THE EFFECTIVENESS OF SENSOR BASED TECHNOLOGY TO DETERMINE NITROGEN DEFICIENCIES IN TURFGRASSES

By

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INTRODUCTION

Sensor based technology as a supplement for soil or tissue testing to determine nutrient levels has received a large amount of attention in recent years. However, much of the recent research has been done on crops and production forages. The purpose of this research is to examine the potential for expanding this technology into the turfgrass industry. The turfgrass industry is a multi-billion dollar industry not only in the United States but the world over. In areas where turf is intensively managed a large portion of the maintenance budget goes toward the application of fertilizer and other chemicals. These costs are often higher than necessary because managers apply nutrients over the entire turf area at a constant rate designed to meet the needs of the most deficient portion. If this new sensor technology proves to have the ability to sense nutrient deficiencies, areas of poor turf, and determine the cause of these problems, it would give the turf managers the potential to treat only those areas. Therefore, they would be able to cut the cost of their maintenance budget while at the same time be able to improve their maintenance practices. These advances would also help the turfgrass industry show that its turf managers are interested in becoming better environmental stewards, since applications in excess of plant requirements would be minimized.

This new sensor technology is based on the measurement of radiant spectra reflected from the turf canopy. The purpose of this research is to determine the wavelengths or index of wavelengths that are directly linked to or associated with the presence of nitrogen deficiencies in two species of Bermudagrass (Cynodon dactylon (L.) and Cynodon dactylonXtransvaalensis (L.)) and 'SR1020' Bentgrass (Agrostis palustris (L.)). The key wavelengths examined in this research are red (670nm), green (550nm), and near-infrared (780nm).

LITERATURE REVIEW

Soil testing is currently the method most widely used to measure and detect soil nutrient availability. This is a reliable method of identifying deficiencies but, the results from such tests only provide an estimate of the average soil test nutrient level for the area sampled, which does not address the variability encountered in that area (Raun et al., 1998). Also, for nutrients like nitrogen (N) availability in the soil changes in relation to plant uptake and soil conditions during a growing season. Soil samples are usually obtained to represent areas of several hectares in size. Wibawa et al. (1993) evaluated spatial soil fertility variation using a grid sampling technique to generate a soil map of each field in their experiment. Results showed that variations in soil NO_3-N existed over short distances in a 15 m^2 grid. Penney et al. (1996) also looked at nutrient variability in the soil by sampling 20 to 25 ha fields using a 67 m x 67 m grid. This study revealed large variations in NO_3-N and indicated that a constant rate of N fertilization would result in an over fertilization of areas with high N content and an under fertilization of areas with low N content. Raun et al. (1998) used this approach to grid sample the soil in a 2.13 by 21.33m area of established bermudagrass forage in 0.30 by 0.30 m cells. Results showed that real differences in both soil test and yield parameters could be detected among cells within a distance of one meter. Penney et al. (1996) stated that the cost of intensive grid sampling is high and alternative methods are needed for mapping the spatial variability of soil nutrients. This information indicates we need a more efficient means of determining nutrient availability in small areas across a landscape.

There have been many studies conducted that have researched the usefulness of spectral reflectance at different wavelengths to detect soil variables, such as soil N content. Marten et al. (1985) indicated that scientists are able to identify plant composition as a result of the reflectance caused by the light-absorption characteristics of H bonding in organic components of forage. Dalal and Henry (1986) researched the use of near infrared diffuse reflectance spectrophotometry (NIR) to simultaneously predict moisture, organic C, and total N contents of air-dried soils. They indicated this is possible because the NIR spectral region is dominated by weak overtones and combinations of vibrational bands of light atoms that have strong molecular bonds. Examples listed were chemical bonds that contain H attached to atoms such as N, O, or C. Morra et al. (1991) stated that each constituent of a complex organic mixture has unique absorption properties in the NIR spectral region of the spectrum (700-2500 nm). They indicated that this was due to stretching and bending vibrations of molecular bonds between elements.

Birth and McVey (1968) developed a two-wavelength reflectance ratio R745/R675 for an objective index of turf color. They found that this ratio provided a very high positive correlation with visual ratings of the turf. Birth and McVey (1968) found that 10% of the reflectance of high quality turf was in the green (550 nm) part of the spectrum and 30% in the far red (750 nm) region. Thomas and Gausman (1977) indicated that leaf reflectance in the visible wavelength interval is influenced primarily by the pigments chlorophyll and carotenoid. Thomas and Oerther (1972) found that reflectance was inversely correlated with leaf N content. Results showed that leaf reflectance could be used for quick estimate of the N status of sweet peppers. Wood et al. (1992) investigated the possibility of using field chlorophyll measurements to evaluate N status in corn. They suggested that leaf chlorophyll may aid in predicting the N requirement for crops, because it is directly related to leaf N concentration. Blackmer et al. (1994) found that reflectance at 550 nm was the best wavelength to separate N treatment differences in corn leaves. This study indicated that the measurement of light reflectance near 550 nm has promise as a technique to detect N deficiencies in corn leaves. Walberg et al. (1982) researched the difference in reflectance patterns of healthy and stressed crop canopies. They determined that red reflectance was increased and NIR reflectance was decreased from N-deprived canopies. Hinzman et al. (1986) investigated the relationships between spectral and agronomic variables in wheat. This research found that N fertilization reduced visible, increased NIR, and decreased middle infrared reflectance. They indicated that these changes were related to lower levels of chlorophyll and reduced leaf area in the nonfertilized plots.

Variable rate technology (VRT) is a field that has received much attention in recent years as a means of changing production inputs to increase yields and help prevent contamination of the environment. Sensor based variable rate technology (s-VRT) is a field that is being explored intensively at Oklahoma State University. On-the-go sensing using s-VRT is still futuristic according to Sawyer et al. (1994). Sawyer et al. (1994) stated that in order for on-the-go sensing along with instantaneous adjustments in application to become a reality and widely adopted, measurements must be correlated to crop response. Stone et al. (1996) demonstrated that sensor based systems are capable of detecting nutrient variability. The sensor based system developed by Oklahoma State University uses an embedded computer and photodiode sensors with interference filters for red (671+/- 6 nm) and near infrared (NIR, 780 +/- 6 nm) to obtain spectral radiance (Stone et al., 1996b). The measurements obtained from these wavelengths are then used to calculate the normalized-difference-vegetative-index (NDVI) which is defined by the equation (NIR-red)/(NIR+red). NDVI was highly correlated with the plant nitrogen uptake in wheat (Stone et al., 1996a).

Perry and Lautenschlager (1984) researched the usefulness of many spectral indices for assessing vegetation characteristics such as species, leaf area, stress, and biomass. One of these indices which they referred to as ND6 was similar, and likely the predecessor to NDVI. They were looking at data produced by the multispectral scanner (MSS) onboard the Landsats satellite which measures the reflectance of the scene in four wavelength intervals (channels) in the visible and NIR portions of the spectrum. Channel 4 (CH4) contained the green (500-600 nm) portion of the spectrum, channel 5 (CH5) contained the red (600-700 nm) portion and channels 6 (CH6) and 7 (CH7) contained the NIR (CH6 700-800 nm and CH7 800-1100 nm). ND6 was defined by the equation (CH6-CH5)/(CH6+CH5). Becker et al. (1988) noted that NDVI is sensitive to chlorophyll absorption. It has been indicated that green normalized vegetative index (GNDVI) is better at detecting nitrogen status in plants than NDVI when the plants do not exhibit N stress symptoms (unpublished data, personal conversation with Dr. James Schepers, University of Nebraska). GNDVI differs from the previously described NDVI in that green (550 nm) radiance is substituted for red.

OBJECTIVE

The objectives of this study were two-fold: (1) to develop an understanding of the spectral reflectance relationships to nitrogen content, chlorophyll content and growth rate of bermudagrass and bentgrass species and (2) to investigate the potential for removing variations in color by applying nitrogen to correct deficiencies identified by spectral measurement indices.

MATERIALS AND METHODS

This research was completed in three separate stages over a period of two years. Stage one was completed in 1997 at four different sites. This stage involved exploratory work to gain experience and a basic understanding of how reflectance measurements and turf parameters responded to differential available soil nitrogen (N). This early work helped guide the project in a more effective manner for the intensive work of later stages. Stage two was completed in 1998 at three different sites and measured the effect of N rate on spectral and turf characteristic data. Stage three was conducted in 1998 at two sites. This stage was designed to evaluate the effectiveness of the spectrometer and associated NDVI indices to detect N deficiencies. The NDVI values, and there relationship to the values of turf quality parameters (% tissue N, visual ratings, and N-fertilizer rates) were used to identify N-fertilizer to correct deficiencies. Turf response to N fertilizer from a single conventional application rate (49 kg N/ha) was compared to response to half the conventional rate or zero N applications made weekly based on NDVI values.

Stage 1. Experiments were conducted to measure the relationships among spectral indices and plant tissue N content, growth rate, and chlorophyll. Experiments were conducted on bentgrass at two locations and on two bermudagrass cultivars. The bermudagrass (Cynodon dactylon and Cynodon X transvaalensis) trials were initiated at the Oklahoma State University Turfgrass Research Center on previously established stands of bermudagrass. The northern site consisted of a mature stand of 'Common' bermudagrass. The southern site was 'Midfield' bermudagrass which had been established in 1992. Completely randomized experimental designs with eight treatments and four replications (thirty-two plots at each location) were used at both sites. The plots were 91 cm x 91 cm with a 152 cm alley between plots. The treatments consisted of four nitrogen rates (0, 24, 48, and 72 kg N/ha) applied once a month and two mowing heights (1.3 and 3.2cm) in a complete factorial arrangement. The fertilizer source in all experiments was urea ammonium nitrate (UAN) solution, with an analysis of 28-0-0. Fertilizer was applied with a CO_2 research sprayer with a spray width of 152 cm and a calibrated output of 187 L ha^{-1}. The trial areas were irrigated with approximately 0.5-1 cm of water immediately after fertilization. The plots were mowed twice a week at there designated heights (1.3 or 3.2 cm) and clippings were collected from selected mowings for analysis. Prior to harvesting the plots, spectral data from two overlapping bandwidths, 300-850nm and 650-1100nm, was collected simultaneously within each plot using a PSD 1000 portable dual spectrometer (Ocean Optics Inc., Dunedin, FL). The PSD1000 was connected to a portable computer through a PCMCIA slot using a PCM-DAS16D/12 A/D converter (Computer Boards Inc., Middleboro, MA). Three readings were taken at randomly selected points within each plot and then averaged to develop an estimate for the entire plot. The fiber optic spectrometer has spectral resolution as low as 1 nm, however all spectral readings were partitioned into 5 nm bandwidths (35-37 wavelengths per reading). These spectral readings were taken in ambient light conditions with the input end of the fiber-optic cable being held over the plots by hand. The height of the readings was approximately one meter, but varied with the height of the individual holding it. The raw spectral data was divided by a white plate reading, which was obtained prior to taking readings on the plots at each site, then multiplied by 100 to transform the raw spectral data into a percent reflectance value. The white plate was made by painting a 46 cm x 20 cm piece of sheet metal with barium sulfate paint. The reflectance in the red (R670 nm) region and the NIR (R780 nm) region were then used to calculate NDVI using the equation (R780-R670)/(R780+R670). After harvest, the clippings were placed in a drying oven at 49°C for twenty-four hours. Once clippings were dry, they were weighed and these weights were used to calculate the growth rate in units of kg ha^{-1} d^{-1} for each plot. Clippings were then ground using a Cyclone Sample Mill (UDY Corporation, Fort Collins, CO) to transform the clippings into a homogeneous sample. These samples were then analyzed for total chlorophyll and total N. The purpose of the chlorophyll analysis was to provide a more objective, quantitative scale of relative greenness than visual ratings.

Chlorophyll analysis was based on a procedure reported by Johnson et al. (1974). This procedure used a methanol extraction in which 50 mg of sample was mixed with 50 ml of ACS grade methanol. After 20 to 22 hours the samples were gently shaken and allowed to settle for 2 hours before analyzing absorbance of the liquid portion using a Spectronic 401 spectrometer (Milton Roy Co., Ivyland, PA). Absorbance levels that were obtained from the spectrometer at 660 nm were converted to mg chlorophyll/liter. The concentration curve

(Figure 1) was developed by plotting the calculated chlorophyll concentrations of serial dilutions of a concentrated solution. The concentrated solution was prepared by extracting a larger quantity of plant material as described above. The calculated chlorophyll concentration for the diluted samples was obtained from absorbance measured at 650- and 665-nm wavelengths using the Spectronic 401 spectrometer, which has a 1 cm path length, and applying the formula: total chlorophyll (g/liter) = 0.0256 absorbance $_{650}$ + 0.004 absorbance $_{665}$. The mg chlorophyll/liter solution will equal the mg chlorophyll/g clippings when a 1 mg:1 ml clipping:extractant ratio is used. Total N was determined using a NA1500 Nitrogen/Carbon/Sulfur dry combustion analyzer (Carlo-Erba Instruments, Milano, Italy).

The bentgrass study was initiated at two separate locations. One was at the Oklahoma State University Turfgrass Research Center Stillwater, OK and the other was at Karsten Creek golf course Stillwater, OK. Both sites were established SR1020 Bentgrass (Agrostis palustris) greens. A completely randomized experimental design with four treatments and three replications was used at each site. Plots were 305 cm x 152 cm without alleys between the plots. Treatments consisted of four different N rates (6, 12, 24, and 36 Kg N/ha/month) and these plots were also fertilized using a small research sprayer with a 152cm spray width. Laboratory analyses and procedures were the same as those used for the bermudagrass cultivars. Relationships between treatments and measured nitrogen response variables were investigated using correlation regression analysis and analysis of variance (ANOVA) (SAS, 1990).

Stage 2. In May 1998, a few refinements were made to the project in an effort to remove sources of possible error and obtain data over a wider range of available N. The Bermudagrass study was continued on the same two cultivars however, the plots were set up in areas just east of the area used in 1997. A completely randomized experimental design was used with six treatments replicated four times. The plots were 91 cm x 183 cm with 26 cm alleys between plots. The treatments were six different levels of nitrogen fertilization (24, 49, 73, 98, 195, and 293 kg N/ha), the number and range of nitrogen treatments were increased in an attempt to increase the range in percent tissue N, chlorophyll content, and growth rate to increase precision of regressions of these variables against NDVI. Mowing height was no longer a variable and all plots were cut at a height of 1.3 cm.

The Bentgrass study was reduced to a single site located just east of the 1997 plots at the turfgrass research center. The experimental design was a completely randomized design with six treatments and four replications. The plots were 305 cm x 152 cm with no alleys between plots. The treatments were N rates of 6, 18, 30, 42, 54, and 67 kg/ha.

The plots in all three locations were fertilized with ammonium nitrate, which was dissolved in water and applied to each plot using a garden sprinkler can. Prior to harvesting, three individuals made visual quality ratings of the plots using a scale of 1 to 9, 1 being brown, 5 yellow-green and 9 being dark blue-green turf. Spectral measurements from 350 to 1000nm were also taken on each plot before harvesting. The spectral measurements were taken using a

S2000 Production fiber optic spectrometer (Ocean Optics inc., Dunedin, FL) This was a different spectrometer than the one used in 1997 in that it separated the bandwidths into smaller portions and did not have two overlapping bandwidths that had to be adjusted, thus removing one possible source of error. This spectrometer was installed in an artificially lighted hood, designed by Dr. Marvin Stone, which contained two 120-watt flood lamps and two 300-watt IR-heat lamps (Figures 2 and 3). The dimensions of the light hood were 61cm tall by 61cm wide and tapered from 46cm long at the base to 15cm long at the top. The use of this light hood also allowed us to remove fluctuations in light intensity resulting from changes in sun light intensity and variation in the height of the spectrometer fiber optic cable lens. Spectrometer height variation was remedied by attaching the input end of the spectrometer fiber optic lens to the top of the hood. This allowed us to standardize the height of the readings to 61cm above the turf surface. At a height of 61cm the spectrometer field-of-view was a circle with a diameter of 41cm. Three readings were taken from each plot and averaged prior to calculating reflectance. In addition to calculating NDVI, the index GNDVI was calculated using the reflectance values from the green (R550 nm) and NIR (R780 nm) regions of the spectrum. These values were then entered into the equation (R780-R550)/(R780+R550). All other methods of analysis and data acquisition were done the same as for 1997.

Stage 3. After defining the relationship between spectral measurements and turf parameters associated with nitrogen response, stage three experiments examined the potential for using spectral measurements to predict N-fertilization needs of turfgrass. These experiments also determined if it was possible to remove nutrient level variability by applying nitrogen based on the spectral indices. During Stage 2 it was determined that the spectral index GNDVI ((NIR-green)/(NIR+green)) was often a more reliable indicator of turf N-deficiency than NDVI.

At the conclusion of Stage 2 each of the existing bermuda plots were divided into three equal subplots, 61 x 91cm. These subplots were randomly assigned new treatments. One subplot became a control plot, one became a constant-rate plot, and the third became a variable-rate plot with rate based on spectral measurements. The first step was to set the GNDVI critical value. This value was intended to identify the nutritional level below which the variable plots would receive N fertilizer and above which no additional N fertilizer would be applied. The critical value was set for each site independently and was different depending on the bermudagrass species. These critical values were developed by substituting a visual rating value of 5, which exhibited moderate values for the measured turf parameters, into the regression equation from the regression of GNDVI vs visual ratings for the first two bermudagrass harvests of 1998(Table 1). The resulting values were averaged to create one GNDVI critical value for each site. The Common bermudagrass GNDVI critical value was thus calculated to be 0.66 and the 'Midfield' bermudagrass GNDVI critical value 0.60.

The next step was to determine the constant and variable nitrogen rates. This was accomplished by substituting the calculated GNDVI critical value into the regression equation of N rate (treatment) vs GNDVI for the first two bermudagrass harvests of 1998 (Table 1). These resulting values were averaged to obtain one constant rate for each site. This process yielded the same constant nitrogen rate for both sites, which was 49 kg N/ha and was applied the first week of the four week trial. The variable rate 24.5 kg N/ha one half the constant rate. This variable N rate was applied once a week on the plots with GNDVI values below the critical value. Spectrometer readings were taken once a week on the plots and GNDVI values were calculated from these readings to determine which of the variable plots would receive additional fertilizer. The GNDVI values were also used to monitor the change in the plots with time after N-fertilizations and to provide a quantitative means of comparing the effectiveness of the variable rate and constant rate for reducing turf quality variations among subplots by fertilizing. Individual plots were harvested at the completion of the trial. The harvested clippings were then dried, ground, and chlorophyll and nitrogen were determined using previously described procedures.

The data provided by the chlorophyll and nitrogen analysis were then used to determine if the variable rate applications reduced the variation among plots. Standard deviations and coefficients of variation (CV) were calculated to determine if variations were reduced. The CV is defined as the standard deviation expressed as a percentage of the mean and is used as a relative measure of variation (Taylor et al. 1999). Therefore, the subplot treatment with the lowest CV would have the least variation among the plots within that treatment (fertilization method).

RESULTS

Stage 1

The results found in this first stage did not provide strong, consistent correlations between parameters of turf N response and spectral NDVI. During this stage there were four harvests conducted on the bermudagrass plots and three harvests conducted on the bentgrass plots. Spectrometer data was collected at only two of the bentgrass harvests.

Results of regression analysis of the measured variables produced from this stage was continually unpredictable in the sense of being unable to provide R^2 values above 0.50 from harvest to harvest, from site to site and species to species for the variables being measured. The R^2 values for regression of spectral index NDVI with treatment and the three measured response components (growth rate, chlorophyll, and % nitrogen) ranged from 0.14 to 0.84 for the July 3 harvest of the Bermudagrass plots which was the first of four harvests. The turf parameter component which provided the best correlation with NDVI (R^2 =0.84) was % N on the 1.3cm mowing height for Common bermudagrass (Figure 4). However, at the 3.2 cm mowed 'Midfield' site, % N regressed with NDVI only produced an R^2 of 0.33 (Figure 5). This trend of diminishing R^2 values continued for the next three harvests of the bermudagrass sites (Table 2). The most consistent decline in R^2 with harvests was for the four harvests of the 1.3cm Common bermuda plots. Values of R^2 decreased from the highest of 0.84 in the first harvest to 0.23 in the fourth harvest. An inconsistency in the NDVI regression data was found to be true for all components, harvests, location, and species and is documented in tabular form in the appendix (Tables 12-18). This inconsistent data along with other problems encountered led to the restructuring of the project for the following year.

Stage 2

The results from this stage were more consistent compared with those of Stage 1. The major factors contributing to the increased significance of correlations over that found in 1997 were increased number and range of nitrogen treatments which increase precision. Modifying the nitrogen treatments increased the range of values measured for percent tissue nitrogen, chlorophyll content and growth rate (Tables 3-6). This change in the range of values for N response parameters became evident (Tables 3 and 4), for bermudagrass data, and bentgrass (tables 5 and 6). Bermudagrass tissue % N went from a range of 2.5-2.8 in 1997 to a range of 2.7-5.3 in 1998 (Tables 3 and 4). Chlorophyll content went from a range of 3.3-3.9 in 1997 to a range of 5.3 to 10.1 in 1998. Growth rate went from a range of 43.2-129.6 in 1997 to a range of 27.2 to 167.9 in 1998. A similar increase in range of N response was found for bentgrass. Tissue % N went from a range of 5.0-5.2 in 1997 to a range of 4.1-6.0 in 1998 (Tables 5 and 6). The chlorophyll content went from a range of 7.2-7.7 in 1997 to a range of 7.5-11.4 in 1998. Growth rate exhibited a change in range from 5.3-8.6 in 1997 to a range of 10.6-60.5 in 1998. Increasing the number of treatments in 1998 provided more information for comparison of NDVI and plant response. Another item that likely added to the better results in stage 2 was the use of the artificial light hood when collecting spectral data. Use of the artificial light hood removed the variation in the light intensity of the sun and standardized the height of the spectrometer's input end of the fiber optic cable to a height of 61cm. One other item that might have added to the success of stage 2 was the elimination of the mowing height variable. Also, the Karsten Creek site was eliminated from the study because the turf area was not uniform and its management was not under our control. An additional index known as GNDVI, was also added in 1998 to be examined as another possible tool for detecting nitrogen deficiencies. Figure 6 offers a visual example of how GNDVI changes with respect to the nitrogen treatments and the color of the the turfgrass.

The regression analysis for the data produced in this stage was much more consistent than that found in 1997. The consistency of the spectral data and thus, the indices derived from that data were greatly enhanced. The R^2 values produced by the regression of NDVI with treatment, the three nitrogen response components (growth rate, chlorophyll, and % N), and visual rating ranged from 0.74 to 0.98 in the two bentgrass harvests and from 0.11 to 0.92 in the four bermudagrass harvests. This data is presented in tabular form in the appendix (Tables 21-24). The unusually low value of 0.11 was produced from the second harvest of the 'Midfield' site. This low R^2 was the result of a mowing injury or scalping of the plots in this site two days prior to the date of harvest. The scalping of these plots caused them to exhibit a yellowed appearance, which drastically reduced the NDVI values, GNDVI values and plant parameters expressing N response. Scalping of turfgrass exposes the non-photosynthesizing juvenile tissues which are yellow in color because there is no chlorophyll in the leaves. The yellow color produces lower NDVI and GNDVI values. The absence of chlorophyll prevents the plant from exhibiting a nitrogen response because there is no variation in color of the plots. The reason that the regression of spectral indices and chlorophyll provided a low R^2 value was that there was no variation in chlorophyll content so the nitrogen response is a horizontal line. The regression of spectral indices and %N provided a low R^2 because chlorophyll content is directly related to the %N in the tissue so the turf did not exhibit the expected variations in color due to different N rates. If the data from that site's harvest were excluded the range of R^2 values would be from 0.48 to 0.92. The range when looking at % N regressed with NDVI would be from 0.78 to 0.96 for the two bentgrass harvests and from 0.66 to 0.85 for the four bermudagrass harvests.

GNDVI regressed with parameters of N response by turf offers strong evidence that turf N status can be optically sensed. The range for the R^2 values produced by the regression of GNDVI with N-rate, the three nitrogen responsive components, and visual ratings yields a range from 0.77 to 0.98 for the two bentgrass harvests and from 0.51 to 0.96 for the four bermudagrass harvests. When examining the relationship between tissue % N and GNDVI the range for R^2 values becomes 0.79 to 0.96 for bentgrass and 0.72 to 0.92 for bermudagrass. Figure 7 provides a strong argument for the ability of GNDVI to predict the % N in the turf tissue. This figure shows the regression of GNDVI vs tissue % N for both bermudagrass sites on the first harvest of 1998. Both sites maintain a strong regression with both R^2 values greater than 0.90. However, a most interesting component of this figure is how close the regression lines come to being overlayed perfectly on top of each other. When comparing the results for the regressions of GNDVI and NDVI with %N we find that when used on bentgrass there is only a minor difference between the two (Table 7). However, when used on bermudagrass we found that the R^2 values for GNDVI were greater than those for NDVI seven out of eight times. It is also evident that the range is slightly narrower for NDVI than for GNDVI (Table 8).

Visual ratings are currently the means used in the turfgrass industry and scientific community to rate the quality of turfgrass research and test plots. This is a subjective measure of the quality of plots and is strongly influenced or biased by the individual rating the plots.

In this stage of the research visual ratings were taken by three individuals prior to harvesting. These ratings were then averaged in an attempt to remove bias in the rating process. The visual ratings obtained were then regressed with all other measured variables: % tissue nitrogen, chlorophyll content, growth rate, NDVI and GNDVI. These measured aspects were also regressed against each other. Tables 9 and 10 show a correlation matrix for these regressions for harvest 1 in 1998. Table 9 is a matrix for the Common bermudagrass site and table 10 is a matrix for the 'Midfield' bermudagrass site. Visual ratings correlated well with the GNDVI values, producing an R^2 value of 0.79 at both sites. However, when we compare GNDVI and visual ratings we find that GNDVI produced better correlation when regressed with the measured turf response parameters than do average visual ratings. When looking at regressions with tissue % N, GNDVI gives an R^2 value of 0.85 for the Common bermudagrass site and visual ratings gives an R^2 value of 0.76. GNDVI and visual ratings were more consistent for the 'Midfield' site when regressing tissue % N, with both producing R^2 values of 0.90. However, that was the only parameter in which GNDVI did not prove to be better than visual ratings in evaluating the measured response components. Analysis of variance data confirmed our hypothesis that the N treatments induced variations in the plant response parameters of % tissue N, chlorophyll content, and growth rate (Table 25).

Stage 3

This stage was included to evaluate the application of sensor-based indexes of turf N status for N-fertilization. The purpose was to use the information gained during the preceding portions of the research and apply it to a situation of variable soil available N. The application of the nitrogen rates over the past year produced an area with multiple levels in available N. Our objective was to see if the differences induced by applying nitrogen variably could be removed on the basis of the calculated GNDVI values for each plot. After variable N application to the plots, the plots were harvested and the clippings were analyzed for chlorophyll and nitrogen to obtain a quantified measure of the variability in the bermudagrass tissue among plots. The chlorophyll data produced mixed results showing that the variable rate N application reduced the variability in chlorophyll compared to the control and the constant rate plots for the Common site, but the variable rate showed difference in variability of chlorophyll compared to the control and constant rate plots in the 'Midfield' site (Table 11). Variable rate N application decreased the variability in tissue N content compared to the other two treatments at both sites (Table 11). Compared to the amount of N-fertilizer used in the constant rate plots, the variable rate method used 21% less fertilizer on the Common bermuda site and 35.5% less on the 'Midfield' site.

CONCLUSIONS

The data acquired in 1997 was very useful in regard to helping to develop sensor technology, however, the data did not directly confirm that sensor based technology could reliably detect nitrogen turf deficiencies in the field. The information obtained by refining techniques and improving sensing technology in 1998 greatly improved the ability to examine turf N-response with a sensor. The regression analysis for stage 2 clearly showed that sensor based technology is more than capable of detecting nitrogen deficiencies associated with changes in growth rate and color which are strongly linked with the plant tissue nitrogen content. This data also leads to the conclusion that NDVI is a good index to identify nitrogen deficiencies in bentgrass and in bermudagrass. However, GNDVI may be a preferred index for turf since it is just as good an index to use in bentgrass, but is better for detecting these N-deficiencies in bermudagrass. GNDVI also shows great potential as a replacement for visual ratings for evaluating turfgrass quality for the turf research community.

The variability trial which was conducted in stage 3 of this research adds strength to the hypothesis that sensor based technologies can not only be used to detect nitrogen deficiencies but to effectively eliminate these variabilities. There should probably be more variability trials conducted to better substantiate the ability of this technology to remove the inherent variability in the landscape. However, based on this research the technology appears to provide a viable method of applying fertilizer on an as-needed basis thus, saving the applicator money and minimizing risk to the environment.

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Figure 1. Chlorophyll concentration curve for determining chlorophyll content.

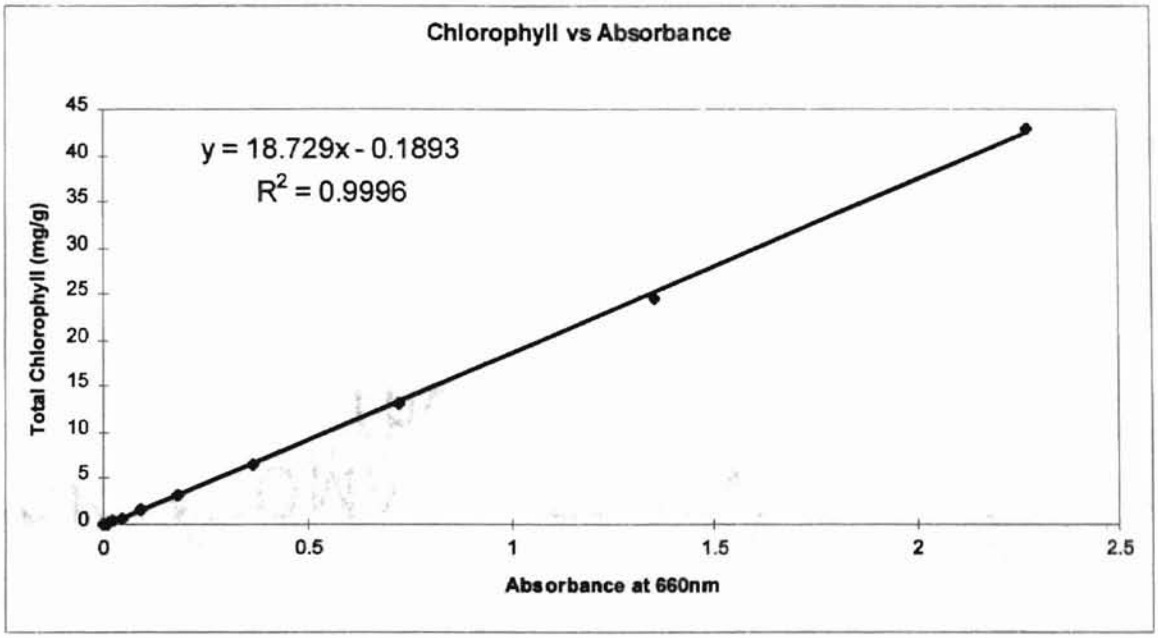

Figure 2. Apparatus for obtaining turf reflectance showing shielded computer compartment (upper portion being viewed by operator) and artificial light hood (light source and shield resting on turf)

Figure 3. Laptop computer and S2000 spectrometer inside viewing hood.

Figure 4. Regression of NDVI and % N Harvest 1 July 3,1997 for 1.3cm Common bermudagrass plots

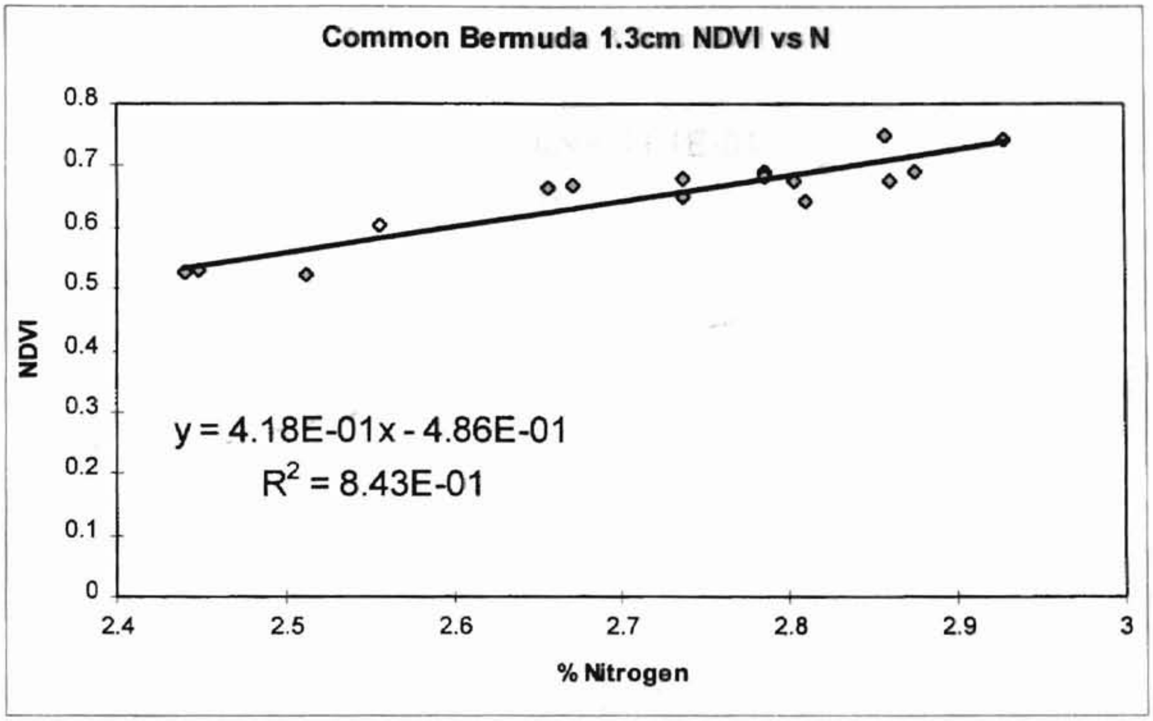

Figure 5. Regression of NDVI and % N Harvest 1 July 3, 1997 for 3.2cm 'Midfield' bermudagrass plots.

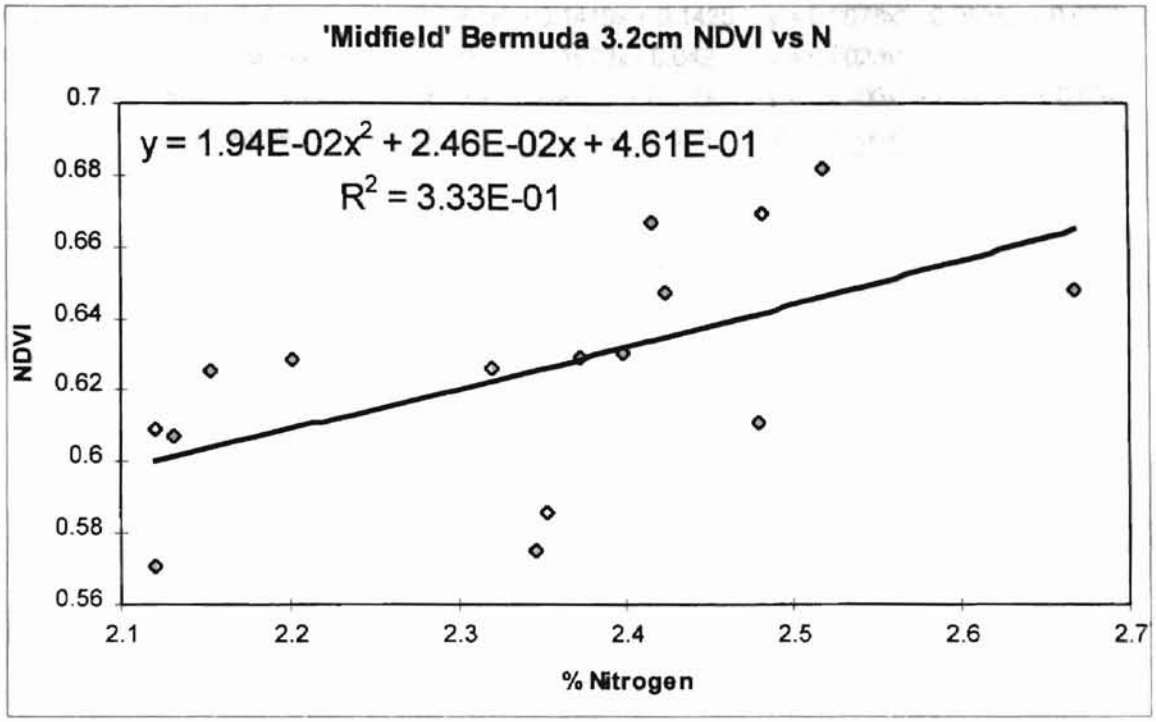

Table 1. Regression equations for the determination of GNDVI critical value and N rate for stage 3.

Regression	Site	Harvest 1	Harvest 2
GNDVI vs Vis Rate	Common	$y = -0.0082x^2 + 0.1419x + 0.1425$	$y = 0.0078x^2 - 0.0538x + 0.6776$
GNDVI vs Vis Rate	Midfield	$y = -0.0092x^2 + 0.1679x - 0.042$	$y = 0.0023x^2 + 0.0007x + 0.5486$
GNDVI vs N Rate	Common	$y = -5E-06x^2 + 0.0021x + 0.5396$	$y = -5E-06x^2 + 0.0019x + 0.6046$
GNDVI vs N Rate	Midfield	$y = -3E-06x^2 + 0.0014x + 0.539$	$y = -2E-06x^2 + 0.0006x + 0.6261$

Table 2. Regression of NDVI vs tissue N for all bermudagrass harvests 1997.

Site	Height	Harvest 1	Harvest 2	Harvest 3	Harvest 4
		R^2			
Common	1.3	0.84	0.58	0.39	0.23
Common	3.2	0.70	0.02	0.82	0.06
Midfield	1.3	0.67	0.10	0.23	0.02
Midfield	3.2	0.33	0.32	0.71	0.09

Table 3. NDVI and associated parameters of Common bermudagrass turf mowed at 1.3 cm July 3, 1997 at four N fertilization levels *

N rate[a]	0	24	48	72
% Tissue N	2.5	2.7	2.8	2.8
Chlorophyll[b]	3.3	3.8	3.8	3.9
Growth Rate[c]	43.2	77.8	94.2	129.6
NDVI	0.54	0.67	0.68	0.71

*Values are an average of 3 reps
[a]Nitrogen rate in units of kg/ha
[b]Chlorophyll in units of mg chlorophyll/g clippings
[c]Growth rate in units of kg/ha/day

Table 4. NDVI and associated parameters of Common bermudagrass turf at six N fertilization levels in July 16,1998.*

N rate[a]	24	49	73	98	195	293
% Tissue N	2.7	3.2	3.6	3.8	4.9	5.3
Chlorophyll[b]	5.3	7.0	7.7	8.9	9.4	10.1
Growth Rate[c]	27.2	45.8	62.2	101.1	157.6	167.9
NDVI	0.75	0.82	0.85	0.89	0.91	0.91
GNDVI	0.57	0.64	0.67	0.71	0.75	0.76

*Values are an average of 4 reps of the first harvest.
[a]Nitrogen rate in units of kg/ha
[b]Chlorophyll in units of mg chlorophyll/g clippings
[c]Growth rate in units of kg/ha/day

Table 5. NDVI and associated parameters of the Turfcenter bentgrass site at four N fertilization levels in 1997.*

N rate[a]	6	12	24	36
% Tissue N	5.0	5.1	5.1	5.2
Chlorophyll[b]	7.2	7.6	7.9	7.7
Growth Rate[c]	5.3	5.3	7.2	8.6
NDVI	0.51	0.53	0.59	0.59

*Values are an average of 3 reps of the second harvest.
[a]Nitrogen rate in units of kg/ha
[b]Chlorophyll in units of mg chlorophyll/g clippings
[c]Growth rate in units of kg/ha/day

Table 6. NDVI and associated parameters of the Turfcenter bentgrass site at six N fertilization levels in 1998.*

N rate[a]	6	18	30	42	54	67
% Tissue N	4.1	4.7	5.3	5.5	5.8	6.0
Chlorophyll[b]	7.5	8.8	9.5	10.6	11.2	11.4
Growth Rate[c]	10.6	15.2	22.5	36.9	43.4	60.5
NDVI	0.81	0.85	0.88	0.89	0.90	0.90
GNDVI	0.64	0.68	0.71	0.72	0.73	0.74

*Values are an average of 4 reps
[a]Nitrogen rate in units of kg/ha
[b]Chlorophyll in units of mg chlorophyll/g clippings
[c]Growth rate in units of kg/ha/day

Figure 6. Example of GNDVI values compared to plot color and treatment on Common bermudagrass 1998 harvest 2.

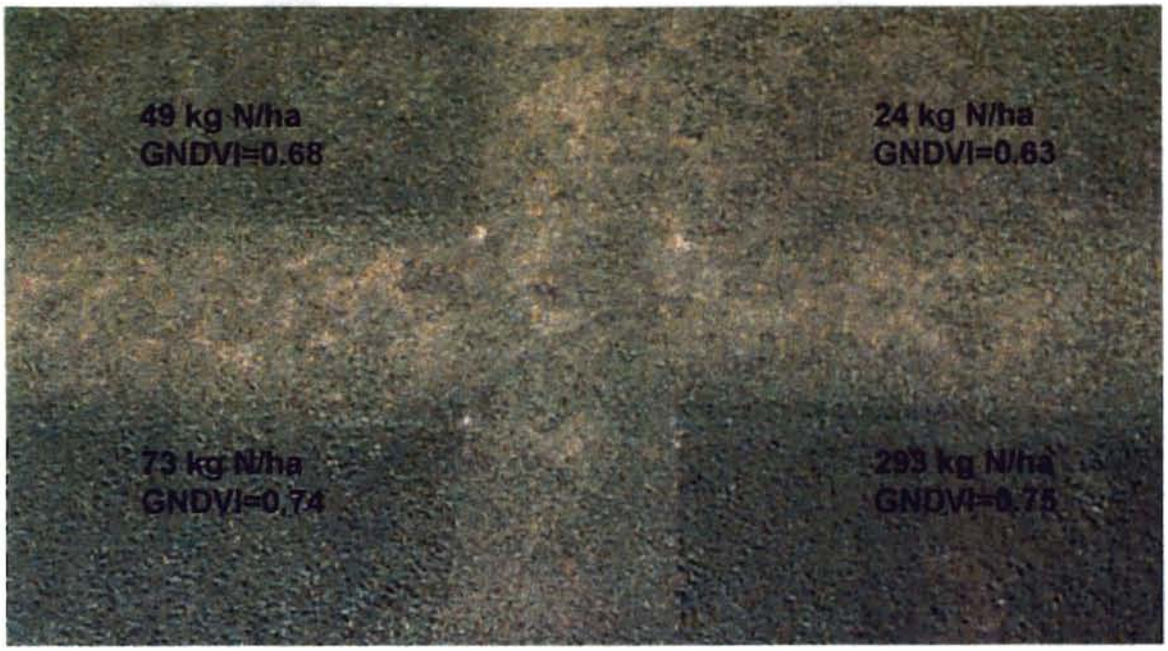

Figure 7. Regression of GNDVI vs. tissue % N for both bermudagrass sites harvest 1 of 1998.

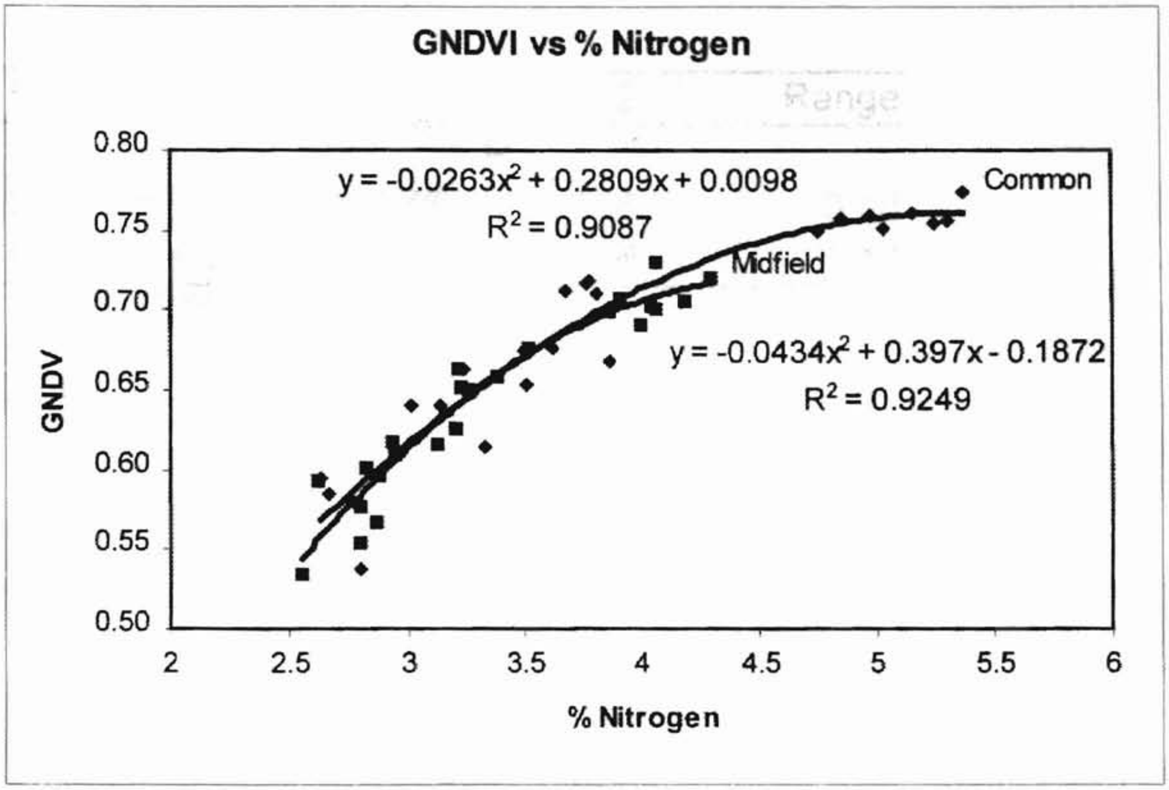

Table 7. Bentgrass comparison of regression for NDVI and GNDVI vs %N for two harvests in 1998.

Regression	H 1	H 2	Range
	R^2		
NDVI vs %N	0.78	0.96	0.18
GNDVI vs %N	0.79	0.96	0.17

H1 and H2 indicate different harvests

Table 8. Bermudagrass comparison of regression of GNDVI and NDVI vs %N 1998.

Regression	Common				Midfield			Range
	H1	H2	H3	H4	H1	H3	H4	
	R^2				R^2			
NDVI vs %N	0.76	0.70	0.68	0.80	0.85	0.66	0.65	0.20
GNDVI vs %N	0.91	0.83	0.74	0.72	0.92	0.79	0.75	0.20

H1-H4 indicate different harvests

Table 9. Correlation matrix for Common bermudagrass July 16, 1998.

	N RATE[a]	NDVI	GNDVI	%N[b]	CHL[c]	GR[d]	VR[e]
N RATE	N/A	0.82	0.95	0.94	0.83	0.91	0.82
NDVI		N/A	0.93	0.64	0.82	0.73	0.69
GNDVI			N/A	0.85	0.89	0.88	0.79
%N				N/A	0.75	0.9	0.76
CHL					N/A	0.71	0.62
GR						N/A	0.7
VR							N/A

[a]Nitrogen rate(treatment)
[b]% Tissue nitrogen
[c]Chlorophyll content
[d]Growth rate
[e]Visual rating

Table 10. Correlation matrix for 'Midfield' bermudagrass July 16, 1998.

	N RATE[a]	NDVI	GNDVI	%N[b]	CHL[c]	GR[d]	VR[e]
N RATE	N/A	0.83	0.9	0.9	0.88	0.89	0.83
NDVI		N/A	0.96	0.79	0.84	0.82	0.69
GNDVI			N/A	0.9	0.88	0.91	0.79
%N				N/A	0.87	0.89	0.9
CHL					N/A	0.92	0.83
GR						N/A	0.85
VR							N/A

[a]Nitrogen rate(treatment)
[b]% Tissue nitrogen
[c]Chlorophyll content
[d]Growth rate
[e]Visual rating

Table 11. Coefficient of variance (CV) values for stage 3.

Site	N-Input	Chlorophyll	% Tissue N
		CV	
Common	Control	28	22
Common	Constant Rate	20	19
Common	Variable Rate	17	13
Midfield	Control	12	13
Midfield	Constant Rate	12	12
Midfield	Variable Rate	12	11

APPENDIX

Table 12. 1997 bermudagrass regressions for harvest 1

Regression[a]	Site	Height[b]	R^2	Equation	Range[c]
NDVI vs Trt	Common	1.3	0.78	y = -4.19E-05x2 + 5.07E-03x + 5.51E-01	0-72
NDVI vs GR	Common	1.3	0.73	y = -1.19E-07x2 + 3.67E-04x + 4.45E-01	6.9-105.2
NDVI vs Chl	Common	1.3	0.56	y = 3.05E-02x2 - 7.75E-02x + 5.15E-01	2.9-4.2
NDVI vs N	Common	1.3	0.84	y = 4.18E-01x - 4.86E-01	2.9-4.2
N vs Trt	Common	1.3	0.79	y = -1.01E-04x2 + 1.18E-02x + 2.50E+00	0-72
N vs GR	Common	1.3	0.64	y = 1.10E+03x2 - 4.08E+03x + 3.76E+03	6.9-105.2
N vs Chl	Common	1.3	0.55	y = -2.34E+00x2 + 1.43E+01x - 1.77E+01	2.9-4.2
Chl vs Trt	Common	1.3	0.50	y = -1.81E-04x2 + 2.17E-02x + 3.28E+00	0-72
Chl vs GR	Common	1.3	0.18	y = -5E-07x2 + 0.0012x + 3.0714	6.9-105.2
GR vs Trt	Common	1.3	0.73	y = 3.21E-03x2 + 1.04E+01x + 4.19E+02	0-72
NDVI vs Trt	Common	3.2	0.55	y = -2.51E-05x2 + 3.60E-03x + 6.44E-01	0-72
NDVI vs GR	Common	3.2	0.68	y = -5.17E-07x2 + 6.46E-04x + 6.05E-01	6.9-105.2
NDVI vs Chl	Common	3.2	0.74	y = -3.15E-02x2 + 2.58E-01x + 2.49E-01	1.9-4.6
NDVI vs N	Common	3.2	0.70	y = -1.65E-01x2 + 9.62E-01x - 6.29E-01	2.5-2.9
N vs Trt	Common	3.2	0.63	y = 2.78E-05x2 + 9.34E-03x + 2.11E+00	0-72
N vs GR	Common	3.2	0.67	y = 4.88E+02x2 - 1.87E+03x + 1.87E+03	6.9-105.2
N vs Chl	Common	3.2	0.95	y = 2.45E+00x - 2.92E+00	1.9-4.6
Chl vs Trt	Common	3.2	0.69	y = -1.65E-04x2 + 4.16E-02x + 2.05E+00	0-72
Chl vs GR	Common	3.2	0.89	y = -7E-06x2 + 0.0097x + 1.3439	6.9-105.2
GR vs Trt	Common	3.2	0.71	y = 8.36E-02x2 + 2.28E+00x + 7.77E+01	0-72
NDVI vs Trt	Midfield	1.3	0.46	y = 3E-06x2 + 0.0012x + 0.6188	0-72
NDVI vs GR	Midfield	1.3	0.36	y = -1.90E-07x2 + 3.95E-04x + 4.95E-01	157.1-340.4
NDVI vs Chl	Midfield	1.3	0.69	y = 2.76E-01x2 - 1.61E+00x + 2.96E+00	2.2-3.6
NDVI vs N	Midfield	1.3	0.67	y = 8.91E-02x2 - 1.43E-01x + 4.31E-01	2.5-2.9
N vs Trt	Midfield	1.3	0.43	y = -2.16E-05x2 + 4.92E-03x + 2.48E+00	0-72
N vs GR	Midfield	1.3	0.37	y = -1.42E+04x2 + 7.69E+04x - 1.01E+05	157.1-340.4
N vs Chl	Midfield	1.3	0.08	y = 8.03E+00x2 - 4.24E+01x + 5.86E+01	2.2-3.6
Chl vs Trt	Midfield	1.3	0.05	y = -8.94E-05x2 + 3.59E-03x + 2.78E+00	0-72
Chl vs GR	Midfield	1.3	0.33	y = -3.22E-07x2 + 1.06E-03x + 2.08E+00	157.1-340.4
GR vs Trt	Midfield	1.3	0.51	y = 5.11E-02x2 + 8.37E+00x + 1.94E+03	0-72
NDVI vs Trt	Midfield	3.2	0.47	y = -4.19E-06x2 + 1.10E-03x + 5.95E-01	0-72
NDVI vs GR	Midfield	3.2	0.44	y = -1.33E-07x2 + 1.95E-04x + 5.86E-01	126.9-260.7
NDVI vs Chl	Midfield	3.2	0.14	y = 4.22E-02x2 - 2.16E-01x + 8.96E-01	2.4-3.6
NDVI vs N	Midfield	3.2	0.33	y = 1.94E-02x2 + 2.46E-02x + 4.61E-01	2.1-2.7
N vs Trt	Midfield	3.2	0.68	y = 8.43E-06x2 + 4.21E-03x + 2.18E+00	0-72
N vs GR	Midfield	3.2	0.19	y = -4.96E+03x2 + 2.41E+04x - 2.75E+04	126.9-260.7
N vs Chl	Midfield	3.2	0.50	y = 4.64E+00x2 - 2.06E+01x + 2.55E+01	2.4-3.6
Chl vs Trt	Midfield	3.2	0.29	y = -3.26E-05x2 + 8.86E-03x + 2.53E+00	0-72
Chl vs GR	Midfield	3.2	0.19	y = -1.06E-06x2 + 3.64E-03x - 1.48E-01	126.9-260.7
GR vs Trt	Midfield	3.2	0.28	y = -1.87E-01x2 + 2.08E+01x + 1.32E+03	0-72

[a] Independent variables are listed last
[b] Height = mowing height in cm
[c] Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %

Table 13. 1997 bentgrass regressions for harvest 1.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Turfcenter			
NDVI vs GR	Turfcenter			
NDVI vs Chl	Turfcenter			
NDVI vs N	Turfcenter			
N vs Trt	Turfcenter	0.57	y = -6.20E-05x2 + 1.08E-02x + 4.69E+00	6-36
N vs GR	Turfcenter	0.01	y = -5.01E+02x2 + 4.83E+03x - 1.11E+04	46.8-69.1
N vs Chl	Turfcenter	0.38	y = -6.42E+00x2 + 6.33E+01x - 1.50E+02	5.7-6.4
Chl vs Trt	Turfcenter	0.32	y = 4.51E-04x2 - 7.06E-03x + 5.98E+00	6-36
Chl vs GR	Turfcenter	0.50	y = -1.21E-05x2 + 1.57E-02x + 1.29E+00	46.8-69.1
GR vs Trt	Turfcenter	0.11	y = 2.26E-01x2 - 9.02E+00x + 5.71E+02	6-36
NDVI vs Trt	Karsten			
NDVI vs GR	Karsten			
NDVI vs Chl	Karsten			
NDVI vs N	Karsten			
N vs Trt	Karsten	0.64	y = 2.56E-04x2 + 1.44E-03x + 4.11E+00	6-36
N vs GR	Karsten	0.41	y = 3.84E+01x2 - 1.83E+02x + 3.60E+02	23.0-36.5
N vs Chl	Karsten	0.56	y = -2.82E-01x2 + 4.14E+00x - 6.93E+00	5.0-6.3
Chl vs Trt	Karsten	0.34	y = 1.51E-04x2 + 1.45E-02x + 5.24E+00	6-36
Chl vs GR	Karsten	0.45	y = 7.67E-06x2 + 2.37E-03x + 4.32E+00	23.0-36.5
GR vs Trt	Karsten	0.39	y = 2.99E-02x2 + 9.56E-01x + 2.47E+02	6-36

[a]Independent variables are listed last
[b] Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha;
GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %.

Table 14. 1997 bermudagrass regressions for harvest 2.

Regression[a]	Site	Height[b]	R^2	Equation	Range[c]
NDVI vs Trt	Common	1.3	0.58	y = -3.48E-05x2 + 3.56E-03x + 7.86E-01	0-72
NDVI vs GR	Common	1.3	0.89	y = -3.91E-06x2 + 1.86E-03x + 6.57E-01	56.8-280.6
NDVI vs Chl	Common	1.3	0.05	y = 2.77E-02x2 - 2.82E-01x + 1.55E+00	4.3-6.2
NDVI vs N	Common	1.3	0.34	y = 1.05E-01x2 - 6.06E-01x + 1.68E+00	1.9-3.8
N vs Trt	Common	1.3	0.01	y = -7.45E-05x2 + 6.78E-03x + 3.05E+00	0-72
N vs GR	Common	1.3	0.89	y = -3.91E-06x2 + 1.86E-03x + 6.57E-01	56.8-280.6
N vs Chl	Common	1.3	0.04	y = -1.38E-01x2 + 1.63E+00x - 1.60E+00	4.3-6.2
Chl vs Trt	Common	1.3	0.14	y = -2.72E-04x2 + 2.43E-02x + 4.92E+00	0-72
Chl vs GR	Common	1.3	0.17	y = -4.38E-05x2 + 1.55E-02x + 4.08E+00	56.8-280.6
GR vs Trt	Common	1.3	0.59	y = -3.10E-02x2 + 4.14E+00x + 8.75E+01	0-72
NDVI vs Trt	Common	3.2	0.16	y = -6.41E-06x2 + 1.19E-03x + 7.80E-01	0-72
NDVI vs GR	Common	3.2	0.62	y = -8.67E-06x2 + 2.12E-03x + 7.25E-01	12.8-248.7
NDVI vs Chl	Common	3.2	0.52	y = -3.79E-02x2 + 3.60E-01x - 1.16E-02	2.7-5.7
NDVI vs N	Common	3.2	0.02	y = -1.90E-02x2 + 1.12E-01x + 6.50E-01	2.2-4.1
N vs Trt	Common	3.2	0.34	y = -4.20E-04x2 + 3.77E-02x + 2.40E+00	0-72
N vs GR	Common	3.2	0.62	y = -8.67E-06x2 + 2.12E-03x + 7.25E-01	12.8-248.7
N vs Chl	Common	3.2	0.23	y = 9.99E-02x2 - 6.20E-01x + 3.53E+00	2.7-5.7
Chl vs Trt	Common	3.2	0.83	y = -4.43E-04x2 + 6.16E-02x + 3.39E+00	0-72
Chl vs GR	Common	3.2	0.90	y = -9.28E-05x2 + 3.36E-02x + 2.75E+00	12.8-248.7
GR vs Trt	Common	3.2	0.61	y = -1.25E-02x2 + 2.79E+00x + 2.03E+01	0-72
NDVI vs Trt	Midfield	1.3	0.67	y = -7.27E-06x2 + 1.56E-03x + 7.58E-01	0-72
NDVI vs GR	Midfield	1.3	0.56	y = 4.56E-07x2 + 1.10E-04x + 7.25E-01	135.4-402.0
NDVI vs Chl	Midfield	1.3	0.05	y = -1.08E-02x2 + 9.90E-02x + 5.78E-01	3.0-4.8
NDVI vs N	Midfield	1.3	0.10	y = -8.31E-02x2 + 4.93E-01x + 8.10E-02	2.3-3.4
N vs Trt	Midfield	1.3	0.00	y = -3.36E-05x2 + 3.05E-03x + 2.87E+00	0-72
N vs GR	Midfield	1.3	0.56	y = 4.56E-07x2 + 1.10E-04x + 7.25E-01	135.4-402.0
N vs Chl	Midfield	1.3	0.06	y = -2.43E-02x2 + 3.71E-01x + 1.81E+00	3.0-4.8
Chl vs Trt	Midfield	1.3	0.15	y = 1.73E-04x2 - 6.10E-03x + 3.91E+00	0-72
Chl vs GR	Midfield	1.3	0.17	y = 2.65E-05x2 - 1.26E-02x + 5.32E+00	135.4-402.0
GR vs Trt	Midfield	1.3	0.77	y = -1.03E-02x2 + 3.08E+00x + 2.06E+02	0-72
NDVI vs Trt	Midfield	3.2	0.77	y = -1.90E-05x2 + 2.58E-03x + 7.78E-01	0-72
NDVI vs GR	Midfield	3.2	0.92	y = -2.88E-06x2 + 2.23E-03x + 4.35E-01	177.6-441.5
NDVI vs Chl	Midfield	3.2	0.36	y = 1.21E-01x2 - 1.11E+00x + 3.37E+00	3.8-5.1
NDVI vs N	Midfield	3.2	0.32	y = 2.36E-01x2 - 1.28E+00x + 2.54E+00	2.1-3.0
N vs Trt	Midfield	3.2	0.35	y = 2.24E-04x2 - 1.94E-02x + 2.81E+00	0-72
N vs GR	Midfield	3.2	0.20	y = -9.29E-07x2 - 1.12E-03x + 2.99E+00	177.6-441.5
N vs Chl	Midfield	3.2	0.24	y = -2.66E-01x2 + 2.71E+00x - 4.18E+00	3.8-5.1
Chl vs Trt	Midfield	3.2	0.18	y = 8.94E-05x2 - 1.15E-02x + 4.63E+00	0-72
Chl vs GR	Midfield	3.2	0.22	y = 1.87E-06x2 - 3.42E-03x + 5.25E+00	177.6-441.5
GR vs Trt	Midfield	3.2	0.71	y = -2.89E-02x2 + 4.19E+00x + 2.10E+02	0-72

[a]Independent variables are listed last
[b] Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %.

Table 15. 1997 bentgrass regressions for harvest 2.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Turfcenter	0.44	y = -1.00E-04x2 + 6.94E-03x + 4.71E-01	6-36
NDVI vs GR	Turfcenter	0.42	y = -6.87E-05x2 + 1.12E-02x + 1.53E-01	41.9-106.4
NDVI vs Chl	Turfcenter	0.37	y = 1.94E-02x2 - 2.40E-01x + 1.25E+00	6.9-8.5
NDVI vs N	Turfcenter	0.18	y = -2.33E-02x2 + 3.73E-01x - 7.45E-01	4.8-5.5
N vs Trt	Turfcenter	0.30	y = -9.85E-05x2 + 1.16E-02x + 4.93E+00	6-36
N vs GR	Turfcenter	0.01	y = -5.71E-05x2 + 8.01E-03x + 4.85E+00	41.9-106.4
N vs Chl	Turfcenter	0.53	y = 1.44E-02x2 + 1.94E-04x + 4.27E+00	6.9-8.5
Chl vs Trt	Turfcenter	0.20	y = -1.83E-03x2 + 9.10E-02x + 6.75E+00	6-36
Chl vs GR	Turfcenter	0.27	y = -7.13E-04x2 + 9.65E-02x + 4.63E+00	41.9-106.4
GR vs Trt	Turfcenter	0.44	y = 1.15E-02x2 + 6.31E-01x + 4.32E+01	6-36
NDVI vs Trt	Karsten	0.54	y = 3.33E-04x2 - 9.68E-03x + 1.46E+00	6-36
NDVI vs GR	Karsten	0.32	y = 4.00E-05x2 + 4.02E-04x + 1.31E+00	34.1-71.2
NDVI vs Chl	Karsten	0.10	y = -3.29E-02x2 + 4.24E-01x + 1.25E-01	5.4-8.1
NDVI vs N	Karsten	0.50	y = 1.35E-01x2 - 1.08E+00x + 3.53E+00	3.2-5.1
N vs Trt	Karsten	0.21	y = -2.32E-04x2 + 2.98E-02x + 4.13E+00	6-36
N vs GR	Karsten	0.14	y = 1.24E-03x2 - 1.17E-01x + 7.19E+00	34.1-71.2
N vs Chl	Karsten	0.67	y = -2.72E-01x2 + 4.20E+00x - 1.14E+01	5.4-8.1
Chl vs Trt	Karsten	0.01	y = -7.30E-04x2 + 3.31E-02x + 7.08E+00	6-36
Chl vs GR	Karsten	0.07	y = 1.60E-03x2 - 1.65E-01x + 1.15E+01	34.1-71.2
GR vs Trt	Karsten	0.07	y = 1.16E-02x2 - 2.88E-01x + 5.18E+01	6-36

[a]Independent variables are listed last
[b]Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %.

Table 16. 1997 bermudagrass regressions for harvest 3.

Regression[a]	Site	Height[b]	R^2	Equation	Range[c]
NDVI vs Trt	Common	1.3	0.40	y = -9.59E-06x2 + 1.11E-03x + 8.15E-01	0-72
NDVI vs GR	Common	1.3	0.50	y = -1.93E-06x2 + 7.95E-04x + 7.67E-01	57.4-222.6
NDVI vs Chl	Common	1.3	0.87	y = -2.13E-02x2 + 2.46E-01x + 1.86E-01	4.6-5.8
NDVI vs N	Common	1.3	0.39	y = -4.59E-02x2 + 3.87E-01x + 4.31E-02	3.2-3.9
N vs Trt	Common	1.3	0.71	y = -1E-04x2 + 0.013x + 3.2734	0-72
N vs GR	Common	1.3	0.59	y = -3.74E-05x2 + 1.26E-02x + 2.59E+00	57.4-222.6
N vs Chl	Common	1.3	0.35	y = -6.76E-02x2 + 1.03E+00x - 3.24E-03	4.6-5.8
Chl vs Trt	Common	1.3	0.38	y = -1.08E-04x2 + 1.58E-02x + 4.90E+00	0-72
Chl vs GR	Common	1.3	0.25	y = -5.97E-05x2 + 1.86E-02x + 3.96E+00	57.4-222.6
GR vs Trt	Common	1.3	0.58	y = -4.65E-02x2 + 4.27E+00x + 8.07E+01	0-72
NDVI vs Trt	Common	3.2	0.18	y = -1.09E-05x2 + 1.17E-03x + 8.63E-01	0-72
NDVI vs GR	Common	3.2	0.05	y = 3.66E-07x2 - 1.15E-04x + 8.89E-01	80.8-422.4
NDVI vs Chl	Common	3.2	0.13	y = 1.99E-04x2 + 1.89E-02x + 6.05E-01	3.5-6.4
NDVI vs N	Common	3.2	0.82	y = -1.18E-01x2 + 8.84E-01x - 7.62E-01	2.8-4.0
N vs Trt	Common	3.2	0.53	y = -4.59E-05x2 + 1.11E-02x + 3.29E+00	0-72
N vs GR	Common	3.2	0.22	y = 2.84E-06x2 + 8.63E-05x + 3.44E+00	80.8-422.4
N vs Chl	Common	3.2	0.49	y = -1.16E-01x2 + 1.44E+00x - 7.82E-01	3.5-6.4
Chl vs Trt	Common	3.2	0.17	y = -3.37E-04x2 + 3.12E-02x + 5.15E+00	0-72
Chl vs GR	Common	3.2	0.06	y = 4.43E-06x2 - 3.74E-03x + 6.12E+00	80.8-422.4
GR vs Trt	Common	3.2	0.46	y = 9.17E-03x2 + 1.68E+00x + 1.17E+02	0-72
NDVI vs Trt	Midfield	1.3	0.37	y = 1.24E-06x2 + 7.17E-04x + 6.69E-01	0-72
NDVI vs GR	Midfield	1.3	0.36	y = 3.52E-06x2 - 1.04E-03x + 7.47E-01	118.0-291.2
NDVI vs Chl	Midfield	1.3	0.13	y = 1.99E-04x2 + 1.89E-02x + 6.05E-01	3.9-6.4
NDVI vs N	Midfield	1.3	0.23	y = 2.14E-01x2 - 1.32E+00x + 2.72E+00	2.8-3.6
N vs Trt	Midfield	1.3	0.50	y = 4.98E-05x2 + 2.59E-03x + 2.94E+00	0-72
N vs GR	Midfield	1.3	0.22	y = 1.73E-06x2 + 1.75E-03x + 2.65E+00	118.0-291.2
N vs Chl	Midfield	1.3	0.28	y = 8.62E-02x2 - 6.79E-01x + 4.40E+00	3.9-6.4
Chl vs Trt	Midfield	1.3	0.36	y = 2.50E-04x2 - 5.64E-03x + 4.37E+00	0-72
Chl vs GR	Midfield	1.3	0.01	y = -2.00E-05x2 + 7.66E-03x + 4.00E+00	118.0-291.2
GR vs Trt	Midfield	1.3	0.54	y = -3.04E-02x2 + 3.25E+00x + 1.69E+02	0-72
NDVI vs Trt	Midfield	3.2	0.58	y = 7.00E-07x2 + 5.72E-04x + 7.85E-01	0-72
NDVI vs GR	Midfield	3.2	0.10	y = -6.50E-07x2 + 5.58E-04x + 6.92E-01	232.2-599.3
NDVI vs Chl	Midfield	3.2	0.65	y = -8.85E-03x2 + 1.10E-01x + 4.97E-01	3.3-5.4
NDVI vs N	Midfield	3.2	0.71	y = -1E-04x2 + 0.013x + 3.2734	2.2-3.3
N vs Trt	Midfield	3.2	0.56	y = -1.54E-05x2 + 8.88E-03x + 2.43E+00	0-72
N vs GR	Midfield	3.2	0.14	y = -3.96E-06x2 + 4.47E-03x + 1.58E+00	232.2-599.3
N vs Chl	Midfield	3.2	0.33	y = -9.89E-02x2 + 1.16E+00x - 4.61E-01	3.3-5.4
Chl vs Trt	Midfield	3.2	0.48	y = 1.50E-04x2 + 3.33E-03x + 4.07E+00	0-72
Chl vs GR	Midfield	3.2	0.20	y = -2.26E-05x2 + 1.77E-02x + 1.17E+00	232.2-599.3
GR vs Trt	Midfield	3.2	0.35	y = -6.84E-02x2 + 5.94E+00x + 3.32E+02	0-72

[a] Independent variables are listed last
[b] Height = mowing height in cm
[c] Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %.

Table 17. 1997 Bentgrass regressions for harvest 3.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Turfcenter	0.14	y = -2.31E-05x2 + 1.79E-03x + 8.01E-01	6-36
NDVI vs GR	Turfcenter	0.13	y = -3.67E-05x2 + 3.48E-03x + 7.58E-01	17.5-63.5
NDVI vs Chl	Turfcenter	0.60	y = 1.24E-02x2 - 1.10E-01x + 1.02E+00	2.7-6.9
NDVI vs N	Turfcenter	0.26	y = 1.05E-02x2 - 6.67E-02x + 9.06E-01	1.7-5.2
N vs Trt	Turfcenter	0.28	y = 4.33E-03x2 - 1.55E-01x + 5.08E+00	6-36
N vs GR	Turfcenter	0.64	y = -3.24E-03x2 + 2.14E-01x + 1.25E+00	17.5-63.5
N vs Chl	Turfcenter	0.94	y = -2.56E-02x2 + 9.67E-01x - 3.13E-01	2.7-6.9
Chl vs Trt	Turfcenter	0.27	y = 5.95E-03x2 - 2.17E-01x + 6.83E+00	6-36
Chl vs GR	Turfcenter	0.46	y = -3.85E-03x2 + 2.59E-01x + 1.92E+00	17.5-63.5
GR vs Trt	Turfcenter	0.48	y = -7.06E-02x2 + 3.43E+00x - 9.85E-01	6-36
NDVI vs Trt	Karsten	0.49	y = 2.16E-05x2 - 2.69E-05x + 7.58E-01	6-36
NDVI vs GR	Karsten	0.19	y = -3.59E-04x2 + 1.72E-02x + 5.67E-01	15.9-27.8
NDVI vs Chl	Karsten	0.55	y = 1.55E-02x2 - 1.99E-01x + 1.39E+00	5.4-7.8
NDVI vs N	Karsten	0.53	y = 1.34E-02x2 - 1.04E-01x + 9.57E-01	3.3-5.5
N vs Trt	Karsten	0.47	y = -1.09E-03x2 + 8.26E-02x + 3.58E+00	6-36
N vs GR	Karsten	0.02	y = -5.73E-03x2 + 2.39E-01x + 2.22E+00	15.9-27.8
N vs Chl	Karsten	0.33	y = 3.07E-01x2 - 3.70E+00x + 1.54E+01	5.4-7.8
Chl vs Trt	Karsten	0.32	y = 2.58E-03x2 - 7.63E-02x + 7.01E+00	6-36
Chl vs GR	Karsten	0.14	y = 9.94E-03x2 - 3.55E-01x + 9.68E+00	15.9-27.8
GR vs Trt	Karsten	0.02	y = -1.22E-03x2 + 9.33E-02x + 2.16E+01	6-36

[a]Independent variables are listed last

[b] Height = mowing height in cm

[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; **N** (tissue nitrogen) = %.

Table 18. 1997 Bermudagrass regressions for harvest 4.

Regression[a]	Site	Height[b]	R^2	Equation	Range[c]
NDVI vs Trt	Common	1.3	0.27	y = -2E-05x2 + 0.0014x + 0.79	0-72
NDVI vs GR	Common	1.3	0.49	y = -9E-06x2 + 0.002x + 0.758	17.0-54.2
NDVI vs Chl	Common	1.3	0.34	y = -0.0201x2 + 0.2031x + 0.31	3.5-5.6
NDVI vs N	Common	1.3	0.23	y = 0.0043x2 + 0.0303x + 0.68	2.6-3.4
N vs Trt	Common	1.3	0.63	y = -0.0002x2 + 0.0163x + 2.73	0-72
N vs GR	Common	1.3	0.23	y = -0.0007x2 + 0.0515x + 2.11	17.0-54.2
N vs Chl	Common	1.3	0.87	y = -0.0552x2 + 0.8535x + 0.26	3.5-5.6
Chl vs Trt	Common	1.3	0.58	y = -0.0005x2 + 0.0442x + 3.91	0-72
Chl vs GR	Common	1.3	0.37	y = -0.0019x2 + 0.1483x + 1.86	17.0-54.2
GR vs Trt	Common	1.3	0.18	y = -0.007x2 + 0.5983x + 26.91	0-72
NDVI vs Trt	Common	3.2	0.05	y = -1E-05x2 + 0.0008x + 0.84	0-72
NDVI vs GR	Common	3.2	0.00	y = -1E-06x2 + 0.0003x + 0.84	30.8-114.
NDVI vs Chl	Common	3.2	0.10	y = 0.1299x2 - 1.1308x + 3.301	3.9-4.8
NDVI vs N	Common	3.2	0.06	y = 0.4869x2 - 2.8303x + 4.960	2.7-3.1
N vs Trt	Common	3.2	0.31	y = -2E-05x2 + 0.0041x + 2.79	0-72
N vs GR	Common	3.2	0.28	y = -2E-05x2 + 0.0052x + 2.62	30.8-114.
N vs Chl	Common	3.2	0.62	y = 0.2425x2 - 1.8069x + 6.118	3.9-4.8
Chl vs Trt	Common	3.2	0.35	y = 1E-06x2 + 0.0067x + 4.190	0-72
Chl vs GR	Common	3.2	0.42	y = -7E-05x2 + 0.0197x + 3.45	30.8-114.
GR vs Trt	Common	3.2	0.56	y = 0.0197x2 - 0.6271x + 58.07	0-72
NDVI vs Trt	Midfield	1.3	0.16	y = -3E-05x2 + 0.0017x + 0.57	0-72
NDVI vs GR	Midfield	1.3	0.67	y = 6E-05x2 - 0.0064x + 0.712	30.8-114.
NDVI vs Chl	Midfield	1.3	0.28	y = -0.0607x2 + 0.3785x + 0.03	2.2-4.5
NDVI vs N	Midfield	1.3	0.02	y = 0.0043x2 - 0.0605x + 0.729	3.0-4.0
N vs Trt	Midfield	1.3	0.33	y = -6E-05x2 + 0.0107x + 3.24	0-72
N vs GR	Midfield	1.3	0.02	y = 8E-05x2 - 0.0114x + 3.859	30.8-114.
N vs Chl	Midfield	1.3	0.47	y = 0.1726x2 - 0.7987x + 3.968	2.2-4.5
Chl vs Trt	Midfield	1.3	0.01	y = -7E-05x2 + 0.0066x + 3.78	0-72
Chl vs GR	Midfield	1.3	0.24	y = 0.0002x2 - 0.0344x + 5.247	30.8-114.
GR vs Trt	Midfield	1.3	0.21	y = -0.0189x2 + 1.3612x + 49.6	0-72
NDVI vs Trt	Midfield	3.2	0.32	y = 3E-05x2 - 0.0016x + 0.636	0-72
NDVI vs GR	Midfield	3.2	0.14	y = -1E-05x2 + 0.002x + 0.564	36.7-147.
NDVI vs Chl	Midfield	3.2	0.06	y = 0.0218x2 - 0.1325x + 0.828	2.6-4.2
NDVI vs N	Midfield	3.2	0.09	y = 0.0523x2 - 0.3236x + 1.128	2.6-4.0
N vs Trt	Midfield	3.2	0.30	y = -4E-05x2 + 0.0104x + 2.93	0-72
N vs GR	Midfield	3.2	0.02	y = -2E-05x2 + 0.0056x + 2.93	36.7-147.
N vs Chl	Midfield	3.2	0.44	y = -0.1103x2 + 1.33x - 0.0779	2.6-4.2
Chl vs Trt	Midfield	3.2	0.34	y = 0.0001x2 + 0.0019x + 3.28	0-72
Chl vs GR	Midfield	3.2	0.13	y = -1E-05x2 - 0.0037x + 3.949	36.7-147.
GR vs Trt	Midfield	3.2	0.07	y = -0.0108x2 + 0.8764x + 69.9	0-72

[a]Independent variables are listed last

[b]Height = mowing height in cm

[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %.

Table 19. 1998 Bentgrass regressions for harvest 1.

Regression[a]	R^2	Equation	Range[b]
NDVI vs Trt	0.93	y = -2E-05x2 + 0.0024x + 0.7269	6-67
NDVI vs GR	0.74	y = -0.0001x2 + 0.0101x + 0.5857	20.0-44.6
NDVI vs Chl	0.76	y = -0.0036x2 + 0.0738x + 0.4404	5.4-9.2
NDVI vs Vis	0.89	y = -0.0031x2 + 0.0555x + 0.565	3.7-7.7
NDVI vs N	0.78	y = 0.0106x2 - 0.0442x + 0.7828	2.2-4.9
GNDVI vs Trt	0.95	y = -1E-05x2 + 0.0021x + 0.5603	6-67
GNDVI vs GR	0.77	y = -1E-04x2 + 0.0089x + 0.4347	20.0-44.6
GNDVI vs Chl	0.80	y = -0.003x2 + 0.0639x + 0.3071	5.4-9.2
GNDVI vs Vis	0.90	y = -0.0022x2 + 0.0443x + 0.4285	3.7-7.7
GNDVI vs N	0.79	y = 0.0123x2 - 0.0593x + 0.6436	2.2-4.9
N vs Trt	0.77	y = -0.0004x2 + 0.0583x + 2.7668	6-67
N vs GR	0.61	y = -0.0042x2 + 0.3263x - 1.8043	20.0-44.6
N vs Chl	0.70	y = -0.0822x2 + 1.7114x - 3.9605	5.4-9.2
N vs Vis	0.62	y = -0.0185x2 + 0.6349x + 0.9719	3.7-7.7
Vis vs Trt	0.84	y = -0.0005x2 + 0.0908x + 3.6678	6-67
Vis vs GR	0.76	y = -0.0033x2 + 0.3544x - 1.5758	20.0-44.6
Vis vs Chl	0.63	y = -0.0263x2 + 1.3116x - 2.1799	5.4-9.2
Chl vs Trt	0.86	y = -0.0002x2 + 0.0607x + 5.5326	6-67
Chl vs GR	0.68	y = -0.0031x2 + 0.3087x + 0.8972	20.0-44.6
GR vs Trt	0.85	y = 0.0004x2 + 0.293x + 19.809	6-67

[a]Independent variables are listed last

[b]Height = mowing height in cm

[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 20. 1998 Bentgrass regressions for harvest 2.

Regression[a]	R^2	Equation	Range[b]
NDVI vs Trt	0.98	y = -3E-05x2 + 0.0036x + 0.7951	6-67
NDVI vs GR	0.88	y = -5E-05x2 + 0.005x + 0.7801	9.8-66.9
NDVI vs Chl	0.91	y = -0.0035x2 + 0.0879x + 0.3546	7.0-12.2
NDVI vs Vis	0.91	y = -0.0021x2 + 0.0486x + 0.6442	4.0-8.3
NDVI vs N	0.96	y = -0.0099x2 + 0.1449x + 0.3897	3.8-6.2
GNDVI vs Trt	0.98	y = -3E-05x2 + 0.0036x + 0.6238	6-67
GNDVI vs GR	0.90	y = -5E-05x2 + 0.0052x + 0.6073	9.8-66.9
GNDVI vs Chl	0.92	y = -0.0036x2 + 0.0904x + 0.1691	7.0-12.2
GNDVI vs Vis	0.90	y = -0.0014x2 + 0.0414x + 0.4938	4.0-8.3
GNDVI vs N	0.96	y = -0.0075x2 + 0.1231x + 0.2686	3.8-6.2
N vs Trt	0.94	y = -0.0004x2 + 0.0605x + 3.754	6-67
N vs GR	0.88	y = -0.0009x2 + 0.0961x + 3.3738	9.8-66.9
N vs Chl	0.88	y = -0.0345x2 + 1.1017x - 2.1949	7.0-12.2
N vs Vis	0.84	y = -0.006x2 + 0.5319x + 1.9398	4.0-8.3
Vis vs Trt	0.92	y = -0.0008x2 + 0.1197x + 3.792	6-67
Vis vs GR	0.87	y = -0.0017x2 + 0.1854x + 3.0821	9.8-66.9
Vis vs Chl	0.82	y = -0.0436x2 + 1.6911x - 5.6138	7.0-12.2
Chl vs Trt	0.91	y = -0.0007x2 + 0.1153x + 6.8734	6-67
Chl vs GR	0.90	y = -0.0019x2 + 0.2056x + 5.8581	9.8-66.9
GR vs Trt	0.94	y = 0.0066x2 + 0.3383x + 7.721	6-67

[a]Independent variables are listed last
[b]Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 21. 1998 Bermudagrass regressions for harvest 1.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Common	0.80	y = -5E-06x2 + 0.0021x + 0.7221	24-293
NDVI vs GR	Common	0.92	y = -1E-05x2 + 0.0032x + 0.6838	13.2-189.8
NDVI vs Chl	Common	0.90	y = -0.0059x2 + 0.1242x + 0.2527	4.4-10.6
NDVI vs Vis	Common	0.79	y = -0.0105x2 + 0.1642x + 0.2677	3.7-8.3
NDVI vs N	Common	0.76	y = -0.0323x2 + 0.3157x + 0.1406	2.6-5.4
GNDVI vs Trt	Common	0.94	y = -5E-06x2 + 0.0021x + 0.5396	24-293
GNDVI vs GR	Common	0.96	y = -8E-06x2 + 0.0028x + 0.5192	13.2-189.8
GNDVI vs Chl	Common	0.91	y = -0.0026x2 + 0.0772x + 0.2365	4.4-10.6
GNDVI vs Vis	Common	0.84	y = -0.0082x2 + 0.1419x + 0.1425	3.7-8.3
GNDVI vs N	Common	0.91	y = -0.0263x2 + 0.2809x + 0.0098	2.6-5.4
N vs Trt	Common	0.98	y = -3E-05x2 + 0.0196x + 2.2913	24-293
N vs GR	Common	0.90	y = -6E-06x2 + 0.0168x + 2.4033	13.2-189.8
N vs Chl	Common	0.75	y = 0.0434x2 - 0.2222x + 2.7525	4.4-10.6
N vs Vis	Common	0.76	y = -0.0039x2 + 0.6055x + 0.3879	3.7-8.3
Vis vs Trt	Common	0.83	y = -9E-05x2 + 0.0395x + 3.2728	24-293
Vis vs GR	Common	0.77	y = -0.0002x2 + 0.0542x + 2.8655	13.2-189.8
Vis vs Chl	Common	0.63	y = -0.0298x2 + 1.1244x - 0.9711	4.4-10.6
Chl vs Trt	Common	0.80	y = -1E-04x2 + 0.0464x + 4.7786	24-293
Chl vs GR	Common	0.82	y = -0.0002x2 + 0.0724x + 3.9397	13.2-189.8
GR vs Trt	Common	0.94	y = -0.0024x2 + 1.3219x - 9.2656	24-293
NDVI vs Trt	Midfield	0.79	y = -3E-06x2 + 0.0013x + 0.7161	24-293
NDVI vs GR	Midfield	0.89	y = -3E-06x2 + 0.0018x + 0.6027	79.1-303.8
NDVI vs Chl	Midfield	0.89	y = -0.0129x2 + 0.2004x + 0.0799	4.3-7.5
NDVI vs Vis	Midfield	0.74	y = -0.0142x2 + 0.2238x - 0.0228	4.7-8.0
NDVI vs N	Midfield	0.85	y = -0.0531x2 + 0.4444x - 0.0691	2.6-4.3
GNDVI vs Trt	Midfield	0.87	y = -3E-06x2 + 0.0014x + 0.539	24-293
GNDVI vs GR	Midfield	0.93	y = -2E-06x2 + 0.0015x + 0.4478	79.1-303.8
GNDVI vs Chl	Midfield	0.88	y = -0.0053x2 + 0.1175x + 0.1318	4.3-7.5
GNDVI vs Vis	Midfield	0.81	y = -0.0092x2 + 0.1679x - 0.042	4.7-8.0
GNDVI vs N	Midfield	0.92	y = -0.0434x2 + 0.397x - 0.1872	2.6-4.3
N vs Trt	Midfield	0.94	y = -2E-05x2 + 0.0112x + 2.4251	24-293
N vs GR	Midfield	0.89	y = 3E-06x2 + 0.0066x + 2.0997	79.1-303.8
N vs Chl	Midfield	0.87	y = 0.0726x2 - 0.3632x + 2.8456	4.3-7.5
N vs Vis	Midfield	0.90	y = -0.0148x2 + 0.699x - 0.4438	4.7-8.0
Vis vs Trt	Midfield	0.90	y = -3E-05x2 + 0.019x + 4.6615	24-293
Vis vs GR	Midfield	0.85	y = 2E-05x2 + 0.0055x + 4.5252	79.1-303.8
Vis vs Chl	Midfield	0.85	y = 0.1542x2 - 0.9152x + 6.0759	4.3-7.5
Chl vs Trt	Midfield	0.90	y = -5E-05x2 + 0.0239x + 4.2058	24-293
Chl vs GR	Midfield	0.91	y = -1E-05x2 + 0.0188x + 3.1945	79.1-303.8
GR vs Trt	Midfield	0.92	y = -0.0027x2 + 1.5275x + 55.363	24-293

[a]Independent variables are listed last

[b]Height = mowing height in cm

[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 22. 1998 Bermudagrass regressions for harvest 2.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Common	0.74	y = -4E-06x2 + 0.0016x + 0.7886	24-293
NDVI vs GR	Common	0.90	y = -3E-06x2 + 0.0014x + 0.7413	39.6-395.6
NDVI vs Chl	Common	0.82	y = -0.0104x2 + 0.1698x + 0.2303	4.5-7.5
NDVI vs Vis	Common	0.78	y = 0.0011x2 + 0.0289x + 0.6012	5.3-8.3
NDVI vs N	Common	0.70	y = -0.0308x2 + 0.3074x + 0.1506	3.0-5.7
GNDVI vs Trt	Common	0.85	y = -5E-06x2 + 0.0019x + 0.6046	24-293
GNDVI vs GR	Common	0.93	y = -3E-06x2 + 0.0015x + 0.5607	39.6-395.6
GNDVI vs Chl	Common	0.82	y = -0.0071x2 + 0.1398x + 0.1247	4.5-7.5
GNDVI vs Vis	Common	0.87	y = 0.0078x2 - 0.0538x + 0.6776	5.3-8.3
GNDVI vs N	Common	0.83	y = -0.0305x2 + 0.319x - 0.068	3.0-5.7
N vs Trt	Common	0.94	y = -3E-05x2 + 0.0175x + 2.8583	24-293
N vs GR	Common	0.91	y = -6E-06x2 + 0.0092x + 2.7603	39.6-395.6
N vs Chl	Common	0.49	y = -0.0042x2 + 0.6983x - 0.0099	4.5-7.5
N vs Vis	Common	0.81	y = 0.4275x2 - 5.209x + 18.952	5.3-8.3
Vis vs Trt	Common	0.77	y = -7E-05x2 + 0.0277x + 5.7519	24-293
Vis vs GR	Common	0.83	y = -4E-05x2 + 0.0222x + 5.0802	39.6-395.6
Vis vs Chl	Common	0.86	y = -0.2785x2 + 4.2545x - 8.0765	4.5-7.5
Chl vs Trt	Common	0.72	y = -9E-05x2 + 0.0323x + 4.4901	24-293
Chl vs GR	Common	0.81	y = -5E-05x2 + 0.0264x + 3.6889	39.6-395.6
GR vs Trt	Common	0.97	y = -0.0031x2 + 2.1383x + 9.1705	24-293
NDVI vs Trt	Midfield	0.21	y = -2E-06x2 + 0.0005x + 0.7785	24-293
NDVI vs GR	Midfield	0.11	y = -4E-06x2 + 0.0022x + 0.4907	190.2-355.2
NDVI vs Chl	Midfield	0.09	y = -0.0091x2 + 0.1089x + 0.4834	4.2-6.4
NDVI vs Vis	Midfield	0.27	y = 0.0127x2 - 0.1384x + 1.1592	5.7-7.3
NDVI vs N	Midfield	0.21	y = -0.0374x2 + 0.3122x + 0.1602	3.2-5.0
GNDVI vs Trt	Midfield	0.37	y = -2E-06x2 + 0.0006x + 0.6261	24-293
GNDVI vs GR	Midfield	0.32	y = -4E-06x2 + 0.0022x + 0.3247	190.2-355.2
GNDVI vs Chl	Midfield	0.28	y = -0.0085x2 + 0.1087x + 0.3208	4.2-6.4
GNDVI vs Vis	Midfield	0.52	y = 0.0023x2 + 0.0007x + 0.5486	5.7-7.3
GNDVI vs N	Midfield	0.48	y = -0.033x2 + 0.2889x + 0.0385	3.2-5.0
N vs Trt	Midfield	0.74	y = -3E-05x2 + 0.0128x + 3.144	24-293
N vs GR	Midfield	0.56	y = -3E-05x2 + 0.0233x - 0.3763	190.2-355.2
N vs Chl	Midfield	0.37	y = -0.0652x2 + 1.248x - 0.7692	4.2-6.4
N vs Vis	Midfield	0.54	y = -0.2443x2 + 3.9696x - 11.512	5.7-7.3
Vis vs Trt	Midfield	0.53	y = -4E-05x2 + 0.0148x + 5.8173	24-293
Vis vs GR	Midfield	0.51	y = -0.0001x2 + 0.0742x - 4.1264	190.2-355.2
Vis vs Chl	Midfield	0.32	y = -0.1926x2 + 2.5168x - 1.2327	4.2-6.4
Chl vs Trt	Midfield	0.48	y = -2E-05x2 + 0.0101x + 4.6639	24-293
Chl vs GR	Midfield	0.31	y = -5E-06x2 + 0.01x + 3.0222	190.2-355.2
GR vs Trt	Midfield	0.70	y = -0.002x2 + 0.9625x + 206.19	24-293

[a]Independent variables are listed last

[b] Height = mowing height in cm

[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 23. 1998 bermudagrass regressions for harvest 3.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Common	0.79	y = -8E-07x2 + 0.0004x + 0.7871	24-293
NDVI vs GR	Common	0.81	y = -1E-06x2 + 0.0006x + 0.7772	20.3-211.6
NDVI vs Chl	Common	0.56	y = -0.0067x2 + 0.0965x + 0.4988	4.1-7.2
NDVI vs Vis	Common	0.61	y = 0.0002x2 + 0.0088x + 0.76	3.7-8.3
NDVI vs N	Common	0.68	y = -0.0053x2 + 0.0556x + 0.7044	1.7-4.3
GNDVI vs Trt	Common	0.84	y = -1E-06x2 + 0.0007x + 0.579	24-293
GNDVI vs GR	Common	0.78	y = -1E-06x2 + 0.0008x + 0.5725	20.3-211.6
GNDVI vs Chl	Common	0.69	y = -0.013x2 + 0.1793x + 0.0495	4.1-7.2
GNDVI vs Vis	Common	0.67	y = -0.0009x2 + 0.0268x + 0.5011	3.7-8.3
GNDVI vs N	Common	0.74	y = -0.0115x2 + 0.1058x + 0.4243	1.7-4.3
N vs Trt	Common	0.89	y = -5E-06x2 + 0.0084x + 2.0436	24-293
N vs GR	Common	0.75	y = -1E-05x2 + 0.0119x + 1.8028	20.3-211.6
N vs Chl	Common	0.71	y = 0.0025x2 + 0.8501x - 1.6994	4.1-7.2
N vs Vis	Common	0.67	y = 0.0205x2 + 0.1482x + 1.2175	3.7-8.3
Vis vs Trt	Common	0.82	y = -9E-05x2 + 0.0415x + 3.2977	24-293
Vis vs GR	Common	0.83	y = -0.0002x2 + 0.0612x + 2.2537	20.3-211.6
Vis vs Chl	Common	0.62	y = -0.4722x2 + 6.9313x - 17.279	4.1-7.2
Chl vs Trt	Common	0.71	y = -2E-06x2 + 0.0064x + 4.6368	24-293
Chl vs GR	Common	0.61	y = -6E-07x2 + 0.0084x + 4.4722	20.3-211.6
GR vs Trt	Common	0.94	y = -0.0026x2 + 1.432x - 4.0609	24-293
NDVI vs Trt	Midfield	0.82	y = -2E-06x2 + 0.0009x + 0.6144	24-293
NDVI vs GR	Midfield	0.74	y = -2E-06x2 + 0.0011x + 0.5502	84.1-266.7
NDVI vs Chl	Midfield	0.56	y = 0.0082x2 - 0.0306x + 0.6313	3.8-6.0
NDVI vs Vis	Midfield	0.63	y = -0.0012x2 + 0.0428x + 0.4544	4.7-8.0
NDVI vs N	Midfield	0.66	y = -0.0252x2 + 0.2391x + 0.1553	2.7-4.9
GNDVI vs Trt	Midfield	0.80	y = -6E-07x2 + 0.0005x + 0.5134	24-293
GNDVI vs GR	Midfield	0.81	y = 3E-06x2 - 0.0004x + 0.547	84.1-266.7
GNDVI vs Chl	Midfield	0.70	y = -0.0021x2 + 0.0695x + 0.2687	3.8-6.0
GNDVI vs Vis	Midfield	0.72	y = 0.0129x2 - 0.143x + 0.9316	4.7-8.0
GNDVI vs N	Midfield	0.79	y = -0.0286x2 + 0.2618x - 0.0034	2.7-4.9
N vs Trt	Midfield	0.85	y = -5E-06x2 + 0.0068x + 2.824	24-293
N vs GR	Midfield	0.73	y = 3E-05x2 - 0.001x + 2.8869	84.1-266.7
N vs Chl	Midfield	0.46	y = 0.0891x2 - 0.1679x + 2.2093	3.8-6.0
N vs Vis	Midfield	0.76	y = 0.1471x2 - 1.4333x + 6.5673	4.7-8.0
Vis vs Trt	Midfield	0.85	y = -3E-05x2 + 0.0188x + 4.784	24-293
Vis vs GR	Midfield	0.84	y = 2E-05x2 + 0.0096x + 4.2146	84.1-266.7
Vis vs Chl	Midfield	0.49	y = 0.3217x2 - 1.8552x + 7.6631	3.8-6.0
Chl vs Trt	Midfield	0.58	y = -1E-05x2 + 0.0083x + 4.1878	24-293
Chl vs GR	Midfield	0.60	y = -1E-05x2 + 0.0116x + 3.3724	84.1-266.7
GR vs Trt	Midfield	0.92	y = -0.0022x2 + 1.2411x + 64.866	24-293

[a]Independent variables are listed last
[b]Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 24. 1998 bermudagrass regression table harvest 4.

Regression[a]	Site	R^2	Equation	Range[b]
NDVI vs Trt	Common	0.77	y = -2E-06x2 + 0.0009x + 0.7432	24-293
NDVI vs GR	Common	0.69	y = -4E-06x2 + 0.0015x + 0.6966	46.8-174.3
NDVI vs Chl	Common	0.53	y = -0.0072x2 + 0.1119x + 0.3944	4.1-8.3
NDVI vs Vis	Common	0.61	y = -0.0026x2 + 0.0478x + 0.6136	3.3-8.0
NDVI vs N	Common	0.80	y = -0.0138x2 + 0.1316x + 0.5169	2.3-5.0
GNDVI vs Trt	Common	0.83	y = -1E-06x2 + 0.0005x + 0.6078	24-293
GNDVI vs GR	Common	0.82	y = -4E-06x2 + 0.0014x + 0.5505	46.8-174.3
GNDVI vs Chl	Common	0.51	y = -0.0049x2 + 0.079x + 0.3545	4.1-8.3
GNDVI vs Vis	Common	0.77	y = -0.0011x2 + 0.0275x + 0.5227	3.3-8.0
GNDVI vs N	Common	0.72	y = -0.0007x2 + 0.0282x + 0.5566	2.3-5.0
N vs Trt	Common	0.94	y = -3E-05x2 + 0.0182x + 2.1119	24-293
N vs GR	Common	0.87	y = -4E-05x2 + 0.03x + 1.0312	46.8-174.3
N vs Chl	Common	0.47	y = -0.1113x2 + 2.0643x - 4.6766	4.1-8.3
N vs Vis	Common	0.72	y = 0.0821x2 - 0.4578x + 3.1909	3.3-8.0
Vis vs Trt	Common	0.77	y = -1E-04x2 + 0.0415x + 3.3251	24-293
Vis vs GR	Common	0.81	y = -0.0004x2 + 0.1249x - 1.5236	46.8-174.3
Vis vs Chl	Common	0.46	y = -0.0445x2 + 1.6869x - 2.3592	4.1-8.3
Chl vs Trt	Common	0.72	y = -8E-05x2 + 0.0307x + 4.166	24-293
Chl vs GR	Common	0.50	y = -0.0002x2 + 0.052x + 2.7046	46.8-174.3
GR vs Trt	Common	0.94	y = -0.0018x2 + 0.9547x + 30.497	24-293
NDVI vs Trt	Midfield	0.82	y = -1E-06x2 + 0.0006x + 0.6887	24-293
NDVI vs GR	Midfield	0.76	y = -2E-06x2 + 0.0012x + 0.5934	100.7-241.2
NDVI vs Chl	Midfield	0.48	y = -0.0114x2 + 0.1772x + 0.0817	5.1-7.1
NDVI vs Vis	Midfield	0.69	y = -0.0024x2 + 0.0617x + 0.4433	5.0-7.7
NDVI vs N	Midfield	0.65	y = -0.0041x2 + 0.0928x + 0.4166	3.4-4.9
GNDVI vs Trt	Midfield	0.84	y = -8E-07x2 + 0.0004x + 0.5703	24-293
GNDVI vs GR	Midfield	0.74	y = -8E-07x2 + 0.0007x + 0.5191	100.7-241.2
GNDVI vs Chl	Midfield	0.54	y = -0.0071x2 + 0.1133x + 0.1794	5.1-7.1
GNDVI vs Vis	Midfield	0.73	y = 0.0009x2 + 0.0102x + 0.5039	5.0-7.7
GNDVI vs N	Midfield	0.75	y = -0.0042x2 + 0.076x + 0.3571	3.4-4.9
N vs Trt	Midfield	0.84	y = -3E-05x2 + 0.0137x + 3.3685	24-293
N vs GR	Midfield	0.70	y = -4E-05x2 + 0.0217x + 1.9064	100.7-241.2
N vs Chl	Midfield	0.73	y = -0.1509x2 + 2.479x - 5.2625	5.1-7.1
N vs Vis	Midfield	0.61	y = -0.0511x2 + 1.0566x - 0.3444	5.0-7.7
Vis vs Trt	Midfield	0.78	y = -4E-05x2 + 0.0188x + 4.9301	24-293
Vis vs GR	Midfield	0.78	y = -6E-05x2 + 0.037x + 2.0942	100.7-241.2
Vis vs Chl	Midfield	0.44	y = -0.4304x2 + 6.1933x - 15.395	5.1-7.1
Chl vs Trt	Midfield	0.47	y = -3E-05x2 + 0.014x + 5.2942	24-293
Chl vs GR	Midfield	0.45	y = -9E-05x2 + 0.0382x + 2.5414	100.7-241.2
GR vs Trt	Midfield	0.92	y = -0.0017x2 + 0.9547x + 85.902	24-293

[a]Independent variables are listed last
[b]Height = mowing height in cm
[c]Range = range of the independent variables in units of: Trt (Nrate) = kg N/ha; GR (growth rate) = kg/ha/day; Chl (chlorophyll) mg/g; N (tissue nitrogen) = %; Vis (visual rating) = no units.

Table 25. Analysis of variance for Common bermudagrass September 9, 1998.

Ind Var[a]	Dep Var[b]	F value	Pr > F
N rate	% tissue N	74.7	0.0001
N rate	Chlorophyll	9.73	0.0001
N rate	Growth Rate	67.43	0.0001

[a]independent variable
[b]dependent variable

VITA

Bryan Howell

Candidate for the degree of

Master of Science

Thesis: EFFECTIVENESS OF SENSOR BASED TECHNOLOGY TO DETERMINE NITROGEN DEFICIENCIES IN TURFGRASSES

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