

ASSESSING THE USE OF REMOTELY SENSED MEASUREMENTS FOR
CHARACTERIZING RANGELAND CONDITION

By

Geoffrey P. Folker

Submitted to the Department of Geography and the Faculty of the Graduate School of the
University of Kansas in partial fulfillment of the requirements for the degree of Master of
Arts

Kevin P. Price, Chairperson

Stephen Egbert, Member

Jerome Dobson, Member

Date Defended: 2/29/08

The Thesis Committee for Geoffrey P. Folker certifies
that this is the approved version of the following thesis:

ASSESSING THE USE OF REMOTELY SENSED MEASUREMENTS FOR
CHARACTERIZING RANGELAND CONDITION

Committee:

Kevin P. Price, Chairperson

Stephen Egbert, Member

Jerome Dobson, Member

Date Approved: 12/8/10

TABLE OF CONTENTS

ABSTRACT	v
ACKNOWLEDGEMENTS	vii
LIST OF FIGURES	ix
LIST OF TABLES	xi
INTRODUCTION	1
BACKGROUND AND LITERATURE REVIEW	4
History of Rangeland Science in the U.S.	4
Rangeland Monitoring and Assessment Approaches	9
The Climax Model	10
The Range Condition Model	12
The State and Transition Model	13
Problems Associated With the Assessment of Rangeland Condition	15
Using Remotely Sensed Measurements to Assess Rangeland Condition	20
Remote Sensing of Rangelands of The Central Great Plains	22
Challenges in Remote Sensing to Assess Rangeland Condition	23
STATEMENT OF HYPOTHESES	30
STUDY AREA	31
Landuse	31
Climate	32
Vegetation	33
Soils	34
METHODS	35

Data Collection	35
Biotic Factors	36
Spectral Factors	36
Data Analysis and Processing.	37
Biotic Data Analysis.	37
Coefficients of Conservatism and the Weediness Index.	38
Spectral Data Analysis	40
RESULTS AND DISCUSSION	42
Ranch Classification Based on Traditional Condition Assessment Methods	42
Descriptive Statistics	42
Simple Correlation Analysis	49
CONCLUSIONS	51
FIGURES	54
TABLES	70
BIBLIOGRAPHY	76

ABSTRACT

There are over 233 million hectares (ha) of nonfederal grazing lands in the United States. Conventional field observation and sampling techniques are insufficient methods to monitor such large areas frequently enough to confidently quantify the biophysical state and assess rangeland condition over large geographic areas. In an attempt to enhance rangeland resource managers' abilities to monitor and assess these factors, remote sensing scientists and land resource managers have worked together to determine whether remotely sensed measurements can improve the ability to measure rangeland response to land management practices. The relationship between spectral reflectance patterns and plant species composition was investigated on six south-central Kansas ranches. Airborne multispectral color infrared images for 2002 through 2004 were collected at multiple times in the growing season over the study area. Concurrent with the image acquisition periods, ground cover estimates of plant species composition and biomass by growth form were collected. Correlation analysis was used to examine relationships among spectral and biophysical field measurements. Results indicate that heavily grazed sites exhibited the highest spectral vegetation index values. This was attributed to increases in low forage quality broadleaf forbs such as annual ragweed (*Ambrosia artemisiifolia* L.). Although higher vegetation index values have a positive correlation with overall above ground primary productivity, species composition may be the best indicator of healthy rangeland condition. A Weediness Index, which was found to be correlated with range condition, was also strongly linked to spectral reflectance patterns recorded in the airborne imagery.

ACKNOWLEDGMENTS

The first person to whom I owe thanks is my advisor Kevin Price. Kevin has eagerly shared his vast knowledge and experience in the field of Remote Sensing and generously provided me access to a wealth of research resources and professional contacts. He has guided me through the research process and helped me further develop my insights and interests by his skillful examples. Our abundant and rewarding hours of discussions about Rangeland Science, Remote Sensing, formal writing, and many important academic and life issues have more than provided me with the opportunity of reflections for a lifetime. He is an inspiration, a mentor, and a friend.

I would like to thank Steve Egbert and Jerry Dobson for their time and guidance. As members of my committee and my teachers, much of what I learned from Steve and Jerry came from informal meetings and conversations. Although both of them have full schedules, they were willing to take time to answer a quick question or open their office doors to me for more engaging discussions. I would like to thank all of the staff and faculty members in the Department of Geography for their help.

Matt Ramspott hired me at the Kansas Applied Remote Sensing (KARS) Program to help with field and aerial data collection and processing towards his Doctoral Dissertation.

Through this experience that occurred during 3 years of my own studies, I learned many of the technical skills needed for organizing, planning, and processing copious amounts of field and aerial data in a project of such scope. Other members of the KARS and Kansas Biological Survey (KBS) staff I would like to thank are: Jerry Whistler, Jude Kastens, Mike Houts, Kelly Kindscher, and Craig Freeman.

I thank the entire ranching community in Comanche and Barber Counties for their gracious hospitality and the opportunity to see the hard work and dedication that goes into feeding thousands of people every day. At the top of that list are Loren Graff (NRCS), Ted Alexander, and the Comanche Pool Prairie Resource Foundation.

At some point in each enriched life, it becomes clear that family is the source of most of our strength. My brother Rick has inspired me to pursue education as a path to experience and live an examined life. I would like to thank all the members of my family and close friends who have encouraged and supported my efforts.

If I tried for a lifetime, I would fall woefully short of adequately describing the positive qualities and attributes of my wife, Tanya. I could never have achieved any of this without your kindness and all the ways you encourage, inspire, and help me see the importance of my blessings. You are my best friend, my best critic, and I think you make the best coffee I have ever tasted. I will try every day but I'll neither have enough time nor words to truly express what you mean to me. Thank you.

LIST OF FIGURES

Figure 1. Diagram of The Range Condition Model according to Dyksterhuis from 1949.	54
Figure 2. Diagram comparing the Clementsian (Succession) and Range Condition Models.	54
Figure 3. Conceptual model of the States and Transitions Model.	55
Figure 4. (A) Photograph taken July, 2004 looking west on US Highway 160 in Barber County, Kansas. (B) Study Area in south-central Kansas including the location and distribution of study sites near Coldwater and Medicine Lodge, Kansas.	56
Figure 5. Three photographs show various amounts of vegetation from the previous growing season: A - sparse short heterogeneous vegetation with significant bare soil, B - dense mixed-height heterogeneous vegetation with relatively small amount of soil, C - dense-tall homogeneous vegetation with almost no bare soil.	57
Figure 6. Transect layout for each of the 20 sites showing quadrat locations and orientation.	58
Figure 7. Mean and annual precipitation amounts per month and mean and annual temperatures for each month in Coldwater, Kansas.	59
Figure 8. Plant species richness index for each of the six ranches.	60
Figure 9. Live cover percent for each of the six ranches.	60
Figure 10. Mean percent cover of warm and cool season grasses on each of the six ranches.	61
Figure 11. Mean percent cover of plants that are categorized as annual or perennial forbs.	61
Figure 12. Mean percent cover of the ten most common plant species in the study area for each of the six ranches.	62
Figure 13. Mean percent cover of invader species for each of the six ranches.	63
Figure 14. Mean percent cover of decreaser species for each of the six ranches.	63
Figure 15. Mean ANPP of each of the six ranches for July, 2002 and July, 2003.	64

Figure 16. Mean ANPP of four major growth forms for each of the six ranches for July, 2002 and July, 2003.	64
Figure 17. Mean Weediness Index for each of the six ranches.	66
Figure 18. Mean NDVI values for each of the six ranches for July, 2002 and 2003, and May, 2004. Data collection dates were selected to correlate with ground data collection dates.	66
Figure 19. X-Y graph of the linear regression results for the relationship between mean NDVI values for July, 2002 and July, 2003 collected over 20 sites.	67
Figure 20. X-Y graph of the linear regression results for the relationship between percent living cover and NDVI for each of the 20 sites for May, 2004.	67
Figure 21. X-Y graph of the linear regression results for the relationship between mean NDVI values and ANPP for July, 2002 and July, 2003 collected over 20 sites.	68
Figure 22. Top: X-Y graph of the linear regression results for the relationship between Weediness Index and NDVI for each of the 20 sites in May, 2004. Bottom: X-Y graph of the linear regression results for the relationship between Weediness Index and NDVI for each of 17 sites with three possible outliers removed.	69

LIST OF TABLES

Table 1. Congressional Acts that affected the characterization of rangeland condition	70
Table 2. Modified Daubenmire cover class intervals with corresponding midpoint percentages.	71
Table 3. Summary of correlation statistics for Figures 19-22.	71
Table 4. List of plant species found throughout the study area. The plant species are ranked by their Presence X Frequency Index.	72 - 73
Table 5. Descriptions for the column headings in Table 4.	74
Table 6. Table showing the 10 most common plant species and the data used to calculate the Weediness Index for each of the 20 sites.	75

INTRODUCTION

Rangelands account for about 50% of the world's land area (Haferkamp and MacNeil, 2004). This converts to 680 million ha of the earth's land area. In the U.S., there are 233 million ha of nonfederal grazing land - rangeland, pastureland, and grazed forest lands that represent nearly 30% of the land surface of the lower 48 contiguous states (USDA, 2002). The National Research Council claims that there are a total of 312 million ha of rangelands in the United States (National Research Council, 1994). Rangelands comprise 30% of lands in Kansas (USDA, 2002).

The economic significance of U.S. rangelands can be partly appreciated by the fact that the United States sold over 82 billion pounds of meat produced from cattle, hogs, and sheep in 2005 (USDA, 2007). The income from the sales grossed \$65.4 billion. Much of this meat was produced from rangeland forage, and the remainder from pastures and feedlots.

Kansas is the second largest producer of cattle in the U.S., exceeded only by Texas. For Kansas, the dollar value of the cattle and calves sold is estimated at \$8,542,872,000 (USDA, 2007). In 2007, income from cattle represented 59.3% of total agricultural sales for the state. Cattle revenue exceeded crop revenue by 1.9 times. The combination of grains, oilseeds, dry beans, and dry peas grown in Kansas represented 31.3% of the total revenue produced by agriculture in Kansas (USDA, 2007). The benefits of rangelands to Kansans go beyond their monetary and food values in that they provide "high quality air and water, open space, and recreation" (USDA, Forest Services (1970) as cited in Vallentine, 1989).

Rangelands are among the most important agricultural ecosystems in the United States and the world (James *et al.*, 2003a). The ability of rangelands to provide optimal benefits in the future depends on their use in a sustainable manner (Sampson, 1981 as cited in Samson and

Knopf, 1994). The sustainable use of agricultural lands that includes rangelands, as legally defined in the 1990 U.S. Farm Bill is,

“The management and conservation of the resource base and the orientation of technological and institutional changes in such a manner as to ensure the attainment and continuous satisfaction of human needs for present and future generations. Such sustainable development is environmentally non degrading, technically appropriate, economically viable, and socially acceptable (FAO (1991) as cited in Heitschmidt et al., 2004).”

Sustainable use of the land requires ranchers and land resource managers to use the tools necessary to “detect ecologically important change” (Booth and Tueller, 2003). The capability of ranchers and rangeland management professionals to inventory and monitor the “indicators of ecosystem health” for the future is driven by the need for sustainable use of soils, plant productivity, and the early detection and management of invasive weed species (Hunt et al., 2003). Furthermore, the ecological condition of rangelands is important to environmental quality, a rangeland’s overall performance as a watershed, and the production of wildlife and livestock (James et al., 2003a).

To use rangelands in a sustainable manner we need to be able to determine how our use of the land is impacting the land (Sampson, 1981; Booth and Tueller, 2003; Hunt et al., 2003). This is done by characterizing rangeland condition, and once condition has been assessed for multiple years one can evaluate changing condition (trend) to determine whether the range is being used in a sustainable manner. Snyman (1998) hints at the problem addressing these issues. He writes “With respect to deterioration and loss of productivity of natural vegetation, a coordinated approach is needed towards establishing a comprehensive inventory of the condition of national vegetation resources on a geographically and scientifically sound basis.” Rowe et al. (2002) point to the importance of “natural resources in relation to

ecological, social, and economic factors” as further indicators of problems associated with the lack of sustainability.

BACKGROUND AND LITERATURE REVIEW

HISTORY OF RANGELAND SCIENCE IN THE U.S.

Rangeland science is the study of rangelands that can be defined as “grasslands, shrublands, and open woodlands managed as natural ecosystems that are traditionally used by grazing animals” (James *et al.*, 2003a). Holechek *et al.* (1998) broadly defines rangelands as “uncultivated land that will provide the necessities of life for grazing and browsing animals.” According to Holechek *et al.*, pasturelands differ from rangelands because pasturelands are periodically cultivated lands that are often planted to nonnative species that may be irrigated or fertilized.

Some of the primary goals of proper rangeland management are the long-term maintenance of sustainable resources such as desirable plant communities, animal production, watershed quality, recreation, and scenic areas (Owensby, 1993; Hunt *et al.*, 2003; James *et al.*, 2003a). On private and federal lands, raising cattle as the means of supporting a livelihood requires ecological and economically sustainable land management practices.

The development of the field of rangeland science has its roots in the late nineteenth to early twentieth century, when widespread ecological problems became apparent to those who lived on the plains and in the western United States (NRC, 1994; Holechek *et al.*, 1998; USDA, 2003; and Worster, 1979). Large portions of the western rangeland experienced a decrease in production of forage caused by grazing too early, overstocking, and improper land management practices. Underlying these problems was the land manager’s failure to recognize overgrazing in its early stages that greatly reduced the carrying capacity of these lands (Sampson, 1919). Holechek (1993) refers to a study by Pieper and Heitschmidt (1988),

in which they concluded that *'stocking rate is and always will be the major factor affecting degradation of rangeland resources.'*

The number of grazing animals that a rangeland can support on a sustainable basis is called the "carrying or grazing capacity," and it is defined as "the maximum population that a given environment can support indefinitely" (Keeton, 1980). Rangeland carrying capacity, or grazing capacity for livestock, can be defined as the number of cattle an area will support indefinitely without causing damage to vegetation or related resources (Holecheck *et al.*, 1998). Rangeland managers often describe the number of grazing animals placed on, or living off the land in terms of an animal unit month (AUM), which is defined as the amount of forage required to feed one cow for one month. Based on the most recent research, a 455 kg cow will consume about 273 kg per month and thus this is the definition of an animal unit month (Holecheck *et al.*, 1998). Stocking rate refers to the maximum stocking rate possible year after year without causing damage to vegetation or related resources. Actual stocking rates may vary considerably among years due to fluctuating climatic conditions that influence forage productivity. Grazing capacity is generally considered the average number of animals that a particular range area has sustained over time.

The Morrill Act of 1862 (Table 1) focused on providing land to the public and the establishment of land-grant colleges to study and advise the public on the proper use of the rangelands. This Act was an early attempt to understand rangeland problems quantitatively and qualitatively, as well as to develop methods to study them. By the 1930s, large areas of the Great Plains and Western U.S., however, were devastated by drought, overgrazing, soil erosion, and dust storms. In the 1880s and 1890s, numerous reports of overgrazing were made by livestock associations in practically all parts of the Western U.S. (Holechek *et al.*, 1998). The U.S. government contributed to this problem as Congress enacted legislation

such as: the Homestead Act (1862) that later became the Enlarged Homestead Act (1909), the Forest Reserves Act (1891), the Stock Raising Homestead Act (1916), and the Taylor Grazing Act (1934). These Congressional acts contributed to overgrazing through allotment of land not well suited for grazing and cultivation of crops where soils were susceptible to wind and water erosion.

Cattle grazing changed dramatically after the Civil War in the U.S. As bison numbers decreased, more land became available for cattle. A significant change was seen in the number of cattle grazing the Western U.S. Cattle numbers rose from 4.6 million head in 1870 to between 35 and 40 million head in 1884 (USDC, 1943 as cited in Holechek *et al.*, 1998). During the 1880s, rangeland degradation in the Western United States was at a maximum (Holechek *et al.*, 1998).

Overgrazing, combined with the conversion of large tracts of land for cropland cultivation, was one outcome of the Homestead Act of 1862 (Table 1). Such lands were easily exploited because few individuals had an appreciation for the multiple land uses associated with rangelands. Heavy grazing, due to demands for more cattle on less land, drove cattle prices high and was the cause of rapid increases in the number of cattle. Many areas of the Western U.S. prairie suffered widespread and severe soil erosion by the 1930s (Holechek *et al.*, 1998). Soil erosion, caused by wind and water, is the most destructive worldwide soil phenomenon. This may result in as much economic and environmental damage to aquatic systems as that created on land conditions (Brady and Weil, 2002). Overgrazing, as well as converting prairie to cropland, reduces vegetation cover that leaves topsoil without anything to hold it in place. Runoff results in diminished water quality due to increased sedimentation loads (Bhuyan *et al.*, 2002).

Erosion of loose topsoil by wind has dramatic and devastating effects. Small soil particles, such as silt, can be set aloft by winds and deposited as far away as the opposite side of the globe (Brady and Weil, 2002). The collection of these particles can form large dust clouds. The dust storm of May 1934 originated in the southern plains and deposited silt, clay, and organic matter as far east as the Atlantic Ocean (Brady and Weil, 2002). “The Dust Bowl was the darkest moment in the twentieth-century life of the southern plains” and was one of the three worst ecological blunders in history (Worster, 1979).

Although not all soil degradation is caused simply by overgrazing, it is appropriate to show a recent statistic from Brady and Weil (2002): *During the past half century, human land use associated activities have degraded some 5 billion ha (about 43%) of Earth’s vegetated land.* If we are to pass the benefits of rangelands’ tremendous resources to future generations, it is necessary that we become better stewards and focus more on sustainability.

The chosen rangeland condition assessment methodology is often driven by the desired land use of the private land owner or resource manager. The way the land is used can significantly alter biophysical factors such as plant and animal species composition and abundance, and abiotic factors such as soil erosion, moisture holding capacity, nutrient availability, and others that all influence the “condition” of the land (Guo *et al.*, 2000a).

In this section, thought was given to government policies that have influenced past rangeland use. As people noticed the effects of land mismanagement coming from past government policies, some realized that methods were needed to assess rangeland conditions and how these lands were being influenced by natural and anthropogenic factors that cause change. In the next section, I will provide information on some of the widely used methods to assess rangeland condition, the evolution of theory relative to rangeland ecosystem processes, and

how humans influenced these processes by varying land management practices. I will discuss how botanists approach this problem as well as three of the major methods for assessing ecosystem condition – two of these methods are referred to as the “Range Condition Model” (Figures 1 and 2B) and the “Climax Model” (Figure 2A). The Climax and the Range Condition Models can be thought of as traditional historical approaches. The third model, the State and Transition Model is currently being tested and applied by evaluating multiple stable “states” of rangeland condition that can exist over time (Figure 3).

RANGELAND MONITORING AND ASSESSMENT APPROACHES

The techniques used in the traditional monitoring and assessment approaches include ground-based measurements of plant cover, frequency and density, and biomass/productivity estimated using various transect methods such as: point sampling, photo interpretation, and ocular estimates using a quadrat method as described by Daubenmire (1959) (Stohlgren *et al.*, 1998; Korb *et al.*, 2003). The purpose for using these field methods is to quantify the plant biophysical properties and community composition that are used to assess site condition in a repeatable method so that plant community conditions can be assessed over time to determine rangeland conditional trends and provide sampling uniformity between and among ranchers and rangeland agencies (Dyksterhuis, 1949).

Botanists have often used a Floristic Quality Index (FQI) to characterize plant communities within a habitat. The FQI, first designed by Swink and Wilhelm (1979), provides observers a method to quantitatively characterize plant communities. Taft *et al.* (2006) suggest that it can be used to measure community-level properties related to vegetation integrity. This index is based on the degree of conservatism of species that depends on the specificity a certain plant has toward its habitat (Jog *et al.*, 2006). One component of the FQI is the Coefficient of

Conservatism (C of C). Bourdaghs *et al.* (2006) found FQI and C of C to be acceptable ecological indicators of condition. Coefficient of Conservatism is an indicator of plant fidelity to specific habitats. Plants with higher fidelity occupy a small ecological niche, cannot tolerate disturbance within surroundings, are habitat specific, and tend to perish easily with changes in habitat. Coefficient of Conservatism ranges from 0-10, with higher values, such as *Asclepias meadii* with a C of C value of 10, indicating plants with higher fidelity to specific habitats. Low C of C plants are tolerant of many different conditions, and are typically weedy generalists (Jog *et al.*, 2006; Taft *et al.*, 2006). Coefficient of Conservatism values have been found to be negatively correlated to gradients of disturbance in wetlands in Ohio (Lopez and Fennessy, 2002) and North Dakota (DeKeyser *et al.*, 2003) and were considered reliable indicators of wetland plant community integrity (Taft *et al.*, 2006). C of C is commonly used in Kansas. The C of C values for Kansas can be obtained from Craig Freeman (Curator-in-Charge, R.L. McGregor Herbarium, Division of Botany, University of Kansas Natural History Museum & Biodiversity Research Center, and University of Kansas) from Freeman and Morse (2002).

The Climax Model

One of the traditional methods for rangeland condition assessment comes from concepts of plant succession as described and named by Cowles (1899), and elaborated upon by Clements (1916), and then applied by Sampson in 1923 (MacDonald, 2003). Examples of other studies that discuss the concepts of traditional rangeland condition assessment are SRM (1995) and West (2003a). Cowles conducted research on primary succession, areas colonized by plants and animals on a previously lifeless surface. Clements worked on secondary succession where an ecosystem was recovering from a disturbance such as fire or flood to become a

“stable” climax community (Clements, 1936; Joyce, 1993; Holecheck *et al.*, 1998; MacDonald, 2003; Briske *et al.*, 2005). Clements (1936) defined the climax community as “a complex organism inseparably connected with its climate and often continental in extent.” He described the climax community as a “major unit of vegetation” that “forms the basis for the natural classification of plant communities.” MacDonald writes about Clements as describing these “climax communities” as “superorganisms” with each species behaving like “organs” within a larger organism. MacDonald (2003) suggests that it is “implicit in Clements’ theory” that species in a community coexisted and evolved together over long periods of time. It should be noted that Clements emphasized the relationship between climate and a climax referring to this relationship as “paramount.” Succession of plant communities ultimately leads to a climax community whereby all plant species that would occupy an area, if given enough time and without human intervention, would be the final mature community established by natural processes (Clements, 1936). The idea of no human energy or intervention would require that the land be allowed to “heal” itself by natural processes. Although there are those who question aspects of the Clementsian theory as it relates to the Climax Community Model, the basic ecological concepts as described by Clements remain as central concepts to many of today’s rangeland management programs. The following section in which the Range Condition Model concept is discussed illustrates that the Climax Model, with its use of an assumed “Excellent” range condition reference, remains well entrenched among the rangeland science community even after significant challenges to this model have been presented.

The Range Condition Model

E. J. Dyksterhuis (1949), like Clements, applied the succession approach to rangeland monitoring and assessment. According to Cingolani *et al.* (2005), Dyksterhuis had formulated the first general theory to explain the response of vegetation to grazing. In his model, Dyksterhuis placed “range condition” on a continuum from “Excellent” to “Poor” based on its relationship to an ideal climax community where “Excellent” would indicate that the area existed in the climax stage of succession.

Dyksterhuis proposed in his 1949 article, *Condition and Management of Range Land Based on Quantitative Ecology* that the method to standardize range condition assessment should be based on quantitative amounts of “coverage per cent” for groups of plants known as *increasers*, *decreasers*, and *invaders* (Figure 1). The increasers become more abundant as condition degenerates from excellent to good, and then become less abundant as condition degenerates from good to poor. The decline in cover by increaser species coincides with an increase in invasive plant species. Cover by “invaders” ranged from nearly 0% for range in excellent condition to nearly 100% cover on poor condition sites. Sites in excellent condition are occupied by nearly 80% decreaser species that decline to nearly 0% cover on poor condition sites. These changes were usually due to grazing practices and if grazing were removed, range condition would return to “excellent condition”. Briske *et al.* (2005) gives a conceptual model of range succession.

Dyksterhuis (1949) notes that many publications dating back to Sampson had popularized the idea of using range condition classes (such as excellent, good, fair, and poor). The use of such classes allowed ranchers and professional rangeland conservationists to come to a better understanding of the range condition concept. Dyksterhuis, however, realized the potential for misinterpreting land cover changes that might be driven by year-to-year variation in climatic conditions – for example, several years of above normal precipitation could lead to a

conclusion that a particular land management practice was responsible for an observed improvement in plant cover and composition. He suggested that range condition assessment could be improved by observing rangelands for lengthier amounts of time and thereby improving the assessment of species compositional changes along a weather continuum.

The State and Transition Model

The State and Transition Model discussed next is a relatively recent concept used in rangeland science to characterize the “condition” and trend of rangelands (Friedel, 1991).

The State and Transition Model provides an alternative view to successional change described by Clementsian and range succession models (Friedel, 1991; Stringham *et al.*, 2001). Gradual and predictable change in vegetation refers to climax succession as defined by Clements (1916), Sampson (1919), and Dyksterhuis (1949) in the previous Climax and Range Condition Model sections. Sampson stated: “the one reliable, indeed the only direct, scientific way of detecting pasture depletion in its early stages is by observing the succession of the conspicuous vegetation, that is, the replacement of one set or type of plants by another.”

The State and Transition Model assumes that rangeland condition can exist in multiple steady states or multiple stable states with transitions between the states. When the rangeland condition exists in a stable state, a threshold has to be crossed for the condition to transition into another state. Cingolani *et al.* (2005) suggests that once the transition across the threshold has occurred, it is not simply reversible when the conditions that triggered the transition cease to act upon the system. Examples of factors that can cause a threshold to be crossed include grazing, climatic variation, and fire, or various combinations of the above factors. For example, when grazing causes rangeland condition to change to a different state,

simply removing the livestock might not be enough to restore the rangeland to its previous condition. Figure 3 illustrates the State and Transition Concept as described by Briske *et al.* (2005).

The State and Transition Model is gaining acceptance because of the dissatisfaction with gradual retrogression and or secondary succession to a climax community (Friedel *et al.*, 1988; Westoby *et al.*, 1989; Laycock, 1991; Bestelmeyer *et al.*, 2003; Cingolani *et al.*, 2005). Laycock (1991) says that the concept of “stable states or domains” is not new to the ecological literature, but only recently has received attention in the rangeland management literature. The State and Transition Model characterizes the dynamics of rangeland conditions as discrete stable “states” of vegetation within an area and a set of discrete “transitions” in time and space that represent changes between the “states.”

Inherent within the State and Transition Model is an understanding of the response to natural and/or management-induced disturbances by providing a framework for organizing a current understanding of potential ecosystem dynamics (Stringham *et al.*, 2003).

PROBLEMS ASSOCIATED WITH THE ASSESSMENT OF RANGELAND CONDITION

The characterization of rangeland condition remains a topic of ongoing debate. As indicated in the previous section on the State and Transition Model, many problems stem from the use of the succession model in reference to rangeland condition or climax that have no sound basis in theory or practice (Friedel *et al.*, 1988; Westoby *et al.*, 1989; Laycock, 1991; Bestelmeyer *et al.*, 2003; Cingolani *et al.*, 2005). When consideration is given to the historical condition of rangelands, SRM (1995) and Smith (2003) refer to the terms used in the succession model that compare managed rangelands to some “imagined” ‘pristine’ or “artificially created natural area” of which neither comparison helps rational decision making

for the use of natural resources. The “traditional” succession model does not apply well to rangeland monitoring and assessment of condition because as Westoby *et al.* (1989) states, “The model supposes a given rangeland has a single persistent state (the climax) in the absence of grazing.” We see these issues continuing to interfere with use of rangeland “condition” assessment because there is still no universally agreed upon method or description to complete this process.

The Task Group on Unity in Concepts and Terminology (SRM, 1995) says the following about rangeland condition:

Range condition score or classification does not tell us, in a general sense, much of what managers and the public want to know about rangelands. Range condition is not a reliable indicator, across all rangelands, of biodiversity, erosion potential, nutrient cycling, value for wildlife species, or productivity. Succession, the basis for the current concept of range condition is not an adequate yardstick for evaluation of rangelands.

The Task Group made three recommendations that were adopted by the Society for Range Management:

- 1) *evaluations of rangelands should be made from the basis of the same land unit classification, ecological site;*
- 2) *plant communities likely to occur on a site should be evaluated for protection of that site against accelerated erosion (Site Conservation Rating, (SCR));*
- 3) *selection of a Desired Plant Community (DPC) for an ecological site should be made considering both SCR and management objectives for that site.*

As suggested in the following excerpt, Scarnecchia thinks range condition should not be the ecology of range science, but it should be a tool to incorporate into the ecological theory of rangeland assessment.

Failure to conceptually isolate the concept of range condition from ecological theory has caused inevitable frustration, and has produced conceptual inadequacies summarized by Risser (1989), Smith (1989), and others. The rangeland condition concept should be conceptualized as a tool

(Scarnecchia, 1991) to apply ecological theory in rangeland assessment
(Scarnecchia, 1995).

Challenges to the Climax Model began as early as 1939 (Joyce, 1993). Henry Gleason concluded that there were no ‘fixed and inviolable laws’ like those that Clements and Cowles had supposed (Kohler, 2008). Tueller (1989) points out that the Climax Model doesn’t work because “The plant community would have long-term stability of productivity, structure, and composition” and this concept is disputed by the State and Transition Model. Joyce (1993) suggests that, in general, other botanists found fault with aspects of Clements’ theory of vegetation, particularly his concept that plant formation (the vegetation of a given area) is itself a living organism subject to growth, maturity, and decay; or what some regarded as his undue stress on climate at the expense of other factors in determining types of vegetation.

Rangeland models for monitoring and assessment of condition and trend continue to evolve. Inconsistent selection of factors to measure and how to measure them limits the ability of resource managers to compare data among and between rangeland organizations (USGAO, 1991; NRC, 1994). James *et al.* (2003a) says “Uniform standards for assessing the health of rangelands do not exist.” He continues by saying that “the development of a set of standards that expresses condition and trend over time and space is essential for proper communication among users, administrators, and other interested parties.” Friedel (1991) states that dissatisfaction of approaches for assessing rangeland condition and trend persists because the traditional models in use do not truly represent the past or potential health of rangelands. If the models are not representative of past or potential rangeland health, one should legitimately ask how one can assess rangeland condition and trend using rangeland measurements that do not accurately represent rangeland health?

The literature on the monitoring of rangeland condition and trend assessment has devoted significant attention to the inconsistency of rangeland-related terms and how they become implemented into rangeland studies and management practices (Joyce, 1993; NRC, 1994; SRM, 1995; Bork, 1997; Winslow and Sowell, 2000; Box, 2003; James *et al.*, 2003a; Laycock, 2003; Smith, 2003; West, 2003a; West, 2003b). For example, West (2003a) published a 50 page paper on the History of Rangeland Monitoring in the U.S.A. in which he felt it necessary to dedicate three pages to definitions on: history, monitoring, inventories and assessment, rangeland, rangeland condition, trends in condition, rangeland health, and ecological integrity. West (2003a) sums up the problem caused by inconsistent monitoring methods with the following statement:

Lack of consistent and comparable monitoring procedures within and between the federal management, advisory, and regulatory agencies has made it impossible to conclude reliably what the overall condition and trends in conditions of our public rangelands are.

Many rangeland science researchers have noticed that standardized measurement and reporting techniques have been problems for consistently monitoring the condition of rangeland (USGAO, 1991; Pyke and Herrick, 2003; West, 2003a; West, 2003b; Briske *et al.*, 2005; Boyd *et al.*, 2007; Rowley *et al.*, 2007). The U.S. Forest Service (USFS), Bureau of Land Management (BLM), National Resources Conservation Services (NRCS), and other federal and state agencies have used different collection and analysis methods that produce dissimilar data, results, and conclusions. In 1991, The U.S. Government Accounting Office (GAO) issued a report to the Subcommittee on National Parks and Public Lands (SCNPPL), Committee on Interior and Insular Affairs (CIIA), House of Representatives. This report addressed a follow up request by the SCNPPL of a report by the GAO in 1991 on the rangeland management programs administered by the Department of Interior's Bureau of

Land Management (BLM) and the USDA's Forest Service. The GAO report compared two reports (Natural Resources Defense Council/National Wildlife Federation, 1989 and BLM, 1990) that were subsequent to their 1988 report. Their 1991 findings are consistent with the 1988 report and illustrate major interagency problems that are representative of data collection and analysis methods between the BLM and Forest Service.

Quotes from the GAO report are provided as examples of the problems the subcommittee found:

One study was issued in 1989 by the Natural Resources Defense Council/National Wildlife Federation (NRDC study)² and the other in 1990 by BLM³. The NRDC study concluded that much of BLM's rangeland was in unsatisfactory condition, while the study by BLM concluded that its public rangeland is improving and in better condition than ever before in this century.

With respect to BLM's conclusion that current range conditions are better than they have been in the past century, we found that the studies BLM used to support this view lack supporting documentation and were produced using different methodologies.

Regarding the data BLM reported for 1936 and 1966, we were unable to determine the methodologies employed in collecting the data because there was no methodology description contained in the supporting documentation we reviewed.

We also found that the data presented were not always comparable between years because different methodologies were used in their collection and compilation. For example, the 1975 rangeland condition data BLM reported were not comparable with the data reported for 1984 and 1989 because BLM changed its collection and reporting methodology.

Recent U.S. General Accounting Office reports suggest that both BLM and USFS are limited in their ability to obtain adequate inventory information. About two-thirds of BLM allotments and one-fourth of USFS allotments did not have management plans, and data for another 16 percent of BLM-managed rangelands and 31 percent of USFS-managed rangelands were more than a decade old (U.S. General Accounting Office, 1988a) (NRC, 1994).

As was noted in the Introduction, rangelands account for 30% of U.S. land surface area in the 48 contiguous states. With this fact in mind, perhaps the most significant failure of the

traditional methods is the amount of data that can be collected in comparison to the amount of land that the data represents. For rangeland managers and researchers to accurately assess the entire landscape using traditional ground methods, vast amounts of time and labor would be required. Given the challenges of traditional methods of assessment, researchers have begun testing the feasibility of satellite and airborne remote sensing methods to measure rangeland condition and trend.

USING REMOTELY SENSED MEASUREMENTS TO ASSESS RANGELAND CONDITION

Given the challenges of assessing rangeland condition discussed above, some scientists and rangeland managers have looked to spectral remote sensing as a possible means for mapping and assessing rangeland geographic distribution and its biophysical factors. Early remote sensing of rangelands focused mostly on land cover classification and plant species mapping (e.g., Tueller *et al.* (1979)). Robinove (1982) used multiple classification image dates to examine rangeland change in Pine Valley. Price (1993) used Landsat to characterize rates of soil erosion in pinyon juniper woodlands. As the remote sensing instruments improved and the scientific methods and technologies advanced, range scientists and resource managers began using remotely sensed imagery to characterize rangeland plant biophysical properties such as cover, biomass, leaf area index, above ground net primary production (ANPP), and Photosynthetically Active Radiation (fPAR) (Everitt *et al.*, 1980; Graetz *et al.*, 1988; Tueller, 1989; Anderson *et al.*, 1993; Myneni and Williams, 1994; NRC, 1994; Paruelo and Golluscio, 1994; Epiphonio and Huete, 1995; Hunt *et al.*, 2003; Running *et al.*, 2004).

Remote sensing techniques also have the potential to significantly improve feedback to rangeland managers by reducing the time that information on rangeland condition is available

for use. Hunt *et al.* (2003) state “Remote sensing techniques offer rapid acquisition of data with generally short turn-around time at costs lower than ground surveys.”

Jensen *et al.* (2000) suggests that in order to revise the planning direction for rangeland grazing allocations with the use of remote sensing, a broad-level characterization of ecosystem integrity and assessment of conditions would require adequate spatial coverage and monitoring techniques that can be implemented in a timely and cost-effective manner. Monitoring rangeland condition and trend could be more cost-efficient and timely if alternatives to labor intensive and time consuming ground data collection methods could be used (Breckenridge *et al.*, 1995; Nouvellon *et al.*, 2001; Hunt *et al.*, 2003; Schmidlein, 2005).

REMOTE SENSING OF RANGELANDS OF THE CENTRAL GREAT PLAINS

Focusing on grasslands of the central Great Plains, the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) was a large-scale climatology project conducted on the Konza Prairie in Kansas from 1987 through 1989. During this experiment, NASA and affiliated scientists studied the connections between tallgrass prairies and their associated biophysical properties to atmospheric conditions and gas exchange. One of the focuses of this experiment was the effects of burning and grazing on Konza tallgrass prairie’s spectral characteristics. Additional objectives of FIFE included: spectral discrimination among bare soil, senescent vegetation, and green vegetation (Asrar *et al.*, 1986 and 1989); measuring the effects of mowing and fertilization on tallgrass productivity and spectral reflectance (Dyer *et al.*, 1991; Turner *et al.*, 1992); examining radiation flux (Irons *et al.*, 1988; Dubayah *et al.*, 1990); assessing biophysical properties of tallgrass vegetation (Weiser *et al.*, 1986); and studying relationships between canopy light interception and leaf

area (Asrar *et al.*, 1986). As part of the FIFE project, Briggs and Nellis (1991) also studied seasonal variation in prairie texture as measured by the SPOT satellite to identify management differences among grazed and burned prairie ecosystems.

Various studies have used remotely sensed data for characterizing grassland biophysical factors (Weiser *et al.*, 1986; Bartlett, 1989; Lauver and Whistler, 1993; Friedl *et al.*, 1994; Guo *et al.*, 2000b; Pickup *et al.*, 2000; Davidson and Csillag, 2001; Peterson *et al.*, 2002a; Guo *et al.*, 2003). Earth observing satellite remote sensing is well suited for detecting terrestrial processes at the global scale. The size of the geographic area, the size and type of the target features, along with temporal requirements, can determine the optimal sensor needed based on its ability to detect objects of interest. Mapping and classification of vegetation types at a global scale can provide spatial and spectral information from satellite sensors to study global ecological problems that can lead towards a more complete understanding of rangeland condition and trend.

CHALLENGES IN REMOTE SENSING TO ASSESS RANGELAND CONDITION

Land cover classification needed to characterize plant species composition on rangelands has had limited success when using small-scale, large-area, or coarse resolution remote sensing systems. Therefore, to many researchers it is apparent that coarse spatial resolution remote sensing is inadequate for some rangeland applications, especially where more detailed discrimination between vegetation types is needed.

Ramspott (2006) found that a time-integrated Normalized Difference Vegetation Index (NDVI) was useful for estimating ANPP since ground-based measurements of ANPP are difficult to obtain across large geographic areas, whereas repeated NDVI measurements are routinely available from satellite remote sensing, albeit most often at coarse spatial

resolution. Also noted was that there is an important link between NPP and time-integrated NDVI that helps assess long term trends as well as seasonal trends.

Regional and landscape-scale remote sensing can detect relatively large areas of vegetation coverage and bare soil (Price *et al.*, 1992; Pickup *et al.*, 1994; Bork *et al.*, 1998). Quantifying relatively small individual components at the sub-pixel level, however, is much more difficult (Ustin *et al.*, 1986; Huete *et al.*, 1987; Graetz *et al.*, 1988; Roberts *et al.*, 1993; Bork *et al.*, 1998). Many researchers have found that higher spatial resolution provides more discrimination of plant species communities (Everitt, *et al.*, 1980; Tueller, *et al.*, 1988; Tueller, 1989; Lewis, *et al.*, 2001; Harris and Asner, 2003). Because plant species composition can be indicative of rangeland condition, the ability to differentiate composition of these communities (species) can affect the success of rangeland condition and trend assessment by remote sensing.

Thematic Mapper data was utilized by Peterson *et al.* (2002b) to evaluate grazing intensity on grasslands in northeast Kansas. They concluded that there was not a direct relationship between spectral characteristics and grazing intensity or rangeland condition. The amount of rangeland that can be directly observed using traditional field ground level survey and mapping techniques is grossly inadequate for monitoring of the rangelands of the world or even at the regional scale (Tueller, 1989; Griffith *et al.*, 2001; Hunt *et al.*, 2003; Hunt and Miyake, 2006). Many of these authors suggest that the inability to monitor large geographic areas on the ground is due to the lack of financial resources, time, and land accessibility. Breckenridge *et al.* (1995) provide some reasons for not achieving early expectations of characterizing grasslands with the following statement: "Assessing the condition of rangelands in the United States presents numerous challenges because of their vast diversity in structure, extent, composition, difficult access, harsh environment associated with

temperature extremes and rugged topography, and our limited knowledge of how they collectively operate.” Measuring characteristics of rangelands at regional or biome scales has unique challenges because most rangelands have a high level of plant species heterogeneity (Goward *et al.*, 1985; Asrar *et al.*, 1986; Briggs and Nellis, 1991; Myneni and Williams, 1994; Wylie *et al.*, 2002). The coarse spatial resolution has limitations due to the inability to accurately identify sub-pixel characteristics of plant species heterogeneity on rangelands.

An ongoing challenge of characterizing rangeland biophysical factors using remotely sensed data is that the universal patchiness in vegetation cover types may not be accurately represented using only large pixels (Adams, 1999). Pixels having multiple cover types within them are sometimes referred to as mixed pixels, or mixels (Campbell, 2002). The considerable biotic and abiotic heterogeneity associated with rangelands makes them particularly vulnerable to the challenges associated with the mixel condition. For example, a pixel with the spectral characteristics of woodlands would frequently contain patches of grass and forbs within them, which might confound one’s ability to correctly classify such sites. The mixed pixel problem has created challenges in using moderate and coarser resolution imagery for characterizing the compositional make up of rangelands. Relative to this spatial resolution issue, Booth *et al.* (2008) summarizes the use of high and low altitude sensors:

Combining information from high and low-altitude sensors appears to offer an optimal path for developing a practical system for cost-effective, data-based, rangeland monitoring and management (Booth, 2003). We conclude that our aerial surveys are a cost-effective monitoring method, that ground with aerial data-set correlations can be equal to, or greater than, those among ground-based data sets (Booth et al., 2008).

For decades, improvements in data quality and analysis of remotely sensed data have increased interest in the use of data for rangeland condition and trend assessment (Tueller, 1989; Peterson *et al.*, 2002b; Harris and Asner, 2003; West, 2003a; Booth *et al.* 2006). Early

attempts at using remotely sensed data to characterize rangeland condition and trend have not been as successful as was hoped. Tueller (1988, 1989) was a pioneer of using remotely sensed data to characterize rangelands. He predicted that remote sensing applications would include inventory, evaluation, and monitoring of rangeland resources and that data available would be incorporated to support and improve the decision processes on the use, development, and management of rangeland resource areas.

Plant communities with sparse vegetation found in the mixed and short-grass prairies are sometimes easier to detect with large pixels that have unique spectral characteristics.

However, coarse spatial resolution satellites can have limitations with identifying small discrete objects due to the inability to accurately identify sub-pixel characteristics of increases in plant species heterogeneity and density found on rangelands. According to Booth *et al.* (2006), “Landsat and other small-scale low-resolution data sets have proved inadequate for identification, inventory, and measurement of detailed rangeland features.”

From the perspective of rangeland management, the goal of a remote sensing method is to extract information that is directly related to management questions at the local scale.

Rangeland management is often categorized under the broad concept known as rangeland health. James *et al.* (2003b) see rangeland condition and trend as an indication of rangeland health and suggest that problems arising from conflicting definitions of terms have been holding the livestock industry to varying and arbitrary standards of environmental stewardship. He suggests that procedures for monitoring health, condition, or any of the descriptive terms used should follow standardized protocols to eliminate the confusion caused by poorly defined standards. He summarizes this in the following excerpt:

*Uniform standards for assessing the health of rangelands do not exist.
Ranchers are being held accountable without the means of accounting for the*

environmental consequences of their actions. A scientifically-based system for monitoring rangeland condition and trend as an indication of rangeland health, a system using a uniform set of standards and procedures to be carried out in a consistent and verifiable manner, is critical for the development of sustainable policies for the management of rangelands for all users. The development of a set of standards that expresses condition and trend over time and space is essential for proper communication between users, administrators, and other interested parties.

The literature (e.g. James, 2003a; Booth *et al.*, 2006, 2008) that was reviewed in this section shows that remote sensing methods have made it possible to measure many features related to the condition of rangelands, but measuring specific indicators of biophysical characteristics such as plant species composition and distribution have been difficult. Booth and Tueller (2003) discuss important considerations about the current methods and applications of remote sensing to characterize rangeland condition. They say that the value of satellite and high-altitude sensors for landscape-level evaluations is well established; however, these tools are inadequate for the inventory and measurement of details, like plant species composition and distribution, needed for valid conclusions about rangeland condition. Finally, they suggest that before remote sensing systems can be widely used to monitor rangeland condition, the sensors must be able to detect characteristics specific to rangeland condition and the data collected needs to be standardized and quantitative.

While remote sensing has become a valuable tool for assessing rangeland condition, improved methods need to be developed to characterize rangeland that can adequately and economically link satellite data to ground data. There is also a need to develop new vegetative condition indicators that can be used to better evaluate biophysical characteristics of plant species. Therefore, the goal of this study is to examine the utility of remotely sensed high-spatial resolution color infrared imagery to characterize rangeland condition on cattle grazing ranches in south-central Kansas by comparing it to the ground-collected biophysical

factors of: above-ground net primary productivity, relative cover of the plant species composition, invasive (weedy) plant species abundance, and abiotic cover.

To answer the issues inherent in characterizing rangeland condition, the following objectives will serve as a guideline:

1. Evaluation of ocular estimates of biotic and abiotic cover within twenty sites on six ranches.
2. Evaluation of the correlation between NDVI and vegetation biomass and species composition.
3. Evaluation of the correlation between NDVI and a newly developed Weediness Index.

STATEMENT OF HYPOTHESES

NULL HYPOTHESIS (H_0) 1. There is no relationship between high-spatial resolution airborne multispectral measurements and plant species percent cover.

NULL HYPOTHESIS (H_0) 2. There is no relationship between high-spatial resolution airborne multispectral measurements and above-ground annual net primary productivity (ANPP) ($\rho = 0$).

NULL HYPOTHESIS (H_0) 3. There is no relationship between high-spatial resolution airborne multispectral measurements and invasive plant species as measured using the Weediness Index.

STUDY AREA

The study area is located on six ranches in Barber and Comanche counties in south-central Kansas (Figure 4B). The center of the study area is approximately 153 km south and west of Wichita, Kansas. The geographic extent of the ranches is within the following geographic boundaries: 37°09'N to 37°18'N latitude and 98°48'W to 99°12'W longitude. This is approximately 32 km from east to west and 14 km from north to south. Elevation for the study sites ranges from 591 m to 616 m. The area within Barber County is part of a region known as the Red Hills and the area within Comanche County is part of the High Plains. The study area is within the Central Mixed-Grass Prairie Ecoregion.

The ranches in both Comanche and Barber Counties are in the lower drainage basin of the Arkansas River. In Comanche County, Mule Creek, the Salt Fork of the Arkansas River, and the tributaries of these streams form the drainage system. In Barber County, the ranches within the study area all drain into the Medicine Lodge River and its tributaries.

LAND USE

About 64% of the land in Comanche County is rangeland, 33% is cropland, and 3% consists of farmsteads, roads, and urban and other areas (USDA, 1989). About 61% of the land in Barber County is grassland, 35% is cropland, and 3% consists of farmsteads, roads, and urban and other areas (USDA, 1977). According to the U.S. Census, Comanche County had a population of 1,967 people within 2,044 km² of land area in 2008 and Barber County had 4,674 people within 2,968 km². These facts yield a human population density of 1.0 person per km² in Comanche County and 1.6 persons per km² in Barber County. In 2002, the cattle population density for Comanche county was 8.4 per mi² and for Barber County it was 5.9 cattle per mi² (USDA, 2002).

CLIMATE

Comanche County, as measured at Coldwater between 1951 and 1980, received an average of 60.91 cm of rainfall annually (Figure 7). Two years in ten will have less than 48.26 cm of precipitation and another two in a ten year time span will have more than 70.61 cm. On average, June is the wettest month with 10.14 cm and December is the driest month with 1.75 cm. Much of the precipitation falls as spring and summer showers and thunderstorms that can be severe at times (USDA, 1989).

Barber County, as measured at Medicine Lodge between the years of 1900 to 1998, received an average of 62.8 cm of rainfall annually (Figure 7). One year in ten will have less than 42.5 cm of precipitation and one year in ten will have more than 85.3 cm (USDA, 1977). On average, May is the wettest month with 10.1 cm of precipitation and December is the driest month with 1.9 cm of precipitation. As with Comanche County, much of the precipitation falls as spring and summer showers and thunderstorms that can be severe at times.

Comanche and Barber Counties have large daily and annual variations in temperature. Both counties have an average high temperature in July of 27.5°C and lowest temperatures of 0.0°C for Comanche and 0.8°C for Barber County in January. A typical year might have a low of -21.7°C in January and a high of 42.5°C in August for both counties (USDA, 1977 and 1989).

Generally speaking, the study sites are within an area that is very similar in climate. This is primarily due to the close proximity and nearly equal elevations.

VEGETATION

The vegetation within the study area occurs within the Central Mixed Grass Prairie Ecosystem, more specifically in the Red Hills Little Bluestem Mixedgrass Prairie vegetation community type. The Red Hills Little Bluestem Mixedgrass Prairie is characterized by the dominance of little bluestem (*Schizachyrium scoparium* (Michx.) Nash) with inclusions of sand bluestem (*Andropogon hallii* Hack.), prairie sandreed (*Calamovilfa longifolia* (Hook.) Scribn.), and shrublands along drainages (Loring et al., 2000). The Soil Survey of Comanche County lists sand bluestem, little bluestem, switchgrass (*Panicum virgatum* L.), and sand sagebrush (*Artemisia filifolia* Torr.) among the species that grow in the Cimarron River drainage basin (USDA, 1989). Big bluestem (*Andropogon gerardii* Vitman), little bluestem, sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.), and blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths) are the dominant plant species in the rest of the county. Both the Comanche and Barber County (USDA, 1977 and 1989) Soil Surveys state that eastern redcedar (*Juniperus virginiana* L.) grow in eroded and ungrazed areas of the two counties.

SOILS

There are nine soil associations in Comanche County (USDA, 1989). My study sites are located on either the Albion-Shellabarger Association or the Pratt-Tivoli-Kingsdown Association. Both are deep, well drained, and have loamy subsoil to sandy surfaces on uplands.

Barber County has 10 soil associations within its boundaries (USDA, 1977). My sites were located on the Albion-Shellabarger Association, Vernon-Kingfisher Association, or the Quinlan-Woodward-Grant Association. All three are characterized as deep, nearly level to moderately steep, and are well drained. Although there are deeply sloped soils within 100 m

of some of the sites, all sites where data were collected are located on nearly level to moderately sloped soils. There was very little erosion observed on the study sites; however, there were areas of serious erosion nearby especially in Barber County where the topography was cut by water into steep canyons. Some of these canyons are quite spectacular with steep walls and exposed red sandstone. The red sandstone is responsible for the name of “Red Hills” given to this region (Buchanan and McCauley, 1987).

METHODS

DATA COLLECTION

Biotic and spectral measurements were collected on 20 sites located on six ranches within the study area (Figure 4B). The site locations were predetermined and marked with polyvinyl chloride stakes by the ranchers and a Rangeland Conservationist from the National Resources Conservation Service (NRCS). The sites were relocated in the field using a Garmin handheld GPSMAP 60CS GPS unit to establish a reference point to use when processing and analyzing the airborne imagery collected over the sites. Digital images were taken on study sites to visually demonstrate relative amounts and varieties of plant types. An example of these images is shown in Figure 5.

Each ranch had at least two data collection sites. Ranch 1 had six sites, Ranch 2 had four sites, Ranches 3 and 6 had three sites each, and Ranches 4 and 5 had two sites each. Figure 6 shows the layout for how each site was arranged. Each site was divided into nine 1.0 m² quadrats within a 21 m x 21 m site so that each site occupied 441 m² (Figure 6). Each observation site formed a square with sides parallel to the cardinal directions. All sites were set up with standardized orientation, size, and shape. The stakes were the initial reference point and a Brunton Lensatic compass was used to determine cardinal directions. A 7° east magnetic declination was used with the compass to accurately measure true north.

Biotic Factors

Ocular estimates of percent cover (PC) of plant species and abiotic factors were collected in May and June of 2004 using a slightly modified quadrat method described by Daubenmire (1959). The original Daubenmire method used six cover categories; however, 10 cover class

categories were used in this study to detect more subtle differences in cover. Above ground net primary productivity (ANPP) samples were collected on the 20 sites by the NRCS in July 2002 and 2003. The procedure for collecting the samples consisted of clipping 1.0 m² samples of above ground vegetation at a height of 1.0 cm and above. Vegetation was separated by grass, forb, succulent, and woody species. Grass was further separated into warm (C₄) and cool (C₃) season grasses. C₄ grasses were then separated into growth forms (i.e., short, mid, and tall). In the lab, standing dead forb and grass were sorted out and placed in separate bags. All biomass was then dried in a 60°C drying oven for at least 48 hours before weighing.

Spectral Factors

High spatial resolution multispectral airborne images were collected over the study sites on July 16, 2002, July 27, 2003, and May 5, 2004 using the DuncanTech MS3100 digital camera mounted in the TerraHawk imaging system produced by TerraVerde. The image acquisition periods were selected to correspond with periods when field data were being collected. The detector in the camera has a pixel array of 1392 X 1040 and, based on the altitude of the aircraft at the time of image acquisition (ca. 3200 m), yielded a ground resolution of approximately 1.0 m x 1.0 m. The camera collected data in the blue (450-520 nm), red (630-690 nm) and near-infrared (NIR) (760-900 nm) spectral bands. These bandwidths are analogous to Landsat Thematic Mapper bands 1, 3, and 4.

DATA ANALYSIS AND PROCESSING

Biotic Data Analysis

The raw data were entered into Microsoft Excel for ease of transformation and basic analytical operations. Plant species cover data were converted into standardized percentages by species using the midpoint of each class interval (Table 2). More detailed analyses were conducted on plant species that were more ubiquitous to the study sites. Such ubiquity was computed using a method modeled after the Presence X Frequency Index (PXF) described by Curtis (1959). For this method, the percentage of quadrats among all sites in which a plant species is found (frequency) is multiplied by the percentage of sites in which a species is found (presence). From this index (PXF Index), the commonness of a species across the entire study area is assessed based on the index value for each species that can vary from 10,000 (a case in which a species is found in every quadrat and in every study site) to a value of 0 (species not found within the study area). The 10 most common species using the PXF Index were selected for further analysis.

The PC and ANPP data were aggregated from quadrat level to site level and were used to calculate the mean and standard deviation of each of the variables within each site. Cover was collected by plant species, total live, cool and warm season grasses, annual and perennial forbs, and plant species designated as invaders and decreasers. ANPP was collected and summarized by total mass and four major growth forms including: warm season grasses (C4), cool season grasses (C3), forbs, and woody/shrubs.

Descriptive statistics were computed for the biotic, abiotic, and spectral variables for each ranch. Simple linear regression (Pearson's Product-Moment Correlation Coefficient) analysis was used to evaluate the strength of the relationships between selected variables.

Coefficients of Conservatism and the Weediness Index

Plant species PC data from May, 2004 were combined with the Coefficients of Conservatism (C of C) to test as a potential indicator of rangeland condition. The C of C is defined as a numerical indicator of a species' fidelity to native plant communities and is the foundation of the Floristic Quality Assessment Index (FQI) (Freeman and Morse, 2002; Jog *et al.*, 2006). Several articles have recently been published that demonstrate the usefulness of FQI and C of C to characterize the quality of grasslands and wetlands (Cohen *et al.*, 2004; Mathews and Bonser, 2005; Bourdaghs *et al.*, 2006; Jog *et al.*, 2006; Taft *et al.*, 2006). Information from these articles, as well as Freeman and Morse (2002), was used to calculate a Weediness Index (WI) that was tested as a potential indicator of relative rangeland condition. Based on work discussed earlier by Sampson and Dyksterhuis concerning the condition of ecosystems and rangelands, a modified model of rangeland condition was developed based on site weediness. The core of this model is derived from PC data and C of C. As discussed earlier in the literature review, C of C values range from 0-10, with higher values indicating plants with higher fidelity to specific habitats and low values indicating weediness (Table 5). A "*" indicated non-native species (Table 5) that have no C of C assigned. Most of the sites in this study had a substantial PC of invasive plant species (Figure 13). For this reason, a weediness index (WI) was developed for this study using a plant's C of C index value.

The method used to calculate this Weediness Index for each plant species is described in the steps mentioned below.

1. The C of C values were converted to integers starting at 1 using the following transformation: * = 1, 0 = 2, 1 = 3, 2 = 4, 3 = 5, 4 = 6, 5 = 7, 6 = 8, 7 = 9, 8 = 10, 9 = 11, and 10 = 12. These new values were labeled as Coefficients of Weediness (C of W) (Table 5). This transformation was necessary to eliminate the use of "*" and "0" as values.

2. To establish a positive correlation between Weediness Index and site weediness, it was necessary to produce factors that were inversely proportional to the C of W. The procedure used was to divide each C of W by 12 and label the results “Weediness Factor” (WF) (Table 5). The following formula was used to calculate the Weediness Factor:

$$WF = C \text{ of } W / 12.$$

3. To establish the Weediness Indices for each study site, the WF of each plant species was multiplied by the corresponding PC of the same plant species and then summed (Table 6). The following formula was used:

$$W I = \sum [\% \text{ Cover } ((C \text{ of } W) / 12)]$$

Weediness Index formula

where % Cover (PC) = the percent of each plant species in the site

Spectral Data Analysis

Aerial imagery was collected in July of 2002, July of 2003, and May of 2004 and then the necessary values for calculating NDVI were extracted from the imagery for each of the dates (NDVI₂₀₀₂, NDVI₂₀₀₃, and NDVI₂₀₀₄). Individual images were selected for processing based on those that covered the site completely. Images that had the ground site near their middle were given highest priority to avoid systematic sensor and platform-induced geometry errors that are more likely to occur further from the nadir location of the sensor. Image georectification and data extraction of spectral values was accomplished using ERDAS Imagine 8.5. Each aerial image was geocorrected using ground control points (GCP) collected from a 2002 Digital Orthophoto Quarter Quadrangle (DOQQ) orthorectified

basemap acquired from the Data Access and Support Center (DASC). Images were resampled and projected to a Universal Transverse Mercator (UTM) projection for Zone 15 (North), North American Datum of 1983. RMS errors in the geo-correction process were generally kept to 0.5 m or less. The aerial image raw digital numbers (DN), for each of the three bands (green, red and NIR) in the image, were transformed to values of radiance (RAD) using a custom calibration procedure developed by Schiebe *et al.* (2001).

A GIS database was constructed from the geocorrected, spectrally transformed aerial images using Environmental Systems Research Institute's (ESRI, 2002) ArcGIS 8.3 in order to calculate NDVI. The spectral pixel values for each study site and their respective overflights were extracted using boundary files (shape files) defining the geographic boundaries for each site. The pixels within each shape file were aggregated to compute the mean spectral value by band within each site. The radiance corrected DN arrays for the red and near infrared bands were used to compute the NDVI values for each pixel within the study sites. NDVI was computed using the raster calculator in the ArcGIS Spatial Analyst. For each site, the following files were created: one polygon shape, one zone layer, one radiance value raster layer each for the red and NIR bands, and an NDVI layer. The NDVI was computed using the traditional formula described by Rouse *et al.* (1974): $(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$.

Correlation analysis with Pearson's product-moment coefficient (Pearson's r) was used to determine if the strength of relationships between variables were statistically significant enough to reject the null hypotheses. I applied a 2 tailed test ($p = 0.05$) between the variables that were measured on each of the 20 (n) study sites. The r critical value (r_{crit}) for a two tailed $n = 20$, $df = 18$, and $p < 0.05$ is 0.44.

RESULTS AND DISCUSSION

RANCH CLASSIFICATION BASED ON TRADITIONAL CONDITION ASSESSMENT METHODS

The species cover data for study sites located at each of the ranches were used to categorize the ranches into relative condition classes based on the Range Condition model described by Dyksterhuis in 1949 (Figure 1). As a result of this, the ranches are classified as Excellent (E), Good (G), Fair (F), or Poor (P) and are given a ⁺ or ⁻ sign if they are high or low within the class (e.g. E⁺, E, or E⁻; G⁺, G, or G⁻; F⁺, F, or F⁻; P⁺, P, or P⁻). Based on the species level cover data collected at each site for the six ranches and adapting the Dyksterhuis condition model, the ranch conditions were classified as follows: Ranch 1 = G⁻, Ranch 2 = F⁺, Ranch 3 = F⁻, Ranch 4 = F, Ranch 5 = F⁺, and Ranch 6 = G⁻. In using this method, it was found that applying the Dyksterhuis categories to each ranch was a challenge in that based on the plant cover composition data, none of ranches fit the model well, which might explain one of the challenges of using past methods for assessing site condition. Most of the ranches were assessed in the “Fair Condition” category because of the high abundance of annual invader species found on many of the sites.

DESCRIPTIVE STATISTICS

Figure 8 shows the plant Species Richness Index, defined as the average number of species present (Chapin *et al.*, 2002), for each of the six ranches in the study area. The mean number of plant species present per ranch was 19.3 and the standard deviation was four. The richness index values varied among ranches from a low of 15 on Ranch 3, to a high of 24 on Ranch 4. Ranches 3, 4, and 6 were more than one standard deviation from the mean. Ranches 1, 2, and

5 were within one standard deviation. Loring *et al.* (2000) found an average of 147 species per site near the location where this study was completed. Their collection time, however, was from June through October, 1999, which covered much more of the growing season, giving them a greater opportunity to encounter more species that grow at different times of the growing season. The much smaller sample size used in this study and less specialized training in plant identification most likely contributed to a lower number of species recorded at each of the study sites.

Figure 9 shows combined PC of live plants for each ranch. The mean PC among the ranches was 76% with a low of 67% and high of 83% with a standard deviation of five. The results show all ranches except Ranches 1 and 2 had PC values within one standard deviation of the mean, indicating that four of the ranches had similar PC values, and two of the ranches were significantly different from the others. The land use history of the ranches in this study has been cattle production for approximately 50 years. The assumption is that modifications in stocking rates have had the biggest impact on the land and that other maintenance and improvements have been similar.

The mixed-grass prairie is characterized by the dominance of warm season (C₄) grasses. Whether we rank ranches by Condition Class, C of C, or WI, increased frequency and amount of warm-season grass species are used as positive indicators of sustainability and better condition especially where cattle have grazed or are currently grazing (Owensby, 1993; Peterson *et al.*, 2002b; Cully *et al.*, 2003).

Figure 10 illustrates that five of the six ranches had more than twice the amount of warm season (C₄) grasses than cool season (C₃) grasses. Ranch 3 was the only ranch that had more C₃ grass cover than C₄ grass cover. Ranch 1 had the most C₄ grass cover and Ranch 3 had the

least amount ranging from 25% to 7%, respectively. Ranch 3 had the highest amount of C₃ grass cover at 13% and Ranches 2 and 4 had the least amount at 2%.

Figure 11 shows the PC of annual and perennial forbs. Ragweed (WI = 0.92) and wooly plantain (WI = 0.83) were the most commonly observed annual forb species as indicated by the PXF Index. Both species have a high Weediness Index (low C of C Index) and therefore are indicators of poor rangeland condition. Scurfpea (WI = 0.25) was the most commonly observed perennial forb according to its PXF Index and therefore contributes most to the PC of perennial forbs. Ranches 2, 3, and 4 were more abundant in annual than perennial forbs. Ranch 3 had the greatest proportion of annuals to perennials. Ranches 1, 5, and 6 had more perennial forbs than annual forbs.

Sixty-three plant species were encountered within the 20 study sites as listed in Table 4. The plant species are ranked according to their calculated PXF Index as described by Curtis (1959). The following are the 10 species most commonly encountered among the 20 study sites: *Ambrosia artemisiifolia* (ragweed) was the most common, followed by *Schizachyrium scoparium* (little bluestem), *Plantago patagonica* (wooly plantain), *Psoralea tenuiflora* (scurfpea), and *Bromus tectorum* (cheat grass), *Artemisia ludoviciana* (white sage), *Andropogon gerardii* (big bluestem), *Buchloe dactyloides* (buffalograss), *Artemisia filifolia* (sand sagebrush), and *Cirsium undulatum* (wavyleaf thistle). The 10 most commonly encountered plant species are categorized according to their longevity as follows: two annuals, six perennials, one annual-biennial, and one annual-biennial-perennial. These plant species categorized by growth form resulted in: four grasses, four forbs, and two shrubs (Tables 4 and 5). Table 4 provides additional information for each plant species as follows: the scientific names, the common names, the USDA symbol, the Growth Habit by Raunkiaer life form codes assigned by the University of Kansas Natural History Museum, R.L.

McGregor Herbarium (KANU), the Coefficient of Conservatism, the Coefficient of Weediness, and the Weediness Factor. For further explanation of this Table's column headings, refer to Table 5 and the description in the Methods section. The Weediness Index, however, is provided in Table 6 because it is site specific.

The 10 most common plant species are shown for each ranch in Figure 12 according to mean PC. The PC of plant species on each ranch gives an indication of the ranch condition based on relative amounts of invader, increaser, or decreaser plant species according to the model described by Dyksterhuis (Figure 1). The invaders, increasers, or decreasers in this study are classified based on their respective C of C provided in Table 4. Invaders range from “*” to one, increasers range from two to three, and anything greater than or equal to four is considered a decreaser. Of the 10 most common plant species found in the study area, there were four invader, one increaser, and five decreaser species. Ragweed is an invader and was the most pervasive plant species in the study area. Ranch 3 had the highest PC of ragweed, approximately twice as much as Ranch 5, which had the next highest amount. Ranch 4 had the least amount of ragweed. Little and big bluestem are perennial grasses and are both decreasers. Ranches 1, 4, and 6 had the highest PC of little bluestem and Ranches 1, 2, and 6 had the highest PC of big bluestem.

Figures 13 and 14 show the mean PC of invader and decreaser plant species. A comparison of relative amounts of invader and decreaser plant species indicates Ranch 3 had the highest PC of invader plant species and therefore exhibited traits often associated with poorer range conditions. Ranch 4 had the lowest PC of decreaser species and Ranch 6 had the highest. Ranch 1 had the second highest PC of decreaser plant species and the lowest PC of invader plant species. Using the range condition model from Dyksterhuis and the data provided in Figures 12, 13, and 14, Ranch 3 stands out with the poorest condition. The other 5 ranches

did not consistently rate as either good or poor but would be classified with higher range condition than Ranch 3.

Above-ground Net Primary Productivity (ANPP) is the amount of standing live biomass (g/m^2) produced annually by plants minus the amount of matter that is converted into energy for use in plant cellular respiration (Miller, 1979). Figure 15 shows the mean ANPP of all plant species combined on the six ranches collected. This figure shows ANPP for measurements made in July of 2002 and July of 2003. In July 2002, Ranch 5 had the highest amount of ANPP at 800 g/m^2 and Ranch 3 had the lowest at 178 g/m^2 . The average for this sample date was 464 g/m^2 . Ranches 1, 2, 4, and 6 were within one standard deviation of the mean, while Ranches 3 and 5 were not. In July, 2003, Ranch 6 had the highest amount of ANPP at 895 g/m^2 and once again Ranch 3 had the lowest at 418 g/m^2 . The average ANPP for this year was 599 g/m^2 and one SD = 193 g/m^2 . Ranch 6 was the only ranch that was not within one standard deviation from the mean for this year.

It is noteworthy that Ranch 5 was the only ranch without an increase in ANPP in 2003. In 2003, the overall mean ANPP of all ranches increased by 135 g/m^2 . Researchers (Knapp *et al.*, 2001; Barrett *et al.*, 2002; Vermeire *et al.*, 2009) have found that ANPP is strongly correlated with variations in seasonal precipitation. The precipitation data for the weather stations near this study area showed higher than average precipitation in late 2002 and early 2003. An increase in precipitation is the only major factor that is known to have changed between the two sample years. Since most of the precipitation in this region comes from isolated spring and summer thunderstorms, the amounts received across the area can vary widely and therefore the study sites within Ranch 5 may not have received as much rainfall as the other ranches used in the study area.

Figure 16 shows ANPP by four major growth forms: warm-season (C_4) grasses, cool-season (C_3) grasses, forbs, and woody/shrubs on the six ranches for July 2002 and 2003. In the study area, the month of July has the highest average temperatures (Figure 7). In July, 2002, all six ranches had more C_4 plant biomass than any other growth form. Ranches 1, 4, 5, and 6 had more C_4 grasses than the other three growth forms combined. This is an indication that these ranches were in better condition relative to Ranches 2 and 3. In 2003, Ranches 1 and 6 were the only ranches to have more C_4 biomass than any other growth form and to have more C_4 grass biomass than all other growth forms combined. Ranch 5 showed the most dramatic decrease in C_4 biomass between study years 2002 and 2003.

Figure 17 illustrates the mean Weediness Index for each of the six ranches. Ranches 2, 4, and 6 had a WI below the mean, while Ranches 3 and 5 had a WI above the mean. Ranch 1 had a WI that was similar to the mean. Ranch 3 was the only ranch that had a WI that was more than one standard deviation above or below the mean. Based on the WI, Ranch 3 had the poorest range condition at the time of this study. The other ranches had a WI that was not significantly different from the mean. According to the Weediness Index, these other ranches demonstrated better condition than Ranch 3.

Figure 18 shows the mean NDVI for July, 2002 ($NDVI_{2002}$), July, 2003 ($NDVI_{2003}$), and May, 2004 ($NDVI_{2004}$) for the six ranches in the study area. $NDVI_{2002}$ and $NDVI_{2003}$ are coincident with the collection of ANPP in July. $NDVI_{2004}$ was coincident with the collection of live PC in May. In the mixed-grass prairie, the July NDVI should be a relative measure of C_4 grasses and the NDVI collected in May should be a relative measure of C_3 grasses. The $NDVI_{2002}$ data varied from 0.38 (Ranch 3) to 0.52 (Ranches 4 and 6). The mean $NDVI_{2002}$ value was 0.47. The $NDVI_{2003}$ data varied from 0.33 (Ranch 3) to 0.51 (Ranch 6). The mean $NDVI_{2003}$

value was 0.43. The NDVI₂₀₀₄ data varied from 0.47 (Ranch 4) to 0.57 (Ranch 3) and the mean was 0.53.

SIMPLE CORRELATION ANALYSIS

ANPP and NDVI data were collected in July, 2002 and 2003 at the 20 sites across the six ranches within the study area. PC and NDVI data were collected in May of 2004 at each of the 20 sites within the study area. The data are reported in graphic form as linear regression analyses and summarized in Table 3. A number of statistically significant correlations are described in the following paragraphs.

Figure 19 shows the correlation and regression results for the relationship between NDVI₂₀₀₂ and NDVI₂₀₀₃ for each of the 20 sites. Results for the test were: $r = 0.79$, $df = 18$, $p < 0.05$ suggesting that factors influencing NDVI values, such as plant cover, remained somewhat constant between 2002 and 2003 for July. The r values for NDVI₂₀₀₂ and NDVI₂₀₀₃ compared to NDVI₂₀₀₄ were: $r = 0.23$, $df = 18$, $p < 0.05$ and $r = 0.13$, $df = 18$, $p < 0.05$, respectively. NDVI₂₀₀₄ was measured in May, whereas NDVI₂₀₀₂ and NDVI₂₀₀₃ were collected in July; therefore, the correlations between data for these dates show that NDVI taken during different parts of the growing season, in different years, had little correlation.

Figure 20 shows the correlation and regression results for the relationship between NDVI and live PC of plant species in May, 2004 for each of the 20 sites. Results for the test were: $r = 0.44$, $df = 18$, $p < 0.05$. This relationship was probably driven by the abundance of cool-season grasses that were present at many of the ranches. The phenology of cool-season grasses results in an early green-up time (May), which most likely explains the linkage between NDVI₂₀₀₄ and PC in May.

Figure 21 shows the correlation and regression results between NDVI and ANPP that were collected in July, 2002 and 2003 for each of the 20 sites. Results for the July, 2002 test were: $r = 0.75$, $df = 18$, $p < 0.05$ and for the July, 2003 test were: $r = 0.57$, $df = 18$, $p < 0.05$. These results indicate the strength of the relationship between NDVI and ANPP in the study area in July, 2002 and 2003 was statistically significant, but varied in strength between years from moderately strong to moderately weak.

Figure 22 shows the correlation and regression results for the relationship between NDVI₂₀₀₄ and WI in May, 2004 ($n = 20$) and between NDVI₂₀₀₄ and WI in May, 2004 ($n = 17$). The lower graph shows the results after removing three sample points from the analysis that appear to be outliers (see the points circled in the top figure). Results for the test on the 20 sites were: $r = 0.67$, $df = 18$, $p < 0.05$, and when the three potential outliers were removed, the results were: $r = 0.88$, $df = 15$, $p < 0.05$ ($r_{crit} = 0.48$).

CONCLUSIONS

The goal of this study was to determine if high-spatial resolution color infrared imagery could be used to characterize rangeland condition. To address this goal, the following objectives were fulfilled:

1. Evaluation of ocular estimates of biotic and abiotic cover within twenty sites on six ranches.
2. Evaluation of the correlation between NDVI and vegetation biomass and species composition.
3. Evaluation of the correlation between NDVI and a newly developed Weediness Index.

The major findings of this study are as follows:

NULL HYPOTHESIS (H_0) 1. There is no relationship between high-spatial resolution airborne multispectral measurements and live PC of plants.

Based on the results reported in Figure 20 that shows a relationship between NDVI and live plant cover, the first Null Hypothesis is rejected. Although the relationship was significant at $p \leq 0.05$, the strength of the model is weak ($r = 0.44$; $r^2 = 0.20$).

NULL HYPOTHESIS (H_0) 2. There is no relationship between high-spatial resolution airborne multispectral measurements and Above-ground Annual Net Primary Productivity.

Based on the results presented in Figure 21, the second Null Hypothesis is rejected. The strength of this relationship between the July 2002 NDVI and ANPP value was $r = 0.75$ ($r^2 = 0.57$). In the following year (July 2003), the relationship between NDVI and ANPP was $r = 0.57$ ($r^2 = 0.33$).

NULL HYPOTHESIS (H_0) 3. There is no relationship between high-spatial resolution airborne multispectral measurements and invasive plant species as measured using the Weediness Index.

Based on the results presented in Figure 22, the third Null Hypothesis is rejected. Regression results show the relationship between NDVI and the Weediness Index was $r = 0.67$ ($r^2 = 0.45$). The strength of this relationship was stronger when possible outliers in the dataset were removed yielding WI of $r = 0.88$ ($r^2 = 0.78$).

Rangeland managers have many unique challenges, most of which depend on the manager's access to reliable and timely information on current management practices and how these practices affect rangeland condition. Rangeland condition is difficult to measure because there is no standard quantitative method for recording or reporting the data. The use of VIs can be helpful when measuring rangeland condition. NDVI, a measure of greenness, is often used as a surrogate to measure total PC of plant species and ANPP. High NDVI values for both of these characteristics may indicate good rangeland condition. However, Ramsey (2004) warned against the "simplistic assumption that greener is better" suggesting instead that "An increase in greenness may mean an increase in annual weeds."

In this study, Ranch 3 had the highest NDVI and the highest WI. This is primarily due to the high PC of annual ragweed as measured in this study. Ragweed is an invasive plant species and is an indicator of poor rangeland condition. Therefore, in this study, the strong correlation between WI and NDVI was a better indicator of rangeland condition than the correlation between PC and NDVI.

The findings in this study demonstrate the value of using high-spatial resolution remote sensing measurements to assess rangeland condition and the need to understand the

biophysical factors influencing spectral characteristics. More work is needed on linking spectral measurements to weediness across a variety of land cover types and varying environmental conditions.

FIGURES

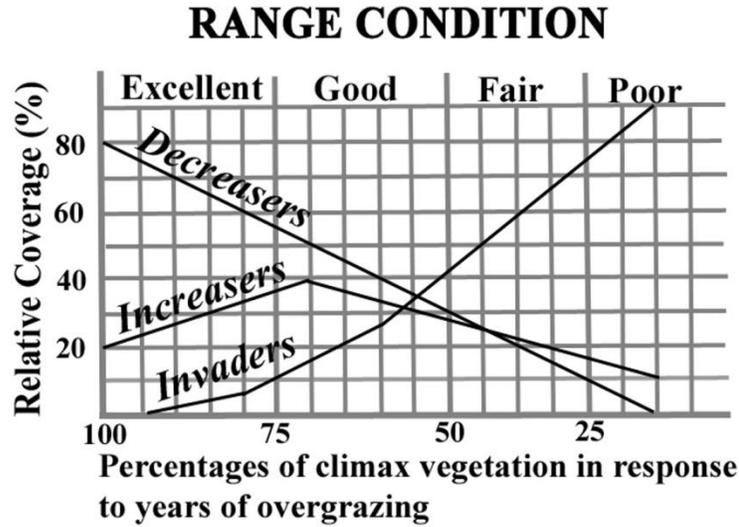


Figure 1. Diagram (Dyksterhuis, 1949) illustrating a quantitative basis for determining rangeland condition by PC of Increasers, Decreasers, and Invaders.

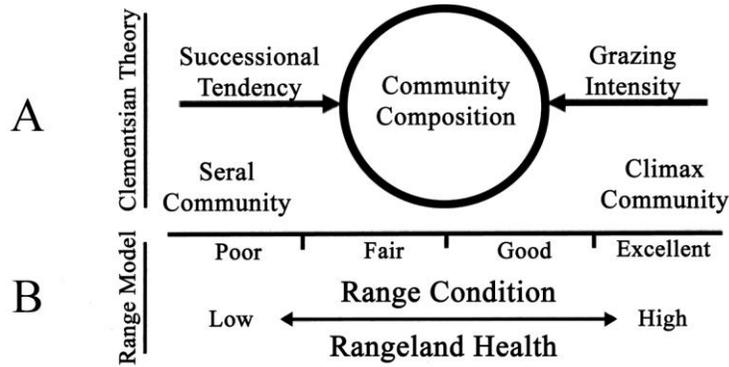


Figure 2. This figure shows the Clementsian (Succession) Model (A) compared to the Rangeland Model (B). The Clementsian Model shows how plant community composition is moved towards a seral community or towards a climax community by grazing intensity to the left (poor condition) and to the right by successional tendency (better condition). The Rangeland Model (B) shows from poor to excellent based on plant community composition. The Rangeland Model classes are often equated with rangeland health (Briske *et al.*, 2005).

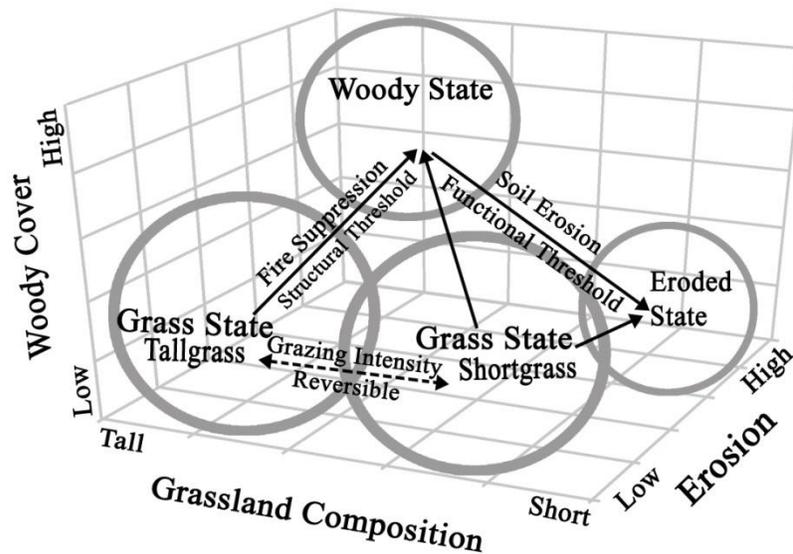


Figure 3. “Conceptual model of the multiple stable state concept illustrating selected stable states that may potentially occur on an individual site. Unique states are depicted as spheres within a three-dimensional volume that represents the potential of the site to support alternative states through time. The Rangeland model is founded on the single horizontal axis defined by succession and grazing intensity, which determines species composition in a grassland state (e.g., tall versus shortgrass structure). State-and-transition models accommodate greater complexity by describing vegetation dynamics in response to multiple drivers and by representing transitions to alternative stable states on individual ecological sites. Structural thresholds are defined by changes in species and growth form composition and spatial vegetation distribution, whereas functional thresholds signify changes in various ecosystem processes. Dashed and solid arrows depict reversible and nonreversible transitions, respectively” (Briske, *et al.*, 2005).

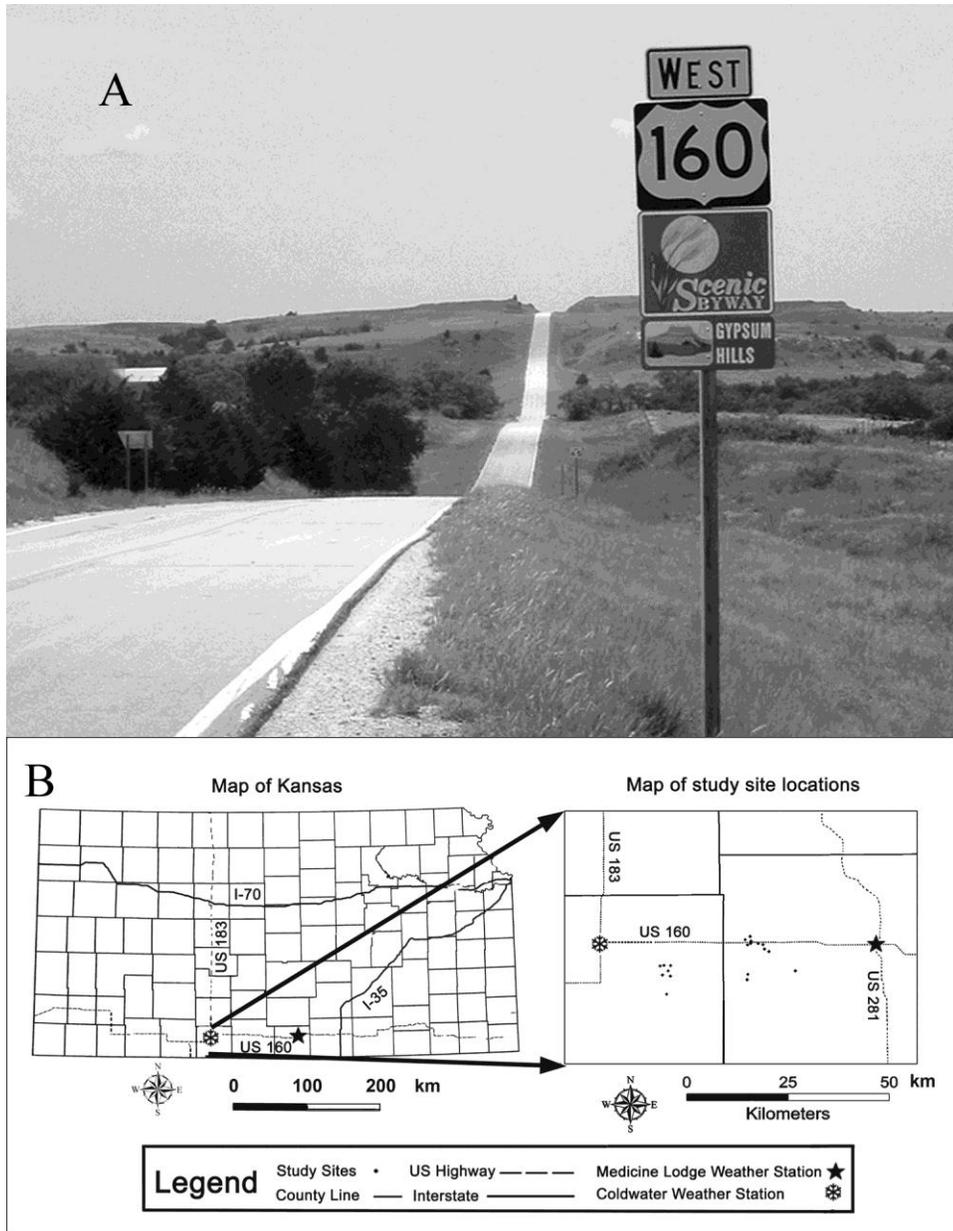


Figure 4. (A) Photograph taken July, 2004 looking west on US Highway 160 in Barber County, Kansas. This illustrates the rolling hills and general vegetation patterns associated with this region. (B) Study area in south-central Kansas including the location and distribution of study sites near Coldwater and Medicine Lodge, Kansas.



Figure 5. Pictures taken at three sites that illustrate various amounts of vegetation from the previous growing season. Picture A shows sparse - short heterogeneous vegetation with a relatively large amount of bare soil. Picture B shows dense - mixed height heterogeneous vegetation with a relatively small amount of bare soil. Picture C shows dense - tall homogeneous vegetation with almost no bare soil.

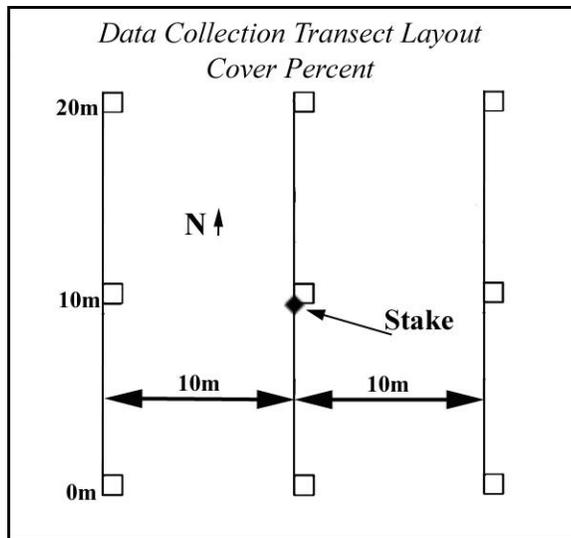


Figure 6. Transect layout for each of the 20 sites showing quadrat locations and orientation.

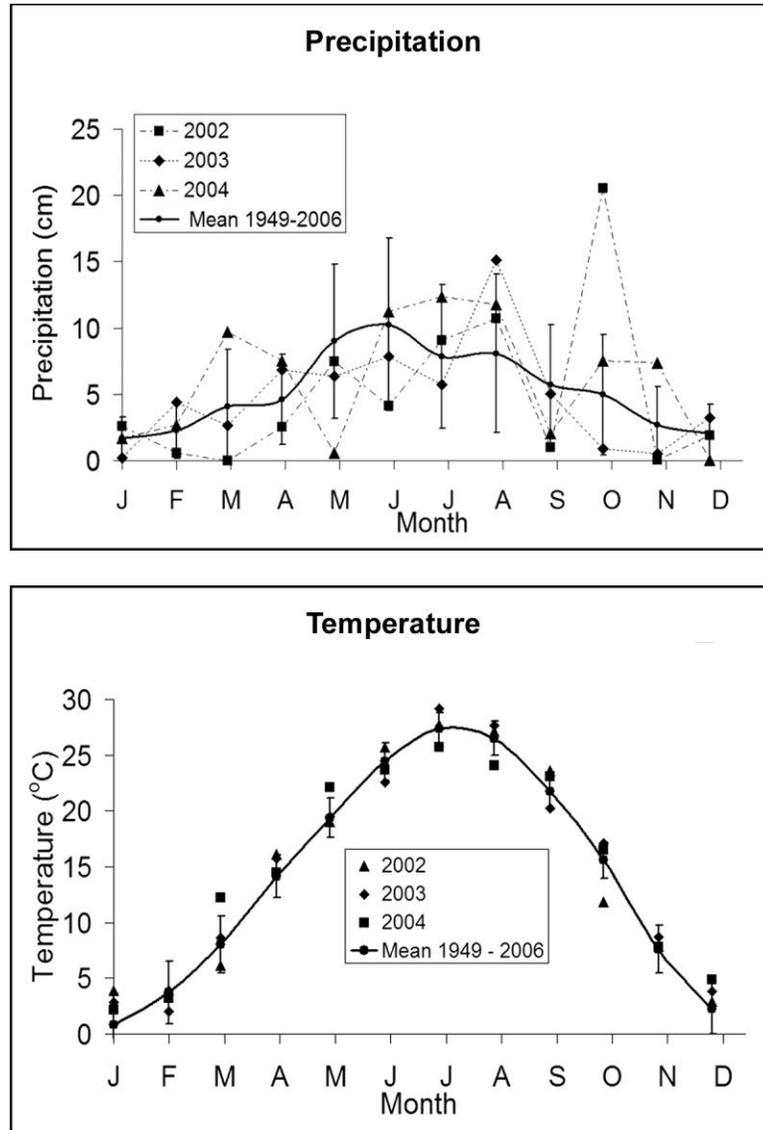


Figure 7. Mean and annual precipitation amounts per month and mean and annual temperatures for each month in Coldwater, Kansas which is closest to the study area.

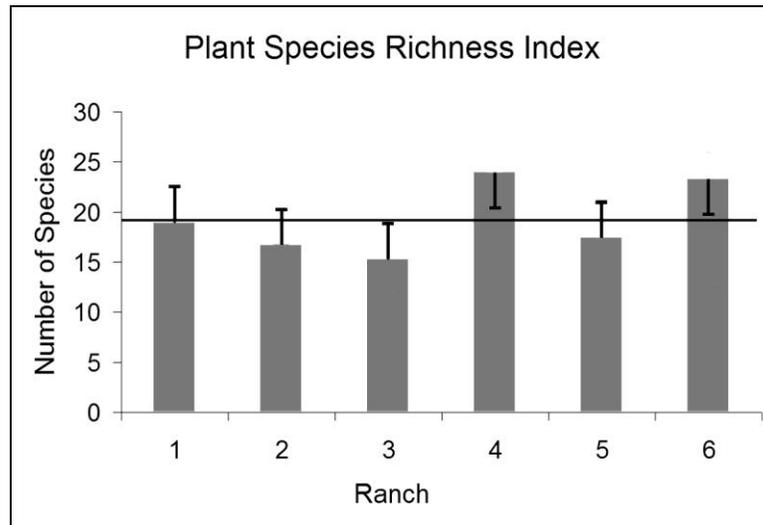


Figure 8. The mean Plant Species Richness for all ranches is 19.3 and is represented by the horizontal line. The black error bar indicates whether the ranch is within 1.0 standard deviation of the mean.

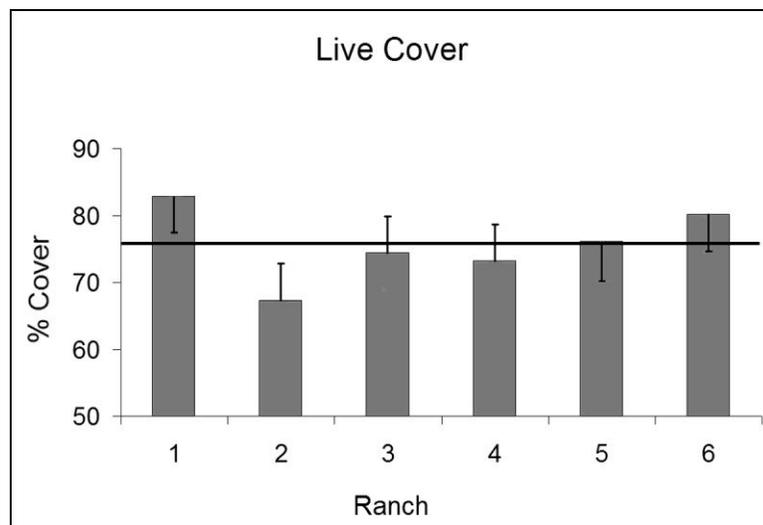


Figure 9. The mean percent live cover for all ranches is 76.0 and is represented by the horizontal line. The black error bar indicates whether the ranch is within 1.0 standard deviation of the mean. The remaining cover consisted of bare ground, rocks, cow dung, and dead plant litter.

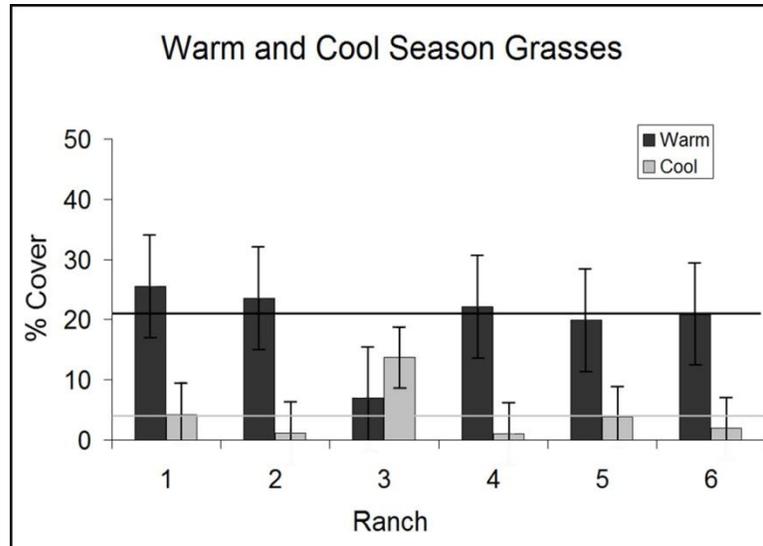


Figure 10. Mean plant cover occupied by warm and cool season grasses on each of the six ranches. Error bars show 1.0 standard deviation from the mean.

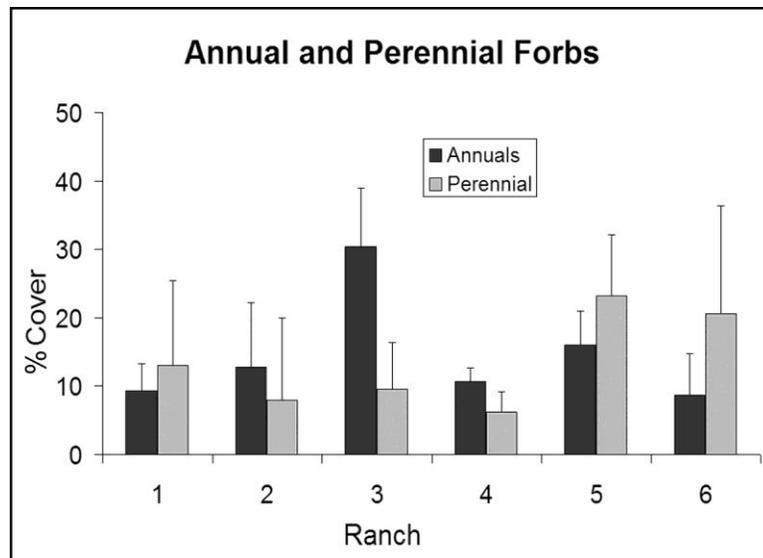


Figure 11. Mean cover of plants that are categorized as annual or perennial forbs. Error bars show 1.0 standard deviation from the mean.

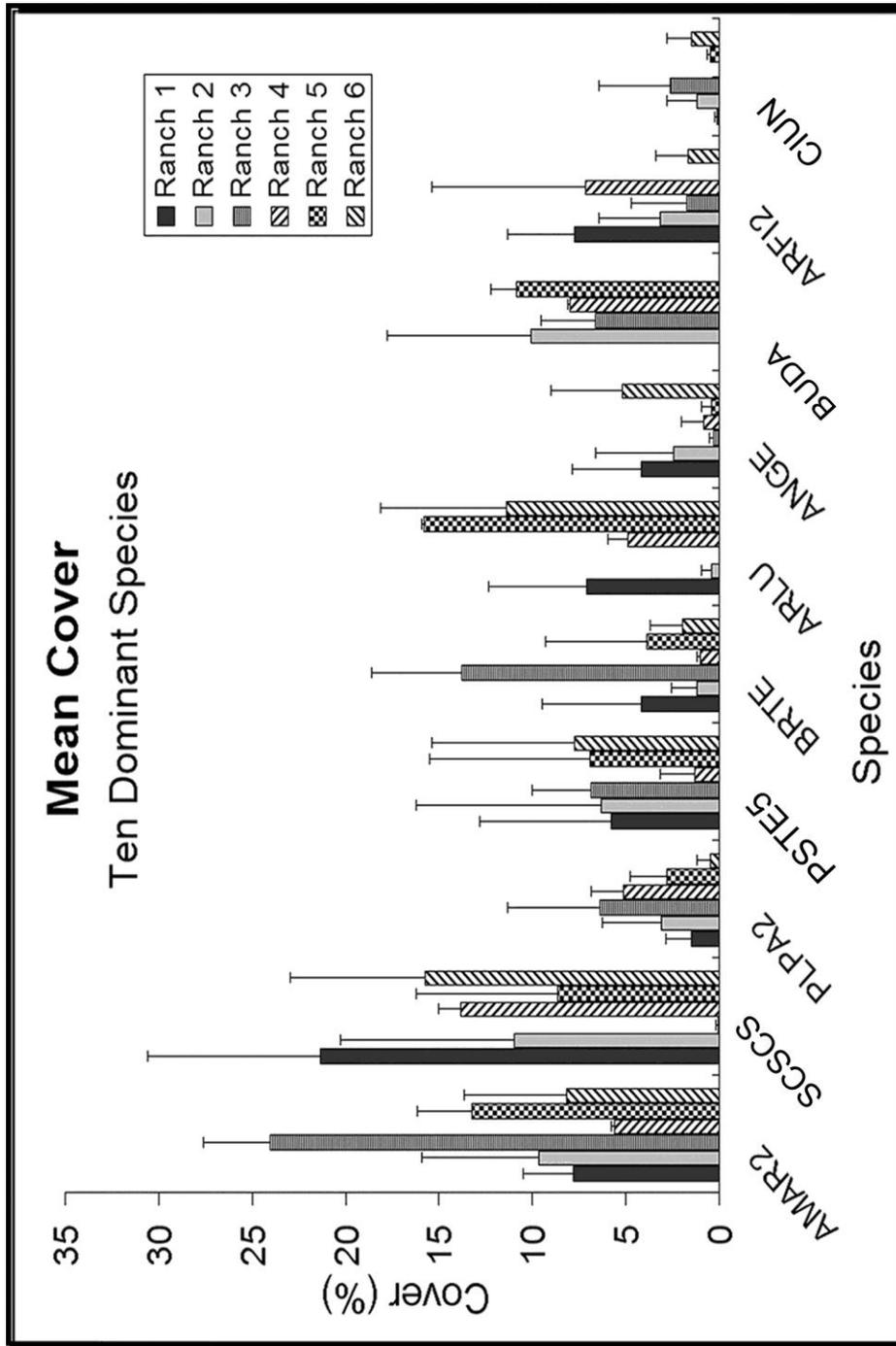


Figure 12. Mean plant cover of the 10 most common plant species in the study area for each of the six ranches. Error bars show 1.0 standard deviation from the mean. Complete information on plant species names and other characteristics are provided in Table 4.

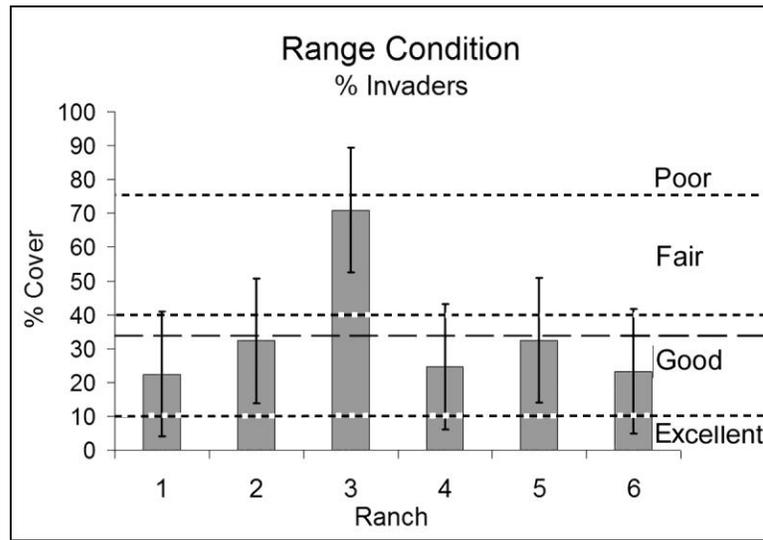


Figure 13. Mean cover of plant categorized as invader species. Refer to Figure 1 for the criteria used to establish the categorical break points shown as “Excellent,” “Good,” “Fair,” and “Poor” “range condition” as described by Dyksterhuis (1949). Error bars show 1.0 standard deviation from the mean.

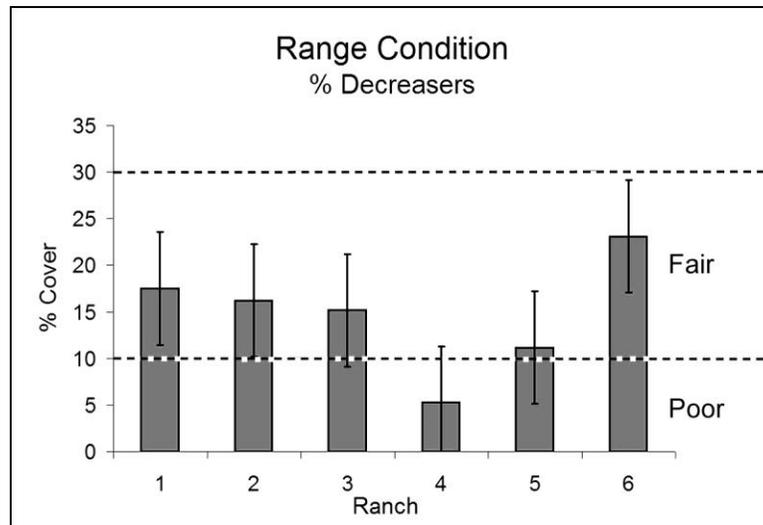


Figure 14. Mean cover of plants categorized as decreaser species. Refer to Figure 1 for the criteria used to establish the categorical break points shown as “Excellent,” “Good,” “Fair,” and “Poor” “range condition” as described by Dyksterhuis (1949). Error bars show 1.0 standard deviation from the mean.

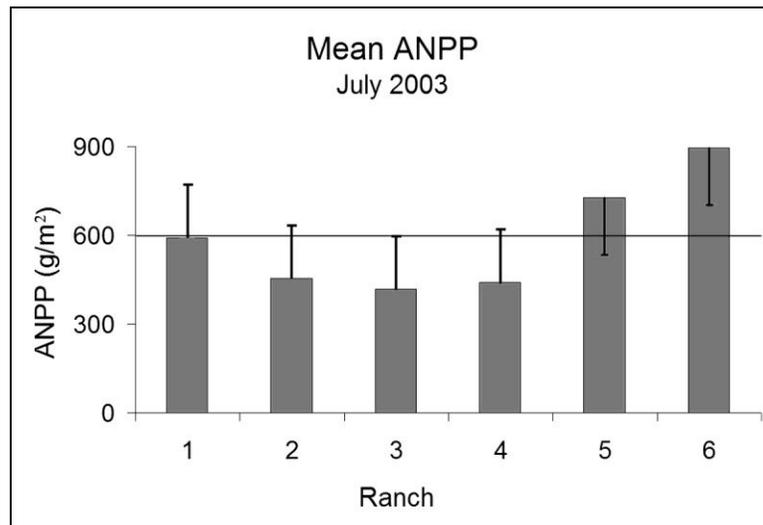
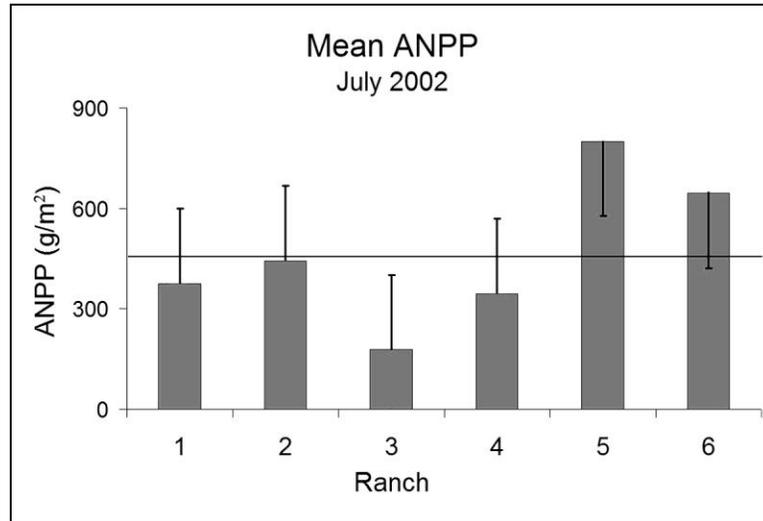


Figure 15. Mean ANPP of each of the six ranches for July, 2002 is 464 g/m^2 and July, 2003 is 599 g/m^2 indicated by the horizontal lines. The black error bars indicate whether the ranch is within 1.0 standard deviation of the mean.

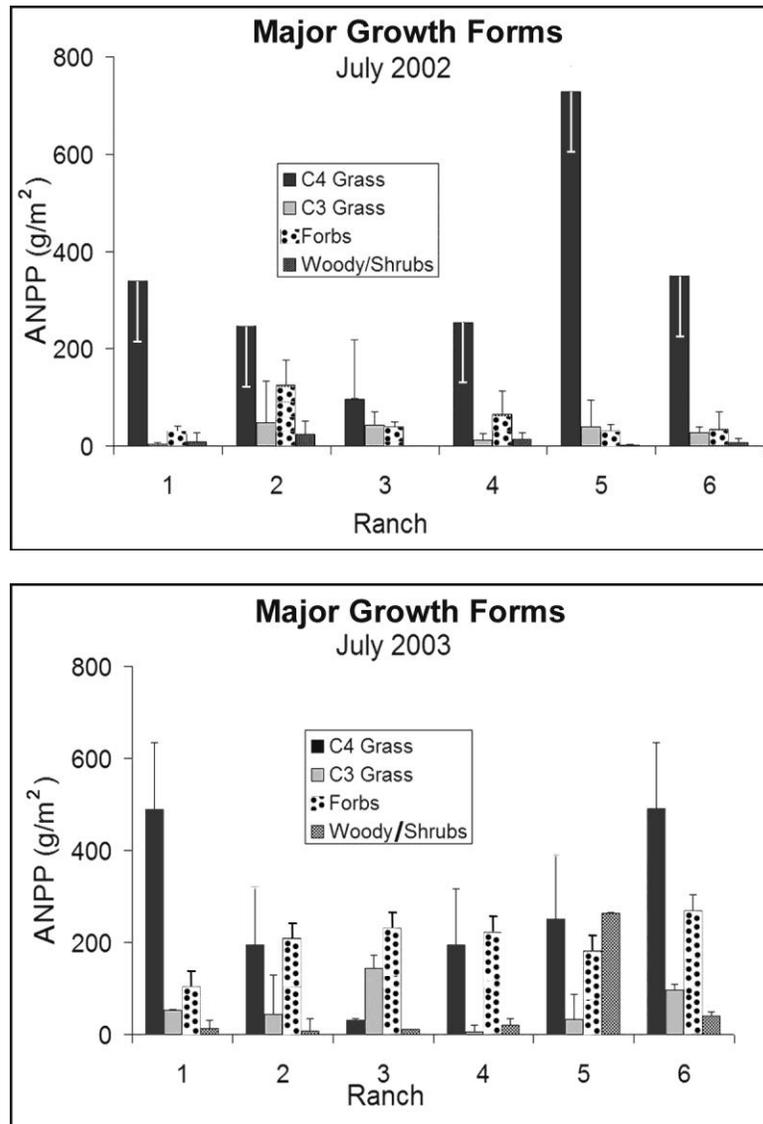


Figure 16. Mean ANPP of four growth forms for each of the six ranches for July, 2002 and July, 2003. Error bars show 1.0 standard deviation from the mean.

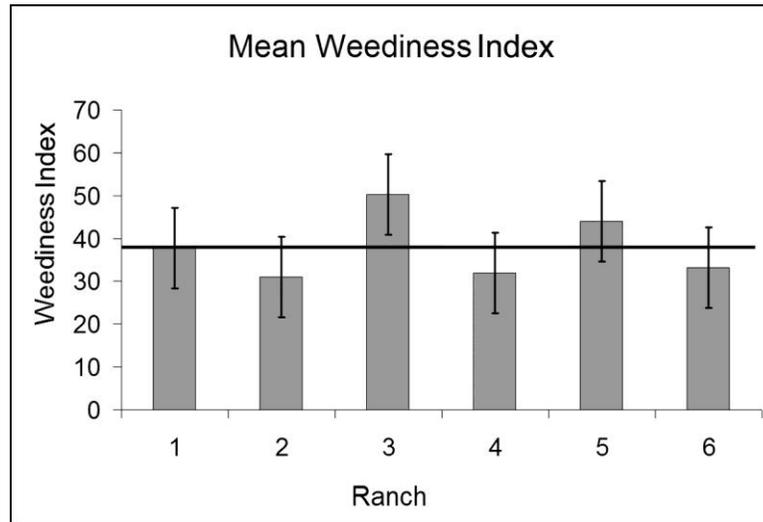


Figure 17. Mean Weediness Indices for each ranch. The dark horizontal bar shows the mean of all ranches and the error bars show 1.0 standard deviation. All ranches are within 1.0 standard deviation with Ranch 3 as the exception.

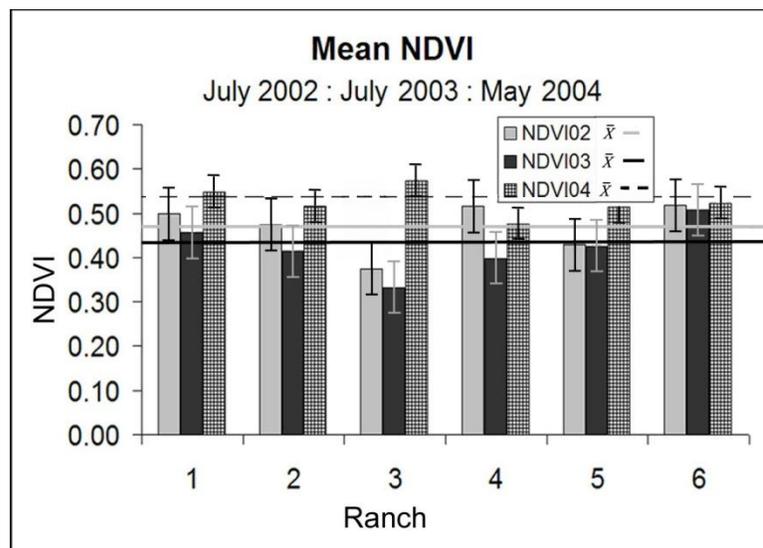


Figure 18. Mean NDVI values for each of the six ranches for July, 2002 and 2003, and May, 2004. The mean value for 2002 was 0.47, for 2003 was 0.43, and for 2004 was 0.53. The error bars show 1.0 SD. Data collection dates were selected to correlate with ground data collection dates.

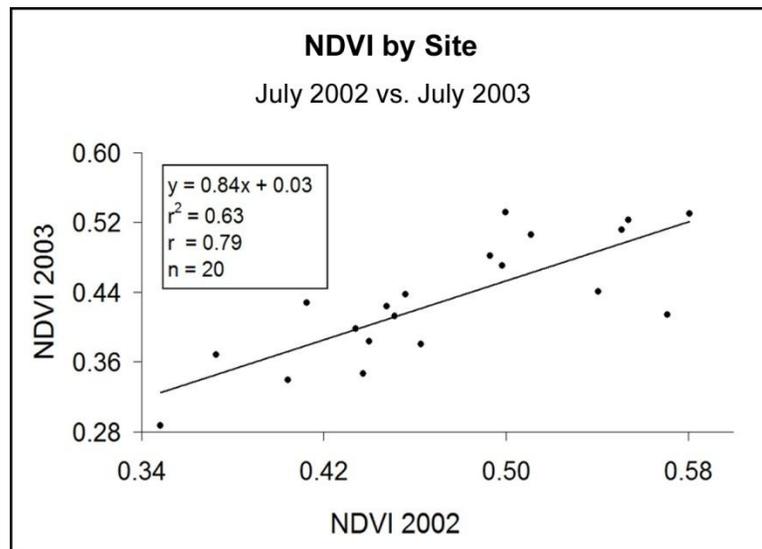


Figure 19. X-Y graph of the linear regression results for the relationship between mean NDVI values for July, 2002 and July, 2003 collected over 20 sites. The $r \geq r_{crit}$; therefore, the relationship is statistically significant at $p < 0.05$.

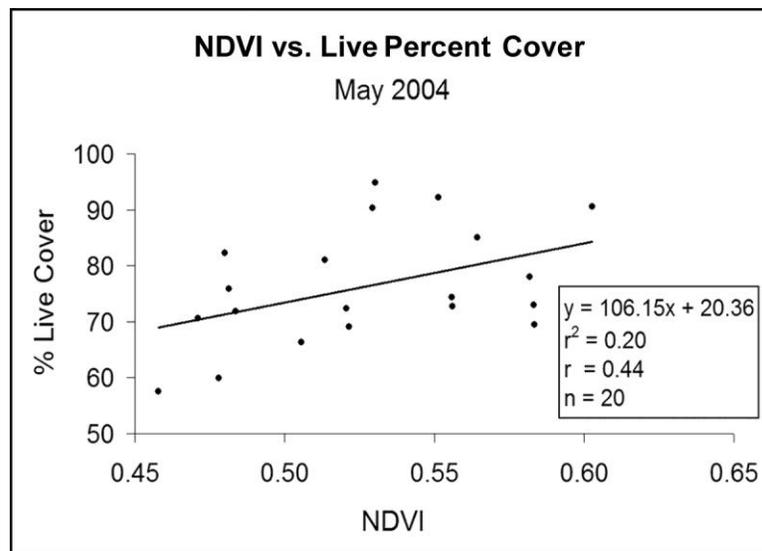


Figure 20. X-Y graph of the linear regression results for the relationship between percent living cover and NDVI for each of the 20 sites. The $r \geq r_{crit}$; therefore, the relationship is statistically significant at $p < 0.05$.

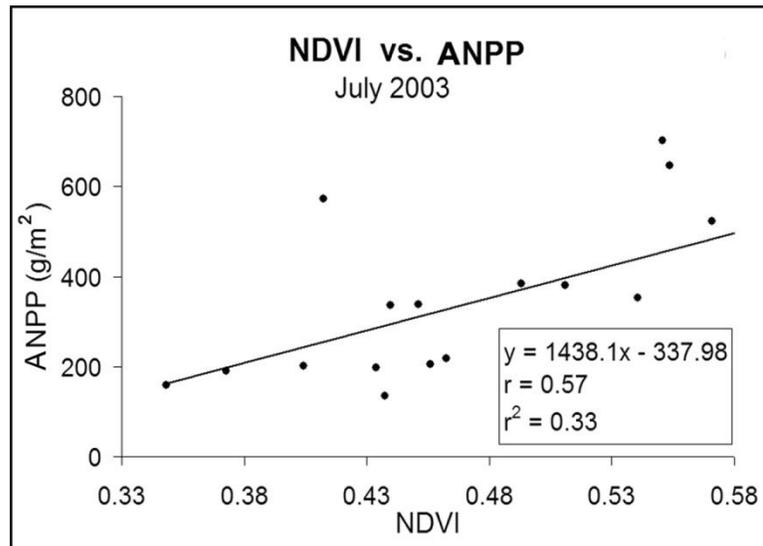
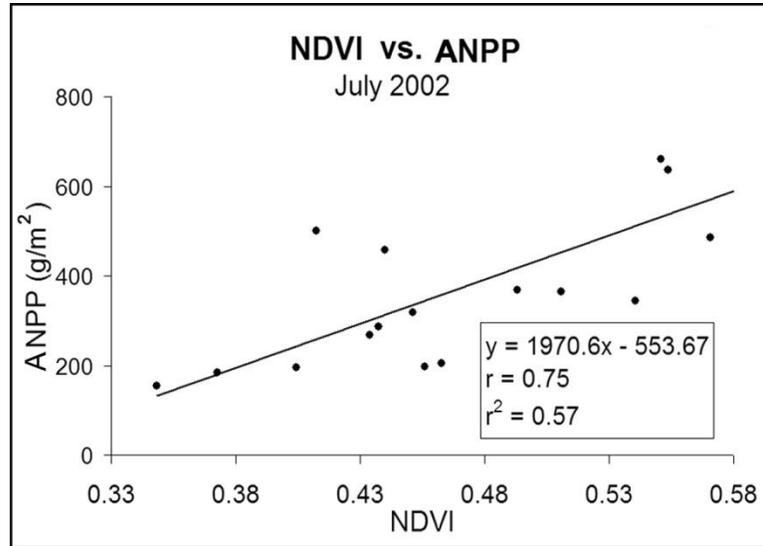


Figure 21. X-Y graph of the linear regression results for the relationship between mean NDVI values and ANPP for July, 2002 and July, 2003 collected over 20 sites. On both graphs, the $r \geq r_{crit}$; therefore, the relationships are statistically significant at $p < 0.05$.

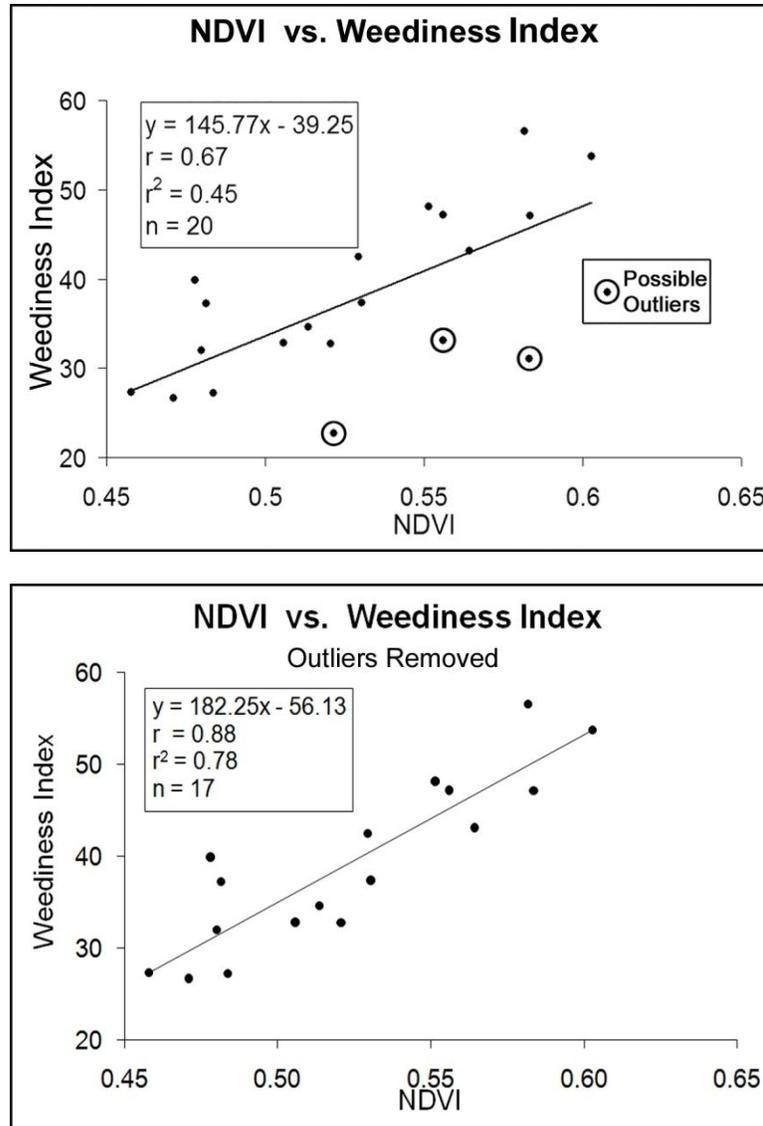


Figure 22. Top X-Y graph of the linear regression results for the relationship between WI and NDVI for each of the 20 sites in May, 2004. Bottom X-Y graph of the linear regression results for the relationship between WI and NDVI for each of 17 sites with three possible outliers removed. On both graphs, the $r \geq r_{crit}$; therefore, the relationships are statistically significant at $p < 0.05$.

TABLES

Table 1. Historical events affecting rangeland condition and assessment in chronological order. Parts of these summaries can be found in Holechek *et. al.* (1998), *ERS (2000).

Year	Event	Effects
1862	Homestead Act	Granted 160 acres after 5 years' residence; encouraged large numbers of people to move west for farming purposes.
1862	Morrill Act	Set up the land-grant colleges (provided land for these institutions)
1905	*Forest Service Created	The primary goal of the Reclamation program at that time was to develop the arid West by promoting farming opportunities for families and limiting speculation on land that would benefit from the introduction of irrigated agriculture.
1909	Enlarged Homestead Act	Granted 320 acres if one-fourth was cultivated; designed to promote farming on remaining federal land; caused rangeland destruction by cultivation of land not suited for farming.
1916	Stockraising Homestead Act	Granted 640 acres raising 50 cows; caused rangeland destruction because 640 acres would not support 50 cows in most areas.
1934	Taylor Grazing act	Allocated grazing privileges on unsold government lands in the West on the basis of the ranchers' ability to provide water (Southwest) or hay (Northwest); this act was passed as the result of actions by ranchers concerned about range deterioration.
1935	Soil Erosion Act	Set up Soil Conservation Service to deal with soil erosion problems on private lands.
1960	Multiple Use Act	Mandated that Forest Service lands be managed for several purposes rather than single use.
1969	National Environmental Policy Act	Required government and private agencies to draft Environmental Impact Statements on proposed actions that would affect federal lands.
1976	Federal Lands Policy and Management Act	Established rationale for keeping lands covered by Taylor Grazing Act in public ownership (Bureau of Land Management lands) and set up multiple use guidelines for these lands.
1978	Rangeland Improvement Act	Set aside 50% of grazing fee receipts from federal lands for range improvement on these lands
1985	Farm Bill	Government payments were provided to private landowners who planted their erodible lands to perennial grasses and retired them for 10 years with no grazing or haying. This program converted 35 million acres of cropland back to grassland.

Table 2. Modified Daubenmier cover class intervals with corresponding midpoint percentages. The midpoint value replaced the class number when correcting for total % cover for statistical analysis. The total % cover was adjusted so that the total = 100%.

class	interval	midpoint	class	interval	midpoint
1	= 1% - 2%	= 1.5%	6	= 39% - 50%	= 44.5%
2	= 3% - 5%	= 4.0%	7	= 51% - 65%	= 58.0%
3	= 6% - 15%	= 10.5%	8	= 66% - 85%	= 75.5%
4	= 16% - 25%	= 20.5%	9	= 86% - 95%	= 90.5%
5	= 26% - 38%	= 32.0%	10	= 96% - 100%	= 98.0%

Table 3. Summary of correlation statistics for Figures 19 – 22.

Figure #	Degrees of freedom (<i>df</i>)	R_{crit} at $p \leq 0.05$	Correlation Coefficient (<i>r</i>)	Significant Relationship
19	18	0.44	0.44	Yes
20	18	0.44	0.79	Yes
21(2002)	18	0.44	0.75	Yes
21(2003)	18	0.44	0.57	Yes
22	18	0.44	0.67	Yes
22	15	0.48	0.88	Yes

Table 4. List of plant species found throughout the study area. The plant species are ranked by their Presence X Frequency Index value located in the fifth column, 7500 is the highest value, and three is the lowest. A key for the column headings is provided in Table 5.

Rank	Scientific Name	Common Name	Symbol	P x F	Lng	G H	CC	CW	WF
1	<i>Ambrosia artemisiifolia</i>	ragweed	AMAR2	7500	A	T	0	2	0.17
2	<i>Schizachyrium scoparium</i>	little bluestem	SCSCS	6092	P	Hm	5	7	0.58
3	<i>Plantago patagonica</i>	wooly plantain	PLPA2	5119	ABP	Hm/T	1	3	0.25
4	<i>Psoralea tenuiflora</i>	scurfpea	PSTE5	4014	P	Hm	8	10	0.83
5	<i>Bromus tectorum</i>	cheat grass	BRTE	3214	A	T	*	1	0.08
6	<i>Artemisia ludoviciana</i>	white sage	ARLU	3000	P	C	2	4	0.33
7	<i>Andropogon gerardii</i>	big bluestem	ANGE	2583	P	Hm	4	6	0.50
8	<i>Buchloe dactyloides</i>	buffalograss	BUDA	1925	P	Hm	3	5	0.42
9	<i>Artemisia filifolia</i>	sand sagebrush	ARFI2	1822	P	P	3	5	0.42
10	<i>Cirsium undulatum</i>	wavyleaf thistle	CIUN	1408	BP	Hm	4	6	0.50
11	<i>Bouteloua curtipendula</i>	side-oats grama	BOCU	1156	P	Hm	5	7	0.58
12	<i>Aristida purpurea</i>	purple threeawn	ARPU9	1100	P	Hm	5	7	0.58
13	<i>Panicum oligosanthes</i>	Scribner's panicum	PAOL2	1039	P	Hm	4	6	0.50
14	<i>Gaillardia pulchella</i>	indian blanketflower	GAPU	800	AP	Hm/T	4	6	0.50
15	<i>Aster ericoides</i>	heath aster	ASER3	644	P	G	5	7	0.58
16	<i>Calylophus serrulatus</i>	evening primrose	CASE12	528	P	Hm	5	7	0.58
17	<i>Solidago mollis</i>	goldenrod	SOMO	525	P	G	5	7	0.58
18	<i>Bouteloua gracilis</i>	blue grama	BOGR2	506	P	Hm	5	7	0.58
19	<i>Liatris punctata</i>	dotted gayfeather	LIPU	422	P	G	5	7	0.58
20	<i>Ratibida columnifera</i>	prairie coneflower	RACO3	400	P	Hm	4	6	0.50
21	<i>Thelesperma megapotamicum</i>	slender greenthread	THME	331	P	Hm	4	6	0.50
22	<i>Cirsium ochrocentrum</i>	yellowspine thistle	CIOC2	289	P	Hm	4	6	0.50
23	<i>Astragalus mollissimus</i>	wooly locoweed	ASMOM5	233	P	Hm	4	6	0.50
24	<i>Carex brevior</i>	straw sedge	CABR10	217	P	Hm	8	10	0.83
25	<i>Gaura coccinea</i>	scarlet gaura	GACO5	194	P	Hm	4	6	0.50
26	<i>Hymenopappus scabiosaeus</i>	old plainsman	HYSC	167	B	Hm	4	6	0.50
27	<i>Lithospermum incisum</i>	hairy gromwell	LIIN2	133	P	Hm	5	7	0.58
28	<i>Panicum virgatum</i>	switchgrass	PAVI2	133	P	Hm	4	6	0.50
29	<i>Bromus japonicus</i>	Japanese brome	BRAR5	128	A	T	*	1	0.08
30	<i>Callirhoe involucrata</i>	purple poppymallow	CAIN2	111	P	Hm	1	3	0.25
31	<i>Opuntia macrorrhiza</i>	prickly pear	OPMA2	111	P	C	3	5	0.42

continued on next page

Table 4. continued

Rank	Scientific Name	Common Name	Symbol	P x F	Lng	G H	CC	CW	WF
32	<i>Monarda citriodora</i>	lemon beebalm	MOCI	108	AB	Hm/T	4	6	0.50
33	<i>Oxalis dillenii</i>	wood sorrel	OXDI2	97	P	C/T	2	4	0.33
34	<i>Erigeron strigosus</i>	daisy fleebane	ERST3	75	AB	Hm/T	4	6	0.50
35	<i>Asclepias viridis</i>	green milkweed	ASVI2	67	P	G	1	3	0.25
36	<i>Gutierrezia sarothrae</i>	broom snakeweed	GUTIE	67	P	P	3	5	0.42
37	<i>Tragia betonicifolia</i>	betonyleaf noseburn	TRBE4	67	P	Hm	5	7	0.58
38	<i>Panicum capillare</i>	witch grass	PACA6	56	A	T	0	2	0.17
39	<i>Sorghastrum nutans</i>	Indiangrass	SONU2	56	P	Hm	5	7	0.58
40	<i>Asclepias verticillata</i>	whorled milkweed	ASVE	42	P	G	1	3	0.25
41	<i>Andropogon saccharoides</i>	silver bluestem	BOLAT	33				2	0.17
42	<i>Bouteloua hirsuta</i>	hairy grama	BOHI2	28	P	Hm	6	8	0.67
43	<i>Prunus angustifolia</i>	sand plum	PRANA	25	P	P	3	5	0.42
44	<i>Dalea purpurea</i>	purple prairie clover	DAPU5	22	P	Hm	7	9	0.75
45	<i>Lotus purshianus</i>	deer vetch	LOUNU	22	A	T	3	5	0.42
46	<i>Festuca octoflora</i>	sixweeks fescue	FEOC3	17	P	Hm	4	6	0.50
47	<i>Yucca glauca</i>	yucca	YUGL	17	P	C	4	6	0.50
48	<i>Pleuraphis jamesii</i>	James' galetta (grass)	PLJA	17	P	Hm	7	9	0.75
49	<i>Digitaria sanguinalis</i>	crabgrass	DISA	14	A	T	*	1	0.08
50	<i>Krameria lanceolata</i>	ratany	KRAME	14	P	Hm	6	8	0.67
51	<i>Amorpha canescens</i>	leadplant	AMCA6	11	P	P	7	9	0.75
52	<i>Mimosa nuttallii</i>	catclaw sensitive briar	MINU6	11	P	Hm	6	8	0.67
53	<i>Commelina erecta</i>	erect dayflower	COER	8	P	Hm	4	6	0.50
54	<i>Echinacea angustifolia</i>	narrowleaf coneflower	ECAN2	8	P	Hm	6	8	0.67
55	<i>Dalea enneandra</i>	nineanther prairie clover	DAEN	6	P	Hm	5	7	0.58
56	<i>Polygala alba</i>	white milkwort	POAL4	6	P	Hm	6	8	0.67
57	<i>Croton texensis</i>	Texas croton	CRTET	3	A	T	1	3	0.25
58	<i>Cynodon dactylon</i>	Bermudagrass	CYDA	3	P	Hm	*	1	0.08
59	<i>Linum rigidum</i>	stiffstem flax	LIRI	3	A	T	5	7	0.58
60	<i>Machaeranthera pinnatifida</i>	cutleaf ironplant	MAPI	3	P	Hm	3	5	0.42
61	<i>Nothocalais cuspidata</i>	wavy-leaf false-dandelion	NOCU	3	P	Hm	7	9	0.75
62	<i>Packera plattensis</i>	groundsel	PAPL12	3	P	Hm	5	7	0.58
63	<i>Sporobolus cryptandrus</i>	sand dropseed	SPCR	3	P	Hm	0	2	0.17

Table 5. This table describes the column headings in Table 4.

Column Headings for Table 4					
Rnk	Rank	Commonness of plant species within the study area according to the Presence X Frequency Index			
Symbol	Assigned by NRCS	USDA, NRCS. 2009. The PLANTS Database (http://plants.usda.gov , 20 November 2009). National Plant Data Center, Baton Rouge, LA 70874-4490 USA			
P x F	Presence X Frequency	Product of presence and frequency			
Lng	Species longevity				
	A	annual			
	B	biennial			
	P	perennial			
	AB	annual-biennial			
	ABP	annual-biennial-perennial			
G H	Raunkiaer life form codes, assigned by KANU				
	C	chamaephyte (low shrubs and cushion plants with buds exposed above ground)			
	G	geophyte/cryptophyte (plants with rhizomes, tubers, or bulbs located well below)			
	He	helophytes (water or swamp plants protruding above the water surface but with)			
	Hm	hemicryptophyte (perennial and biennial herbs and graminoids with buds located)			
	Hy	hydrophytes (submerged or floating aquatic plants with winter buds at the bottom)			
	N	nanophanerophytes (woody plants with winter buds 0.10-0.25 m above ground)			
	P	phanerophyte (trees and tall shrubs with buds >0.25 m above ground)			
	T	therophyte (annual plants that survive unfavorable periods as seeds)			
CC	Coefficient of Conservatism Plant Stability				
	*	non-native species	Exotic taxa are all assigned a 0		
	0	weediest	tolerant of many different conditions,		
	5	intermediate			
	10	most conservative	plants with higher fidelity to specific habitats:		
CW	Coefficient of Weediness		CC	Weediness Factor (WF)	Weediness Index
	1		*	1/12 = 0.08	WI = WF x (% Cover)
	2		0	2/12 = 0.16	
	3		1	3/12 = 0.25	
	12		10	12/12 = 1.00	

Table 6. Table showing the 10 most common plant species and the data used to calculate the Weediness Index for each site.

Site Weediness Index

WF	0.92	0.5	0.83	0.25	1	0.75	0.58	0.67	0.67	0.58	Site WI =
Species	AMAR	SCSCS	PLPA	PSTE5	BRTE	ARLU	ANGE	BUDA	ARFI	CIUN	Sum (WF x % Cover)
Site	Weediness Factor X Mean Cover (%)										
1	5.06	9.15	3.40	3.75	11.10	2.48	2.49	0.00	5.49	0.17	43.10
2	8.10	5.95	1.25	0.80	0.00	2.10	4.81	0.00	4.22	0.00	27.23
3	8.83	13.70	0.58	0.15	10.50	11.33	0.17	0.00	8.31	0.17	53.74
4	10.21	5.20	0.83	0.00	0.00	4.50	4.81	0.00	7.57	0.00	33.13
5	7.36	13.50	0.25	0.33	3.50	9.08	0.00	0.00	3.35	0.00	37.36
6	3.68	16.60	1.16	3.63	0.00	2.48	2.32	0.00	2.14	0.00	32.01
7	0.28	10.55	0.42	5.28	2.60	0.53	5.05	0.60	5.36	2.09	32.74
8	10.58	3.60	5.40	0.00	0.00	0.75	0.35	10.85	0.87	0.41	32.80
9	12.14	0.00	4.23	0.45	2.10	0.00	0.00	11.19	0.67	0.23	31.02
10	12.51	7.80	0.17	0.60	0.00	0.00	0.23	4.42	1.54	0.06	27.33
11	25.85	0.00	1.99	2.05	19.10	0.00	0.23	3.28	0.00	4.06	56.57
12	19.78	0.00	9.88	0.83	9.70	0.00	0.00	6.70	0.00	0.29	47.17
13	20.70	0.10	4.07	2.28	12.60	0.00	0.29	3.35	3.48	0.23	47.10
14	5.27	7.34	5.26	0.00	1.15	4.24	0.00	5.27	8.70	0.00	37.24
15	5.08	6.47	3.21	0.65	0.87	3.12	0.98	5.41	0.88	0.00	26.68
16	14.08	1.65	3.49	0.20	0.00	11.78	0.46	7.91	0.00	0.35	39.91
17	10.30	7.00	1.16	3.25	7.70	11.93	0.00	6.63	0.00	0.17	48.15
18	9.95	11.88	0.13	1.89	2.65	10.44	3.55	0.00	0.63	1.33	42.45
19	1.76	6.84	0.00	3.86	3.23	12.40	4.88	0.00	0.31	1.30	34.58
20	10.86	4.87	1.07	0.05	0.00	2.83	0.56	0.00	2.45	0.00	22.69

BIBLIOGRAPHY

- Adams, J. M., 1999. A suggestion for an improved vegetation scheme for local and global mapping and monitoring. *Environmental Management*, 23(1):1-13.
- Anderson, G. L., J. D. Hanson, and R. H. Haas, 1993. Evaluating Landsat Thematic Mapper derived vegetation indices for estimating above-ground biomass on semiarid rangelands. *Remote Sensing of Environment*, 45(2):165-175.
- Asrar, G., R. L. Weiser, D. E. Johnson, E. T. Kanemasu, and J. M. Killeen, 1986. Distinguishing among tallgrass prairie cover types from measurements of multispectral reflectance. *Remote Sensing of Environment*, 19(2):159-169.
- Asrar, G., R. B. Myneni, Y. Li, and E. T. Kanemasu, 1989. Measuring and modeling spectral characteristics of a tallgrass prairie. *Remote Sensing of Environment*, 27(2):143-155.
- Barrett, J. E., R. L. McCulley, D. R. Lane, I. C. Burke, and W. K. Lauenroth, 2002. Influence of climate variability on plant production and N-mineralization in Central US grasslands. *Journal of Vegetation Science*, 13(3):383-394.
- Bartlett, D. S., G. J. Whiting, J. M. Hartman, 1989. Use of vegetation indices to estimate intercepted solar radiation and net carbon dioxide exchange of a grass canopy. *Remote Sensing of Environment*, 30(2):115-128.
- Bestelmeyer, B. T., J. R. Brown, K. M. Havstad, R. Alexandar, G. Chavez, and J. E. Herrick, 2003. Development and use of state-and-transition models for rangelands. *Journal of Range Management*, 56(2):114-126.
- Bhuyan, S. J., L. J. Marzen, J. K. Koelliker, J. A. Harrington, Jr., and P. L. Barnes, 2002. Assessment of runoff and sediment yield using remote sensing, GIS, and AGNPS. *Journal of Soil and Water Conservation*, 57(6):351-364.
- Booth, D. T., and P. T. Tueller, 2003. Rangeland monitoring using remote sensing. *Arid Land Research and Management*, 17:455-467.
- Booth, D. T., S. E. Cox, T. W. Meikle, and C. Fitzgerald, 2006. The accuracy of ground-cover measurements. *Rangeland Ecology & Management*, 59(2):179-188.
- Booth, D. T., S. E. Cox, T. Meikle, and H. R. Zuuring, 2008. Ground-cover measurements: Assessing correlation among aerial and ground-based methods. *Environmental Management*, 42:1091-1100.
- Bork, E. W., 1997. Rangeland condition assessment using high spatial and spectral resolution remote sensing. Ph.D. Dissertation, Department of Rangeland Resources, Utah State University, Logan, Utah, 299 p.

- Bork, E. W., N. E. West, and K. P. Price, 1998. In situ narrow-band reflectance characteristics of cover components in sagebrush-steppe. *Geocarto International*, 13(4):5-15.
- Bourdagh M., C. A. Johnston, and R. R. Regal, 2006. Properties and performance of the Floristic Quality Index in Great Lakes coastal wetlands. *Wetlands*, 26 (3):718-735.
- Box, T., 2003. The last 25 years: Changes & reflections. *Rangelands*, 25(6):31-35.
- Boyd, C. S., J. D. Bates, and R. F. Miller, 2007. The influence of gap size on sagebrush cover estimates with the use of line intercept technique. *Rangelands Ecology & Management*, 60:199-202.
- Brady, N. C., and R. R. Weil, 2002. *The Nature and Properties of Soils*. (13th ed). Upper Saddle River, NJ: Pearson Education Inc. 960 p.
- Breckenridge, R. P., W. G. Kepner, and D. A. Mouat, 1995. A process for selecting indicators for monitoring conditions of rangeland health. *Environmental Monitoring and Assessment*, 36:45-60.
- Briggs, J. M., and M. D. Nellis, 1991. Seasonal variation of heterogeneity in the tallgrass prairie: A quantitative measure using remote sensing. *Photogrammetric Engineering & Remote Sensing*, 57(4):407-411.
- Briske, D. D., S. D. Fuhlendorf, and F. E. Smeins, 2005. State-and-transition models, thresholds, and rangeland health: A synthesis of ecological concepts and perspectives. *Rangeland Ecology & Management*, 58(1):1-10.
- Buchanan, R. C., and J. R. McCauley, 1987. *Roadside Kansas: A Traveler's Guide to Its Geology and Landmarks*. Lawrence, KS: University Press of Kansas, Lawrence, Kansas, 365 p.
- Campbell, J. B., 2002. *Introduction to Remote Sensing*. (3rd ed) New York, NY: The Guilford Press, 621 p.
- Chapin, F. S., III, P. A. Matson, H. A. Mooney, 2002. *Principles of Terrestrial Ecosystem Ecology*. New York, NY: Springer-Verlag New York, Inc., 436 p.
- Cingolani, A. M., I. Noy-Meir, and S. Di'az, 2005. Grazing effects on rangeland diversity: A synthesis of contemporary models. *Ecological Applications*, 15(2): 757-773.
- Clements, F. E., 1916. *Plant succession: An analysis of the development of vegetation*. Publication 242, Carnegie Institute of Washington, Washington, D. C., 512 p.
- Clements, F. E., 1936. Nature and structure of the climax. *The Journal of Ecology*, 24(1):252-284.

- Cohen, M. J., S. Carstenn, and C. R. Lane, 2004. Floristic quality indices for biotic assessment of depressional marsh condition in Florida. *Ecological Applications* 14(3):784-794.
- Cully, A. C., J. F. Cully Jr., and R. D. Hiebert, 2003. Invasion of exotic plant species in tallgrass prairie fragments. *Conservation Biology*. 17(4):990-998.
- Curtis, J. T., 1959. *The Vegetation of Wisconsin*. Madison, WI: University of Wisconsin Press, 657 p.
- Daubenmire, R., 1959. A canopy-coverage method of vegetational analysis. *Northwest Science*, 33(1):43-64.
- Davidson, A., and F. Csillag, 2001. The influence of vegetation index and spatial resolution on a two-date remote sensing-derived relation to C4 species coverage. *Remote Sensing of Environment*, 75:138-151.
- DeKeyser, E. S., D. R. Kirby, and M. J. Ell, 2003. An index of plant community integrity: Development of the methodology for assessing prairie wetland plant communities. *Ecological Indicators*, 3(2):119-133.
- Dubayah, R., J. Dozier, and F. W. Davis, 1990. Topographic distribution of clear-sky radiation over the Konza Prairie, Kansas. *Water Resources Research*. 26(4):679-690.
- Dyer, M. I., C. L. Turner, and T. R. Seastedt, 1991. Mowing and fertilization effect on productivity and spectral reflectance in *Bromus Inermis* plots. *Ecological Applications*, 1(4):443-452.
- Dyksterhuis, E. J., 1949. Condition and management of range land based on quantitative ecology. *Journal of Range Management*, 2(3):104-115.
- Epiphanio, J. C. N., and A. R. Huete, 1995. Dependence of NDVI and SAVI on sun/sensor geometry and its effect on fAPAR relationships in alfalfa. *Remote Sensing of Environment*, 51:351-360.
- ESRI (2002). *Using ArcGIS Spatial Analyst*. Environmental System Research Institute, Inc. Redlands, CA, USA.
- Everitt, J. H., A. H. Gerbermann, M. A. Alaniz, and R. L. Bowen, 1980. Using 70-mm aerial photography to identify rangeland sites. *Photogrammetric Engineering & Remote Sensing*, 46(10):1339-1348.
- Freeman, C. C., and C. A. Morse. 2002. Kansas floristic quality assessment: Coefficients of conservatism for plants in southeast Kansas. Kansas Department of Health and Environment, Lawrence, Kansas, 15 p.
- Friedel, M. H., G. N. Bastin, and G. F. Griffin, 1988. Range assessment and monitoring in arid lands: The derivation of functional groups to simplify vegetation data. *Journal of Environmental Management*, 27(1):85-97.

- Friedel, M. H., 1991. Range condition assessment and the concept of thresholds: A viewpoint. *Journal of Range Management*, 44(5):422-426.
- Friedl, M. A., J. Michaelsen, F. W. Davis, H. Walker, and D. S. Schimel, 1994. Estimating grassland biomass and leaf area index using ground and satellite data. *International Journal of Remote Sensing*, 15(7):1401-1420.
- Goward, S. N., C. J. Tucker, and D. G. Dye, 1985. North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetatio*, 64:3-14.
- Graetz, R. D., R. P. Pech, and A. W. Davis. 1988. The assessment and monitoring of sparsely vegetated rangelands using calibrated Landsat data. *International Journal of Remote Sensing*, 9(7):1201-1222.
- Griffith, Jerry A., K. P. Price, and E. A. Martinko, 2001. A multivariate analysis of biophysical parameters of tallgrass prairie among land management practices and years. *Environmental Monitoring and Assessment*, 68:249-271.
- Guo, X., K. P. Price, and J. M. Stiles, 2000a. Biophysical and spectral characteristics of cool- and warm-season grasslands under three land management practices in eastern Kansas. *Natural Resources Research*, 9(4):321-331.
- Guo, X., K. P. Price, and J. M. Stiles, 2000b. Modeling biophysical factors for grasslands in eastern Kansas using Landsat TM data. *Transactions of the Kansas Academy of Science*, 103(3-4):122-138.
- Guo, X., K. P. Price, and J. Stiles, 2003. Grasslands discriminant analysis using Landsat TM single and multitemporal data. *Photogrammetric Engineering & Remote Sensing*, 69(11):1255-1262.
- Haferkamp, M. R., and M. D. MacNeil, 2004. Grazing effects on carbon dynamics in the northern mixed-grass prairie. *Environmental Management*, 33(Supp 1):S462-S474.
- Harris, A. T., and G. P. Asner, 2003. Grazing gradient detection with airborne imaging spectroscopy on a semi-arid rangeland. *Journal of Arid Environments*, 55:391-404.
- Heitschmidt, R. K., L. T. Vermeire, and E. E. Grings, 2004. Is rangeland agriculture sustainable? *Journal of Animal Science*, 82(E Supp):E138-E146.
- Holechek, J. L., 1993. Policy changes on federal rangelands: A perspective. *Journal of Soil and Water Conservation*, 48(3):166-174.
- Holechek, J. L., R. D. Pieper, and C. H. Herbel, 1998. Range Management: Principles and Practices. (3rd ed), Upper Saddle River, NJ: Prentice-Hall, Inc., 542 p.

- Huete, A. R., H. Q. Liu, K. Batchily, and W. van Leeuwen, 1987. A Comparison of Vegetation Indices over a Global Set of TM Images for EOS-MODIS. *Remote Sensing of Environment*, 25(2):185-199.
- Hunt, E. R., Jr., J. H. Everitt, J. C. Ritchie, M. S. Moran, D. T. Booth, G. L. Anderson, P. E. Clark, and M. S. Seyfried, 2003. Applications and research using remote sensing for rangeland management. *Photogrammetric Engineering & Remote Sensing*, 69(6):675-693.
- Hunt, E. R. Jr., and B. A. Miyake, 2006. Comparison of stocking rates from remote sensing and geospatial data. *Rangeland Ecology & Management*, 59(1):11-18.
- Irons, J. R., K. J. Ranson, and C. S. T. Daughtry, 1988. Estimating big bluestem albedo from directional reflectance measurements. *Remote Sensing of Environment*, 25(2):185-199.
- James, L. F., J. A. Young, and K. Sanders, 2003a. A new approach to monitoring rangelands. *Arid Land Research and Management*, 17(4):319-328.
- James, L. F., N. E. West, and J. A. Young, 2003b. Genesis of a new rangeland monitoring system. *Arid Land Research and Management*, 17:317-318.
- Jensen, M. E., R. L. Redmond, J. P. Dibenedetto, P. S. Bourgeron, and I. A. Goodman, 2000. Application of ecological classification and predictive vegetation modeling to broad-level assessments of ecosystem health. *Environmental Monitoring and Assessment*, 64:197-212.
- Jog, S., K. Kindscher, E. Questad, B. Foster, and H. Loring 2006. Floristic quality as an indicator of native species diversity in managed grasslands. *Natural Areas Journal*, 26(2):149-167.
- Joyce, L. A., 1993. The life cycle of the range condition concept. *Journal of Range Management*, 46(2):132-138.
- Keeton, W. T., 1980. *Biological Science*. 3rd Edition. New York, New York: W. W. Norton & Company, 1079 pp.
- Knapp, A. K., J. M. Briggs, and J. K. Koelliker, 2001. Frequency and extent of water limitation to primary production in a mesic temperate grassland. *Ecosystems*, 4(1):19-28.
- Kohler, R. E., 2008. Plants and pigeonholes: Classification as a practice in American ecology. *Historical Studies in the Natural Sciences*, 38(1):77-108.
- Korb, J. E., W. W. Covington, and P. Z. Fule, 2003. Sampling techniques influence understory plant trajectories after restoration: An example from Ponderosa pine restoration. *Restoration Ecology*, 11(4):504-515.

- Lauver, C. L. and J. L. Whistler, 1993. A hierarchical classification of Landsat TM imagery to identify natural grassland areas and rare species habitat. *Photogrammetric Engineering & Remote Sensing*, 59(5):627-634.
- Laycock, W. A., 1991. Stable states and thresholds of range condition on North American rangelands: A viewpoint. *Journal of Range Management*, 44(5):427-433.
- Laycock, W. A., 2003. Lessons from the past: Have we learned from our mistakes? *Arid Land Research and Management*, 17:359-367.
- Lewis, M., V. Jooste, and A. A. de Gasparis, 2001. Discrimination of arid vegetation with airborne multispectral scanner hyperspectral imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 39(7):1471-1479.
- Lopez, R. D., and M. S. Fennessy, 2002. Testing the floristic quality assessment index as an indicator to wetland condition. *Ecological Applications* 12(2):487-497.
- Loring, H., K. Kindscher, and M. Bullerman. 2000. An inventory of the Central Mixed-Grass Prairie ecoregion in Kansas, Oklahoma, and Nebraska. *Report No. 97*. Kansas Biological Survey, Lawrence, Kansas.
- MacDonald, G., 2003. *Biogeography: Introduction to Space, Time and Life*. New York, NY: John Wiley and Sons, Inc., 518 p.
- Mathews, S., and S. P. Bonser, 2005. Life histories, ecological tolerance limits, and the evolution of geographic range size in *Eucalyptus* (Myrtaceae). *Australian Journal of Botany*, 53(6):501-508.
- Miller, G. T., 1979. *Living in the Environment* (2nd ed). Belmont, CA: Wadsworth Publishing Company, 699 p.
- Myneni, R. B., and D. L. Williams, 1994. On the relationship between FAPAR and NDVI. *Remote Sensing of Environment*, 49(3):200-211.
- NRC (National Research Council), 1994. *Rangeland health: New methods to classify, inventory, and monitor rangelands*. Washington D. C.: National Academy Press, 180 p.
- Nouvellon, Y., M. S. Moran, D. L. Seen, R. Bryant, S. Rambal, W. Ni, A. Begue, A. Chehbouni, W. E. Emmerich, P. Heilman, and J. Qi, 2001. Coupling a grassland ecosystem model with Landsat imagery for a 10-Year simulation of carbon and water budgets. *Remote Sensing of Environment*, 78:131-149.
- Owensby, C. E., 1993. *Introduction to Range Management*. Manhattan, KS: Department of Agronomy, Kansas State University, 311 p.
- Paruelo, J. M. and R. A. Golluscio, 1994. Range assessment using remote sensing in northwest Patagonia (Argentina). *Journal of Range Management*, 47(6):498-502.

- Peterson, D. L., K. P. Price, and E. A. Martinko, 2002a. Discriminating between cool season and warm season grassland cover types in northeastern Kansas. *International Journal of Remote Sensing*, 23(23):5015-5030.
- Peterson, D. L., K. P. Price, and E. A. Martinko, 2002b. Investigating grazing intensity and range condition of grasslands in northeastern Kansas using Landsat Thematic Mapper data. *Geocarto International*, 17(4):13-23.
- Pickup, G., G. N. Bastin, and V. H. Chewings, 1994. Remote-sensing-based condition assessment for nonequilibrium rangelands under large-scale commercial grazing. *Ecological Applications*, 4(3):497-517.
- Pickup, G., G. N. Bastin, and V. H. Chewings, 2000. Measuring rangeland vegetation with high resolution airborne videography in the blue-near infrared spectral region. *International Journal of Remote Sensing*, 21(2):339-351.
- Pieper, R. D., and R. K. Heitschmidt, 1988. Is short-duration grazing the answer? *Journal of Soil and Water Conservation*, 43(2):133-137.
- Price, K. P., D. A. Pyke, and L. Mendes, 1992. Shrub dieback in a semiarid ecosystem: The integration of remote sensing and geographic information systems for detecting vegetation change. *Photogrammetric Engineering & Remote Sensing*, 58(4):455-463.
- Price, K. P., 1993. Detection of soil erosion within pinyon-juniper woodlands using Thematic Mapper (TM) data. *Remote Sensing of Environment*, 45(3):233-248.
- Pyke, D. A., and J. E. Herrick, 2003. Transitions in rangeland evaluations. *Rangelands*, 25(6):22-30.
- Ramsey, R. D., 2004. *Development of new approaches to rangeland monitoring and assessment of condition and trend*. Project Outline for Proposal: Utah Agricultural Experiment Station, 11p.
- Ramspott, M. E., 2006. *Remote sensing-based characterization of land management and biophysical factors in grassland* [Dissertation]. Lawrence, KS: University of Kansas, Publication Number: AAI3214812, 202p.
- Roberts, D. A., M. O. Smith, and J. B. Adams, 1993. Green vegetation, non-photosynthetic vegetation, and soils in AVIRIS data. *Remote Sensing of Environment*, 44(2-3):255-269.
- Robinove, C. J., 1982. Space platform albedo measurements as indicators of change in arid lands. *Advances in Space Research*, 2(8):31-35.
- Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering, 1974. Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings, Third Earth Resources Technology Satellite-1 Symposium*. NASA SP-351, Science and Technical

Information Office, Goddard Space Flight Center, NASA Washington, DC,
Greenbelt, MD: 1(A):309-317.

- Rowe, H. I., K. Maczko, E. T. Bartlett, and J. E. Mitchell, 2002. Sustainable rangelands roundtable. *Rangelands*, 24(6):3-6.
- Rowley, R. J., K. P. Price, and J. H. Kastens, 2007. Remote sensing and the rancher: Linking rancher perception and remote sensing. *Rangeland Ecology & Management*, 60(4):359-368.
- Running, S. W., R. R. Nemani, F. A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto, 2004. A continuous satellite-derived measure of global terrestrial primary production. *BioScience*, 54(6):547-560.
- Sampson, A. W., 1919. Plant succession in relation to range management. United States Department of Agriculture Bulletin No. 791 Washington, D.C: Government Printing Office.
- Sampson, R. N., 1981. *Farmland or Wasteland: A Time to Choose: Overcoming the Threat to America's Farm and Food Future*. Emmous, PA: Rodale Press, 439 p.
- Samson, F., and F. Knopf, 1994. Prairie conservation in North America. *BioScience*, 44(6):418-421.
- Scarnecchia, D. L., 1995. The rangeland condition concept and range science's search for identity: A systems viewpoint. *Journal of Range Management*, 48(2):181-186.
- Schiebe, F. R., D. A. Waits, J. H. Everitt, and J. Duncan, 2001. Evaluation of the SST crop reflectance imaging system. *Proceedings, 18th Biennial Workshop on Color Photography and Videography in Resource Assessment*, Amherst, MA.
- Schmidtlein, S., 2005. Imaging spectroscopy as a tool for mapping Ellenberg indicator values. *Journal of Applied Ecology*, 42:966-974.
- Smith, E. L., 2003. The struggle for a uniform monitoring system. *Arid Land Research and Management*, 17:347-358.
- Snyman, H. A., 1998. Dynamics and sustainable utilization of rangeland ecosystems in arid and semi-arid climates of southern Africa. *Journal of Arid Environments*, 39:645-666.
- SRM Task Group (Society for Range Management Task Group on Unity in Concepts and Terminology Committee, Society for Range Management), 1995. New concepts for assessment of rangeland condition. *Journal of Range Management*, 48(3):271-282.
- Stohlgren, T. J., K. A. Bull, and Y. Otsuki, 1998. Comparison of rangeland vegetation sampling techniques in the Central Grasslands. *Journal of Range Management*, 51(2):164-172.

- Stringham, T.K., W.C. Krueger, and P.L. Shaver, 2001. States, transitions, and thresholds: Further refinement for rangeland applications. Agricultural Experiment Station, Oregon State University, Special Report 1024, March 2001. 15p
- Stringham, T. K., W. C. Krueger, and P. L. Shaver, 2003. State and transition modeling: An ecological process approach. *Journal of Range Management*, 56(2):106-113.
- Swink, F., and G. Wilhelm. 1979. *Plants of the Chicago Region* (3rd edRev). Lisle, IL: Morton Arboretum.
- Taft, J. B., C. Hauser, and K. R. Robertson, 2006. Estimating floristic integrity in tallgrass prairie. *Biological Conservation*, 131:42-51.
- Tueller, P. T., C. D. Beeson, R. J. Tausch, N. E. West, and K. H. Rea, 1979. Pinyon-juniper woodlands of the Great Basin: Distribution, flora, vegetal cover. USDA, Forest Service, Research Paper INT-229, Washington, D.C., 22p.
- Tueller, P. T., P. C. Lent, R. D. Stager, E. A. Jacobsen, and K. A. Platou, 1988. Rangeland vegetation changes measured from helicopter-borne 35-mm aerial photography, *Photogrammetric Engineering & Remote Sensing*, 54(5):609-614.
- Tueller, P. T., 1989. Remote sensing technology for rangeland management applications. *Journal of Range Management*, 42(6):442-453.
- Turner, C. L., T. R. Seastedt, M. I. Dyer, T. G. F. Kittel, and D. S. Schimel, 1992. Effects of management and topography on the radiometric response of a tallgrass prairie. *Journal of Geophysical Research*, 97(D17):18855-18866.
- USDA, 1977. *Soil Survey of Barber County, Kansas*. United States Department of Agriculture Soil Conservation Service in Cooperation with the Kansas Agricultural Experiment Station, Washington, DC.
- USDA, 1989. *Soil Survey of Comanche County, Kansas*. United States Department of Agriculture Soil Conservation Service in Cooperation with the Kansas Agricultural Experiment Station, Washington, DC.
- USDA, 2002. National Resources Conservation Service. 2002 National Resources Inventory (NRI). *A statistical survey of land use and natural resource conditions and trends on U.S. non-Federal lands*. Available at: <http://www.nrcs.usda.gov/technical/NRI>
- USDA, 2003. National Resources Conservation Service, *National Range and Pasture Handbook*. U.S. Government Printing Office, Washington, DC.
- USDA, 2007. National Agricultural Statistics Service (NASS). *2007 Census Report*. Available at: http://www.agcensus.usda.gov/Publications/2007/Full_Report/index.asp

- USDA, 2009. Natural Resources Conservation Service, Available at:
<http://www.nrcs.usda.gov/programs/CRP>.
- USGAO, 1991. United States General Accounting Office, Report to the Chairman, Subcommittee on National Parks and Public Lands, Committee on Interior and Insular Affairs, House of Representatives, *Rangeland Management: Comparison of Rangeland Condition Reports*. Washington, D. C., 7 p.
- Ustin, S. L., J. B. Adams, C. D. Elvidge, M. Rejmanek, B. N. Rock, M. O. Smith, R. W. Thomas, and R. A. Woodward, 1986. Thematic Mapper studies of semiarid shrub communities. *BioScience*, 36(7):446-452.
- Vallentine, J. R., 1989. *Range Development and Improvements*. (3rd ed) San Diego, CA: Academic Press, Inc, 524 p..
- Vermeire, L. T., R. K. Heitschmidt, and M. J. Rinella, 2009. Primary productivity and precipitation-use efficiency in mixed-grass prairie: A comparison of northern and southern US sites. *Rangeland Ecology & Management*. 62(3):230-239.
- Weiser, R. L., G. Asrar, G. P. Miller, and E. T. Kanemasu, 1986. Assessing grassland biophysical characteristics from spectral measurements. *Remote Sensing of Environment*, 20(2):141-152.
- West, N. E., 2003a. Theoretical underpinnings of rangeland monitoring. *Arid Land Research and Management*, 17:333-346.
- West, N. E., 2003b. History of rangeland monitoring in the U.S.A. *Arid Land Research and Management*, 17:495-545.
- Westoby, M., B. Walker, and I. Noy-Meir, 1989. Opportunistic management for rangelands not at equilibrium. *Journal of Range Management*, 42(4):266-274.
- Winslow, S. R., and B. F. Sowell, 2000. A comparison of methods to determine plant successional stages. *Journal of Range Management*, 53(2):194-198.
- Worster, D., 1979. *Dust Bowl: The Southern Plains in the 1930's*. New York, NY: Oxford University Press, 277 p.
- Wylie, B. K., D. J. Meyer, L. L. Tieszen, and S. Mannel, 2002. Satellite mapping of surface biophysical parameters at the biome scale over the North American grasslands: A case study. *Remote Sensing of Environment*, 79:266-278.