COMPARING HYPERSPECTRAL REFLECTANCE CHARACTERISTICS OF CAUCASIAN BLUESTEM AND NATIVE TALLGRASS PRAIRIE OVER A GROWING SEASON

by

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B.S., Arizona State University, 2006

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2010

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Abstract

Caucasian bluestem [*Bothriochloa bladhii* (Retz) S.T. Blake] is a perennial, C_4 warm-season bunchgrass that was first introduced in 1929 from Russia as a potential forage crop in the Great Plains. Due to its invasiveness and tolerance of drought and grazing pressure, Caucasian bluestem can out-compete native prairie species. Research has shown that this species, when compared to native tallgrass species in the Flint Hills of Kansas causes decreased cattle weight gains because of its poor forage quality relative to tallgrass prairie species. Traditional methods of plant data measurements and mapping are costly and time consuming. Use of remotely sensed data to map and monitor the distribution and spread of this plant would be most useful in the control of this aggressive invader. Spectroradiometer data were collected over the 2009 growing season to determine if and when Caucasian bluestem was spectrally unique from native tallgrass prairie species. Observations were made from June through September as the plants were going into a senescent state. Reflectance data were measured approximately every two weeks or when clear/near clear sky conditions prevailed. Statistical analyses for differences in spectral characteristics were conducted to determine the optimal spectral bands, indices and timing for discriminating Caucasian bluestem from native tallgrass species. Difference in reflectance for spectral reflectance of bands 760 nm, 940 nm, 1,070 nm, and 1,186 nm were found to be statistically significant on the June 17th and June 30th sampling dates. The following band ratios and indices were found to be significantly different between Caucasian bluestem and native range on the June 17th collection date: Simple Ratio, Modified Normalized Difference Index, Normalized Phaeophytinization Index, Plant Index 1, Normalized Water Difference Index, Water Band Index, Normalized Difference Nitrogen Index, and the Normalized Difference Lignin Index. Findings of this study suggest that Caucasian bluestem can be spectrally discriminated from native tallgrass prairies of the Flint Hills in Kansas if the measurements are collected in mid to late June. Statistical analyses also showed differences between treatments for percent litter, grass, and forb basal cover.

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Acknowledgements

I would like to express my sincere thanks to my major professors Dr. Walter Fick and Dr. Kevin Price for all their help over the years. For their patience when answering my questions, guidance, and support, I am truly grateful. I would also like to thank Dr. Clenton Owensby for serving on my committee and all of his support and guidance through this process and for giving me the opportunity to participate in the Rannells research projects. I have enjoyed all my summers of sorting grasses and forbs and working cattle. These are experiences and times that I will always value. I would also like to thank the Department of Agronomy for all the teaching opportunities that I have been given over the years.

I would like to thank the following individuals: Lisa Auen, Brandy Iams, Mark Davis, and Dr. Carolyn Blocksome for their assistance in the field, I'm sorry for all the bee issues; Tim Taylor for allowing me access to his property for the entire growing season; and Dr. Leigh Murray for statistical consulting.

Lastly, I would like to thank my family and friends for their continued emotional support. My parents were always excited to hear about my field work and my picture messages early in the morning of cattle and turtles. I have made some amazing friendships throughout graduate school. Adam, Holly, Kevin, Lisa, and Carol you are the best friends that anyone could ever ask for and I have enjoyed my time in Manhattan with you.

Dedication

This is dedicated to my husband Gabe and our dogs Maebe and Arlo for their love, support, encouragement, patience, and for always being there for me. Sometimes you just need a nice walk or hours of tennisball to make you realize the important things in life.

CHAPTER 1 - Literature Review

Introduction

There are approximately 3,310 non-native plant species populations in the United States (Duncan *et al.* 2005). Of these species, 60 are said to cause significant economic and ecologic damages on rangelands and wildlands (Mullin *et al.* 2000). Invasive species cost approximately 120 billion dollars per year for herbicide and pesticide use, crop production losses, and other control efforts in the United States (Pimentel *et al.* 2004). The invasion process consists of four stages: introduction, establishment, spread, and impact (Lockwood *et al.* 2007). The first stage, introduction, occurs when the species is originally collected in its native range and subsequently transported and introduced to a new ecosystem. Individual propagules must then establish a population within the new range. Once the population establishes, it can increase and expand from the original site of introduction or remain locally distributed. When the introduced species is widespread, the populations may cause economic, environmental, or human health harm and are considered an invasive species (Lockwood *et al.* 2007, USA 1999).

Invasive species can cause severe impacts to the environment by altering native plant distributions, soil stability, and increasing erosion, changing litter composition, and changing fire disturbance regimes (Brooks *et al.* 2004). The most dramatic effect of invasive species would be the change in spatial and temporal variations in disturbances (Brooks *et al.* 2004, D'Antonio and Vitousek 1992). For example cheatgrass (*Bromus tectorum L.*) is an annual invasive grass introduced from Europe (Brooks *et al.* 2004). Cheatgrass produces a prolific seed set and also matures faster than the native species in the Great Basin region. The Great Basin consists of shrub-steppe vegetation and the introduction of cheatgrass into the region has increased the fire frequency and extent (Bradley and Mustard 2005, Brooks *et al.* 2004).

Caucasian bluestem (*Bothriochloa bladhii* (Retz.) S.T. Blake) is a non-native grass that originates from Eurasia and was introduced in 1929 into the United States from the Botanical Garden at Tiflis, Georgia in the former U.S.S.R. (Harlan and Chheda 1963). The plant material was distributed in Texas and Kansas by the Soil Conservation Service Plant materials centers as a potential livestock forage species (Harlan and Chheda 1963). Since the original distributions, Caucasian bluestem has been extensively planted in the Great Plains including Nebraska, Colorado, Kansas, Oklahoma, and Texas (Great Plains Flora Association 1986). Many other members of the *Bothriochloa* genus have been introduced to the US including yellow bluestem (*Bothriochloa ischaemum* (L.) Keng), and yellow bluestem cultivars King Ranch bluestem, Plains bluestem and WW-Spar bluestem. The non-native species of the genus *Bothriochloa* are commonly referred to as Old World bluestems (OWB). Caucasian bluestem is a perennial, C_4 warm-season bunchgrass (Reed et. al. 2005) that reproduces by seeds via apomixis (Harlan and Chheda 1963). Anatomically, it will have a hyaline groove on the pedicel of the pedicellate spikelet that can be accentuated with red coloration although sometimes the groove will be minute (Celarier and Harlan 1955). Caucasian bluestem has a short compact raceme, dark reddish color and with secondary branching. The sessile spikelets may be found with or without pits (Celarier and Harlan 1955). The spikelets appear to be smaller with fewer spikelets per raceme than other similar species like *Bothriochloa ischaemum* (L.) Keng (Celarier and Harlan 1955).

Old World bluestem species are well known invaders. These species have survived through the disturbances in their native ranges and have the necessary traits to invade disturbed areas (di Castri 1989, Lockwood *et al.* 2007). When occurring together in a stand, cattle generally select native grass species over OWB's (Harmoney and Hickman 2004). Old World bluestems have many traits in common with invasive species such as higher seedling vigor, higher biomass production, and higher leaf area per plant , small seed size (Coyne and Bradford 1985), and rapid growth to maturity as compared to native species (Harmoney and Hickman 2004). Vegetative tiller height of little bluestem (*Schizachyrium scoparium* (Michx.) Nash) and big bluestem (*Andropogon gerardii* Vitman) was reduced by the presence of Caucasian bluestem (Schmidt *et al.* 2008, Eck and Sims 1984). Caucasian bluestem also demonstrated interspecific competition by aboveground and belowground biomass of those two species (Schmidt *et al.* 2008). Sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.) was the only native species in the study to inhibit the growth of Caucasian bluestem (Schmidt *et al.* 2008). Eck and Sims (1984) also found sideoats grama to be the only native species to invade into the monotypic planted stands of Caucasian bluestem. Caucasian bluestem was able to inhibit the root growth of big bluestem, little bluestem, and sideoats grama. In an Illinois study, Caucasian bluestem was the only Old World bluestem species to survive the winter with no winter injury observed (Faix *et al.* 1980). Sims and Dewald (1982) reported Caucasian bluestem has higher leaf, stem, and whole plant dry matter yield than the yellow bluestem cultivars, Plains bluestem and WW-Spar bluestem.

Non-native species have been shown to reduce biodiversity in novel areas (Lockwood *et al.* 2007). Hickman *et al.* (2006) found significantly lower forb cover and vegetation height in OWB monoculture pastures than on native pastures. Native pastures had four times more arthropod biomass per transect than OWB pastures. Fewer bird species and a significantly lower number of avian individuals were found in OWB pastures. Reed *et al.* (2005) found plant species richness and diversity were significantly lower in Caucasian bluestem dominated areas. Caucasian bluestem dominated areas were monotypic areas with sparsely-vegetated soils between clumps. The area between clumps ranged from 12 to 100 cm. Annual burning increased aboveground biomass production on Caucasian bluestem plots compared to big bluestem plots. Reed *et al.* (2005) observed increased erosion in the invaded Caucasian bluestem areas.

Enemy release hypothesis tests to determine if natural enemies will attack non-native species introduced to the novel environment (Lockwood *et al.* 2007). Han *et al.* (2008) reported that rust incidence was 30 fold higher on big bluestem than on Caucasian bluestem. Caucasian bluestem significantly increased in abundance in burned plots, but big bluestem was significantly abundant in unburned plots (Han *et al.* 2008). Native species also had more insect damage to green leaf area and greater missing leaf area than non-native species (Han *et al.* 2008).

Only one grazing study has been conducted on Caucasian bluestem in Kansas. In this study, Launchbaugh (1971) found that steer gains per head were 36 kg less on Caucasian bluestem plots than steers grazing on native prairie and switchgrass monoculture plots. The steer gains per hectare were also lowest on Caucasian bluestem at 69 kg per ha while native prairie pastures were approximately 75 kg per ha and switchgrass monocultures were approximately 112 kg per ha. The potential grazing period for Caucasian bluestem was the shortest of all the treatments. Caucasian bluestem crude protein content was similar to switchgrass and native grass early in the season but deteriorated more rapidly and was consistently lowest in crude protein the last 3 or 4 months of the growing season. Dabo *et al.* (1988) found crude protein content in the leaves and stems to rapidly decline with maturity and would not meet the minimum daily requirements for crude protein in steers. The decline in crude protein occurred around 7 to 8 weeks into the growing season (Dabo *et al.* 1988). Svejcar and Christiansen

(1987) found under heavy grazing, Caucasian bluestem had reduced water stress while stomatal conductance was increased and soil moisture was conserved.

Due to the negative grazing impacts and competitive abilities of Caucasian bluestem compared to native tallgrass species, there is a need to map the distribution of this species for control and management in the Flint Hills of Kansas. By mapping invasive species, land managers can know what species are present, how much and where invasive species are located, changes of the infestation over time, and how to predict invasive spread using modeling (Barnett *et al.* 2007). Remote sensing is an option for the detection and mapping of Caucasian bluestem infestations in the region and is an effective management tool for determining invasion at the local, regional, and landscape scales (Stohlgren *et al*. 2005). Remote sensing can be a useful tool when the invasive species has a novel structure, phenology, or biochemistry when compared to the surrounding native vegetation (Huang and Asner 2009). Predictive models can be used to prepare "habitat matching" by using environmental factors from the remotely sensed data (Stohlgren *et al.* 2006). In the case of Caucasian bluestem, the grass has a bunchgrass structure compared to the rhizomatous native grasses and Caucasian bluestem has an earlier phenological development than the native species as demonstrated by the change in nutritional quality studies. The information gained by sampling large areas can be used to determine areas of greatest resource needs for control using mechanical, cultural and chemical measures. Remote sensing tools have been developed to resolve costly and time consuming ground based monitoring (Everitt *et al.* 1995).

Field spectroscopy is defined as the interactions between electromagnetic energy and objects in the natural environment (Jacquemoud and Ustin 2001). The field of spectroscopy has three roles in remote sensing per Milton (1987): calibration, prediction, and modeling. Calibration using a Spectralon panel is used to measure the total irradiance from the current atmospheric conditions. The field spectroradiometer should be calibrated to a steady energy source. If that source is the sun, the spectra should be collected during periods of clear sky conditions to avoid temporal changes in irradiance (Milton 1987). The predictive role involves identifying optimum spectral bands, geometric configuration to the source from the sensor and the optimal timing of year for a particular project (Milton 1987). The predictive role has been well documented in the field of spectrometry specifically in distinguishing weeds from agriculture crops. The third role is modeling using correlative, analytical, and structural models

(Milton 1987). Correlative models are used to determine relationships between biophysical data and spectroradiometer data. Analytical models are typically canopy reflectance models like WinSAIL (WinSAIL, USDA-ARS Hydrology and Remote Sensing Lab, Beltsville, MD, available at http://www.ars.usda.gov/services/software/software.htm, verified 15 September 2010). Structural models include details on the intrinsic data structures (Milton 1987).

Imaging spectrometry is the acquisition of images in hundreds of contiguous, registered, spectral bands such that for each pixel a radiance spectrum can be derived (Goetz 2009). Due to many narrow bands, detailed information can be acquired about mineral resources, plant biochemical and plant biophysical characteristics (Jensen 1996, Price *et al.* 1993). The most widely used imaging spectrometry system is the Airborne Visible Infrared Imaging Spectrometer (AVIRIS). AVIRIS acquires images that have a nominal spatial resolution of 20 x 20 m and has 224 bands from 400 nm to 2500 nm of the electromagnetic spectrum. The use of imaging spectrometry coupled with hand-held spectroradiometers has yielded significant results in classifying non-native species from natural landscapes (Andrew and Ustin 2006, Williams and Hunt 2002).

Hyperspectral imaging with contiguous bands has allowed for the detection of fine spectral features that can be used to identify minerals, chlorophyll concentration and biochemical aspects of vegetation (Goetz 2009). Development of hand-held field spectroradiometers covering the visible, near infrared, and shortwave infrared were produced to provide on the ground information about the earth's resources. Advances in portable field spectroradiometers were developed to minimize the disturbance in the field and eliminate the time between clipping of vegetation samples and transporting the field samples to a laboratory for analysis (Milton 1987).

The advancement of remote sensing techniques has provided an abundance of information for detection of vegetation types and species level classification. The visible portion of the electromagnetic spectrum (EMS) (400 - 700 nm), describes the photosynthetic activity of chlorophyll a, b, and carotenoids (Cochrane 2000, Tucker and Garrett 1977, Williams and Hunt 2002, Jacquemoud and Ustin 2001). The near-infrared portion of the EMS (700 - 1300 nm) describes the cellular structure of plant tissue specifically air spaces at the cellular level (Cochrane 2000, Williams and Hunt 2002). The mid-infrared portion of the EMS (1300 - 2500 nm) describes water capabilities of the canopy or cell (Cochrane 2000, Jacquemoud and Ustin

2001). Spectral reflectance curves were originally thought to be different for every species (Cochrane 2000). Price (1994) found that similar species may have spectral reflectance characteristics that are not different due to variations in reflectance within species.

One way to determine differences is through multi-temporal measurements. Multi-temporal imagery has been used to improve classification methods when compared to the classical single date methods (Egbert *et al.* 1998). The importance of date of imagery acquisition was demonstrated by Price *et al.* (2002) when imagery was acquired in September when warm-season grasses were entering senescence and cool-season grasses were just emerging. There was no difference between the two vegetation types on the September date and would have yielded better results with the acquisition of another imagery date (Price *et al.* 2002). Multi-temporal collection of hyperspectral measurements provides information throughout the growing season and can be used to determine the optimal timing for detection of particular species. This multi-temporal data collection can be particularly useful when species develop at different phenological stages (Everitt and Deloach 1990, Andrew and Ustin 2006). Multi-spectral data has limited use due to the few broad bands used on most satellite remote sensing systems. The development of hyperspectral reflectance data allows thousands of narrow bands to detect subtle differences in vegetation (Williams and Hunt 2002). These narrow bands provide a wealth of information as well as challenges of larger data sets. The high dimensionality of data results in highly intercorrelated bands and studies have been conducted to determine the optimal way to reduce redundancy in the datasets (Thenkabail *et al.* 2000). To reduce the dimensionality of hyperspectral data, spectral band indices were used to determine differences from the visible through the mid-infrared portions of the EMS (Andrew and Ustin 2006 and Thenkabail *et al.* 2000).

Hyperspectral reflectance data has been used for detecting weeds within agriculture settings. Koger *et al.* (2003) was able to distinguish pitted morningglory (*Ipomoea lacunosa* L.) at the two and four leaf stage from soybean (*Glycine max* (L.) Merr.). In this study Koger *et al.* (2003) implemented three feature extraction methods: selecting a reduced set of spectral bands without transforming the data, using Principle Component Analysis (PCA) to reduce the data down to a set of coefficients, and using Discrete Wavelet Transform (DWT) to produce a reduced set of coefficients. The PCA and DWT were both applied to the hyperspectral signals. The resulting coefficients were sorted using the receiver operative characteristics (ROC) to achieve an optimum subset. The DWT was used with a dyadic filter tree that has a series of high pass and low pass filters. In order to filter; a mother wavelet function has to be used in the transform. Thirty-six mother wavelet functions and only the pertinent results will be discussed within this literature review. The PCA method resulted in the lowest classification accuracies at three of the four pitted morningglory growth stages and the overall classification accuracies were from 72 to 83%. The reduced set of untransformed spectral bands resulted in accuracies of 80 to 87%. The DWT method resulted in overall accuracies of 90 to 100%. A majority of the mother wavelet functions resulted in the highest classification accuracies at the two and four leaf growth stage of pitted morningglory. The authors indicated the significance of this finding to be particularly useful from a management viewpoint for the application of herbicides at the early growth stages for control. The DWT method was able to obtain classification accuracies of 90 to 100% resulting in early detection of pitted morningglory in soybean fields to ensure proper spraying methods at an appropriate timing.

Andrew and Ustin (2006) found perennial pepperweed (*Lepidium latifolium* L.) was spectrally unique when the white flowers are open before senescence. In this study, the reflectance spectra were resampled to the spectral resolution of AVIRIS and the imaging spectrometer HyMap. The reflectance data that was resampled to match AVIRIS and HyMap were used to create 19 physiological indices. The indices were submitted to a classification and regression tree (CART) model to discriminate among perennial pepperweed and surrounding species. The indices were also used to test for significant difference among spectra over time comparisons using analysis of variance (ANOVA). If the statistical assumptions were not met, a non parametric Wilcoxon test was used. The same statistics were run for the resampled spectra when applied to the imagery. Using the CART model, the HyMap imaging spectrometer accuracy declined more from the degradation of the spectral resolution than from the loss at the shorter wavelengths (< 450 nm). The authors also analyzed the raw bands as well as 30 principle components and found that both methods reduced the accuracy of the CART classification results. The indices that were found more often in the CART model nodes were indicated to be more significant in species discrimination. The indices that were more often used were the Normalized Phaeophytinization Index (NPQI), Photochemical Index (PRI), and red/green ratio (RG). The study found that the normalized difference vegetation index contributed little to the discrimination of species. The lack of significant differences between the dates of spectral collection was attributed to the collection of spectral data only in June and July instead of over the growing season. The June dates classified perennial pepperweed correctly using the spectrometer data and the AVIRIS CART models. Differences found in the physiological indices between perennial pepperweed and the surrounding vegetation types indicate that perennial pepperweed has unique spectral characteristics that may be from physiological development. Some of the deficiencies of this study include the limited collection of imaging and spectroradiometer data to only the flowering and fruiting stage as well as only one year of data collection. Despite the one growing season, the results are useful in the detection of this invasive plant in the Delta and Davis, California area.

Henry *et al.* (2004) examined the ability to discriminate soybean from common cocklebur (*Xanthium strumarium* L.) and sicklepod (*Cassia obtusifolia* L.) across varying levels of moisture stress. Henry *et al.* (2004) found moisture stress did not influence the ability to discriminate between species but as moisture stress increased, the ability to discriminate improved. The data were analyzed to detect the important features extracted for moisture stress using indices, Signature Amplitudes (SA), and Discrete Wavelet Transformation (DWT). Indices used were Difference Vegetation Index (DVI), Infrared Percentage Vegetation Index (IPVI), Moisture Stress Index (MSI), Normalized Difference Vegetation Index (NDVI), NDVI green (NDVIg), Ratio Vegetation Index (RVI), and a series of Drought Indices of Normalized Observations (DINO). Signature amplitude analysis method was able to discriminate common cocklebur from soybean overall 96% across five dates after stress in 2000. The SA method was able to discriminate at 100% on three out of the five dates. SA was also able to discriminate sicklepod from soybean with an overall accuracy of 99% in 2000. When using species by species (sicklepod vs. soybean, common cocklebur vs. soybean, and common cocklebur vs. sicklepod) comparisons of classification accuracies under no stress (100% moisture), moderate stress (60% moisture) and high stress (40% moisture) in 2000 and 2001 overall accuracies were over 85% using the vegetation and drought indices. Soybean discriminated against sicklepod and common cocklebur and had over 91% accuracies at the no, moderate, and high moisture stress levels. Lower accuracies were found in discriminating common cocklebur from sicklepod. The DWT had lower overall classification accuracies. In some instances, accuracies were as low as 71% when discriminating soybean vs. sicklepod. The Signature Amplitude method was considered a very promising statistical method of discriminating soybean from common cocklebur and sicklepod because of it simple computational process and analysis when compared to DWT. The overall classification accuracies across all analysis techniques yielded 85% on average indicating that all methods would be useful in identifying weed patches within soybean fields across varying moisture stress levels.

Hyperspectral imaging spectrometry has been used as a tool to detect leafy spurge (*Euphorbia esula* L.). Leafy spurge is an invasive species that has invaded the northern Great Plains (Williams and Hunt 2002). Leafy spurge has unique yellow/green bracts that reflected differently than many other native species. Hyperspectral imagery was obtained using AVIRIS and the spectral mixture analysis, mixture tuned matching filtering (MTMF), was performed to find the pixels with pure pixels called endmembers. The endmember only has to be identified for one particular object, the object in this case being leafy spurge. Leafy spurge could then be discriminated from background objects. Field spectra were resampled to match the AVIRIS bands. Leafy spurge cover data were also collected and applied to the MTMF using simple linear regression. The field spectroscopy portion of the study found leafy spurge was differentiated from surrounding vegetation mostly using wavelengths from 500 nm – 700 nm. Leafy spurge was spectrally different from yellow sweetclover (*Melilotus officinalis* (L.) Lam.). Overall the MTMF was a good indicator (r^2=0.69) of percent cover of leafy spurge on all geographic sites.

Other studies have been conducted using spectroradiometer data to distinguish between land cover types and management practices. Price *et al.* (1993) found that native prairie and untreated prairie were spectrally different from reestablished prairies under hayed, mowed, grazed, and burned treatments. The untreated treatment was similar to the species composition found on CRP (Conservation Reserve Program) lands and could be used to distinguish native prairie and CRP from other land cover classes. The mowed and hayed treatments also had a pattern of greenness in October that could indicate a later senescence date than the other treatments (Price *et al.* 1993). Guo *et al.* (2000) found vegetation cover was moderately correlated with spectral data and that forb cover was highly correlated with spectral data. Grass cover data was uncorrelated with spectral data. Landsat TM data could be used to estimate biomass and cover in warm-season and cool-season grasses under different land management practices (i.e. grazed, hayed, and CRP) (Guo *et al.* 2000).

Justification of Research

Caucasian bluestem is a threat to the native tallgrass prairie in the central Great Plains. Kansas Agriculture Statistics (USDA, NASS 2007) reported that Kansas has approximately 6.4 million hectares in permanent rangelands and pastures and approximately 1.3 million hectares in the Conservation Reserve Program. Caucasian bluestem, an introduced grass, has been shown to decrease biodiversity, inhibit the growth of the native vegetation, and be inferior as a forage grass as compared to the native tallgrass species. Approximately 1% of the original tracts of North American tallgrass prairie remain due to development (Sampson and Knopf 1994). Kansas historically had 6.9 million hectares of tallgrass prairie, but current estimates state only 1.2 million hectares (Sampson and Knopf 1994). In Kansas there has been a decline of 82.6% of the native prairie (Sampson and Knopf 1994). Caucasian bluestem could potentially have a devastating effect on the native grassland fed beef cattle production in the state of Kansas. Launchbaugh (1971) found significant decreases in steer gains per head on cattle grazing Caucasian bluestem as compared to native grassland species. Due to the increasing interests from livestock special interest groups on the spatial distributions of Caucasian bluestem, this study was developed to initiate the process in detecting Caucasian bluestem in the tallgrass prairie. Knight (2004) was able to produce classifications that were better than random at distinguishing between Old World bluestem monocultures, rangelands, and other land cover types. Knight (2004) found Old World bluestem was best identified from Landsat TM data in October followed by June. These data were useful for distinguishing spread from planted monocultures to rangelands, but the question still remains as to the best time and portion of the electromagnetic spectrum for distinguishing Old World bluestems from native tallgrass prairie species. Such information is critical before any attempts to map the species over large geographic regions are initiated.

Statement of Objectives

In this study, I sought to develop a method for detecting Caucasian bluestem in the tallgrass prairie region of the Central Great Plains using hyperspectral spectroradiometer data. The objectives of this study were:

Objective 1- Determine the regions of the electromagnetic spectrum for discriminating between Caucasian bluestem and native tallgrass prairie canopies.

Objective 2- Determine the optimal date or dates for spectrally discriminating between Caucasian bluestem and native tallgrass prairie canopies.

Objective 3- Examine how different cover classes and species composition between the two treatments affect spectral reflectance patterns.

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CHAPTER 2 - Comparing Hyperspectral Reflectance Characteristics of Caucasian Bluestem and Native Tallgrass Prairie Over a Growing Season

Abstract

Caucasian bluestem [*Bothriochloa bladhii* (Retz) S.T. Blake] is a perennial, C_4 warm-season bunchgrass that was first introduced in 1929 from Russia as a potential forage crop in the Great Plains. Due to its invasiveness and tolerance of drought and grazing pressure, Caucasian bluestem can out-compete native prairie species. Research has shown that this species, when compared to native tallgrass species in the Flint Hills of Kansas causes decreased cattle weight gains because of its poor forage quality relative to tallgrass prairie species. Traditional methods of plant data measurements and mapping are costly and time consuming. Use of remotely sensed data to map and monitor the distribution and spread of this plant would be most useful in the control of this aggressive invader. Spectroradiometer data were collected over the 2009 growing season to determine if and when Caucasian bluestem was spectrally unique from native tallgrass prairie species. Observations were made from June through September as the plants were going into a senescent state. Reflectance data were measured approximately every two weeks or when clear/near clear sky conditions prevailed. Statistical analyses for differences in spectral characteristics were conducted to determine the optimal spectral bands, indices and timing for discriminating Caucasian bluestem from native tallgrass species. Difference in reflectance for spectral reflectance of bands 760 nm, 940 nm, 1,070 nm, and 1,186 nm were found to be statistically significant on the June 17th and June 30th sampling dates. The following band ratios and indices were found to be significantly different between Caucasian bluestem and native range on the June 17th collection date: Simple Ratio, Modified Normalized Difference Index, Normalized Phaeophytinization Index, Plant Index 1, Normalized Water Difference Index, Water Band Index, Normalized Difference Nitrogen Index, and the Normalized Difference Lignin Index. Findings of this study suggest that Caucasian bluestem can be spectrally discriminated from native tallgrass prairies of the Flint Hills in Kansas if the measurements are collected in mid

to late June. Statistical analyses also showed differences between treatments for percent litter, grass, and forb basal cover.

Introduction

Kansas has approximately 6.4 million hectares in permanent rangelands and pasturelands and 1.3 million hectares of land in the Conservation Reserve Program (USDA, NASS 2007). Approximately 1% of the original tracts of North American tallgrass prairie remain due to development (Sampson and Knopf 1994). Of the remaining 1% of North American tallgrass prairie, Kansas has approximately 1.2 million hectares remaining (Sampson and Knopf 1994). One particular threat to Kansas rangelands is Caucasian bluestem (*Bothriochloa bladhii* (Retz.) S.T. Blake). Caucasian bluestem is a perennial, C_4 warm-season bunchgrass (Reed *et al.* 2005) which reproduces by seeds via apomixis (Harlan and Chheda 1963) and was introduced as a potential high quality forage species. Other non-native members of the *Bothriochloa* genus including yellow bluestem (*Bothriochloa ischaemum* (L.) Keng) and yellow bluestem cultivars King Ranch bluestem, Plains bluestem and WW-Spar bluestem, collectively referred to as Old World bluestems (OWB), have been introduced as potential warm-season forage alternatives as well.

Caucasian bluestem has many traits in common with invasive species such as higher seedling vigor, higher biomass production, and higher leaf area per plant, small seed size (Coyne and Bradford 1985), and rapid growth to maturity as compared to native species (Harmoney and Hickman 2004). Caucasian bluestem inhibits the growth of aboveground and belowground biomass (Schmidt *et al.* 2008, Eck and Sims 1984). Caucasian bluestem also decreases biodiversity. Reed *et al.* (2005) found plant species richness and diversity was significantly lower in Caucasian bluestem dominated areas and also increased erosion in the monotypic stands.

Caucasian bluestem forage quality rapidly declines with maturity (Dabo *et al.* 1988, Launchbaugh 1971).   Launchbaugh (1971) found that steer gains per head were 36 kg less on Caucasian bluestem plots than steers grazing on native prairie and switchgrass monoculture plots. The steer gains per hectare were also lowest on Caucasian bluestem at 69 kg per ha while native prairie pastures were approximately 75 kg per ha and switchgrass monocultures were approximately 112 kg per ha. Caucasian bluestem has also been shown to respond positively to heavy grazing. Svejcar and Christiansen (1987) found that under heavy grazing, Caucasian bluestem had reduced water stress while stomatal conductance was increased and soil moisture was conserved.

Knight (2004) found individual OWB's moved from the original planted sites and supports the observations that OWB's are invasive. The spread of OWB's occurred most often in native grasslands and ungrazed OWB's were more likely to spread than hayed, grazed or a combination of both management practices.

Due to the negative grazing impacts and competitive abilities of Caucasian bluestem compared to native tallgrass species, there is a need to map the distribution of this species for control and management in the Flint Hills of Kansas. By mapping invasive species, land managers can know what species are present, size of infestation, locations, changes in the area of the infestation over time, and how to predict the spread using modeling (Barnett *et al.* 2007). Remote sensing is an effective management tool for determining invasion at the local, regional, and landscape scales (Stohlgren *et al.* 2005). Remote sensing can be a useful tool when the invasive species has a novel structure, phenology, or biochemistry when compared to the surrounding native vegetation (Huang and Asner 2009). Predictive models can be used to prepare "habitat matching" by using environmental factors from the remotely sensed data (Stohlgren *et al.* 2006). Dewey *et al.* (1991) created maps of suitability to invasion for the non-native Dyer's woad (*Isatis tinctoria* L.) and found much of the Cache National Forest in Utah to be susceptible habitat for invasion. In the case of Caucasian bluestem, the grass has a bunchgrass structure compared to the rhizomatous native grasses and Caucasian bluestem has an earlier phenological development than the native species as demonstrated by the change in nutritional quality studies. The information gained by sampling large areas can be used to determine areas of greatest resource needs for control using mechanical, cultural and chemical methods. Remote sensing tools have been developed to resolve costly and time consuming ground based monitoring (Everitt *et al.* 1995).

Remote sensing using satellite imagery has long been used for classifying land surface cover types using spectral reflectance (Dewey *et al.* 1991). These land cover type maps have been used to determine habitat suitable for invasion and to predict potential distributions maps (Dewey *et al.* 1991). These predictive models can also be used in a ranking system to determine where to best focus resources for monitoring areas of high invisibility potential (Dewey *et al.*

1991). Although remotely-sensed imagery can be used for a wide range of mapping, traditional remote sensing tools have wide bandwidths that prevent detection of subtle features in the electromagnetic spectrum. Hyperspectral sensors have been developed for detecting the subtle differences in land cover and land uses. To discriminate between two species, remotely-sensed data need to be collected on different dates when the species of interest is spectrally unique from the surrounding vegetation (Jensen 1996). Spectral reflectance curves were originally thought to be different for every species (Cochrane 2000). Price (1994) found that similar species may have spectral reflectance characteristics that are not different due to variations in reflectance within species. One way to determine differences is through multi-temporal measurements. Multi-temporal imagery has been used to improve classification methods when compared to the classical single date methods (Egbert *et al.* 1998). The importance of imagery acquisition date was demonstrated by Price *et. al.* (2002) when imagery was acquired in September when the warm-season grasses were entering senescence and cool-season grasses were just emerging. There was no difference between the two vegetation types on the September date and would have yielded better results with the acquisition of another imagery date (Price *et al.* 2002). Price *et al.* (1993) found that native prairie and the untreated treatment were spectrally different from reestablished prairies under hayed, mowed, grazed, and burned treatments. The untreated treatment was similar to species composition found on CRP (Conservation Reserve Program) lands and could be used to distinguish native prairie and CRP from other land cover classes. The mowed and hayed treatments also had a pattern of greenness in October which could indicate a later senescence date than the other treatments (Price *et al.* 1993).

Multi-temporal data collection can be particularly useful when species develop at different phenological stages (Everitt and Deloach 1990, Andrew and Ustin 2006). For example, Andrew and Ustin (2006) found perennial pepperweed (*Lepidium latifolium* L.) was spectrally unique when the white flowers are open before senescence using indices derived from hyperspectral spectroradiometer data and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) imagery using a classification and analysis regression tree (CART). Differences were found in the physiological indices between perennial pepperweed and the surrounding native species that indicates that perennial pepperweed has unique spectral characteristics that may be from physiological development. The CART technique was used to determine important indices at each node to determine the indices that generated the greatest accuracy in the classification of the AVIRIS imagery (Andrew and Ustin 2006). Koger *et al.* (2003) was able to distinguish pitted morningglory (*Ipomoea lacunosa* L.) at the two and four leaf stage from soybean (*Glycine max* (L.) Merr.) with classification accuracies of 90 to 100% using discrete wavelet transformation (DWT) to improve appropriate timing of herbicide control.

Hyperspectral imaging spectrometry has been used as a tool to detect leafy spurge (*Euphorbia esula* L.). Leafy spurge is an invasive species that has invaded the northern Great Plains (Williams and Hunt 2002). Leafy spurge has unique yellow/green bracts that reflected differently than many other native species. Hyperspectral imagery was obtained using AVIRIS and the spectral mixture analysis, mixture tuned matching filtering (MTMF), was performed to find the pixels with pure pixels called endmembers. The study found leafy spurge was differentiated from surrounding vegetation mostly using wavelengths from 500 nm – 700 nm. Overall the MTMF was a good indicator (r^2=0.69) of percent cover of leafy spurge on all geographic sites.

The objectives of this study were to: 1.) Determine the regions of the electromagnetic spectrum for discriminating between Caucasian bluestem and native tallgrass prairie canopies, 2.) Determine the optimal date or dates for spectrally discriminating between Caucasian bluestem and native tallgrass prairie canopies, and 3.) Examine how different cover classes and species composition between the two treatments affect spectral reflectance characteristics.

Study Area

The study was located near Olsburg, Kansas (39.41°N, 96.65°W) approximately 24 km north of Manhattan, Kansas and was conducted on grassland dominated by native tallgrass prairie species and Caucasian bluestem monocultures (Figure 2.1). The region is characterized by a typical continental climate. Monthly precipitation records (Kansas State Weather Data Library) from the Fostoria, KS weather station were used to calculate the 31-year monthly station normal for precipitation (1971-2000) and the monthly precipitation for 2009 (Figure 2.2). During the growing season, May precipitation was below average followed by an above average June. The precipitation data in July, August and September were similar to the long-term average. The total precipitation was higher in 2009 with 97 cm while the 31 year average was 90 cm. In 2009 the average high temperature was 17.6 ^{o}C and the average minimum was 4.5 ^{o}C. The soils series is Benfield silty clay loam which is classified as fine, mixed, superactive, mesic

Udertic Argiustolls. Benfield soils are typically found on uplands with slopes between 3 to 35 percent. The study area has slopes between 3 to 7 percent. The soils are well drained with slow permeability and high to very high runoff. The native grass dominated (NGD) sites were composed of 59% grass and 41% forb basal cover. The Caucasian bluestem (CB) sites were composed of 85% grass and 15% forb basal cover. Table A.1 has a comprehensive list of species found within the study area. Plant names follow nomenclature provided by the USDA, NRCS (2010). The major grass species on the site were big bluestem (*Andropogon gerardii* Vitman.), Caucasian bluestem, and switchgrass (*Panicum virgatum* L.). Some of the major forb species were Cuman ragweed (*Ambrosia psilostachya* D.C.), white sagebrush (*Artemisia ludoviciana* Nutt.), and sericea lespedeza (*Lespedeza cuneata* (Dum. Cours.) G. Don). The complete history of the study area is unknown due to land owner changes. Portions of the property were farmed with evidence of terracing and later planted to Caucasian bluestem. The site had not been burned in approximately 20 years until late April 2009. The complete grazing history is unknown, but the site had not been grazed in the recent management.

Materials and Methods

Modified step point data were collected on June 22, 2009 to determine basal cover for NGD and CB sites (Owensby 1973). Approximately 200 points were taken per transect as hit, closest plant and closest forb. The hit category could include a plant that was hit, bare ground or litter. Plant hits were recorded by species. In addition to the plant species by hit, the nearest forb was recorded after a hit on grass or when the closest plant was a grass (Rensink 2003). The data were categorized as percent litter, bare ground, and total basal cover. The basal cover was also subdivided to include the percent of grasses and forbs on each transect. Percent composition of individual grass species and forb species were determined and ranked by percent to determine the species that were more often found on the treatments (Owensby 1973).

Spectroradiometer measurements were collected on June 17, June 30, July 19, August 12, and September 28 during the 2009 growing season from the NGD and CB sites. Within each treatment, measurements were taken in 22, 1.0 m x 1.0 m quadrats permanently placed along two, 200-m transects.

At each sample location, five spectra (ten internal scans were averaged for every reading) were taken randomly within each quadrat above the canopy and averaged. Due to the fact that each reading contained multiple portions of the canopy structure (bare ground, grasses, forbs etc.) the readings per quadrat were averaged using the Analytical Spectral Devices (ASD) program ViewSpec Pro to yield a comprehensive reflectance curve of the two treatment types.

Measurements were taken with an ASD Field Spec® 3 Portable Spectroradiometer on cloudless or near cloudless days from 10:00 a.m. to 2:00 p.m. CST. Spectral data were collected from the quadrats in 2,150 discrete bands ranging from 350 to 2,500 nm. The Field Spectroradiometer has bandwidths of 1.4 nm in the visible to near-infrared (350 to 1,050 nm) and 2 nm in the near and mid-infrared (1,000 to 2,500 nm). Readings were recorded using a nadir view and a 25^o field-of-view angle with the spectroradiometer located 1.4 m above the canopy, yielding a spot size on the ground of approximately 0.5 m^2. Calibration readings were taken at the first and sixth quadrat from a calibrated Spectralon (ASD) reference panel. These measurements were used to convert spectrometer readings to values of percent reflectance. Atmospheric water absorption bands around approximately 1,470 nm and 1,900 nm were removed from the reflectance dataset due to low signal and associated high degree of noise.

Hyperspectral instruments provide an over abundance of data that would violate statistical assumptions of data independence since bands near each other in the electromagnetic spectrum are highly correlated. For this reason, a series of individual reflectance bands and spectral indices were used to test for spectral differences between the two treatments and among the dates. Spectral reflectance of bands 550 nm, 668 nm, 760 nm, 940 nm, 1,070 nm, 1,186 nm, 1,660 nm, and 2,160 nm were chosen to test for differences between treatments where difference were most visibly noticeable on a spectral reflectance graph near reflectance and absorption and water absorption features. Spectral differences between treatments were also tested using indices designed to be sensitive to variations in plant pigment, water content, and foliar chemistry (Table 2.1). These indices were selected to cover the visible through the middle infrared portion of the spectrum and their selection was based in part on work by Andrew and Ustin (2006).

Simple ratio (SR) and Normalized Difference Vegetation Index (NDVI) were developed as greenness indices for measuring biomass (Tucker 1979, Jensen 1996). These indices are derived from ratios using NIR and red bands. The modified NDVI (MNDVI) was developed to measure sensitivity to leaf chlorophyll content at the 700 nm portion of the electromagnetic spectrum (Fuentes *et al.* 2001, Gitelson and Merzlyak 1997). The Photochemical Reflectance Index (PRI) tests xanthophylls response to photosynthetic efficiency (Rahman *et al.* 2001). The red/green ratio (RG) measures absorption by anthocyanins and chlorophyll (Fuentes *et al.* 2001). The Normalized Pigments Chlorophyll Ratio Index (NPCI) is indicative of total chlorophyll absorption (Penuelas *et al.* 1995). The Simple Ratio Pigment Index (SRPI) and the Structure Intensive Pigment Index (SIPI) are used to estimate carotenoid and chlorophyll concentrations and content (Zarco-Tejada 1999). The Normalized Phaeophytinization Index (NPQI) measures plant stress via chlorophyll (Zarco-Tejada 1999) and Pigment Indices 1, 2, 3, and 4 (PI1, PI2, PI3, PI4) were designed for measuring plant stress and health (Zarco-Tejada 1999, Lichtenthaler *et al.* 1996).

Two water indices were evaluated for detecting differences between NGD and CB treatments. The Normalized Difference Water Index (NDWI) measures the leaf water content as well as soil humidity (Gao 1996). The Water Band Index (WBI) was developed for estimating the leaf water content (Penuelas *et al.* 1997).

Three foliar chemistry indices were also evaluated in this analysis. The Normalized Difference Nitrogen Index (NDNI) is sensitive to bare ground and leaf area index (LAI) (Serrano *et al.* 2002). The Normalized Difference Lignin Index (NDLI) is sensitive to low LAI and bare ground reflectance. Cellulose Absorption Index (CAI) was developed to discriminate plant litter from bare soils (Nagler *et al*. 2000).

Daubenmire (1959) cover data were collected on the day before or after spectra collecting dates. The cover was collected in cover categories of litter, bare ground, native grasses, Caucasian bluestem, and forbs and used in a stepwise multiple linear regression with the significant spectral bands and indices on the June 17th date.

The percent litter, bare ground, and total basal cover data were analyzed using ANOVA with a significance level of $p \leq 0.10$ due to the variation within biological data. An Analysis of Variance (ANOVA) and Scheffe's test for pairwise comparisons were used to determine if the treatment types and sampling dates were statistically different. Differences between treatment types and sampling dates were tested at the significance levels of $p \leq 0.05$ (Price et al. 1993). The June 17th cover data were subjected to linear multiple regression utilizing the stepwise method to determine how the cover categories contributed to the June 17th significant individual bands and vegetation indices. The cover categories had to meet a significance level 0.15 to be entered into the model. All statistical analyses were completed using Statistical Analysis Software (SAS 9.1, SAS Institute, Cary, NC).

Results and Discussion

Vegetation Cover Analysis

Percent litter ($p = 0.09$), grass ($p = 0.07$), and forbs ($p = 0.07$) were different on NGD and CB sites (Table 2.2). Table 2.3 provides a list of mean and standard deviation of each cover class for the NGD and CB sites. From Table 2.4, we see litter ranged between 32 and 45% cover on the NGD transects and between 13 and 19% cover on CB transects. Tables 2.5 and 2.6, and 2.7, and 2.8 provide the percent composition for the two treatments as well as the individual grass species and forb species ranked by percent composition on each transect. The grass cover ranged from 59 to 70% on NGD sites and from 84 to 92% cover on CB sites (Table 2.4). On the NGD sites, 23% of the species composition consisted of big bluestem (*Andropogon gerardii* Vitman.) followed by switchgrass (*Panicum virgatum* L.), Cyperus spp. (*Cyperus* L.), Indiangrass (*Sorghastrum nutans* (L.) Nash), and little bluestem (*Schizachyrium scoparium* (Michx.) Nash) (Table 2.5). On the CB sites, Caucasian bluestem contributed about 54 % of the species composition followed by big bluestem (Table 2.6). The NGD sites had 29 and 40% forb cover and sericea lespedeza (*Lespedeza cuneata* (Dum. Cours.) G. Don), white sagebrush (*Artemisia ludoviciana* Nutt.), and Cuman ragweed (*Ambrosia psilostachya* D.C.) contributed 7, 3, and 5% composition, respectively. CB sites had 7 and 15% forb cover and the highest ranked forb species were whorled milkweed (*Asclepias verticillata* L.) (1.5%) and white heath aster (*Symphyotrichum ericoides* (L.) G.L. Nesom) (1.3%). Although bare ground was not found to be statistically significant between the two treatments ($p = 0.11$), CB had between 66 and 75% bare ground and NGD had between 41 and 55% bare ground. The CB sites had large amounts of pedastelling of bunches of Caucasian bluestem and bare areas between clumps that display signs of erosion (Figure 2.3). The amount of bare ground and large interspaces may be from the lack of grazing on the study area. Grazing can stimulate tillering expanding the crown and decreasing the amount of bare ground between clumps (Barnes *et al*. 2003). Leaves absorb most of the visible light and reflect the near infrared light (Kasperbauer 1990). Tillering is the result of a low infrared/red ratio (phytochrome system) when the axillary buds have been activated by the increased light inception (Kasperbauer 1990). In terms of the number of forb species per treatment, CB sites had 35 species on each transect and NGD sites had 24 to 26 different species per transect.

Spectral Analysis

Analysis of hyperspectral reflectance bands were used to determine the optimal band(s) and timing(s) to distinguish between NGD and CB sites (Tables 2.9). Figure 2.4 displays average NGD and CB spectral measurements for all collection dates. No bands were statistically significant in distinguishing NGD from CB sites on the September collection date (Figure 2.5). Figures 2.6 and 2.7 show the mean spectral response patterns for the NGD and CB sites collected on July 19th August 12th respectively. From among the spectral reflectance of bands analyzed, only the green band (550 nm) was spectrally different on the July19th and August 12th at p = 0.0243 and p = 0.0098, respectively (Table 2.9). Table 2.9 shows that bands 760 nm ($p < 0.04$), 940 nm ($p = 0.04$), and 1,070 nm ($p= 0.03$) were spectrally different in reflectance for NGD and CB on the June 30th collection date (Figure 2.8). These three bands reside within the near infrared of the spectrum and are influenced by the plant cellular structure and canopy. Figure 2.9 shows the spectral response patterns for NGD and CB created from the data collected on June 17th. During this period, NIR bands at 760 nm ($p = 0.0001$), 940 nm ($p = 0.0017$), 1,070 nm ($p = 0.0035$), and 1,186 nm ($p = 0.03$) were spectrally different (Table 2.9). These bands are influenced by the plant cell structure, water absorption and plant canopy variations. In general, the NIR portion of the spectrum showed a higher reflectance for the NGD sites than the CB sites in the early sampling periods, but it became more similar in September towards the end of the sampling dates (Figure 2.10). Statistical significance levels shown in Table 2.9 indicate that spectral difference between NGD and CB sites was greatest for the most bands in the month of June with fewer differences in July.

Table 2.10 shows statistical significance levels for differences between NGD and CB among vegetation indices. No differences ($p \leq 0.05$) between treatments were found among any of the indices for July, August, and September. Differences between treatments were found on June 17th for the Simple Ratio ($p = 0.0077$), modified Normalized Difference Vegetation Index ($p = 0.03$), Normalized Phaeophytinization Index ($p = 0.0065$), Plant Index 1 ($p = 0.02$), Normalized Difference Water Index ($p = 0.02$), Water Band Index ($p = 0.02$), Normalized Difference Nitrogen Index ($p = 0.01$), and Normalized Difference Lignin Index ($p = 0.01$).

The Simple Ratio (SR) is a broad index using the red band at 665 nm and the near infrared band at 845 nm. Simple Ratio was developed to monitor photosynthetically active biomass. The NGD sites had higher grass and forb cover on the sites than the CB sites. Visual differences could also be seen in the greenness of Caucasian bluestem while the native grasses typically have darker green leaves.

Andrew and Ustin (2006), while using a Classification and Regression Tree (CART) classification approach found NPQI to be frequently selected as the best spectral discriminator of perennial pepperweed (*Lepidium latifolium* L.) from surrounding vegetation types. NPQI measures the difference between blue bands 415 nm and 435 nm was designed for detecting plant leaf chlorophyll degradation and vegetation stress (Zarco-Tejada *et al*. 1999). NPQI may have been found to be significant due to the variation in vegetation cover in the NGD and CB sites.

Spectral difference between NGD and CB sites were also found using the Modified Normalized Difference Vegetation Index (mNDVI). The mNDVI is sensitive to differences in leaf chlorophyll concentrations (Fuentes *et al*. 2001). Wavelengths used to compute the mNDVI (705 nm and 750 nm) are near the “red edge” portion of the vegetation spectral response curves. The “red edge” is the maximum slope on spectral reflectance curve around 680 – 740 nm and has been used as an indicator of stress and senescence in vegetation (Dawson and Curran 1998). No statistical difference between treatments were found using the most commonly used vegetation index, the Normalized Difference Vegetation Index (NDVI) ($p = 0.06$). The ineffectiveness of this index for discriminating between treatments is believed to be due to the broadness of the bands used in the ratio. Andrew and Ustin (2006) also found NDVI to be ineffective for discriminating perennial pepperweed from surrounding vegetation types and attributed it to the insensitivity to subtle differences among species spectral characteristics. In the case of NGD and CB sites, it is believed that the spectral difference between the two was not different enough in the bands used for the NDVI to discriminate between the types.

Normalized Difference Water Index (NDWI) and the Water Band Index were designed to be sensitive to leaf water content (Gao (1996), Penuelas *et al*. (1997). NDWI was developed using MODIS (Moderate Resolution Imaging Spectroradiometer) data and was less sensitive to atmospheric scattering effects, but it can also be used to detect soil humidity (Gao 1996). This index measures the leaf water content using bands 860 nm and 1,240 nm. The Water Band Index (WBI) is computed using the near infrared bands at 900 nm and 970 nm. These bands are located within a water absorption feature of the electromagnetic spectrum. The ratio of WBI measures the water absorption feature near 900 nm through 970 nm and visual differences can be seen in the average reflectance as well and the depth of the absorption feature (Figure 2.9).

The last two indices that showed significant differences between NGD and CB reflectance on the June dates were the Normalized Difference Nitrogen Index (NDNI) and the Normalized Difference Lignin Index (NDLI), which suggests that there are differences in the foliar chemistry of the plants growing on the NGD and CB sites. These indices are computed using wavelengths in the mid infrared portion of the electromagnetic spectrum that is influenced by water content and also foliar chemistry (Serrano *et al*. 2002). Differences in lignin have been reported between Caucasian bluestem and a combination of big bluestem and little bluestem of 5.6 and 6.6 respectively (%, dry basis) (Allen *et al*. 1976, Dabo *et al*. 1988). The percent nitrogen over the growing season for Caucasian bluestem and a combination of big bluestem and little bluestem were similar with values of 1.14 and 1.17 respectively (Allen *et al*. 1976, Dabo *et al*. 1988). These values were averaged over the growing season.

Multiple Regression of cover categories and reflectance

Stepwise multiple linear regression was used to determine which portions of the spectrum or indices best explained variance in the cover categories for NGD and CB sites. In general, all bands and indices were negatively correlated with the cover categories. (Tables 2.11 through 2.14). When the regression was run for the individual bands on the NGD sites, bare ground was the most highly significant factor contributing to the model followed by litter (Table 2.11). For the indices that were significant in detecting the spectral differences between NGD and CB sites, bare ground, litter, and forbs were the significant cover class variables (Table 2.12).

For the stepwise multiple linear regression results for the CB sites using the individual spectral bands, the Caucasian bluestem cover category was the most highly significant factor contributing to the model followed by litter (Table 2.13). For the indices that were significant in detecting the spectral differences between NGD and CB sites, a variety of cover categories were significant in contributing to the regression models (Table 2.14).

Conclusions

The results of this study show that the optimal time for detection of Caucasian bluestem in the tallgrass prairie study area is mid to late June. Reflectance for bands 760 nm, 940 nm, 1,070 nm, and 1,186 nm were spectrally different between NGD and CB sites on the June 17th collection date. Among vegetation indices, SR, mNDVI, NPQI, PI1, NDWI, WBI, NDNI, and NDLI showed significant differences between NGD and CB treatments on the June 17th and June 30th. No indices were significantly different on the July, August, and September dates. These findings suggest that the acquisition of aerial or satellite imagery in mid to late June would be the best time for spectrally discriminating areas invaded in Caucasian bluestem and tallgrass prairie.

The invasion of Caucasian bluestem has been known to change the species richness and diversity in the tallgrass prairie (Reed et al. 2005). The CB sites had lower forb cover and more bare ground than the NGD sites. The total native grass cover was also higher on the NGD and CB sites with big bluestem and Caucasian bluestem being the most dominant on the sites respectively. Although the NGD sites had less forb diversity, the NGD sites had significantly higher forb cover. Litter was also found to be significantly different with the NGD sites having higher percentages of litter. Caucasian bluestems negative effect on biodiversity and also negative effects to the cattle grazing industry makes this $C_{4,}$ warm-season competitor a serious threat to the tallgrass prairie ecosystem.

With the June 17th date having the most significant spectral reflectance of bands and indices, cover categories of bare ground, litter, native grass, Caucasian bluestem, and forbs were used in multiple linear regression to determine how the categories correlated with the significant spectral reflectance at bands and indices. All the spectral data were negatively correlated with the bands and indices. The variables that enter the models were similar for the native sites with the cover categories bare ground and litter. The abiotic cover categories were contributing to spectral variability on the NGD treatment. On the CB sites the cover categories were not as uniform. When using the reflectance of the bands, Caucasian bluestem and litter categories entered the models consistently, indices resulted in a wide range of categories in the models.

To mitigate the invasion of Caucasian bluestem, a current assessment of the distribution is needed. Mapping of invasive species can be used to determine the current distributions and to predict the further spread into new areas. Future research should use the spectral bands and physiological indices selected in this study and apply the findings to aerial and satellite imagery for the detection of Caucasian bluestem from native tallgrass prairie in the Flint Hills of Kansas. Proper band width and pixel size for use in aerial and satellite imagery should be determined to improve the ability to discriminate Caucasian bluestem and native tallgrass prairie canopies.

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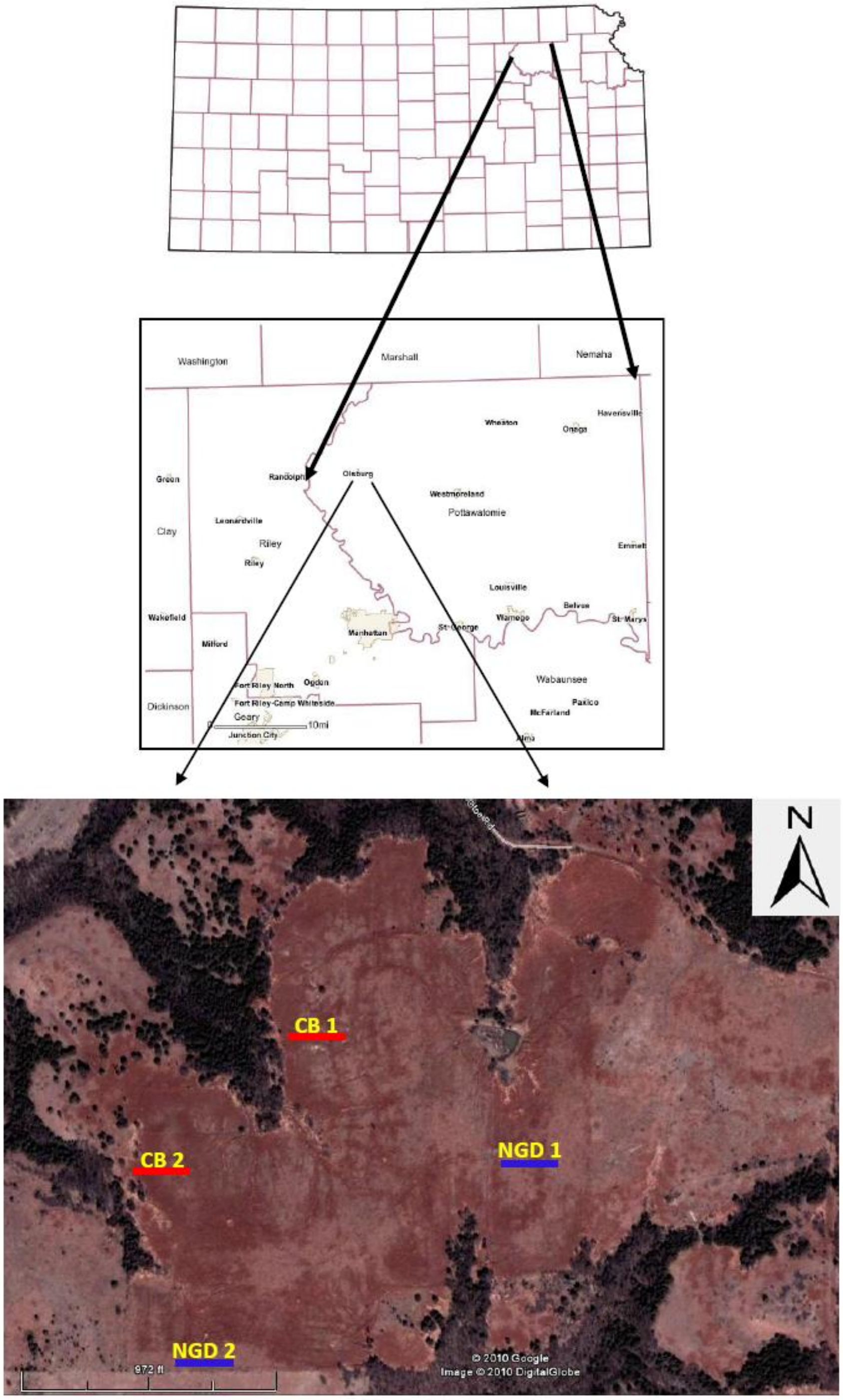

Figure 2.1 The study area is in Pottawatomie County, Kansas, USA, which is shown in the northeastern part of the state. The study area (bottom picture) located outside Olsburg, Kansas had 200 meter transects for each treatment type. The blue lines represent the native grass dominated treatment (NGD) transects and the red lines represent the Caucasian bluestem (CB) treatment transects.

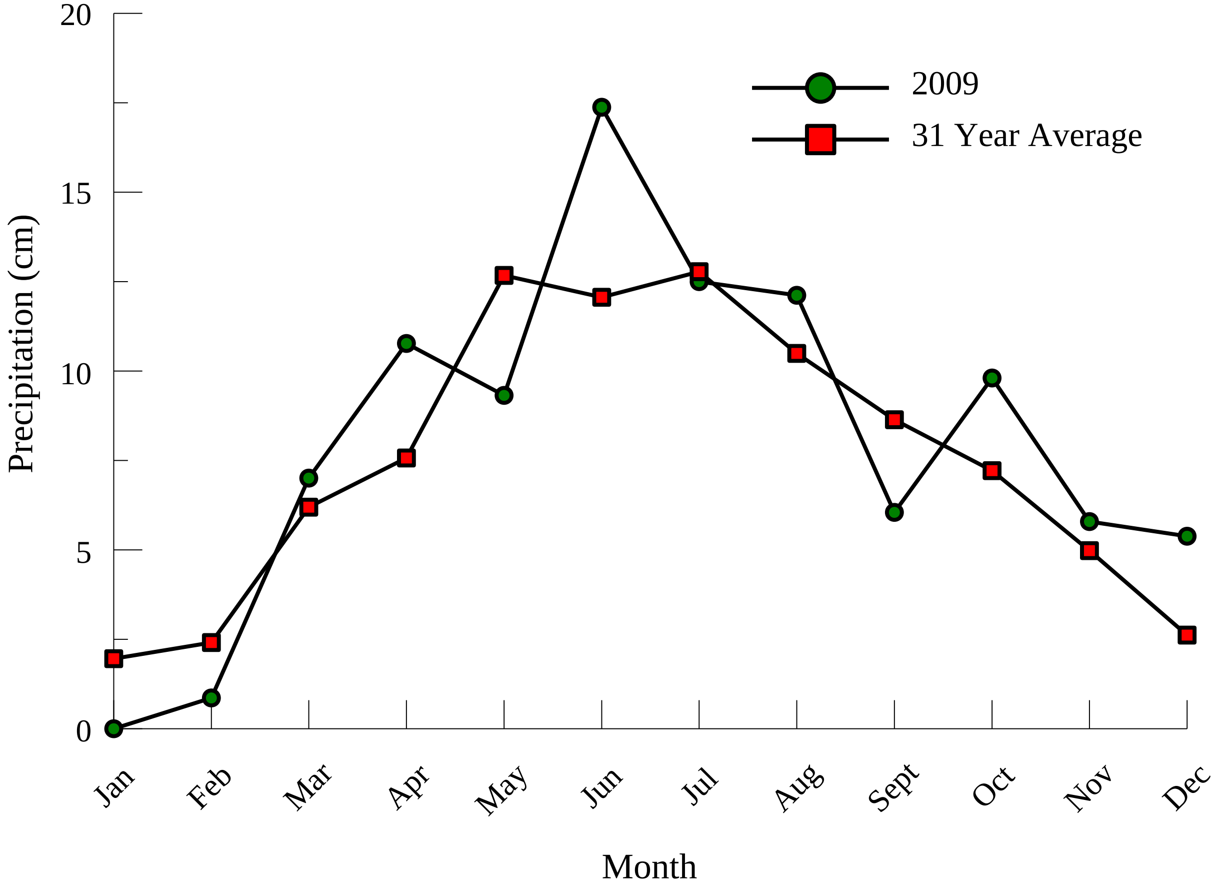

Figure 2.2 Precipitation average for 31 year period from 1971-2000 and for 2009. The 2009 study year was below normal precipitation in May, well above normal in June and near normal in July and August.

Figure 2.3 The top picture is from a NGD quadrat where the spectral readings were taken. The bottom picture is from a CB quadrat where the evidence of erosion is present.

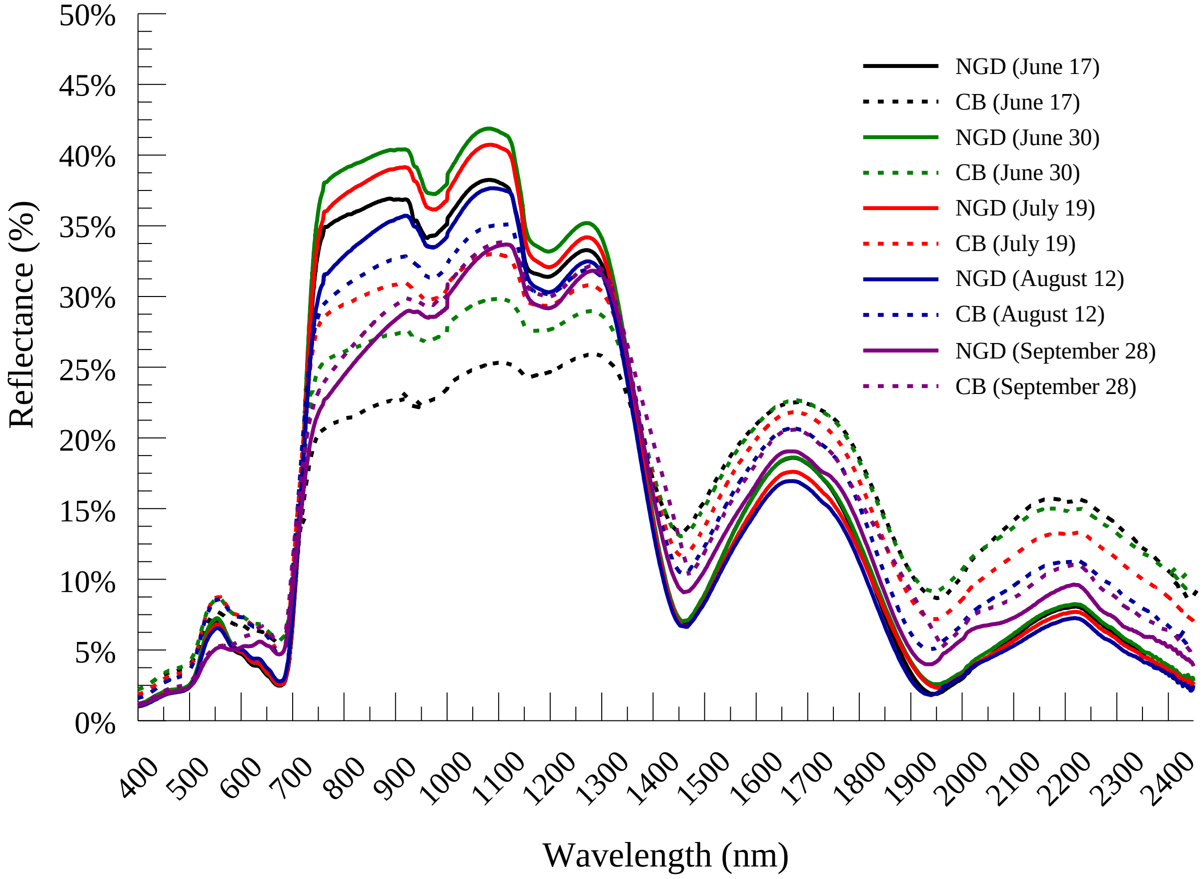

Figure 2.4 Average spectral reflectance curves for native grass dominated (NGD) sites (solid lines) and Caucasian bluestem (CB) sites (dashed lines) across the growing season. Note NGD sites were mostly lower in visible and higher in NIR, and then lower in the middle IR bands.

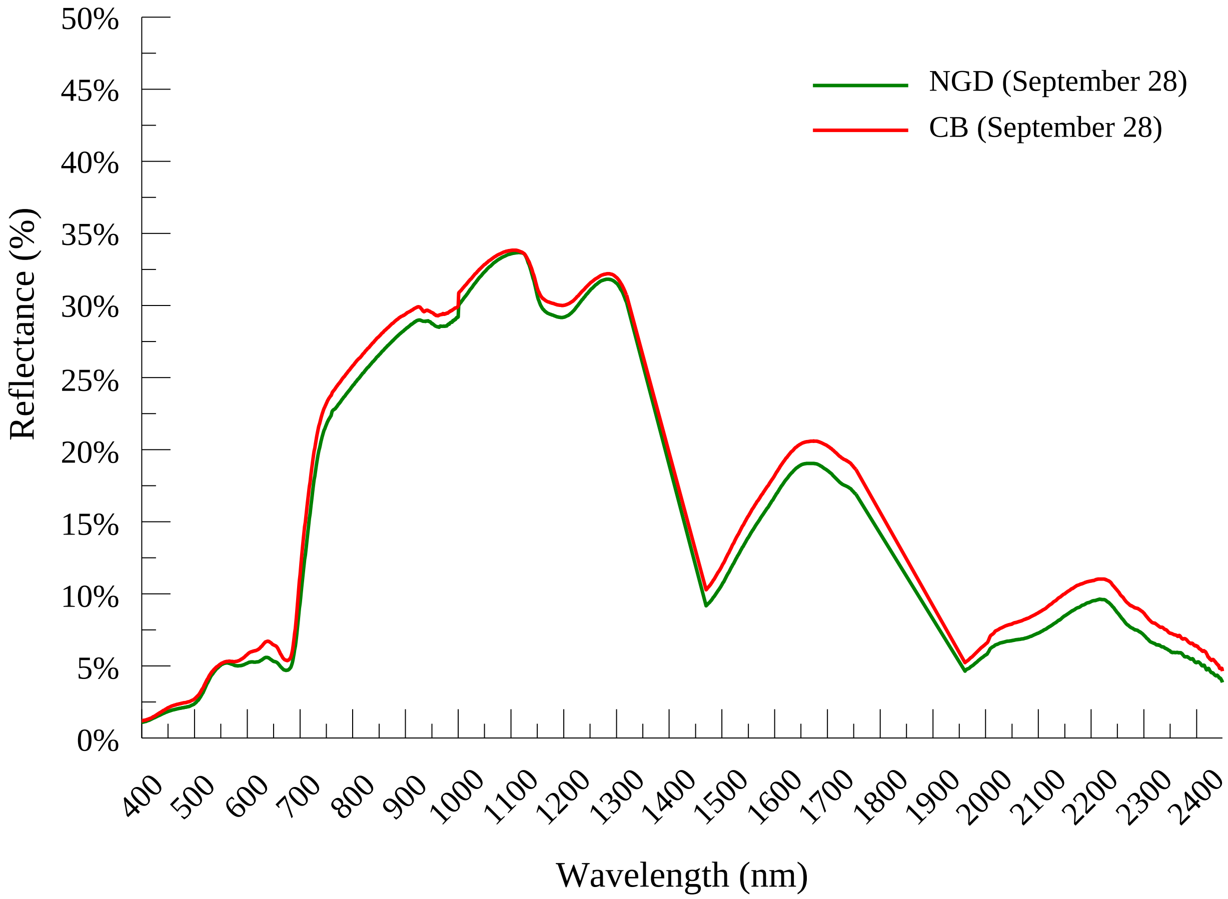

Figure 2.5 Spectral reflectance curve for the September 28th collection date. NGD is indicated by the green line and CB by the red line. Notice that the two types are spectrally similar near the end of September.

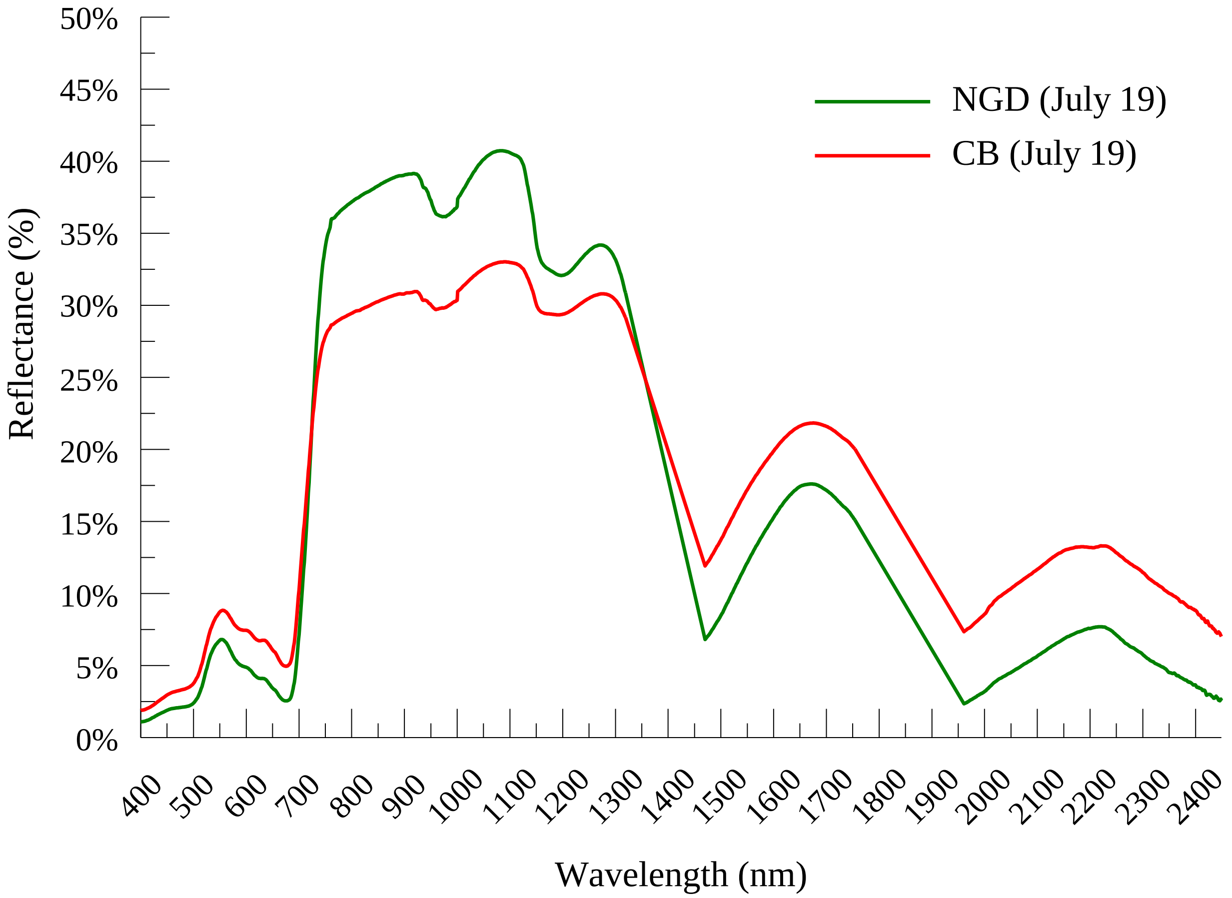

Figure 2.6 Spectral reflectance curve for the July 19th collection date. NGD is indicated by the green line and CB by the red line. The sites are mostly spectrally unique across most wavelengths.

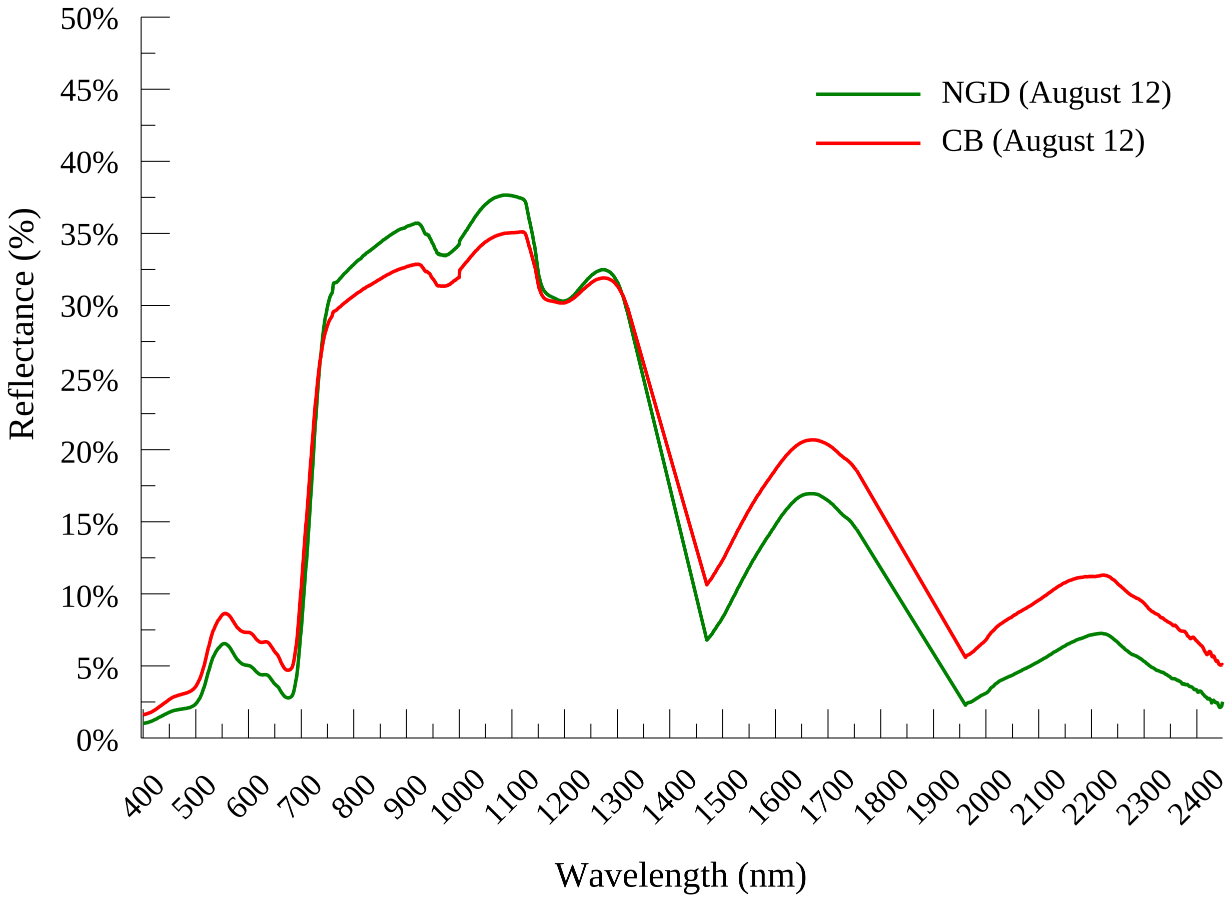

Figure 2.7 Spectral reflectance curve for the August 12th collection date. NGD is indicated by the green line and CB by the red line. Spectral similarities are common in parts of the visible and NIR regions.

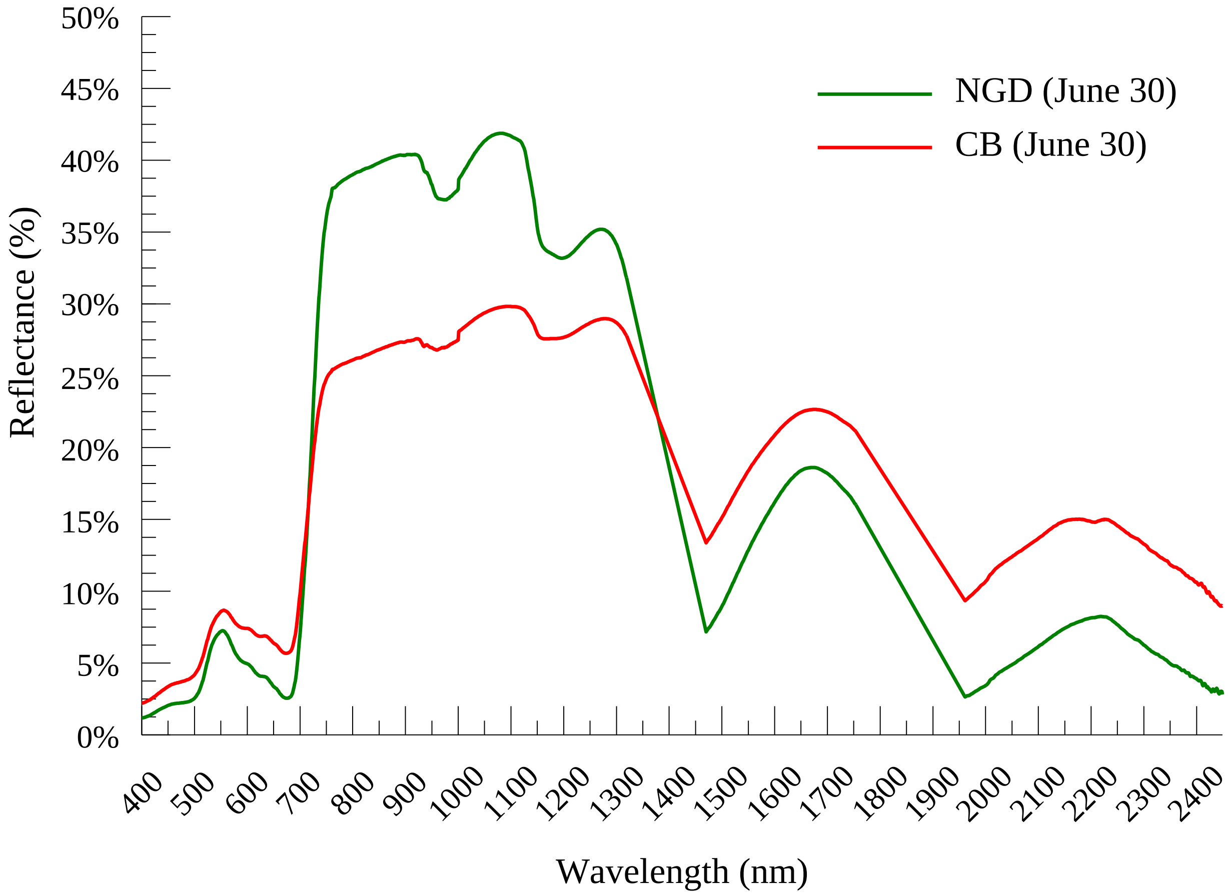

Figure 2.8 Spectral reflectance curve for the June 30th collection date. NGD is indicated by the green line and CB by the red line. This is a period when spectral dissimilarities are found throughout the spectrum.

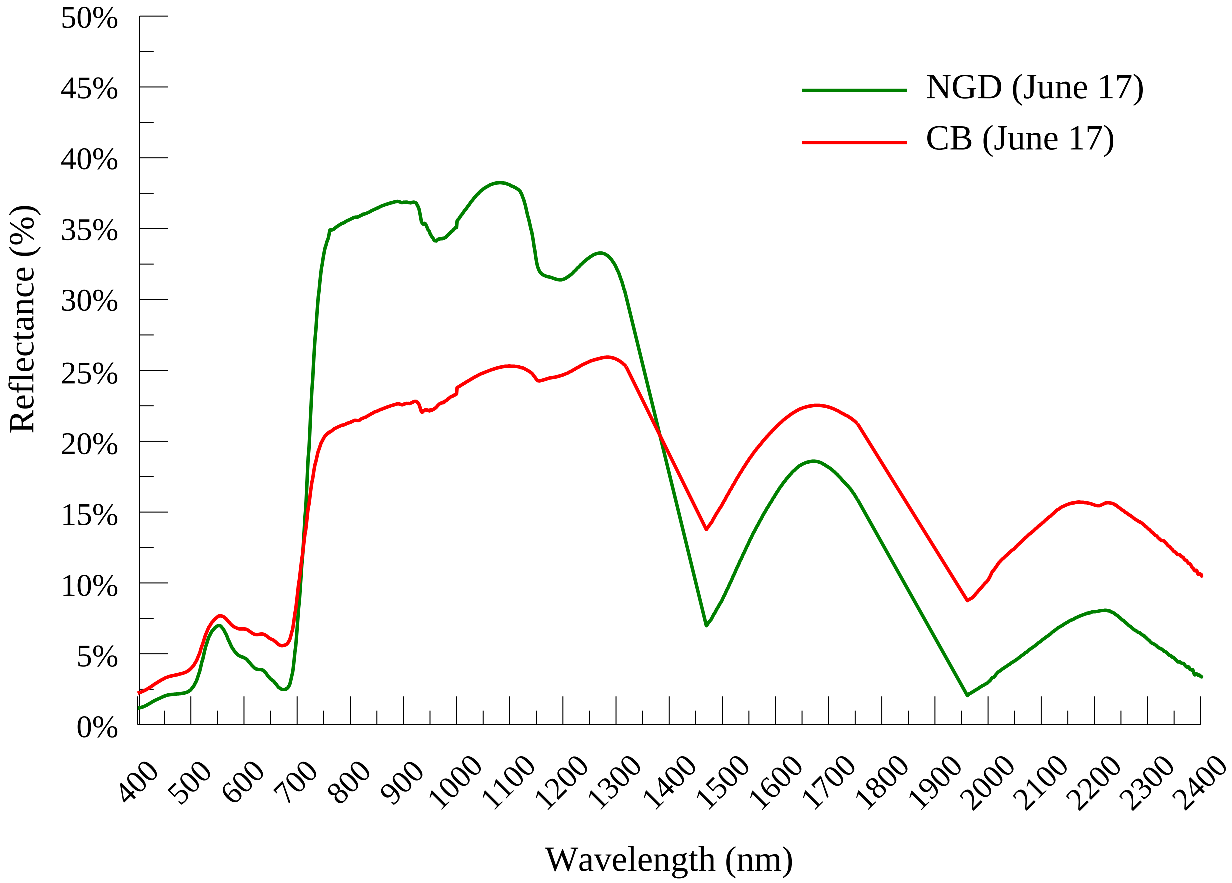

Figure 2.9 Spectral reflectance curve for the June 17th collection date. NGD is indicated by the green line and CB by the red line. This sample period was found to be the period where the two treatments are most spectral dissimilar.

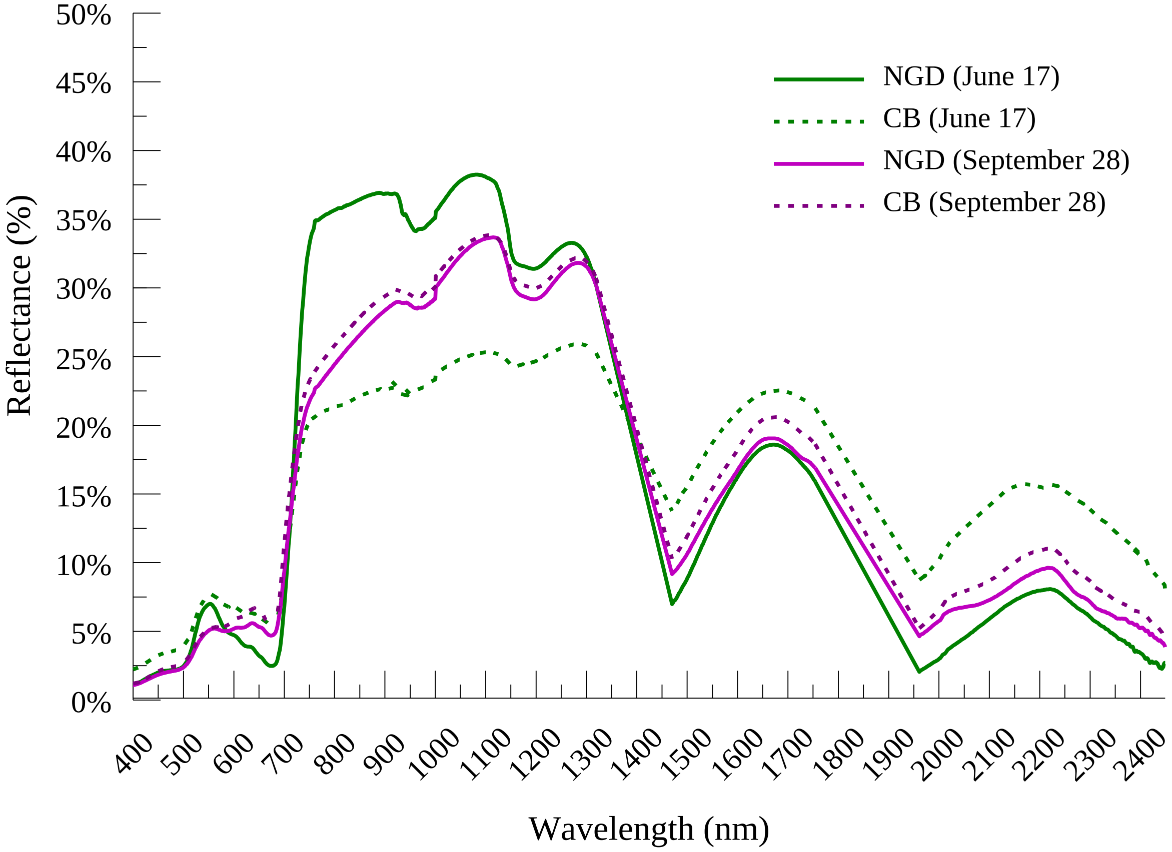

Figure 2.10 Average spectral reflectance curves for the June 17th and September 28th collection date. June 17th had the most statistically significant bands and vegetation indices for discriminating NGD and CB sites. The September 28th collection date found no significant differences between NGD and CB sites.

Table 2.1 Indices calculated from reflectance data to determine if there is a significant difference between the treatment types and sampling dates for detection of Caucasian bluestem.

Index	Formula	Bands	Citation
Simple Ratio (SR)	$\frac{NIR_1}{Red_1}$	NIR_1 = 845 nm, Red_1 = 665 nm	Tucker (1979)
Normalizes Difference Vegetation Index (NDVI)	$\frac{NIR_1 - RED_1}{NIR_1 + Red_1}$	NIR_1 = 845 nm, Red_1 = 665 nm	Tucker (1979)
Modified NDVI (mNDVI)	$\frac{NIR_1 - NIR_2}{NIR_1 + NIR_2}$	NIR_1 = 750 nm, NIR_2 = 705 nm	Fuentes *et al.* (2001)
Photochemical Reflectance Index (PRI)	$\frac{Green_1 - Green_2}{Green_1 + Green_2}$	$Green_1$ = 531 nm $Green_2$ = 570 nm	Rahman *et al.* (2001)
Red/Rreen Ratio (RG)	$\frac{Red_1 - Red_2}{Green_1 - Green_2}$	Red_1 = 600 nm, Red_2 = 699 nm, $Green_1$ = 500 nm, $Green_2$ = 599 nm	Fuentes *et al.* (2001)
Normalized Pigments Chlorophyll Ratio Index (NPCI)	$\frac{Red_1 - Blue_1}{Red_1 + Blue_1}$	Red_1 = 680 nm, $Blue_1$ = 430 nm	Penuelas *et al.* (1995)
Simple Ratio Pigment Index (SRPI)	$\frac{Blue_1}{Red_1}$	$Blue_1$ = 430 nm, Red_1 = 680 nm	Zarco-Tejada (1999)

Index	Formula	Bands	Citation
Normalized Phaeophytinization Index (NPQI)	$\frac{Blue_1 - Blue_2}{Blue_1 + Blue_2}$	$Blue_1$ = 415 nm, $Blue_2$ = 435 nm	Zarco-Tejada (1999)
Structure Intensive Pigment Index (SIPI)	$\frac{NIR_1 - Blue_1}{NIR_1 + Red_1}$	NIR_1 = 800 nm, $Blue_1$ = 445 nm, Red_1 = 680 nm	Zarco-Tejada (1999)
Pigment Index 1 (PI1)	$\frac{Red_1}{Blue_1}$	Red_1 = 695 nm, $Blue_1$ = 420 nm	Zarco-Tejada (1999)
Pigment Index 2 (PI2)	$\frac{Red_1}{NIR_1}$	Red_1 = 695 nm, NIR_1 = 760 nm	Zarco-Tejada (1999)
Pigment Index 3 (PI3)	$\frac{Blue_1}{Red_1}$	$Blue_1$ = 440 nm, Red_1 = 690 nm	Lichtenthaler *et al.* (1996)
Pigment Index 4 (PI4)	$\frac{Blue_1}{NIR_1}$	$Blue_1$ = 440 nm, NIR_1 = 740 nm	Lichtenthaler *et al.* (1996)
Normalized Difference Water Index (NDWI)	$\frac{NIR_1 - MIR_1}{NIR_1 + MIR_1}$	NIR_1 = 860 nm, MIR_1 = 1,240 nm	Gao (1996)

Index	Formula	Bands	Citation
Water Band Index (WBI)	$\frac{NIR_1}{NIR_2}$	NIR_1 = 900 nm, NIR_2 = 970 nm	Penuelas *et al.* (1997)
Normalized Difference Nitrogen Index (NDNI)	$\frac{\log\left(\frac{MIR_1}{MIR_2}\right)}{\log\left(\frac{1}{MIR_1 MIR_2}\right)}$	MIR_1 = 1,680 nm, MIR_2 = 1,510 nm	Serrano *et al.* (2002)
Normalized Difference Lignin Index (NDLI)	$\frac{\log\left(\frac{MIR_1}{MIR_2}\right)}{\log\left(\frac{1}{MIR_1 MIR_2}\right)}$	MIR_1 = 1,680 nm, MIR_2 = 1,754 nm	Serrano *et al.* (2002)
Cellulose Absorption Index (CAI)	$0.5(MIR_1 + MIR_2) - MIR$	MIR_1 = 2,020 nm, MIR_2 = 2,220 nm, MIR_3 = 2,100 nm	Nagler *et al.* (2000)

Table 2.2 Significant differences between NGD and CB treatments for the cover variables. Statistical significance was set at $p \leq 0.10$ and significant findings are indicated by * and also the blue shaded fields.

	Litter	Bare ground	Total Basal Cover	Grass	Forbs
Treatment	0.0869*	0.1154	0.7246	0.0725*	0.0725*

Table 2.3 The means and standard deviations for the cover variables made on June 22, 2009 using the modified step point method. The means for each treatment type were calculated using the step point data from the two transects per treatment.

Cover Variables:	NGD		CB	
	Mean	S.D.	Mean	S.D.
Litter (%)	39.03	9.21	16.23	4.33
Bare ground (%)	48.12	9.96	70.37	6.19
Total Basal Cover (%)	12.85	0.74	13.40	1.85
Total (%)	100		100	
• Grass Composition (%)	64.7	7.91	88.7	5.56
• Forb Composition (%)	35.3	7.91	11.3	5.56
• Total (%)	100		100	

Table 2.4 Cover variables in percent for NGD transects and CB transects using Modified Step Point data.

NGD 1		NGD 2	
Litter	32.51	Litter	45.54
Bare ground	55.17	Bare ground	41.09
Total Basal Cover	12.32	Total Basal Cover	13.37
• Grass Cover	59.11	• Grass Cover	70.30
• Forb Cover	40.89	• Forb Cover	29.70

CB 1		CB 2	
Litter	19.29	Litter	13.16
Bare ground	65.99	Bare ground	74.74
Total Basal Cover	14.72	Total Basal Cover	12.11
• Grass Cover	84.77	• Grass Cover	92.63
• Forb Cover	15.23	• Forb Cover	7.37

Table 2.5 Percent composition by grass species for NGD transects in ranked order from highest to lowest percent.

NGD 1		NGD 2	
Grass	% composition	Grass	% composition
big bluestem	24.14%	big bluestem	22.77%
switchgrass	10.84%	Carex spp.	15.84%
Indiangrass	6.40%	switchgrass	9.90%
Carex spp.	5.42%	little bluestem	5.94%
Caucasian bluestem	4.93%	Indiangrass	5.45%
little bluestem	3.45%	Caucasian bluestem	3.47%
prairie Junegrass	1.48%	smooth brome	1.98%
Kentucky Bluegrass	0.99%	Kentucky bluegrass	1.49%
hairy grama	0.49%	prairie Junegrass	0.99%
Heller's rosette grass	0.49%	tall dropseed	0.99%
tall dropseed	0.49%	Canada bluegrass	0.50%
		Heller's rosette grass	0.50%
		western wheatgrass	0.50%

Table 2.6 Percent composition by grass species for CB transects in ranked order from highest to lowest percent.

CB 1		CB 2	
Plant	% composition	Plant	% composition
Caucasian bluestem	53.30%	Caucasian bluestem	54.74%
big bluestem	10.66%	big bluestem	14.74%
Carex spp.	7.11%	switchgrass	10.00%
Indiangrass	5.08%	Carex spp.	5.79%
little bluestem	4.06%	little bluestem	3.68%
switchgrass	3.55%	Indiangrass	3.16%
tall dropseed	0.51%	tall dropseed	0.53%
yellow foxtail	0.51%		

Table 2.7 Percent composition by forb species for NGD transects in ranked order from highest to lowest percent.

NGD 1		NGD 2	
Forb	% composition	Forb	% composition
sericea lespedeza	14.19%	white sagebrush	5.79%
Cuman ragweed	5.12%	Cuman ragweed	5.20%
ashy sunflower	3.74%	whorled milkweed	3.86%
white heath aster	2.96%	stiff goldenrod	3.12%
roundhead lespedeza	2.56%	white heath aster	2.08%
stiff goldenrod	1.97%	field pussytoes	1.63%
daisy fleabane	1.58%	western yarrow	1.63%
whorled milkweed	1.18%	purple prairie clover	1.19%
white sagebrush	0.79%	common yellow oxalis	1.04%
many-flowered scurfpea	0.79%	aromatic aster	0.74%
aromatic aster	0.59%	Missouri goldenrod	0.45%
mountain mint	0.59%	mountain mint	0.45%
field pussytoes	0.59%	smooth sumac	0.45%
white milkwort	0.59%	curly dock	0.30%
Korean lespedeza	0.39%	daisy fleabane	0.30%
purple prairie clover	0.39%	false boneset	0.30%
western yarrow	0.39%	fringe-leafed ruellia	0.30%
curly dock	0.20%	Virginia threeseed mercury	0.30%
elm species	0.20%	green antelopehorn	0.15%
fringe-leafed ruellia	0.20%	spotted sandmat	0.15%
green antelopehorn	0.20%	roundhead lespedeza	0.15%
Indianhemp	0.20%	slender lespedeza	0.15%
serrate leaf evening primrose	0.20%	violet lespedeza	0.15%
white prairie clover	0.20%	violet oxalis	0.15%
common yellow oxalis	0.20%		

Table 2.8 Percent composition by forb species for CB transects in ranked order from highest to lowest percent.

CB 1		CB 2	
Forb	% composition	Forb	% composition
whorled milkweed	2.39%	ashy sunflower	2.06%
white heath aster	1.62%	white heath aster	1.03%
Cuman ragweed	1.23%	whorled milkweed	0.52%
stiff goldenrod	0.93%	stiff goldenrod	0.44%
aromatic aster	0.85%	Missouri goldenrod	0.37%
purple prairie clover	0.85%	Cuman ragweed	0.37%
roundhead lespedeza	0.69%	purple prairie clover	0.29%
Baldwin's ironweed	0.54%	prairie rose	0.22%
ashy sunflower	0.46%	azure blue sage	0.22%
white sagebrush	0.46%	Indianhemp	0.18%
many-flowered scurfpea	0.46%	green antelopehorn	0.15%
field pussytoes	0.46%	carelessweed	0.11%
western yarrow	0.46%	field pussytoes	0.11%
unknown forb 1	0.39%	rough leaf dogwood	0.11%
common yellow oxalis	0.39%	sericea lespedeza	0.11%
violet lespedeza	0.31%	stiff sunflower	0.11%
white milkwort	0.31%	white sagebrush	0.08%
prairie rose	0.23%	curly dock	0.07%
daisy fleabane	0.23%	Baldwin's ironweed	0.07%
green antelopehorn	0.23%	pinkladies	0.07%
carelessweed	0.23%	fragrant sumac	0.07%
buckbrush	0.15%	slender lespedeza	0.07%
Indianhelp	0.15%	white milkwort	0.07%
Illinois tickclover	0.15%	aromatic aster	0.04%
serrate evening primrose	0.15%	daisy fleabane	0.04%
Virginia strawberry	0.15%	dotted blazing star	0.04%
false boneset	0.08%	fringe leafed ruellia	0.04%
Illinois bundleflower	0.08%	Illinois bundleflower	0.04%
Missouri goldenrod	0.08%	Illinois ticktrefoil	0.04%
prairie ragwort	0.08%	late goldenrod	0.04%
purple poppymallow	0.08%	prairie ragwort	0.04%
showy evening primrose	0.08%	spotted sandmat	0.04%
slender lespedeza	0.08%	roundhead lespedeza	0.04%
stiff sunflower	0.08%	smooth sumac	0.04%
grooved flax	0.08%	wavyleaf thistle	0.04%

Table 2.9 Individual band analysis by date. Statistical significance was set at $p \leq 0.05$ and significant findings are indicated by * and also the blue shaded fields.

Individual Band	June 17th	June 30th	July 19th	August 12th	September 28th
Green 550 nm	0.3664	0.2444	0.0243*	0.0098*	0.7124
Red 668 nm	0.1382	0.1376	0.1794	0.1774	0.1743
NIR 760 nm	<0.0001*	0.0373*	0.1098	0.5888	0.5644
NIR 940 nm	0.0017*	0.0350*	0.0629	0.3692	0.7329
NIR 1,070 nm	0.0035*	0.0338*	0.0520	0.2273	0.8884
NIR 1,186 nm	0.0282*	0.0933	0.0676	0.7614	0.6402
MIR 1,660 nm	0.1917	0.1733	0.1030	0.0918	0.3268
MIR 2,160 nm	0.0733	0.0696	0.1091	0.1276	0.1888

Table 2.10 Index analysis by date. Statistical significance was set at $p \leq 0.05$ and significant findings are indicated by * and also the blue shaded fields.

INDEX	June 17th	June 30th	July 19th	August 12th	September 28th
SR	0.0077*	0.0144*	0.0582	0.1410	0.5186
NDVI	0.0618	0.0792	0.1527	0.1999	0.4900
mNDVI	0.0284*	0.0500*	0.0710	0.1086	0.1276
PRI	0.1138	0.1538	0.1341	0.2293	0.0810
RG	0.8782	0.2043	0.2162	0.3012	0.0798
NPCI	0.0827	0.1059	0.2534	0.4061	0.1807
SRPI	0.0709	0.0927	0.2437	0.4017	0.1625
NPQI	0.0065*	0.0154*	0.1106	0.2503	0.2023
SIPI	0.1585	0.1667	0.2423	0.2976	0.7182
PI1	0.0197*	0.1646	0.7106	0.5088	0.1070
PI2	0.0628	0.0859	0.1307	0.1733	0.2666
PI3	0.1048	0.1539	0.1739	0.2512	0.1277
PI4	0.0538	0.0655	0.1427	0.2102	0.8563
NDWI	0.0250*	0.0379*	0.1352	0.3815	0.5069
WBI	0.0202*	0.0342*	0.0996	0.4050	0.4832
NDNI	0.0132*	0.0300*	0.1102	0.2099	0.8421
NDLI	0.0109*	0.0157*	0.0669	0.1014	0.1912
CAI	0.1007	0.0840	0.1323	0.0933	0.1945

Table 2.11 Regression models using cover categories against the significant bands for the NGD transects.

Native Cover Bands- Stepwise Multiple Regression				
Band (nm)	Cover Categories	P value	R^2	Equation
NIR 760	Bare ground (B)	<.0001	0.3901	$y = 0.44097 + (-0.00285)x_B + (-0.00182)x_L$
	Litter (L)	0.0240	0.4622	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NIR 940	Bare ground (B)	<.0001	0.3694	$y = 0.42049 + (-0.00237)x_B + (-0.00153)x_L$
	Litter (L)	0.0288	0.4395	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NIR 1070	Bare ground (B)	<.0001	0.3468	$y = 0.46675 + (-0.00253)x_B + (-0.00167)x_L$
	Litter (L)	0.0344	0.4151	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NIR 1186	Bare ground (B)	0.0009	0.2328	$y = 0.36281 + (-0.00135)x_B + (-0.00108)x_L$
	Litter (L)	0.0508	0.3017	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		

Table 2.12 Regression models using cover categories against the significant indices for the NGD transects.

Native Cover Indices- Stepwise Multiple Regression				
Band (nm)	Cover Categories	P value	R^2	Equation
SR	Bare ground (B)	0.0009	0.2328	$y = 0.36281 + (-0.00135)x_B + (-0.00108)x_L$
	Litter (L)	0.0508	0.3017	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
mNDVI	Bare ground (B)	<.0001	0.4400	$y = 0.62608 + (-0.00289)x_B$
	Litter (L)	did not enter		
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NPQI	Bare ground (B)	0.0017	0.2119	$y = -0.013927 + (0.00034103)x_B + (-0.00033561)x_N$
	Litter (L)	did not enter		
	Native grasses (N)	0.0026	0.2524	
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
PI1	Bare ground (B)	did not enter		$y = 0.3.14670 + (0.03159)x_F$
	Litter (L)	did not enter		
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	0.0333	0.1034	
NDWI	Bare ground (B)	<.0001	0.3901	$y = 0.07098 + (-0.00174)x_B + (0.00373)x_F$
	Litter (L)	did not enter		
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	0.0641	0.4067	

Band (nm)	Cover Categories	P value	R^2	Equation
WBI	Bare ground (B)	<.0001	0.3727	$y = 1.08141 + (-0.00127)x_B + (0.00334)x_F$
	Litter (L)	did not enter		
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	0.018	0.4536	
NDNI	Bare ground (B)	<.0001	0.3806	$y = -0.18293 + (0.00058982)x_B + (0.00034948)x_L$
	Litter (L)	0.0424	0.4405	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NDLI	Bare ground (B)	<.0001	0.4689	$y = -0.05137 + (0.00024740)x_B + (0.00011982)x_L$
	Litter (L)	0.0492	0.5173	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		

Table 2.13 Regression models using cover class variables against the significant bands for the CB transects.

CB sites cover bands- Stepwise Multiple Regression				
Band (nm)	Cover Categories	P value	R^2	Equation
NIR 760	Bare ground (B)	did not enter		$y = 0.11808 + (0.00202)x_L + (0.00175)x_C$
	Litter (L)	<.0001	0.4212	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.0078	0.1568	
	Forbs (F)	did not enter		
NIR 940	Bare ground (B)	<.0001	0.3694	$y = 0.13404 + (0.00190)x_B + (0.00185)x_C$
	Litter (L)	did not enter		
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.0043	0.1787	
	Forbs (F)	did not enter		
NIR 1070	Bare ground (B)	did not enter		$y = 0.15236 + (0.00215)x_L + (0.00202)x_C$
	Litter (L)	0.0002	0.3589	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.0085	0.1537	
	Forbs (F)	did not enter		
NIR 1186	Bare ground (B)	did not enter		$y = 0.15753 + (0.00164)x_L + (0.00194)x_C$
	Litter (L)	0.0066	0.3195	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.0037	0.1834	
	Forbs (F)	did not enter		

Table 2.14 Regression models using cover class variables against the significant indices for the CB transects.

CB Cover Indices- Stepwise Multiple Regression				
Band (nm)	Cover Categories	P value	R^2	Equation
SR	Bare ground (B)	did not enter		$y = 3.20083 + (0.06946)x_L$
	Litter (L)	0.0028	0.1937	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
mNDVI	Bare ground (B)	did not enter		$y = 0.25958 + (0.00332)x_L$
	Litter (L)	0.0037	0.1842	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NPQI	Bare ground (B)	0.0375	0.0990	$y = -0.10661 + (0.00026534)x_B + (-0.00049663)x_L + (0.00372)x_N$
	Litter (L)	0.0133	0.2700	
	Native grasses (N)	0.1348	0.1474	
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
PI1	Bare ground (B)	did not enter		$y = 2.62878 + (0.00695)x_L + (0.00758)x_C$
	Litter (L)	0.0186	0.2362	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.019	0.1242	
	Forbs (F)	did not enter		
NDWI	Bare ground (B)	did not enter		$y = -0.08725 + (0.00122)x_L$
	Litter (L)	0.0302	0.107	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		

Band (nm)	Cover Categories	P value	R^2	Equation
WBI	Bare ground (B)	did not enter		$y = 0.98445 + (0.00069359)x_L$
	Litter (L)	0.025	0.1140	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	did not enter		
	Forbs (F)	did not enter		
NDNI	Bare ground (B)	did not enter		$y = -0.07184+ (-0.00099014)x_L + (-0.00042087)x_C$
	Litter (L)	0.0050	0.1732	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.0891	0.2302	
	Forbs (F)	did not enter		
NDLI	Bare ground (B)	did not enter		$y = -0.00906 + (-0.00038609)x_L + (-0.00013505)x_C$
	Litter (L)	0.0021	0.2037	
	Native grasses (N)	did not enter		
	Caucasian bluestem (C)	0.1359	0.2462	
	Forbs (F)	did not enter		

Appendix A - Species List

Table A-1 Species list from the study area.

Genus	Species	Authority	Common Name	Native or Introduced	Growth Form	Growth Habit	Cool or Warm Season	Duration
Andropogon	*gerardii*	Vitman	big bluestem	Native	Bunch	Graminoid	Warm	Perennial
Bothriochloa	*bladhii*	(Retz) S.T. Blake	Caucasian bluestem	Introduced	Bunch	Graminoid	Warm	Perennial
Bouteloua	*hirsuta*	Lag.	hairy grama	Native	Colonizing	Graminoid	Warm	Perennial
Bromus	*inermis*	Leyss.	smooth brome	Native and Introduced	Rhizomatous	Graminoid	Cool	Perennial
Carex		L.	Sedge					
Dichanthelium	*oligosanthes*	(Schult.) Gould	Heller's rosette grass	Native	Bunch	Graminoid	Cool	Perennial
Koeleria	*macrantha*	(Ledeb.) Schult.	prairie Junegrass	Native	Bunch	Graminoid	Cool	Perennial
Panicum	*virgatum*	L.	switchgrass	Native	Rhizomatous	Graminoid	Warm	Perennial
Pascopyrum	*smithii*	(Rydb.) A. Love	western wheatgrass	Native	Rhizomatous	Graminoid	Cool	Perennial
Poa	*compressa*	L.	Canada bluegrass	Introduced	Rhizomatous	Graminoid	Cool	Perennial
Poa	*pratensis*	L.	Kentucky bluegrass	Native	Rhizomatous	Graminoid	Cool	Perennial
Schizachyrium	*scoparium*	(Michx.) Nash	little bluestem	Native	Bunch	Graminoid	Warm	Perennial
Setaria	*pumila*	(Poir.) Roem. & Schult	yellow foxtail	Introduced	Bunch	Graminoid	Warm	Annual
Sorghastrum	*nutans*	(L.) Nash	Indiangrass	Native	Bunch	Graminoid	Warm	Perennial
Sporobolus	*compositus*	(Poir.) Merr.	tall dropseed	Native	Bunch	Graminoid	Warm	Perennial
Acalypha	*virginica*	L.	Virginia threeseed mercury	Native		Forb		Annual
Achillea	*millefolium*	L.	western yarrow	Native		Forb		Perennial
Amaranthus	*palmeri*	S. Watson	carelessweed	Native		Forb		Annual
Ambrosia	*psilostachya*	D.C.	Cuman ragweed	Native		Forb		Annual / Perennial
Antennaria	*neglecta*	Greene	field pussytoes	Native		Forb		Perennial
Apocynum	*cannabinum*	L.	Indianhemp	Native		Forb		Perennial
Artemisia	*ludoviciana*	Nutt.	white sagebrush	Native		Subshrub/ Forb		Perennial

Genus	Species	Authority	Common Name	Native or Introduced	Growth Form	Growth Habit	Cool or Warm Season	Duration
Asclepias	*verticillata*	L.	whorled milkweed	Native		Forb		Perennial
Asclepias	*viridis*	Walter	green antelopehorn	Native		Forb		Perennial
Brickellia	*eupatorioides*	(L.) Shinners	false boneset	Native		Subshrub Forb		Perennial
Callirhoe	*involucrata*	(Torr. & A. Gray) A. Gray	purple poppymallow	Native		Forb		Perennial
Calylophus	*serrulatus*	(Nutt.) P.H. Raven	serrate-leaf evening primrose	Native		Subshrub Forb		Perennial
Chamaesyce	*maculata*	(L.) Small	spotted sandmat	Native		Forb		Annual
Cirsium	*undulatum*	(Nutt.) Spreng.	wavyleaf thistle	Native		Forb		Biennial / Perennial
Cornus	*drummondii*	C.A. Mey.	roughleaf dogwood	Native		Tree Shrub		Perennial
Dalea	*candida*	Michx. ex Willd	white prairie clover	Native		Subshrub Forb		Perennial
Dalea	*purpurea*	Vent.	purple prairie clover	Native		Subshrub Forb		Perennial
Desmanthus	*illinoensis*	(Michx.) MacMill. Ex B.L. Rob. & Fernald	Illinois bundleflower	Native		Subshrub Forb		Perennial
Desmodium	*illinoense*	A. Gray	Illinois ticktrefoil	Native		Forb		Perennial
Erigeron	*annuus*	(L.) Pers.	daisy fleabane	Native		Forb		Annual
Fragaria	*virginiana*	Duchesne	Virginia strawberry	Native		Forb		Perennial
Helianthus	*mollis*	Lam.	ashy sunflower	Native		Forb		Perennial
Kummerowia	*stipulacea*	(Maxim.) Makino	Korean clover	Introduced		Forb		Annual
Lepidium	*virginicum*	L.	Virginia pepperweed	Native		Forb		Annual / Biennial / Perennial
Lespedeza	*capitata*	Michx.	roundhead lespedeza	Native		Forb		Perennial
Lespedeza	*cuneata*	(Dum. Cours.) G. Don	sericea lespedeza	Native		Forb		Perennial
Lespedeza	*violacea*	(L.) Pers.	violet lespedeza	Native		Forb		Perennial
Lespedeza	*virginica*	(L.) Britton	slender lespedeza	Native		Forb		Perennial
Liatris	*punctata*	Hook.	dotted blazing star	Native		Forb		Perennial
Linum	*sulcatum*	Riddell	grooved flax	Native		Forb		Annual
Oenothera	*speciosa*	Nutt.	pinkladies	Native		Subshrub Forb		Perennial

Genus	Species	Authority	Common Name	Native or Introduced	Growth Form	Growth Habit	Cool or Warm Season	Duration
Oligoneuron	*rigidum*	(L.) Small	stiff goldenrod	Native		Forb		Perennial
Oxalis	*stricta*	L.	common yellow oxalis	Native		Forb		Perennial
Oxalis	*violacea*	L.	violet oxalis	Native		Forb		Perennial
Packera	*plattensis*	(Nutt.) W.A. Weber & A. Love	prairie groundsel	Native		Forb		Biennial / Perennial
Polygala	*alba*	Nutt.	white milkwort	Native		Forb		Perennial
Polygonum	*aviculare*	L.	prostrate knotweed	Introduced		Forb		Annual / Perennial
Psoralidium	*tenuiflorum*	(Pursh) Rydb.	many-flowered scurfpea	Native		Forb		Perennial
Pycnanthemum	*tenuifolium*	Schrad.	mountain mint	Native		Forb		Perennial
Rhus	*aromatica*	Aiton	fragrant sumac	Native		Shrub		Perennial
Rhus	*glabra*	L.	smooth sumac	Native		Tree Shrub		Perennial
Rosa	*arkansana*	Porter	prairie rose	Native		Subshrub		Perennial
Ruellia	*humilis*	Nutt.	fringe-leafed ruellia	Native		Forb		Perennial
Rumex	*crispus*	L.	curly dock	Introduced		Forb		Perennial
Salvia	*azurea*	Michx. Ex Lam.	azure blue sage	Native		Forb		Perennial
Solidago	*missouriensis*	Nutt.	Missouri goldenrod	Native		Forb		Perennial
Symphoricarpos	*orbiculatus*	Moench	coralberry	Native		Shrub		Perennial
Symphyotrichum	*ericoides*	(L.) G.L. Nesom	white heath aster	Native		Forb		Perennial
Symphyotrichum	*oblongifolium*	(Nutt.) G.L. Nesom	aromatic aster	Native		Forb		Perennial
Vernonia	*baldwinii*	Torr.	Baldwin's ironweed	Native		Forb		Perennial