THE RELATIONSHIP AMONG NDVI, NITROGEN AND IRRIGATION ON BERMUDAGRASS

(*Cynodon dactylon* [L.] Pers.)

BY

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CHAPTER 1

INTRODUCTION

GreenSeeker Optical Handheld Sensor Study

To evaluate turfgrass health status, response to treatments, or environment stresses, people usually use a subjective turfgrass quality evaluation system. Evaluation of turf quality is a routine but important job for turfgrass managers, researchers, and breeders. Turf quality includes both aesthetic and functional characteristics (Turgeon, 2001) qualities such as density, color, and texture are especially important to turf grass managers and clientele.

Visual quality ratings are the standard evaluation method for turf. Visual rating usually evaluates overall turfgrass quality, density, genetic color, turfgrass texture and percent living ground cover. Except for percent living ground cover, the precendented subjective system is based on a 1 to 9 rating using a whole number scale. One is the poorest or lowest and 9 is the best or highest. Other important attributes include spring green-up, winter color, pest problems, drought stress, winter injury, traffic tolerance and thatch accumulation. The practice of visual rating is not complicated, but it does require a properly trained and experienced evaluator to make the rating valuable. Evaluation timing is also important, because direct solar radiation coming from a nearly horizontal direction may disturb the evaluator, the time between midmorning and early afternoon is the best choice for rating (Bell et al., 2002a). Another limitation of visual rating may be its subjective nature (Bell et al., 2000a). Ratings may be inconsistent from person to person and from day to day for same person (Trenholm et al., 1999). Bell et al. (2002a) demonstrated that the ratings of individual evaluators differed significantly (P = 0.05) for turf color, texture, and percent live cover among three researchers with 12, 7 and 3 years' experience. Furthermore, some minor or subtle differences in turf response to different treatments or early stages of environmental stress are not easily discerned by human eyes (Bell et al., 2002b; Fitz-Rodríguez et al., 2002), or simply may not be discriminated using a whole number scale. By contrast, optical detectors provide an unbiased, highly consistent method for turfgrass quality evaluation that requires minimal training and experience.

Optical sensors measure the irradiance reflected from a turfgrass canopy. Solar radiation or artificial radiation projected by the sensor apparatus may also be transmitted to the soil or absorbed by plants. Compared with reflectance or absorbance, transmittance is usually lower because of the normally dense turf canopy (Trenholm et al., 1999; Knipling, 1970). In the visible spectrum (400-700 nm), referred to as photosynthetically active radiation (PAR), the irradiance reflected from a plant canopy is relatively low because PAR is strongly absorbed by plant pigments, especially chlorophylls. However, near-infrared (NIR) radiation (700-1300 nm) is highly reflected because of internal leaf scattering and low absorption (Knipling, 1970; Asrar, 1984). Absorption can be relatively high again in the infrared beyond 1300 nm due to absorption by water. Within PAR, chlorophyll absorbs light with peaks at 430 nm (blue) and 680 nm (red) wavelengths. Green light (500-600 nm) is not as highly absorbed as red and blue and a comparatively large portion is reflected from a plant canopy (Buchanan et al, 2000; Knipling, 1970;

Blackmer, 1994; Bell, 2000b). This accounts for the green color perceived by human eyes.

Leaf physical characteristics, such as cell structure, tissue water content, and pigment concentration may affect plant canopy reflectance, transmittance, and absorption (Maas, 1989). Knipling (1970) indicated that a leaf reflectance spectrum change in the visible wavelengths can be caused by the sensitivity of chlorophyll to metabolic disturbances under stress. This research further indicated that leaf chlorophyll content has a negative relationship with green light reflection (500-600 nm) and a positive relationship with near- infrared reflection (Blackmer, 1994; Adcock, 1990). In the near and middle infrared wavelengths (1300-3000 nm), stress-induced leaf reflectance variations have been attributed to altered leaf mesophyll structure and water content (Gausman, 1969; Knipling, 1970; Carlson, 1971). From N-deprived canopies, reflectance of red wavelengths (600-700 nm) increased while near-infrared reflectance decreased according to Walburg (1981). These studies confirmed that optical sensing has potential for monitoring the growth and development of a crop (Walburg, 1981).

In the 1980s, remote sensing was introduced into agriculture as a complementary monitoring tool to estimate crop health status, growth, environmental stress and crop yield (Fitz-Rodríguez et al., 2002). Many scientists have contributed in the effort to find the relationship between the spectral and agronomic characteristics of plant canopies and the ultimately attempt to determine useful vegetation indices based on spectral reflection. In the early 1980s, Walburg et al. (1981) used an Exotech 20C spectroradiometer to detect reflected radiance from 400 nm to 2400 nm on corn (Ze*a mays* L.) grown under four N treatment levels. All wavelengths measured responded to nitrogen treatment effects. Research on soybean (*Glycine max* (L.) Merr*)* indicated that reflectance near the 550 nm wavelength was best for separating three N treatments (Chappelle et al., 1992). This result was supported by Blackmer et al. (1994) on corn. Filella et al. (1995) measured several reflectance wavebands on wheat receiving five different fertilization treatments and found that reflectance at 550 nm, 680 nm, and all the red edge parameters (defined as maximum slope in the vegetation reflectance spectra between the red and near infrared regions) were significantly correlated with canopy chlorophyll a content. Osborne et al. (2002) also suggested that plant N concentration was best predicted using reflectance in the red and green regions of the spectrum, however, the blue region were found best to predict early season P stress on corn among reflectance measured from 350 to 1000 nm. Riedell et al. (1999) measured leaf reflectance from 350 to 1075 nm on wheat (*Triticum aestivum* L.) and found that reflectance in the 625 to 635 nm and the 680 to 695 nm bands were good indicators of chlorophyll loss and leaf senescence caused by Russian wheat aphids (*Diuraphis noxia* Mordvilko). Daughtry et al. (1992) demonstrated that the fraction of absorbed PAR can be estimated with remotely sensed multispectral data (seven wavebands from 450-2350 nm) and that phytomass production can be estimated as a function of accumulated absorbed PAR for corn and soybean. The researchers also proposed that since grain yield of corn crops is closely linked to the accumulation of dry phytomass, it may be possible to estimate grain yields from total dry phytomass. The combination of these two concepts may provide the basis to estimate crop yield by monitoring canopy multispectral reflectance. Since chlorophyll content is highly correlated with leaf N concentration (Filella et al, 1995; Serrano et al, 2000;

Daughtry et al., 2000), finding the best way to estimate leaf N concentration became a major thrust for agronomic optical sensing.

To help achieve estimations of leaf N concentration, new detectors called chlorophyll meters were developed and became commercially available. Among them, the Minolta SPAD 502 chlorophyll meter (Spectrum Technologies, Plainfield, Illinois) is most popular. It measures the amount of chlorophyll in the leaf, that is, the greenness of the leaf, by transmitting light from light emitting diodes (LED) through a leaf at wavelengths of 650 and 940 nm. The meter calculates an index normalized for variables, such as leaf thickness and cuticle reflectance properties which are not directly related to pigment concentration (Adamsen et al, 1999). The chlorophyll meter and canopy reflectance provide two nondestructive methods to estimate leaf N concentration and determine fertilizer requirements. Some researchers recommended the chlorophyll meter as a good choice for nitrogen management (Turner et al, 1991; Hussain et al., 2000), but others disagreed. Johnson et al. (2003) believed that the SPAD 502 meter was unable to distinguish between levels of nitrogen in cotton *(Gossypium hirsutum* L.*)* at the first week of bloom, although it was able to distinguish between plots with or without nitrogen treatments. Other research compared light reflectance and the Minolta SPAD 502 chlorophyll meter. Blackmer et al. (1994) measured light reflectance (400-700 nm) on corn and demonstrated that reflectance near 550 nm was better able to separate N treatment differences than the chlorophyll meter. However, the authors believed that a better relationship with yield could be expected if the chlorophyll meter readings were taken from 30 leaves as recommended, a time intensive process, instead of collecting 30 readings from only 10 leaves, the method used in the study. Again, in similar research conducted on corn, canopy light reflectance recorded from eight wavelengths between 450 nm and 800 nm was more strongly correlated with field greenness at almost all growth stages compared to the SPAD 502 chlorophyll meter (Ma et al., 1996). It was suggested by the authors that light reflectance measurements may provide better in-season indications of N deficiency. Other researchers were not only concerned about the large number of random chlorophyll meter observations needed to make statistical comparisons meaningful, but were also concerned about the physical contact with the leaf by the meter that makes damage inevitable (Adamsen et al, 1999). Therefore, canopy reflectance was deemed a more reliable method for estimating plant status.

Although many researchers successfully demonstrated that several different canopy reflectance wavebands had strong relationships with plant status, dissension still existed concerning methods of optical measurement and derived plant indices. Some researcher believed that one single wavelength was inaccurate in some cases because of its sensitivity to biomass, variable irradiance, and background effects (Munden et al., 1994). Filella et al. (1995) confirmed the limitations of single wavebands for chlorophyll a estimation when sensitivity was reduced due to wavelength saturation at medium chlorophyll concentrations. Walburg et al. (1981) demonstrated that the near-infrared/red ratio was better than any single waveband from 400 to 2400 nm for measuring the response to N treatments in corn. The researchers found that the NIR/RED ratio enhanced the difference in treatment effects in canopy reflectance by reducing reflectance variability caused by extraneous factors, such as soil moisture. Wanjura et al. (1987) indicated that usually vegetation indices (VI), which were defined as the combination of observations from two or more spectral wavelengths according to mathematic formulas to derive single spectrally-based numbers, have greater sensitivity to plant vegetation reflectance than does the reflectance of a single wavelength. There are different indices used to estimate crop quality or yield, including R_{750}/R_{550} (maximum reflectance near 750 nm / maximum reflectance near 550 nm), R_{750}/R_{650} (maximum reflectance near 750 nm / minimum reflectance near 650 nm), simple ratios like SR (SR=R_{900}/R_{680}), the photochemical reflectance index (PRI), (R_{531}-R_{570}) / (R_{531}+R_{570}), the relative nitrogen vegetation index (RNVI) (near-infrared / green reflectance), the normalized total pigment to chlorophyll a ratio index (NPCI), (R_{380}-R_{430}) / (R_{680}+R_{430}), the water band index (WBI) (R_{950}/R_{900}), the normalized difference vegetation index (NDVI), [(R_{nir}-R_{red}) / (R_{nir}+R_{red}),] and other new indices like the yellowness index (YI), which estimate the degree of leaf chlorosis from the concavity-convexity of the reflectance spectrum at a wavelength near the midpoint between the maximum at 550 nm and the minimum at 670 nm (Adams et al., 2000). Most of these indices involve the green (500-600 nm), red (600-700 nm), and near infrared (700-900 nm) bands (Plant et al., 1999). Among them, normalized difference vegetation index (NDVI) is the most commonly used (Tucker, 1979).

According to Perry et al. (1984), the first proposal for use of the normalized difference vegetation index (NDVI) was in the 1970s. Asrar et al. (1984) procedure was developed: compared to soil, green vegetation reflectance is very high in near-infrared wavelengths, while most visible radiation is absorbed. Consequently, combining visible and near infrared reflectance would estimate the fraction of incident radiation absorbed by the plant canopy as a function of leaf area index. Since around 680 nm, chlorophyll a absorption is maximum and red reflectance increases and near infrared reflectance decreases when plant greenness declines, the comparison of red and NIR wavebands should be most effective. NDVI was defined as (R_{NIR} –R_{red}) / (R_{NIR} + R_{red}). The specific NIR and red wavelength range used for the calculation varies with individual studies but often corresponds to the bands used in resource monitoring satellites (Adamsen et al, 1999). Normalized difference vegetation indices typically range from 0.1 up to 0.9, with higher values associated with greater density and greenness of the plant canopy. Soil values are close to zero. When plants are under water stress, disease or other environment stress, their leaves reflect significantly less NIR and more red irradiance. As a result, the NDVI value is smaller than usual when plants are stressed.

A number of experiments suggested that NDVI was a good indicator of plant status. Adamsen et al. (1999) compared NDVI and G/R on wheat and found that both of the two indices were good chlorophyll concentration indicators, but NDVI was more sensitive at low values than G/R. Adams et al. (2000) compared NDVI and R_{750}/R_{650} on soybean with micronutrient deficiency treatments and found that NDVI was more sensitive than R_{750}/R_{650} at lower chlorophyll concentrations. They concluded that NDVI is a more valuable measure for detecting deficiencies, because it will plateau when the plant is adequately supplied with nutrients. Other research showed that NDVI was a good indicator of barley (*Hordeum vulgare* L.) biomass and yield affected by salinity treatments (Peñuelas et al., 1997). On corn, Ma et al. (1996) demonstrated that NDVI was strongly correlated with field greenness, therefore NDVI could be used to estimate corn yield at harvest. On cotton, NDVI indicated the presence of nitrogen stress even in those cases where the stress did not result in a significant yield reduction and also showed NDVI decline approximately coincident with the onset of measurable water stress (Plant et al., 1999). In summary, NDVI has been related to many important crops and crop stresses.

On turfgrass, Schuerger et al. 2003 used NDVI, (R_{760}-R_{695}) / (R_{760}+R_{695}), to detect zinc stress in Bahiagrass (*Paspalum notatum* Flugge) and demonstrated that it was effective for predicting the concentrations of chlorophyll in canopies grown at various levels of Zn. Green et al. (1998) related NDVI to disease measurement. Bell et al. (2000a) indicated that NDVI, (R_{780}-R_{671}) / (R_{780}+R_{671}), was effective for measuring herbicide damage on bermudagrass turf. Trenholm et al. (1999) measured NDVI (R_{935}-R_{661}) / (R_{935}+R_{661}) on seven seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes and three hybrid bermudagrass (*Cynodon dactylon* L. × *C. transvaalensis* Burtt-Davy) cultivars and regressed against visual quality scores. The results demonstrated that NDVI was highly correlated with visual turf quality, shoot density, and shoot tissue injury rating; and the relationship between NDVI and visual quality were approximately linear. This relationship was supported by Fitz-Rodríguez et al. (2002). Bell et al. (2002a) measured NDVI on a National Turfgrass Evaluation Program (NTEP) tall fescue (*Festuca arundinacea* Schreb) trial and creeping bentgrass (*Agrostis palustris* Huds., *A. stolonifera* L.) trial. They found that NDVI was closely correlated with visual evaluations for turf color, moderately correlated with percent live cover, and independent of texture, and developed an empirical prediction equation. Trenholm et al. (1999) predicted that NDVI could further be used to discriminate water stress in turf. Research has also focused on relating NDVI with nitrogen content response. Keskin et al. (2001) developed empirical relationships between the nitrogen contents and the spectral reflectance data and NDVI from creeping bentgrass (*Agrostis palustris* Huds.) clippings and found that the reflectance values in green band (520-580 nm) and the NIR band (770-1050 nm) increased as the nitrogen content increased. Among all of these single wavelength reflections and NDVI, a discrimination analysis showed that the regression models performed no difference.

In summary, NDVI has been used to measure a number of crop status parameters. However, the relationships among these parameters and resulting NDVI have not been determined. Although research has demonstrated that turf water stress (Trenholm et al. 1999) and N content (Keskin et al., 2001) affects NDVI, research has not examined NDVI resulting from the interaction of water stress and nitrogen status. If this relationship can be determined, turf managers will be able to make accurate assessments of moisture status and N status independently using NDVI measurements obtained from a single sensor scan. It will be helpful to relieve turf from highly intensive management practices based on superintends' past experiences. With the optimizing fertilizer and water applications practices, the turf can be maintained in good quality while reducing the risk of environment pollution.

Airfield Sand System Study

Sports field superintendents try to maintain a firm, smooth, and well drained turfgrass playing surfaces. To achieve these goals, researchers and practitioners have found that native silt or clay soils are not satisfactory to encourage a root zone which remains highly oxygenated without severely restricting its water-holding capacity. On the other hand, sand with its ideal physical characteristics, including proper particle size, better compaction resistance and aeration porosity, and high infiltration rate, is considered a best replacement as a growing medium for turfgrass. By 1960, the USGA

(United State Golf Association) Green Section had recommended using sand based root zones to construct more acceptable putting or playing surfaces with tolerance for traffic and compaction.

The traditional recommended sand based root zone system is the USGA sand system. It consists of a 90:10 sand-peat mixes (v/v) for 30.48 cm (12 inches) with a perched water table resulting from the fine sand-peat mix over 10.16 cm (4 inches) of gravel. In this system, water must fill all of the finer pores of the sand before entering the coarser pea gravel for vertical drainage. The USGA sand system effectively increases drainage while providing a certain amount of water holding capacity. However, there is another concern that during humid warm summers, the extra moisture potentially available in the perched water table may have a negative function. With extra water stored, the root zone has less air-filled porosity. Also the water acts as an insulator, resulting in root zones with high relative soil temperature which is not easy to cool (Ervin and Fresenburg, 1999). High soil temperature and less air availability imply greater root stress, especially in summer.

Due to these concerns and high price of construction, several non-USGA sand systems have been developed. One of them is the California system. The California sand system is a 10 inch sand layer with high total porosity over native soil. In general, the California sand system has finer particle size distribution than recommended by the USGA. Because it does not employ the perched water table concept like USGA, it is usually cheaper in establishment. According to Ervin and Fresenburg (1999), the California sand system displayed better germination and early establishment after seeding and greater root mass to a four inch depth compared with the USGA sand system in Missouri.

Another non-USGA sand system is the Airfield System distributed by Airfield Systems, LLC (Edmond, OK). The Airfield system utilizes a custom porous sand root-zone mix which is placed on a Lutradur filter fabric which allows for the migration of fine particles (e.g. sand, silt, clay and organic materials) to pass through without clogging. Below the filter fabric is the Draincore2 ring and grid structure that provides the void space (1 inch) for both water and air movement. These movements make drainage and air exchange very effective. Below the Draincore2 structure lays an impervious membrane against the sub grade which slopes to perimeter drains where water is collected. According to Airfield Systems, this construction maximizes air in development, drains water 13 times faster and reduces irrigation requirements by up to 70 percent over any other system available. It also reduces construction time which contributes to the lower overall cost of the system. This system has utilized on the Texas A&M soccer field and "has met or exceeded all of expectations on performance," Craig Potts, Texas A&M Athletic Field Manager.

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CHAPTER II

The Relationship among NDVI, Nitrogen, and Irrigation on Bermudagrass (*Cynodon dactylon* [L.] Pers.).

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Abstract

The normalized difference vegetation index (NDVI) is one of the most widely used vegetation indices for determining crop parameters. It has been associated with plant nitrogen deficiency, dehydration and other stresses. The purpose of this study was to examine the relationships among bermudagrass responses to NDVI, nitrogen (N) fertilization and irrigation and measure the individual contributions of N and irrigation on NDVI. Two common bermudagrass (*Cynodon dactylon* [L.] Pers.) cultivars 'Yukon' and 'Riviera', were managed under three irrigation and six nitrogen treatments during the growing seasons in 2003 and 2004. Tissue moisture, tissue nitrogen, NDVI, green NDVI (GNDVI), and chlorophyll concentration response to N fertilization and irrigation were measured.

Based on this study, both NDVI and GNDVI were good indices of turf quality. The average NDVI of 0.82 and 0.85 were determined to the minimum acceptable and target turf quality indices on bermudagrass. As seasonal changes occurred, it was necessary to adjust the minimum acceptable and target turf NDVI values according to early, peak, mid and late seasons.

The result of this study suggested that tissue moisture was not affected by soil water availability (providing dehydration stress did not exist), but did vary by N fertilization and seasonal influences. Similar to tissue moisture, chlorophyll did not vary by irrigation amount, but was affected by N fertilization. Bermudagrass tissue nitrogen was affected by soil N availability, and higher N fertilization led to higher tissue N. Tissue N varied by season, and was highly correlated with NDVI. Cultivar 'Yukon' maintained better turf quality in the late growing season, while cultivar 'Riviera' performed better in the early growing season.

The results from path analysis suggested that NDVI was mainly influenced by tissue moisture and chlorophyll concentration. The path coefficients for chlorophyll concentration and tissue moisture effects on NDVI were 0.39 and 0.35 respectively. Tissue N had a small direct influence on NDVI (path coefficient = 0.06), and a much larger indirect influence through tissue moisture and chlorophyll. Tissue N and tissue moisture both influenced chlorophyll concentration, but the influence of tissue N on chlorophyll was 2.7 times greater than the influence of tissue moisture on chlorophyll.

Introduction

To evaluate turfgrass health status, response to treatments, or environment stresses, people usually use a subjective (visual) turfgrass quality evaluation system. Evaluation of turf quality is a routine but important job for turfgrass managers, researchers, and breeders. Turf quality includes both aesthetic and functional characteristics (Turgeon, 2001). Qualities such as density, color, and texture are especially important to turfgrass managers and clientele.

Visual quality ratings are the standard evaluation method for turf. Visual rating is used to evaluate overall turfgrass quality, density, genetic color, turfgrass texture and other important factors. Except for percent living ground cover, the precendented subjective system is based on a 1 to 9 visual rating using a whole number scale. One is the poorest or lowest and 9 is the best or highest. Other important attributes include spring green-up, winter color, pest problems, drought stress, winter injury, and traffic tolerance. The practice of visual rating is not complicated, but it does require a properly trained and experienced evaluator to make the rating valuable. Evaluation timing is also important, because direct solar radiation coming from a nearly horizontal direction may affect the evaluation. The time between midmorning and early afternoon is the best choice for accurate rating (Bell et al., 2002a). Another limitation of visual rating may be its subjective nature (Bell et al., 2000a). Ratings may be inconsistent from person to person and from day to day for the same person (Trenholm et al., 1999). Bell et al. (2002a) demonstrated that the ratings of individual evaluators differed significantly (P = 0.05) for turf color, texture, and percent live cover among three researchers with 12, 7 and 3 years' experience. Furthermore, some minor or subtle differences in turf response to different treatments or early stages of environmental stress are not easily discerned by human eyes, or simply may not be discriminated using a whole number scale (Bell et al., 2002b; Fitz-Rodríguez et al., 2002). By contrast, optical detectors provide an unbiased, highly consistent method for turfgrass quality evaluation that requires minimal training and experience.

Optical sensors measure the irradiance reflected from a turfgrass canopy. Solar radiation or artificial radiation projected by the sensor apparatus may also be transmitted to the soil or absorbed by plants. Compared with reflectance or absorbance, transmittance is usually lower because of the normally dense turf canopy (Trenholm et al., 1999; Knipling, 1970). In the visible spectrum (400-700 nm), referred to as photosynthetically active radiation (PAR), the irradiance reflected from a plant canopy is relatively low because PAR is strongly absorbed by plant pigments, especially chlorophylls. However, near-infrared (NIR) radiation (700-1300 nm) is highly reflected because of internal leaf scattering and low absorption (Knipling, 1970; Asrar, 1984). Absorption can be relatively high again in the infrared beyond 1300 nm due to absorption by water. Within PAR, chlorophyll absorbs light with peaks at 430 nm (blue) and 680 nm (red) wavelengths. Green light (500-600 nm) is not as highly absorbed as red and blue and a comparatively large portion of green light is reflected from a plant canopy (Buchanan et al, 2000; Knipling, 1970; Blackmer, 1994; Bell, 2000b). This accounts for the green color of plants perceived by human eyes.

Leaf physical characteristics, such as cell structure, tissue water content, and pigment concentration may affect plant canopy reflectance, transmittance, and absorption (Maas, 1989). Knipling (1970) indicated that spectral changes within the PAR can be caused by the sensitivity of chlorophyll to metabolic disturbances under stress. This research further indicated that leaf chlorophyll content has a negative relationship with green light reflection (500-600 nm) and a positive relationship with near-infrared reflection (Blackmer, 1994; Adcock, 1990). In the near and middle infrared wavelengths (1300-3000 nm), stress-induced leaf reflectance variations have been attributed to altered leaf mesophyll structure and water content (Gausman, 1969; Knipling, 1970; Carlson, 1971). From N-deprived canopies, reflectance of red wavelengths (600-700 nm) increased while near-infrared reflectance decreased according to Walburg (1981). These studies suggested that optical sensing has potential for monitoring the growth and development of a crop (Walburg, 1981).

In the 1980s, remote sensing was introduced into agriculture as a complementary monitoring tool to estimate crop health status, growth, environmental stress and crop yield (Fitz-Rodríguez et al., 2002). Many scientists have contributed in the effort to find the relationship between the spectral and agronomic characteristics of plant canopies and ultimately the attempt to determine useful vegetation indices based on spectral reflection. Walburg et al. (1981) used an Exotech 20C spectroradiometer to detect reflected radiance from 400 nm to 2400 nm from corn (Ze*a mays* L.) grown under four N treatment levels. All of the wavelengths measured responded to nitrogen treatment effects. Research on soybean (*Glycine max* (L.) Merr*)* indicated that reflectance near the 550 nm wavelength was best for separating three N treatments (Chappelle et al., 1992). This result was supported by Blackmer et al. (1994) on corn. Filella et al. (1995) measured several reflectance wavebands on wheat (*Triticum aestivum* L.) receiving five different fertilization treatments and found that reflectance at 550 nm, 680 nm, and all the red edge parameters (defined as maximum slope in the vegetation reflectance spectra between the red and near infrared regions) were significantly correlated with the canopy content of chlorophyll a. Osborne et al. (2002) also suggested that plant N concentration was best predicted using reflectance in the red and green regions of the spectrum but the blue region was the best predictor of early season P stress in corn among wavelengths from 350 to 1000 nm. Riedell et al. (1999) measured leaf reflectance from 350 to 1075 nm on wheat and found that reflectance in the 625 to 635 nm and the 680 to 695 nm bands were good indicators of chlorophyll loss and leaf senescence caused by Russian wheat aphids (*Diuraphis noxia* Mordvilko). Daughtry et al. (1992) demonstrated that the fraction of absorbed PAR can be estimated with remotely sensed multispectral data (seven wavebands from 450-2350 nm) and that phytomass production can be estimated as a function of accumulated absorbed PAR for corn and soybean. The researchers also proposed that since grain yield of corn crops is closely linked to the accumulation of dry phytomass, it may be possible to estimate grain yields from total dry phytomass. The combination of these two concepts may provide the basis to estimate crop yield by monitoring canopy multispectral reflectance. Since chlorophyll content is highly correlated with leaf N concentration (Filella et al, 1995; Serrano et al, 2000; Daughtry et al., 2000), finding the best way to estimate leaf N concentration became a major thrust for agronomic optical sensing.

To help achieve accurate estimations of leaf N concentration, leaf absorbance detectors called chlorophyll meters were developed and became commercially available. Among them, the Minolta SPAD 502 chlorophyll meter (Spectrum Technologies, Plainfield, Illinois) is most popular. It measures the amount of chlorophyll in the leaf, that is, the greenness of the leaf, by transmitting light from light emitting diodes (LED) through a leaf at wavelengths of 650 and 940 nm. The meter calculates an index normalized for variables, such as leaf thickness and cuticle reflectance properties which are not directly related to pigment concentration (Adamsen et al, 1999). The chlorophyll meter and canopy reflectance detectors provide two nondestructive methods to estimate leaf N concentration and determine fertilizer requirements. Some researchers recommended the chlorophyll meter as a good choice for nitrogen management (Turner et al, 1991; Hussain et al., 2000), but others did not support it. Johnson et al. (2003) found that the SPAD 502 meter was unable to distinguish between levels of nitrogen in cotton *(Gossypium hirsutum* L*.)* at the first week of bloom, although it was able to distinguish between plots with or without nitrogen treatments. Blackmer et al. (1994) measured light reflectance (400-700 nm) on corn and demonstrated that reflectance near 550 nm was better able to identify N treatment differences than the chlorophyll meter. However, the authors believed that a better relationship with yield could be expected if the chlorophyll meter readings were taken from 30 leaves as recommended, a time intensive process, instead of collecting 30 readings from only 10 leaves, the method used in the study. Again, in similar research conducted on corn, canopy reflectance recorded from eight wavelengths between 450 nm and 800 nm was more strongly correlated with field greenness at almost all growth stages compared to the SPAD 502 chlorophyll meter (Ma et al., 1996). The authors suggested that light reflectance measurements could provide better in-season indications of N deficiency. The use of chlorophyll meters is time consuming because large numbers (~30) of observations are needed to make statistical comparisons meaningful. There is also a concern about the physical meter to leaf contact that makes damage inevitable (Adamsen et al, 1999). Therefore, canopy reflectance was deemed faster, less destructive, and more reliable than chlorophyll meters for estimating plant status.

Although many researchers successfully demonstrated that several different canopy reflectance wavebands had strong relationships with plant status, dissension still existed concerning methods of optical measurement and derived plant indices. Some researchers believed that a single wavelength was inaccurate in some cases because of its sensitivity to biomass, variable irradiance, and background effects (Munden et al., 1994). Filella et al. (1995) confirmed the limitations of single wavebands for chlorophyll a estimation when sensitivity was reduced due to wavelength saturation at medium chlorophyll concentrations. Walburg et al. (1981) demonstrated that the near-infrared/red ratio was better than any single waveband from 400 to 2400 nm for measuring corn plant response to N treatments. The researchers found that the NIR/RED ratio enhanced the difference in treatment effects in canopy reflectance by reducing reflectance variability caused by extraneous factors, such as soil moisture. Wanjura et al. (1987) indicated that vegetation indices (VI), which were defined as the combination of observations from two or more spectral wavelengths according to mathematic formulas to derive single spectrally-based numbers, usually had greater sensitivity to plant reflectance than did the reflectance of a single wavelength. There are several VI used to estimate crop quality or yield, including R_{750}/R_{550} (maximum reflectance near 750 nm / maximum reflectance near 550 nm), R_{750}/R_{650} (maximum reflectance near 750 nm / minimum reflectance near 650 nm), simple ratios like SR (SR=R_{900}/R_{680}), the photochemical reflectance index [PRI; $(R_{531}-R_{570})$ / $(R_{531}+R_{570})$], the relative nitrogen vegetation index [RNVI; (near-infrared /

green reflectance)], the normalized total pigment to chlorophyll a ratio index [NPCI; $(R_{380}-R_{430})$ / $(R_{680}+R_{430})$], the water band index [WBI; (R_{950}/R_{900})], the normalized difference vegetation index [NDVI; $(R_{nir}-R_{red})$ / $(R_{nir}+R_{red})$] and other indices like the yellowness index (YI), which estimate the degree of leaf chlorosis from the concavity-convexity of the reflectance spectrum at a wavelength near the midpoint between the maximum at 550 nm and the minimum at 670 nm (Adams et al., 2000). Most of these indices involve the green (500-600 nm), red (600-700 nm), and near infrared (700-900 nm) bands (Plant et al., 1999). Among them, normalized difference vegetation index (NDVI) is the most commonly used (Tucker, 1979).

According to Perry et al. (1984), the first proposal for use of the normalized difference vegetation index (NDVI) was in the 1970s. Compared to soil reflectance, green vegetation reflectance is very high in near-infrared wavelengths but low in visible radiation because most is absorbed (Asrar et al., 1984). Consequently, combining visible and near infrared reflectance would estimate the fraction of incident radiation absorbed by the plant canopy as a function of leaf area index. Since chlorophyll a absorption is maximum at 680 nm and red reflectance increases and near infrared reflectance decreases as plant greenness declines, the comparison of red and NIR wavebands should be most effective. NDVI was defined as $(R_{NIR} - R_{red})$ / $(R_{NIR} + R_{red})$. The specific NIR and red wavelength range used for the calculation varies with individual studies but often corresponds to the bands used in resource monitoring satellites (Adamsen et al, 1999). Normalized difference vegetation indices typically range from 0.1 up to 0.9, with higher values associated with greater density and greenness of the plant canopy. Soil values are close to zero. When plants are under water stress, disease or other environment stress, their leaves reflect significantly less NIR and more red irradiance. As a result, the NDVI value becomes smaller as plant greenness declines.

A number of experiments suggested that NDVI was a good indicator of plant status. Adamsen et al. (1999) compared NDVI and G/R on wheat and found that both of the indices were good chlorophyll concentration indicators, but NDVI was more sensitive at low values than G/R. Adams et al. (2000) compared NDVI and R_{750}/R_{650} on soybean with micronutrient deficiency treatments and found that NDVI was more sensitive than R_{750}/R_{650} at lower chlorophyll concentrations. They concluded that NDVI was a more valuable measure for detecting deficiencies, because it will plateau when the plant is adequately supplied with nutrients. Other research showed that NDVI was a good indicator of barley (*Hordeum vulgare* L.) biomass and yield affected by salinity treatments (Peñuelas et al., 1997). On corn, Ma et al. (1996) demonstrated that NDVI was strongly correlated with field greenness, therefore NDVI could be used to estimate corn yield at harvest. On cotton, NDVI indicated the presence of nitrogen stress even in those cases where the stress did not result in a significant yield reduction and also showed NDVI decline approximately coincident with the onset of measurable water stress (Plant et al., 1999). In summary, NDVI has been related to many important crops and crop stresses.

On turfgrass, Schuerger et al. 2003 used NDVI, $(R_{760}-R_{695}) / (R_{760}+R_{695})$, to detect zinc stress in Bahiagrass (*Paspalum notatum* Flugge) and demonstrated that it was effective for predicting the concentrations of chlorophyll in canopies grown at various levels of Zn. Green et al. (1998) related NDVI to disease measurement. Bell et al. (2000a) indicated that NDVI, $(R_{780}-R_{671}) / (R_{780}+R_{671})$, was effective for measuring herbicide damage on bermudagrass turf. Trenholm et al. (1999) measured NDVI, (R_{935}-R_{661}) / (R_{935}+R_{661}), on seven seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes and three hybrid bermudagrass (*Cynodon dactylon* L. × *C. transvaalensis* Burtt-Davy) cultivars and regressed against visual quality scores. The results demonstrated that NDVI was highly correlated with visual turf quality, shoot density, and shoot tissue injury visual rating; and the relationship between NDVI and visual quality were approximately linear. This relationship was supported by Fitz-Rodríguez et al. (2002). Bell et al. (2002a) measured NDVI on a National Turfgrass Evaluation Program (NTEP) tall fescue (*Festuca arundinacea* Schreb) trial and creeping bentgrass (*Agrostis palustris* Huds., *A. stolonifera* L.) trial. They found that NDVI was closely correlated with visual evaluations for turf color, moderately correlated with percent live cover, and independent of texture. Trenholm et al. (1999) predicted that NDVI could further be used to discriminate water stress in turf. Research has also focused on relating NDVI with nitrogen content response. Keskin et al. (2001) developed empirical relationships between the nitrogen contents and the spectral reflectance data and NDVI from creeping bentgrass clippings and found that the reflectance values in green band (520-580 nm) and the NIR band (770-1050 nm) increased as the nitrogen content increased.

Alternatively, Gitelson et al. (1996) proposed the use of a green normalized difference vegetation index (GNDVI). The GNDVI was calculated by replacing the red band in the NDVI equation with a green band. The green color reflected from plants and seen by human eyes had a peak wavelength of ~550 nm. This greenness is generally recognized as an indication of N status for many agronomic crops (Blackmer, et al., 1994). As early as the 1970's, Thomas and Oerther (1972) demonstrated that leaf nitrogen content could be quickly estimated by measuring leaf reflectance at 550 nm. Blackmer et al. (1994) showed that light reflectance near 550 nm was the best wavelength to separate N treatment differences in corn leaves. The author also predicted that the measurement of light reflectance near 550 nm was a promising technique for detection of N deficiencies. The reason that green light reflectance was better than red light was believed to be that the low reflectance around 675 nm, where chlorophyll a absorption is maximum, reduced its sensitivity to chlorophyll changes. Filella, et al. (1995) reported that the 550 nm reflectance had a higher sensitivity for chlorophyll a concentrations; half saturation of the reflectance was reached at 550 mg Chl a m^{-2} at 680 nm and for 700 mg Chl a m^{-2} at 550 nm. Shanahan, et al. (2001) compared NDVI and GNDVI as a means of assessing canopy variation and its impact on corn grain yield under five N rates and found that GNDVI was the most highly correlated with grain yield, and suggested that GNDVI offered a potentially attractive alternative for use as a combine yield monitor. Humburg et al. (2002) compared NDVI and GNDVI of a sugarbeet canopy and documented that both GNDVI and NDVI were strongly correlated to recoverable sucrose concentration, a sugarbeet quality variable, in sugarbeet roots receiving six nitrogen treatments. On turfgrass, Bell et al. (2004) documented that GNDVI and NDVI were equally effective for estimating turfgrass N status and chlorophyll content.

In summary, NDVI has been used to measure a number of crop status parameters. However, the relationships among these parameters and resulting NDVI have not been determined. Although research has demonstrated that turf water stress (Trenholm et al. 1999) and N content (Keskin et al., 2001) affects NDVI, research has not examined

NDVI resulting from the simultaneous influence of water stress and nitrogen status. If this relationship can be determined, turf managers may be able to make accurate assessments of moisture status and N status independently using NDVI measurements obtained from a single sensor scan. By optimizing fertilizer and water application practices using NDVI, turf could be maintained at high quality while reducing expenditures and the risk of environmental pollution. The objectives of this research were:

1. To use a hand-held sensor that measures NDVI differences in detect combinations of irrigation and Nitrogen treatment in bermudagrass responses throughout the growth season.
2. To determine the interaction of water status and N status and the resulting affects on NDVI response.
3. To quantify the relationships among NDVI, tissue moisture, tissue nitrogen and chlorophyll.
4. To compare the responses of NDVI and GNDVI to nitrogen and irrigation treatments in bermudagrass.

Materials and methods

This study was conducted at the Oklahoma State University Turfgrass Research Center, Stillwater, OK. Two common bermudagrass cultivars (*Cynodon dactylon* [L.] Pers.) 'Yukon' and 'Riviera' were established by seed in June 1999. Yukon was developed by the OSU Turfgrass Breeding and Development Team and was tested as OKS 91-11 in the 1991-1996 National Turfgrass Evaluation Program (NTEP) bermudagrass trial. It has improved quality, cold hardiness and improved tolerance/resistance to spring dead spot disease. It is well adapted for use in lawn and park and possibly sports field and golf course fairways throughout Oklahoma where irrigation is available (Martin, 2002). Mowing height is flexible, from 1.27 to 5.08 cm (0.5 to 2.0 inches). Riviera was developed by the OSU Turfgrass Breeding and Development Team and was tested as OKS 95-1 in the 1997-2001 NTEP bermudagrass trial. It has improved cold hardiness, slightly improved resistance to spring dead spot disease, and demonstrates rapid recovery from injury. Mowing height is flexible, from 0.97 to 5.08 cm (0.38 to 2.0 inches). Under intensive management, both of the cultivars are prone to excessive thatch production (Martin, 2002). From 1999 to 2001, the research site was maintained at a mowing height of 12.7 mm (0.5 inches). Beginning in 2002 the mowing height was increased to 38.1 mm (1.5 inches). During the 2003 and 2004 growing seasons, N and water were applied according to study parameters. During each season, 1.38 kg ha^{-1} (1.5 lbs/acre) of Barricade 65WG (0.897 kg of Prodiamine ha^{-1}) was applied to control summer annual weeds in March; 1.23 kg ha^{-1} (16 oz/acre) Roundup Pro 4S (0.46 kg Glyphosate ha^{-1}) and 2.46 kg ha^{-1} (32 oz/acre) Weedar 4EC (0.92 kg of 2, 4-D Amine ha^{-1}) was applied in late winter to control winter annual weeds.

This study was conducted as a three-factor split-plot experiment for a completely randomized design. There were three replications each with two levels of factor A, cultivars ‘Yukon’ and ‘Riviera’, split into three levels of factor B, irrigation rate at 2.54 cm/week (1 inch/week), 1.27 cm/week (0.5 inch/week) and 0.63 cm/week (0.25 inch/week), split into six levels of factor C, nitrogen rate at 0, 12, 24, 36, 48, and 60 kg ha^{-1} per month.

The fertilizer used was urea 46-0-0. Urea was dissolved in water and sprayed with constant pressure and speed at the desired concentration. The turf was fertilized every two weeks beginning on June 3rd 2003 through October 17th 2003 and from May 15th, 2004 through October 15th 2004. After fertilizing, light irrigation was used to wash fertilizer from the leaf blades into the soil. The irrigation sprinklers at the site were I-10/I-20 Ultra Rotary Sprinklers (Hunter Industries, San Marcos, California) with nozzles of 0.75SR, 1.5SR, and 3.0SR to provide irrigation rates of 0.63 cm (0.25 inch), 1.27 cm (0.5 inch), or 2.54 cm (1 inch) per week respectively.

During the growing season (from May to October in Stillwater), this stand was managed at a mowing height of 38mm (1.5inch) with mowing frequency 2 to 3 times per week according to seasonal growth speed variation and the sampling schedule.

NDVI and GNDVI Data Collection

Commercially available GreenSeeker Handheld sensors (NTech Industries, Ukiah, CA) were used to collect two types of NDVI, GNDVI (green sensor) and NDVI (red sensor). The sensors detected the illumination produced by sensor-integrated light emitting diodes and did not detect ambient radiation. The red sensor (NDVI) produced and measured red and near-infrared radiance at wavelengths of 671 ± 6 nm and 780 ± 6 nm respectively and the green sensor (GNDVI) produced and measured green and near-infrared radiance at wavelengths of 550 ± 6 nm and 780 ± 6 nm respectively. Ambient reflection was filtered using a phase shift technique (Beck and Vyse, 1994) eliminating the variation caused by atmospheric conditions common to ambient light detectors. When the trigger was depressed, the sensor evaluated an area of 0.6 m (2.0 feet) wide and 9.5

mm (0.4 inches) long in the direction of travel. The sensor produced a result by pulse every 100 milliseconds. In this way, it produced 4 or more reflectance measurements in a 1m (3.1 feet) long plot with normal walking speed. The NDVI and R/NIR or GNDVI and G/NIR ratio of each measurement was recorded and stored on a personal data assistant (PDA) attached to the handheld units. The resulting data was recorded in spreadsheet format and was easily transferred to a desktop computer for statistical analysis.

The NDVI and GNDVI data were collected on two week intervals when the turf was dry and free from dew. The turf was scanned using the two sensors, one immediately followed by the other. Data was transferred to a desktop computer and saved in an Excel file (Microsoft, Redmond, WA). For each plot, the average NDVI or GNDVI data was obtained and analytical procedures performed using SAS analytical software (SAS Inc., Cary, NC).

Soil Water Content

Soil water content was measured using a commercially available soil moisture probe (HydroSense Soil Water Content Measurement System, Campbell Scientific, Logan, Utah). This portable probe estimated percent volumetric water content by calculating time domain reflectometry from 12 cm probes. The measurements were made every two weeks following the collection of NDVI and GNDVI scans. Three replicate measurements were made on each N-treated plot and a mean calculated for comparisons.

Clipping Moisture Content

Following soil moisture content measurements, bermudagrass clippings were collected for each N-treated plot using a walk-behind reel-type mower adjusted to a mowing height of 38mm (1.5 inch). Clippings were collected in one pass and transported in sacks cooled with ice. The fresh weight was measured immediately after tissue sampling, and before the clippings were placed in a forced-air drier at 50ºC and dried to constant weight. The difference between clipping dry weight and fresh weight was used to determine the water content of each sample.

Tissue Nitrogen Content and Chlorophyll Concentration

Tissue nitrogen content was also determined every two weeks by the Oklahoma State University soil lab (Stillwater, Oklahoma). After measuring tissue water content, the clipping samples were sent to the soil lab to determine nitrogen content. Total nitrogen was determined using a dry combustion Nitrogen Analyzer (LECO TruSpec) (NFTA, 1993).

Tissue chlorophyll concentration measurements were made every six weeks, i.e., every third time tissue moisture and nitrogen content were determined. The method of chlorophyll measurement followed the procedure of Inskeep and Bloom (1985) with little modification.

Immediately following collection, clippings were stored in the dark with ice and transported to the lab. At the laboratory, 30mg of fresh leaf sample was transferred to brown bottles and chlorophyll extracted by adding 10 ml DMF (N, N-Dimethylformamide) to each bottle. The bottles were covered and stored in a freezer (-

20ºC) for at least 30 days. A UV/VIS spectrophotometer (Shimadzu spec, Shimadzu, Japan) was used to measure sample absorbance (*A*) at 647 nm and 665 nm wavelengths for chlorophyll determination. Chlorophyll *a*, chlorophyll *b* and total chlorophyll were calculated using the formulas of Inskeep and Bloom (1985). Chl $a = 12.70A_{665} - 2.79A_{647}$; Chl $b = 20.70A_{647} - 4.62A_{665}$; Total Chl $= 17.90A_{647} + 8.08A_{665}$. The final results were converted to mg chlorophyll per g fresh weight.

Visual Rating

Visual rating for the overall turf quality was conducted during the 2004 growing season on a 1 to 9 scale (9 = the best quality, all plants were healthy and green; 1 = worst quality, all plants were dead or brown).

Environmental Information

Seasonal rainfall, average daily temperature, maximum and minimum temperatures, accumulated GDD, evapotranspiration, and soil temperatures at 10 cm (4 inches) were obtained from the Oklahoma Mesonet Station (Stillwater, OK), located less than 0.8 km (0.5 mile) from the research site.

Statistic Analysis

The NDVI, GNDVI, tissue moisture, tissue N, and soil water were collected and evaluated 9 times in 2003 and 10 times in 2004. Visual evaluations were made 10 times in 2004. Chlorophyll concentration was evaluated 3 times in 2003 and 4 times in 2004. Repeated measurements were pooled by early, peak, mid, and late growing season determined by the relationship between NDVI and day of year (Figure 1). The main effects of cultivar, nitrogen treatment, irrigation treatment and season, and their interactions were determined by analysis of variance (ANOVA) according to the mixed model procedure of the Statistical Analysis System (SAS Inc., Cary, NC). The significant means were separated using LSD (P = 0.05). Trend analyses were performed when ANOVA indicated a significant seasonal difference in nitrogen or irrigation induced responses. Relationships were determined by linear regression and empirical prediction equations by multiple regressions. A model describing the contribution of tissue N, tissue moisture, and tissue chlorophyll to NDVI was built using path analysis procedures.

Results and Discussion

Section 1

Relationship of optical sensing with turf quality

A visual rating of 6 is on a scale of 1 to 9 was considered a minimal acceptable value for highly maintained turf. For purposes of this study, a target visual rating or satisfactory value was also determined. This target value was determined by calculating the mean visual rating during June, July, and August 2004, the optimum growing season for bermudagrass in Oklahoma, treated with 48 kg ha^{-1} mon^{-1} N, the maximum recommended fertilization rate, under 2.54 cm wk^{-1} irrigation. The calculation resulted in a target mean visual rating of 6.7.

Simple linear regression equations were developed to determine the relationships between visual rating with NDVI and GNDVI (Table 1). The regression equations were: Visual rating = 18.61 NDVI – 9.18 (r^2=0.93), and Visual rating = 55.10 GNDVI – 37.65

(r^2=0.93). This result indicated that both NDVI and GNDVI were significantly (P<0.0001) related to visual quality ratings, and the visual rating could be predicted by both indices with approximately equal efficiency.

Based on the regression equations, the corresponding minimum acceptable and target NDVI and GNDVI were calculated. The minimum acceptable NDVI and GNDVI were 0.82 and 0.79 respectively. The target NDVI and GNDVI were 0.85 and 0.80 respectively. Both the minimum acceptable and target NDVI were higher than the GNDVI. NDVI raised 0.03 points from minimum acceptable visual rating of 6 to target visual rating of 6.7, but GNDVI only increased 0.01 point. This result indicated that NDVI spread wider than GNDVI and could reflect turf subtle quality differences in magnified scope.

Section 2

Seasonal trends in turf quality

The NDVI mean response in 2003 was significantly different (P<0.0001) from the NDVI response in 2004. The mean NDVI generated during the 2004 growing season, 0.82 (n=1080), was significantly higher than the mean NDVI produced during 2003, 0.73 (n=972). These differences were believed to be caused primarily by differences in weather from year to year. The NDVI response also differed significantly (P<0.0001) in among sampling times within each year. In the early growing season, NDVI response accelerated rapidly to a peak value in July (0.89, 12 Jul 2004 and 0.81, 3 Jul 2003), then declined to its lowest values in September (0.78, 10 Sep 2004) and early October (0.64, 3 Oct 2003) (Figure 1). A slight improvement occurred in mid to late October near the end of the growing season. This NDVI pattern corresponded to the visual quality evaluation in 2004. The relationship of NDVI with visual quality in this and other research suggests that NDVI is an accurate measure of bermudagrass quality (Bell et al. 2000a; Trenholm et al. 1999).

To demonstrate bermudagrass seasonal growth patter, which was indicated by NDVI, a trend line was developed in both of the growing seasons (Figure 1). The NDVI indicated that bermudagrass quality during both seasons could be explained by third order polynomial regressions with days of year. The coefficients of determination of the two regressions were 0.75 and 0.96 and 0.75 in 2003 (n=9) and 2004 (n=10) respectively. Because bermudagrass quality differed with date, a season factor was introduced. The growing season was divided into four seasons, early, peak, mid and late seasons, based on the bermudagrass response curve (Figure 1). The early season was characterized by rapidly improving quality and received from approximately 28 May (148 days of year) to 22 June (172 days of year). The peak season was characterized by the highest quality during the growing season and was classified from 22 June (172 days of year) to 3 August (214 days of year). The mid season followed the peak season and represented a quality decline from the peak quality, and was divided from 3 August (214 days of year) to 5 October (277 days of year). The late season was characterized by a slight quality improvement started from 5 October (277 days of year) to 17 October (289 days of year). According to this seasonal classification, there were two sets of samples in 2004 early season and one sample in 2003 early season, three sets of samples in peak season, four sets of samples in mid season, and one sample in late season in the two years. The NDVI responses differed significantly ($P<0.0001$) among the seasons during the two years. The mean NDVI in the 2004 early season was 0.78, 0.88 in the peak season, and 0.82 in the mid season, and 0.77 in late season (Figure 3). In 2003, the mean NDVI was 0.79, 0.77, 0.69 and 0.72 for the early, peak, mid and late seasons respectively.

According to the NDVI seasonal response pattern, it was necessary to adjust the minimum acceptable and target NDVI in different seasons. Simple linear regressions (P<0.0001) were conducted in early, peak and mid season. For the late season, regression was not conducted because there was only one set sample included (n=108). Instead, the minimum acceptable and target NDVI in late season was estimated by the mean NDVI ± standard error. The regression equation for early season was: NDVI = 0.47 + 0.05 visual rating (r^2 = 0.27, n = 216). The regression equation for peak season was: NDVI = 0.64 + 0.04 visual rating (r^2 = 0.46, n = 324). The regression equation for mid season was: NDVI = 0.63 + 0.03 visual rating (r^2 = 0.23, n = 432). Minimum acceptable and target NDVI were estimated based on these regression equations in different seasons as visual rating 6.0 and 6.7 as minimum acceptable and target turf quality respectively (Table 2). The results indicated that in the early season, the minimum acceptable turf quality had an NDVI value of 0.76, and the satisfactory turf quality had an NDVI value of 0.79. In the peak season, the minimum acceptable turf had an NDVI of 0.87, and the satisfactory turf had an NDVI value of 0.90. In the mid season, the minimum acceptable and satisfactory turf had NDVI values of 0.82 and 0.84 respectively. In the late season, the minimum acceptable and satisfactory turf had NDVI values of 0.76 and 0.78 respectively. These minimum and target NDVI values could be served as the quality standards in bermudagrass growing season and be used to provide information in guiding management practices to improve bermudagrass qualities into a satisfactory level.

Section 3

Bermudagrass response to irrigation

The NDVI response tended to increase with increasing irrigation rate. In 2003, the mean NDVI were 0.71, 0.74 and 0.75 for treatments of 0.63, 1.27 and 2.54 cm wk^{-1} irrigation respectively (Figure 4). In 2004, the corresponding NDVI were 0.82, 0.82 and 0.83 respectively. In 2003, the NDVI followed the response expected increasing NDVI with increasing irrigation. In 2004, however, natural rainfall was sufficient to provide acceptable turf quality regardless of irrigation treatment. The responses of GNDVI were similar to the responses of NDVI (Figure 5). Tissue moisture (g g^{-1}) was also not significantly influenced by irrigation and followed the same response trend as NDVI (Figure 6). In 2003, tissue moisture was 0.58, 0.60, and 0.62 g g^{-1} in treatments of 0.63, 1.27 and 2.54 cm wk^{-1} irrigation respectively. The corresponding tissue moisture in 2004 was 0.63 for all the irrigation treatments. This result suggested that the bermudagrass did not absorb more water just because the environmental moisture was more abundant. Therefore turf quality was not influenced by environmental moisture status unless the turf was water deficient. The NDVI response also indicated this condition.

Tissue moisture did vary significantly ($P<0.0001$) by season (Figure 7). In 2003, tissue moisture was 0.60 g g^{-1} in the early season, 0.61 g g^{-1} in the peak season, 0.59 g g^{-1} in the mid season, and 0.62 g g^{-1} in the late season. In 2004, tissue moisture was 0.59 g g^{-1} in the early season, 0.63 g g^{-1} in the peak season, 0.65 g g^{-1} in the mid season, and 0.63 g g^{-1} in the late season. The mid season had the lowest tissue moisture in 2003 and the highest tissue moisture in 2004 reflecting the seasonal differences in natural rainfall. This difference was also affected by a high white grub population in mid season 2003.

There was a significant irrigation × season interaction both in 2003 ($P<0.0001$) and 2004 ($P<0.01$). In 2003, tissue moisture was 0.53, 0.55, and 0.53 g g^{-1} at 0.63, 1.27, and 2.54 cm wk^{-1} irrigation in the early season, and in the late season the corresponding tissue moisture was 0.56, 0.56, and 0.55 g g^{-1} respectively (Figure 8). However mean separation (LSD; $P=0.05$) indicated that the tissue moisture in these two seasons was not significantly different within the three irrigation rates. In the peak and the mid seasons, tissue moisture in the 0.63 cm wk^{-1} irrigation treatment were significantly ($P<0.05$) lower than the tissue moisture in the 1.27 and 2.54 cm wk^{-1} irrigation treatments. In 2004, tissue moisture did not differ significantly among the four seasons. Tissue moisture in the mid season was significantly higher ($P<0.05$) than tissue moisture during other season in both 2003 and 2004 (Figure 9). Tissue moisture in the peak and the late seasons were statistically the same among the three irrigation rates, but the values were significantly higher than the tissue moisture values in early season regardless of irrigation treatment.

The relationship between tissue moisture with days of the year was described in Figure 10. The tissue moisture responses in 2003 ($r^2=0.76$) and 2004 ($r^2=0.18$) followed a high degree (3^{rd} order) polynomial trend. The trend in 2004 had a smooth curve and reached the peak value near 8 August (220 days of year). In comparison, the tissue moisture trend in 2003 had two peaks, one was near 10 July (190 days of year) and one was near 3 September (245 days of year). The low value between the two peaks was probably caused by a high white grub population during 2003.

Tissue moisture was significantly influenced by N fertilizer treatment both in 2003 ($P<0.0001$) and 2004 ($P<0.05$). Tissue moistures increased with increasing fertilizer treatments from 0.53 to 0.56 g g^{-1} in 2003 (Figure 11). The relationship between tissue moisture and N fertilizer treatment in 2003 were found to be linear, and the tissue moisture = 0.0004 N + 0.53 (r^2=0.98). This close relationship was probably caused by tissue water potential changes influenced by N fertilizer uptake. The increasing solute concentration decreased the solute potential, leading to a decrease in cellular water potential and a resulting increase in tissue moisture. In 2004, tissue moisture was generally higher than 2003 and was not responded N fertilizer linearly. In 2004, tissue moisture was 0.63 g g^{-1} in control, maintained 0.61 g g^{-1} in 12, 24, 36 kg ha^{-1} mo^{-1} N treatments, and increased to 0.62 g g^{-1} in 48 and 60 kg ha^{-1} mo^{-1} N treatments. It did demonstrated a increase with increasing N fertilization in mid to high N rates, but the relationship between tissue moisture and N fertilizer treatment were found better to be a curve linear (r^2 = 0.86). These results suggested that increasing N fertilizer had the linear effect of increasing tissue moisture when tissue moisture was low. When tissue moisture was excess than 0.60 g g^{-1} in this research, increasing N fertilizer failed to result in a tissue moisture increase linearly.

The NDVI was significantly (P<0.0001) related with tissue moisture (r^2 = 0.27; n = 2052) when pooled over years. This result indicated that tissue moisture was an important factor influencing NDVI response. The rationale behind this relationship might be that near infrared reflectance was affected by tissue water content (Gausman, 1969; Knipling, 1970; Carlson, 1971).

Soil water had a negative but weak relationship with tissue water (r^2 = 0.04, P<0.0001, n=1475). As a result, NDVI also had a weak negative relationship with soil water (r^2 = 0.03, P<0.0001, n=1475). Apparently, the bermudagrass did not absorb more water when the soil media had more water available. This result was also supported by the indications that bermudagrass did not have higher tissue moisture under higher irrigation rates. The small strength of correlation between soil water and tissue moisture, also suggested that soil water was probably not an important factor affecting tissue moisture. Similarly, soil water was not a major factor affecting NDVI.

In summary, tissue moisture was not affected by soil moisture availability (providing dehydration stress did not exist) but was varied with season, and was an important factor influencing NDVI and bermudagrass quality.

Section 4

Bermudagrass response to N fertilization

The NDVI response increased significantly (P<0.05) with increasing N fertilizer rates. In 2003, NDVI were 0.70, 0.72, 0.74, 0.74, 0.75 and 0.76 mg g^{-1} in the 0, 12, 24, 36, 48 and 60 kg ha^{-1} mo^{-1} N treatments respectively (Figure 12). In 2004, the corresponding NDVI were higher than 2003, and were 0.77, 0.80, 0.82, 0.83, 0.86 and 0.87 mg g^{-1} respectively. The GNDVI and NDVI responses were similar (Figure 13). In 2003, tissue N increased from 22.6 in control to 26.4 mg g^{-1} in 60 kg ha^{-1} mo^{-1} N treatment (Figure 14). The tissue nitrogen in 2004 had stronger response to fertilization than in 2003, increasing from 18.3 in control to 28.2 mg g^{-1} in 60 kg ha^{-1} mo^{-1} N treatment. Bermudagrass tissue N was linearly related with N fertilization (P<0.0001; r^2 =0.20).

Similar to tissue moisture, tissue N varied by season (Figure 15). In 2003, tissue N averaged 26.3 mg g^{-1} in the early season, 25.4 mg g^{-1} in the peak season, 23.1 mg g^{-1} in the mid season, and 25.4 mg g^{-1} in the late season. In 2004, tissue N averaged 18.7 mg g^{-1}

in the early season, 22.6 mg g^{-1} in the peak season, 25.6 mg g^{-1} in the mid season, and 24.8 mg g^{-1} in the late season. Tissue N changes in both of the years could be explained by a second order polynomial trend. However, the mid season had the highest tissue nitrogen in 2004 and the lowest in 2003. The same phenomenon was observed in the comparison of tissue moisture with season. It was believed that high grub populations in 2003 and more natural rainfall in 2004 caused a major difference in mid season response between years.

There was a significant N × season interaction both in 2003 ($P<0.01$) and 2004 ($P<0.0001$). In 2003, tissue N ranged from 25.8 to 26.6 mg g^{-1} in the early season (Figure 16), but did not differ significantly. In the peak, mid and late seasons, the tissue N in higher N rates (48 and 60 kg ha^{-1} mo^{-1}) was significantly higher than the tissue N in the lower rates and control. In 2004, tissue N in the early season ranged from 16.9 to 20.9 mg g^{-1} in control and 60 kg ha^{-1} mo^{-1} N respectively (Figure 17). There was a stronger tissue N response to N fertilization in the year progressed in 2004 but not in 2003. Higher N rates (48 and 60 kg ha^{-1} mo^{-1}) resulted in significantly (LSD; $P<0.05$) higher tissue N occurred in all four seasons. Tissue N with did not have a strong relationship with days of the year (Figure 18). In addition, the growing season trends were of consistent between years.

The NDVI was significantly ($P<0.0001$) related with tissue N ($r^2 = 0.17$; n=2052) when pooled over years. This result indicated that tissue nitrogen was a factor that influenced NDVI response. This relationship was attributed to increasing chlorophyll with increasing tissue N as it is unlikely that tissue N affects reflectance directly. A higher chlorophyll content caused by an increase in tissue N resulted in less red light reflected and a higher NDVI value.

In summary, tissue N was affected by soil N availability, resulting from higher N fertilization leading to higher tissue nitrogen. Tissue nitrogen varied by season but a significant trend could not be determined. Tissue N and NDVI were significantly related, and tissue N was believed to be an important factor influencing NDVI.

Section 5

Chlorophyll response to tissue moisture and tissue nitrogen

Chlorophyll concentrations were not significantly affected by irrigation treatments in 2003 and 2004. However, chlorophyll concentration increased significantly ($P<0.0001$) with increasing N fertilization in a simple linear manner in both years. In 2003, chlorophyll concentration increased from 2.35 to 2.60 mg g^{-1} with increasing fertilization (Figure 20). In 2004, chlorophyll concentration was increased from 2.38 to 3.31 mg g^{-1} with increasing fertilizations.

The NDVI significantly ($P<0.0001$) increased with increasing chlorophyll concentration (r^2 = 0.29; n=648) in a simple linear manner. This result suggested that chlorophyll concentration was also an important factor that influenced NDVI response. Higher chlorophyll content is believed to absorb more red light, resulting in higher NDVI's.

A significant relationship occurred between chlorophyll concentration and tissue moisture, and between chlorophyll concentration and tissue N ($P<0.0001$) resulting in coefficients of determination of 0.21 (n=648) and 0.13 (n=648) respectively. The correlation between chlorophyll concentration and tissue moisture may due to the sensitivity of chlorophyll to water stress.

Section 6

Comparison of NDVI and GNDVI

GNDVI generally had lower values than NDVI in this study, but NDVI and GNDVI had similar responses to irrigation (Figure 4 and 5), N fertilization (Figure 12 and 13), and visual rating (Table 1). However, compared to NDVI, GNDVI had a lower maximum value and higher minimum value, which suggested that NDVI had wider response range than GNDVI. Wider response range might have the advantage of improving the detection of subtle differences in turf quality. This may be why NDVI was better for detecting differences in N fertilization rates. According to this study, the best indices to detect N fertilization were NDVI and visual rating.

However, there was a concern about the NDVI's sensitivity to chlorophyll. On a dense and green turf canopy, the reflectance of red light could be very low and most of the red light near 680 nm wavelengths could be absorbed leading to a value of NDVI close to 1. This phenomenon occurred in this study when NDVI was as high as 0.99.

Section 7

Cultivar effect on NDVI

NDVI was significantly ($P<0.01$) affected by a cultivar × season interaction. In the early and peak seasons, Riviera had significantly (LSD; $P<0.05$) higher NDVI (0.79 and 0.83 respectively) than Yukon (0.77 and 0.82 respectively) but in the mid and late seasons, the NDVI responses were opposite (Figure 21). During the mid and late season, Yukon had significantly (LSD; $P<0.05$) higher NDVI (0.76 and 0.75 respectively) than Riviera (0.75 and 0.74 respectively). This result suggested that Yukon maintained better turf quality in the late growing season, while Riviera performed better in the early growing season. This resulted was similar to the result of visual rating response to cultivar × season interaction ($P<0.0001$). In the early season, the two cultivars did not differ significantly, but in the peak, mid and late seasons, Yukon had significantly higher (LSD; $P<0.05$) visual rating in than Riviera (Figure 22). This result confirmed that Yukon had better quality than Riviera in the late growing seasons.

Section 8

Contributions of tissue moisture, tissue N, and chlorophyll to NDVI response

To quantify the relationship among NDVI, tissue moisture, chlorophyll concentration and tissue N, path analysis was conducted. Path analysis is an extension of multiple regression used to determine the individual contributions and relationships among multiple independent variables that determine the quantity of a dependent variable. Earlier analysis indicated that NDVI was affected by chlorophyll, tissue moisture, and tissue nitrogen, and that each variable also had a relationship with the others. Tissue N influenced chlorophyll concentration, because N is a component of chlorophyll. Tissue N also affected tissue moisture because higher tissue N causes a decrease in plant water potential that leads to greater water absorption.

The result of path analysis is demonstrated in Figure 23. The arrows indicate causal relations with arrows pointing from cause to effect. The exogenous variable (variables without an arrow pointed to them) in this model was tissue N. The three endogenous variables (variables with arrows pointed to them) were tissue moisture, chlorophyll concentration, and NDVI the dependent variable. Each endogenous variable was explained by one or more variables in the model. For instance, tissue moisture affected NDVI directly and affected NDVI indirectly by its influence on chlorophyll concentration. The path coefficients indicated the strength of each relationship and were validated by standard better weight in a multiple regression process. Because all of the path coefficients were standardized, they are compatible. The path coefficients between NDVI with tissue moisture and NDVI with chlorophyll concentration were similar (0.35 and 0.39 respectively) suggesting that chlorophyll and tissue moisture directly influence NDVI with similar strength. NDVI with tissue N had a much lower path coefficient (0.06) indicating that tissue N had less direct influence on NDVI compared with chlorophyll and tissue moisture. The path coefficients of chlorophyll with tissue N and chlorophyll with tissue moisture were 0.39 and 0.15 respectively indicating that tissue N had a greater direct influence on chlorophyll concentration than tissue moisture. The path coefficient between tissue moisture with tissue N was 0.54. Compared with the path coefficient of chlorophyll concentration with tissue N (0.39), tissue N had a greater effect on tissue moisture than it did on chlorophyll concentration.

Within the model, the relationships among these variables were decomposed to direct, indirect and spurious effects (Table 3). The relationship between tissue moisture with tissue N was entirely due to direct effects. The relationship between chlorophyll with tissue N was due to the direct effect of tissue nitrogen on chlorophyll (0.39) and an indirect effect of tissue nitrogen through tissue moisture on chlorophyll concentration

(0.08). According to these results, most of the relationship's strength was determined by the direct effect of tissue nitrogen on chlorophyll. The sum of the direct and indirect effects makes the predicted path correlation identical with the Pearson correlation coefficient for that relationship. The correlation between chlorophyll with tissue moisture was decomposed to the direct effect of tissue moisture on chlorophyll (0.15) and the spurious effect of tissue moisture by tissue nitrogen on chlorophyll (0.21). The reason the effect of tissue moisture through tissue nitrogen on chlorophyll was spurious instead of indirect was because tissue nitrogen influenced chlorophyll, but tissue moisture did not influence tissue nitrogen. This is also indicated by the direction of the arrow in Figure 23. Tissue N was the source of spurious effects in the relationships of NDVI with chlorophyll and NDVI with tissue moisture. Comparing the spurious effect with the direct effect indicated that nearly half of the relationship's strengths of chlorophyll with tissue moisture were due to the direct effect of tissue moisture on chlorophyll.

The relationships between NDVI with tissue N was decomposed of the direct effect of nitrogen on NDVI (0.06), and the indirect effect of nitrogen through tissue moisture on NDVI plus nitrogen through chlorophyll concentration on NDVI plus nitrogen through tissue moisture through chlorophyll concentration on NDVI (0.37). Consequently, the relationship between NDVI with tissue N was influenced mainly by the indirect effects through tissue moisture and chlorophyll.

The relationship between NDVI with tissue moisture was decomposed to the direct effect of tissue moisture on NDVI (0.35), the indirect effect of tissue moisture through chlorophyll concentration on NDVI (0.06), and the spurious effect of tissue moisture through tissue N on NDVI plus a second spurious effect of tissue moisture through tissue N through chlorophyll on NDVI (0.12). These results implied that most of the relationship strengths of NDVI with tissue moisture were due to the direct effect of tissue moisture on NDVI.

The relationship between NDVI with chlorophyll was decomposed to the direct effect of chlorophyll concentration on NDVI (0.39), and the spurious effect of chlorophyll through tissue N on NDVI plus a second spurious effect of chlorophyll through tissue moisture through tissue nitrogen on NDVI plus a third spurious effect of chlorophyll through tissue nitrogen through tissue moisture on NDVI plus a fourth spurious effect of chlorophyll through tissue moisture on NDVI (0.15). These results suggested that 70% of the relationship strength of NDVI with chlorophyll were contributed by the direct effect of chlorophyll concentration on NDVI. The remaining effects were influenced by tissue moisture and tissue nitrogen.

Based on the path analysis, a predicted correlation matrix was generated (Table 3), and compared to the actual Pearson correlation. Predicted correlation matrices were compared with the correlation matrices generated from data of 2003 and the data of 2004 separately. A Root-Mean-Square-Residual (RMSR) was calculated to evaluate this fitness. The RMSR was computed by subtracting the predicted from the actual, and squaring the result. The squared results were averaged over the correlations, and a square root of the average determined the RMSR. The RMSR indicated that the model fit the data of 2004 (RMSR=0.13) better than the data of 2003 (RMSR=0.15) (Tables 4a and 4b). The analysis also revealed that tissue N was the major source of error in 2003 and that tissue moisture was the major source of error in 2004.

Summary and Conclusion

Both NDVI and GNDVI were reliable indications of turf quality. The minimum acceptable NDVI (0.82) and target NDVI (0.85) could be used to indicate the need for maintenance practices such as fertilization and irrigation providing they were adjusted for seasonal differences.

Based on this study, tissue moisture was not affected by soil moisture availability (providing dehydration stress did not exist), but varied by N fertilization and season effect. Similar to tissue moisture, chlorophyll was not affected by irrigation, but was affected by N fertilization. Bermudagrass tissue N was affected by soil N availability, and higher N fertilization led to higher tissue nitrogen. Tissue N varied by season, and influenced NDVI. The two cultivars, Yukon and Riviera, had different responses to the seasonal change. Yukon maintained better turf quality in the late growing season, while Riviera performed better in the early season than the rest of growing seasons.

The results from path analysis suggested that NDVI was mainly influenced by tissue moisture and chlorophyll concentration. The path coefficients for chlorophyll concentration and tissue moisture effects on NDVI were 0.39 and 0.35 respectively. Tissue N had small direct influence on NDVI, but primarily affected NDVI indirectly through tissue moisture and chlorophyll. Tissue nitrogen and tissue moisture both influenced chlorophyll concentration, but the influence of tissue nitrogen on chlorophyll was 2.7 times greater than the influence of tissue moisture.

This research proposed an acceptable and a satisfactory NDVI for bermudagrass with adjustment in different seasons, which provided standards to guide management practices. This research also found that tissue moisture was equally important as chlorophyll in influencing NDVI response. The relationships among NDVI, chlorophyll, tissue moisture and tissue N were also clearly described and modeled.

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Table 1. Simple linear regressions[z] between normalized difference vegetation index (NDVI), green normalized difference vegetation index (GNDVI) and turf quality visual rating.

Variable		Parameter		Coefficients of determination
Independent	Dependent	a	b	r^2
NDVI	Visual Rating	-9.18	18.61	0.93
GNDVI	Visual Rating	-37.65	55.10	0.93

[z]Regression equations (y = a + bx) and parameter estimated were significant ($P < 0.0001$).

Table 2. Minimum and target NDVI adjusted by early, peak, mid and late seasons.

Variable	Visual Rating	NDVI			
		Early Season	Peak Season	Mid Season	Late Season[z]
Minimum Acceptable	6.00	0.76	0.87	0.82	0.76
Target	6.68	0.79	0.90	0.84	0.78

[z]Late season minimum acceptable and target NDVI were calculated by the mean ± standard error.

Table 3. Decomposed correlations among NDVI, tissue nitrogen, tissue moisture (W) and chlorophyll (chl) based on path analysis.

Correlations	Decomposed Effects			Predicted Correlation	Pearson Correlation
	Direct	Indirect	Spurious		
$r_{N,W}$	0.54			0.54	0.54
$r_{N,chl}$	0.39	0.08		0.47	0.47
$r_{W,chl}$	0.15		0.21	0.36	0.36
$r_{N,NDVI}$	0.06	0.37		0.43	0.43
$r_{W,NDVI}$	0.35	0.06	0.12	0.52	0.52
$r_{chl,NDVI}$	0.39		0.15	0.54	0.54

Table 4a. Root-Mean-Square-Residual (RMSR) for 2003.

Correlation	Predicted	Actual	Difference	Squared Difference
$r_{W,NDVI}$[z]	0.5213	0.5393	-0.0180	0.0003
$r_{chl,NDVI}$	0.5444	0.5058	0.0387	0.0015
$r_{N,NDVI}$	0.4348	0.6443	-0.2095	0.0439
$r_{W,chl}$	0.3557	0.2870	0.0687	0.0047
$r_{N,W}$	0.5417	0.8365	-0.2948	0.0869
$r_{N,chl}$	0.4672	0.4732	-0.0060	0.0000
Mean				0.0229
RMSR				0.1513

Table 4b. Root-Mean-Square-Residual (RMSR) for 2004.

Correlation	Predicted	Actual	Difference	Squared Difference
$r_{W,NDVI}$	0.5213	0.3291	0.1922	0.0369
$r_{chl,NDVI}$	0.5444	0.4378	0.1067	0.0114
$r_{N,NDVI}$	0.4348	0.4476	-0.0128	0.0002
$r_{W,chl}$	0.3557	0.2950	0.0607	0.0037
$r_{N,W}$	0.5417	0.3499	0.1918	0.0368
$r_{N,chl}$	0.4672	0.5507	-0.0835	0.0070
Mean				0.0160
RMSR				0.1264

[z]N, W, chl, and NDVI represented nitrogen input, tissue moisture, chlorophyll concentration, and NDVI respectively.

Figure 1. NDVI responses in 2003 and 2004 growing seasons and the polynomial trend on days of year.

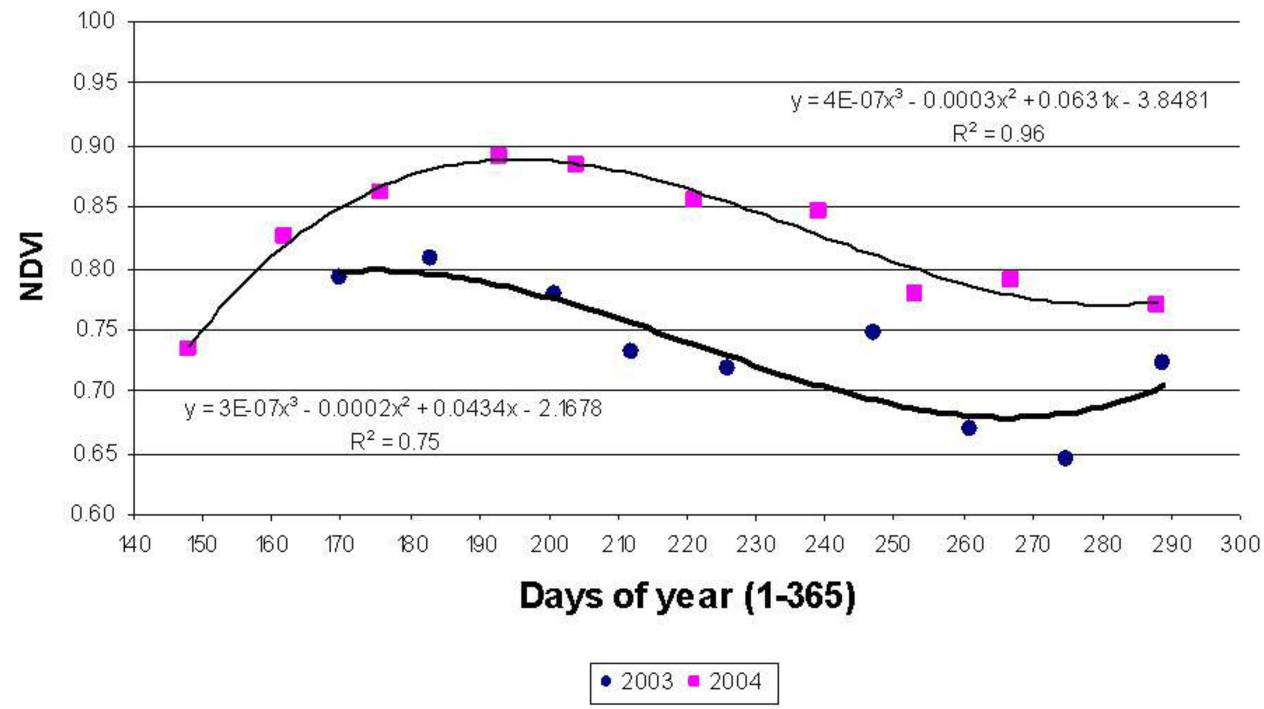


Figure 2. GNDVI responses in 2003 and 2004 growing seasons and the polynomial trend on days of year.

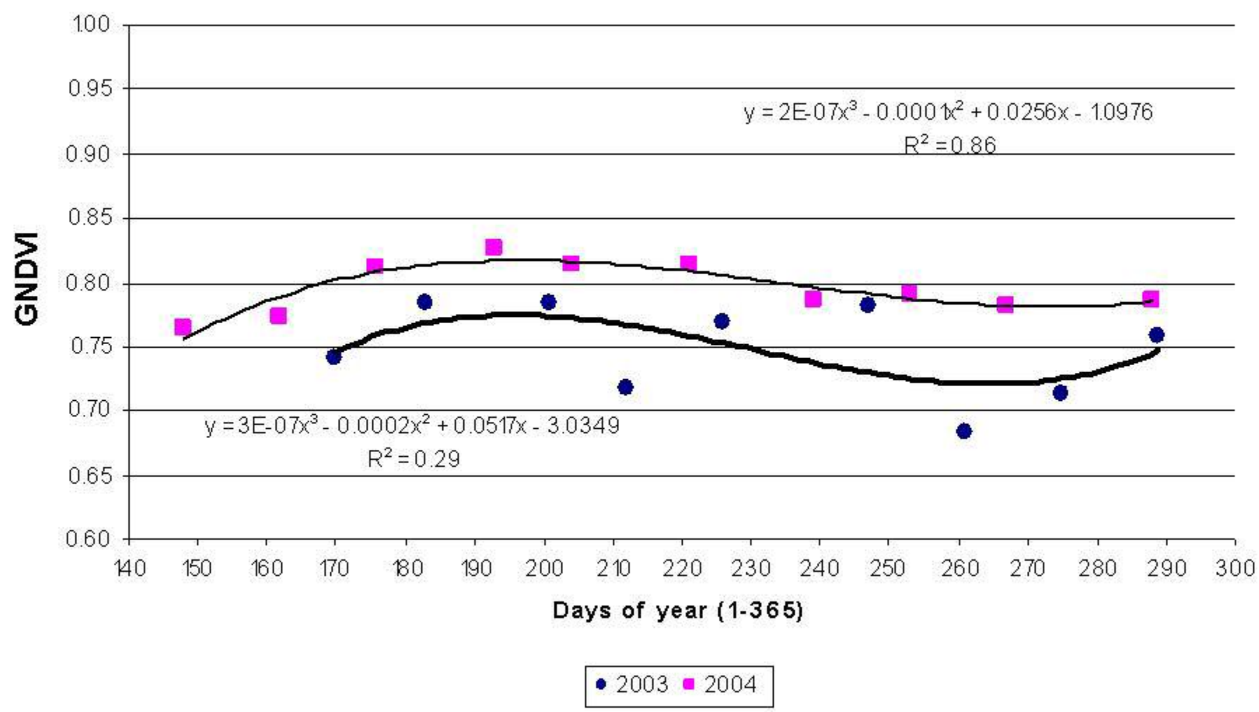


Figure 3. NDVI responses to early, peak, mid and late season environment in 2003 and 2004. Bars indicate the standard error intervals.

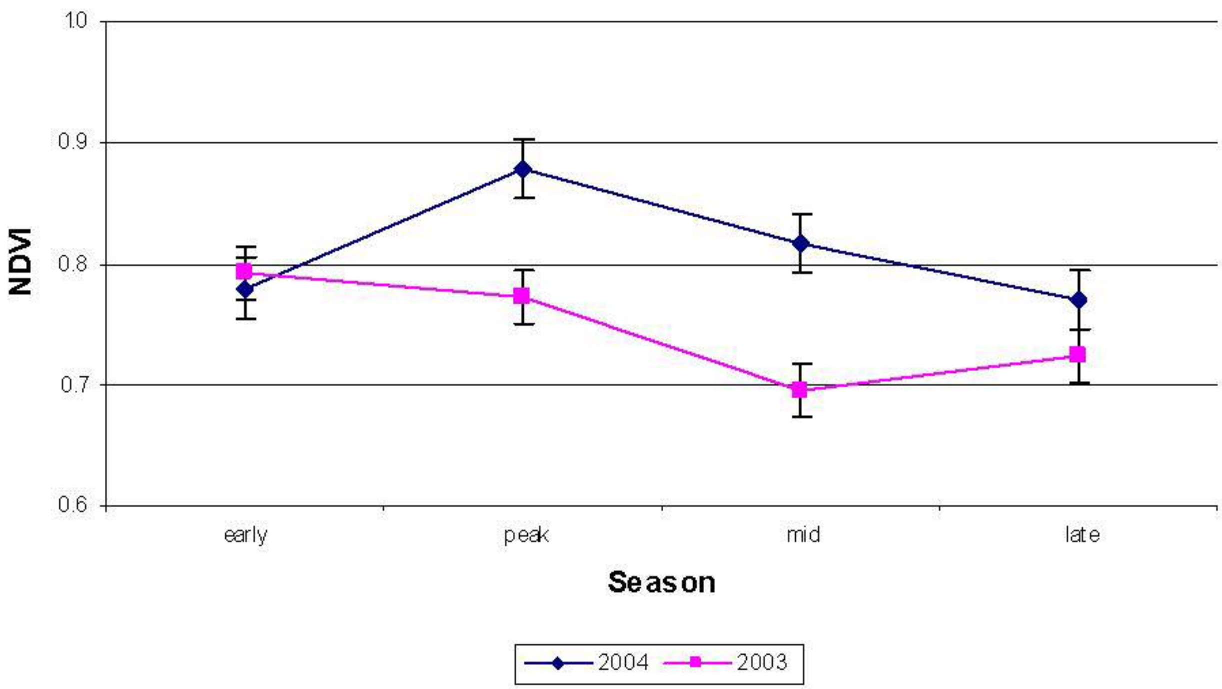


Figure 4. Mean NDVI responses to irrigation of 0.63, 1.27 and 2.54 cm wk^{-1} in 2003 (n=324) and 2004 (n=360). Bars indicate the standard error intervals.

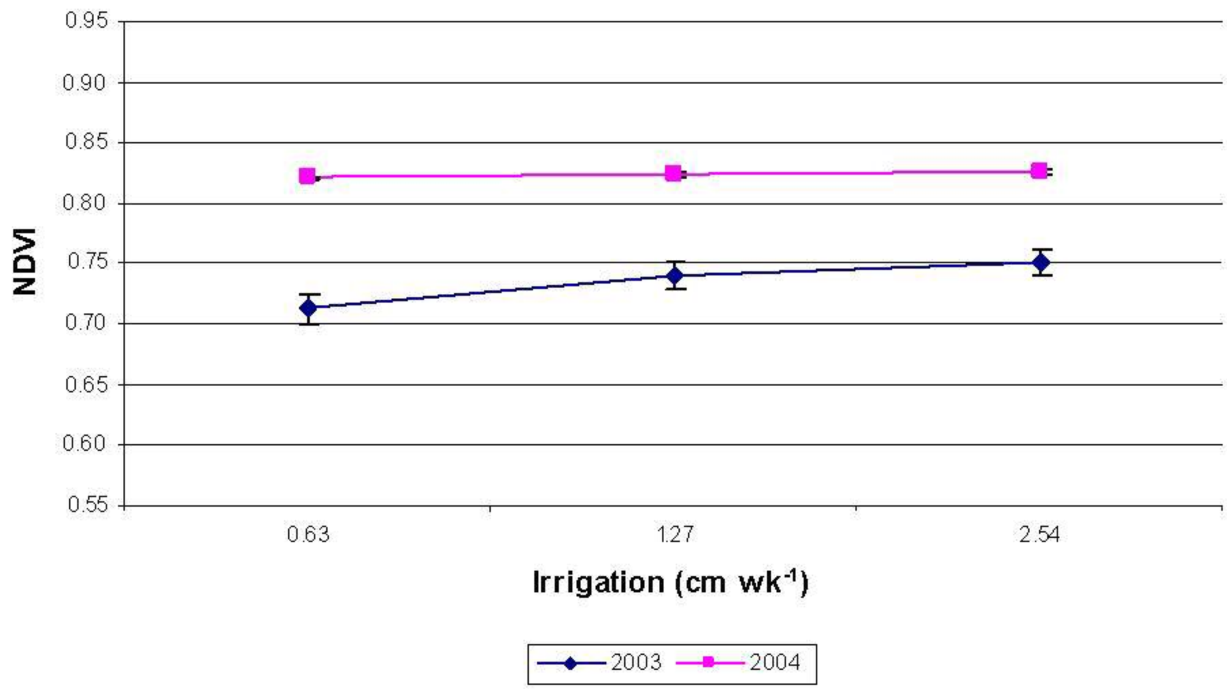


Figure 5. Mean GNDVI responses to irrigation of 0.63, 1.27 and 2.54 cm wk^{-1} in 2003 (n=324) and 2004 (n=360). Bars indicate the standard error intervals.

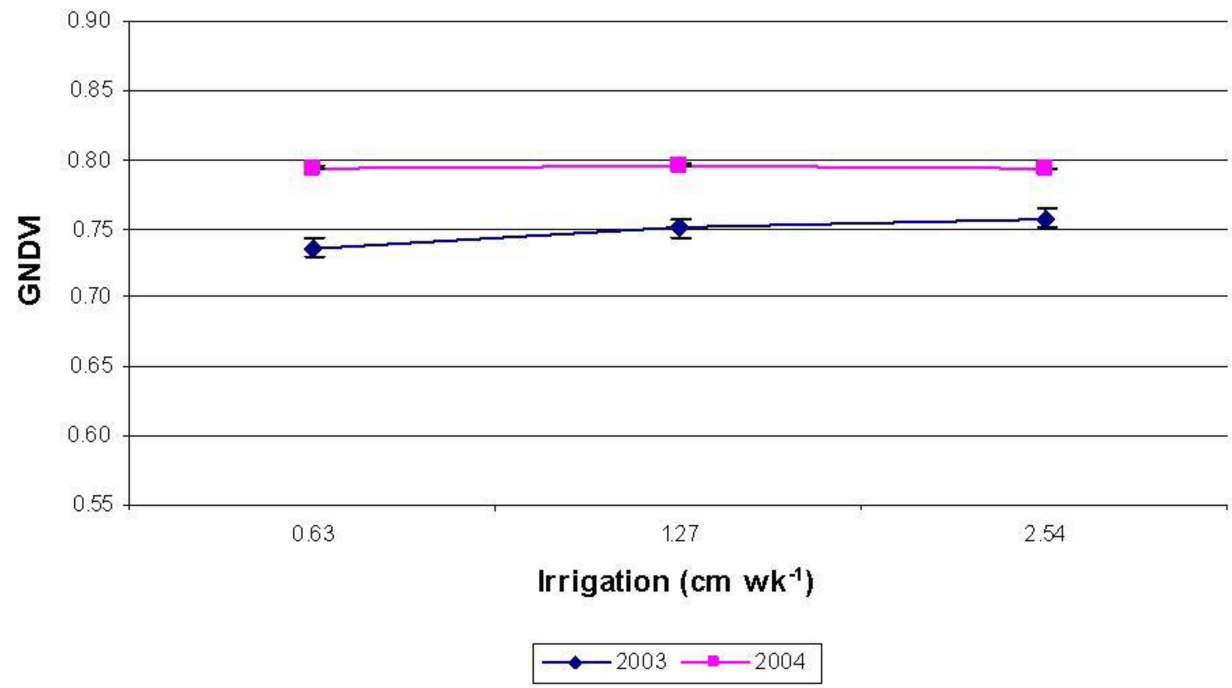


Figure 6. Mean tissue moisture responses to irrigation of 0.63, 1.27 and 2.54 cm wk^{-1} in 2003 (n=324) and 2004 (n=360). Bars indicate the standard error intervals.

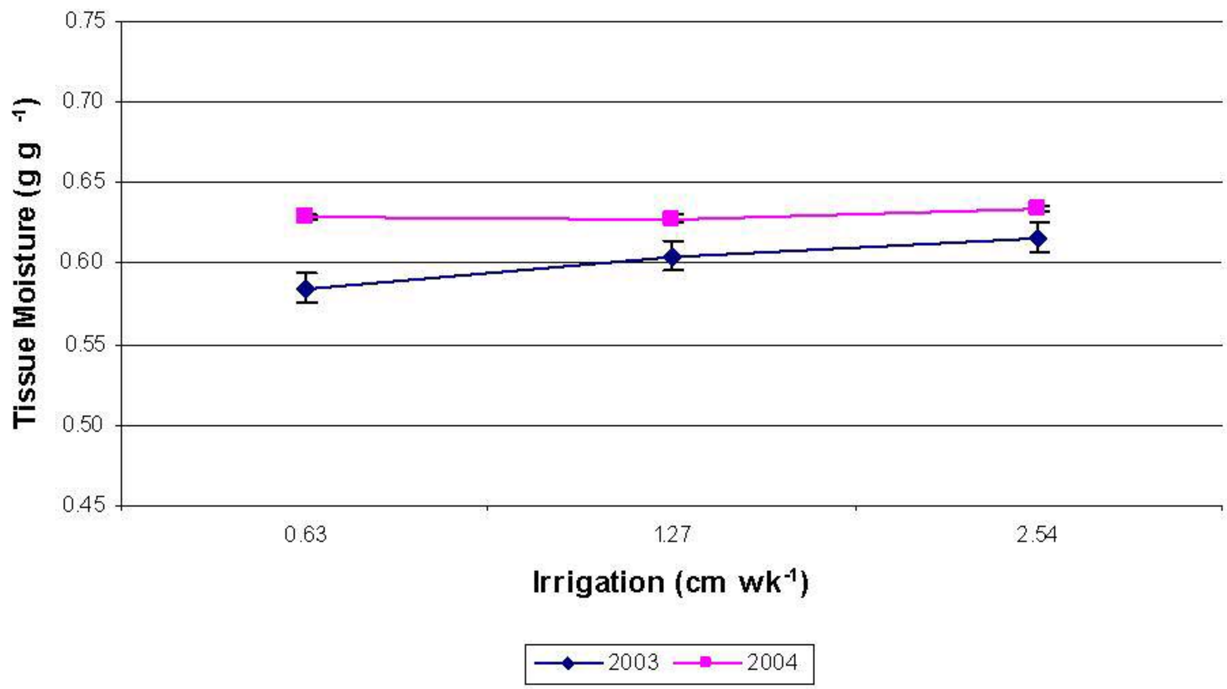


Figure 7. Tissue moisture responses to early, peak, mid and late seasons in 2003 and 2004. Bars indicate the standard error intervals.

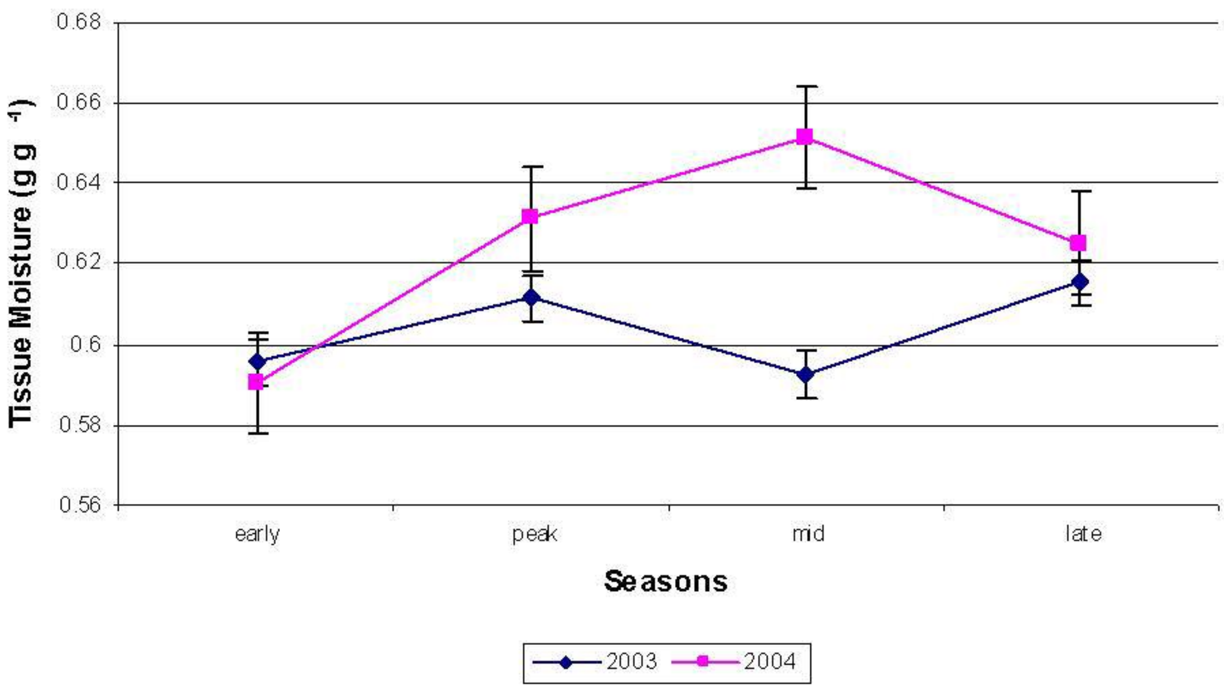


Figure 8. Tissue moisture response to irrigation treatments by season in 2003. Bars indicate the standard error intervals.

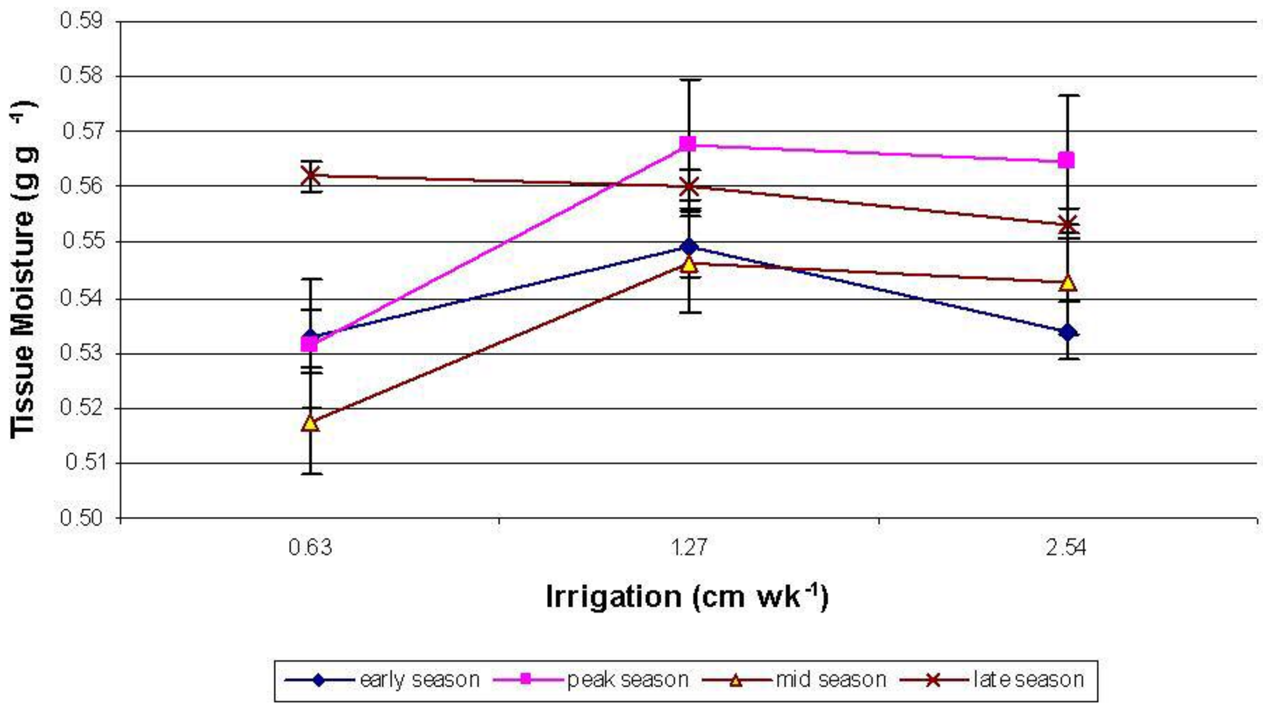


Figure 9. Tissue moisture response to irrigation treatments by season in 2004. Bars indicate the standard error intervals.

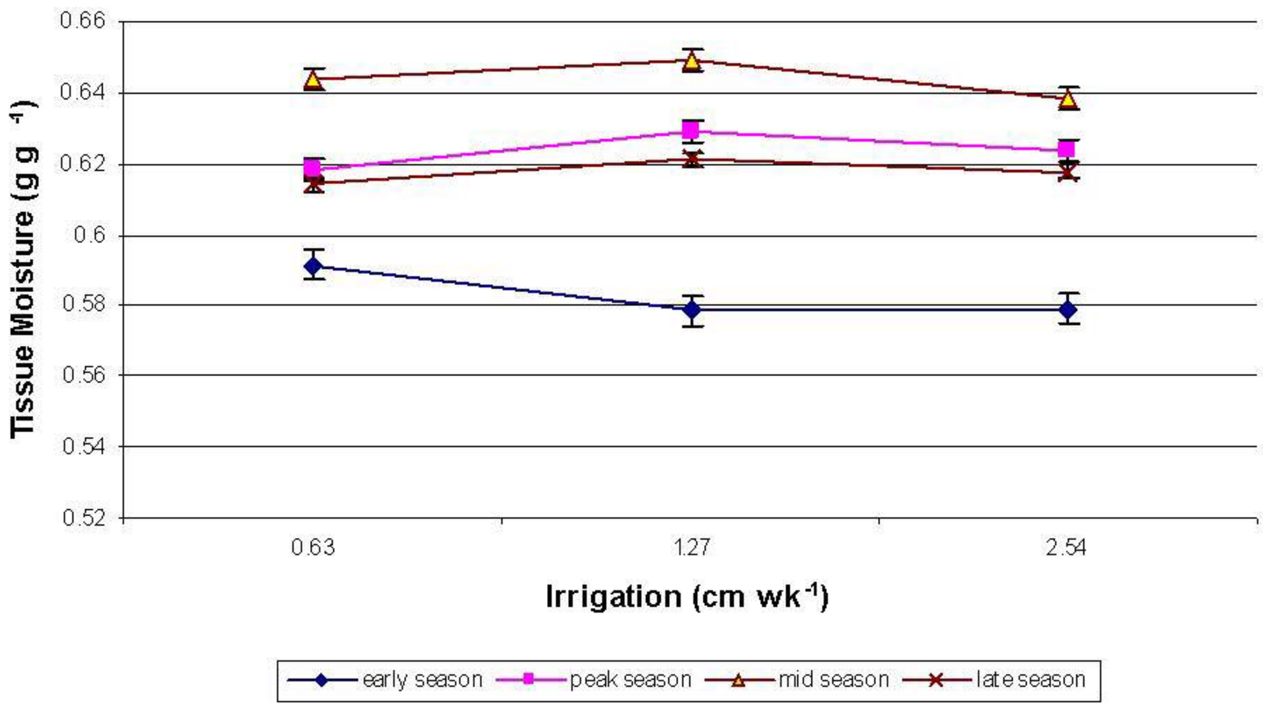


Figure 10. Tissue moisture response by days of the year in 2003 and 2004 and the polynomial trend.

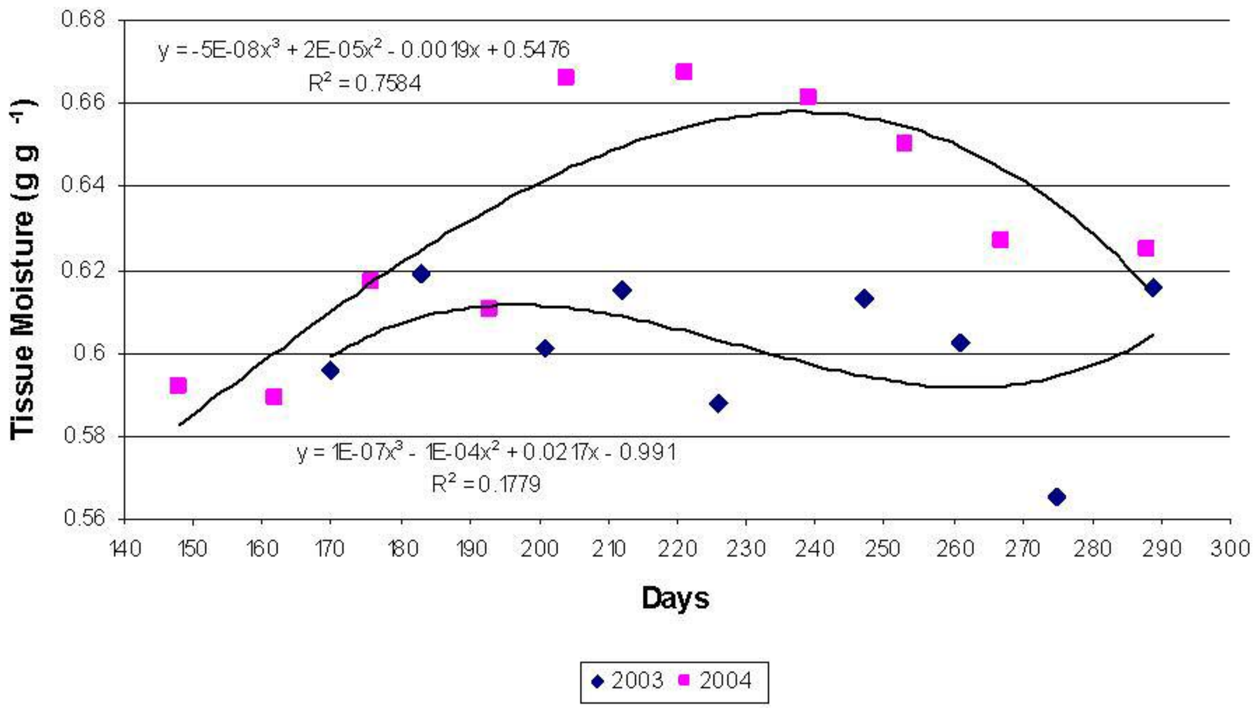


Figure 11. Tissue moistures response to N fertilizer treatment in 2003 and 2004.

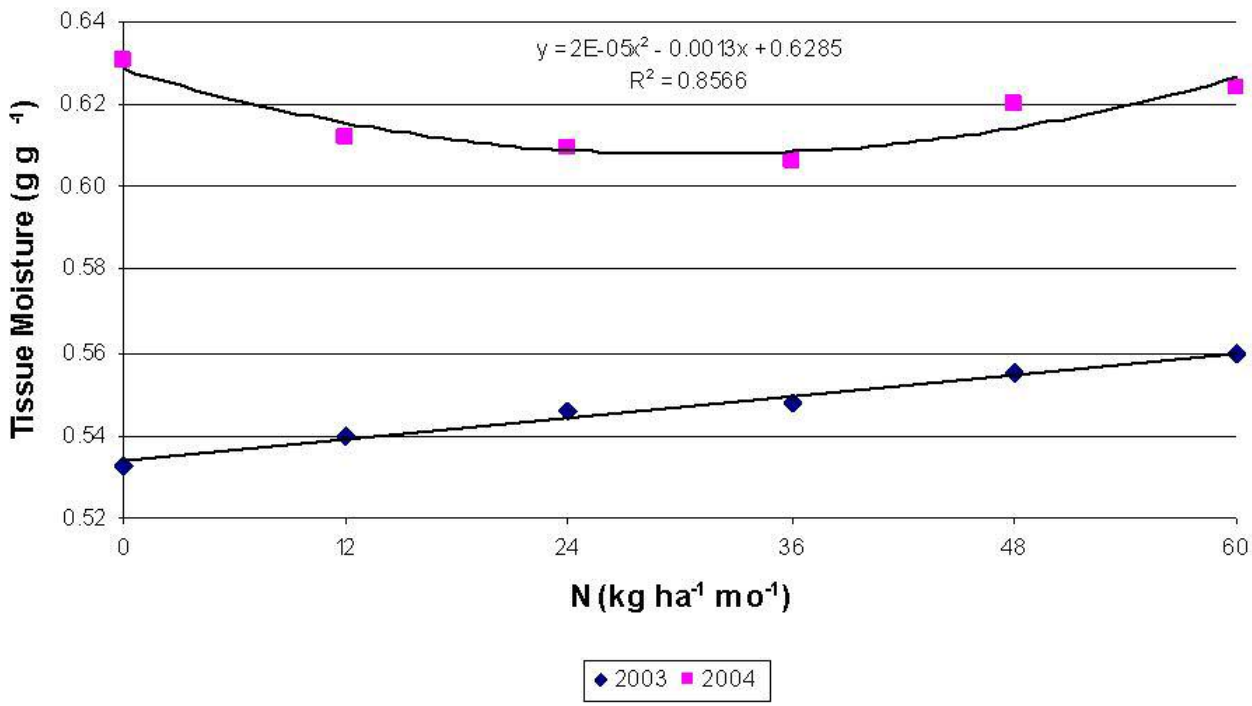


Figure 12. Mean NDVI responses to N fertilization in 2003 (n=162) and 2004 (n=180). Bars indicate the standard error intervals.

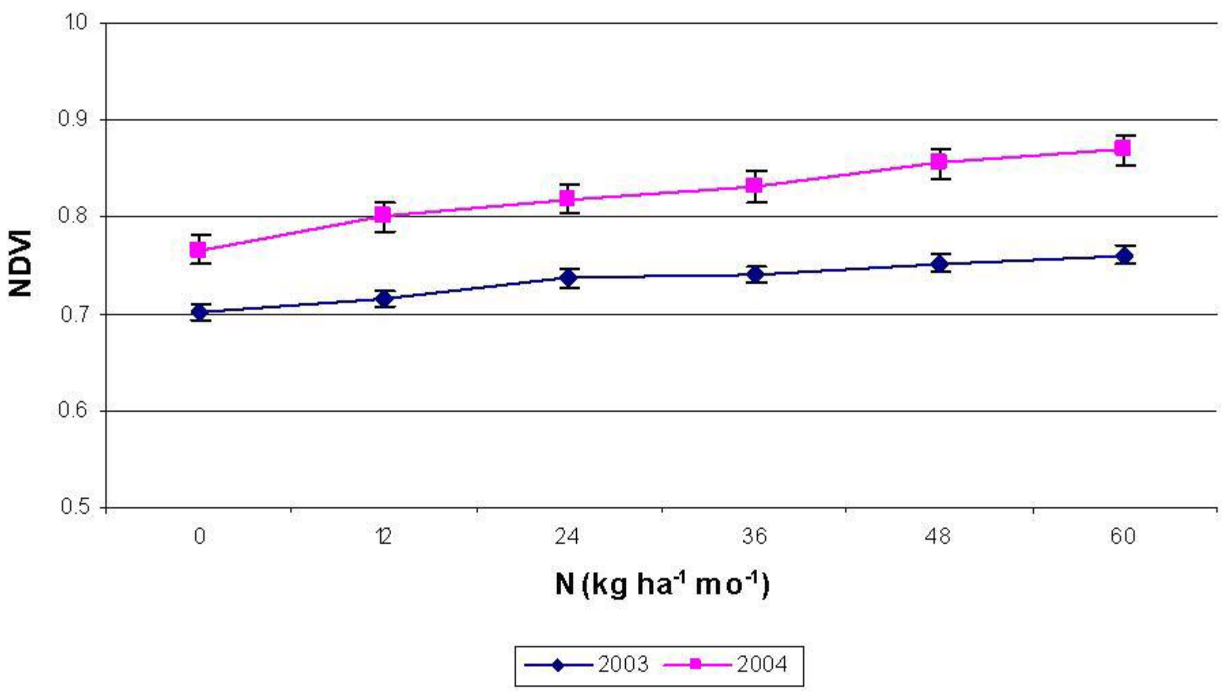


Figure 13. Mean GNDVI responses to N fertilization in 2003 (n=162) and 2004 (n=180). Bars indicate the standard error intervals.

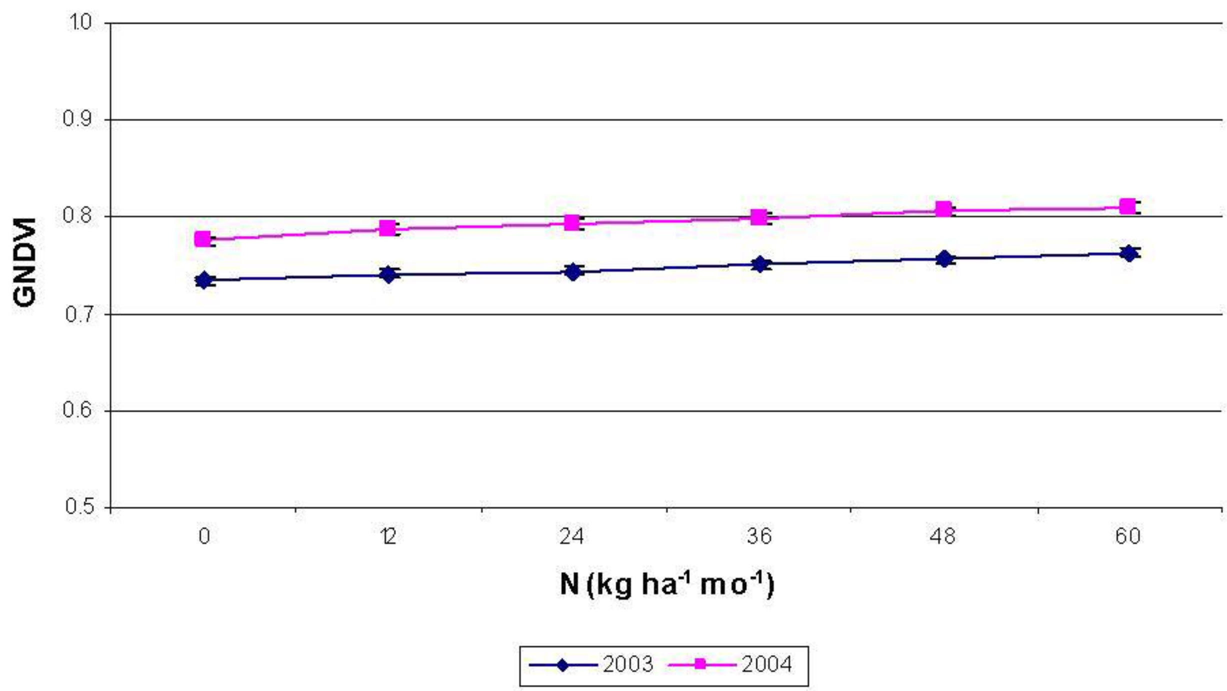


Figure 14. Mean tissue nitrogen response to N fertilization in 2003 (n=162) and 2004 (n=180). Bars indicate the standard error intervals.

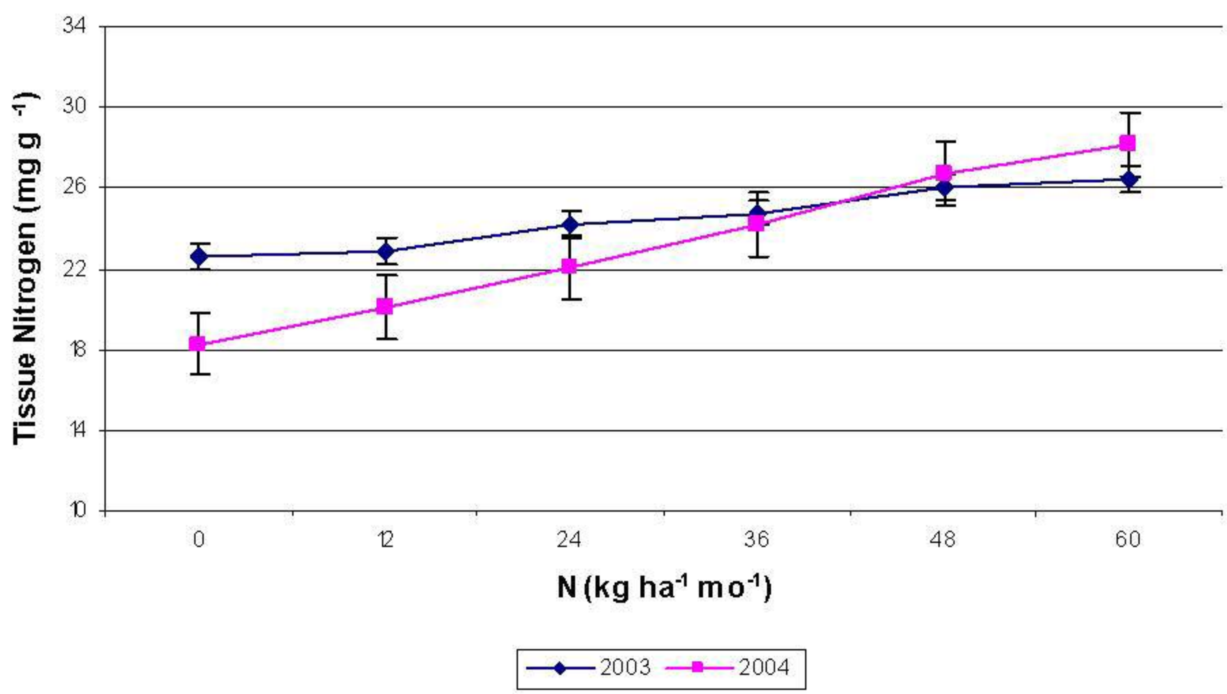


Figure 15. Tissue nitrogen response to the early, peak, mid and late seasons in 2003 and 2004.

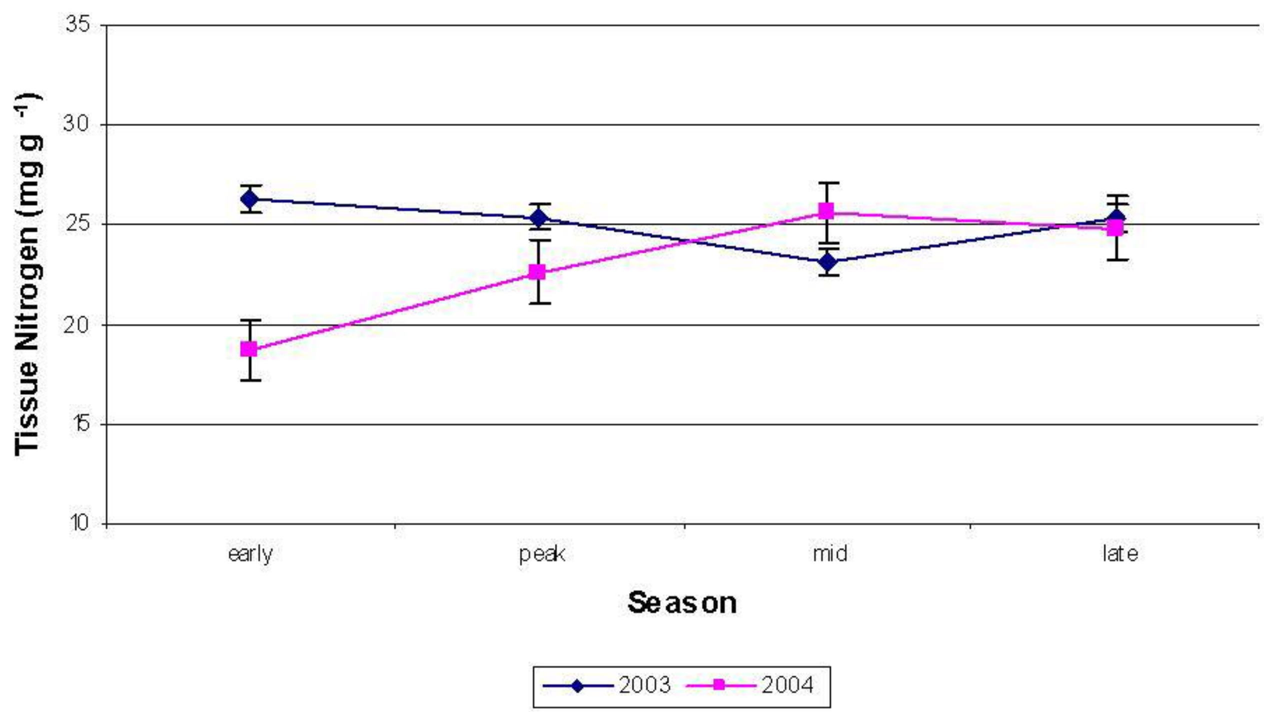


Figure 16. Tissue nitrogen response to N fertilization by season in 2003.

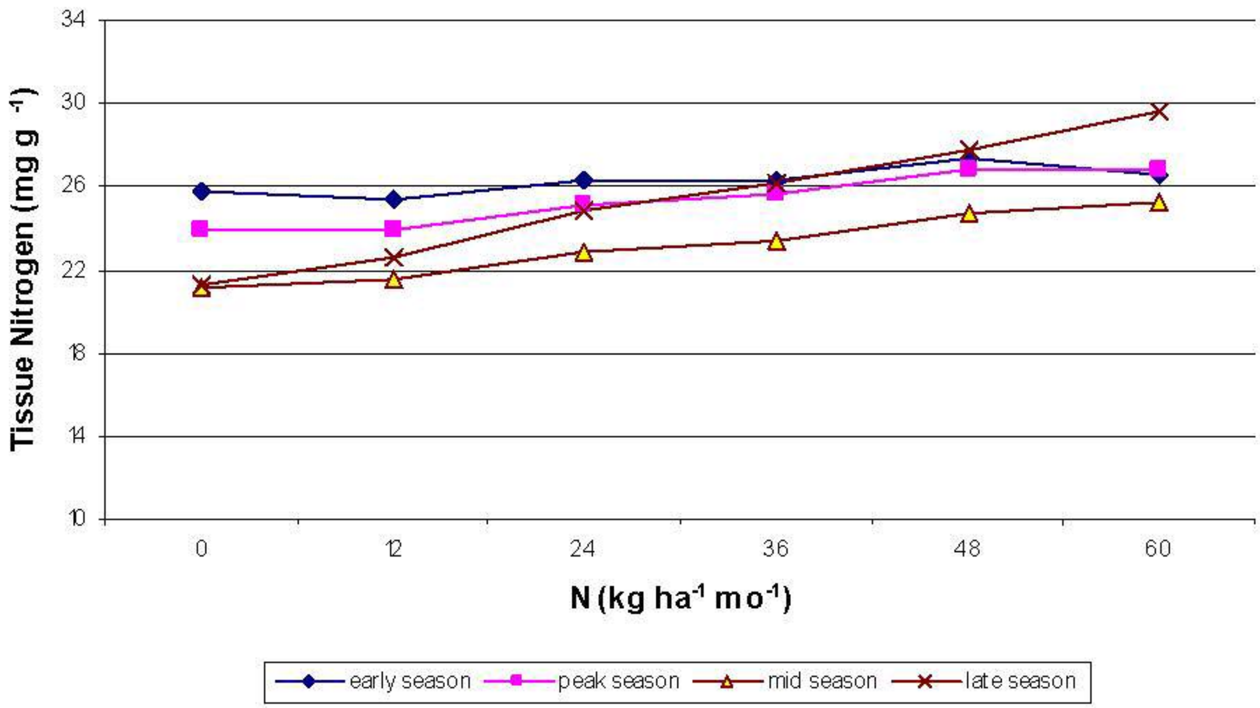


Figure 17. Tissue nitrogen response to N fertilization by season in 2004.

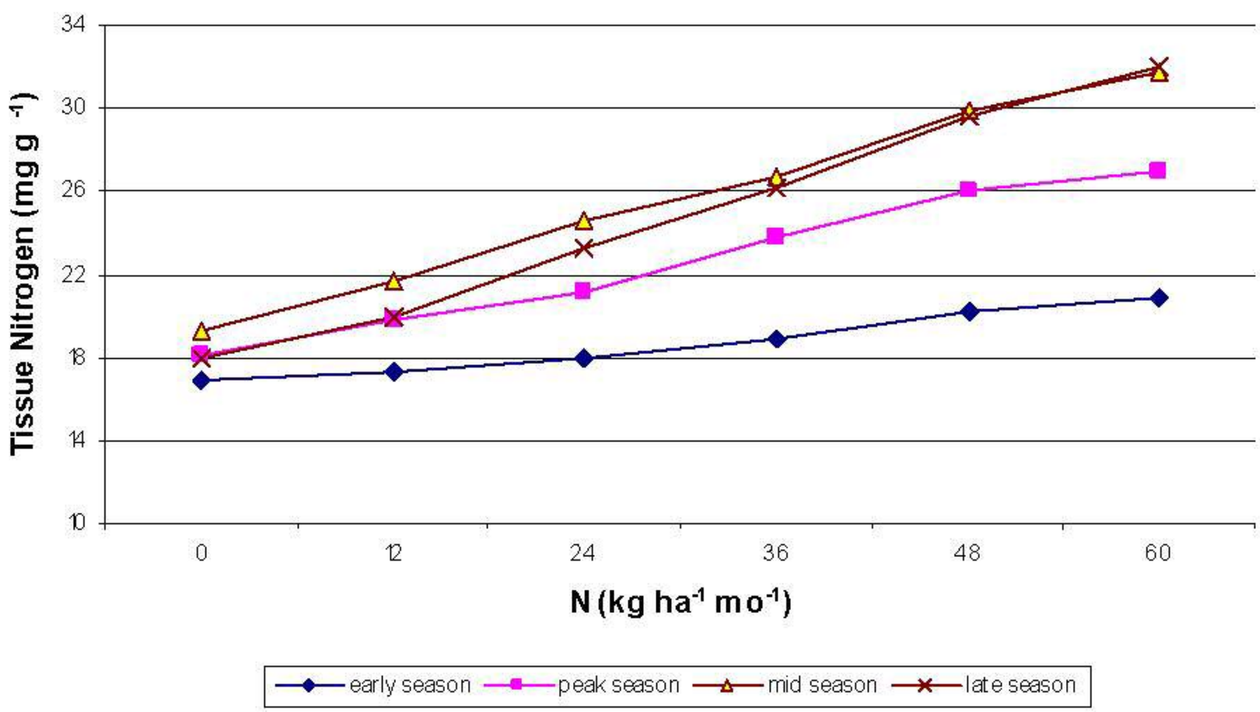


Figure 18. Tissue nitrogen response in days of year in 2003 and 2004 and the polynomial trend.

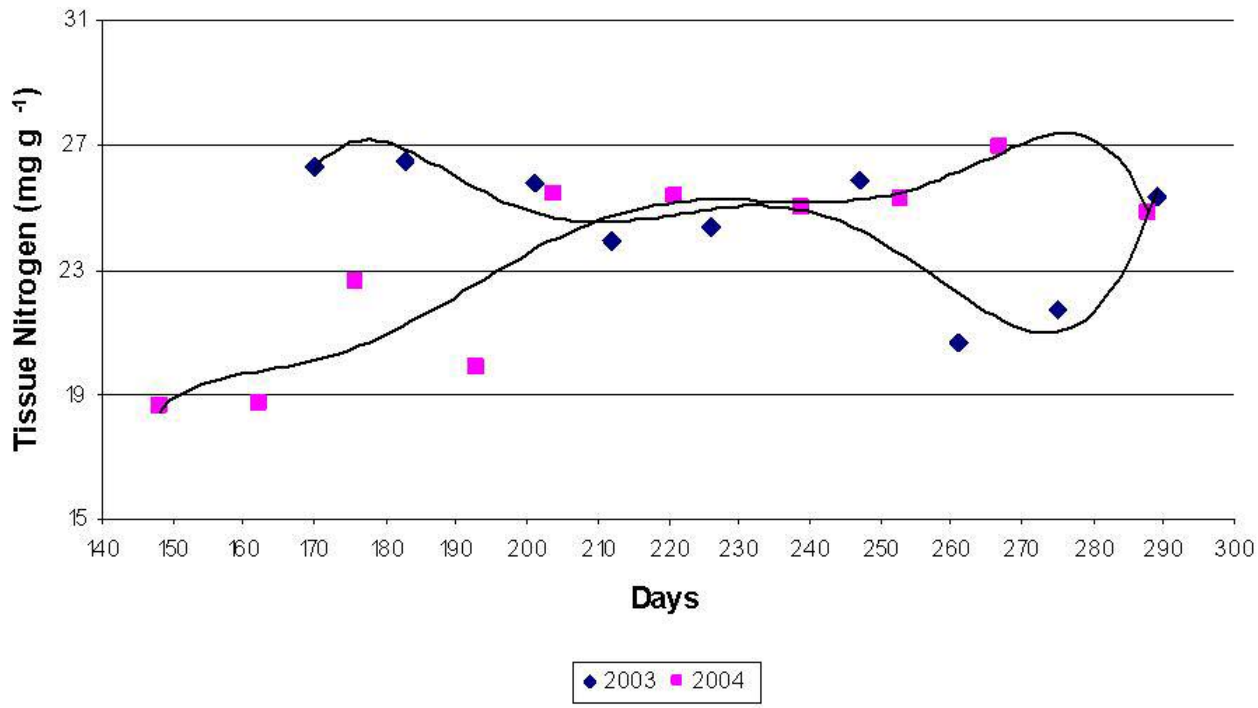


Figure 19. Chlorophyll concentration response to 0.63, 1.27 and 2.54 irrigation in 2003 (n=108) and 2004 (n=108). Bars indicate the standard error intervals.

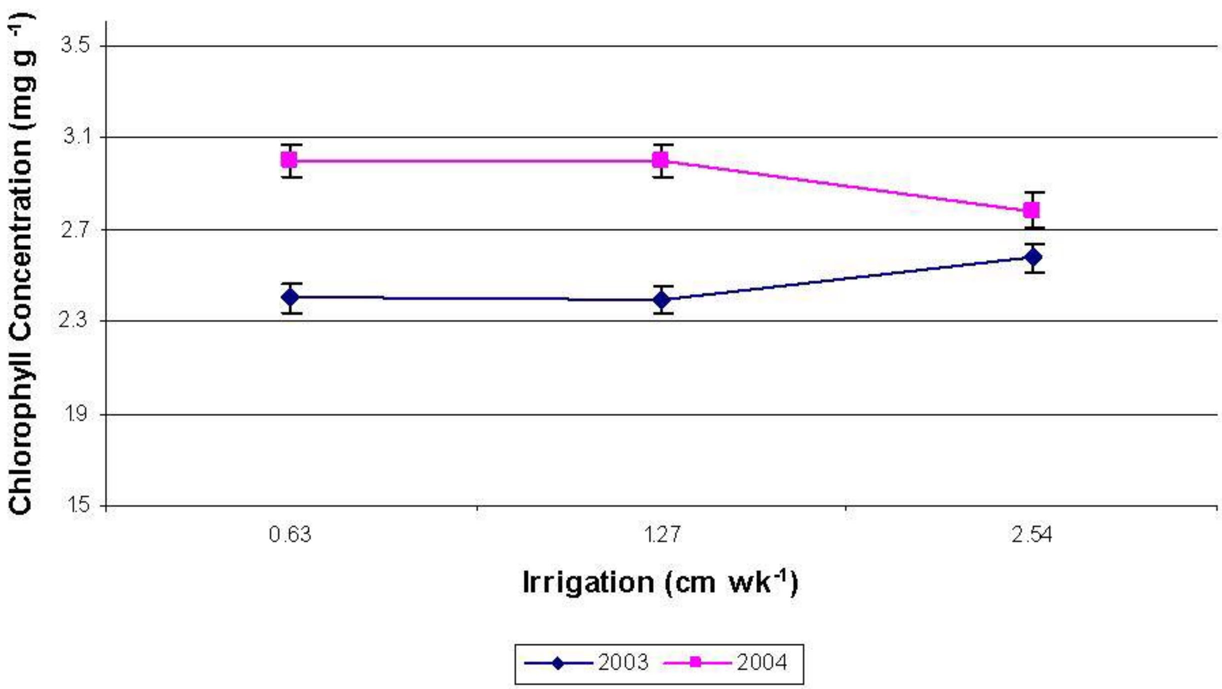


Figure 20. Chlorophyll concentration response to N fertilization in 2003 (n=54) and 2004 (n=54) and the trend lines.

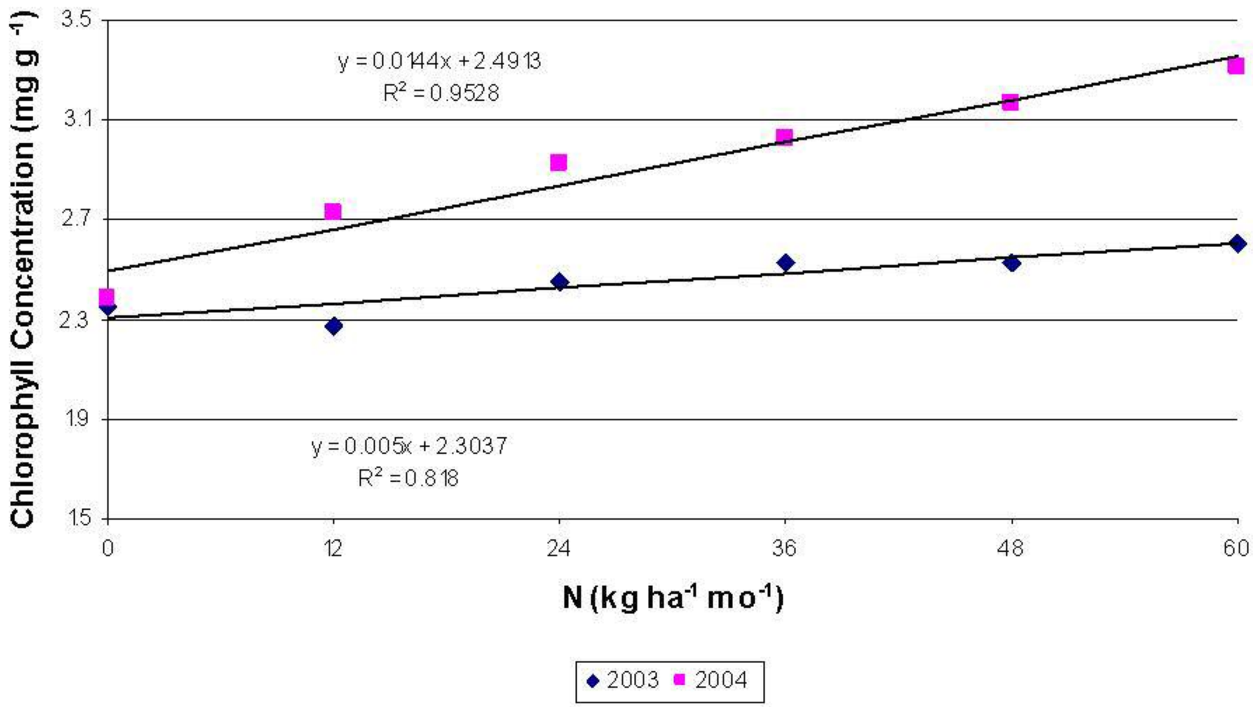


Figure 21. NDVI response to cultivar by season.

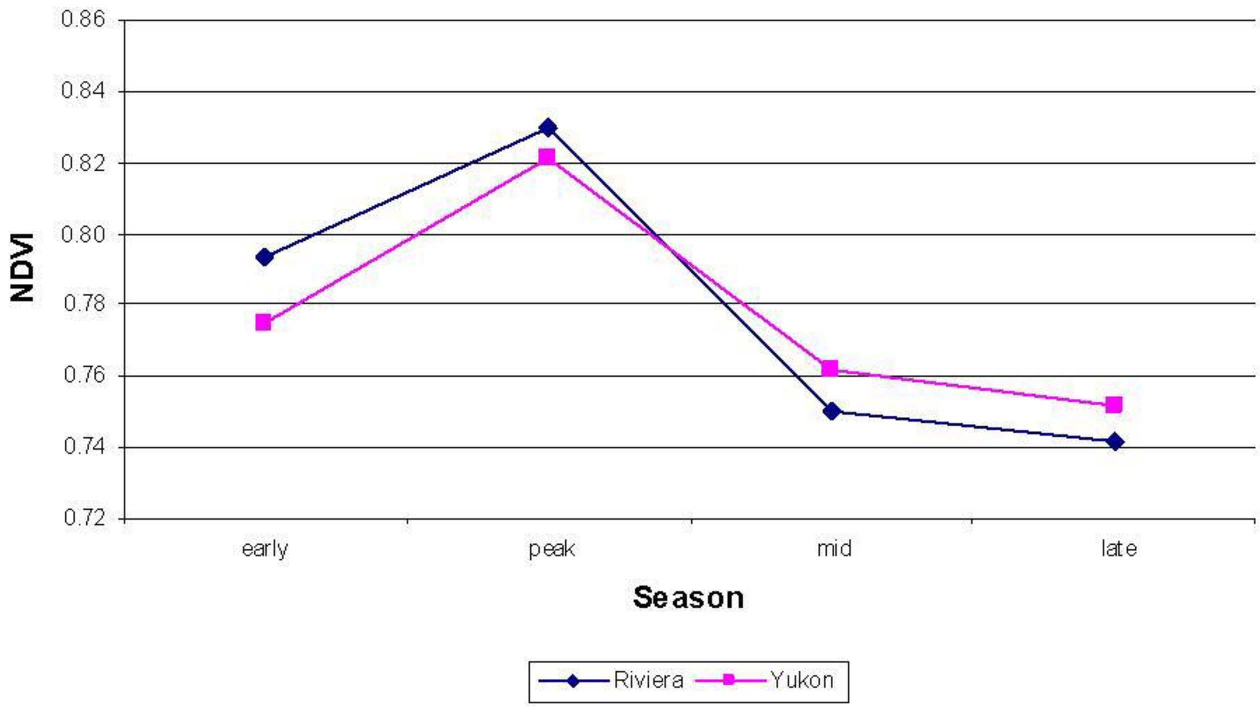


Figure 22. Visual rating response to cultivar by season. Bars indicate the standard error intervals.

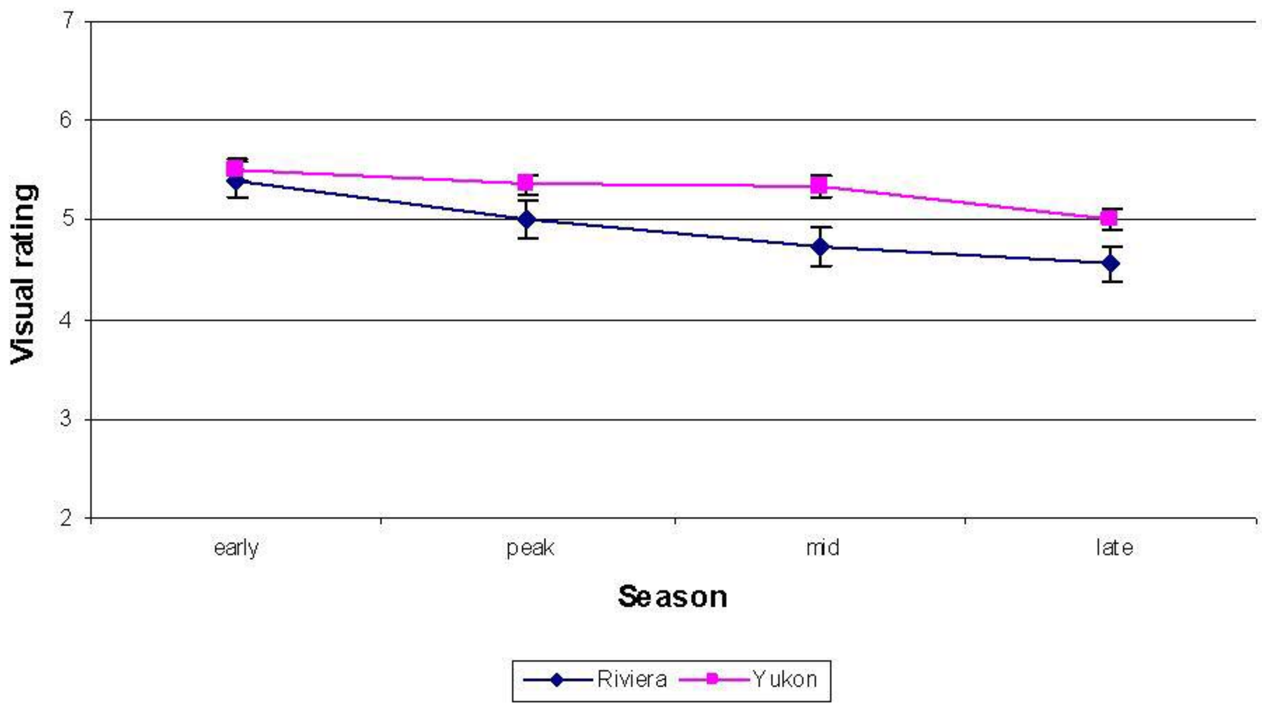
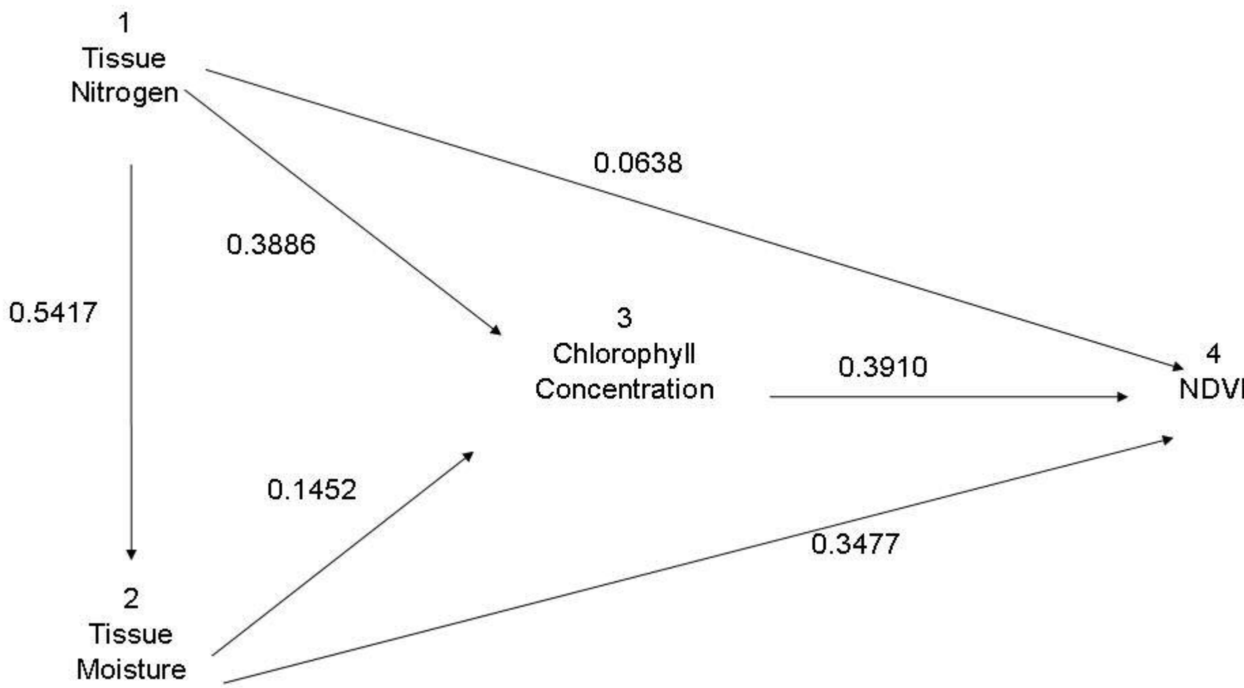


Figure 23. The Path Diagram of Bermudagrass NDVI, Tissue Moisture, Tissue Nitrogen, and Chlorophyll Concentration Relationship.



CHAPTER III

Airfield Sand System----Compared with Modified USGA Sand System.

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Abstract

USGA sand system is the most widely used method of constructing sand-based putting greens in the United States. Recently, several non-USGA sand systems have been developed for their cheap prices. One of them is the Airfield sand system. The Airfield system is currently in use at several sites with generally favorable reports but scientific research is not available. The purpose of this research was to compare the Airfield sand system with a modified USGA system for soil factors that affect turf growth potential. **'**Tifsport' bermudagrass (*Cynodon dactylon* L. × *C. transvaalensis* Burtt-Davy) was established on an Airfield sand system and a modified USGA sand system and managed similar to an athletic field. Canopy temperature, soil temperature, soil volumetric water content, soil gravimetric water content, and root density at the 0.0-7.6, 7.6-15.2, and 0.0-

15.2 cm sand layers were evaluated monthly from May to October in 2003 and 2004. Turf visual quality was evaluated during 2004. This study found that the two systems did not differ in soil temperature, canopy temperature, soil gravimetric water content, and root mass at 7.6-15.2 cm and 0.0-15.2 cm sand layers. The Airfield sand system had significantly higher ($P<0.05$) volumetric water content (12 %) at a depth of 12 cm compared with the modified USGA sand system (11 %). The modified USGA sand system had significantly higher ($P<0.05$) root density (1.13 mg cm-3) than the Airfield sand system (0.95 mg cm-3) in the 0.0 to 7.6 cm sand layer. These differences, however, did not affect the turf quality and the two systems had same visual quality ratings. In this research, the bermudagrass root density in both systems were found significantly higher ($P<0.05$) in September (1.01 mg cm-3) and October (0.90 mg cm-3) compared to the rest of months in 0.0-15.2 cm soil layer. The lowest root density was found in August (0.65 mg cm-3). A comparison of root density with soil temperature found that bermudagrass root growth declined when the soil temperature excess of 21oC. Along the surface and subsurface drainage flow from high to middle to low elevations, both of the systems had significantly higher ($P<0.05$) gravimetric water content at low elevations in each soil layer evaluated (8.7 %, 5.4 %, and 6.8 % in 0.0-7.6, 7.6-15.2, and 0.0-15.2 cm soil layer respectively) than did in high elevations (7.2 %, 4.7 %, and 5.8 % in 0.0-7.6, 7.6-15.2, and 0.0-15.2 cm soil layer respectively). Both systems also had significantly higher ($P<0.05$) root density in 0.0-15.2 cm sand layers in low elevations (0.94 mg cm-3) than did in high elevations (0.69 mg cm-3). These results suggested that the Airfield sand system was not substantial different from the modified USGA system but did indicate that both systems retained significantly more water, drained more poorly and encouraged increasing root growth at lower elevations. These findings are important to turfgrass managers who strive to maintain consistent turfgrass quality and adequate irrigation throughout a sand-based system.

Introduction

Sports field managers try to maintain firm, smooth, and well drained turfgrass playing surfaces. To achieve these goals, researchers and practitioners have found that native silt or clay soils are not satisfactory to encourage a root zone which remains highly oxygenated without severely restricting its water-holding capacity. On the other hand, sand with its ideal physical characteristics, relatively consistent particle size, better compaction resistance and aeration porosity, and high infiltration rate, is considered a best replacement as a growing medium for turfgrass playing surfaces. By 1960, the USGA (United State Golf Association) Green Section had recommended using sand based root zones to construct more acceptable putting or playing surfaces with tolerance for traffic and compaction (Beard 1982).

The traditional recommended sand based root zone system is the USGA sand system. It usually consists of a 90:10 sand-peat root zone (v/v) 30 cm deep with a perched water table resulting from placement of a fine sand-peat mix over 10 cm of gravel. In this system, the fine sand must be at or near saturation before water enters the coarser pea gravel for vertical drainage. Excess water drains through pipes in the sub base below the gravel layer. The USGA sand system effectively increases drainage while providing a certain amount of water holding capacity. This construction has become the most widely used method of constructing sand-based putting greens in the United States

(Christians, 1998). However, it is possible that during humid warm summers, the extra moisture potentially available in the perched water table may have a negative affect. With extra water stored, the root zone has less air-filled porosity. Also the water acts as an insulator, resulting in root zones with high relative soil temperature (Ervin and Fresenburg, 1999). High soil temperature and less air availability imply greater root stress during warm summer temperatures.

Because of these concerns and the high price of construction, several non-USGA sand systems have been developed. One of these is the Airfield sand system distributed by Airfield Systems, LLC (Edmond, OK). The Airfield sand system utilizes 28 cm of custom porous sand root-zone mix placed over a Lutradur filter fabric that allows for the migration of fine particles (e.g. silt, clay and organic materials) from the root zone to a composite grid support structure below. The Draincore2 composite ring and grid structure provides a 2.5 cm layer of mostly air that encourages rapid drainage and constant air exchange. The Draincore2 structure rests on an impervious membrane against the sub grade which slopes to perimeter drains where water is collected. According to the distributor, the Airfield reduces construction time which contributes to the lower overall cost of the system.

The Airfield system is currently in use at several sites with generally favorable reports but scientific research is not available. The purpose of this research was to compare the Airfield sand system with a modified USGA system for soil factors that affect turf growth potential.

Materials and methods

This study was conducted at Oklahoma State University Turfgrass Research Center, Stillwater, OK. The plant material was Tifsport bermudagrass.

The experimental site was constructed in the summer of 2000 and consisted of two Airfield systems and two modified USGA systems 7.0 m × 3.5 m each. The Airfield system consisted of a 28 cm root zone of US Department of Transportation concrete specification sand. This sand was similar to USGA specifications for particle size except for a small component of coarse particles. The root zone in the Airfield system was supported by a Lutradur filter fabric (Freudenburg spunweb company, Durham, NC) over the Draincore2 grid system (airfield system), constructed of 100% recycled plastic, that provided an area of mostly air 2.5 cm deep beneath the entire surface. The grid was placed on an impervious waterproof sheet over a firm subsoil base. Drainage was collected in pipes installed on the sides of the system. No organic materials were added to the root zone sand.

The modified USGA construction consisted of a 30 cm root zone of USGA specification sand with no organic component. The root zone rested on 10 cm of washed pea gravel over firm subsoil. Drainage was provided by a single 10 cm diameter drain pipe located in the sub grade below the gravel and extending down the middle of the plot for its entire length.

The bermudagrass in both systems were maintained at 2.5 cm and fertilized at 240 kg ha^{-1} N per growing season. Pre-emergent herbicide, 0.897 kg Prodiamine ha^{-1} (2, 6-Dinitroaniline), was applied each spring to control summer annual weeds. A non-selection herbicide, 0.46 kg Glyphosate ha^{-1} (N-phosphonomethyl glycine), and a broadleaf herbicide, 0.92 kg 2, 4-D Amine ha^{-1} (2, 4-Dichlorophenoxyacetic Acetic Acid), were applied each winter to control cool-season weeds.

The experiment was conducted as a split block design with repeated measurements. The treatment structure was a 2×3 factorial with two sand base system treatments (Airfield and modified USGA sand system), and 3 location treatments based on surface and subsurface drainage flow direction from high to middle to low locations. Sampling was performed monthly during the Oklahoma growing season from May through October in 2003 and 2004.

Soil and Canopy Temperature

Soil temperature was measured using a Bimetal Thermometer (Reotemp Instruments, San Diego, CA) that produced a direct measurement of soil temperature at a depth of 5 cm. Each temperature was measured three times within each experimental unit and a mean calculated for analysis. Experimental units consisted of locations within systems.

The canopy temperature was measured using a ST27™ Turf Monitor infrared thermometer (Standard Oil Engineered Materials Co., Solon, Ohio). Each canopy temperature was measured three times within each experimental unit and a mean calculated for analysis.

Soil water content

Soil water content was measured using two methods. A commercially available soil moisture probe (HydroSense Soil Water Content Measurement System, Campbell

Scientific, Utah) was used to estimate volumetric water content (cm^3 cm^{-3}) by time domain reflectometry using 12 cm probes. The results were presented as percentage. Each plot was measured three times and a mean calculated for analysis.

A second soil moisture measurement employed soil samples collected using a standard soil probe (2.5 cm in diameter). Samples consisted of 15 randomly selected cores removed from the 0.0-7.6 cm soil layer within each experimental unit. The shoots and thatch layer were removed from each core and the soil and roots used for analysis. All 15 cores were mixed for one measurement. An additional 15 cores were also collected at a lower depth of 7.6-15.2 cm and handled in the same manner. After collection, the soil sample fresh weight was measured prior to drying at 50 ºC to constant weight. The difference between the dry soil weight and the fresh soil weight was used to determine the soil gravimetric water content (g g^{-1}) and the results were presented as percentage. After collecting soil samples, the holes were filled with the same sand used in the corresponding systems, and the same holes were not sampled again during the following months.

Root density

After the soil moisture was determined, the roots were washed free of soil under tap water and collected in U.S. Standard Sieves (Fisher Scientific Company, Pittsburgh, PA). Three sieves were used together to separate the roots from the soil under running water. The opening sizes of the sieves were 6.35 mm, 2.54 mm, and 1.00 mm each from top to bottom. The roots from the 0.0-7.6 cm samples were also separated from the rhizomes. The roots were collected from each sieve and dried in an oven at 50 ºC. The root mass was determined after the roots were dried to constant weight and the root density (mg cm^{-3}) was calculated.

Visual rating

Visual rating for turf quality was conducted during the 2004 growing season on a 1 to 9 scale (9 = the best quality, all plants were healthy and green; 1 = worst quality, all plants were dead or brown).

Statistic Analysis

The main effects of sand system, location, and date of measurement, and their interactions were determined by analysis of variance (ANOVA) according to the mixed model procedure of Statistical Analysis System (SAS, Cary, NC). Significant treatment means were separated using LSD (P=0.05). Trend analyses were performed when ANOVA indicated a significant difference among the dates of measurement.

Results and Discussion

Soil and canopy temperature responses

Soil temperature was nearly the same for the Airfield and modified USGA systems in each month of measurement (Figure 24). There was no significant difference in soil temperatures between the two sand systems and the three locations (Table 5). However, soil temperature differed significantly by month. From May to August, the soil temperature increased from 25 to 30 ºC and then decreased in September and October to 19 and 21 ºC respectively.

The canopy temperature responded to the Airfield and modified USGA systems similarly to soil temperature response during two growing seasons. The canopy temperatures were nearly equal for the two systems (Figure 25). There was no significant difference between systems and locations (Table 5). The canopy temperature trend by month was similar to that of soil temperature. From May to August, the canopy temperature increased from 33 to 37 ºC, decreased in September to 17 ºC, and increased to 29 ºC in October.

Canopy temperatures in both of the systems were consistently higher than the surrounding air temperatures (mean difference = 4 ºC) each month (Figure 26). This observation implied that during the sampling time (~ solar noon), transpiration was not sufficient to cool the turf. This response was believed to be abscisic acid (ABA) dependent (Davies and Zhang, 1991; Trejo et al, 1995; Franks and Farquhar, 2001). When roots sensed dehydration in the media, ABA synthesized in the root was transported to the shoot causing the stomata to close reducing transpiration cooling.

Soil water content

The Airfield sand system had significantly ($P<0.01$) higher soil volumetric water content (12.0 %) at the 12 cm depth than the modified USGA system (10.6 %) (Table 5 and Figure 27).

Gravimetric water content was statistically the same for the two systems in each soil layer tested (Figures 28, 29, and 30). However, the gravimetric water content in the 0.0-7.6 cm layer of soil, 7.6-15.2 cm layer of soil, and the overall 0.0-15.2 cm layer of soil consistently demonstrated an increasing pattern along the locations of drainage from high to middle to low (Figures 31, 32 and 33). In the 0.0-7.6 cm layer, gravimetric water content significantly increased from 7.2 % to 8.4 % in the Airfield system and from 6.8 % to 8.6 % in the modified USGA system along elevation from high to low (Table 6). In the 7.6-15.2 cm layer, the gravimetric water content increased from 4.6 % to 4.9 % in the Airfield system and from 4.5 % to 5.5 % in modified USGA system with decreasing elevation. Consequently, the gravimetric water content in 0.0-15.2 cm layer increased from 5.8 % to 6.4 % and from 5.6 % to 6.9 % in the Airfield system and the modified USGA system respectively. The two systems were consistent in response to locations and no location × system interaction occurred.

Volumetric water content in the Airfield sand system in the 0-12 cm layer was significantly higher than in the modified USGA system. However, the differences in gravimetric water content between the systems were not significant. Significantly different (t test; P<0.0001) bulk densities of the sand used in the two systems (0.88 g cm^{-3} in the Airfield system; 0.83 g cm^{-3} in the modified USGA system) probably contributed to this result.

Root density

The root density in 0.0-7.6 cm of soil was significantly (P<0.05) higher in the modified USGA system (1.13 mg cm^{-3}) than in the Airfield system (0.95 mg cm^{-3}) resulting in 16 % higher root density in the modified USGA system (Table 7). The root density was less in the 7.6 to 15.2 cm layer than in the 0.0 to 7.6 cm layer and averaged 0.73 mg cm^{-3} in both systems. The overall mean root density in the 0.0 to 15.2 cm layer of sand in the Airfield system (0.78 mg cm^{-3}) was not significantly different from the modified USGA system (0.87 mg cm^{-3}). However, the overall mean root density in the 0.0 to 15.2 cm layer of sand increased significantly with decreasing elevation (Figure 34). The root density in the highest location (0.69 mg cm^{-3}) was significantly ($P<0.05$) less than in the lowest location (0.94 mg cm^{-3}) in spite of increased water availability at the lowest elevation (Table 7). This result suggested that there was more root mass per unit of soil in location when soil water was more abundant. This result was similar to a study on tall fescue (*Festuca arundinacea* Schreb). Huang and Fry (1998) found that under soil drying conditions, turfgrass produced finer roots than a well watered control which resulted in a longer root length per unit root mass and lower total root mass.

Roots were most plentiful in the 0.0 to 7.6 cm layer in September (1.59 mg cm^{-3} in the modified USGA system and 1.40 mg cm^{-3} in the Airfield system), and October (1.33 mg cm^{-3} in the modified USGA system and 1.13 mg cm^{-3} in the Airfield system) (Figure 35). Mean comparison indicated that root density in September and October were significantly higher (LSD; $P<0.05$) than other months (Table 7). The root density in the 7.6 to 15.2 cm layer was significantly (LSD; $P<0.05$) higher in October, June, and May than in July, August, and September (Figure 36). The overall root density in the 0.0 to 15.2 cm layer in September (1.06 and 0.96 mg cm^{-3} in the modified USGA and in the Airfield system respectively) and in October (0.96 and 0.85 mg cm^{-3} in the modified USGA and in the Airfield system respectively) had the highest root density. The lowest root density occurred in August (0.67 and 0.64 mg cm^{-3} in the modified USGA and in the Airfield system respectively) (Figure 37).

Shoot growth was largely affected by air temperature and root growth was mainly affected by soil temperature similar to the result of Xu and Huang (2000). For warm season grasses, the best adapted shoot growth temperatures are generally believed to be 27-35 ºC. For root growth, the best soil temperatures are believed to be 17-21 ºC. A comparison of the root density and soil temperature found that root density decreased when the soil temperature reached 21 ºC. Regression analysis suggested that root density was significantly (P<0.05) affected by soil temperature in each soil layer evaluated. The linear relationship between soil temperature and root mass at 0.0-7.6 cm soil layer (r^2 = 0.32) was stronger than the relationship between soil temperature and root mass in the 7.6-15.2 cm layer (r^2 = 0.06) suggesting that the upper root mass was more sensitive to soil temperature. In this study, root density demonstrated a summer decline and a fall increase. This pattern has been reported in cool-season grasses (B. Huang and X. Liu, 2003), but not in warm-season grasses. Root growth in bermudagrass is generally believed to increase over the summer. These results suggest that high soil temperatures in excess of 21 ºC may cause a decline in bermudagrass root growth during summer.

Visual rating

Visual ratings of turf quality conducted in 2004 indicated no significant differences between the two systems (Table 5). Although the soil volumetric water content and 0.0-7.6 cm layer root mass were significantly different, this result implied that the differences in root mass between these two systems were not large enough to affect shoot quality. The monthly trend of visual ratings suggested that bermudagrass visual quality was greatest in May (6.3 in both systems) and worst in October (4.0 in both systems) (Figure 38). The location effect indicated that visual rating in the highest location (5.3 and 5.4 in the modified USGA and in the Airfield system respectively) was significantly higher (P<0.05) than the lower locations (5.1 for both systems) (Figure 39 and Table 5). The two systems were consistent in visual rating response and no location × system interaction occurred.

Summary

In summary, the Airfield sand system and modified USGA system did not differ in soil temperature, canopy temperature, soil gravimetric water content, and root mass at 7.6-15.2 cm and 0.0-15.2 cm soil layer. However, the Airfield system had higher soil volumetric water content and lower root mass in the 0.0 to 7.6 cm layer compared with the modified USGA system. These differences, however, were probably caused by soil bulk density difference and did not affect the overall turf quality. In this research, the bermudagrass root density in both systems were found significantly higher in September and October compared to the rest of months in 0.0-15.2 cm soil layer. The lowest root density was found in August. A comparison of root density with soil temperature found that bermudagrass root growth declined when the soil temperature excess of 21 ºC. This research did not result in substantial differences between the Airfield and modified USGA systems but did indicated that both systems retained significantly more water and drained more poorly at lower elevations. Both systems also encouraged increasing root growth at lower elevations. These findings are important to turfgrass managers who strive to maintain consistent turfgrass quality and adequate irrigation throughout a sand-based system.

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Table 5. Soil and Bermudagrass responses to Airfield and modified USGA Sand Systems in 2003 and 2004.

	Soil Temperature (°C)	Canopy Temperature (°C)	Soil Volumetric Water Content[x] (%)	Visual rating[y] (1-9=best)
Sand System				
Airfield Sand System	25.62a[z]	31.52a	12.02b	5.18a
Modified USGA Sand System	25.77a	31.32a	10.55a	5.18a
Location				
High	25.69a	31.02a	10.90a	5.38b
Middle	25.65a	31.65a	11.11a	5.00a
low	25.75a	31.58a	11.84a	5.10a
Monthly Response				
May	25.01c	33.22c	9.75a	6.33d
June	27.96d	34.85cd	10.54ab	4.92b
July	29.64e	36.48d	12.00bc	5.33c
August	30.18e	37.36d	12.18c	5.21bc
September	19.68a	17.55a	11.83bc	NA[w]
October	21.71b	29.06b	11.41bc	4.00a
Significant Effects				
Sand System Major effect	NS[v]	NS	**	NS
Location Major Effect	NS	NS	NS	***
Month Changes Major effect	***	***	*	***
Monthly Trend Analysis				
Month linear trend	***	***	NS	**
Month quadratic trend	*	***	**	***
Month cubic trend	NS	**	NS	NS
Month quartic trend	NS	NS	NS	NA
Month lack of fit trend	NS	NS	NS	***

[z]Means follows the same letter are not significant at LSD's 5% level.
[y]The visual rating (1~9) of the overall turfgrass evaluation was conducted as 1 was the poorest responses and 9 was the highest overall fitness.
[x]The Soil volumetric water content (%) was measured by HydroSense Soil Water Content sensor and estimated as volumetric water content at 12 cm.
[w]The NA means the missing data or not applicable.
[v]NS, *, **, *** are Non significant or significant at $p \leq 0.05$, 0.01 or 0.001, respectively.

Table 6. Soil gravimetric water content responses to Airfield and modified USGA Sand Systems in 2003 and 2004.

	Gravimetric Water Content (0.0-7.6 cm)[y] (%)	Gravimetric Water Content (7.6-15.2 cm) (%)	Gravimetric Water Content (0.0-15.2 cm) (%)
Sand System			
Airfield Sand System	7.95a[z]	4.97a	6.28a
Modified USGA Sand System	7.72a	5.13a	5.32a
Location			
High	7.17a	4.69a	5.81a
Middle	7.63a	5.10ab	6.27a
low	8.70b	5.37b	6.84b
Monthly Response			
May	6.81a	4.30a	5.40a
June	10.31c	5.41b	7.54b
July	7.28a	4.58a	5.74a
August	6.82a	4.68a	5.69a
September	9.02b	6.51c	7.70b
October	6.75a	4.83a	5.76a
Significant Effects			
Sand System Major effect	NS[v]	NS	NS
Location Major Effect	***	*	**
Month Changes Major effect	***	***	***
Monthly Trend Analysis			
Month linear trend	NS	***	***
Month quadratic trend	NS	**	NS
Month cubic trend	***	***	***
Month quartic trend	***	NS	***
Month lack of fit trend	***	**	***

[z]Means follows the same letter are not significant at LSD's 5% level.
[y]The gravimetric water content percentage was measured by soil probe (2.54 cm diameter) with mixed 15 randomly selected cores.
[v]NS, *, **, *** are Non significant or significant at p≤ 0.05, 0.01 or 0.001, respectively.

Table 7. Bermudagrass root density responses to Airfield and modified USGA Sand Systems in 2003 and 2004.

	Root Mass (0.0-7.6 cm) (mg cm^{-3})	Root Mass (7.6-15.2 cm) (mg cm^{-3})	Root Mass (0.0-15.2 cm) (mg cm^{-3})
<u>Sand System</u>			
Airfield Sand System	0.95a[z]	0.73a	0.79a
Modified USGA Sand System	1.13b	0.73a	0.87a
<u>Location</u>			
High	0.88a	0.61a	0.69a
Middle	1.08a	0.74a	0.85ab
low	1.05a	0.83a	0.94b
<u>Monthly Response</u>			
May	0.87a	0.82b	0.81bc
June	0.94a	0.96b	0.83bc
July	0.87a	0.57a	0.76ab
August	0.82a	0.48a	0.65a
September	1.50c	0.52a	1.01d
October	1.23b	1.01b	0.90cd
<u>Significant Effects</u>			
Sand System Major effect	**	NS	NS
Location Major Effect	NS[v]	NS	*
Month Changes Major effect	***	***	***
<u>Monthly Trend Analysis</u>			
Month linear trend	***	NS	***
Month quadratic trend	***	***	NS
Month cubic trend	NS	NS	NS
Month quartic trend	NS	NS	NS
Month lack of fit trend	NS	*	NS

[z]Means follows the same letter are not significant at LSD's 5% level.
[v]NS, *, **, *** are Non significant or significant at $p \leq 0.05$, 0.01 or 0.001, respectively.

Figure 24. The monthly soil temperature changes in Airfield and Modified USGA sand systems.

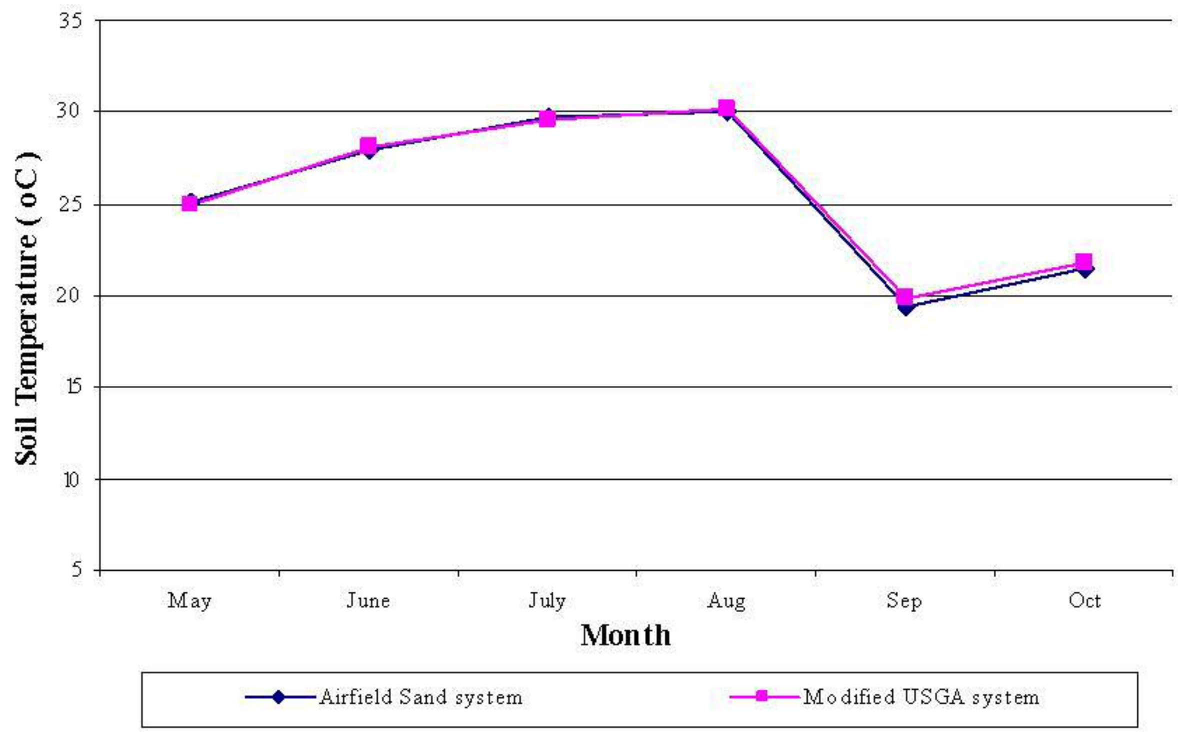


Figure 25. The monthly canopy temperature changes in Airfield and Modified USGA sand systems.

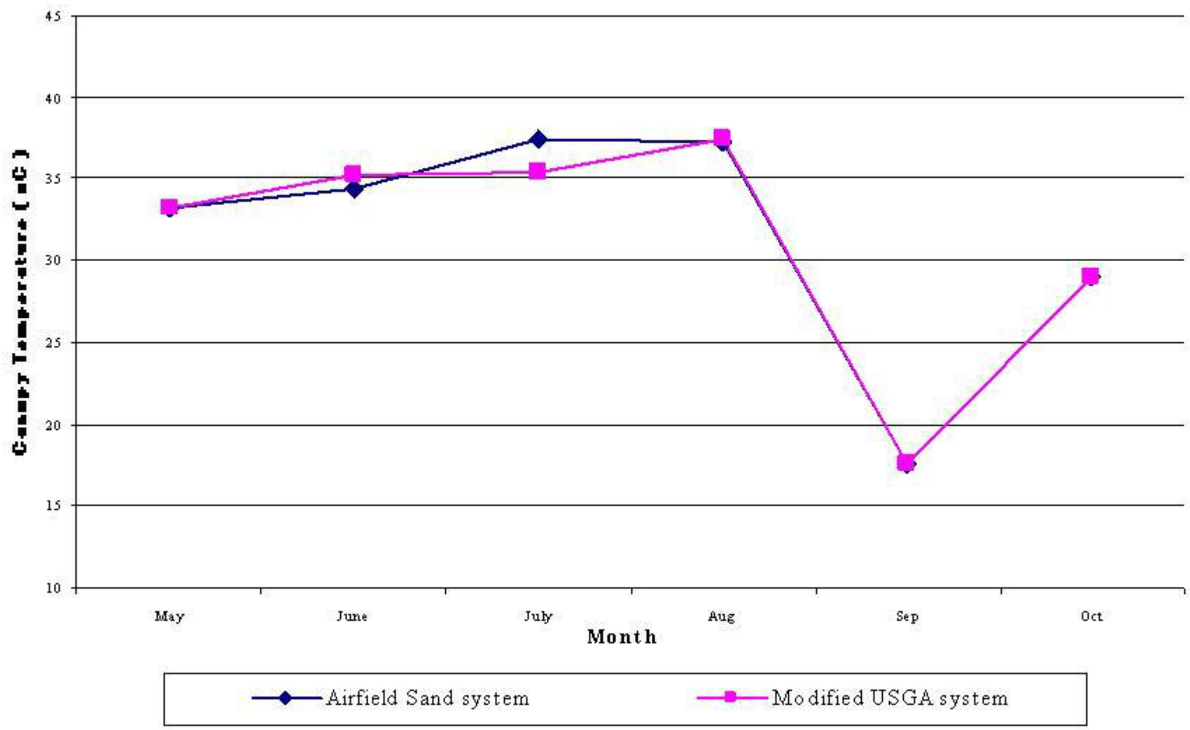


Figure 26. Mean (n=12) canopy Temperature and mean air temperature comparisons.

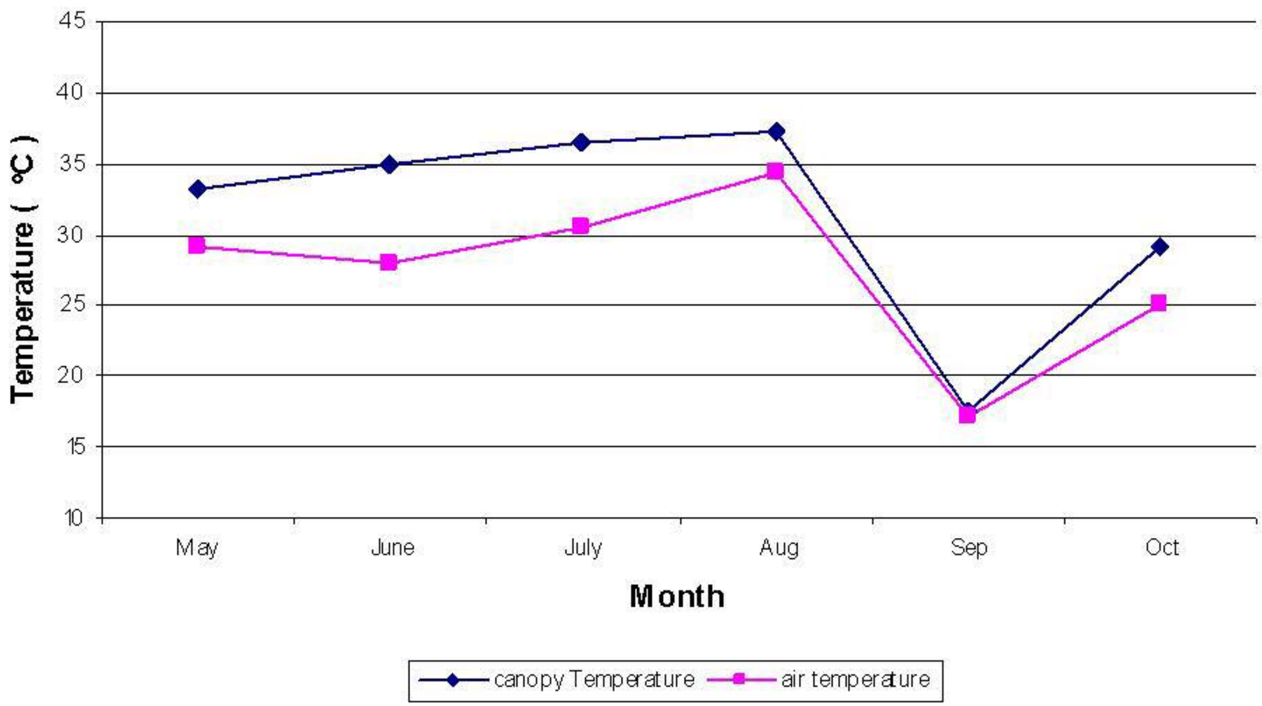


Figure 27. The monthly soil volumetric water content changes in Airfield and modified USGA sand systems.

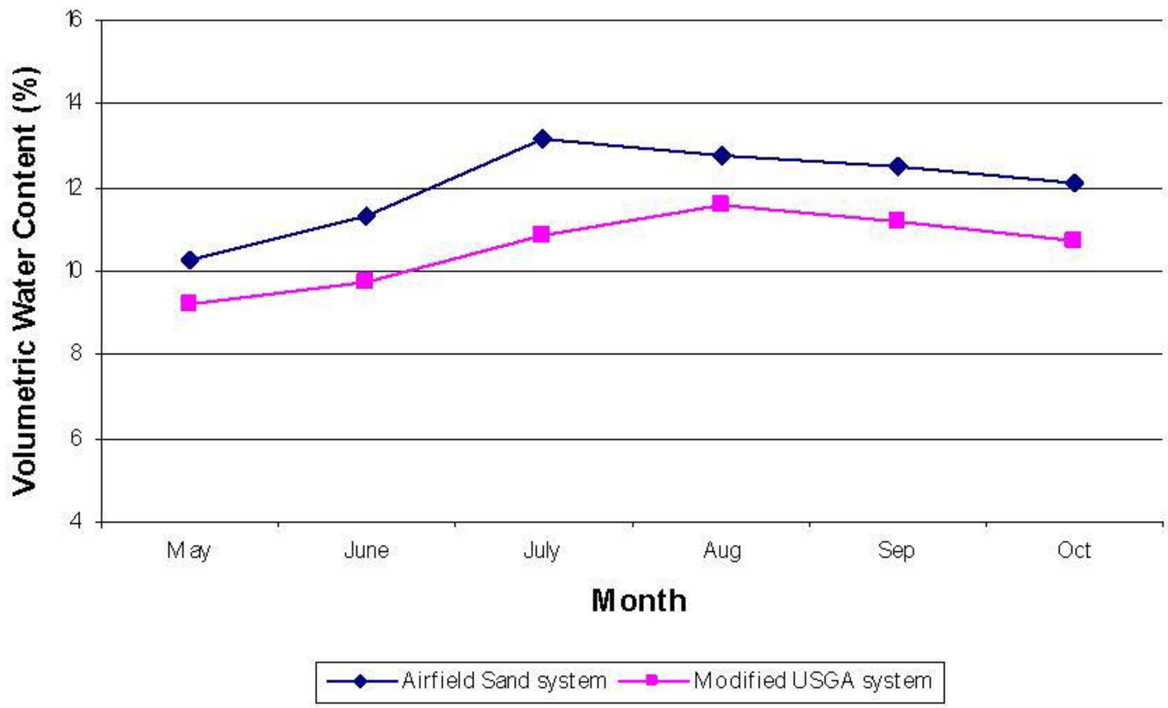


Figure 28. The mean (n=12) monthly 0.0-7.6 cm layer soil gravimetric water content changes in Airfield and modified USGA sand systems.

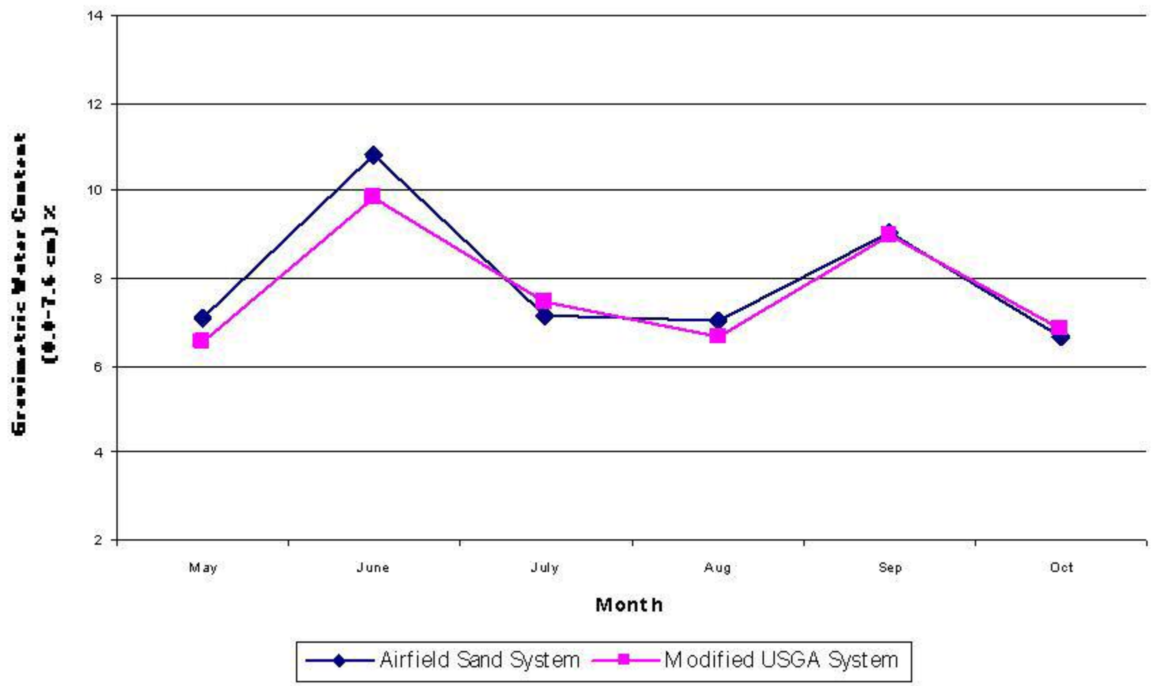


Figure 29. The mean (n=12) monthly 7.6-15.2 cm layer soil gravimetric water content changes in Airfield and modified USGA sand systems.

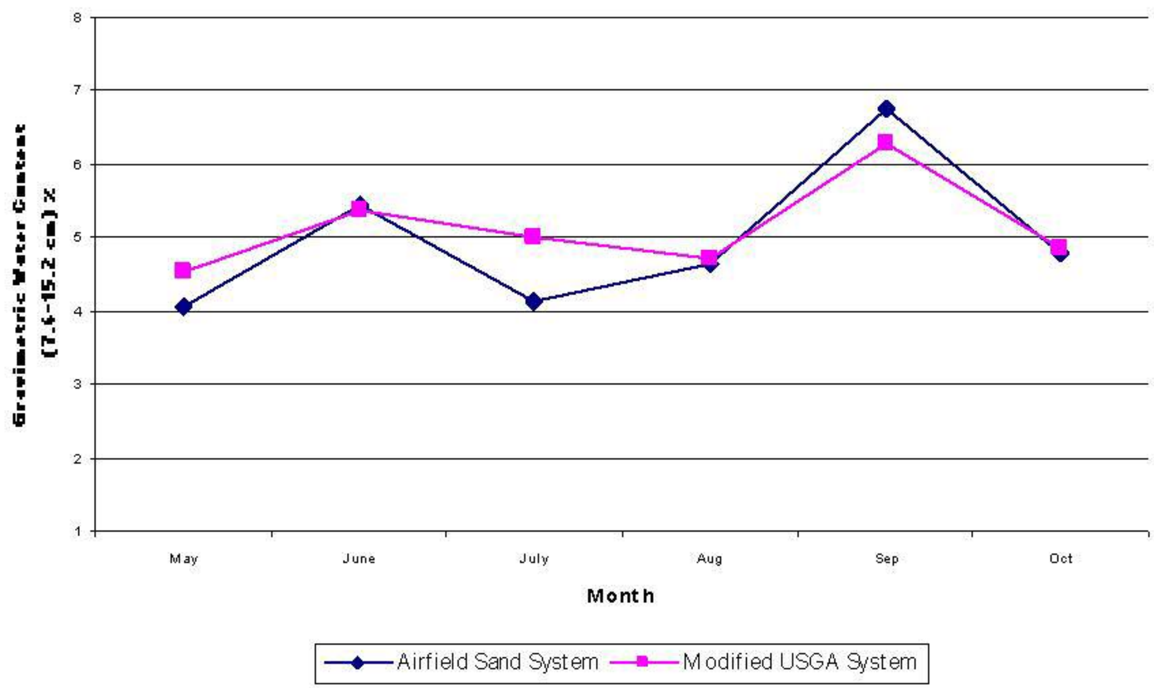


Figure 30. The mean (n=12) monthly 0.0-15.2 cm layer soil gravimetric water content changes in Airfield and modified USGA sand systems.

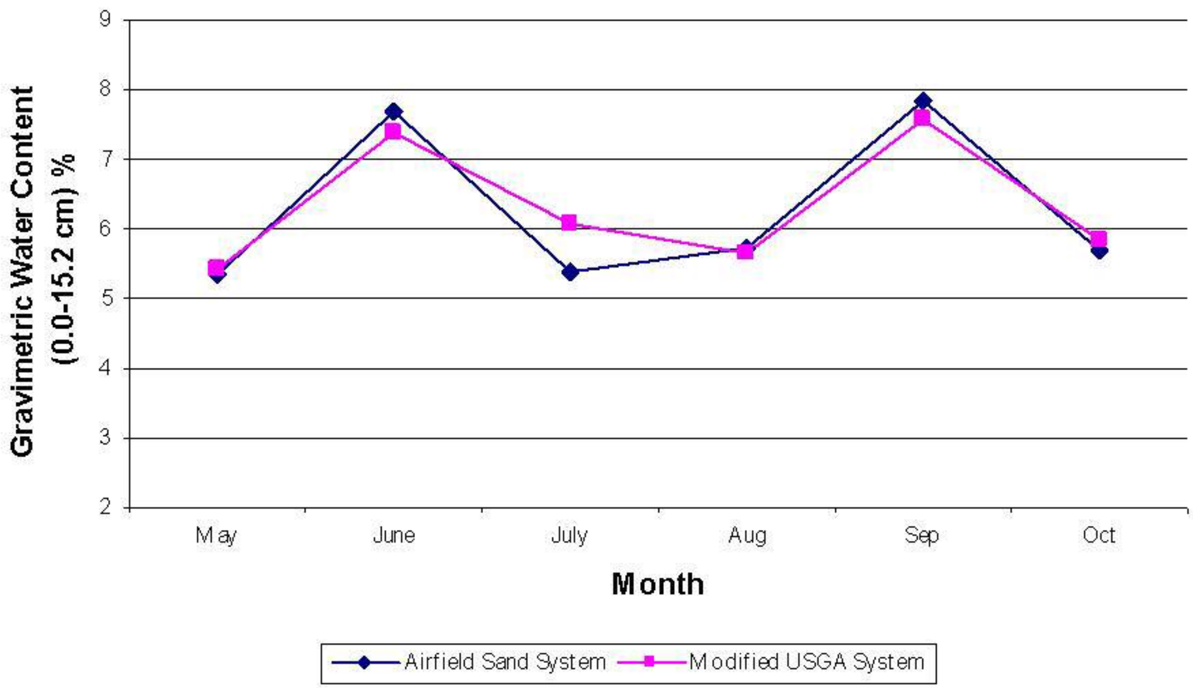


Figure 31. The mean (n=24) 0.0-7.6 cm layer soil gravimetric water content changes in different locations in Airfield and modified USGA sand systems.

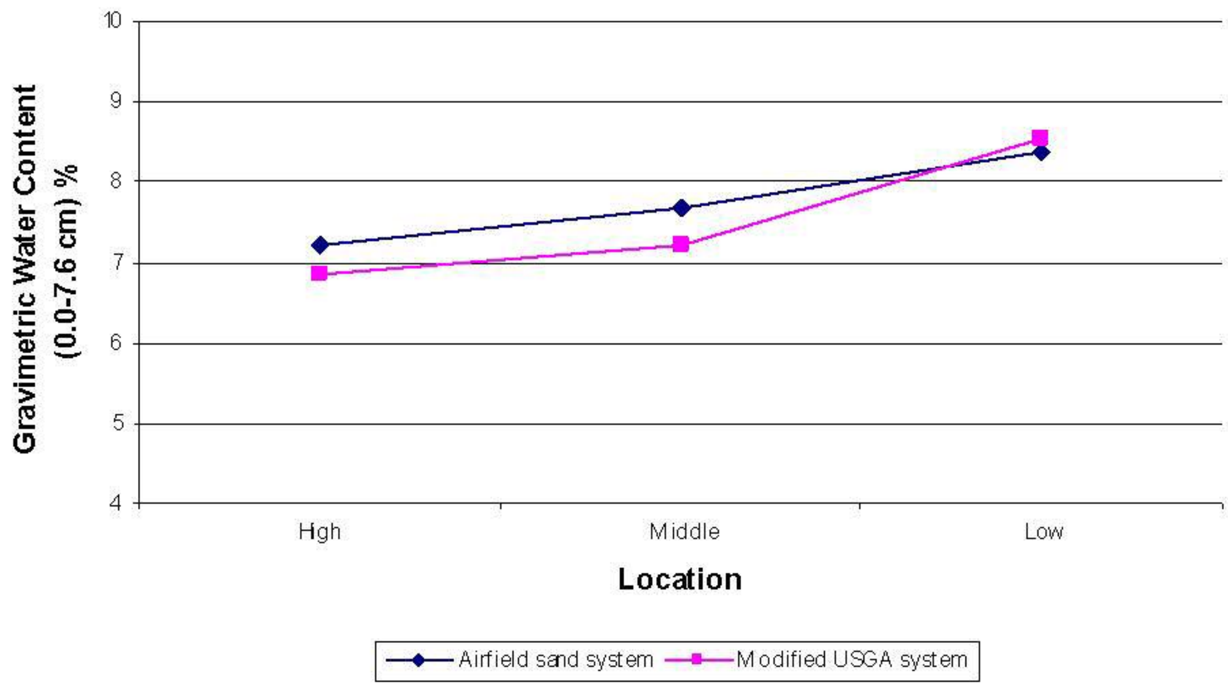


Figure 32. The mean (n=24) 7.6-15.2 cm layer soil gravimetric water content changes in different locations in Airfield and modified USGA sand systems.

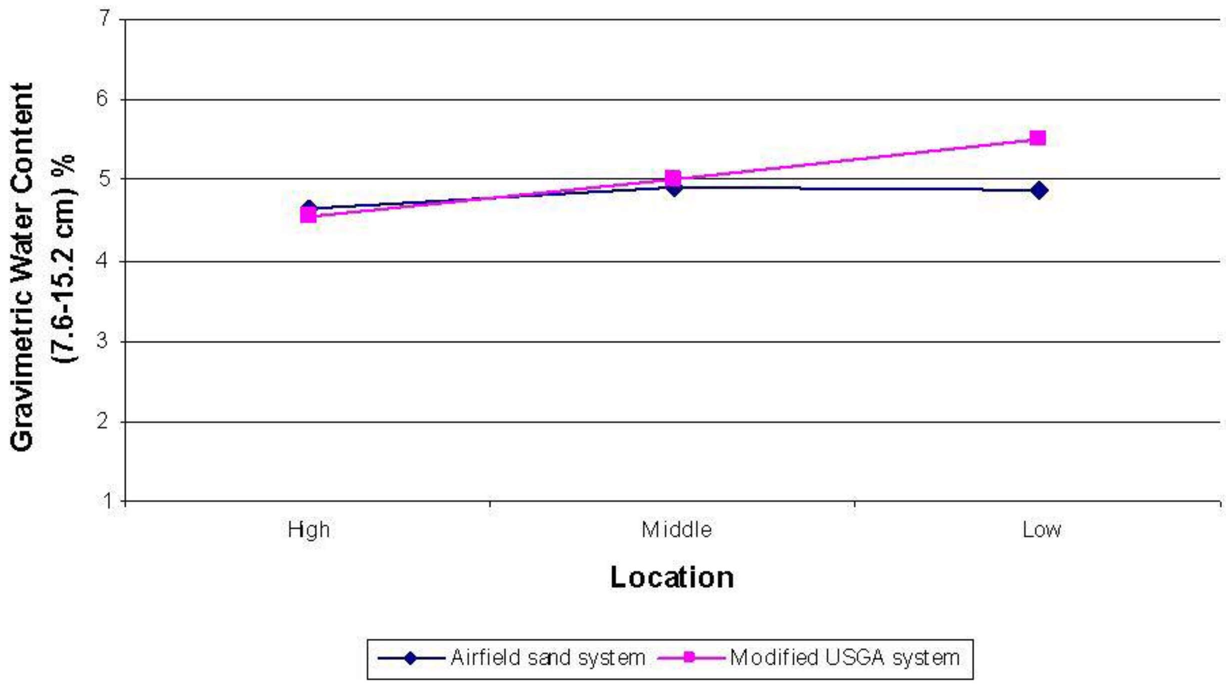


Figure 33. The mean (n=24) 0.0-15.2 cm layer soil gravimetric water content changes in different locations in Airfield and modified USGA sand systems.

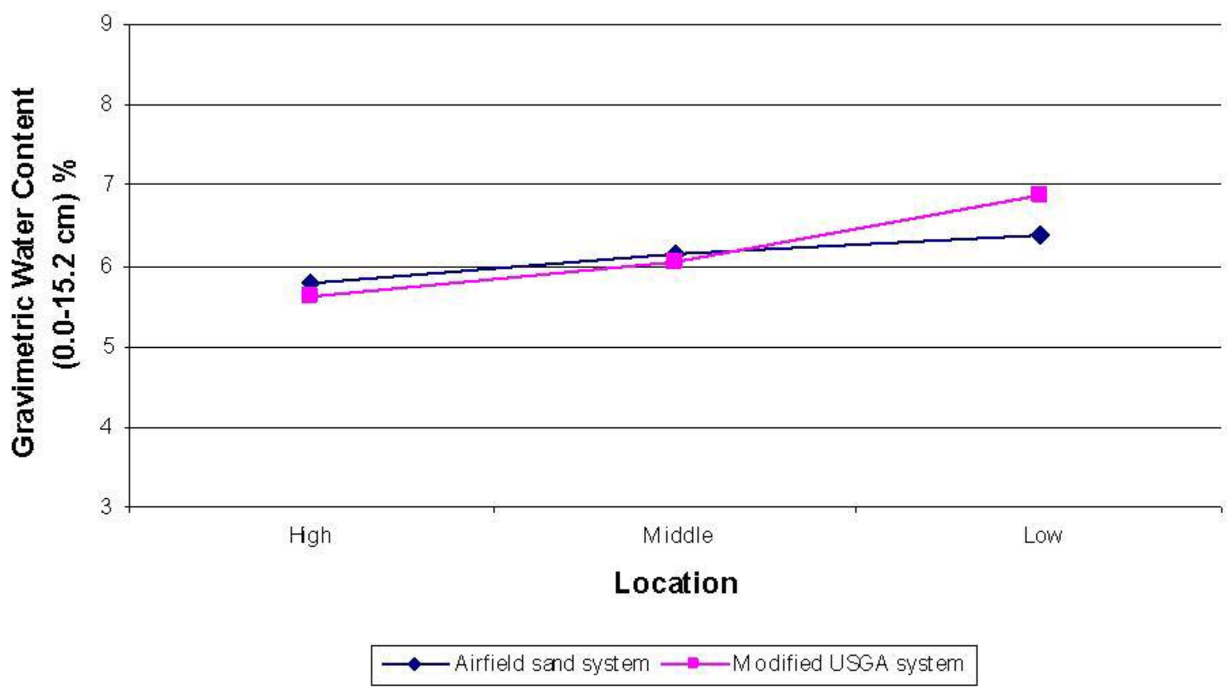


Figure 34. The mean (n=24) 0.0-15.2 cm layer root density changes in different locations in Airfield and modified USGA sand systems.

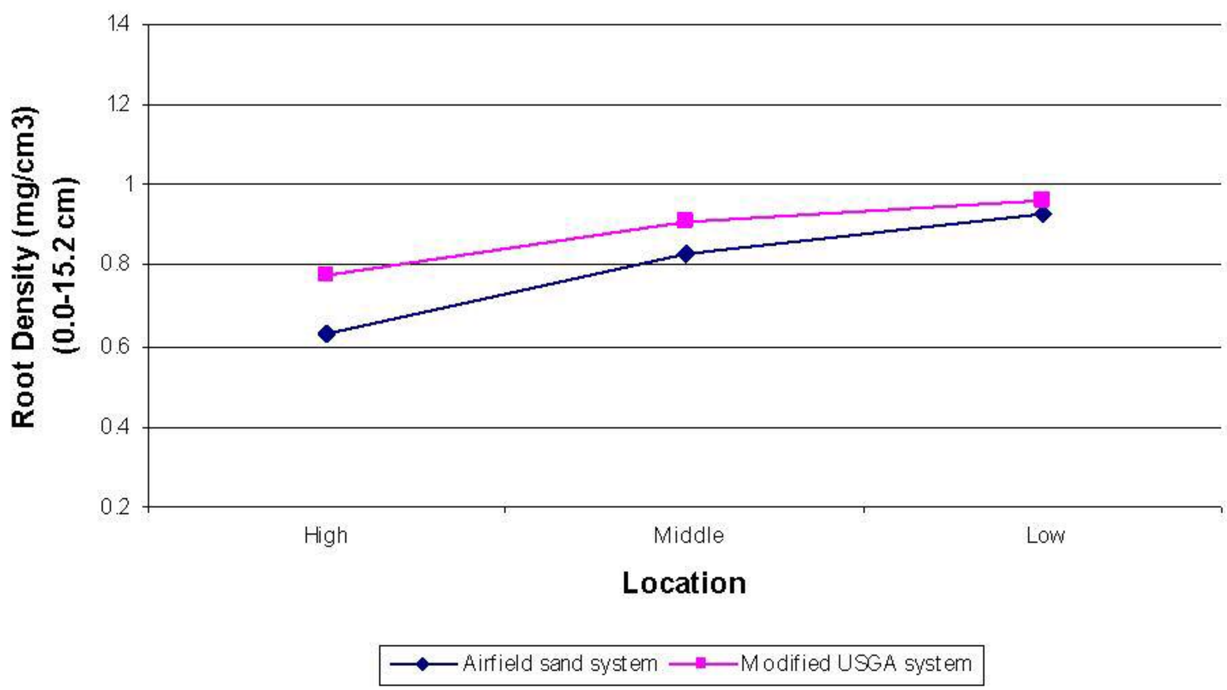


Figure 35. The mean (n=12) monthly 0.0-7.6 cm layer root density changes in Airfield and modified USGA sand systems.

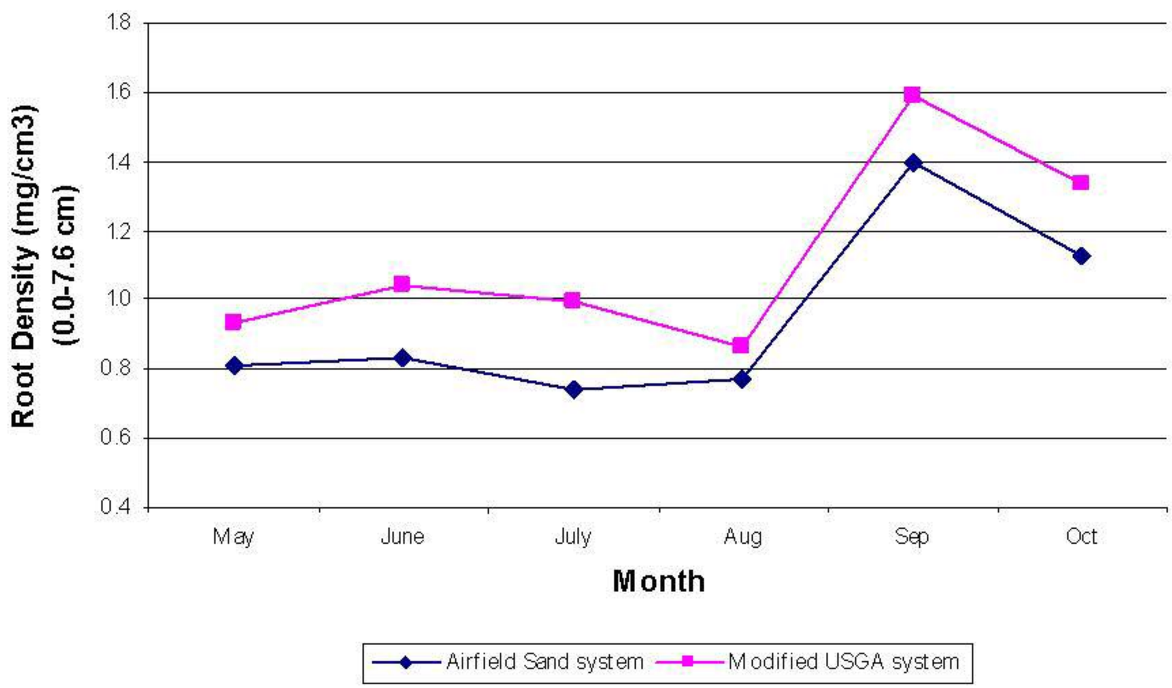


Figure 36. The mean (n=12) monthly 7.6-15.2 cm layer root density changes in Airfield and modified USGA sand systems.

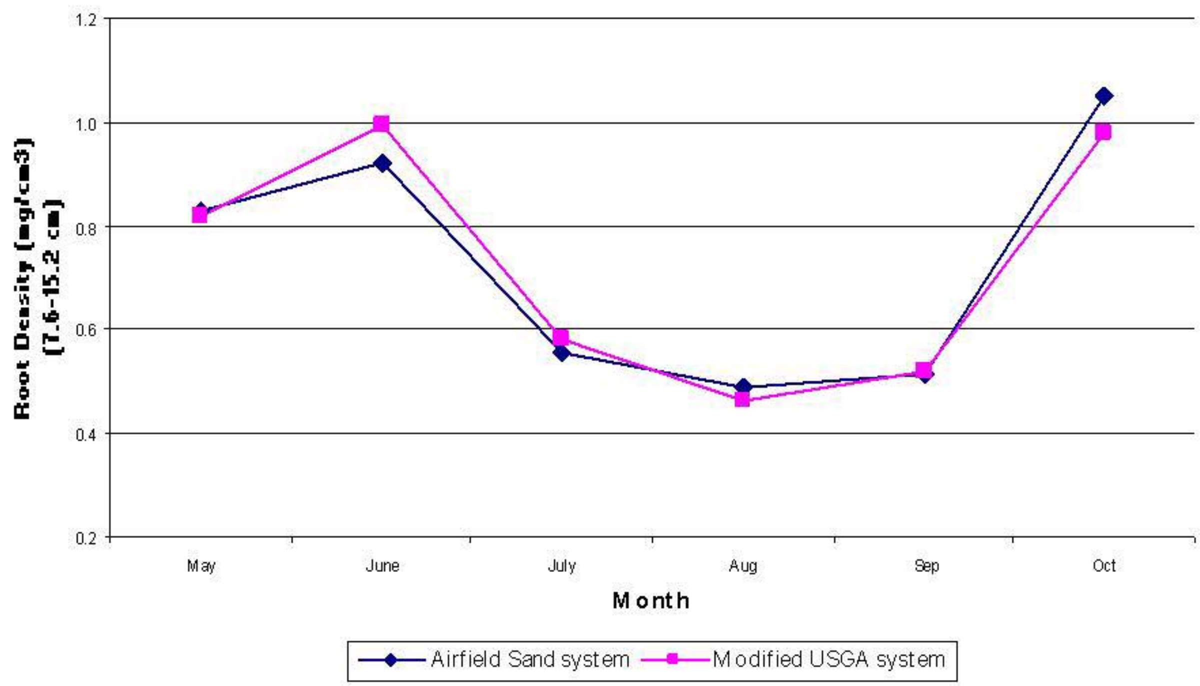


Figure 37. The mean (n=12) monthly 0.0-15.2 cm layer root density changes in Airfield and modified USGA sand systems.

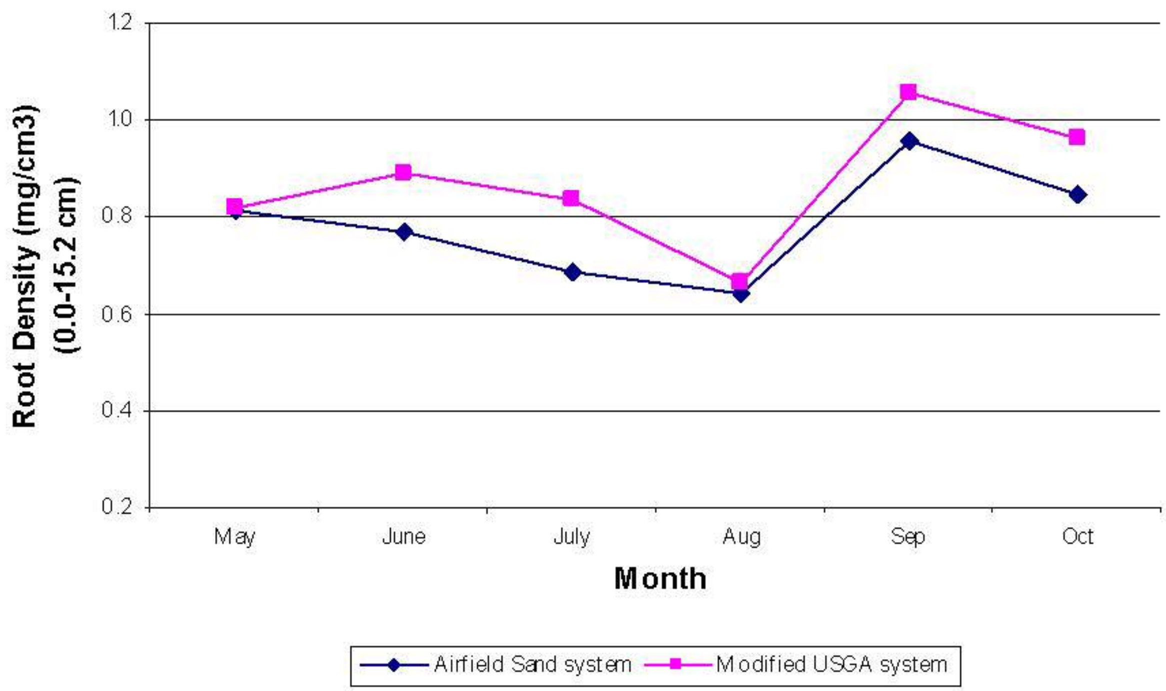


Figure 38. The mean (n=6) monthly visual rating changes in Airfield and modified USGA sand systems on 2004.

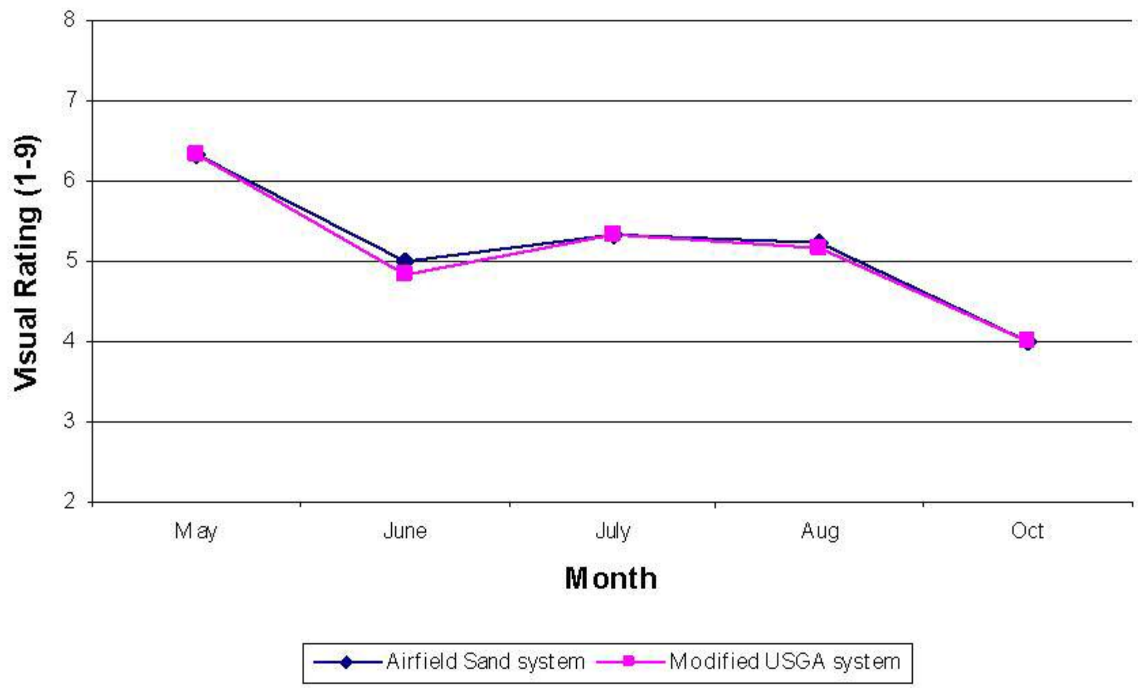
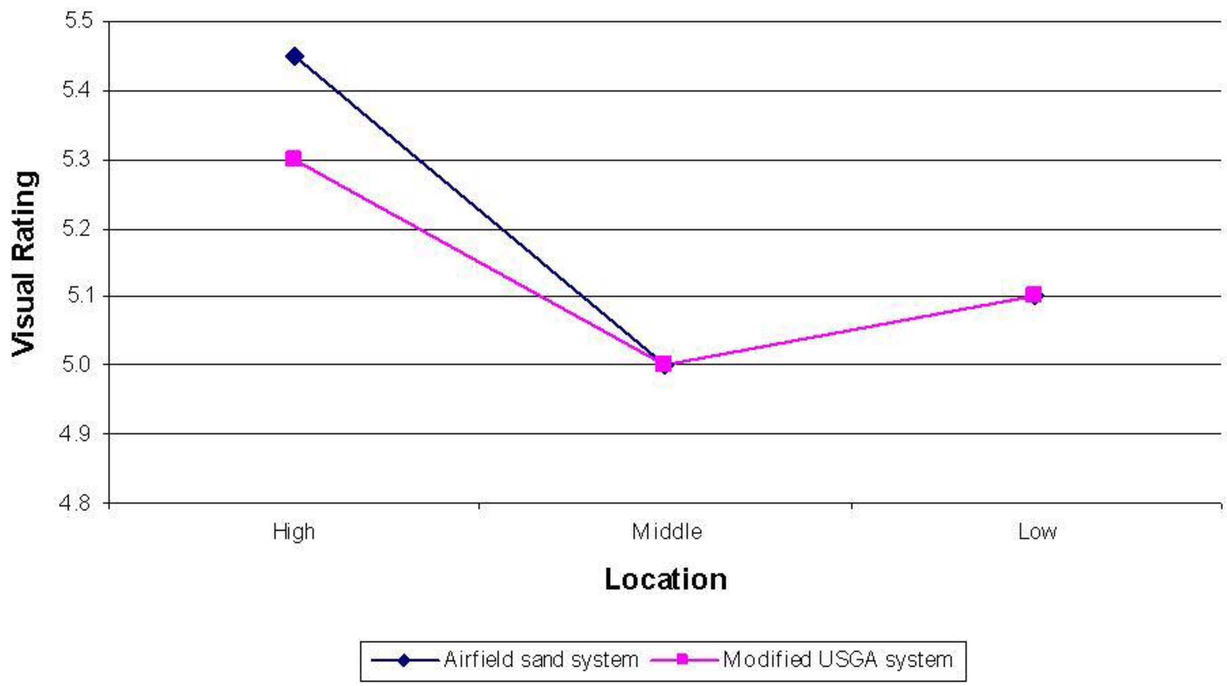


Figure 39. The mean (n=10) visual rating changes in different locations in Airfield and modified USGA sand systems on 2004.



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