Near real-time satellite and ground based radiometric estimation of vegetation biomass, and nitrogen content in Montana rangelands
by David P Thoma

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
New methods for assessing rangeland forage quantity and quality are needed. These methods should cover large areas and provide periodic coverage several times during a grazing season. This study evaluates the Normalized Difference Vegetation Index (NDVI), derived from two radiometric sensors (MSR16 and AVHRR), for estimating forage biomass, and nitrogen content. It also evaluates a visual method for estimating biomass, and correlates forage quality, as measured by fecal analysis, with AVHRR-NDVI.

Plots in seven Montana grassland study areas were sampled for change in live and dead biomass as well as vegetation nitrogen content through the 1997 growing season. Vegetation was clipped on bi-weekly or monthly intervals, then dried, weighed and analyzed for nitrogen content. Linear regression of biomass components and nitrogen content on AVHRR-NDVI provides correlation coefficients for comparison.

Clipped plots were used as a standard for testing a boom-mounted radiometer (MSR16) NDVI and a visual technique for estimating live, dead and total above ground biomass. Clipped biomass components and vegetation nitrogen content were regressed on MSR16-NDVI and visual estimates of biomass components.

Fecal samples from cattle herds were collected on a biweekly basis and analyzed for crude protein, digestible organic matter, and animal unit equivalent, which were regressed on AVHRR-NDVI pixel values for dates and locations corresponding to fecal sample collection.

AVHRR-NDVI has a strong correlation with live biomass ($r^2 = 0.637$) for six grassland areas when live biomass was below 1800 kg/ha. The strongest correlation with five biomass for an individual study area was $r^2 = 0.715$. AVHRR-NDVI did not correlate well with dead biomass ($r^2 = 0.206$) at any level, or vegetation nitrogen content ($r^2 = 0.034$).

The MSR16-NDVI and visual estimates had moderate to strong correlation with live biomass ($r^2 = 0.579$ and 0.825 respectively). The MSR16-NDVI estimated live biomass better when data were grouped by month ($r^2 = 0.756$ for June, $r^2 = 0.646$ for July, and $r^2 = 0.686$ for August). Correlation coefficients for the models estimating dead biomass were 0.073 and 0.663 for MSRl6-NDVI and visual estimate respectively. The MSR16-NDVI does not correlate well with vegetation nitrogen content ($r^2 = 0.042$). MSR16-NDVI plot values averaged for large areas (9 km^2) correlated strongly with AVHRR-NDVI for the corresponding area and time ($r^2 = 0.845$).

We found a strong relationship ($r^2 = 0.62$) between animal unit equivalent, determined by fecal analysis, and AVHRR-NDVI. Crude protein content and digestible organic matter, determined by fecal analysis, did not correlate strongly with AVHRR-NDVI.

NEAR REAL-TIME SATELLITE AND GROUND BASED RADIOMETRIC ESTIMATION OF VEGETATION BIOMASS, AND NITROGEN CONTENT IN MONTANA RANGELANDS

by

David P. Thoma

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Soils

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

April 1998

APPROVAL

of a thesis submitted by

David P. Thoma

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Cliff Montagne ______________________ April 22, 1998
Date

Approved for the Department of Plant, Soil and Environmental Sciences

Jeffrey S. Jacobsen ______________________ 4/23/98
Date

Approved for the College of Graduate Studies

Joseph J. Fedock ______________________ 4/24/98
Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature David Thoma

Date April 22, 1998

ACKNOWLEDGMENTS

I thank Cliff Montagne, Jerry Nielsen, Henry Shovic, Gordon Brittan, Dan Long, Bill Quimby and Derek Bailey for advice throughout this project. Much credit goes to Mari Henry for image processing, clipping and encouragement. I especially appreciate Meagan Breneman's tremendous effort in all aspects of the project from field work to data analysis. Thanks also to Elizabeth Roberts for computer support. I want to thank Matt Ricketts for help with fecal analysis and patience in explaining how it works as a management tool. Thanks to Connie Williams and Kristin Gerhart for GIS support, and Eric Compas for GIS support and field work. Clain Jones provided stimulating discussion and many excellent suggestions along the way.

Thank you Doug and Zena Ensign, Don Ross, Warren Lybeck, and Jeff Hockett for allowing us to work on your land. Thank you Deb Habernicht for help running the Leco furnace. Thank you Sonja Skovlin, Arsil Saleh, Meagan Breneman, and Beth Miller for describing soil profiles. Thank you Julie Thoma, Ivan Legg, Dan McAvoy, Darren Sackman, Tracy Higgens, Chad Ferguson, Shane Porter, Northern Agricultural Research Center staff, Tom Oliniki, Steve Bay, Lori and Tommy Compas for help collecting and processing samples.

Funding for this project was provided by the Upper Midwest Aerospace Consortium, Montana Space Grant, MSU Mountain Research Center, the Department of Plant, Soils and Environmental Sciences, and the Natural Resources Conservation Service.

Finally, I extend my enduring gratitude to Kristin Legg for unwavering emotional support, encouragement, and a willingness to listen.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES - Continued

ABSTRACT

New methods for assessing rangeland forage quantity and quality are needed. These methods should cover large areas and provide periodic coverage several times during a grazing season. This study evaluates the Normalized Difference Vegetation Index (NDVI), derived from two radiometric sensors (MSR16 and AVHRR), for estimating forage biomass, and nitrogen content. It also evaluates a visual method for estimating biomass, and correlates forage quality, as measured by fecal analysis, with AVHRR-NDVI.

Plots in seven Montana grassland study areas were sampled for change in live and dead biomass as well as vegetation nitrogen content through the 1997 growing season. Vegetation was clipped on bi-weekly or monthly intervals, then dried, weighed and analyzed for nitrogen content. Linear regression of biomass components and nitrogen content on AVHRR-NDVI provides correlation coefficients for comparison.

Clipped plots were used as a standard for testing a boom-mounted radiometer (MSR16) NDVI and a visual technique for estimating live, dead and total above ground biomass. Clipped biomass components and vegetation nitrogen content were regressed on MSR16-NDVI and visual estimates of biomass components.

Fecal samples from cattle herds were collected on a biweekly basis and analyzed for crude protein, digestible organic matter, and animal unit equivalent, which were regressed on AVHRR-NDVI pixel values for dates and locations corresponding to fecal sample collection.

AVHRR-NDVI has a strong correlation with live biomass ($r^2 = 0.637$) for six grassland areas when live biomass was below 1800 kg/ha. The strongest correlation with live biomass for an individual study area was $r^2 = 0.715$. AVHRR-NDVI did not correlate well with dead biomass ($r^2 = 0.206$) at any level, or vegetation nitrogen content ($r^2 = 0.034$).

The MSR16-NDVI and visual estimates had moderate to strong correlation with live biomass ($r^2 = 0.579$ and 0.825 respectively). The MSR16-NDVI estimated live biomass better when data were grouped by month ($r^2 = 0.756$ for June, $r^2 = 0.646$ for July, and $r^2 = 0.686$ for August). Correlation coefficients for the models estimating dead biomass were 0.073 and 0.663 for MSR16-NDVI and visual estimate respectively. The MSR16-NDVI does not correlate well with vegetation nitrogen content ($r^2 = 0.042$). MSR16-NDVI plot values averaged for large areas (9 km^2) correlated strongly with AVHRR-NDVI for the corresponding area and time ($r^2 = 0.845$).

We found a strong relationship ($r^2 = 0.62$) between animal unit equivalent, determined by fecal analysis, and AVHRR-NDVI. Crude protein content and digestible organic matter, determined by fecal analysis, did not correlate strongly with AVHRR-NDVI.

CHAPTER 1

INTRODUCTION

The National Aeronautic and Space Administration (NASA) and National Oceanographic and Atmospheric Administration (NOAA) have been providing space imagery of Earth features since 1972. These products have been used for mapping, urban planning, oceanographic and atmospheric research, as well as agriculture and environmental monitoring. The abundance of remotely sensed information is currently under-utilized and new applications await discovery and implementation. Recent efforts have been stepped-up to create public access to data and technology that can provide for more applications. Making such technology readily available to the public allows determination of its usefulness for resource monitoring. Remotely sensed data must first be accessible before it can be assessed for user needs. NASA's Mission to Planet Earth (MTPE) and the Fund for Rural America (FRA) help address these needs through access channels and applied research (Nielsen, pers. comm.). Public Access Resource Centers (PARC's) are similarly designed to deliver data and applications to the public (Seielstad *et al.*, 1996).

In this work we investigate a PARC objective for using Advanced Very High Resolution Radiometer derived Normalized Difference Vegetation Index satellite imagery (AVHRR-NDVI) for monitoring rangeland resources. Our goal is to test the estimation capability of AVHRR-NDVI to estimate forage nitrogen content (quality) and biomass (quantity) on a ranch scale (1-9 km^2) as it changes over a growing season.

AVHRR-NDVI has high spectral resolution, but low spatial resolution (1 km^2). It is available on a bi-weekly basis for tracking rapid natural and human induced change on landscape or broader scales. An NDVI is calculated as a reflectance intensity ratio of near infrared and red electromagnetic energy. Due to its frequent availability AVHRR-NDVI has promise for tracking relatively rapid change in vegetation as the growing season progresses. It is a forerunner to more advanced remote sensing systems that will soon supply data at higher spatial and spectral resolution (Nelson 1997; Wanzel 1998).

Private land owners, the Natural Resource Conservation Service (NRCS), and other agencies are interested in rapid assessment of large areas for forage quality and quantity. In 1996 private ranchers and the NRCS began working together to initiate a fecal analysis program for forage quality assessment. We decided then to look for relationships between AVHRR-NDVI and results from fecal analysis to see if AVHRR-NDVI might be useful in areas where fecal analysis was not used.

Radiometric techniques for estimating vegetation quality and quantity may prove useful in determining grazing duration and stocking density in pastures, stage of range readiness for grazing, and year to year changes in climate (Richardson and Everitt 1992). These techniques could be used in grazing programs to help determine rates of biomass consumption then other data sources are not available.

In the process of evaluating AVHRR-NDVI for ranch-level range assessment we increased the sample size of data collected on the ground by double-sampling. Double-sampling involves sampling a population by two methods, one of which provides data directly, and another, faster method, which provides data highly correlated to that collected directly (Piepper 1978; Wilm *et al.*, 1944).

The double sampling method included use of a boom mounted spectral radiometer (MSR16) (Cropscan Inc. 1995) and visual estimates of live and dead above-ground biomass components. Like AVHRR-NDVI, MSR16-NDVI is calculated as a reflectance intensity ratio in the near infrared and visible red wave bands. The MSR16 is portable and quick for estimating vegetation parameters. We also used visual estimates for double-sampling. Neither of the double sampling approaches improved correlations between AVHRR-NDVI and data collected on the ground. MSR16-NDVI and visual estimates were tested independently of AVHRR-NDVI for estimating parameters of interest on small plot scales.

In chapter two we quantitatively investigate the ability of AVHRR-NDVI to estimate rangeland above-ground biomass and nitrogen content at discrete points in time emphasizing AVHRR-NDVI ability to detect change over time. Chapter three focuses on the comparisons of MSR16-NDVI, AVHRR-NDVI, and visual estimates to estimate biomass and nitrogen content of vegetation. Chapter four compares AVHRR-NDVI to beef cattle fecal analysis of forage quality.

CHAPTER 2

AVHRR-NDVI AS A NEAR-REALTIME ESTIMATOR OF TEMPORAL CHANGE IN BIOMASS, AND NITROGEN CONTENT IN MONTANA RANGELANDS

Introduction

Need for Monitoring Tools

Determining quantity and quality of forage is important for short term management of grazing lands through a growing season, and long term management to control change in range condition and trend. Live biomass accumulation (quantity) and vegetation nitrogen content (quality) are a product of many environmental factors, including climate, duration of growing season, soils and grazing pressure. These are not easy to monitor because of natural variability and the large size of areas monitored. These difficulties as well as limited resources often restrict frequent and comprehensive monitoring on rangelands. Traditional range monitoring methods are time consuming and consequently occur infrequently. As a result, management decisions are often based on subjective long-term experience of range managers (Carneggie *et al.*, 1983). If more frequent and comprehensive monitoring of quality and quantity were possible confidence in range management decisions would increase and greater control of outcomes could be expected.

New methods for range management should: 1) be able to cover large areas 2) provide periodic coverage over years as well as several times during a grazing season, and 3) be practical and cost effective (Luckock 1997). While new methods may never entirely replace traditional methods, they can help increase effective area, timing and frequency of monitoring (Carneggie *et al.*, 1983). Below, we examine the potential of AVHRR-NDVI to estimate biomass and nitrogen content of grasslands.

What is NDVI?

Several linear combinations of red and infrared reflectance have been shown to be good predictors of plant canopy biomass (Kennedy 1989; Tucker 1979). Live green plant leaves typically have low reflectance (10%) in the visible red region of the electromagnetic spectrum due to strong absorption of these wave lengths by chlorophyll. The same leaves have a high reflectance (40-60%) in the near-infrared region due to scattering of these wavelengths by leaf mesophyll (Knipling 1970). The NDVI is especially sensitive to characteristics of green vegetation (Box *et al.*, 1989; Kennedy 1989; Kremer and Running 1993). Thus NDVI gives a measure of the absorption of red light by plant chlorophyll and the reflection of infrared radiation by water filled leaf cells. The absorbance of radiation indicates the capacity for photosynthesis enabled by energy capture, while the reflectance indicates surface area participating in photosynthesis. NDVI is a good measure of the plant's photosynthetic capacity and effective use of photosynthetically active radiation (PAR) (Bennedetti and Rossini 1993; Daughtry *et al.*, 1992). The captured energy stored in above ground plant biomass is in part energy that can be utilized by grazing animals.

AVHRR-NDVI imagery is obtained from the AVHRR instrument carried on the NOAA-14 polar orbiting satellite that makes two passes over the United States per day. AVHRR-NDVI has 1.1km^2 pixel resolution for local area coverage, or 8km^2 pixel resolution at nadir for global coverage (Smith *et al.*, 1997).

Unobstructed views of the Earth surface are necessary for monitoring vegetation change. Since a single daily NOAA-14 overpass is seldom entirely cloud free, new AVHRR-NDVI images are made on a bi-weekly basis in the form of Maximum Value Composites (MVC). 'Compositing' is a process that creates a new image based on the highest NDVI value for each pixel in two weeks of multitemporal coverage (EROS Data Center 1996). Compositing is necessary because of variation in atmospheric attenuation of radiance by aerosols, water vapor and clouds. These interference factors lower NDVI values, so choosing the highest NDVI value for a compositing period will usually give the value with least interference (Justice and Hiernaux 1986). Low sun angle and off nadir viewing will also affect NDVI values. Composited images significantly improve image quality by capturing pixels from days when radiance interference is lowest, sun angle is highest, and view angle is closest to nadir (Holben 1986). False colors are assigned to NDVI values for visual interpretation that represent green at higher values (vegetated areas), and brown (senesced vegetation or bare ground) at lower values. The result is an image that approximates true ground colors.

AVHRR-NDVI imagery is registered to Lambert Azimuthal Equal Area map projection. Registration accuracy within one pixel between successive images in ensured by using 250 ground control points for base images, and image to image correlation there after. Image registration accuracy is verified by the U.S. Geological Survey Earth Resources Observation Systems Data Center (EDC) to have a root-mean-square error less than one pixel (EROS Data Center 1996).

NDVI is a unitless value derived from scanned reflectance intensities in the visible red (VIS = 0.58-0.68μm) and very near infrared (NIR = 0.725-1.1μm) wavelengths.

$$NDVI = (NIR-VIS)/(NIR+VIS)$$

NDVI is expressed in a unitless range from -1.0 to 1.0 and rescaled to 0-200 (EROS Data Center 1996).

Vegetated areas on the ground which are actively photosynthesizing yield high NDVI values due to relatively high infrared reflectance and low visible red reflectance. Clouds, water, bare ground and snow yield lower NDVI values because of larger visible reflectance relative to infrared reflectance. NDVI values near zero indicate rock and bare soil which have similar reflectance in both the visible and infrared wavelengths (EROS Data Center 1996; Lillesand and Kiefer 1994).

AVHRR-NDVI for Rangeland Monitoring

Many types of satellite imagery including vegetation indicies from Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) have been used in vegetation studies (Merrill *et al.* 1993; Tucker *et al.* 1983). However, infrequent temporal availability of imagery and lack of repeated sampling throughout the growing season has limited the ability to estimate rapid change in forage quality and quantity through time. The 1.1km^2 coarse resolution of AVHRR-NDVI imagery limits it's usefulness for detailed spatial analysis of vegetation change, but its frequent temporal availability makes it well suited to broad scale investigations where real-time seasonal change is of interest. While both private and government sectors plan to make NDVI data available at resolutions as fine as 30 m^2 within the near future (Nelson 1997; Moody and Woodcock 1994), we can take advantage of the high temporal resolution of AVHRR-NDVI to monitor near real-time rangeland change although at low spatial resolution. Understanding the potential of NDVI for assessing range condition even at coarse resolution will aid technology transfer to ranch-scale applications when finer resolution imagery becomes available.

Use of AVHRR-NDVI in Rangelands

Vegetation index imagery of various types has proven to be effective at differentiating phenological stage of plant growth (Samson 1993), vegetation community type (Kremer and Running 1993), estimating biomass (Wylie *et al.*, 1996), and vegetation cover (Kennedy 1989). Workers in Washington state have shown AVHRR-NDVI is efficient in differentiating grassland dominated ecosystems from sagebrush dominated ecosystems (Kremer and Running 1993), while others have shown the relationships of

AVHRR-NDVI to vegetation, precipitation, and soil moisture characteristics in Botswana (Nicholson and Farrar 1994). Wylie *et al.* (1996) have shown strong correlations (r^2 = 0.81 to 0.87) between live biomass and 30 m resolution SPOT derived NDVI in the Nebraska Sandhills. Work in the Senegalese Sahel of Africa has shown good correlation between both integrated AVHRR-NDVI versus end of season biomass ($r^2 = 0.69$) and maximum AVHRR-NDVI versus end of season biomass ($r^2 = 0.64$) over a 30,000 km^2 study area (Tucker *et al.*, 1983, Tucker and Vanparet 1985). In Tunisia strong correlations between AVHRR-NDVI and above ground vegetation biomass ($r^2 = 0.72$) as well as vegetation cover ($r^2 = 0.81$) exist over wide ranging vegetation, soil, topographic, and management conditions (Kennedy 1989).

Many of these studies took advantage of the temporal frequency of AVHRR-NDVI to track change in vegetation as a way to differentiate vegetation cover type and phenology (Bennedetti and Rossini 1993; Gutman 1991; Kremer and Running 1993; Samson 1993). However, those that focused on biomass estimation usually did so at coarse scales (1000's of km^2) (Tucker *et al.*, 1983; Tucker and Vanparet 1985) and only at one time in the growing season (Kennedy 1989; Merrill *et al.*, 1993; Wylie *et al.*, 1996), or focused on end of growing season cumulative productivity (Tucker *et al.*, 1983). Work at small scales (ie. small areas) for temporal assessment of vegetation parameters has focused on cropped land (Bennedetti and Rossini 1993), overlooking ranch scale (1-9 km^2) applications.

Sampling only once during a growing season can cause problems in determining estimated relationships between reflectance and biomass for different times in a growing season. Work with hand-held radiometers show correlation coefficients decrease as more time intervals are included in the data set (chapter three). This indicates a unique calibration equation is necessary for different times during the growing season due to changes in phenology that change reflectance properties of vegetation.

Few workers have studied the fit of AVHRR-NDVI with estimates of live biomass at discrete points in time for the purpose of tracking change in biomass through the growing season. Fewer still have shown correlation with vegetation nitrogen content. In describing what NDVI measures, Box *et al.* (1989) noted the temporal nature of NDVI being more closely related to rates of biomass accumulation or growing season totals than to structural features such as biomass amounts at a point in time. Hence the area under the NDVI seasonal profile has been shown to be an effective measure of productivity (Box *et al.*, 1989; Tucker and Vanparet 1985). However, processes and biomass are not independent as growing season progresses. That is, as normal seasonal processes advance, biomass will accumulate if not heavily grazed, and NDVI should reflect this as abundance of green vegetation increases and decreases.

Purpose

Our intentions in this study were to determine how well AVHRR-NDVI correlates with above ground biomass, and how well it correlates with above ground vegetation nitrogen concentration and content on a ranch scale at any point in a growing season.

Methods

General Study Design

Study areas need to be sufficiently large to encompass the variability on the ground that is averaged into a single pixel representing that area. Additionally, due to pixel shift between successive images large study areas (9 km^2) were established where possible. Both spatial differences and temporal differences in vegetation quality and quantity were investigated. We chose a variety of landscapes and vegetation compositions for study areas to make the results useful over a wide range of conditions.

Study Area Descriptions

Seven Montana grassland study areas (Figure 1) were selected to represent variability in biotic and abiotic factors such as species assemblage, soils, and climate. Four study areas were in short grass prairie, two were in foothills prairie, and one was in a large riparian corridor. Landscape and vegetation variability within study areas ranged from relatively homogenous on the glacial till plains near Chinook, Montana to complex on deeply incised mountain slopes near Barber Butte, Montana. Vegetation cover (live plus dead) of the seven study areas ranged from 48 to 87 percent. A complete description of the study area and a table of information pertaining to surface physical properties is in Appendix A and B respectively.

Four of the seven study areas were established as replicate pairs representative of high (1350 m) and low elevation (750 m) rangelands in the Havre, Montana vicinity. These pairs served to test the ability of AVHRR-NDVI to discriminate gross spatial differences in grassland biomass. Detailed descriptions of the study areas are in Appendix A.

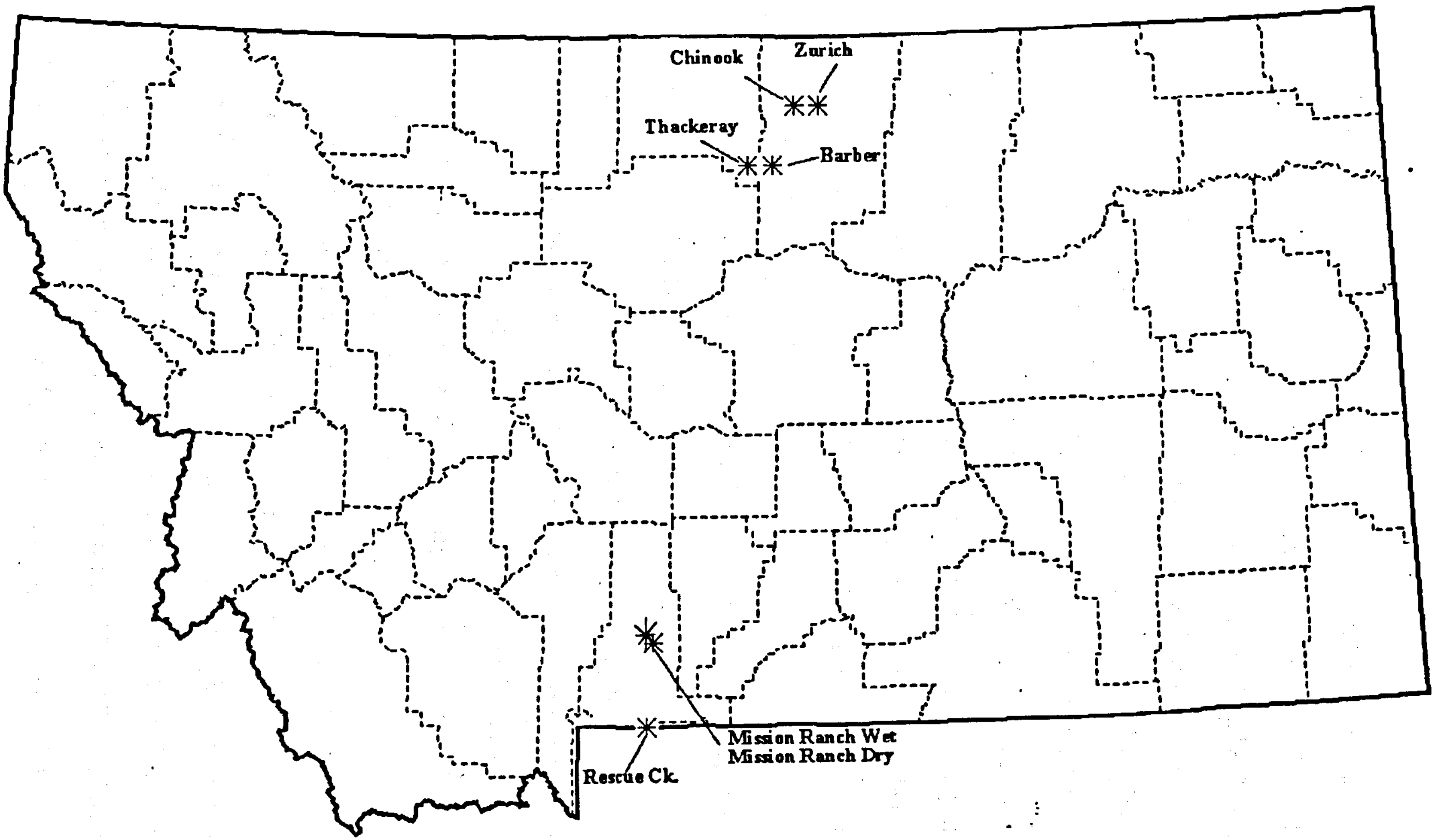

Figure 1. Location of the seven Montana Study Sites

Premapping

We created map units for stratified random sampling within study areas based on repeating vegetation pattern related to landscape features (Holdorf and Donahue 1990) and management as recommended by workers in this field of study (Townshend and Justice 1986; Tucker *et al.*, 1983). All study area boundaries were delineated according to ownership where appropriate to minimize effects on biomass and vegetation nitrogen content resulting from management. The only exceptions were the Rescue Creek area, in Yellowstone National Park and the Mission Ranch Wet study area near the Yellowstone River east of Livingston, Montana. In these two areas it was necessary to delineate map units according to constraining natural topographic features that made these study areas about one fourth the size of the other five. Maps of each study area and map unit delineations are in Appendix C.

A combination of low elevation color infrared, true color (approximately 1:20,000) and black and white ortho-rectified (1:24,000) air photography and 7.5 minute topographic quad sheets were used to map landscape/vegetation/management units in each study area. Map unit delineations were drawn directly over ortho-rectified air photographs on mylar sheets which served as a stable base for digitizing. Prior to digitizing, the mylar map sheet was draped over the corresponding 7.5 minute topographic map to check fit with topographic breaks.

An obstacle to correlating data collected on the ground with AVHRR-NDVI imagery involves successive image to image registration. Since the error in image registration can be up to one kilometer, an area large enough to capture any pixel movement must be sampled on the ground. A nine km^2 area for all but two study areas was chosen for correspondence to a three by three AVHRR-NDVI pixel cluster. This cluster covers all potential ground positions of a single pixel if it shifts up to one kilometer in any direction between successive images. Values for three by three pixel clusters of

AVHRR-NDVI imagery centered over portions of the study area were averaged for use in regression with weighted measures of biomass and nitrogen. The use of relatively homogenous study areas when possible also offsets problems associated with geometric registration of satellite imagery (Benedetti and Rossini 1993). Even in non-homogenous conditions the mean of the nine pixel AVHRR-NDVI can estimate the central pixel AVHRR-NDVI, if map units are sampled and weighted according to total area they represent.

Sampling

We wanted to determine AVHRR-NDVI capability to estimate change through a growing season, so we sampled each study area periodically on a bi-weekly or monthly basis to establish relationships with the imagery at times corresponding to sampling dates. Additionally, the sampling had to cover enough area to include ground variability that was averaged into AVHRR-NDVI pixels. So sample locations were selected at random from within mapping units that represented the three by three pixel cluster.

Clipping and sorting vegetation is time consuming, so few plots (5 to 30) could be sampled at each of the seven study areas in the periodic sampling schedule. This is another reason we initially placed the majority of our study locations in homogenous landscapes where the minimum clipping would represent the largest area.

At least two clipped plots were chosen in a pseudo random fashion (blind quadrat toss) within stratified map units for above ground biomass sampling. One-half m^2 quadrats (0.71 cm * 0.71 cm) were clipped at ground level on a bi-weekly or monthly basis for the 1997 growing season (Richardson and Everitt 1992). Live and dead components were separated in the field and placed in paper bags. Standing crop was determined as the the sum of live and dead biomass. We followed sample handling procedures outlined by Richardson *et al.* (1983). All units of weight are on an oven dry basis. Percent nitrogen by weight was determined on ignition with a Leco FP-328 combustion furnace.

Merrill *et al.* (1993) and Kremer and Running (1993) indicate little hope of using satellite derived NDVI to differentiate type of vegetation beyond shrub versus grass, hence separations of only live and dead were made without regard to species. Quadrat locations were georeferenced to the nearest 20 m on 7.5 minute topographic maps and imported to ARC/View™ for spatial registration with map units and satellite imagery.

We measured soil temperature to a depth of ten cm at every clipped plot with a push-in, steel tipped thermometer. The thermometer face was kept shaded while it reached equilibrium for consistent readings on both cloudy and sunny days.

Processing AVHRR-NDVI Imagery

The bi-weekly composited AVHRR-NDVI imagery supplied by the EDC was imported to ARC/INFO™. In the five largest study areas a three by three cluster of pixels centered on each was extracted and averaged to determine an AVHRR-NDVI value for the study area corresponding to clipping dates. A single pixel AVHRR-NDVI was used in regression against biomass and nitrogen content for the two smaller study areas.

Data Analysis

We obtained components of biomass (live, dead and standing crop) estimates for map units by first averaging and then scaling up quadrat measurements (Kennedy 1989). Map unit biomass estimates were weighted by percent of the study area they represented and then summed to determine a study area biomass. Estimates of percent nitrogen were made in a similar manner. Standing nitrogen was calculated as the biomass component * percent nitrogen in each component of biomass. Analysis of variance was used to determine if measurable differences exist in biomass and AVHRR-NDVI between high and low elevation sites. We used AVHRR-NDVI as the predictor and weighted estimates of biomass components (kg/ha) and vegetation nitrogen content (% by weight) as responses in linear regression. Weighted estimates of above ground biomass (kg/ha) and vegetation nitrogen content (% by weight) were regressed on associated AVHRR-NDVI values via simple linear regression. In multiple linear regression we tested the response of AVHRR-NDVI to observed changes in factors of biomass, temperature, and nitrogen content. We also investigated factor interactions for biomass*nitrogen (standing nitrogen), and biomass*temperature in their effects on AVHRR-NDVI. We used Minitab™, Table Curve 2-D™ and Quattro Pro 7.0™ for statistical analysis.

Results and Discussion

Live Biomass Relationships

We found significant differences in live biomass and corresponding AVHRR-NDVI (Table 1 and Table 2) for the 1997 growing season on the replicated high and low elevation sites. This illustrates the ability of AVHRR-NDVI to differentiate gross differences in live biomass.

The higher biomass at the high elevation site is due to greater plant available water at those sites. This is consistent with other results showing higher AVHRR-NDVI values associated with higher elevations which generally have more plant available water and consequently higher biomass, in addition to greater variety of species (Box *et al.*, 1989).

Table 1. Analysis of Variance for live biomass (kg/ha) at high elevation and low elevation sites.

Source	*DF*	*SS*	*MS*	*F*	*P*
Study Area	1	1106959	1106959	13.91	0.003
Error	11	875272	79570		
Total	12	1982231			

Level	*N*	*Mean*	*StDev*
High	7	936.8	367.0
Low	6	351.4	116.1

Pooled StDev = 282.1

```
Individual 95% CIs For Mean
Based on Pooled StDev
-------+---------+---------+---------
                          (-------*-------)
(--------*-------)
-------+---------+---------+---------
      300       600       900
```

Table 2. Analysis of Variance for AVHRR-NDVI at high elevation and low elevation sites.

Source	*DF*	*SS*	*MS*	*F*	*P*
elevation	1	1210.6	1210.6	33.60	0.000
Error	11	396.4	36.0		
Total	12	1606.9			

Level	*N*	*Mean*	*StDev*
High	7	144.86	6.47
Low	6	125.50	5.39

Pooled StDev = 6.00

```
Individual 95% CIs For Mean
Based on Pooled StDev
----------+---------+---------+------
                    (----*----)
(-----*----)
----------+---------+---------+------
         130       140       150
```

The ANOVA results indicate AVHRR-NDVI is sensitive to large differences in biomass at the high and low elevation sites. Since biomass changes during a growing season, AVHRR-NDVI may be capable of differentiating temporal differences as well. Additionally it may be capable of estimating biomass more accurately over large areas than some clipping methods. Justice and Hiernaux (1986) have noted that the minimum change in biomass that AVHRR-NDVI can detect is less than 250 kg/ha. The difference in mean biomass levels for the high and low sites is 585 kg/ha, more than twice the maximum estimate of minimum resolution of AVHRR-NDVI determined by Justice.

Figure 2 shows representative growing season trends in live biomass and corresponding

AVHRR-NDVI for one of the seven study areas. This trend is representative of how AVHRR-NDVI tracks biomass through a growing season in semi-arid grasslands. The match of the two lines is quantified by the correlation coefficient obtained by linear regression of live biomass on AVHRR-NDVI for the corresponding time period (Figure 3).

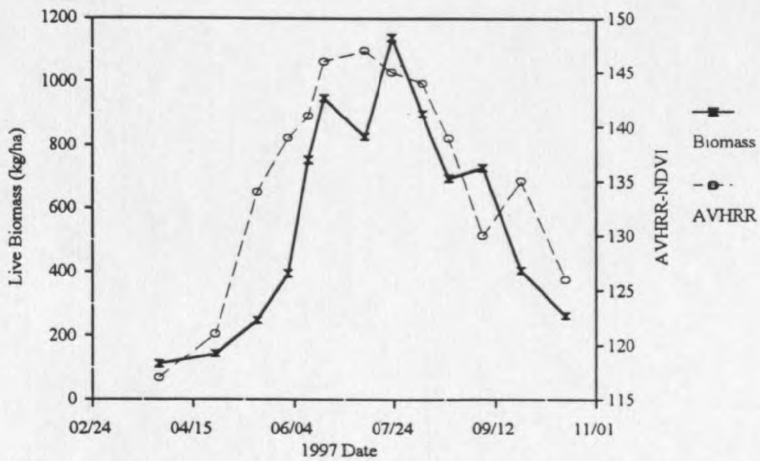

Figure 2. AVHRR-NDVI tracking live biomass estimated by clipping for the 1997 growing season on the Mission Ranch Dry study site. The growing season trends represented here are typical for both AVHRR-NDVI and live biomass in rangelands that are not heavily grazed.

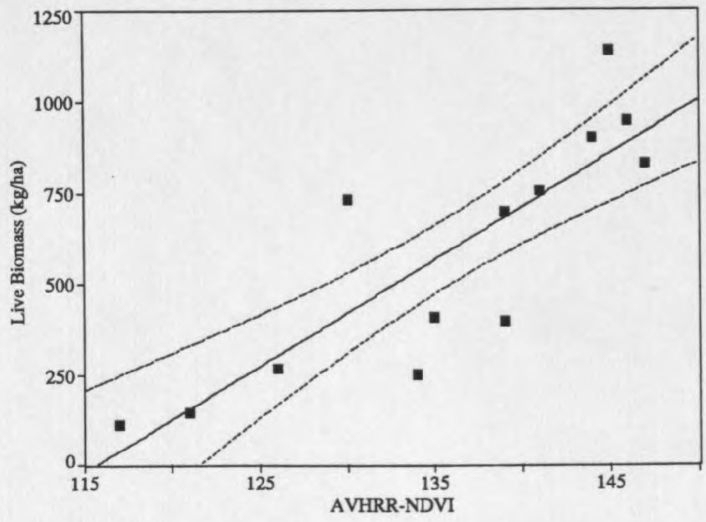

Figure 3. Live biomass as a function of AVHRR-NDVI for the Mission Ranch Dry study area. The regression equation is: live = - 3386 + 29.2ndvi, sd = 187.7, $r^2 = 0.715$, n = 13, p-value for regression relationship = 0.00, 90% confidence interval for slope 19.2 to 39.3. 90% confidence intervals shown.

Estimation Range for Live Biomass

We determined that the estimation capability of AVHRR-NDVI for a combination of several grassland habitat types is below 1800 kg/ha. The relationship between AVHRR-NDVI and live biomass for all seven study areas shows a moderate positive relationship (Figure 4). The response curve indicates a saturation relationship, or asymptote, where above NDVI values of 150, correlation with live biomass weakens. Saturation asymptotes have been noted with other functions of vegetation such as actual evapotranspiration, and biomass as estimated by vegetation indicies (Box *et al.,* 1989; Carneggie *et al.*, 1983). A clear asymptote would be apparent in Figure 4 if the two outlying AVHRR-NDVI values were removed.

Most of the high biomass samples were collected from the Mission Ranch Wet study area along the flood plain of the Yellowstone River. If these data are excluded from analysis a straight line relationship with much higher correlation and lower standard deviation is observed (Figure 5). This relationship has good estimation capability with low deviation in estimated biomass, indicating the types of rangeland vegetation where AVHRR-NDVI may provide reliable estimates of biomass.

Other researchers have noted a low and high threshold where satellite derived NDVI estimation capability breaks down. The lower limit of AVHRR NDVI to detect differences in live biomass over space or time is related to the strength of signal to background noise ratio (Gutman 1991; Justice and Hiernaux 1986). The higher the signal to noise ratio, the better the ability to differentiate change in either space or time. At low live biomass levels background reflectance from bare soil and dead biomass will result in a noisy signal that has little relationship to live biomass. At high biomass levels a saturation response occurs where after canopy closure an increase in biomass does not correspond to an increase in NDVI. This indicates that AVHRR-NDVI is not a good estimator of live biomass after canopy closure occurs in highly productive vegetation communities.

In Tunisian grasslands the low AVHRR-NDVI threshold was determined to be 105 which corresponded to areas where soils were exposed (Kennedy 1989). Tucker and Vanparet (1985) reported the lower limit of sensitivity exists at about 250 kg/ha in the total biomass production integrated normalized difference relationship. Justice and Hiernaux (1986) estimated the lower limit for detecting the presence of biomass in African rangelands was at an AVHRR-NDVI value of 105.6. AVHRR-NDVI values this low are only likely to occur very early in the growing season in Montana.

Carneggie (1983) reviewed research conducted in grasslands with relatively high biomass and cover and found the lower and upper biomass thresholds where Landsat MSS derived vegetation indicies failed were 500 kg/ha, and 4000 kg/ha respectively. Box *et al.* (1989) noted an asymptote at AVHRR-NDVI = 140 for several vegetation parameters and AVHRR-NDVI. The results of this study agree with those of Tucker and Box.

Grassland biomass in Montana is generally higher than in areas of Tunisia where Kennedy worked, and lower than in California where Carneggie worked.

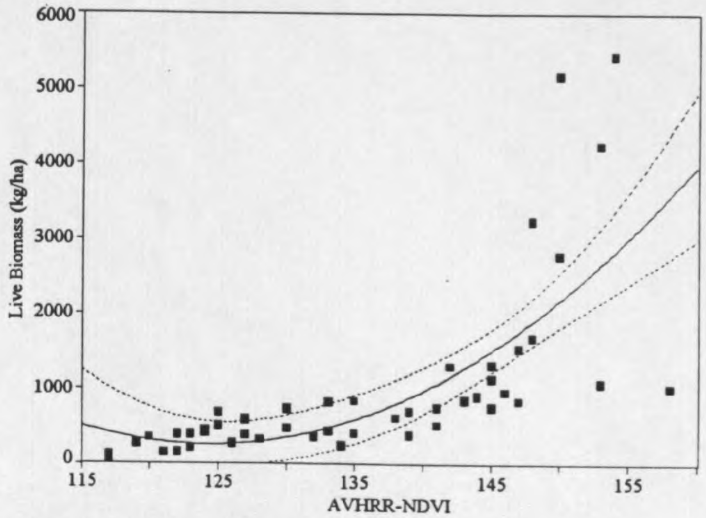

Figure 4. Live biomass as a function of AVHRR-NDVI for all seven study areas. There is a saturation response above NDVI 145 due to canopy closure in the highly productive riparian area. All but one of the data points above 145 are from the riparian area. The regression equation is: live = 45544 - 728.5ndvi + 2.9ndvi^2, sd = 875.72 r^2 = 0.493, n = 48, p-value for regression relationship = $2.45*10^{-7}$, linear slope coefficient p-value=$8.02*10^{-7}$, quadratic slope coefficient p-value = 0.001, 90% confidence interval for linear slope coefficient -1241.6 to -215.4, 90% confidence interval for quadratic slope coefficient = 1.0 to 4.8. 90% confidence interval shown.

The high and low thresholds in these studies and the upper threshold in our study underscores the importance of using an estimation equation suited to the conditions where it will be applied.