Comparisons of phenological variability and precipitation of ecoregion and grassland cover types in the northern Great Plains from 1988 to 1993
by Linda E Gillett

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

Abstract:
The Normalized Difference Vegetation Index (NDVI) is useful in identifying land cover types and in monitoring land cover changes through time. This study compared selected temporal NDVI metrics and evaluated their association with precipitation in the northern Great Plains during the period .1988-93. The study area covered parts of Montana, Nebraska, North Dakota, South Dakota and Wyoming, and measured 364,400 km^2 in extent. Nine unique ecoregion/ grassland areas were identified from Omerik's ecoregion map (42-Northwestern Glaciated Plains; 43-Northwestern Great Plains; 46-Northern Glaciated Plains) and the EROS land cover database (1-grass/crop; 2-grassland; 3-grass/shrub), although 46-3 was later eliminated because of its small area. Two-week maximum composite NDVI values were calculated for 1 km^2 cells and monthly precipitation totals were compiled for 69 stations during the 1988-93 growing seasons. The 1993 mean total NDVI was 20.5 percent larger than the 1988 mean and these years also displayed the lowest (1993) and highest (1988) variability. 1988 was very dry and 1993 very wet. The 1990-92 NDVI values were very similar and the 1989 values split the difference between these and the 1988 values. The largest NDVI values occurred in ecoregion/grassland types 46-1 and 46-2. Types 43-1 and 42-1 came next. Types 43-2, 42-2, and 42-3 displayed intermediate values. Type 43-3 recorded much lower NDVI values and greater year-to-year variability. ANOVA was used to test for significant differences between the eight ecoregion/grassland areas. The null hypothesis was rejected when ecoregions, grasslands, and ecoregion/grassland cover types were separated in five, six, and three years, respectively. This result was repeated when multiple regression models were constructed to examine the relationships between growing season NDVI and monthly precipitation. Slightly less than 50 percent of the variability in NDVI were explained by ecoregion/grassland areas (included as indicator variables), prior monthly precipitation, and their interactions. Overall, the results demonstrate that different ecoregion/grassland cover types have unique NDVI signatures that respond to the timing and quantity of precipitation in the northern Great Plains. Additional work to characterize the lag between precipitation events and NDVI metrics may permit the construction of more powerful regression models.

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ABSTRACT

The Normalized Difference Vegetation Index (NDVI) is useful in identifying land cover types and in monitoring land cover changes through time. This study compared selected temporal NDVI metrics and evaluated their association with precipitation in the northern Great Plains during the period 1988-93. The study area covered parts of Montana, Nebraska, North Dakota, South Dakota and Wyoming, and measured 364,400 km^2 in extent. Nine unique ecoregion/ grassland areas were identified from Omerik's ecoregion map (42-Northwestern Glaciated Plains; 43-Northwestern Great Plains; 46-Northern Glaciated Plains) and the EROS land cover database (1-grass/crop; 2-grassland; 3-grass/shrub), although 46-3 was later eliminated because of its small area. Two-week maximum composite NDVI values were calculated for 1 km^2 cells and monthly precipitation totals were compiled for 69 stations during the 1988-93 growing seasons. The 1993 mean total NDVI was 20.5 percent larger than the 1988 mean and these years also displayed the lowest (1993) and highest (1988) variability. 1988 was very dry and 1993 very wet. The 1990-92 NDVI values were very similar and the 1989 values split the difference between these and the 1988 values. The largest NDVI values occurred in ecoregion/grassland types 46-1 and 46-2. Types 43-1 and 42-1 came next. Types 43-2, 42-2, and 42-3 displayed intermediate values. Type 43-3 recorded much lower NDVI values and greater year-to-year variability. ANOVA was used to test for significant differences between the eight ecoregion/grassland areas. The null hypothesis was rejected when ecoregions, grasslands, and ecoregion/grassland cover types were separated in five, six, and three years, respectively. This result was repeated when multiple regression models were constructed to examine the relationships between growing season NDVI and monthly precipitation. Slightly less than 50 percent of the variability in NDVI were explained by ecoregion/grassland areas (included as indicator variables), prior monthly precipitation, and their interactions. Overall, the results demonstrate that different ecoregion/grassland cover types have unique NDVI signatures that respond to the timing and quantity of precipitation in the northern Great Plains. Additional work to characterize the lag between precipitation events and NDVI metrics may permit the construction of more powerful regression models.

CHAPTER 1

INTRODUCTION

Scope and Purpose

The Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the National Oceanic and Atmospheric Administration (NOAA) series of polar orbiting satellites has been an important source of data for numerous investigations of vegetation cover and dynamics at regional, continental and global scales for more than a decade. These studies have shown that the Normalized Difference Vegetation Index (NDVI), derived from a ratio of Channels 1 and 2 of the AVHRR sensor, is useful in identifying land cover types (e.g., Justice et al., 1985; Goward et al., 1987; Townshend et al., 1987; Loveland et al., 1991; Soriano and Pareulo, 1992), monitoring land cover over time (e.g., Malingreau, 1986; Andres et al., 1994), and measuring phenological response to climatic fluctuations (e.g., Hellden and Eklundh, 1988; Paruelo et al., 1993) over large areas. NDVI shows significant correlation to green biomass and net primary production (e.g., Tucker et al., 1983, 1985; Prince, 1991; Mougin et al., 1995), and is related to rangeland and crop vitality (e.g., Wade et al., 1994; Hobbs, 1995), crop production (e.g., Gallo and Flesch, 1989; Nicholson et al., 1990; Benedetti and Rossini, 1993; Quarmby et al., 1993; Fischer, 1994), soil moisture (e.g., Nicholson and Farrar, 1994) and precipitation (e.g.,Tucker and Choudhury, 1987; Johnson et al., 1993). Goward et al. (1985) demonstrated that AVHRR NDVI temporal curves correspond to the known seasonal variability of vegetation in North America, and that they are also valuable in monitoring the extent and diversity of vegetation spatially and temporally over large areas. Loveland et al. (1991) suggest that the importance of using AVHRR data resides in its capability to monitor seasonal plant variations within and between years.

AVHRR NDVI information is currently a primary data source in surface cover identification because the low cost and timely, continuous coverage is unmatched by any other sensor. Though SPOT and Landsat images offer much greater resolution for land cover studies, their infrequent coverage and cloud contamination results in land cover information derived from only one, or at best, a few images during a growing season (Table 1).

To date, applications using AVHRR NDVI have concentrated on a continental or global scale using 4 km^2 or 16 km^2 resolution data, which may be too coarse for some regional studies. Regional analysis is a crucial step in monitoring environmental phenomena, and choosing and evaluating environmental management options. Many researchers (e.g., Roller and Colwell, 1986; Lozano-Garcia et al.,1991; Paruelo and Laurenroth, 1995) recommend partitioning landscapes into homogenous units for description and statistical analysis.

Table 1. AVHRR, SPOT and Landsat Satellite Data Comparisons.

Satellite	Orbit Repeat	Altitude	Resolution	Price
AVHRR[1]	12 hours	833 km	1.1 km^2	$ 32 per CD
SPOT[2]	26 days	832 km	20 meter	$ 2000 + per img
Landsat[2]	16 days	705 km	30 meter	$ 2000 + per img

[1] Kidwell (1991)
[2] Lillesand and Kiefer (1987)

One logical, natural stratification for regional studies at the 1 km^2 scale is the ecoregion (Kemp et al., 1996). Omernik (1995) describes ecoregions as mosaics of distinct patterns reflecting land use, land cover, weather patterns, soil, altitude, and topography. He also suggested that further analysis of pattern differences within these subsystems to investigate their utility in examining variations in land cover is needed. A current, comprehensive land cover database was developed by Loveland et al. (1993) (Figure 1) based on AVHRR NDVI and ancillary data, and this was used in conjunction with Omernik's (1995) ecoregion classes to differentiate regional-scale study zones within the Northern Great Plains for this project.

In an effort to improve ecosystem studies, some researchers have recently expanded their analysis of NDVI temporal signatures beyond the traditional minimum and maximum NDVI, and mean and total seasonal NDVI (ΣNDVI) metrics. The time of minimum and maximum NDVI, rate of green-up and

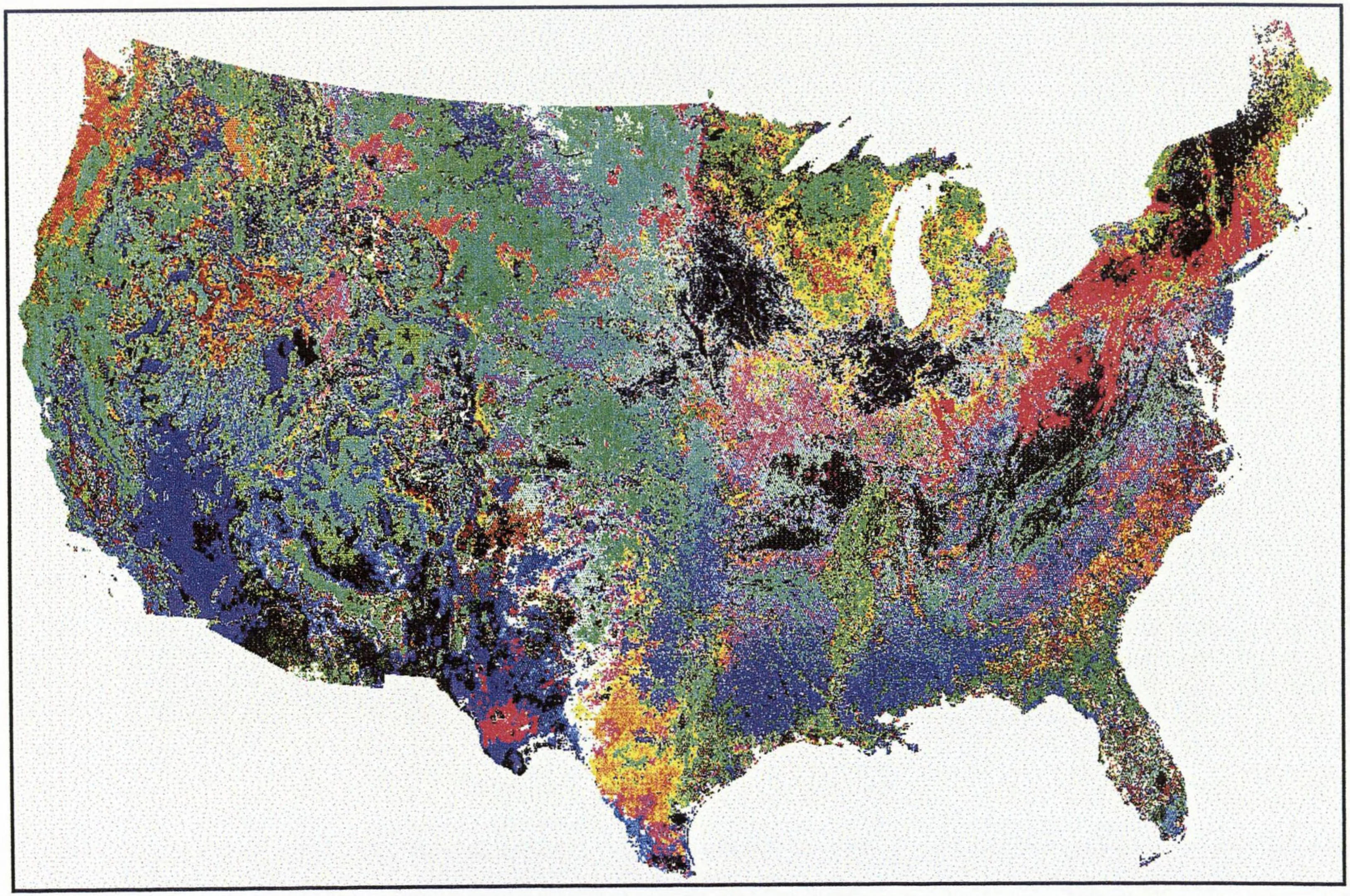


Figure 1. Map of 1990 EROS prototype land cover classification.

senescence, and shape of the area under the seasonal curve are used to describe temporal variations among land cover types (e.g., Lloyd, 1990; Olsson and Eklundh, 1994; Reed et al., 1994).

Many researchers have also compared NDVI values and precipitation to monitor the extent and severity of drought, crop condition, and yield. These data are also used as input parameters for early warning systems, particularly in Africa, where drought and associated crop failures often have catastrophic consequences (e.g., Hielkema et al., 1986; Justice and Hiernaux, 1986; Huete and Jackson, 1987). The Great Plains region of the U.S. is also vulnerable to drought, and several studies have examined the association between AVHRR NDVI values and precipitation (e.g., Peters, 1989; Kogan, 1990; Burke et al., 1991; Johnson et al., 1993).

The main objective of this study was to compare selected temporal NDVI metrics extracted from ecoregion/grassland areas in the Northern Great Plains and to evaluate their association with precipitation over a period of six years (1988 -1993). Few previous studies have examined NDVI data for more than a few seasons, or examined regional scale grassland NDVI metrics using land cover and ecoregions as a defining limit at the 1 km^2 scale. The temporal span of six years also provides a unique opportunity to measure the effects of precipitation on NDVI between the extreme drought year of 1988 (the year of the Yellowstone fires), several "normal" years, and the extreme cool and wet summer of 1993 (the year of extensive flooding on the Missouri and Mississippi Rivers).

Specifically, the objectives of this research project were: (1) to evaluate the variability of NDVI between selected years, ecoregions, and grassland types in a portion of the U.S. Northern Great Plains; and (2) to assess the relationship between NDVI metrics and precipitation data for selected ecoregions and grassland types in the U.S. Northern Great Plains from 1988 to 1993.

Literature Review

One of the earliest projects using satellite data to analyze vegetation phenology of the Great Plains was performed by Rouse et al. (1973), who pioneered the NDVI equation as a measure of "greenness" from Landsat MSS instruments (Landsat Channels 5 and 7 are similar to AVHRR Channels 1 and 2). These researchers confirmed that remotely sensed data from satellites were effective in identifying distinct patterns of grassland phenology over a growing season. Tucker et al. (1983) first applied AVHRR NDVI in a 1982 study of African land cover, and since then, employment of AVHRR NDVI has followed two general trends; identification and analysis of land cover, and correlation of NDVI to weather patterns.

Land Cover Identification and Temporal Analysis

NDVI metrics are used for both land cover identification and analysis of land cover between years. The most frequently used metric to differentiate land cover types is ∑NDVI, which reflects net primary production (e.g., Goward et al., 1985; Justice and Hiernaux, 1986; Prince and Tucker, 1986; Hellden and Eklundh, 1988). Gallo and Heddinghaus (1989) compared drought affected crops in the U.S. corn belt in 1988 to a non-drought year (1987) and they confirmed that seasonal ∑NDVI values are less for drought-effected areas.

However, other researchers (e.g., Samson, 1993; Running et al., 1994) ascertained that cumulative measures of seasonal NDVI do not adequately describe the phenological profile of plants, since different vegetation can produce identical seasonal values. Samson (1993) argued the shape of the seasonal NDVI curve was also an important measure of variation, reflecting precipitation and temperature status at different times in the growing season. He compared the integral before and after the peak (skew), and the range of variation to differentiate land cover types.

Lloyd (1990) proposed broadening NDVI metrics to include several additional descriptors (Table 2). These variables were applied by Reed et al. (1994) in a comprehensive examination of multiple NDVI attributes to compare a U.S. NDVI time series from 1989 to 1992. Their metrics included onset and end of greenness, peak NDVI, time of peak NDVI, rate of greenup and senescence, and ∑NDVI. The results showed a strong correspondence between the derived metrics and predicted phenological characteristics of grasslands and forested regions for land cover identification purposes.

Soriano and Paruelo (1992) proposed application of NDVI metrics as the

Table 2. Lloyds' (1990) Phytophenological Variables.

NDVI Definition	Phytophenological Interpretation
Date when minimum NDVI recorded	Time of minimum photosynthetic activity
Date when maximum NDVI recorded	Time of maximum photosynthetic activity
Dates above .099 threshold	Time of start of growing season
Number of periods above .099	Number of growing seasons
Length of period above .099	Length of growing season
Minimum NDVI	Lowest level of phytophenological activity
Maximum NDVI	Maximum level of phytophenological activity
Mean daily NDVI (time-integrated NDVI) for some predefined period	Mean daily maximum potential photosynthetic rate
Mean daily NDVI for period above .099	Mean daily maximum potential photosynthetic rate during growing season
Time-integrated NDVI	Gross primary production

exclusive data source to separate vegetation into "biozone" classifications, or "homogenous functioning vegetation zones", based on the integral, maximum value, duration and rate of change. Nicholson et al. (1990) also concluded that primary vegetation classes could be discriminated using these values in a four year study of rainfall in Africa. In contrast, Omernik (1995) used NDVI data as only one of several traits in his classification of ecoregions, employing multiple ancillary data sources such as land use, elevation, natural vegetation, soil, geology, climate and agricultural statistics to improve accuracy.

As noted previously, few studies have compared a time series of NDVI measurements within specific ecoregions. One recently completed study by Ramsey et al. (1995) extracted three years of NDVI values from 1990 to 1992 for each of Omerniks' five ecoregions in Utah. They documented conspicuous differences between the NDVI values in different ecoregions and concluded that Omerniks' classification could be used to delineate fine-scale ecoregion divisions in the state of Utah.

NDVI and Climate Studies

The main focus of studies that examine the association between climate and NDVI has been identification of the extent and severity of drought for early warning of crop damage. In many of these studies, time lags were noted between precipitation events and increasing NDVI, influenced by soil and vegetation type, which have important ramifications for crop assessment. For instance, Nicholson and Farrar (1994) identified a general 2-month time lag between maximum precipitation and the highest NDVI in Botswana, identical to the lag noted by Hellden and Eklundh (1988) for a similar study of Ethiopia. Studies conducted in other areas such as India and the U.S., however, registered shorter lags, varying from 2-6 weeks (e.g., Johnson et. al., 1993; Di, 1991).

Tucker and Choudhury (1987) monitored changes in NDVI from 1984 to 1986 in Africa and successfully identified drought conditions based on the premise that drought correlates with decreased photosynthesis. A series of 4 km^2 NDVI composites were later used to develop a drought early warning system in Ethiopia. This study also illustrated the strong relationship between NDVI and precipitation (Hellden and Eklundh, 1988). They used a pixel window extraction of 1 x 1, 3 x 3 and 5 x 5 around each weather station and correlated measured precipitation with mean NDVI. They found a stronger relationship for larger window sizes, with the driest regions yielding the highest correlations.

NDVI has also been used as a qualitative measure of drought severity by comparing "normal" year curves to those of selected years. Walsh (1987) related three meteorological drought measures to four vegetation indices for Oklahoma covering the drought year of 1980. His results showed that the spatial and temporal variations in drought conditions could be estimated by a combination of vegetation indices, including NDVI. Johnson et al. (1993) used a similar approach in India for 1986 to 1989 and later verified the satellite-based assessments of crop conditions with ground data. These studies demonstrated that NDVI is reflective of general vegetation dynamics, and that specific crop conditions can be inferred over large uniform areas. It also confirmed a two- to four-week time lag between precipitation events and increasing NDVI in the crop systems evaluated in India.

In analyses conducted over the Great Plains and the Corn Belt of the

United States during 1987-1988, Gallo (1990) compared a set of climatic variables, including actual evapotranspiration, seasonal precipitation, Crop Moisture Index (CMI) and temperature to NDVI in agricultural and rangeland climatic divisions. All but the temperature variable correlated well with NDVI values, suggesting that the NDVI can be used indirectly to monitor meteorological variations. Teng (1990) monitored crops in the United States during the 1988 drought using vegetation index curves for 1988 compared to previous years in the four-state area of Iowa, Illinois, Indiana, and Ohio. These comparisons provided an early, unequivocal indication of severe drought that complemented site-specific observations of declines in crop production and estimates made by the CMI and the Palmer Drought Severity Index (PDSI).

A NDVI-derived Vegetation Condition Index (VCI) was used by Kogan (1990) to analyze vegetation stress associated with the 1988 drought in the conterminous United States using 16 km^2 resolution data. This study detected drought intensity, duration, and impacts that matched weekly weather and crop bulletins. A good correspondence was shown between precipitation-derived spatial drought patterns and this index. Peters (1989) compared the NDVI to the PDSI and CMI in Nebraska from 1985 to 1988. He found the CMI correlated better with the mean NDVI than the PDSI. Another Nebraska study by Di (1991) used three AVHRR channels to estimate regional-scale soil moisture, and confirmed that cumulative precipitation in each climatic division associated better with the mean NDVI than either PDSI or CMI. He also noted a two-week time lag for NDVI response to precipitation. Svoboda (1992) found similar correlations between the drought indices, cumulative precipitation and NDVI in the Sandhills of Nebraska in 1988. His results showed a 43 day time lag between precipitation and higher NDVI values, or about two weeks longer than other studies in the same area (e.g., Di, 1991), which was attributed to examination of only grasslands.

Nicholson and Farrar (1994) examined the variability of NDVI in Botswana from 1982-1987 and its relationship to rainfall in six vegetation and six soil types. The response of NDVI to rainfall varied by vegetation and region, but in all areas there was a linear relationship between rainfall and NDVI as long as the rainfall did not exceed 500 mm per year. Once this "saturation point" was reached, NDVI no longer increased with more precipitation. Lastly, in a similar study, Lozano-Garcia et al. (1995) associated NDVI values from a normal year (1987), and the drought year (1988) to soil types in Nebraska, concluding that NDVI was an excellent method to monitor vegetation patterns and the effect of drought. In their results, each combination of vegetation/soil type showed distinctive reactions to precipitation levels. For instance, claypan soil under cultivation had the least water retention capacity, and this was reflected by extremely low NDVI values. In contrast, sandy or organic soils under cultivation had less severe reduction of NDVI.

Description of the Study Area

The study area was defined by combining three major grassland types from the EROS landcover data (Figure 1) and Omernik's three primary northern Great Plains ecoregions (Figure 2) within the spatial extent of the 1988 NDVI images (Figure 3). This approach generated eight distinct ecoregion/grassland areas covering approximately 364,400 km^2 in the Northern Great Plains (Figure 4). The eight areas were labeled 42-1 (ecoregion 42, grass/crop type 1), 42-2 (ecoregion 42, grassland type 2), 42-3 (ecoregion 42, grass/shrub type 3), 43-1 (ecoregion 43, grass/crop type 1), 43-2 (ecoregion 43, grassland type 2), 43-3 (ecoregion 43, grass/shrub type 3), 46-1 (ecoregion 46, grass/crop type 1), and 46-2 (ecoregion 46, grassland type 2). The geographical area encompassed included North and South Dakota, portions of eastern Montana, northeast Wyoming and northern Nebraska.

The dominant climatic regions are interior mid-latitude steppe in the western portion and humid continental in the east (Trewartha, 1957). The steppe region is noted particularly for temperature extremes, seasonal and irregular precipitation patterns, and windy conditions, all of which contribute to frequent moisture deficits. Low precipitation levels (< 50 cm per year) and recurrent drought precludes tree growth except in the moist river bottoms. Consequently, the native land cover consists mainly of mixed shortgrasses and annual grasses. The humid continental region experiences slightly higher annual precipitation and

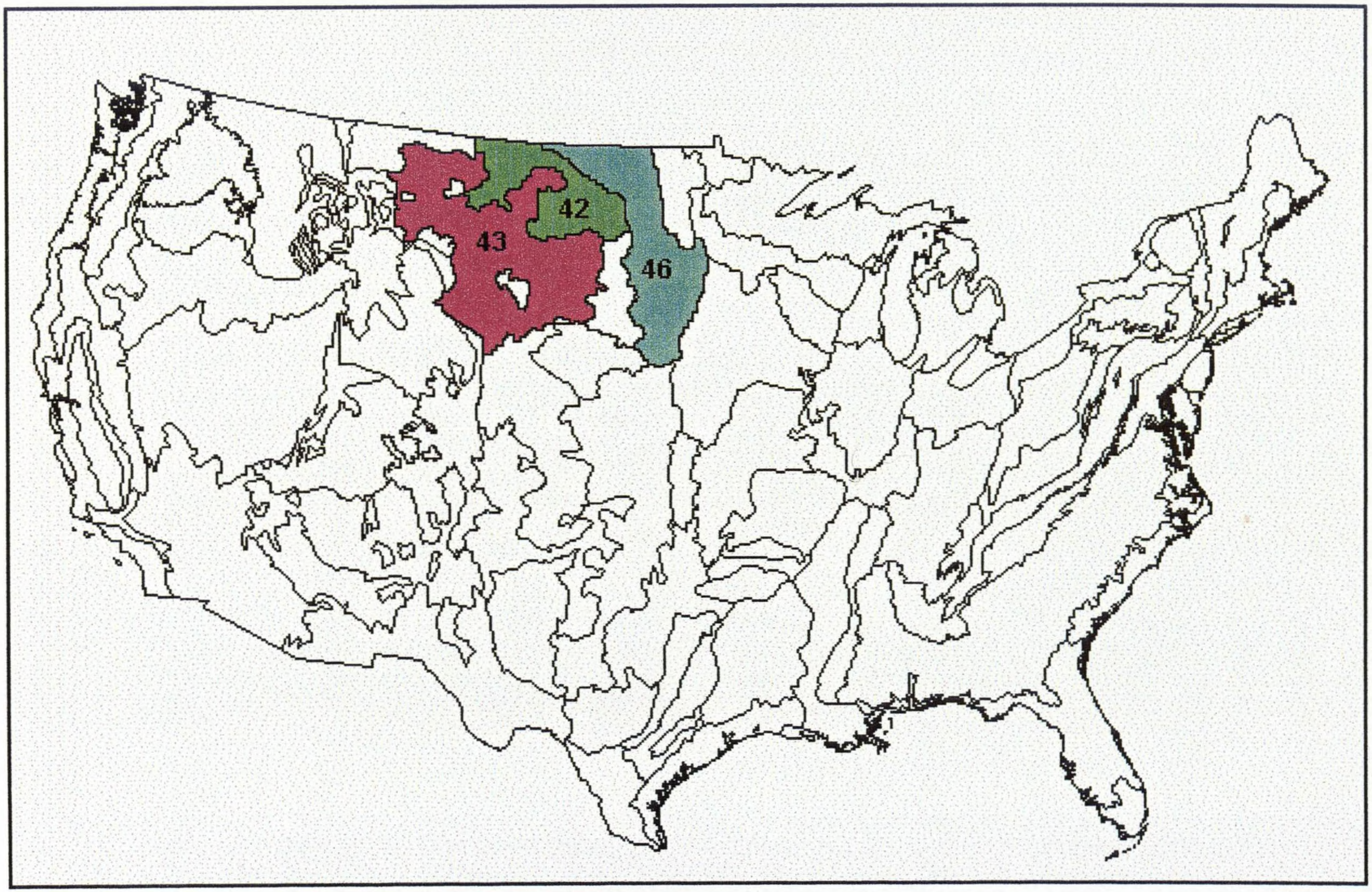


Figure 2. Map of Omernik's (1995) ecoregions 42, 43 and 46.

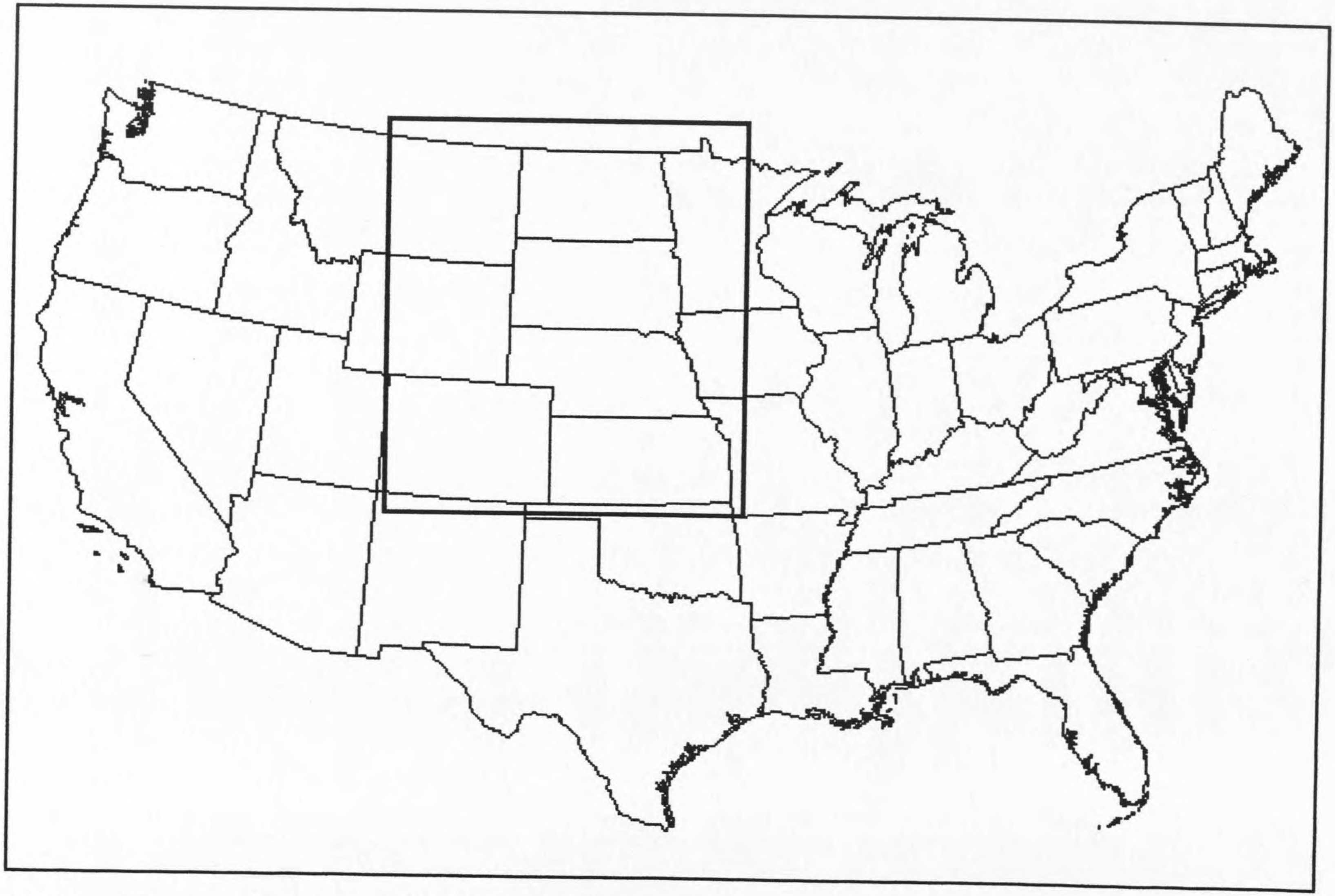


Figure 3. Map of spatial extent of 1988 EROS NDVI images.

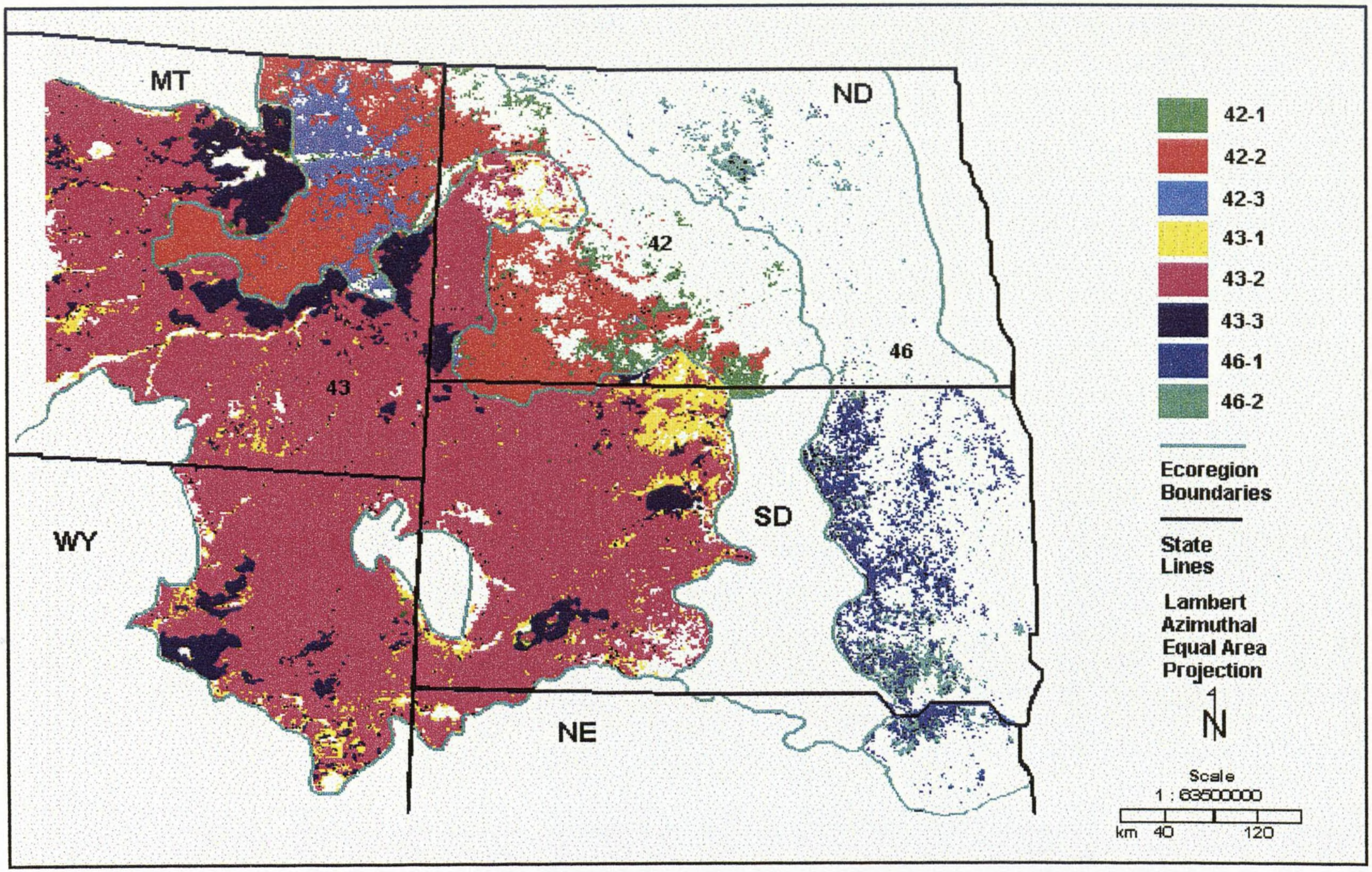


Figure 4. Map of major ecoregion/grassland cover types used in current study.

contains more tallgrass prairie than the western steppe.

Elevation gradually declines from about 1495 m at the western edge of the study area (central Wyoming) to approximately 430 m along the Red River Valley of eastern North and South Dakota. Land use also changes from west to east, from grazing and dryland agriculture to more intensive grain and livestock production, due to changes in climate, soils, and increasing availability of irrigation water. The land surface in the western study area is dominated by flat to rolling plains with some higher tablelands, dissected intermittently by rivers and streams. There are also several limited areas of severely eroded, sparsely vegetated badlands and mountain areas such as the Black Hills. The land surface in the eastern portion tends to more uniformly level plains.

CHAPTER 2

DATA SOURCES AND METHODS

Data Sources

EROS Data

The primary data used for this project were NDVI digital images obtained from a set of CD-ROM's supplied by the United States Geological Survey's (USGS) Earth Resources Observation Systems (EROS) Data Center, covering the years 1988-1993. The 1988 data set was originally intended to monitor green standing biomass and grassland fire danger, so encompasses only the north-central portion of the United States, where the bulk of grasslands exist (Figure 3). The 1988 data were obtained from the NOAA-9 satellite, and geometrically registered to the Albers Equal Area projection. In contrast, the 1989-1993 and Landcover data sets were obtained from NOAA-11, cover the conterminous United States, and were registered to the Lambert Azimuthal Equal Area projection. Other differences in pre-processing between 1988 and the other data sets, due to continuously evolving improvements, include solar illumination correction and radiometric calibration of the 1989-1993 data sets (Eidenshink,

1992) which were not applied to 1988 data.

The original 1.1 km^2 resolution data was resampled to 1 km^2, and computation of NDVI and scaling procedures were identical for all data sets. NDVI was computed using Channels 1 and 2. The NDVI combines the low visible reflectance in the red band (Channel 1, 0.4-0.7 μm) with the near-infrared (NIR) reflectance band (Channel 2, 0.7-1.10 μm) as follows:

$$NDVI = [Ch.2\ (NIR) - Ch.1\ (RED)] / [Ch.2\ (NIR) + Ch.1\ (RED)] \quad [1]$$

Photosynthetically active vegetation has a low reflectance in the red band due to absorption by chlorophyll and a high reflectance in the NIR. Clouds, snow and water reflect higher in the visible than NIR and result in negative values. Barren areas have about equal reflectance in the two bands and have values near zero. The NDVI ranges from -1.0 to 1.0 with the higher values associated with greater vegetative cover and more photosynthetically active vegetation. The data is then scaled to byte range between 100-200, where values <100 and >200 are non-vegetated areas (Kidwell, 1991).

Maximum value compositing, which eliminates most pixels contaminated by clouds by assigning each pixel the highest NDVI value recorded for a given time period (Holben 1986), was applied to reduce cloud contamination. The 1988 NDVI values were composited on a weekly basis, whereas the 1989-1993 comprise bi-weekly composites.

The EROS landcover database (Loveland et al. 1993, 1995) was produced using the 1990 eight-month growing season maximum value NDVI composites of the conterminous U.S. The NDVI signatures were statistically clustered into 70 regions, and further refined using information from Landsat imagery, elevation, climate, ecoregion, land use, precipitation, and vegetation data from other sources to produce the database of 159 seasonal land cover regions (Figure 1).

Ecoregions

The digital ecoregion map, developed by Omernik (1995), classifies the U.S. into 76 major regions, identified by multiple landscape characteristics of varying importance (Figure 2). Other ecoregion classifications had restricted functional potential because they tended to rely upon a limited number of parameters for classification, and were often suitable for only single-purpose applications. His classification schema was developed for general applicability to various resource and subject requirements, defined by soils, land use, geology, vegetation, climate, and land cover for national-level studies. This small-scale delineation (1:7,500,000) is intended to be the basis for on-going, collaborative studies between several state and federal agencies to further refine ecoregion definitions at larger scales (1:250,000) for use at state and regional levels.

Precipitation Data

The climate station locations and precipitation data were obtained from the Montana State Climate Office at Montana State University-Bozeman. The ASCII data set included 2,384 stations for Montana, North and South Dakota, Wyoming and Nebraska, listing station name, station identification number, latitude, longitude, elevation and monthly precipitation totals from 1988-1993.

Data Processing

EROS Image Data

The large multiple data sets required extensive processing to extract subsets for analysis. The first step was automating the necessary procedures (Figure 5). The majority of the approximately 130 images are 13 MB in size, and each transformation created duplicates, multiplying the data and disk space required to maintain them many times. Several custom programs combining UNIX shell language and batch processing within two raster-based GIS packages: ERDAS (ERDAS, Inc., Atlanta, GA) and ARC/INFO (Environmental Systems Research Institute, Inc., Redlands, CA) were developed to improve computational efficiency. Separate programs were initially required for the 1988 and 1989-93 data sets due to file name, header, location, and projection attribute differences. Image files from each year were copied from the CD's into their own

Figure 5. Flowchart Showing Processing Steps for EROS NDVI, Land Cover and Precipitation Data (Part 1).

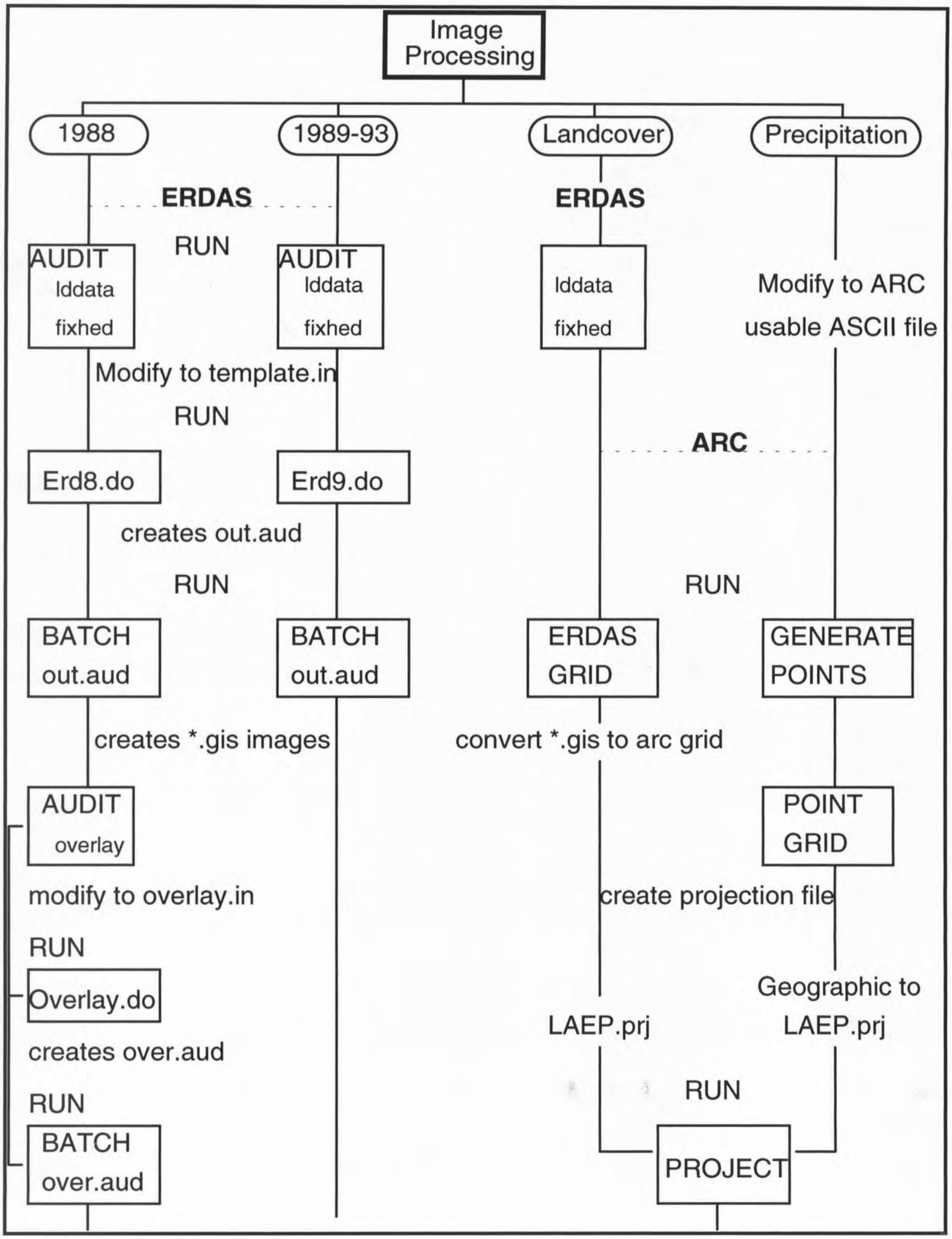


Figure 5. Flowchart Showing Processing Steps for EROS NDVI, Land Cover and Precipitation Data (Part 2).

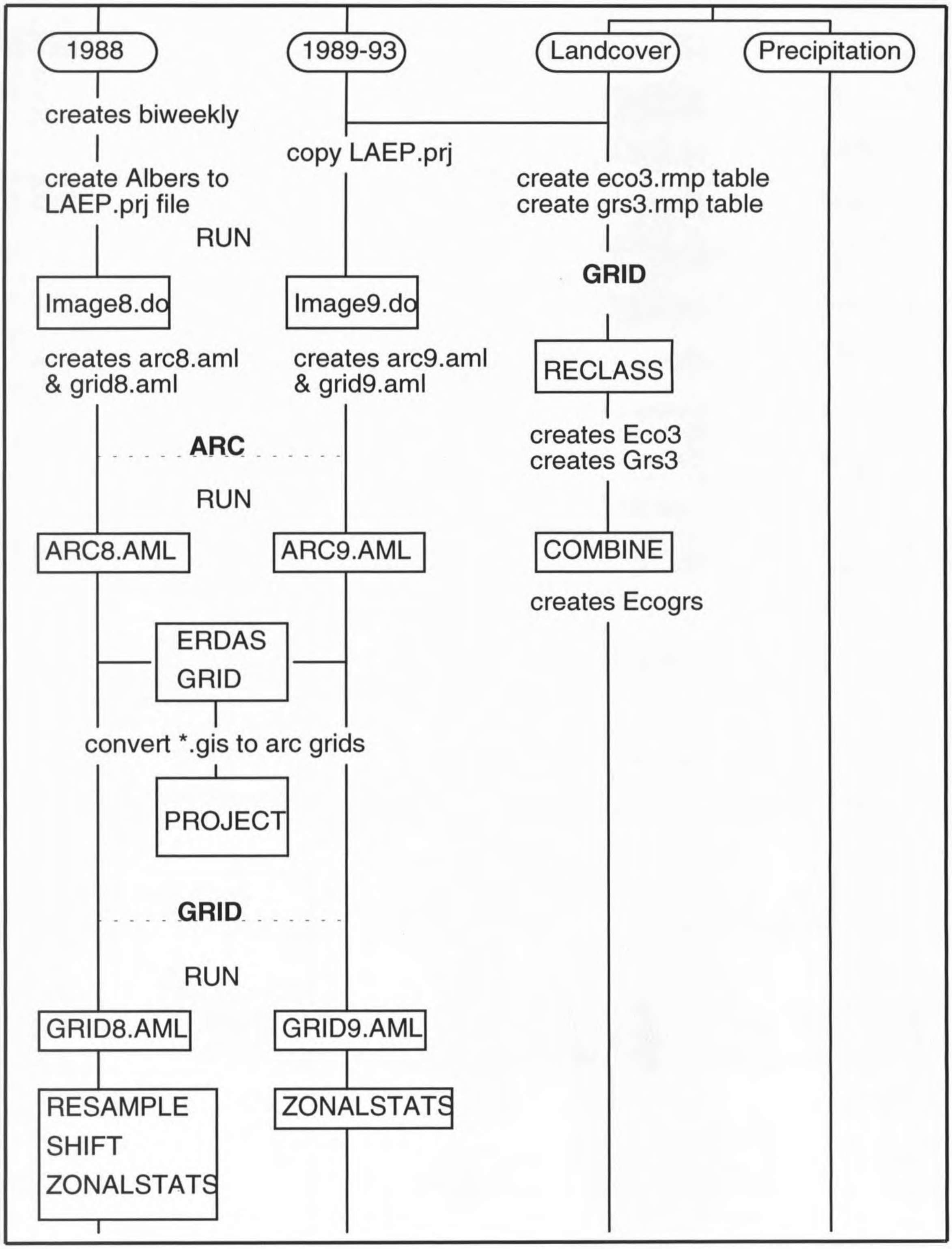
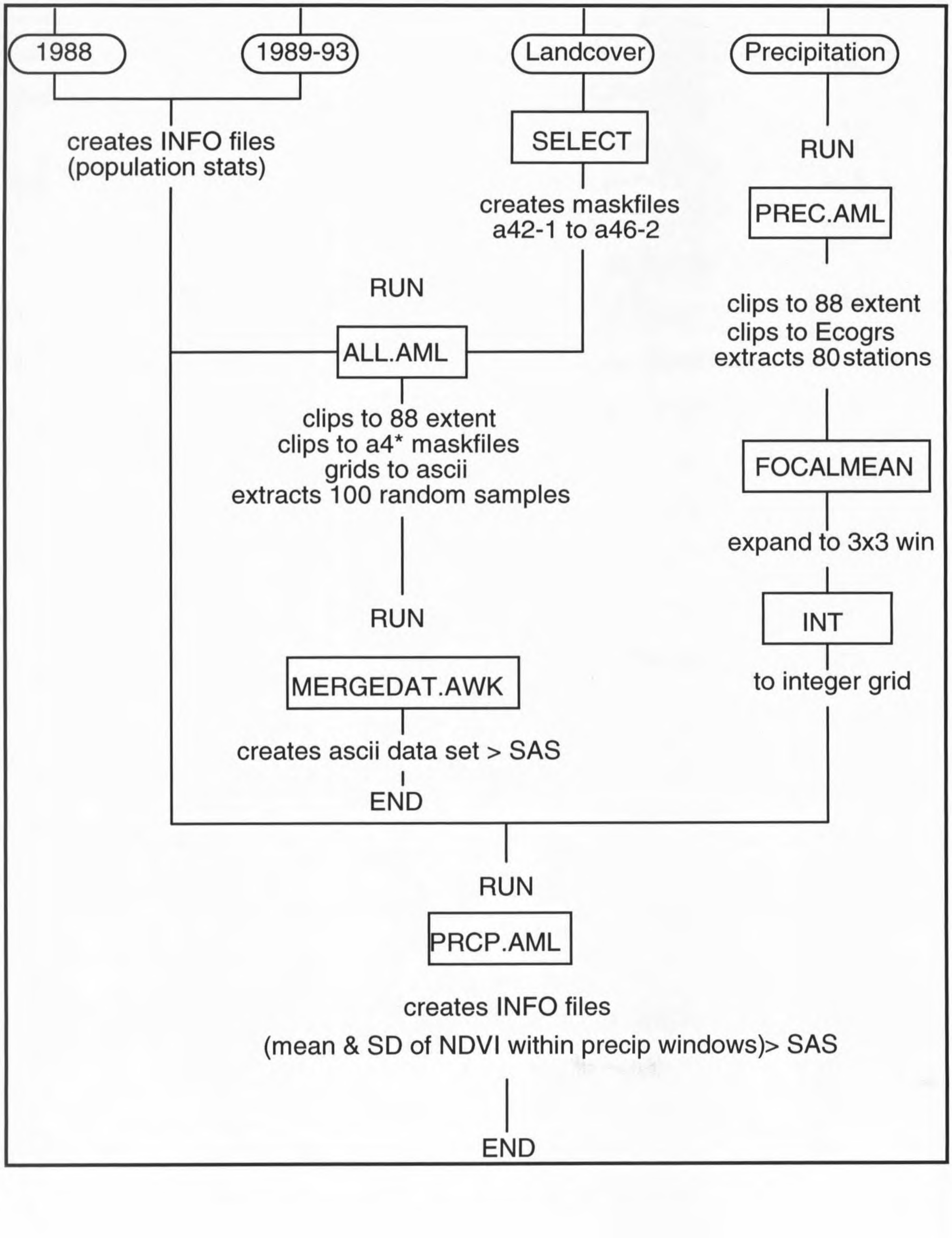


Figure 5. Flowchart Showing Processing Steps for EROS NDVI, Land Cover and Precipitation Data (Part 3).



directories, identified by year. The file names from the original CD's are identical, i.e., P05NDVI.IMG, so separate directories were necessary. One image was processed with ERDAS, using the AUDIT command that preserves all keyboard input. The original file name in the audit template was modified to a generic file name (i.e., image1.img) and a customized UNIX script program was run that altered all the image file names in the directories to unique identifiers (i.e., 9005.img, thus distinguishing images by year, 90, and image number, 05). A new audit file was then created by looping through the template, substituting actual file names in the current directory in place of the generic file name. This new audit file was run in ERDAS with the BATCH command (once for each directory/year), and all *.IMG or *.ND images were renamed and geographically defined according to projection and extent. The 1988 data required the additional step of compositing the weekly images to bi-weekly images. All temporary and duplicate files were automatically removed.

The NDVI ERDAS *.gis images were then transformed to grids in ARC/INFO. Additional UNIX script programs created Arc Macro Language (AML) programs by the same process used in the ERDAS audit files; a WATCH file which preserved keyboard input was altered to accommodate the looping procedure, and all *.gis images were transformed to ARC/INFO grids. The 1988 images again required additional manipulation to transform the images from the Albers Equal Area to a Lambert Azimuthal Equal Area projection. This procedure in turn made resampling necessary since transformation altered the pixel size. A shift was also performed to obtain a closer match to geographical boundaries with the other data sets. Accuracy may have suffered slightly with this resampling and shift, but the estimated location error of $\pm$ 5 pixels was deemed acceptable for the scale of my investigations.

Masks defining the area and land cover of interest were then created by combining the reclassified USGS EROS Data Center Landcover Prototype image (Table 3) and a digital copy of Omernik's (1995) ecoregion map. First, a subset of grassland areas was extracted from the 159 original EROS cover classes and regrouped into three general categories defined as grass/crop-1, grass-2, and grass/shrub-3. Then, the three major ecoregions covering the study area, the northwestern glaciated plains (42), northwestern Great Plains (43), and northern glaciated plains (46), were combined with the three land cover classes to create nine distinct zones (Table 4). The ninth region, grass/shrub area of ecoregion 46 (46-3) was discarded due to the small number of pixels (29). The images from all years were then clipped to the 1988 coverage area to provide identical images for evaluation. The zonal statistics option within ARC/INFO provided the count, range, minimum, maximum, mean and standard deviation for each of the eight unique grassland and ecoregion populations.

An AML was then used to further reduce the data sets by converting all grids to ASCII files, discarding the nodata values (-9999) and selecting random sample NDVI values from each of the areas. A preliminary test was run to determine an appropriate sample size. Sample sizes of 50, 100, and 150

Table 3. Land Cover Reclassification from 159 EROS Cover Classes to Three Grassland Subsets.

EROS Class	Land Cover	Pixel Count	Reclassified to
35	bluestem,grama,wheatgrass	123328	
36	grama,buffalograss,wheat	165348	grass/crop (1)
39	bluestem,wheatgrass,wheat	64584	
55	wheatgrass,needlegrass,needle&thread	26226	
56	wheatgrass,needlegrass,needle&thread	146695	
58	blue grama,wheatgrass,buffalograss	50514	
59	wheatgrass,blue grama,needle&thread	133374	grass (2)
61	wheatgrass,blue grama,sage	135717	
64	wheatgrass,neddle&thread,needlegrass	67345	
65	bluestem,indiangrass,switchgrass	49450	
72	greasewood,sage,rabbitbrush,needlegrass	182975	
73	sand sage,creosote,ricegrass,bluegrama	30274	
74	bige sage,rabbitbrush,wheatgrass,fescue	91626	grass/shrub (3)
75	greasewood,sage,wheatgrass,needle&th	132011	
80	blue grama,buffalograss,sage	140798	

Table 4. Total Cell Count of Final Ecoregion and Grassland Classification Zones.

Area	Ecoregion	Cover		Cell Count
42-1	42	1	grass/crop	7379
42-2	42	2	grass	50602
42-3	42	3	grass/shrub	10935
43-1	43	1	grass/crop	16567
43-2	43	2	grass	227871
43-3	43	3	grass/shrub	27263
46-1	46	1	grass/crop	7998
46-2	46	2	grass	15784
46-3	46	3	grass/shrub	29

observations were tested. The results showed higher standard deviation in the smallest sample set (50) compared to the population, while the 100 and 150 set observations were identical, so the smaller of these two (100 samples) was selected as the most efficient sample size. The sampling program then extracted 100 values from each area in each image. (This method of random sampling loses any spatial reference, so the location of the selected samples is unknown). The resulting columnar sample data sets were transformed in UNIX to row data, combined in one large data set for export to SAS (SAS Institute, Raleigh, NC), where the mean NDVI's were evaluated for differences.

The remaining metrics, including date of onset, date of end of greenness, duration, and date of maximum NDVI were calculated by comparisons of the mid-point Julian day of each bi-weekly period in which the metric occurred. For instance, in 1990, the onset of greenness, defined as NDVI $\geq$ 115 for area 42-1 occurred in the 9003 image, covering the dates 3/30 to 4/12, or days 89 to 102 in Julian range. The midpoint Julian day of 96 was the value entered in the metric table. The end of greenness was the midpoint Julian day of the image where the NDVI value fell below 115. The same procedure was used to estimate time of maximum NDVI. The duration value was the midpoint onset-of-greenness day subtracted from the midpoint end-of-greenness day. All of the NDVI values were initially computed to three decimal points (i.e., 147.633) and then truncated to whole numbers (i.e., 147) for simplicity. In cases where peak NDVI was identical in separate time periods, the highest value was chosen to limit the peak period to only one time interval. Hence, the eighth image was chosen as the peak NDVI value for 1990 42-1 because the seventh image peak NDVI was 142.721, and the eighth image peak was 142.900.

Designating a value for date of onset and end of greenness is a subjective decision, and has ramifications for several other metrics, including length of season and integral (e.g., Lloyd, 1990; Reed et al., 1994). Lloyd (1990) identified any values above 99 (or .099) as the beginning of the growth cycle. Reed et al. (1994) assumed that any rapid increase in NDVI reflects the start of season, noting also that grassland areas of the northern Great Plains often show a rapid rise of NDVI associated with snowmelt rather than actual growth. These previous studies also indicated that beginning and end values should reflect local adaptation. Examination of NDVI values for my study area show that values above 99 were frequent when no growth could have occurred, and the `rapid-rise' method of identification was not appropriate either. The earliest date to expect constant temperatures above freezing, and for actual growth to occur is mid-March. The NDVI values at this time were generally between 110 and 115, with most areas registering NDVI of ≥115 by mid-April, so I selected an NDVI value of ≥115 to measure growing season duration. This choice resulted in variable seasonal lengths that should reflect individual land cover seasonal phenologies. At this point, images in which all sample means ≤115 were deleted. The final list of images used in the analysis, including dates of coverage, and Julian Day mid-point of each two-week interval, are reproduced in Table 5.

Table 5. Final List of Images Used in Analysis: Year, Image Number, Dates and Julian Day midpoint of NDVI Images (Part 1).

Year	Image Number	Calendar Days	Julian Days	(Mid)
1988	1 & (2)	3/29 - 4/07	088 - 097	(092)
	3 & (4)	4/13 - 4/24	103 - 114	(108)
	5 & (6)	4/26 - 5/07	116 - 127	(121)
	7 & (8)	5/10 - 5/23	130 - 143	(137)
	9 & (10)	5/25 - 6/06	145 - 157	(151)
	11 & (12)	6/07 - 6/20	158 - 171	(164)
	13 & (14)	6/21 - 7/04	172 - 185	(178)
	15 & (16)	7/06 - 7/17	187 - 198	(193)
	17 & (18)	7/23 - 7/31	204 - 212	(208)
	19 & (20)	8/02 - 8/14	214 - 226	(220)
	21 & (22)	8/19 - 8/25	231 - 239	(235)
	23 & (24)	8/30 - 9/10	242 - 253	(247)
	25 & (26)	9/17 - 9/24	260 - 274	(267)
	27 & (28)	9/29 -10/10	279 - 290	(285)
	29 & (30)	10/12-10/23	292 - 303	(298)
1989	5	3/29 - 4/11	088 - 101	(095)
	6	4/12 - 4/25	102 - 115	(109)
	7	4/26 - 5/09	116 - 129	(123)
	8	5/10 - 5/23	130 - 143	(137)
	9	5/24 - 6/06	144 - 157	(151)
	10	6/07 - 6/20	158 - 171	(165)
	11	6/21 - 7/04	172 - 185	(179)
	12	7/05 - 7/18	186 - 199	(195)
	13	7/19 - 8/01	200 - 213	(207)
	14	8/02 - 8/15	214 - 227	(221)
	15	8/16 - 8/29	228 - 241	(235)
	16	8/30 - 9/12	242 - 255	(249)
	17	9/13 - 9/26	256 - 269	(263)
	18	9/27 -10/10	270 - 283	(277)
	19	10/11-10/24	284 - 297	(291)
	20	11/01-11/14	305 - 318	(312)
1990	2	3/16 - 3/29	075 - 088	(082)
	3	3/30 - 4/12	089 - 102	(096)
	4	4/13 - 4/26	103 - 116	(109)
	5	4/27 - 5/10	117 - 130	(123)
	6	5/11 - 5/24	131 - 144	(137)

Table 5. Final List of Images Used in Analysis: Year, Image Number, Dates and Julian Day midpoint of NDVI Images (Part 2).

Year	Image Number	Calendar Days	Julian Days	(Mid)
	7	5/25 - 6/07	145 - 158	(151)
	8	6/08 - 6/21	159 - 172	(165)
	9	6/22 - 7/05	173 - 186	(179)
	10	7/06 - 7/19	187 - 200	(193)
	11	7/20 - 8/02	201 - 214	(207)
	12	8/03 - 8/16	215 - 228	(221)
	13	8/17 - 8/30	229 - 242	(235)
	14	8/31 - 9/13	243 - 256	(249)
	15	9/14 - 9/27	257 - 270	(263)
	16	9/28 -10/11	271 - 284	(278)
	17	10/12-10/25	285 - 298	(292)
	18	11/09-11/29	313 - 326	(320)
1991	5	3/29 - 4/11	088 - 101	(095)
	6	4/12 - 4/25	102 - 115	(108)
	7	4/26 - 5/09	116 - 129	(122)
	8	5/10 - 5/23	130 - 143	(136)
	9	5/24 - 6/06	144 - 157	(150)
	10	6/07 - 6/20	158 - 171	(164)
	11	6/21 - 7/04	172 - 185	(178)
	12	7/05 - 7/18	186 - 199	(192)
	13	7/19 - 8/01	200 - 213	(206)
	14	8/02 - 8/15	214 - 227	(220)
	15	8/16 - 8/29	228 - 241	(234)
	16	8/30 - 9/12	242 - 255	(248)
	17	9/13 - 9/26	256 - 269	(262)
	18	9/27 -10/10	270 - 283	(277)
	19	10/11-10/24	284 - 297	(291)
	20	11/08-11/21	312 - 325	(319)
1992	4	3/20 - 4/02	080 - 093	(087)
	5	4/03 - 4/16	094 - 107	(101)
	6	4/17 - 4/30	108 - 121	(114)
	7	5/01 - 5/14	122 - 135	(128)
	8	5/15 - 5/28	136 - 149	(142)
	9	5/29 - 6/11	150 - 163	(156)
	10	6/12 - 6/25	164 - 177	(170)
	11	6/26 - 7/09	178 - 191	(184)

Table 5. Final List of Images Used in Analysis: Year, Image Number, Dates and Julian Day midpoint of NDVI Images (Part 3).

Year	Image Number	Calendar Days	Julian Days	(Mid)
	12	7/10 - 7/23	192 - 205	(198)
	13	7/24 - 8/06	206 - 219	(212)
	14	8/07 - 8/20	220 - 233	(226)
	15	8/21 - 9/03	234 - 247	(240)
	16	9/04 - 9/17	248 - 261	(254)
	17	9/18 -10/01	262 - 275	(268)
	18	10/02-10/15	276 - 289	(283)
	19	10/16-10/29	290 - 303	(297)
1993	4	3/19 - 4/01	078 - 091	(085)
	5	4/02 - 4/15	092 - 105	(099)
	6	4/16 - 4/29	106 - 119	(112)
	7	4/30 - 5/13	120 - 133	(126)
	8	5/14 - 5/27	134 - 147	(140)
	9	5/28 - 6/10	148 - 161	(154)
	10	6/11 - 6/24	162 - 175	(169)
	11	6/25 - 7/08	176 - 189	(182)
	12	7/09 - 7/22	190 - 203	(196)
	13	7/23 - 8/05	204 - 217	(210)
	14	8/06 - 8/19	218 - 231	(224)
	15	8/20 - 9/02	232 - 245	(238)
	16	9/03 - 9/16	246 - 259	(252)
	17	9/17 - 9/30	260 - 273	(266)
	18	10/01-10/14	274 - 287	(281)
	19	10/15-10/28	288 - 301	(295)
	20	11/12-11/25	316 - 329	(323)

The integrated growing season NDVI ($\sum$NDVI) was computed using the following formula:

$$\sum NDVI = \left(115 + \frac{a_2 - a_1}{2}\right) + \left(\sum_{i=2}^{n-1} \min(a_i, a_{i+1}) + \frac{|a_{i+1} - a_i|}{2}\right) + \left(115 + \frac{a_{n-1} - a_n}{2}\right) \quad [2]$$

where n represents the number of time segments, and a is the consecutive NDVI values, which were summed to estimate total seasonal values.

Precipitation Data

An ASCII file, listing all weather station geographic locations (n = 2385) for the five-state area, was used to generate a point coverage within ARC/INFO. This point coverage was then converted to a raster format, with 1 km^2 pixel representing each station. This map was georeferenced to the Lambert Azimuthal Equal Area projection, and reduced to incorporate only those stations that were located entirely within the eight ecoregion/grassland areas, for a total of 555 stations. Initially, ten stations from each area were selected randomly, but numerous sites had incomplete precipitation records and were discarded. Because area 43-2 was substantially larger than most of the other zones, the random sampling was expanded to 15 stations, with a final station count of 11. Thus, the total count for stations included in this study was 69 as shown in Figure 6 and listed in Table 6.

Since the station locations were recorded to the nearest minute, positional accuracy can vary from 1.3 to 1.8 km (1 minute $\doteq$ 20 x 65 m running east-west or 20 x 93 m running north-south). These differences justify adding one kilometer in each direction, i.e. a single pixel, in order to include all possible pixels where the station may be located, creating a 3 x 3 neighborhood, or a 9 km^2 zone

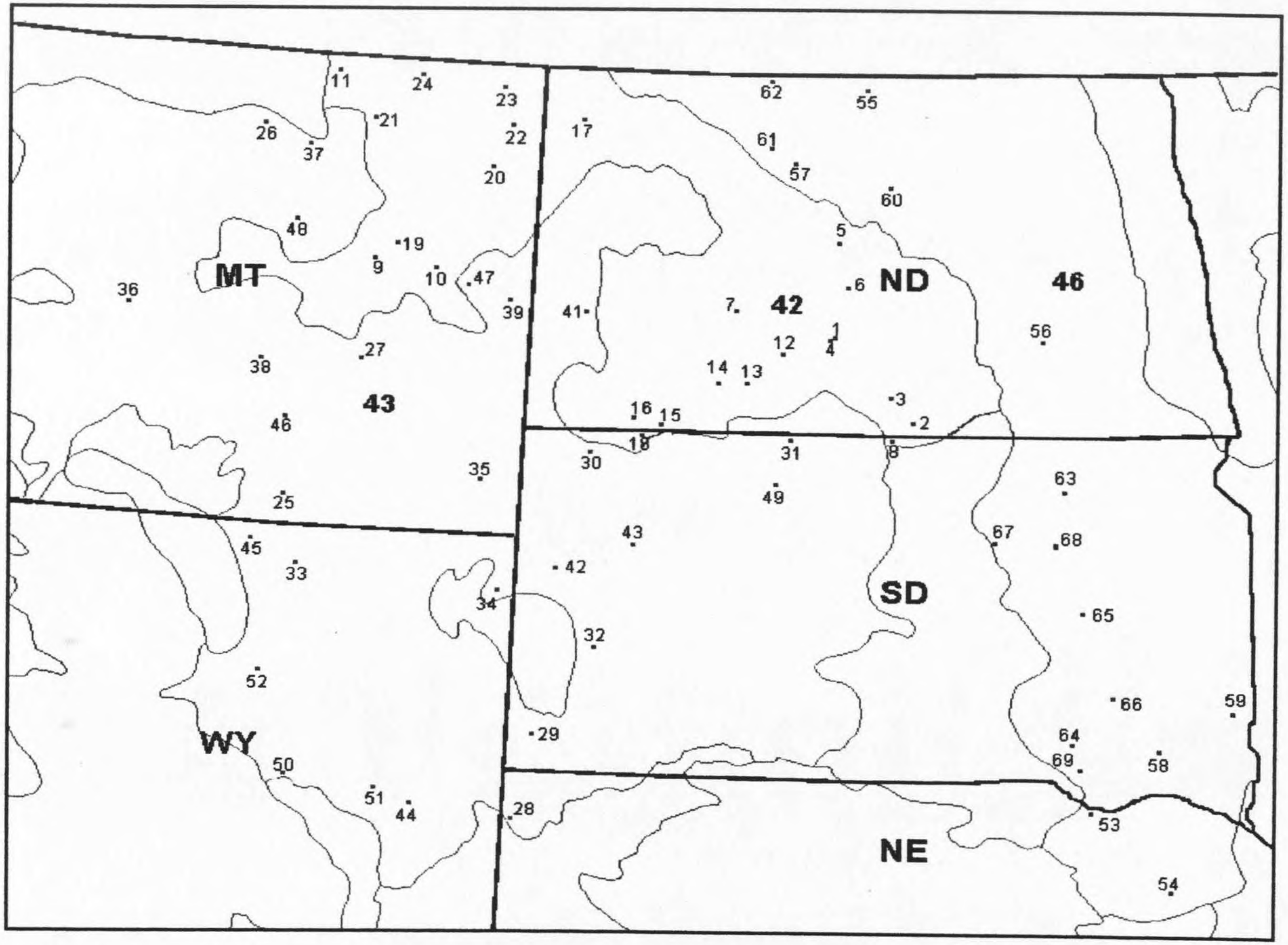


Figure 6. Map of precipitation stations (69) used in current study.

Table 6. Names and Geographic Coordinates of Precipitation Stations (Part 1).

ID#	State	Area	Location	Latitude	Longitude
1	ND	421	BISMARCK AP	46.7667	-100.767
2	ND	421	HAGUE	46.0333	-100.00
3	ND	421	LINTON	46.25	-100.233
4	ND	421	MANDAN EXP ST	46.80	-100.90
5	ND	421	MAX	47.8167	-101.30
6	ND	421	TURTLE LAKE	47.5167	-100.883
7	ND	421	ZAP	47.2833	-101.917
8	SD	421	POLLOCK	45.90	-100.283
9	MT	422	BROCKWAY3SW	47.2833	-105.817
10	MT	422	LINDSAY	47.2333	-105.15
11	MT	422	OPHEIM 12SE	48.70	-106.317
12	ND	422	ALMONT	46.7167	-101.517
13	ND	422	CARSON	46.4167	-101.567
14	ND	422	ELGIN	46.3667	-101.85
15	ND	422	HETTINGER	45.9833	-102.65
16	ND	422	REEDER	46.10	-102.95
17	ND	422	WILLISTON AP	48.1833	-103.633
18	SD	422	LEMMON	45.9333	-102.167
19	MT	423	CIRCLE	47.4333	-105.583
20	MT	423	CULBERTSON	48.15	-104.50
21	MT	423	LUSTRE 4NW	48.45	-105.933
22	MT	423	MEDICINE L. 3SE	48.4833	-104.45
23	MT	423	PLENTYWOOD	48.7833	-104.55
24	MT	423	SCOBEY 3N	48.8333	-105.433
25	MT	431	BIRNEY	45.3167	-106.517
26	MT	431	MALTA 7E	48.40	-107.733
27	MT	431	MILES CITY AP	46.4333	-105.867
28	NE	431	AGATE 3E	42.45	-103.833
29	SD	431	EDGEMONT	43.30	-103.817
30	SD	431	GLADVALLEY 2W	45.40	-101.817
31	SD	431	MCINTOSH 6SE	45.8833	-101.30
32	SD	431	RAPIDCITY	44.0833	-103.267
33	WY	431	CLEARMONT5SW	44.5833	-106.45
34	WY	431	SUNDANCE	44.40	-104.35

Table 6. Names and Geographic Coordinates of Precipitation Stations (Part 2).

ID#	State	Area	Location	Latitude	Longitude
35	MT	432	BELLTOWER	45.65	-104.383
36	MT	432	FLATWILLOW4NE	46.85	-108.317
37	MT	432	GLASGOW AP	48.2167	-106.617
38	MT	432	INGOMAR 11NE	46.70	-107.217
39	MT	432	WIBAUX 2E	46.9833	-104.15
40	NE	432	HARRISON	42.6833	-103.883
41	ND	432	MEDORA	46.9167	-103.517
42	SD	432	BELLE FOURCHE	45.00	-103.916
43	SD	432	DUPREE	44.833	-101.616
44	WY	432	DOUGLASAV	42.75	-105.383
45	WY	432	SHERIDAN FLD	44.8333	-106.833
46	MT	433	COLSTRIP	45.8833	-106.617
47	MT	433	GLENDIVE	47.10	-104.717
48	MT	433	JORDAN	47.3167	-106.90
49	SD	433	MOBRIDGE	45.516	-100.466
50	WY	433	CASPERAP	42.9167	-106.467
51	WY	433	GLENRCK 5SE	42.8333	-105.783
52	WY	433	KAYCEE	43.7167	-106.633
53	NE	461	NIOBRARA	42.75	-98.0333
54	NE	461	NORFOLK AP	41.9833	-97.4333
55	ND	461	BOTTINEAU	48.8333	-100.45
56	ND	461	JAMESTOWN AP	46.9167	-98.6833
57	ND	461	MINOT EXPST	48.1833	-101.30
58	SD	461	MENNO	43.2333	-97.5833
59	SD	461	SIOUX FALLS AP	43.5667	-96.7333
60	ND	462	DRAKE8NE	48.0333	-100.283
61	ND	462	FOXHOLM7N	48.4333	-101.55
62	ND	462	SHERWOOD 3N	49.00	-101.633
63	SD	462	ABERDEENAP	45.45	-98.4333
64	SD	462	ARMOUR	43.3167	-98.35
65	SD	462	HURON AP	44.383	-98.2166
66	SD	462	MITCHELL	43.70	-97.966
67	SD	462	ORIENT	44.8833	-99.0833
68	SD	462	REDFIELD 6E	44.8833	-98.3833
69	SD	462	WAGNER	43.0833	-98.30

representing each climate station. This precipitation zone map was then used as a mask to extract mean NDVI values from each image, which were exported as an ASCII file to SAS for regression analysis.

Statistical Analysis Design

Mean NDVI

The statistical design was a two-factor ANOVA of ecoregion and grassland in SAS. The 100 NDVI random samples drawn from each year, image and the eight ecoregion and grassland combinations resulted in the following number of observations by year: 1988 = 97, 1989 = 104, 1990 = 111, 1991 = 104, 1992 = 109, and 1993 = 107, for a total of 632 observations. Only those samples with average mean NDVI values $\geq$ 115 (growing season) were used in the analysis, so the unbalanced design required use of the General Linear Model (GLM) procedure in SAS. The data set was examined for normal distribution and equal variance prior to the ANOVA by comparison of sample means to medians, sample means to population means, and variability of standard deviation (SD) within the groups. The population and sample means were virtually identical and sample means to medians occasionally varied by one NDVI unit. Variation of SD is considered acceptable if the ratio of highest to lowest is <2, so the assumption of equal variance was not violated. If sample sizes are large ($n > 30$) or equal in size, the ANOVA F test is considered robust enough to use with data of moderate non-normality and unequal variance (Moore and McCabe, 1989; McGrew and Monroe,1993).

Other NDVI Metrics

Onset, end, duration of greenness, time of maximum NDVI, maximum NDVI and integrated NDVI values were examined for differences between them and aggregated into ecoregion/grassland types and year using descriptive statistics to measure central tendencies and dispersion. The time-dependent variables were compared in Julian day units, and the analysis examined the mean, standard deviation, variance and range of each aggregation.

NDVI and Precipitation

The NDVI images recorded values at approximately two-week intervals, whereas the precipitation data were tallied on a monthly basis, yielding roughly twice as many NDVI values as precipitation values. In addition, the dates of the images rarely coincided neatly with the start and end of individual months (Table 5). Two NDVI data sets were created corresponding to the first and second two weeks of each month, and the two-week NDVI values were matched with monthly precipitation totals at approximately 2-4, 4-6, and 6-10 week intervals (lags). Stepwise multiple regression was used to explore the relationships between the NDVI values reported in the first two weeks of each growing season month and precipitation in the previous two months. Hence, the NDVI values reported for the period 26 April through 10 May 1990 were compared with the climate station precipitation totals in March and April of that year. Ecoregion and grassland cover types were used as indicator variables in subsequent regression models, and only those variables with p values ≤ 0.05 were retained in the final models. The same approach was used for the NDVI data set corresponding to the second half of each month except that these values were compared to the precipitation in the current month as well as the previous two months.

CHAPTER 3

RESULTS

Variability of NDVI

NDVI Metrics

Plots of the growing season mean NDVI of the eight ecoregion/grassland areas from 1988 through 1993 are shown in Figure 7. The *x*-axis shows mean NDVI values during two-week time periods from mid-March until early November, and the *y*-axis reflects NDVI values $\geq$115 to 155. The shape of the temporal curves pulses as senescence approached in each of the first four graphs. In contrast, 1992 and 1993 had a low initial green-up, a plateau or drop in values, then a rapid rise to maximum peaks in mid-season, and a later, small jump in NDVI.

Area 46-2, the grasslands in ecoregion 46 (eastern Nebraska, North and South Dakota) consistently had earliest green-up and the highest NDVI values. Area 46-1, the crop/grasslands in the same sector, tended to be the next highest, followed closely by 42-1, the crop/grasslands in the central part of the study area. Area 42-1 peaked at a higher NDVI value than 46-1 in 1991. Area 43-3 (western

Figure 7. Seasonal Mean NDVI Curves for Eight Ecoregion/Grassland Zones of the Northern Great Plains from 1988-1993 (Part 1).

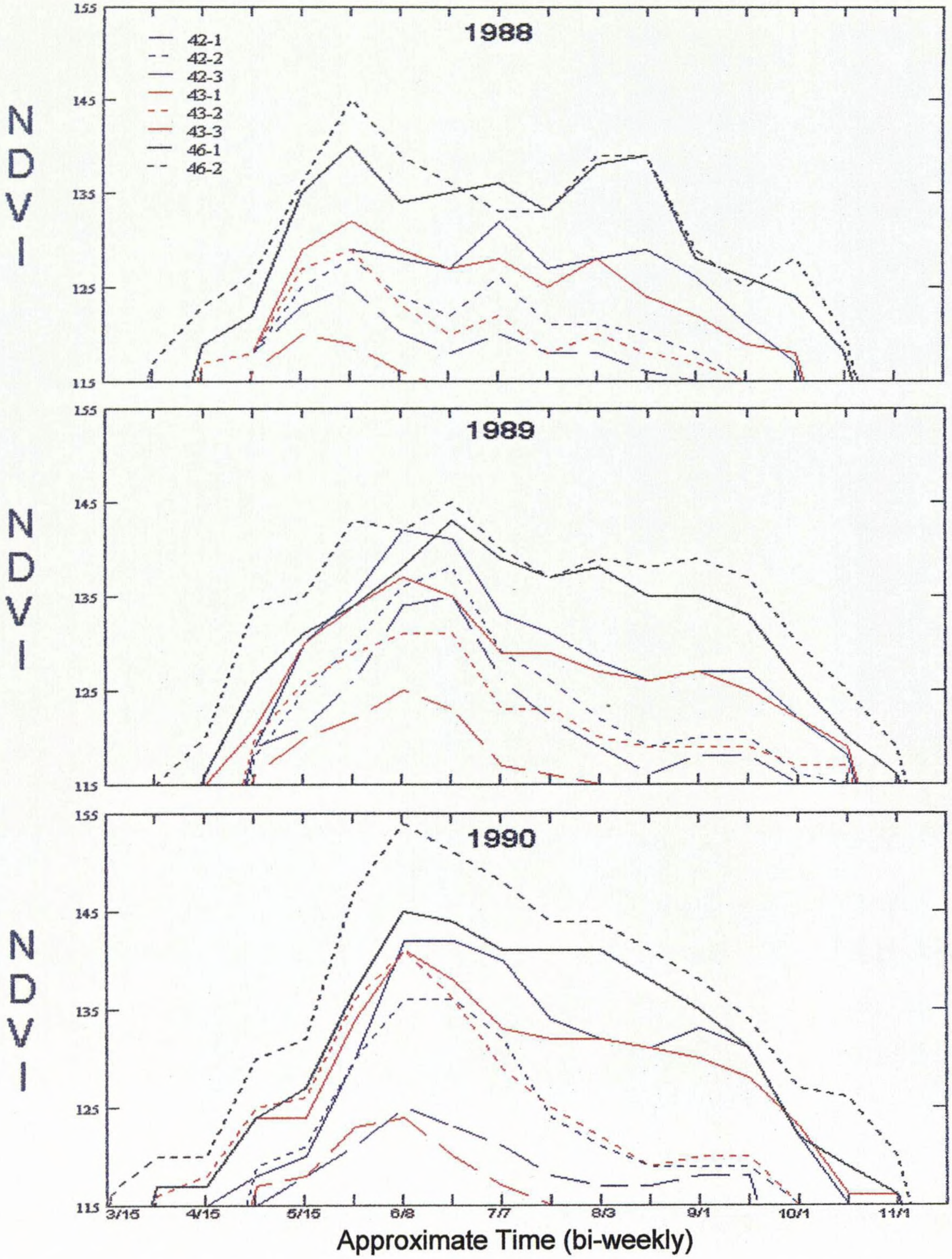
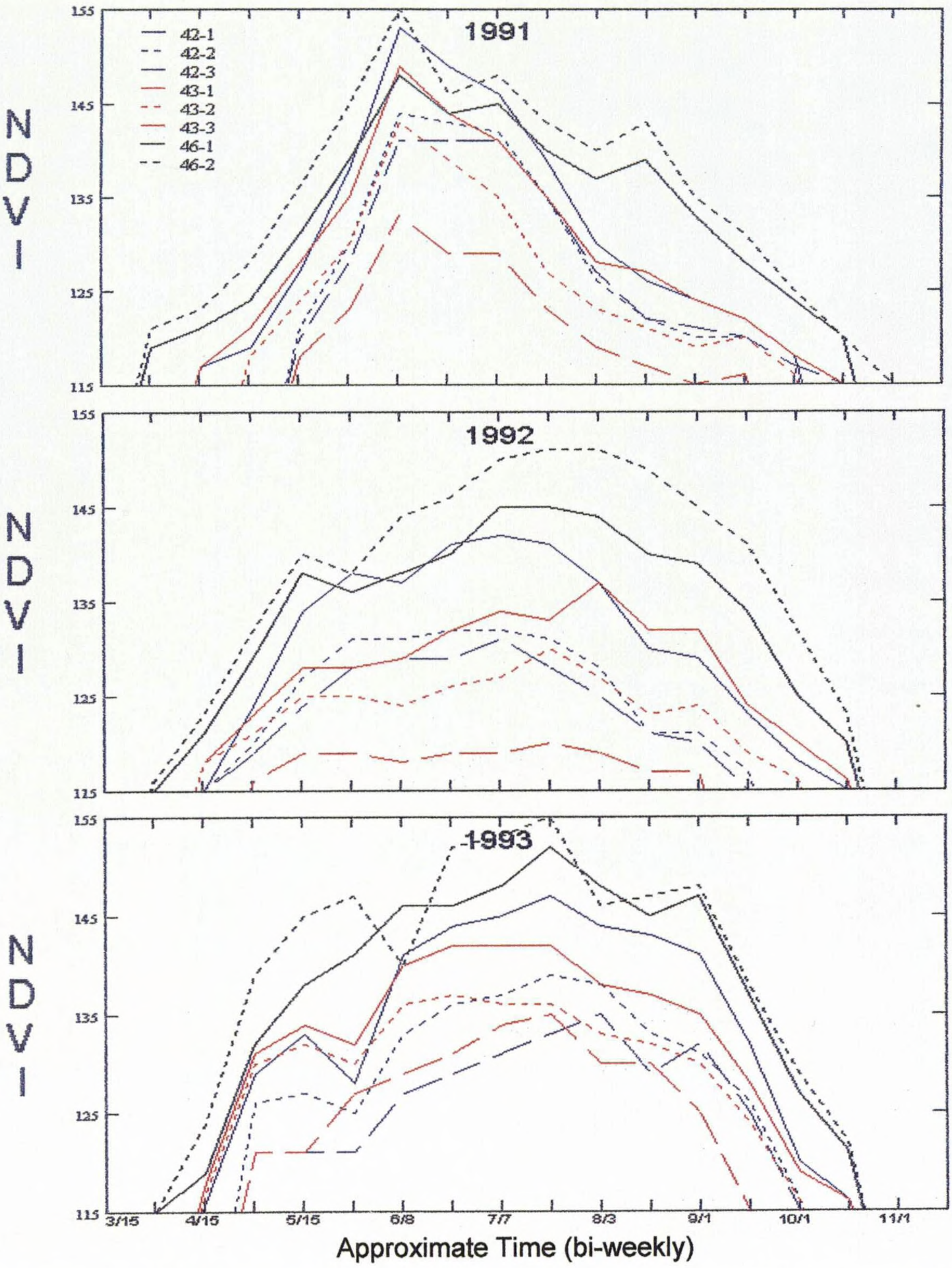


Figure 7. Seasonal Mean NDVI Curves for Eight Ecoregion/Grassland Zones of the Northern Great Plains from 1988-1993 (Part 2).



shrub/grassland) had the shortest growing season and the lowest NDVI values in all six years. Although the maximum NDVI in 43-3 approached that in 42-3 in 1990 and 1993, the 43-3 growing season was shorter in both years. Areas 42-2, 42-3, 43-1 and 43-2 occupied the middle ranges in the temporal curves. Generally, area 43-1 was inclined to have a longer season and higher maximum NDVI than 42-2. Area 42-3 and 43-2 were quite similar, except in 1990, when 43-2 is unusually low.

Additional trends and patterns can be observed by comparing some of the other NDVI metrics by ecoregion/landcover type and year (Table 7). For example, it was difficult to assess which year had the greatest green standing biomass by comparing the time plots of 1991, 1992 and 1993. Although 1991 had higher peak NDVI values in most areas compared to 1992 and 1993, 1993 showed higher total NDVI values in six of the eight regions. In addition, 1991 and 1992 displayed almost identical total NDVI values in most regions, notwithstanding the disparate shapes of the growing season curves. The total NDVI for 1988 was lowest in seven of the eight regions, although the 1989 total NDVI values were less than 5 percent higher than those recorded for 1988 in two out of eight areas. The contrast between 1988 and 1993 NDVI was the most dramatic, showing a 20 percent difference (as compared to approximately 10-15 percent difference for other years).

The onset, end, duration and time of maximum NDVI values must be interpreted with caution. The dates of image acquisition between years did not

Table 7. Selected NDVI Metrics by Ecoregion/Grassland Cover Type and Year (Part 1).

Year/Area	Onset ≥115	End <115	Duration	Time of Peak	Peak NDVI	ΣNDVI
42-1 (Ecoregion 42, grass/crop)						
88	108	298	190	193	132	1619
89	123	312	189	165	142	1669
90	109	320	211	179	143	1805
91	108	291	183	164	153	1736
92	114	325	211	198	142	1709
93	112	323	211	210	147	1788
42-2 (Ecoregion 42, grassland)						
88	108	285	177	151	128	1372
89	123	312	189	179	138	1556
90	123	292	169	165	137	1468
91	136	291	155	164	144	1461
92	114	283	169	198	133	1448
93	126	295	169	210	139	1615
42-3 (Ecoregion 42, grass/shrub)						
88	108	267	159	137	123	1225
89	123	291	168	179	135	1410
90	123	278	155	165	125	1282
91	136	319	183	192	142	1509
92	114	283	169	198	131	1369
93	126	295	169	224	134	1480
43-1 (Ecoregion 43, grass/crop)						
88	108	298	190	151	132	1627
89	109	312	203	165	137	1753
90	109	320	211	165	141	2016
91	108	319	211	164	149	1766
92	114	325	211	224	137	1756
93	112	323	211	210	143	1797
43-2 (Ecoregion 43, grassland)						
88	108	298	190	151	129	1481
89	123	312	189	179	132	1620
90	109	292	183	165	141	1662

Table 7. Selected NDVI Metrics by Ecoregion/Grassland Cover Type and Year (Part 2).

Year/Area	Onset ≥115	End <115	Duration	Time of Peak	Peak NDVI	ΣNDVI
91	122	291	169	164	143	1543
92	114	297	183	212	130	1616
93	112	295	183	182	137	1479
43-3 (Ecoregion 43, grass/shrub)						
88	121	193	072	151	119	473
89	123	291	168	165	125	858
90	123	249	126	165	124	764
91	136	277	141	164	133	1233
92	128	268	140	212	120	1184
93	126	295	169	224	135	1480
46-1 (Ecoregion 46, grass/crop)						
88	108	298	190	151	140	1846
89	109	320	211	179	143	1864
90	109	320	211	165	145	2041
91	081	319	238	164	148	2010
92	087	325	238	198	146	2066
93	099	323	224	210	152	2063
46-2 (Ecoregion 46, grassland)						
88	108	298	190	151	145	1909
89	095	320	225	179	145	2057
90	095	320	225	165	154	2272
91	081	319	238	164	155	2137
92	101	325	224	212	152	2115
93	085	323	238	210	155	2216

match very well, and differences between the above mentioned metrics may be inflated due to the date offsets. For instance, area 43-2 showed 1988 as having the longest growing season duration, which seems unlikely. Considering the date offsets, the duration span for 43-2 was actually very similar for all years except 1991, which did have an abbreviated season according to the curves. This shorter season in 1991 was also apparent for 42-1, 42-2 and 43-3, whereas the longest growing season was recorded for 42-3 in 1991. However, the duration of the growing season did not vary much from year to year for several ecoregion/grassland cover types.

Onset values were very consistent in 1988. All areas started measurable green-up on Julian day 108, except 43-3, which shows delayed onset. This area also exhibited a very early end to phenological activity, and a very low peak NDVI. Area 46-1 generally had the earliest starting dates, and end-of greenness was identical between 46-1 and 46-2. Duration was also quite similar, but the higher integrated NDVI for 46-2 can be explained by the greater maximum values. 1992 and 1993 consistently had the latest peak NDVI, and 1988 the earliest, except in area 42-1. 1991 generally had the highest maximum NDVI, except in 43-3 and 46-1.

The metrics were then evaluated by aggregating the data by ecoregion-grassland cover type and years, and calculating a series of summary statistics. Table 8 summarizes the mean, standard deviation (SD), coefficient of variation, and range for each metric and ecoregion-grassland cover type. The mean results for onset or start of greenness show a range of 32 days across cover types. The same is not true for the end and duration of greenness that showed much higher levels of variability between ecoregion-grassland cover types. The

Table 8. NDVI metrics summarized by ecoregion and grassland cover type (Part 1).

Metric	Class	Mean	SD	CoV	Range
Onset	42-1	112	5.7	0.05	15
(Julian days)	42-2	121	9.7	0.08	28
	42-3	121	9.7	0.08	28
	43-1	110	2.4	0.02	6
	43-2	114	6.4	0.06	15
	43-3	126	5.4	0.04	15
	46-1	98	12	0.12	28
	46-2	94	9.9	0.11	27
End	42-1	311	14	0.05	34
(Julian days)	42-2	293	10	0.03	29
	42-3	288	17	0.06	52
	43-1	316	9.9	0.03	27
	43-2	297	7.6	0.03	21
	43-3	262	37	0.14	102
	46-1	317	9.8	0.03	27
	46-2	317	9.8	0.03	27
Duration	42-1	199	18	0.09	28
(Julian days)	42-2	171	11	0.06	34
	42-3	167	9.7	0.06	28
	43-1	206	8.5	0.04	21
	43-2	182	7.4	0.04	21
	43-3	136	35	0.26	97
	46-1	218	18	0.08	48
	46-2	223	17	0.08	48
Time of Max.	42-1	184	18	0.10	46
(Julian days)	42-2	177	22	0.12	59
	42-3	182	29	0.16	87
	43-1	179	29	0.16	73
	43-2	175	21	0.12	61
	43-3	180	30	0.17	73
	46-1	177	22	0.12	59
	46-2	180	25	0.14	61

Table 8. NDVI metrics summarized by ecoregion and grassland cover type (Part 2).

Metric	Class	Mean	SD	CoV	Range
Max. NDVI	42-1	143	6.9	0.05	21
	42-2	136	5.4	0.04	16
	42-3	131	6.8	0.05	18
	43-1	139	5.8	0.04	17
	43-2	135	5.9	0.04	14
	43-3	126	6.6	0.05	16
	46-1	145	4.1	0.03	12
	46-2	150	4.7	0.03	10
ΣNDVI	42-1	1721	71	0.04	186
	42-2	1487	86	0.06	243
	42-3	1379	111	0.08	284
	43-1	1786	127	0.07	389
	43-2	1567	77	0.05	183
	43-3	999	367	0.37	1007
	46-1	1982	100	0.05	220
	46-2	2118	127	0.06	363

time at which the maximum NDVI value was recorded and the magnitude of the maximum values were fairly similar for all areas. The largest maximum values were reported for cover types 46-1 and 46-2. This result reflects their favorable geographic locations (Figure 4). The lowest values were calculated for 43-3 followed by 42-3, as would be expected of grass/shrub cover.

The sum of the NDVI values (ΣNDVI) integrates the aforementioned metrics as it combines the length and magnitude of greenness values larger than 115 by ecoregion/grassland cover type. The largest integrated NDVI totals occurred in ecoregion/grassland cover types 46-1 and 46-2. Types 43-1 and 42-1 came next, and all four of these classes were characterized by low year-to-year variability (i.e., low coefficients of variation). Ecoregion/grassland cover types 43-2, 42-2, and 42-3 displayed intermediate mean values with low year-to-year variability. Ecoregion/grassland cover type 43-3 was unique in that the mean was much lower and the annual variability much higher compared to the other ecoregion/grassland cover types.

Table 9 summarizes the same metrics by year as opposed to ecoregion/grassland cover type. The earliest and latest onsets of greenness were recorded in 1988 and 1989 respectively, although the differences were small and much less than the differences reported across ecoregion/grassland cover types. The mean dates for the end and duration of greenness varied by ≤ 30 days across the six years. This variability matched the within-year variability for the end of greenness in two of the six years (1989, 1993). Three years (1988 and to a lesser extent 1990 and 1992) displayed much higher variability for end of greenness across key ecoregion/grassland cover types. The duration of greenness varied by more than 90 days in four of the six years (1988, 1990-92) and is indicative of a large range of growing conditions across the study area. The time and magnitude of maximum NDVI metrics show an earlier and lower peak value in 1988 and later occurrences of maximum NDVI values in 1992 and1993. In addition, the timing of the maximum NDVI values was much more variable in 1988 and 1993 than the other years, and the magnitudes of the

Table 9. NDVI metrics summarized by year.

Metric	Year	Mean	SD	CoV	Range
Onset	1988	109	4.5	0.04	28
(Julian days)	1989	116	10	0.09	28
	1990	112	9.8	0.09	28
	1991	113	23	0.20	55
	1992	110	12	0.11	41
	1993	112	14	0.13	41
End	1988	279	36	0.13	105
(Julian days)	1989	308	11	0.04	29
	1990	298	26	0.09	71
	1991	303	17	0.06	42
	1992	303	23	0.08	57
	1993	309	14	0.05	28
Duration	1988	169	41	0.24	118
(Julian days)	1989	192	19	0.10	57
	1990	186	34	0.18	99
	1991	189	36	0.19	97
	1992	193	33	0.17	98
	1993	196	27	0.14	69
Time of Max.	1988	154	16	0.10	56
(Julian days)	1989	173	7.2	0.04	14
	1990	166	4.9	0.03	14
	1991	167	9.8	0.06	28
	1992	206	9.8	0.05	26
	1993	210	12	0.06	42
Max. NDVI	1988	131	8.4	0.06	26
	1989	137	6.5	0.05	20
	1990	138	10	0.07	30
	1991	145	7.0	0.05	22
	1992	136	9.9	0.07	31
	1993	142	7.9	0.06	21
$\sum$NDVI	1988	1444	453	0.31	1436
	1989	1598	358	0.22	1199
	1990	1664	485	0.29	1508
	1991	1674	299	0.18	904
	1992	1658	325	0.20	931
	1993	1740	282	0.16	737

maximum values were more consistent than the other metrics.

The $\sum$NDVI values confirmed that 1988 and 1993 were the lowest and highest NDVI years. The 1993 mean was 20.5% larger than the 1988 mean and these two years also displayed the lowest (1993) and largest (1988) variability across ecoregion/grassland cover types. The 1990-1992 means were very similar, although 1990 was more variable than the other two years. A comparison of the coefficient of variation values reported for $\sum$NDVI in Tables 8 and 9 shows that the variability within years was substantially higher than the variability within ecoregion/grassland cover types (with the exception of ecoregion/grassland cover type 43-3). This variability was explored further with Analysis of Variance (ANOVA) and the results are reported in the next section.

ANOVA

An ANOVA procedure was used to test the hypothesis that there were no significant differences between the eight ecoregion/grassland areas from 1988 through 1993. Accepting the null hypothesis required that variation between the sample means was no larger than would occur by chance, producing an *F*-ratio near one. There appeared to be significant differences between the eight areas in three out of six years, based on the large *F*-ratio values, therefore the null hypothesis was rejected. Table 10 summarizes the *F*-ratio and *P*-values for sources of variance due to ecoregion, grassland and their interaction in separate years. Notably, the null hypothesis was not rejected in all cases, so the means in

Table 10. Type III General Linear Models Procedure (GLM) ANOVA Results.

	Ecoregion		Grassland		Ecoregion*Grassland	
	F Ratio	Pr>F	F Ratio	Pr>F	F Ratio	Pr>F
1988	20.69	.0001	7.95	.0007	4.84	.0036
1989	10.49	.0001	6.28	.0027	7.68	.0001
1990	25.61	.0001	26.22	.0001	2.34	.0779
1991	2.40	.0958	6.97	.0015	1.95	.1262
1992	18.62	.0001	18.49	.0001	5.36	.0018
1993	6.04	.0033	14.24	.0001	0.73	.5372

these cases were indistinguishable from the other means. Grouping the means by ecoregion produced one nonsignificant value in 1991 (*P*>.0958). The null hypothesis was rejected for all grassland groupings, but the interaction effect of ecoregion/grassland classification proved nonsignificant for 1990, 1991 and 1993.

NDVI and Precipitation

The second objective was to examine the connection between rainfall and NDVI response by year, ecoregion, grassland cover, and ecoregion/grassland cover types. Tables 11-15 summarize these results for two subsets of NDVI values: one set corresponds to the first two weeks of each month, and the other corresponds to the second two weeks in each month. This split was necessary because the first half-month NDVI values were regressed against the previous one and two month precipitation totals, and the second half month NDVI values were regressed against the same month and previous one and two month precipitation totals. The effective lags measured 0-6 and 4-10 weeks for the first half NDVI values and the previous 1 and 2 month precipitation totals, respectively. The effective lags measured 0-2, 2-8, and 6-12 weeks for the second half NDVI values and the same month, previous 1 and 2 month precipitation totals, respectively.

Table 11 summarizes the results of regressing NDVI against precipitation across all eight ecoregion/grassland cover types. The precipitation two months before NDVI was measured explained most of the variability in first half NDVI (35 percent on average) suggesting a lag of 4-10 weeks between NDVI and precipitation. The previous month's precipitation had a minor but significant impact on NDVI in two out of six individual years. The second half NDVI results were roughly similar (previous one and two month precipitation explained 37 percent of the variability in NDVI) with previous one and two month precipitation explaining most of the variability in second half NDVI in three out of six years and some variability in every year. The cumulative results showed that the previous month's precipitation explained more of the variability in NDVI and that a lag of 2-8 weeks best represented the relationship between NDVI and precipitation in this instance.

Table 11. Multiple Regression Results for NDVI Regressed against Precipitation by Year (Part 1).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
1988					
	Dependent variable: NDVI (1st half)				
	Intercept	119.94			
1	Precip2[1]	3.03	0.181	0.181	0.0001
2	Precip1[2]	1.35	0.023	0.204	0.0002
	Dependent variable: NDVI (2nd half)				
	Intercept	116.16			
1	Precip2	4.00	0.316	0.316	0.0001
2	Precip1	1.81	0.054	0.370	0.0001
3	Precip0[3]	0.94	0.010	0.380	0.0060
1989					
	Dependent variable: NDVI (1st half)				
	Intercept	115.87			
1	Precip2	4.26	0.273	0.273	0.0001
2	Precip1	2.15	0.058	0.331	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	112.83			
1	Precip1	4.02	0.205	0.205	0.0001
2	Precip0	3.06	0.075	0.279	0.0001
3	Precip2	1.90	0.037	0.317	0.0001
1990					
	Dependent variable: NDVI (1st half)				
	Intercept	116.22			
1	Precip2	3.84	0.461	0.461	0.0001
2	Precip1	2.17	0.088	0.549	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	114.74			
1	Precip2	3.25	0.355	0.355	0.0001
2	Precip1	2.63	0.152	0.507	0.0001
3	Precip0	1.31	0.024	0.531	0.0001

Table 11. Multiple Regression Results for NDVI Regressed against Precipitation by Year (Part 2).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
1991					
	Dependent variable: NDVI (1st half)				
	Intercept	114.13			
1	Precip2	2.96	0.366	0.366	0.0001
2	Precip1	2.55	0.169	0.534	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	110.27			
1	Precip1	2.93	0.314	0.314	0.0001
2	Precip2	2.50	0.074	0.388	0.0001
3	Precip0	2.04	0.076	0.464	0.0001
1992					
	Dependent variable: NDVI (1st half)				
	Intercept	117.96			
1	Precip2	4.94	0.427	0.427	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	115.55			
1	Precip2	3.11	0.310	0.310	0.0001
2	Precip1	3.11	0.146	0.456	0.0001
1993					
	Dependent variable: NDVI (1st half)				
	Intercept	119.13			
1	Precip2	2.49	0.429	0.429	0.0001
2	Precip1	1.58	0.107	0.536	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	119.25			
1	Precip1	2.06	0.378	0.378	0.0001
2	Precip2	1.38	0.092	0.470	0.0001
3	Precip0	0.77	0.025	0.495	0.0001

Table 11. Multiple Regression Results for NDVI Regressed against Precipitation by Year (Part 3).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
1988-93					
	Dependent variable: NDVI (1st half)				
	Intercept	119.56			
1	Precip2	3.74	0.349	0.349	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	118.08			
1	Precip1	2.89	0.285	0.285	0.0001
2	Precip2	1.90	0.089	0.373	0.0001

1 Precip2 = precipitation recorded two months prior to NDVI measurements
2 Precip1 = precipitation recorded in month immediately prior to NDVI measurements
3 Precip0 = precipitation recorded in same month as NDVI measurements

Tables 12 and 13 show that larger percentages of the variability in NDVI can be explained if ecoregions or grassland cover types are incorporated in the multiple regression models as indicator (dummy) variables. The regression model in the top half of Table 12, for example, shows that the variability in ecoregion and precipitation explained 43 percent of the variability in NDVI. These results mean that slightly different regression models were constructed for ecoregions 42, 43, and 46 (the default in this instance) as follows:

$$\text{NDVI (first half)} = 119.86 - 0.59\,\text{Pr1} + 3.88\,\text{Pr2} \qquad \text{(Ecoregion 42)} \qquad [3]$$

$$\text{NDVI (first half)} = 118.15 + 3.25\,\text{Pr2} \qquad \text{(Ecoregion 43)} \qquad [4]$$

$$\text{NDVI (first half)} = 125.07 + 3.25\,\text{Pr2} \qquad \text{(Ecoregion 46)} \qquad [5]$$

These models confirm that ecoregion 46 displayed larger NDVI values and the precipitation recorded two months earlier had the largest effect on the maximum NDVI value measured during the first two weeks of each month in the growing season.

The equivalent equations for the NDVI values measured during the second two weeks of each month are:

$$\text{NDVI (2}^{\text{nd}}\text{ half)} = 117.08 + 0.86\text{Pr0} + 2.15\,\text{Pr1} + 2.31\,\text{Pr2} \qquad \text{(Eco 42)} \qquad [6]$$

$$\text{NDVI (2}^{\text{nd}}\text{ half)} = 116.42 + 3.39\,\text{Pr1} + 0.98\text{Pr2} \qquad \text{(Ecoregion 43)} \qquad [7]$$

$$\text{NDVI (2}^{\text{nd}}\text{ half)} = 122.31 + 2.15\,\text{Pr1} + 2.31\,\text{Pr2} \qquad \text{(Ecoregion 46)} \qquad [8]$$

This set of the equations is similar to the first set even though the NDVI values are positively correlated to precipitation in two or three of the previous months since the two week offset in the two sets of NDVI values means the lags are

Table 12. Multiple Regression Results for NDVI Regressed against Ecoregion Type and Precipitation during the Period 1988-93.

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
	Dependent variable: NDVI (1st half)				
	Intercept	125.07			
1	Precip2[1]	3.25	0.349	0.349	0.0001
2	Eco42[2]	-5.21	0.019	0.368	0.0001
3	Ec42 x Pr1[3]	-0.59	0.032	0.400	0.0001
4	Ec42 x Pr2[4]	0.63	0.002	0.402	0.0007
5	Eco43[5]	-6.92	0.030	0.432	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	122.31			
1	Precip1[6]	2.15	0.285	0.285	0.0001
2	Precip2	2.31	0.089	0.374	0.0001
3	Eco42	-5.23	0.008	0.382	0.0001
4	Ec42 x Pr0[7]	0.86	0.006	0.388	0.0001
5	Eco43	-5.89	0.010	0.398	0.0001
6	Ec43 x Pr1[8]	1.24	0.005	0.403	0.0001
7	Ec43 x Pr2[9]	-1.33	0.030	0.433	0.0001

1 Precip2 = precipitation recorded two months prior to NDVI measurements in ecoregion 46 (i.e. the default case for this series of regression models)
2 Eco42 = ecoregion 42
3 Ec42 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in ecoregion 42
4 Ec42 x Pr2 = precipitation recorded two months prior to NDVI measurements in ecoregion 46
5 Eco43 = ecoregion 43
6 Precip1 = precipitation recorded in month immediately prior to NDVI measurements in ecoregion 46
7 Ec42 x Pr0 = precipitation recorded in same month as NDVI measurements in ecoregion 42
8 Ec43 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in ecoregion 43
9 Ec43 x Pr2 = precipitation recorded two months prior to NDVI measurements in ecoregion 43

approximately the same. These two sets of equations, taken as a whole, show that the NDVI values are positively correlated with the precipitation recorded during the previous 4-10 weeks in all three ecoregions (as would be expected) but that the relationship varies slightly from one ecoregion class to the next.

The same patterns hold for the grassland classes as summarized in Table 13. The NDVI measurements for the first two weeks of each month are correlated with precipitation two months prior to the NDVI measurements. Two of the regression curves share the same slope but a different intercept and the other differs in terms of both the intercept and slope as documented in Equations [9] through [11] below:

$$\text{NDVI (1}^{st}\text{ half)} = 121.74 + 3.35\ \text{Pr2} \qquad \text{(Grassland Area 1)} \qquad [9]$$

$$\text{NDVI (1}^{st}\text{ half)} = 119.82 + 3.94\ \text{Pr2} \qquad \text{(Grassland Area 2)} \qquad [10]$$

$$\text{NDVI (1}^{st}\text{ half)} = 116.03 + 3.35\ \text{Pr2} \qquad \text{(Grassland Area 3)} \qquad [11]$$

The equivalent equations reproduced below for the second half NDVI show a similar pattern after allowing for the two week offset and lumpiness of the monthly precipitation data:

$$\text{NDVI (2}^{nd}\text{ half)} = 120.29 + 2.49\ \text{Pr1} + 1.83\ \text{Pr2} \quad \text{(Grassland Area 1)} \qquad [12]$$

Table 13. Multiple Regression Results for NDVI Regressed against Grassland Cover Type and Precipitation during the Period 1988-93 (Part 1).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
	Dependent variable: NDVI (1st half)				
	Intercept	116.03			
2	Precip2[1]	3.35	0.349	0.349	0.0001
3	Grass1[2]	5.71	0.009	0.359	0.0001
4	Grass2[3]	3.79	0.027	0.386	0.0001
5	Pr2 x Gr2[4]	0.59	0.002	0.388	0.0014
	Dependent variable: NDVI (2nd half)				
	Intercept	114.92			
1	Precip1[5]	2.49	0.285	0.285	0.0001
2	Precip2	1.83	0.089	0.373	0.0001
3	Grass1	5.37	0.008	0.381	0.0001
4	Grass2	3.93	0.024	0.405	0.0001
5	Gr2 x Pr1[6]	0.68	0.003	0.407	0.0002

1 Precip2 = precipitation recorded two months prior to NDVI measurements in grassland area 3 (i.e. the default case for this series of regression models)
2 Grass1 = grassland area 1
3 Grass2 = grassland area 2
4 Pr2 x Gr2 = precipitation recorded two months prior to NDVI measurements in grassland area 2
5 Precip1 = precipitation recorded in month immediately prior to NDVI measurements in grassland area 3
6 Gr2 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in grassland area 2

NDVI (2nd half) = 118.85 + 3.17 Pr1 + 1.83 Pr2 (Grassland Area 2) [13]

NDVI (2nd half) = 114.92 + 2.49 Pr1 + 1.83 Pr2 (Grassland Area 3) [14]

These six equations show once again that NDVI (greenness) is positively correlated with precipitation across the study area.

Tables 14 and 15 summarize the results of building regression models with first half and second half NDVI as dependent variables and ecoregion x grassland cover type, precipitation, and the interaction of ecoregion x grassland cover type x precipitation as independent variables. The two models summarized in Table 14 explained a little less than 50 percent of the variability in NDVI in each instance even though we compared two-week maximum NDVI with monthly precipitation. The final models produced with this process are summarized in Table 15 and show the same general trends as the previous models (as would be expected given their components). The correlation coefficients reported in Table 14 and individual regression models summarized in Table 15 indicate that the variability in monthly precipitation in the previous 2-12 weeks can explain approximately 50 percent of the variability in NDVI when the landscape is divided into regional-scale ecoregion and grassland cover types.

Table 14. Multiple Regression Results for NDVI Regressed against Ecoregion Type, Grassland Cover Type, and Precipitation during the Period 1988-93 (Part 1).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
	Dependent variable: NDVI (1st half)				
	Intercept	120.74			
1	Precip2[1]	4.67	0.364	0.364	0.0001
2	Ec42 x Gr1 x Pr1[2]	1.38	0.005	0.369	0.0001
3	Ec42 x Gr1 x Pr2[3]	-1.73	0.002	0.371	0.0001
4	Ec42 x Gr2[4]	-3.43	0.003	0.374	0.0001
5	Ec42 x Gr2 x Pr1[5]	1.75	0.010	0.384	0.0001
6	Ec42 x Gr2 x Pr2[6]	-1.31	0.001	0.385	0.0001
7	Ec42 x Gr3 x Pr2[7]	-2.78	0.015	0.400	0.0001
8	Ec43 x Gr1 x Pr2[8]	-1.54	0.002	0.402	0.0001
9	Ec43 x Gr2[9]	-2.93	0.020	0.422	0.0001
10	Ec43 x Gr2 x Pr2[10]	-1.53	0.002	0.424	0.0001
11	Ec43 x Gr3[11]	-6.26	0.021	0.445	0.0001
12	Ec43 x Gr3 x Pr2[12]	-2.28	0.002	0.447	0.0001
13	Ec43 x Gr3 x Pr1[13]	1.89	0.003	0.450	0.0001
14	Ec46 x Gr1[14]	2.37	0.001	0.451	0.0040
15	Ec46 x Gr1 x Pr1[15]	1.58	0.007	0.458	0.0001
16	Ec46 x Gr1 x Pr2[16]	-2.47	0.005	0.463	0.0001
	Dependent variable: NDVI (2nd half)				
	Intercept	119.86			
1	Precip1[17]	3.08	0.285	0.285	0.0001
2	Precip2	2.48	0.089	0.374	0.0001
3	Ec42 x Gr1 x Pr0[18]	0.54	0.001	0.375	0.0199
4	Ec42 x Gr1 x Pr1	-1.13	0.002	0.377	0.0001
5	Ec42 x Gr2	-3.56	0.003	0.380	0.0001
6	Ec42 x Gr2 x Pr0[19]	1.06	0.003	0.383	0.0001
7	Ec42 x Gr2 x Pr1	-0.61	0.001	0.384	0.0240
8	Ec42 x Gr3 x Pr1[20]	-1.73	0.013	0.397	0.0001
9	Ec42 x Gr3 x Pr2	-1.47	0.003	0.400	0.0001
10	Ec43 x Gr1[21]	-1.61	0.001	0.401	0.0235
11	Ec43 x Gr1 x Pr2[22]	-0.78	0.003	0.404	0.0084
12	Ec43 x Gr2	-2.51	0.003	0.407	0.0001
13	Ec43 x Gr2 x Pr2	-1.79	0.021	0.428	0.0001
14	Ec43 x Gr3	-6.61	0.019	0.447	0.0001

Table 14. Multiple Regression Results for NDVI Regressed against Ecoregion Type, Grassland Cover Type, and Precipitation during the period 1988-93 (Part 2).

Step	Variable	Parameter Estimate	Partial R^2	Model R^2	Prob>F
15	Ec43 x Gr3 x Pr0[23]	1.19	0.003	0.450	0.0015
16	Ec43 x Gr3 x Pr2	-1.30	0.002	0.452	0.0008
17	Ec46 x Gr1 x Pr0[24]	0.83	0.002	0.454	0.0007
18	Ec46 x Gr1 x Pr1	-1.61	0.003	0.457	0.0001

1 Precip2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 46 and grassland area 2 (i.e. the default case for this series of regression models)

2 Ec42 x Gr1 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 42 and grassland area 1

3 Ec42 x Gr1 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 42 and grassland area 1

4 Ec42 x Gr2 = combination of ecoregion 42 and grassland area 2

5 Ec42 x Gr2 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 42 and grassland area 2

6 Ec42 x Gr2 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 42 and grassland area 2

7 Ec42 x Gr3 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 42 and grassland area 3

8 Ec43 x Gr1 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 43 and grassland area 1

9 Ec43 x Gr2 = combination of ecoregion 43 and grassland area 2

10 Ec43 x Gr2 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 43 and grassland area 2

11 Ec43 x Gr3 = combination of ecoregion 43 and grassland area 3

12 Ec43 x Gr3 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 43 and grassland area 3

13 Ec43 x Gr3 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 43 and grassland area 1

14 Ec46 x Gr1 = combination of ecoregion 43 and grassland area 1

15 Ec46 x Gr1 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 46 and grassland area 1

Table 14. Multiple Regression Results for NDVI Regressed against Ecoregion Type, Grassland Cover Type, and Precipitation during the period 1988-93 (Part 3).

16	Ec46 x Gr1 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 46 and grassland area 1
17	Precip1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 46 and grassland area 3
18	Ec42 x Gr1 x Pr0 = precipitation recorded in same month as NDVI measurements in combination of ecoregion 42 and grassland area 1
19	Ec42 x Gr2 x Pr0 = precipitation recorded in same month as NDVI measurements in combination of ecoregion 42 and grassland area 2
20	Ec42 x Gr3 x Pr1 = precipitation recorded in month immediately prior to NDVI measurements in combination of ecoregion 42 and grassland area 3
21	Ec43 x Gr1 = combination of ecoregion 43 and grassland area 1
22	Ec43 x Gr1 x Pr2 = precipitation recorded two months prior to NDVI measurements in combination of ecoregion 43 and grassland area 1
23	Ec43 x Gr3 x Pr0 = precipitation recorded in same month as NDVI measurements in combination of ecoregion 43 and grassland area 3
24	Ec46 x Gr1 x Pr0 = precipitation recorded in same month as NDVI measurements in combination of ecoregion 46 and grassland area 1

Table 15. Final Multiple Regression Models for Each Combination of Ecoregion and Grassland Cover Type.

Class 42-1

$NDVI\ (1^{st}\ half) = 120.74 + 1.38Pr1 + 2.94Pr2$

$NDVI\ (2^{nd}\ half) = 119.86 + 0.54Pr0 + 1.95Pr1 + 2.48Pr2$

Class 42-2

$NDVI\ (1^{st}\ half) = 117.31 + 1.75Pr1 + 3.37Pr2$

$NDVI\ (2^{nd}\ half) = 116.31 + 1.06Pr0 + 2.47Pr1 + 2.48Pr2$

Class 42-3

$NDVI\ (1^{st}\ half) = 120.74 + 1.90Pr2$

$NDVI\ (2^{nd}\ half) = 119.86 + 1.35Pr1 + 1.01Pr2$

Class 43-1

$NDVI\ (1^{st}\ half) = 120.74 + 3.13Pr2$

$NDVI\ (2^{nd}\ half) = 118.26 + 3.08Pr1 + 1.70Pr2$

Class 43-2

$NDVI\ (1^{st}\ half) = 117.81 + 3.14Pr2$

$NDVI\ (2^{nd}\ half) = 117.35 + 3.08Pr1 + 0.70Pr2$

Class 43-3

$NDVI\ (1^{st}\ half) = 114.98 + 1.89Pr1 + 2.40Pr2$

$NDVI\ (2^{nd}\ half) = 113.26 + 1.19Pr0 + 3.08Pr1 + 1.19Pr2$

Class 46-1

$NDVI\ (1^{st}\ half) = 123.11 + 1.58Pr1 + 2.20Pr2$

$NDVI\ (2^{nd}\ half) = 119.86 + 0.83Pr0 + 1.47Pr1 + 2.48Pr2$

Class 46-2

$NDVI\ (1^{st}\ half) = 120.74 + 4.67Pr2$

$NDVI\ (2^{nd}\ half) = 119.86 + 3.08Pr1 + 2.48Pr2$

CHAPTER 4

DISCUSSION

One of the objectives of my research was to examine the variability of NDVI and derived metrics extracted from a combination of ecoregion and grassland cover areas. My analysis leads me to conclude that coarse resolution NDVI data, separated into sub-regions based on Omerniks' ecoregion divisions and EROS Land Cover classifications, can be a useful tool for regional analysis of phenological cycles in grassland areas of the Northern Great Plains.

This conclusion was not fully supported by all the analysis, particularly ANOVA. Based on the evidence from the NDVI plots and other metrics, I expected the null hypothesis that the means of the eight areas would be indistinguishable from one another would be rejected by ANOVA in all years except 1991. The growing season NDVI curves were very similar in 1991 (Figure 7). However, 1990, and 1992 also had low *F*-values and nonsignificant *P*-values, suggesting that separation based on combining ecoregions and land cover types may be less useful than anticipated when using growing season mean NDVI alone. Under this assumption, the differences noticeable in the plots in these years could be attributable to factors not examined in this study, or chance.

However, the other derived metrics illustrated the unique phenological patterns of each year, ecoregion and land cover type. By examining the metrics, it was obvious 1988 and 1993 were non-typical years. The onset, end and duration in 1988 showed an abbreviated season, and the variability was high compared to other years. 1993 consistently showed the opposite of 1988, with the longest and most productive season and low variability. This result reflected ample growing season rainfall throughout the study area.

The difference between the eight ecoregion-grassland areas was also apparent in the descriptive statistics tables. Each area appears to be phenologically unique. Area 42-2 and 42-3 exhibited identical onset values, but all the other metrics were divergent enough to supply a singular overall description for each area. Area 46-2, which had the highest mean values for all metrics, also had generally low measures of dispersion. Reed et al. (1994) identified consistency of phenological metrics in areas of crops and reliable moisture, but in this study, the most consistent metrics seem to apply to grassland type 2 (grassland alone), regardless of ecoregion. Though area 42-1 and 43-1 (grass/crop type) had longer seasons, higher maximum NDVI and higher integrated NDVI than their counterparts (grassland type 2), which was as expected, the grassland areas often had lower variance. Results of linear regression also supported separation by ecoregion/ grassland types. The R^2 value for the ecoregion/grassland division was .42, compared to .37 for grasslands and .39 for ecoregions by themselves. The progressively higher correlation for each aggregation suggests that the ecoregion/grassland division was superior to ecoregion or land cover type alone.

The second objective of my research was to assess the relationship between mean NDVI and precipitation data for selected ecoregions and grassland types, and this was accomplished with regression analysis. Table 11 summarizes the results of regressing NDVI against precipitation across all eight ecoregion/grassland cover types. The precipitation two months before NDVI was measured explained most of the variability in first half NDVI (35 percent on average) suggesting a lag of 4-10 weeks between NDVI and precipitation. The previous month's precipitation had a minor but significant impact on NDVI in two out of six individual years. The second half NDVI results were roughly similar with the variability in precipitation in the two previous months explaining most of the variability in second half NDVI in three out of six years and some variability in every year. The cumulative results showed that the previous month's precipitation explained more of the variability in NDVI and that lags of 2-8 weeks best represented the relationship between NDVI and precipitation in this instance.

My results were generally similar to previous examinations of NDVI and precipitation. Though all the previous studies approached the analysis differently from one another, and mine, the one common conclusion was that NDVI and rainfall show only a loose association in short-term analysis. The correlation and regression values in other studies (e.g., Hellden and Eklundh, 1988; Nicholson and Farrar, 1994) inevitably improved when cumulative seasonal precipitation was associated with seasonal integrated NDVI, and when larger window areas were compared to smaller ones. Another common result was arid regions had the best linear associations, and NDVI also showed a more immediate response to precipitation, and my study confirmed this.

The lag times varied from one study to another, depending on where the studies were done. African rangelands tended to have longer lags between precipitation and increased NDVI than rangelands in the U.S; one-to-two month lags versus two-to-five week lags.

Sources of Error

The shortcomings of coarse-resolution AVHRR satellites and NDVI data have been well documented (e.g. Moreno and Melia, 1993; Moody and Strahler, 1994; Privette et al., 1995). Correction techniques based on these, and numerous other studies, have been used to improve the accuracy of AVHRR data steadily since the earliest applications, with recent data benefiting more than earlier years. In this case, 1988 data was subject to fewer correction procedures than 1993. For instance, correction for on-board sensor degradation was applied to 1993 data, but not to 1988 data. In addition, this study used data from two different satellites, which were not inter-calibrated (Rao and Chen, 1995).

Some of the problems identified with NDVI values include variations due to clouds and other types of atmospheric interference such as smoke or dust (Mitchell and O'Brien, 1993). Heavy cloud cover is usually detected and those pixels tend to be automatically deleted by maximum value compositing, but lighter cloud cover can reduce NDVI without being rejected. At least some portions of the study area from June to September of 1988 were probably affected by smoke in the atmosphere from the extensive forest fires nearby. In addition, it has been estimated that some tracts of rangeland lost up to 50% of their forbs and grass coverage, so it was possible that unusually large quantities of dust may have been present in the atmosphere as well.

Sparse vegetative cover and soil composition can also affect NDVI values. The direction of the change can be higher or lower, depending on type and color of soil, and moisture content. Though bare soil generally lowers NDVI values, Bausch (1993) noticed higher values for corn on dark soil because NDVI registers higher index values over dark backgrounds. This finding was duplicated by Elvidge and Chen (1995) with reflectance characteristics of juniper and darker versus lighter soils. Huete and Tucker (1991) also documented higher NDVI for dark than light colored soils in areas of sparse vegetation, influenced by soil wetness. Prince (1990) also noted that extensive patches of bare soil are brighter in all channels, which can significantly influence the NDVI measurement for a pixel as a whole. The cropping pattern of strip wheat and fallow results in mixed pixels of vegetation and soil which may alter the NDVI for a significant number of pixels. This may be an issue in areas where wheat is a major crop, as it is in parts of my study area, or where drought has severely depleted land cover as it did in 1988.

Another possible source of error exists in the EROS Land Cover Prototype. Since the classes are based only on 1990 NDVI values, and field verification of a resolution of 1 km^2 is impossible, some error is likely. In lieu of actual field verification, accuracy estimates were developed by the U.S. Forest Service (Turner et al.1993) and Merchant et al. (1994) using forest, agricultural and land cover inventories from other sources. They estimated an approximate accuracy rate of 70-82%, which they considered acceptable at this scale.

The mean NDVI values extracted around the precipitation stations may have included some irrigated pixels. Many of the selected stations are located on, or nearby rivers and reservoirs, and the presence of trees and shrubs common along the banks, in addition to the irrigated land that is usually nearby, may have influenced the NDVI values.

Conclusions

The results of this study show that regions grouped by land cover types and ecoregion areas display unique NDVI signatures, influenced by the timing and quantity of precipitation.

NDVI trends of the eight distinct regions through six years, compared by various metrics, illustrate the contrast between the areas. The ecoregion/

grassland cover types located predominantly in the southeast, such as 46-1 and 46-2, consistently show earliest green-up, longest growing season, highest peak and total NDVI values. These areas also show low inter-annual variability. The shrub/grasslands, located primarily in the central portion of the study area (43-3) display a much lower mean, duration and peak, and much higher inter-annual variability. The other areas, consisting of 42-1, 42-2, 42-3, 43-2 and 43-2 tend to fall in between areas 46-1/2 and 43-3. 42-3 and 43-2 were the most similar.

Evaluation by year illustrates the extreme contrast between 1988 and 1993, showing a 20 percent difference in total NDVI values. 1993 had the highest total NDVI in six of the eight regions, while in 1988, total NDVI was lowest in seven of the eight regions. The variability between regions was lowest in 1991 and 1992.

The differences between the areas were further examined with ANOVA. This analysis showed distinct characteristics for all grassland groupings, no distinction between ecoregions (except in 1991), and significant differences in ecoregion/grassland group in three out of six years. The ANOVA analysis only partially supports the theory of ecoregion/grassland groupings as discrete units. The ANOVA results suggest the need for further refinement of the areas by additional characteristics, such as soil type.

Regression models by year, ecoregion, grassland, ecoregion/grassland cover types, and precipitation show a time lag of approximately 2-8 weeks for NDVI to respond to the precipitation. The models explained less than 50 percent of the variability in NDVI for all interactions.

The accuracy of regression between NDVI and precipitation could be improved by using daily rather than monthly precipitation totals. This would result in a much larger data set, using all of the images, and lag periods could be more accurately matched. Other factors could be added to the regression model to improve its fit as well, including temperature, soil type and its response to moisture, land use, elevation, etc. Some of these data were included with the EROS data sets, so inclusion in future models should be considered.

I would also advise altering the beginning and end value of the growing season from NDVI $\geq$115 to at least $\geq$120. The growing season lengths reflected in the metrics table appears to be longer than actual growing seasons by my estimate in many cases. Reed et al. (1994) calculated even longer growing seasons than I did for short-grass areas, extending into the middle of November/early December, with durations of 224-238 days. These beginning and end-of greenness dates should be chosen with more certainty by verifying their accuracy in conjunction with other sources, and so estimates of growing season length and related integrated NDVI could be established with more confidence as well.

In conclusion, the results from this study are a continuation of previous research using AVHRR NDVI data to monitor land cover. The subdivision of land cover by ecoregion was unique, and appears to be a valid method to examine variability between years and ecoregion land cover.

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APPENDIX

PROGRAMS FOR AUTOMATION

Erd8.do

```
#!/bin/sh

# Title: erd8.do (UNIX shell program); enter this at UNIX prompt.
# For multiple file processing of EROS AVHRR 1988 data.
# Output is ERDAS batch file; type batch out.aud at ERDAS prompt.
# Authors: Lou Glassy, Linda Gillett.
# Montana State University-Bozeman, 1994
# Requires file template.in in directory.

        echo "Which year are these files?"
        echo -n "In the form xxxx (ie 1993) : "
        read YEAR
        YEAR=`echo $YEAR | colrm 1 2`

        echo
        echo "Now copying files to valid names"
        echo
    for f in WEEK[0-9][0-9]NDVI.ND
        do echo $f | sed 's/WEEK//' | sed 's/\.ND//'`
        FOUT=`echo b$YEAR$NUM.img`
        mv $f $FOUT
        echo Old name is $f and New name is $FOUT
        done

# The above section replaces WEEK with b, replaces .ND with
# .img, and Year and Week as identifiers.  The following section
# removes temporary files created by any previous run of this
# program, and removes the .img extension.

    rm -f template.temp
    rm -f out.aud
    rm -f *.dat

    for f in *.img
        do
        basename=`echo $f | sed 's/\.img$//'`
        echo Basename is $basename
        sedcmd="s/file1/"basename"/"
        sed $sedcmd template.in > $basename.dat
```

```
    cat $basename.dat >> template.temp
   done
   sed '/noaudit/d' template.temp > out.aud
  #  temp1= " >noaudit"
  #  cat $temp1 >> out.aud
# The basename .img extension is removed, and will replace the
# generic file1 designation in the template, a temporary .dat
# file which in turn is sent to template.temp, creating an audit
# file which processes all .img files to .gis files.

  echo "Now start ERDAS and type: batch out.aud"
```

Over.do

```
#!/bin/sh

# Title: over.do (UNIX shell program); enter this at UNIX prompt.
# For multiple file processing of EROS AVHRR 1988 data.
# Output is ERDAS batch file; type batch over8.aud at ERDAS
# prompt.
# Authors: Lou Glassy, Linda Gillett.
# Montana State University-Bozeman, 1994
# Requires file template8.in in directory.

rm -f out8.aud
touch out8.aud

FILELIST=`ls b88[0-9][0-9].gis`
echo Original file list is $FILELIST

set - $FILELIST
while [ $# -ne 0]
  do
   firstname=$1
   secondname=$2
   echo First name is $firstname  Secondname is $secondname
# verify that these are the combinations you want
   substcmd1="s/file1/"$firstname"/"
   substcmd2="s/file2/"$secondname"/"

   overlay1=`echo $1 | colrm 1 3 | colrm 3`
   overlay2=`echo $2 | colrm 1 1 `
   substcmd3="s/file3/e"$overlay1"-"overlay2"/"

   sed $substcmd1 template8.in | sed $substsmd2 | sed
$substcmd3 >> out8.aud

   shift
   shift
done

echo Now start ERDAS and type batch out8.aud.
```

Erd9.do

```
#!/bin/sh
# Title erd9.do (UNIX shell program); enter this at UNIX prompt
# For multiple file processing of 1990-93 EROS AVHRR images.
# Output is ERDAS batch file; type batch out.aud at ERDAS prompt.
# Authors: Linda Gillett and Lou Glassy.
# Montana State University-Bozeman, 1994.
# Requires file template.in in directory

        echo "Which year are these files?"
        echo -n "In the form xxxx (ie 1993) : "
        read YEAR
        YEAR=`echo $YEAR | colrm 1 2`

# Takes entered year and removes the first two digits
        echo
        echo "Now copying files to valid names"
        echo
    for f in P[0-9][0-9]NDVI.IMG
        do echo -n $f "->"
        NUM=`echo e$YEAR$NUM.img`
        mv $f $FOUT
        done

# In the filenames, P is replaced with e, the last two digits
# of year is added, week number is saved ie. 09, and lowercase
# .img is added.

    rm -f template.temp
    rm -f out.aud
    rm -f *.dat

# Old template, audit and .dat files are deleted

    for f in *.img
        do
        basename=`echo $f | sed 's/\.img$//'`
        echo Basename is $basename
        sedcmd="s/file1/"basename"/"
        sed $sedcmd template.in > $basename.dat
        cat $basename.dat >> template.temp
      done
      sed '/noaudit/d' template.temp > out.aud
```

```
    # temp1= " >noaudit"
    # cat $temp1 >> out.aud
# The basename .img extension is removed, and will replace the
# generic file1 designation in the template, a temporary .dat
# file which in turn is sent to template.temp, creating an audit
# file which processes all .img files to .gis files.

    echo "Now start ERDAS and type: batch out.aud"
```

Image9.do

```
#!/bin/sh

# Title: image9.do (UNIX shell program); enter at UNIX prompt.
# For multiple file processing of EROS AVHRR 1990-93 data.
# Output is ARC aml's; type arc9.aml at ARC prompt, then
# enter GRID and type grid9.aml.
# Authors: Linda Gillett and Lou Glassy.
# Montana State University-Bozeman, 1994.

    rm -f arc9.aml grid9.aml
    touch arc9.aml grid9.aml
    echo "&echo &on" >> arc9.aml

  for f in *.gis
    do
      echo "Now processing $f"
      basename=`echo $f | sed 's/.gis//'`
      echo "ERDASGRID $f  a $basename" >> arc9.aml
      echo "PROJECTCOPY grid wecogrs a$basename" >> arc9.aml
# Enter GRID to run zonalstats
      echo "t$basename = zonalstats(wecogrs, a$basename,
all) >> grid9.aml
    done
```

Random90.aml

```
/* Title; RANDOM90.AML; type &r random90.aml at ARC prompt.
/* reduces original images to study area (setwindow), and
/* specifies study area further by SETMASK.
/* Samples 100 random NDVI values within these specified areas
/* from GRIDASCII files.
/* Authors: Linda Gillett and Lou Glassy.
/* Montana State University-Bozeman, 1994.

&echo &on
&sv year 90
/* change this variable for each year
&do image &list 04 05 06 07 08 09 10 11 12 13 14 15
 &do maskfile &list a42-1 a42-2 a42-3 a43-1 a43-2 a43-4 a46-1
a46-2
/* change these variables as needed

/* build GRID.AML initialization file for grid
&sys rm -f grid.aml
&sys echo "setwindow box 2" > grid.aml
&sys echo "kill clipgrid" >> grid.aml
&sys echo "clipgrid = ae%year%%image%" >> grid.aml
&sys echo "setmask %maskfile%" >> grid.aml
&sys echo "outgrid = clipgrid" >> grid.aml
&sys echo "q" >> grid.aml

grid
gridascii outgrid outgrid.asc
&sv ecograss = %maskfile%
take_sample.sh %year% %image% %ecograss%

rm -f outgrid.asc
kill outgrid
kill clipgrid
 &end
&end
```

Stats.awk

```
# Title: stats.awk (UNIX shell program).
# Author: Lou Glassy.
# Montana State University-Bozeman, 1994
# Used with EROS AVHRR ASCII *.sample files.
# Output is file ALLSTATS, used to compare sample stats to
# population stats obtained from ZONALSTATS in ARC.

# to run: at UNIX prompt type
# rm -f allstats
# sh
# $ for file in *.sample
#   >do
#   >gawk -f stats.awk $file >> allstats
#   >echo done with $file
#   >done
# ctrl-d

BEGIN { i=1
      minval = 999
      maxval = 0
      sumX = 0
    }
# on every line, read in the data..
{
 X[i] = $1
 sumX = sumX + X[i]
# minval is the smaller of X[i] and minval
 if ($1 < minval) minval = $1
# maxval is the larger of X[i] and maxval
 if ($1 > maxval) maxval = $1

 i = i + 1
}

END {
   Howmany = NR
   meanval = arithmetic_mean(X, Howmany)
   SD = sample_std_deviation(X, Howmany, meanval)
   range = maxval - minval
# print out all the values in ZONALSTATS-like format
   print " "
   print "count  ", Howmany
```

```
  print "mean   ", meanval
  print "min    ", minval
  print "max    ", maxval
  print "range  ", range
  print "sum    ", sumX
  print "SD     ", SD
  print FILENAME
  }

function sample_std_deviation(X, Howmany, Xbar,   sum, i, i,
deviation) {
  sum = 0
  for (i=1; i<=Howmany; i++) {
    i_deviation = X[i] - Xbar
    sum = sum + i_deviation^2
                    }
      }
      return sqrt(sum/(Howmany -1))
}
function arithmetic_mean(list, Howmany,    i,sum) {
  sum = 0;
  for (i=1; i<=Howmany; i++) {
    sum = sum + list[i]
                    }
                              }
  return sum / Howmany;
}
```

Take_sample.sh

```
#!/bin/sh

# Title: take_sample.sh(UNIX shell program); type at UNIX prompt.
# Output is a row of 100 sample values extracted from EROS AVHRR
# ASCII files.
# Requires strain_out_nodata.awk & picker.awk programs.
# Author: Lou Glassy.
# Montana State University-Bozeman, 1994.

echo "Straining out NODATA values:"
gawk -f strain_out_nodata.awk outgrid.asc > outgrid.strained
echo "Picking out sample data:"
gawk -f picker.awk outgrid.strained > $1$2-$3.sample

rm -f outgrid.strained
```

Strain_out_nodata.awk

```
# Title: strain_out_nodat.awk (UNIX program).
# Required by take_sample.sh
# Author: Lou Glassy.
# Montana State University-Bozeman, 1994.
# Reads ascii files, disposing of novalue -9999

NR > 6
# for all records greater than 6 (6 lines in header)
{
 for (i=1; i <= NF; i++)
  {
   if ($i! = "-9999")
    {
     print $i
    }
  }
}
```

Picker.awk

```
# Title: picker.awk (UNIX program).
# Required by take_sample.sh.
# Picks out 100 random numbers from sample files.
# Author: Lou Glassy.
# Montana State University-Bozeman, 1994.

BEGIN {
     i = 1
    }

{
 data[i] = $1
 i = i + 1
}
END {
    size = i
    for (output=1; output<=100; output++)
      {
       randnum = roll(size)
       print data[randnum]
      }
   }
function roll(n) { return 1 = int(rand() * n) }
```