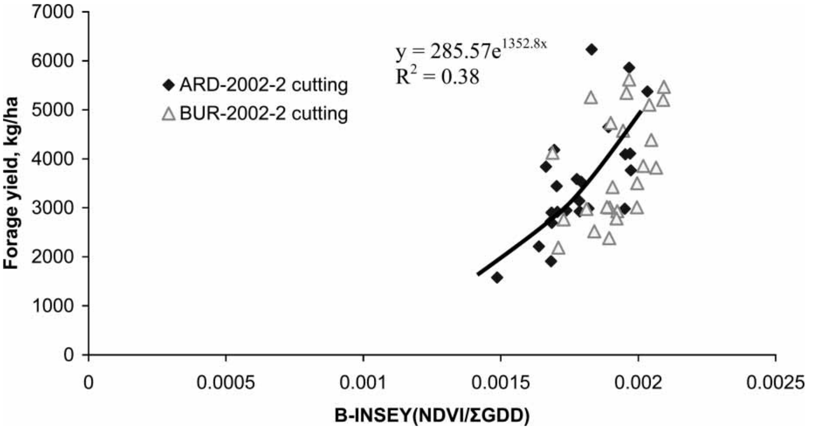

Figure 4. Relationship between forage yield and B-INSEY in bermudagrass forage collected at the time of harvest in 2002 at Burneyville and Ardmore, OK.

correlation ($R^2 = 0.43$) across 12 site years (Figure 7). When problematic weedy site years (Ardmore) were excluded, 54% of the variation in forage N uptake was explained (Figure 8). Cumulative growing degree days from dormancy to midseason and midseason sensing followed by subsequent harvests provided a reliable estimate for predicting forage yield in bermudagrass after eliminating the problematic two site years at Ardmore. Cumulative growing degree days worked in bermudagrass, contrary to wheat (Raun et al. 2001), because it is a warm season crop and most of the days are warmer than the temperature growth requirement once it breaks dormancy, and no days are

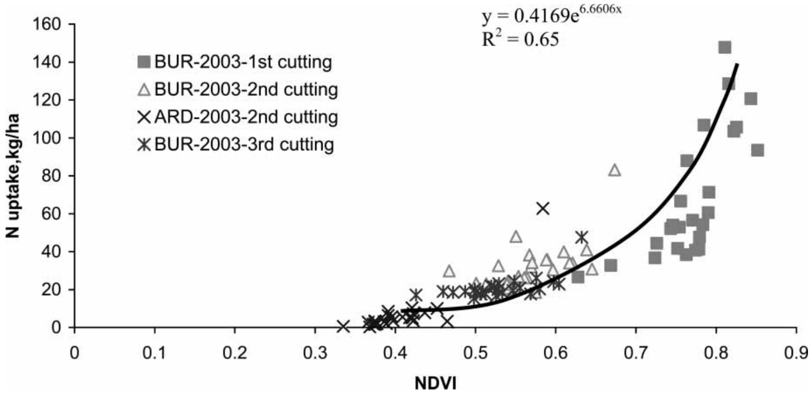

Figure 5. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest without Ardmore first cutting in 2003 at Burneyville and Ardmore, OK.

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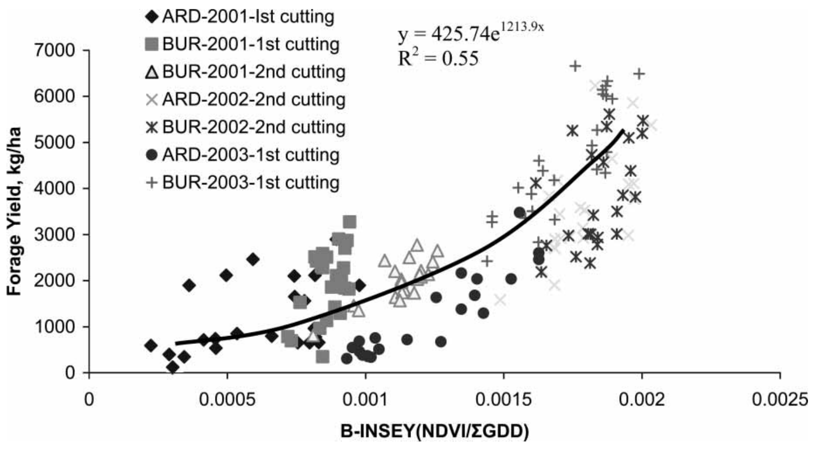

Figure 6. Relationship between B-INSEY and forage yield in bermudagrass forage collected at the time of harvest in all site years at Burneyville and Ardmore, OK.

cool enough to have no growth take place. Either way, it was difficult to use either the ΣGDD or days where GDD>0 because if moisture became a limiting factor and there was no growth for a long period of time, ΣGDD or days where GDD>0 would not account for the lack of growth when moisture was limiting. Thus moisture availability combined with GDD would likely be ideal. If more in-season sensor readings are available along with rainfall and soil moisture data, the prediction confidence increases using these components. Even without the moisture component and enough

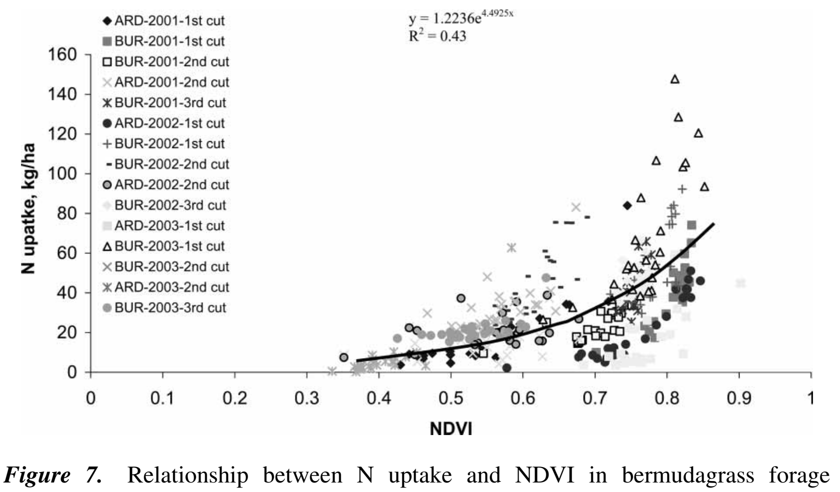

Figure 7. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in all site years at Burneyville and Ardmore, OK.

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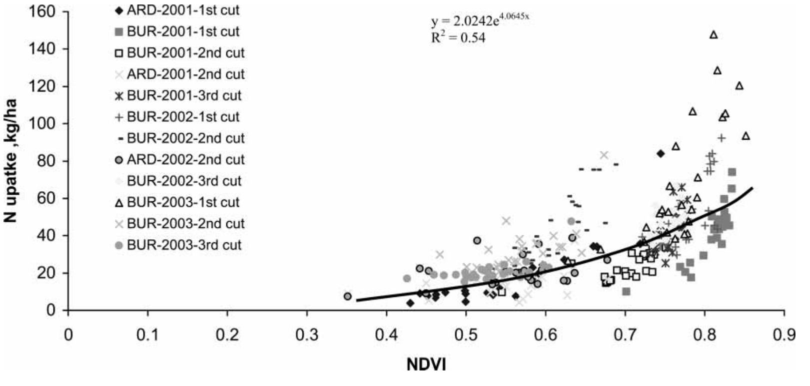

Figure 8. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in all site years (removing the bad sites) at Burneyville and Ardmore, OK.

readings throughout the growing season, it was exciting to see that most of the variation in forage yield was explained by the B-INSEY index.

CONCLUSIONS

The NDVI was highly correlated with forage N uptake in bermudagrass for most of the harvest dates, excluding the first cutting at Ardmore. The B-INSEY (calculated using cumulative GDDs) index was also highly correlated with final dry-matter forage yield when evaluated over locations and years. The problem with this research is determining the correct time to apply fertilizer. The grass should have sufficient growth (at least 2–3 inches of growth) to make accurate recommendations. This research shows potential in managing the temporal variability that occurs from year to year and harvest to harvest within a bermudagrass field. It was exciting to find that prediction of bermudagrass forage yield could be accomplished using a single sensor measurement. Rainfall combined with profile moisture needs to be incorporated into the yield. Also, added work is needed to document the minimum amount of regrowth needed to guarantee reliable prediction of yield.

REFERENCES

Cabrera, M.L. and Kissel, D.E. (1988) Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. *Soil Sci. Am. J.*, 52: 1027–1031

Carr, P.M., Carlson, G.R., Jacobsen, J.S., Nielsen, G.A., and Skogley, E.O. (1991) Farming soils, not fields: A strategy for increasing fertilizer profitability. *J. Prod. Agric.*, 4 (1): 57–61.

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Crawford, R.F., Kennedy, W.K., and Johnson, W.C. (1961) Some factors that affect nitrate accumulation in forages. *Agron. J.*, 53: 159–162.

Dahnke, W.C., Swenson, L.J., Goos, R.J., and Leholm, A.G. (1988) Choosing a crop yield goal. North Dakota State Ext. Ser. SF-822. Fargo, N.D.: North Dakota University.

Eastin, J.D. and Sullivan, C.Y. (1984) Environmental stress influences on plant physiology and production. In *Physiological Basis of Crop Growth and Development*; Tesar, M.B. (ed.); CSSA and ASA: Madison, Wisc., 201–213.

Johnson, G.V. (1991) General model for predicting crop response to fertilizers. *Agron. J.*, 83: 367–373.

Johnston, A.E. (2000) Efficient use of nutrients in agricultural production systems. *Commun. Soil Sci. Plant Anal.*, 31: 1599–1620.

Kincheloe, S. (1994) Tools to aid management: The use of site specific management. *J. Soil Water Conserv.*, 49 (2): 43–47.

Mathias, E.L., Bennett, O.L., and Lundberg, P.E. (1978) Fertilization effects on yield and N concentration of Midland bermudagrass. *Agron. J.*, 70: 973–976.

Osborne, S.L., Raun, W.R., Johnson, G.V., Rogers, J.L., and Altom, W. (1999) Bermudagrass response to high nitrogen rates, sources, and season of application. *Agron. J.*, 91: 438–444.

Raun, W.R. and Johnson, G.V. (1999) Improving nitrogen use efficiency for cereal production. *Agron. J.*, 91: 357–363.

Raun, W.R., Johnson, G.V., Stone, M.L., Solie, J.B., Lukina, E.V., and Thomason, W.E. (2001) In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agron. J.*, 93: 131–178.

Raun, W.R., Solie, J.B., Freeman, K.W., Stone, M.L., Martin, K.L., Johnson, G.V., and Mullen, R.W. (2005) Growth stage, development, and spatial variability in corn evaluated using optical sensor readings. *J. Plant Nutr.*, 28: 173–182.

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E., and Lukina, E.V. (2002) Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agron. J.*, 94: 815–820.

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Whitney, R.W., Lees, H.L., Sembiring, H., and Phillips, S.B. (1998) Micro-variability in soil test, plant nutrient, and yield parameters in bermudagrass. *Soil Sci. Soc. Am. J.*, 62: 683–690.

Rodriguez, I.R. and Miller, G.L. (2000) Using near infrared reflectance spectroscopy to schedule nitrogen applications on dwarf-type bermudagrasses. *Agron. J.*, 92: 423–427.

SAS Institute. 2001. *SAS/STAT user's guide, release 8.1.* Cary, N.C.: SAS Institute.

Schepers, J.S., Francis, D.D., and Thompson, M.T. (1989) Simultaneous determination of total C, total N and 15 N on soil and plant material. *Commun. Soil Sci. Plant Anal.*, 20: 949–959.

Sembiring, H., Raun, W.R., Johnson, G.V., Stone, M.L., Solie, J.B., and Phillips, S.B. (1998) Detection of nitrogen and phosphorus nutrient status in bermudagrass using spectral radiance. *J. Plant Nutr.*, 21: 1189–1206.

Solie, J.B., Raun, W.R., and Stone, M.L. (1999) Submeter spatial variability of selected soil and bermudagrass production variables. *Soil Sci. Soc. Am. J.*, 63: 1724–1733.

Solie, J.B., Raun, W.R., Whitney, R.W., Stone, M.L., and Ringer, J.D. (1996) Optical sensor based field element size and sensing strategy for nitrogen application. *Trans. ASAE*, 39 (6): 1983–1992.

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Stone, M.L., Solie, J.B., Raun, W.R., Whitney, R.W., Taylor, S.L., and Ringer, J.D. (1996a) Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Trans. ASAE*, 39 (5): 1623–1631.

Stone, M.L., Solie, J.B., Whitney, R.W., Raun, W.R., and Lees, H.L. (1996b) Sensors for detection of nitrogen in winter wheat. SAE Technical Paper No. 961757. SAE: Warrendale, Penn.

Taylor, S.L., Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., and Whitney, R.W. (1998) Use of spectral radiance for correcting nitrogen deficiencies and estimating soil test variability in an established bermudagrass pasture. *J. Plant Nutr.*, 21: 2287–2302.

West, C.P. (1990) A proposed growth stage system for bermudagrass. In *Proceedings of American Forage and Grassland Conference*, Blacksbury, VA. 6–9 June 1990. American Forage and Grass Council: Georgetown, TX.