VARIATIONS IN GRASSLAND BIOMASS IN CENTRAL OKLAHOMA: A SPATIAL AND TEMPORAL ANALYSIS

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VARIATIONS IN GRASSLAND BIOMASS IN CENTRAL OKLAHOMA: A SPATIAL AND TEMPORAL ANALYSIS

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PREFACE

I wish to express my sincere appreciation to the members of my graduate committee who initially encouraged me to continue my education and had confidence in my abilities to do so. I would like to thank Dr. Stephen Walsh for allowing me the opportunity to gain practical experience through work at the Remote Sensing Center and participation in this research effort. His statistical assistance and financial support made completion of the project possible. I would also like to acknowledge the invaluable comments and editorial assistance provided to me by Dr. Jack Vitek and Dr. David Butler. Their suggestions were greatly appreciated.

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CHAPTER I

INTRODUCTION

Plant communities occupy a definite location in space at one specific time. The dynamic nature of vegetation with respect to changes over time, however, reveal problems associated with a static approach to vegetation analysis. These problems may be alleviated by incorporating a spatial and temporal aspect to the vegetation analysis. The complex of climatic and edaphic factors that act upon an ecological plant community ultimately determines its existence and survival. Lauenroth (1979) noted a lack of grassland research, and proposed a need for studies of the interactive forces associated with grassland development. It is important to recognize the highly interactive and multifactorial nature of a grassland ecosystem (McNaughton, 1982). The complex relations among environmental factors often create situations that are difficult to evaluate. Our ability to interpret these complex ecological relationships is limited because of the inherent variability of vegetation in nature; however, an attempt will be made to assess the influences upon vegetation changes over time and space.

This investigation focuses on general abiotic influences on a grassland environment over a broad area depicting spatial trends over time. The spatial pattern in plant communities has previously been seen as a manifestation of processes which are cyclical in time, without reference to location, because of a lack of concrete research to support vegetation associations over a wide area (Grieg-Smith, 1961; Watt, 1947). For purposes of examining large-scale relationships between vegetation and environment, methods such as drawing transect profiles, regression analysis, and careful intuitive inspection of the data are relevant steps in the examination of spatial data (Hill, 1973). McNaughton (1983) also stresses spatial pattern as a key feature in vegetation analysis, leading to an increased understanding of the relationship between vegetation and associated environmental influences.

Grasslands occur in areas characterized by a period of the year when the amount of available soil water falls below the requirements for ecosystems demanding more moisture, such as forests, yet precipitation received is sufficient part of the year to sustain grasses as the dominant component of vegetation (Lauenroth, 1979). The tendency for drought occurrence to be concentrated in the grassland region of the United States (based on climatic records) recognizes the significance of environmental evaluation (Borchert, 1950). The presence of prairie grassland as a dominant native landcover is evident in western Oklahoma, owing to the adaptive tendencies of grasses to periods of deficient available moisture and extreme temperatures. Grasslands can accommodate environmental stresses to some extent because of their occurrence over a wide range of temperature and precipitation conditions. Grasslands exist in areas receiving 250 to 1000 mm annual precipitation and having mean annual temperatures between 0°C and 26°C (Lauenroth, 1979). The average precipitation and temperature values across the study transect area are 725 mm and 16.1°C, respectively, which correspond to the appropriate grassland range (USDA County Soil Surveys).

Purpose

In an attempt to evaluate and understand the changes of vegetation over time, the plant/soil and the plant/atmosphere interface should be considered. The edaphic influence of soil physics relative to texture, holding capacity, and ease of water movement through the soil, in combination with the atmospheric influence of meteorologic variables on evaporation and transpiration affect the energy balance between the plant and its surrounding environment. The interplay between abiotic driving variables, such as temperature, terrain orientation, evapotranspiration, and the ability of the soils to store moisture for plant utilization, will directly influence the moisture supply and demand of the prairie ecosystem (Griffiths, 1982).

This study evaluates what ecological influences affect biomass fluctuations (the growth of native grass) associated with sites positioned along an environmental gradient in Oklahoma. Moreover, the investigation interprets the temporal and spatial characteristics of dynamic vegetation conditions sampled over a broad area in central Oklahoma, during a 15-week growing season extending from May 07-August 13, 1985.

Research Objectives

This study investigates the temporal and spatial variations associated with changes in dry mean biomass measured at 12 selected sites sampled during a growing season and situated in an environment which normally experiences conditions of moisture stress. An increase in dry weight, the material actually engaged in growth per unit time, depends on various external factors (West et al, 1921; French, 1979; Sandland et al, 1982; McNaughton, 1983; White and Glenn-Lewin, 1984). The collection and measurement of native rangeland grass (dry weight biomass) was monitored in order to illustrate:

(1) a change in plant biomass relative to spatial variation in available moisture, which decreases westward along an east-west transect;

(2) a change in plant biomass relative to temporal variation in available moisture measured throughout the growing season, and;

(3) the impact of selected environmental variables on plant biomass fluctuations throughout the growing season across the transect.

The transect is positioned in an east-west direction, across the north-central portion of Oklahoma, in order to sample the moisture, vegetation, and atmospheric conditions of the existing moisture gradient in Oklahoma. The spatial aspect will be utilized to investigate if a decrease in biomass content as a function of decreased moisture availability westward across the transect actually exists. The temporal aspect will be evaluated relative to each site, to illustrate the effect of changing moisture availability and increased temperature on vegetational growth patterns and corresponding biomass content throughout the season.

The interactive environmental influences of interest will act as the independent variables in the development of an empirical ecological response model relative to the dependent variable of biomass. By determining the statistical significance of the plant responses to each factor, a weighted value can be obtained (Wang, 1960).

The microclimate measurements of the grassland ecosystem are presented in order to document the environmental conditions under which plant growth occurs. Table I presents the influential environmental factors being considered in this analysis.

Temperature effects on biomass growth were incorporated not only using air temperature values, but

TABLE I

SELECTED ENVIRONMENTAL FACTORS

Dependent	Independent	Derived Independent
Dry Mean Biomass	Weekly Mean Air Temperature (°C)	Heat Units
	Weekly Mean Precipitation (cm)	Two-Week Accumulated Precipitation
	Solar Radiation Relative Humidity Percent Sunshine Topographic Elevation (m) Air Temperature (°C) Wind Speed	Potential Evapotranspiration
	Soil Texture	Sand, Silt, Clay
	Soil Moisture	
	Soil Temperature (°C)	
	Week	Time
	Site	Location

also soil temperature and the heat unit concept (Scott, 1979). Similarly, moisture effects on biomass growth were incorporated not only using precipitation values, but also soil moisture and two-week accumulations to illustrate a "carryover concept" or lag response of vegetation to precipitation events (Webb et al, 1978). Atmospheric influences relative to the water balance of the plant/soil interface, such as solar radiation, air temperature, humidity, sunshine, wind, and elevation, were incorporated through the calculation of weekly Christiansen potential evapotranspiration values (Bordne and McGuinness, 1973). The actual calculation of the combined variables will be explained in detail in the subsequent chapters.

Summary

The goal of this investigation is to assess the impact of environmental influences on native grassland biomass. The spatial and temporal characteristics will be evaluated relative to the dynamic vegetaion conditions monitored along an environmental gradient in central Oklahoma throughout the 15-week sampling period. The following chapters will coordinate the efforts of site selection, data collection, analysis, and interpretation to evaluate the influences on biomass variation. Chapter II presents supporting literature to augment gradient analysis and modeling of factors affecting vegetation, owing to the growing interest in studying the interactive forces associated with grassland development. Chapter III provides a detailed description of the study area including the climate, physiography and geology, vegetation, and soil characteristics associated with the climatic transition zone of central Oklahoma. Chapter IV documents the preliminary considerations, site preparation and design, and sampling procedures involved in the biomass measurements and organization of appropriate selected variables. Chapter V employs multiple regression analysis to evaluate the significance of selected environmental variables relative to biomass growth. Chapter VI includes quantitative, analytical results and qualitative interpretation derived in this investigation and possible recommendations to aid in future vegetation research.

CHAPTER II

LITERATURE REVIEW

An attempt is made in this chapter to review current literature related to vegetation analysis. The organization scheme of the supporting research is as follows: (1) gradient analysis, (2) environmental limiting factors on biomass production, including moisture, temperature, and interactive influences, and (3) regression analysis and modeling of factors affecting vegetation.

Skroch (1965), Hake et al (1984), and Knapp (1984), have been concerned with vegetation responses to moisture influence at one site or in a laboratory setting. They have found that biomass increases with time, but moisture stress delays the time of maximum growth and the magnitude of the biomass. The transect sampling scheme utilized in this study offers a different approach to vegetation analysis, combining not only evaluation at a site over time, but also, the spatial influence over a broad area across a climatic transition zone. The investigation will compare the changes in biomass content (not specific species distributions) across the transect throughout the growing season relative to environmental influences. McNaughton (1983) recognized that temporal and spatial patterns have important roles in species interactions and may lead to an increased understanding of environmental influence on vegetation distribution and abundance.

Gradient Analysis

Pioneering efforts concerning gradient analysis of vegetation and a quantitative approach to vegetation analysis were reported by Whittaker (1967); however, he emphasized analyzing and describing particular species associations relative to the gradient. Varying species associations will affect the resulting biomass content at each site, therefore, cover type differences will be considered in the final analysis of dry weight biomass trends. This study, however, does not focus on predicted species distributions and dominance patterns as Brown and Gershmehl (1985), Mohler (1983), White and Glenn-Lewin (1984), and Whittaker (1967) emphasized.

Gradient analysis is often employed in the geographic study of climatic trends. Marotz (1983) utilized sites arranged along a longitudinal environmental gradient across the central United States to monitor the spatial variability of average precipitation measures during a growing season. He also noted that the plant communities reflect precipitation amounts received. Metcalfe and Elkins (1980) related the importance of the distribution of precipitation in determining adaptations of plants to a given area, with available soil moisture decreasing westward from the Atlantic coast and nortwestward from the Gulf. Prentice (1980) supported these trends in establishing that plant species are expected to respond to environmental gradients, relative to a uniform change in environmental conditions. He further explained, however, that field data will not conform perfectly to predictive laboratory gradient models because of natural complexity.

Similarly, Borchert (1950) was concerned with the trend of transition boundary zones from forest through prairie grasslands to the steppe environment relative to climatic gradients. Both Marotz (1983) and Borchert (1950) noted that vegetation gradients appeared to coincide with climatic gradients. In contrast, however, Brown and Gershmehl (1985) did not support the idea that species distributions are controlled primarily by climatic factors.

Oberbauer and Billings (1981) characterized and compared water relations relative to plant adaptations along an alpine topographic gradient. They monitored macro-climatic variables (precipitation, temperature, soil moisture, soil temperature) and corresponding plant characteristics (leaf conductance and leaf water potential) at different positions along topographic gradients located in eastern Wyoming. They concluded that gradient analysis is a worthwhile mechanism to predict the effects of drought and water use on the spatial pattern of alpine vegetation.

White and Glenn-Lewin (1984) examined vegetation associations relative to both species composition analysis and vegetation-environment relationships along a topographic-moisture gradient. In the investigation of the tallgrass prairie vegetation of Iowa and eastern Nebraska, the complex pattern of geographical variation in vegetation was revealed, emphasizing topographic position and soil moisture as fundamental factors influencing vegetation composition and structure. Rather than random fluctuation, an attempt was made to identify factors influencing vegetation distribution by trends among groups (White and Glenn-Lewin, 1984).

No one site or landscape encompasses the full range of environmental influence indicative of a regional study utilizing gradient analysis (Whittaker, 1967; Marotz, 1983). White and Glenn-Lewin concluded that the tallgrass prairie vegetation varied in a complex, multidimensional manner, reflecting vegetational responses at various scales to topographic position, local edaphic characteristics, and geography. The primary vegetation pattern corresponded to a soil moisture gradient, which is most evident along topographic gradients (White and Glenn-Lewin, 1984).

Environmental Limiting Factors on Biomass Production

The growth components of the grassland ecosystem are controlled directly by abiotic driving variables or indirectly through the combined influence of these variables on other system processes (i.e. water uptake, transpiration, nutrient balance). In order to evaluate the total performance of the ecosystem and to estimate the effects of modified input parameters on system functions, it is essential to focus on the key factors that control system functions such as temperature and precipitation (French, 1979).

West, Briggs, and Kidd (1921) introduced general pioneering interest in plant growth analysis. They proposed an increase in dry weight as the best measure of growth; dry weight being recognized as the measure of the material actually engaged in growth. An interest in the rate of growth and the factors limiting growth was emphasized, with the increase in dry weight over time being dependent on the precise determination and evaluation of both internal and external limiting factors (West et al, 1921; French, 1979; Sandland et al, 1982). Measurements of dry weight and leaf area, accompanied by measurements of respiration, transpiration, and records of various environmental factors are necessary variables in the consideration of influence on plant growth (West et al, 1921; French, 1979; Sala and Lauenroth, 1982; Robertson et al, 1984). Changes in growth rates would be expressions of changes in the environment if growth rates were constant under constant external conditions (West et al, 1921; French, 1979; McNaughton, 1982).

Environmental conditions, however, represent a dynamic influence; therefore, consistency is difficult to presume and monitor (McNaughton, 1982). The need for sound statistical procedures (i.e. regression analyses) utilizing weekly measurements of material as uniform as possible are recognized as a plausible basis for plant research (West et al, 1921; Cable, 1975; Sims and Singh, 1978; Olson et al, 1985). Though West, Briggs, and Kidd introduced the concept of environmental influence on plant growth, actual field investigations were not implemented. West et al (1921) concluded that quantitative analysis of plant growth had not been carried out at that time, but offered suggestions to be utilized in future research to stimulate interest in factors affecting plant growth.

Moisture Influence

Moisture often limits the growth of plants. Reserves of soil moisture play an important role in determining plant activity (DeJong and MacDonald, 1975). Water is one of the priciple factors in limiting growth on the shortgrass prairie (Detling, 1979). Cable (1975) investigated the influence of precipitation on perennial grass production in the semi-desert southwest. He noted that range grass production varied greatly from year to year; however, a sufficiently strong relationship existed between precipitation and grass production. Perennial grass production (warm season, native shortgrass) in the semi-desert environment was dependent primarily on the interaction between current summer rainfall and previous summer rainfall. The best overall relationship between precipitation and grass production was more specifically related to the timing of current August rainfall, previous rainfall between June and September, and the interaction of the two (Cable, 1975). Cable (1975) did not reveal, however, any consistent effect of winter precipitation on the perennial grass production the following summer.

Similarly, Smoliak (1956) found that current summer rainfall correlated well (r=0.833) with the average growth of black grama stalks. Smoliak (1956) further reported that 90 percent of the total herbage was produced during the rainy season summer months. It is apparent that seasonal precipitation amounts strongly influence the growth and development of the native perennial grasses (Smoliak, 1956).

Precipitation effectiveness for plant utilization and corresponding growth were also evaluated (Cable, 1975). Cable (1975) revealed that rains of short duration and magnitude may evaporate too quickly to be effective and large rain amounts of intense storms may rapidly run off because of the soil reaching field capacity and its inability to store additional water. Cable (1975) and Smoliak (1956) concluded that storm size, intensity and spacing (distribution) influence the effectiveness of precipitation available for plant growth, but quantification of influences of storm size and spacing on grass production is difficult.

Cable (1975) felt that even though isolated and unusual rainfall events appeared to be responsible for some otherwise unexplainable changes in production, such events are too infrequent to be of value in developing rainfall/production correlations. In contrast, Sala and Lauenroth (1982) hypothesized an ecologically significant role of rainfall events of short duration and magnitude as an important resource for grass ecosystems in semiarid regions, specifically Bouteloua gracilis, the dominant grass species of the central and southern Great Plains of North America. They noted a remarkable short response time of Bouteloua gracilis to utilize these rainfall events of short duration and magnitude.

The production of plant biomass is often the most assessed response to indicate the effectiveness of rainfall for plant utilization. Ludlow et al (1980) recognized the ability of precipitation to initiate measurable increments in biomass as a popular effectiveness indicator. The difficulty of measuring and monitoring relatively small changes in the biomass of a plant community often caused the importance of short duration rainfall events to be previously underestimated. Sala and Lauenroth (1982), therefore, incorporated response variables (leaf water potential and leaf conductance influence on the water and carbon cycle) that do not directly represent measurements of biomass, but indirectly indicate the potential for biomass production relative to the influence on the water cycle. Sala and

Lauenroth (1982) concluded that precipitation events of short duration and magnitude are ecologically significant and have a qualitatively distinct effect on grass ecosystem dynamics. The processes related to growth (water/nutrient cycles), are concentrated near the soils surface and are tightly controlled by water availability.

Webb et al (1978) recognized a significant relationship between aboveground primary production and moisture in their analysis of native grass ecosystems. Webb et al (1978) investigated the moisture effect with respect to water use efficiency. The primary production of a population depends on its genetic composition and on the abiotic driving variables associated with growth (McNaughton, 1982). Water use is evaluated as the evapotranspirational cost of converting radiant energy to plant biomass. Basically, water use efficiency relates primary production and evapotranspiration (Daubenmire, 1947). Webb et al (1978) focused on this water use efficiency concept to represent the plant/environment relationship. The evapotranspiration was estimated from annual precipitation because surface runoff and deep drainage of soil water are negligible under the semi-arid conditions of the shortgrass prairie (Begg and Turner, 1976; Webb et al, 1978). In the shortgrass prairie under investigation, Webb et al (1978) revealed that grasslands represent a gradient from vegetation water stressed toward vegetation not water stressed. Above ground production correspondingly declined per unit water used. Webb et al

(1978) suggested that plants tend to more efficiently utilize available water when the source is limited. They concluded that above the minimum amount of water (38-170 mm) required to sustain the system, the aboveground primary production is linearly related to annual water use efficiency (Webb et al,1978). The interpretation of regression equations of water-stressed systems supports the idea that only a minimum amount of water is needed to sustain productivity which increases per increment of water above the minimum requirement. Analysis of the relationship between production and evapotranspiration for grassland sites along a gradient of low to high evapotranspiration suggests that the rate of increasing production is a function of decreasing water use efficiency (Webb et al, 1978).

Just as an attempt is made in the transect investigation to evaluate a "lag effect" in moisture influence utilizing two-week accumulated values, both Webb et al (1978) and Cable (1975) supported a "carryover concept," refering to a significant influence of precipitation during a previous year on the performance of plant populations during the year of sampling. The carryover of productive potential may be explained by the combined effects of several phenomena, but Webb et al (1978) and Cable (1975) were primarily interested in precipitation effects. Smoliak (1956), on the other hand, found a poor relation ($r^2=0.4$) between forage production during the current year and precipitation in the previous year. Differences in precipitation-dependence characteristics shown between area studies probably are related to differences in moisture and temperature regimes and their influence on growth and development of plants. Webb et al (1978) also defended different results in the production lag reaction with respect to annual climatic data because of the difference in growth forms (i.e. grass, crop, and forage).

Olson et al (1985) suggested that climate appears to be a major factor in controlling plant growth in the Great Plains. The research focused on appropriate, predicted management practices to be economically employed for planning decisions. An important step in this planning procedure, however, was to evaluate and predict the changes in basal cover of vegetation in response to variations in precipitation (Olson et al, 1985). The effects of grazing intensities were also evaluated relative to basal cover. Though the transect study deals with native grass cover specifically, the precipitation influence on different vegetative cover types is of related interest. Olson et al (1985) concluded that each species reacts to precipitation regimes in a distinctive manner. They concluded that continual changes can be expected in species composition of the plant community as the precipitation regime fluctuates over time. Management decisions for land use may, therefore, be affected by possible fluctuations in dominant cover relative to changing environmental conditions.

DeJong and MacDonald (1975) discussed the important role that moisture plays in determining plant activity. Soil moisture data were collected with neutron probes at one to two week intervals throughout the growing season in an attempt to monitor detailed measurements of the soil moisture regime under untreated native grassland. A simplified model, driven by climatic parameters of potential evapotranspiration, precipitation, and temperature, was correlated to the soil moisture data obtained under the native grassland sites. The study revealed that average water use (29.4 cm) accounted for about 90 percent of the annual precipitation (32.6 cm). DeJong and MadDonald (1975) added that the remaining 10 percent is probably lost by evaporation during the late fall, winter, and early spring. The study also established that a very good relationship existed between growing-season water use and production. Specifically, water use data for an untreated grassland were related to aboveground dry matter production ($r^2=0.99$).

A high degree of temporal variability is associated with plant/moisture relationships (French, 1979). French (1979) attempted to demonstrate the high degree of interaction among factors controlling biomass production. An indication of the relationship between plant growth and soil water was demonstrated by the comparison of aboveground live plant biomass in a natural, ungrazed shortgrass prairie and cumulative precipitation during the season. Figure 1 represents measurements over four

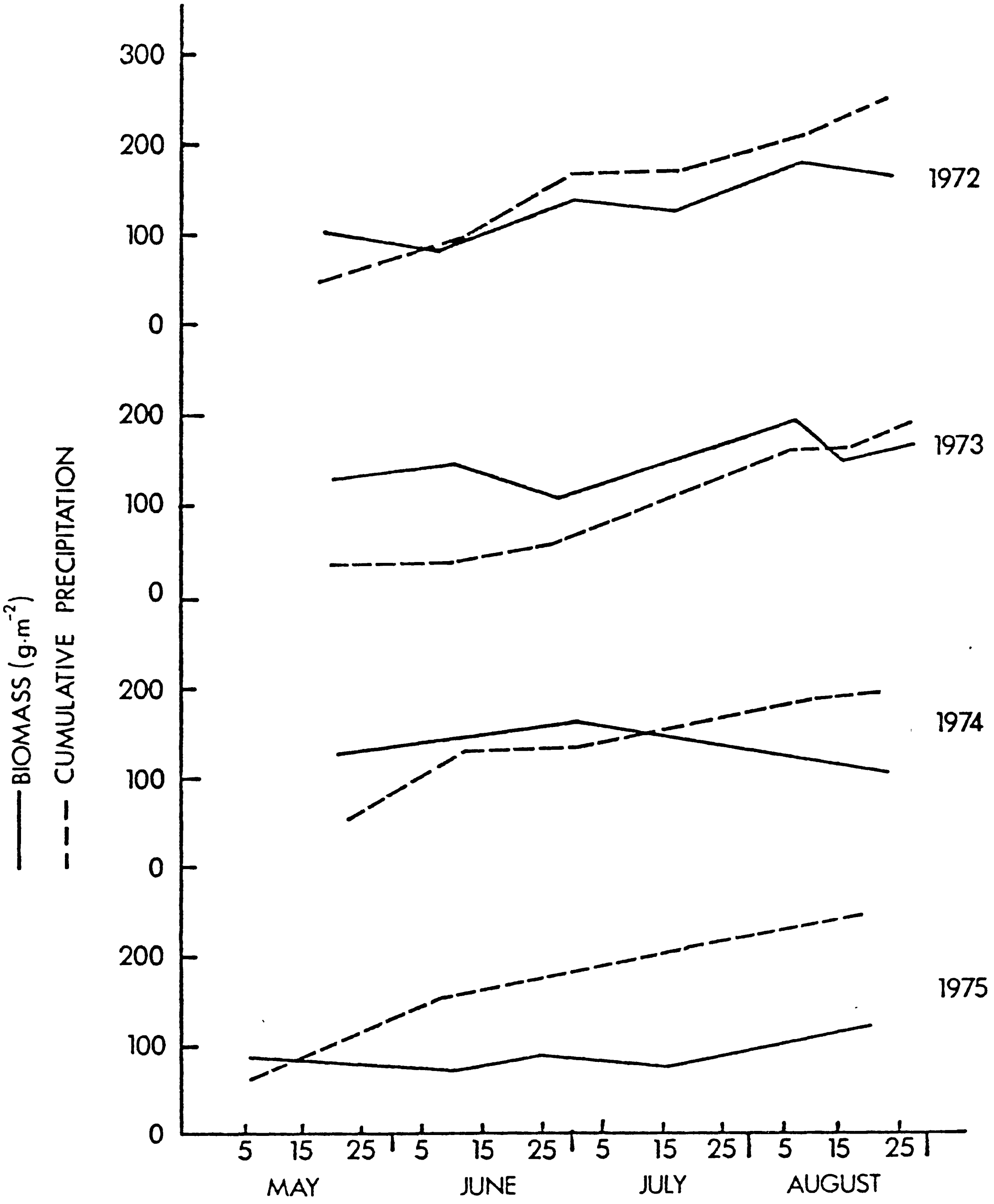

Figure 1. Grassland Biomass and Cumulative Precipitation Over Time at a Northern Shortgrass Prairie Site

Source: French, 1979

separate growing seasons that show a relationship between biomass and precipitation over time on a northern shortgrass prairie. The rapid increase in precipitation after June 1 correlated with an increased rate of vegetation biomass production. French (1979) recognized that later in the season, precipitation is less effective in promoting an increase in primary production, possibly because of high evaporation rates. The rate of early spring regrowth is, however, controlled primarily by water availability (Detling, 1979). Regression analysis indicated a very strong correlation between biomass and mean annual precipitation for various grassland sites in the United States, with the exception of a mixed-prairie site where vegetative growth was highly dependent upon the seasonal distribution of rainfall for that year because of differing environmental responses of cool-season and warm-season grasses to precipitation timing (French, 1979; Lauenroth and Whitman, 1977). Figure 2 provides a graphical representation of seasonal biomass dynamics for a mixed-grass prairie in western North Dakota (Lauenroth and Whitman, 1977).

Sims and Singh (1978) discussed the differing growth patterns of seasonal live biomass. Grasslands with only cool-season or warm-season plants showed a unimodal growth pattern, while grasslands dominated by both cool-season and warm-season species had a bimodal seasonal growth pattern. Long-term fluctuations in available water influences the relative abundance of different species in

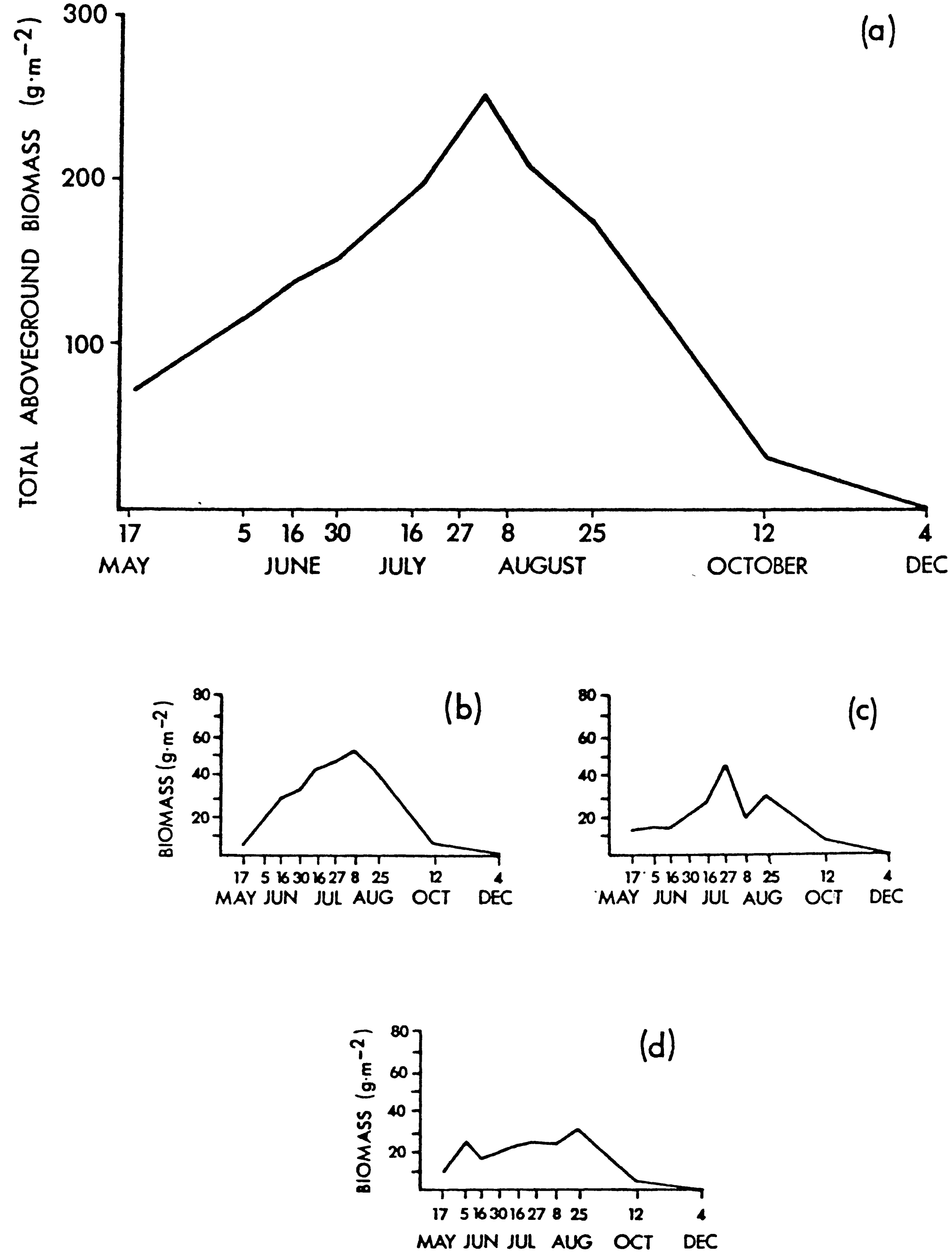

Figure 2: Seasonal Biomass Dynamics for a Mixed-Grass Prairie in Western North Dakota: (a) Total Aboveground Biomass, (b) Warm Season Species, (c) Cool Season Species, and (d) Total Forbs

Source: Lauenroth and Whitman, 1977

different ways (Ares, 1976). The growing conditions of arid grassland sites are limited more by rainfall distribution than by temperature (French, 1979).

A regional comparison between northern and southern shortgrass prairie sites revealed spatial differences in the timing of peak biomass (French, 1979; Ares, 1976). Peak biomass levels were reached after 38 percent of the growing season was completed in the north, compared to peak biomass being reached after 65 percent of the growing season was completed in the south (French, 1979). Correlation analysis established a good relationship between these peak biomass distributions and rainfall. Hake et al (1984) and Dunn (1981) suggested that peak aboveground live biomass in a tall grass prairie in central Oklahoma varied from June to August depending on precipitation and temperature effect of the specific growing season.

The primary production of 52 grassland sites grouped according to the proportional distribution of humid and drought conditions (introducing the moisture aspect) was evaluated by Lauenroth (1979). A strong relationship was recognized between grass production and precipitation, with the greater annual precipitation values of a site corresponding to the greater aboveground production values. Hake et al (1984) indicated that growth patterns on grasslands are greatly influenced by spring and summer rainfall events. Lauenroth (1979), however, suggested an important limitation in the effect of precipitation on production. Whereas primary production on a local scale is limited mainly by spring and summer precipitation, a linear relationship between production and precipitation should not be expected over a wide range of precipitation values, because at some point, production would reach an asymptote, indicating precipitation in excess of the amounts which current vegetation can utilize (Dodd and Lauenroth, 1979). Sims and Singh (1978) suggested similar findings that illustrated a linear increase in peak live biomass of increasing amounts of growing season precipitation. At higher values of precipitation, however, the increasing trend in live biomass tended to level out. Lauenroth (1979) establishes precipitation and temperature as important determinants of the average annual production of grasslands, but, relative to a wide climatic range, as variation among sites increased, the influence of other factors (i.e. soil properties, terrain orientation and elevation, site location and successional status) increased in significance.

Denmead and Shaw (1962) were interested in the dynamic aspects of water available for plant growth and discussed the moisture effect on dry matter production relative to potential transpiration rate and available soil moisture content. They predicted a decline in transpiration rate with decreasing soil moisture content. Measurements of dry matter production suggested that once the soil moisture content was less than the point at which transpiration rate decreased, the plants virtually ceased to assimilate.

Temperature Influence

Temperature has proven to be one of the important controls of growth in grasslands. French (1979) recognized the significant effect of temperature relative to the internal and external system functions of the plant as indicated by the characteristic photosynthetic mechanisms of different plant species. French (1979) introduced a predominant response to temperature using the concept of spatial variability by noting an increase in the proportion of cool season (C_3) plants relative to an increase in latitude northward. French (1979) summarized that temperature was important in controlling the primary production of grassland as evidenced by the proportion of C_3 and C_4 plants at different latitudes with different temperature regimes.

The key physiological response of plants to temperature is contingent upon the growth type or photosynthetic rate associated with cool and warm season types. Cool season (C_3) plants utilize a Calvin cycle-dependent photosynthesis, while warm season (C_4) plants utilize a dicarboxylic acid-dependent photosynthesis (French, 1979; Lauenroth, 1977). Temporal variation in temperature responses reveal two distinct grassland types as seen in warm season plants, exhibiting higher photosynthetic rates, more efficient water use, and a short, active growing season in the early summer. In comparison, cool season plants exhibit a longer growing season, beginning in early spring, and late attainment of peak biomass (Doliner and Jolliffe, 1979). The maximum rate of photosynthesis for cool season and warm season plants occurs at temperatures between 10-25°C and 30-45°C, respectively, revealing differences in the number of degree days above 10°C characteristic for peak vegetative biomass (French, 1979). The proportion of cool season plants decreased as a function of an increase in cumulative degree days (synonymous with the term heat units). It is significant to note the differences in the response of cool season and warm season grasses, as they will have an effect on the evaluation of the mixed grass prairie sites in central and western Oklahoma.

Scott (1979) described a systems model for plants, other organisms, and weather to simulate energy flow in a dynamic ecosystem environment. The abiotic influences of temperature and soil water were introduced into the model. Temperature was used to calculate degree days to drive growth and respiration processes. Scott (1979) utilized aboveground air temperature data collected at a weather station and soil temperature data at 15 cm to incorporate the temperature effects on growth according to the degree-day concept. The number of degree days, or heat units, was represented as the area between the temperature curve and the developmental zero line for 10°C. Scott (1979) noted that if the maximum temperature was less than or equal to 10°C, then the number of heat units was zero. A bioenergetics model was developed to reveal a significant influence of abiotic factors on the biotic invertebrate/plant system.

Wang (1960) incorporated a heat unit approach for studying plant-temperature relationships by the accumulation of daily mean temperatures above a certain threshold temperature during the growing season. He recognized that, over the growing season, plant growth is a continuous function of temperature. Growth versus time is sometimes a near-linear function. The summation of heat units versus time should reveal similar results. Daubenmire (1947), however, noted that the heat units required in a given process is constant only for that range within which a direct proportionality exists between growth rate and temperature. Temperature extremes may have a negative effect on plant rate of development. Plants respond differently to the same environmental factor during various stages of their life cycle. Wang (1960) concluded that the non-linearity of plant-environmental relationships should be recognized in the evaluation of plant growth response.

Lauenroth (1979) suggests a relationship between the environmental influences of temperature and precipitation on grassland production. He recognized a general trend of increased production with increased temperature and precipitation. Multiple regression analysis was utilized to evaluate the relationship. The results failed to indicate a significant relationship between temperature and grassland production. Lauenroth (1979) did not interpret the regression results as a lack of relationship, but emphasized the interaction of temperature and precipitation on growth.

Rice and Parenti (1978) examined the production of the tall grass prairie in Oklahoma. In comparison between grazed, mowed, and burned plots, they concluded that high soil temperature was the single factor likely to explain increased grassland productivity. Their results support the suggestion that the higher production in burned and mowed prairie is primarily a function of higher soil temperature which stimulates early spring growth. Detling (1979) also supports the suggestion that temperature is a significant determinant of spring regrowth initiation.

Interactive Environmental Influences

Attempting an empirical evaluation of the importance of each of the many direct factors that ultimately affect community composition is currently technically impossible (McNaughton, 1983). Temperature and moisture act as composite factors interacting in complex ways with other environmental factors to affect plant growth. McNaughton (1983) stated that the cumulative effects are large, but the individual effects are often minor. Whittaker (1967) recognized a loosely ordered complexity exists in ecological communities and that a simple model projecting the effects of single overpowering forces may be misleading. McNaughton (1983) concluded that the understanding of spatial pattern and tracing a multitude of weak forces that cumulatively have may effects may be instrumental in understanding the organization of the vegetation community.

Single-factor gradient analysis is not as useful in accounting for variation in vegetation data as multivariate gradient analysis (Robertson et al, 1984). Independent moisture and temperature relationships are often not straightforward alone, and it is evident that other combined factors are interacting with precipitation and temperature to affect biomass growth rates (French, 1979). French (1979) attempted to demonstrate the high degree of interaction among factors controlling the grassland ecosystem processes. He established that primary production was dependent upon the interrelated abiotic factors of temperature and available moisture. The unidimensional continuum approach does not suffice to describe the complexity of prairie vegetation and differences among localities or regional landscapes (White and Glenn-Lewin, 1984).

Austin et al (1984) introduced a functional, multifactorial approach to vegetation analysis expressing vegetation properties as a function of five factors:

$$v = f(cl,p,r,o,t)$$

where cl=climate, p=parent material, r=topography, o=biotic factor, t=time. If four of the five factors were held constant, the relationship between vegetation and the remaining factor could be demonstrated and statistically analyzed. They utilized a simplified environment gradient analysis as a correlative procedure to describe vegetation-environment relationships. Whittaker (1967) similarly assumed a relationship between vegetation properties and related factors: climate and topography when parent material, the biotic factor and time are held constant. Several factors also indirectly influence plant performance (Austin et al, 1984):

$$p = f(n,w,t,l)$$

where n=nutrient, w=water, t=temperature, and l=light. Topography and climate provide inputs to drive the ecosystem functions (i.e. precipitation and solar radiation) or act as modifiers of those inputs (i.e. aspect, slope, or soil texture), which combine to influence the resources available to plants. Given the nature of plant growth responses, significant interactions among environmental variables are very significant (Austin et al, 1984).

Regression Analysis and Modeling

The complexity of interactions and subsystem response mechanisms to environmental influences dictates the necessity for an empirical modeling approach to augment our understanding of ecosystem dynamics (French, 1979). Multivariate statistical analyses do little to enhance our understanding of the complex biological processes at work, but serve to indicate related trends among sets of variables (French, 1979; Steele and Torrie, 1980). French (1979) utilized simulation modeling to recognize the effect of precipitation on biomass production. He believed that it provided a useful mechanism to indicate the dynamic relationship between key factors of the subsystem or ecosystem processes. Detling et al (1979) emphasized the usefulness of empirical grassland models as a function of temperature, moisture, light and nitrogen to aid in the interpretation of field data and in the design of future research.

Hake et al (1984) expressed the plant growth response in terms of water potential. Water potentials declined quickly in Oklahoma after June because of increasing temperatures and decreasing soil moisture. The results of a regression model of aboveground live biomass over a growing season indicate that the biomass declined sharply at about the same time the potential values of plant water decreased sharply. It is, therefore, assumed that plant water potential data are useful for interpreting range plant growth responses and predicting the ability of species to harsh growing conditions of low precipitation and high temperatures (Hake et al, 1984).

Knapp (1984) similarly expressed the seasonal course of limited water relations and growth parameters in common tallgrass prairie grasses as a statistical graphic representation of seasonal aboveground biomass over two growing seasons (June-September, 1982 and 1983). Knapp (1984) stated the important ecological determinant seen in the variable environment of growing season precipitation being bimodal with abundant rainfall early (May-June) and late (September) in the season.

Sims and Singh (1978) investigated the relationship of abiotic variables to seasonal peak live biomass values on North American grasslands. The net growth over the season was analyzed, employing a statistical analysis technique to assess the relationships between independent and dependent variables with appropriate interaction products. Possible coefficients of determination (r^2) values were calculated revealing combinations of independent variable relationships. Temperature, preciptation, solar radiation, and evapotranspiration combined in single-variable, two-variable and three-varible combinations to develop predictive equations to best explain seasonal live biomass values. The results of the single-variable analysis revealed that three precipitation terms and two actual evapotranspiration terms were most important in explaining the variability in peak live biomass (63 percent). The two-variable combination analysis showed that a temperature term with either a precipitation or evapotranspiration variable accounted for 42-79 percent of the variability in the peaks across grassland types. The three-variable independent abiotic combinations revealed only a small increase in r^2 values over the two-factor combinations. Sims and Singh (1978) concluded from these multiple regression analyses that the independent abiotic variables most important for explaining the variability in growth of the dependent biomass variable are precipitation and water use, or a combination of these variables with a solar radiation or temperature term.

Regression analysis has been utilized in several research efforts to quantitatively describe changes in vegetation. Olson et al (1985) used basal vegetation cover as a dependent variable and precipitation as independent variables to develop predictive equations to predict vegetational response to fluctuating precipitation values. Similarly, Cable (1975) expressed a precipitation/grass production relationship in terms of a linear regression model used to evaluate the effects of daily, weekly, monthly and seasonal precipitation (independent) on perennial grass production (dependent). The utility of these prediction equations is that they permit the computation of firm estimates of perennial grass production for the current summer at the end of the growing season in September (Cable, 1975).

Austin et al (1984) incorporated a general linear response model approach to predict the probability of plant occurrence from mean annual precipitation, mean annual temperature, radiation index as a measure of aspect, and a qualitative geology variable. They utilized the model to analyze the resulting curvilinear relationships. They concluded that a curvilinear (quadratic) approach is significant for mean annual temperature and radiation index, but not usually applicable for rainfall, where only the linear term is significant.

Collins (1983) employed multivariate techniques to study succession on three permanent plots in a central Oklahoma grassland. He emphasized the temporal analysis of vegetational changes over time and concluded that grassland succession is difficult to predict because general successional trends are difficult to quantify.

In relating microclimate variables to plant biomass dynamics, Lauenroth and Whitman (1977) indicated that the aboveground and belowground biomass dynamics are significantly (α<0.05) related to air and soil temperature, soil water, and precipitation. From the correlation analysis, equations relating biomass dynamics to microclimate conditions were constructed by multiple regression. Mean biomass and total or average values of microclimate factors for the two weeks preceeding each biomass sample were used as input parameters into the regression equations. Variables of interest to Lauenroth and Whitman included total net radiation, evapotranspiration (representing water balance), total soil water, available soil water, and precipitation calculations, as well as average air and soil temperatures (15 cm depth). Lauenroth and Whitman (1977) noted that while biomass dynamics are recognized as the product of complex interactions of all abiotic variables, soil temperature, soil water, and the evaporative demand of the atmosphere are the critical variables in the regression combinations. The dependent grass variable and the independent abiotic factors were integrated into an empirical energy flow dynamics model to evaluate the influences responsible for biomass response (Lauenroth and Whitman, 1977).

Cool/warm season grass associations in relation to climatic factors were analyzed by Doliner and Jolliffe (1979). In an attempt to determine environmental characteristics associated with grass, statistical regression procedures were used to evaluate the similarity of cool and warm season groups relative to environment and climate factors. Stepwise multiple regression was utilized to test whether a measure of the proportion of species in a community could be predicted from some linear combination of climatic factors (Doliner and Jolliffe, 1979). The environmental varibles of interest were light, temperature, soil moisture, soil salinity, and soil nitrogen. The climate factors specified were annual precipitation, number of frost free days, mean summer maximum temperature and mean winter minimum temperature. The multivariate techniques proved to be powerful statistical tools for the identification of ecological differences between plants and the results reveal the distribution of warm season species tends to be associated with conditions of relatively low moisture availabilty and high temperature (Doliner and Jolliffe, 1979). The warm season grasses exhibit a physiological competitive advantage over cool season grasses under periods of high temperature and intermittent water stress.

Summary

This chapter included literature available to support an analytical study of the spatial and temporal changes in biomass conditions along an environmental gradient. The study area is detailed in Chapter III to describe the characteristics of the 12 sites positioned along a 200 km transect that traverses the climatic transition zone. The following chapters present the methods and analysis employed in the evaluation of interactive influences affecting the growth of native grassland vegetation.

CHAPTER III

DESCRIPTION OF THE STUDY AREA

Oklahoma is an ideal location in which to monitor a transition in moisture levels and the subsequent impact upon plant growth. The environmentally diverse nature of the state can be recognized by a low mean annual precipitation of 40 cm in the northwestern portion of the state compared to a mean annual precipitation of 140 cm in the southeastern part of the state (Albert and Wyckoff, 1984). This variation in moisture conditions creates a climatic gradient within a region which normally experiences moisture deficiencies and periods of vegetation stress.

The study area transect extends 200 km from Stillwater, Oklahoma in the east to Woodward, Oklahoma in the west (Figure 3). The study region extends through a zone of climatic transition and within a relatively pronounced moisture, temperature, and vegetation gradient. The 12 sample sites distributed along the transect are positioned in an attempt to characterize the impact of meteorologic variables, location, time, and soil conditions within this transition zone to sample biomass content associated with each site. General location characteristics, along with corresponding elevation

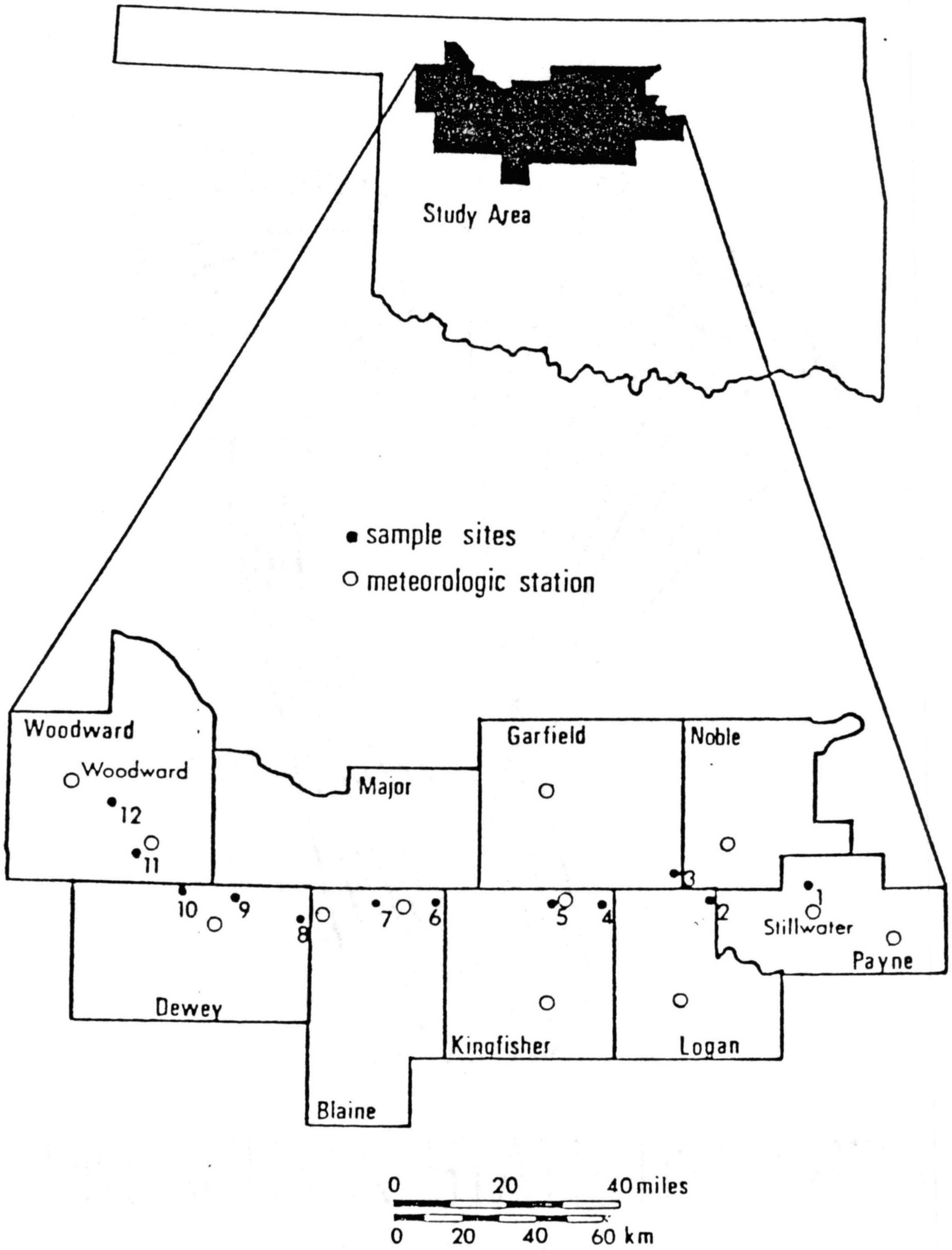

Figure 3. Study Area with Corresponding Sites and Meteorologic Weather Stations

TABLE II

LOCATION CHARACTERISTICS

Site Number	Topographic Map	Legal Description	County	UTM (m)	Elevation (m)
1	Stillwater North	S4,T19N,R2E SE¼,SE¼	Payne	671,940	293
2	Orlando East	S12,T19N,R2W SW¼,SE¼	Logan	647,560	345
3	Orlando West	S26,T20N,R3W NE¼,NW¼	Garfield	635,700	354
4	Lovell	S15,T19N,R5W SW¼,SE¼	Kingfisher	615,480	305
5	Hennessey	S18,T19N,R6W NW¼,SW¼	Kingfisher	599,120	354
6	Ames	S15,T19N,R11W SE¼,SW¼	Blaine	569,120	357
7	Okeene	S15,T19N,R11W SE¼,SW¼	Blaine	557,390	378
8	Canton SW	S11,T19N,R14W NW¼,NE¼	Dewey	527,290	534
9	Seiling	S11,T19N,R14W NW¼,SW¼	Dewey	510,480	538
10	Mutual NE	S1,T19N,R18W NW¼,NW¼	Dewey	493,200	564
11	Mutual	S3,T20N,R19W NW¼,SE¼	Woodward	481,060	579
12	Sharon	S32,T22N,R19W NW¼,SW¼	Woodward	476,440	598

Source: USDA County Soil Surveys and USGS Topographic Maps figures, for each of the 12 sample sites may be found in Table II. The transect, positioned in an east-west direction across the north-central portion of Oklahoma, is an attempt to traverse the existing moisture gradient.

Climate

Climate is one of the major factors in controlling plant growth (Olson, 1985). The general climate of Oklahoma is typical of a temperate, continental, subhumid regime with pronounced fluctuations in precipitation and temperature occurring thoughout the seasons. These climatic fluctuations are characteristic of the regime, and are largely a result of Oklahoma's interior continental postion relative to combined environmental influences of the warm, moist Gulf air masses, eastward-flowing jet stream, and frigid winter air masses from the north (Albert and Wyckoff, 1984). Oklahoma therefore has a dynamic climatic regime.

Precipitation effectiveness for plant utilization is dependent not only upon the amount of the event, but also upon the intensity, in addition to site specific soil permeability and infiltration rates. An attempt was made in the study to control for soil permeability and infiltration variability by choosing sites of similar soil type and terrain orientation (i.e. slope angle and slope aspect). In general, the precipitation events along the western portion of the transect are more torrential with an erratic distribution, in comparison to the longer duration, more predictable showers along the eastern portion of the transect (Albert and Wyckoff., 1984). Bruner (1931) recognized this moisture distinction in describing the character of shower events in terms of the length of the moist season, which decreases from eight months in the eastern part of the state to five in the western part of the state. He also noted a depletion of the water supply for root absorption and an eventual lack of soil moisture available for plant growth prior to the end of the growing season, increasing in an east to west direction. The range in the length of the growing season from 180 days in the northwest, 210 days in the central portion of the state, and 230 days in the southeast is indicative of the moisture and temperature variation (Albert and Wyckoff, 1984; USDA County Soil Surveys; Gray and Galloway, 1969).

The average annual precipitation decreases from east to west along the study transect. Payne county, in the eastern part of the transect, has an annual precipitation rate of 86 cm; Blaine county, in the central portion of the transect, has a rate of 65 cm; Woodward county, in the western portion of the transect, has 64 cm of precipitation annually. Average summer (June, July, and August) precipitation for Payne, Blaine, and Woodward counties are 7.8 cm, 7.4 cm, and 6.3 cm, respectively. The average annual temperatures for Payne, Blaine, and Woodward counties are 17.8°C, 16.2°C, and 15.2°C, respectively. Corresponding summer (June, July, and August) averages are 26°C, 28.5°C, and 27°C.

A gradual decrease in temperature corresponds to an increase in elevation westward across the state. Bruner (1931) stated that plant distributions may be controlled by temperature extremes. High temperatures and temperature variations are important factors in grassland soil, the former being conducive to conditions of increased transpiration, increased evaporation and root absorption.

Though the moderately warm temperatures during the spring are most favorable for plant growth after the first of April, Oklahoma does exhibit four distinct seasonal periods (Bruner, 1931). The long, balmy variable spring season is preceeded by a relatively short, dry moderate to cold winter and followed by hot, dry summers with a pleasant cool autumn season with moderate to heavy rains completing the cycle.

Wind, also an important factor in plant growth, directly influences evaporation, transpiration, and the water balance of the plant/soil environment. Prevailing southerly winds vary across the study area with wind velocities averaging approximately 14 km/hr in the eastern reaches of the transect, while velocities of 22 km/hr are common for the western portion. During frequent unstable, violent spring storms, winds in the western part of the area may vary between 40 and 64 km/hr (Woodward County Soil Survey, 1963).

The average annual precipitation and temperature across the transect region correspond to the climatic transition zone present in Oklahoma (Table III). The moisture gradient is much more evident than the subtle temperature transition as previously mentioned. The length of the growing season in terms of frost-free days is also included in order to support the environmental variation along the transect.

Physiography and Geology

The physiography of Oklahoma is diverse and complex relative to changes in geology, soils, and climatic variation (Bruner, 1931). Geologic formations and deposits range from Holocene eolian and alluvial materials to Permian gypsum formations. of the Wichita and Arbuckle mountains. The terrain of Oklahoma slopes in a southeastward direction from an elevation of 1370 m above sea level in the northwest to less than 120 m above sea level in the southeastern corner of the state. The varied geologic history of uplift, faulting, and folding alternating with periods of subsidence contributed to the topographic and physiographic characteristics.

The physiographic associations occurring along the transect are shown in Figure 4. The area of the transect, located primarily across the gently rolling hills of the Redbed plains, consists of Permian clays and shales covered by native prairie grasslands (Gray and Galloway,

TABLE III

AVERAGE ANNUAL PRECIPITATION, TEMPERATURE, AND LENGTH OF GROWING SEASON ACROSS THE STUDY AREA

County	Average Annual Precipitation (cm)	Average Annual Temperature (°C)	Growing Season Length (days)
Payne	86.0	17.8	219
Logan	81.3	16.1	214
Garfield	74.2	16.0	205
Kingfisher	73.7	16.1	208
Blaine	64.8	16.2	207
Dewey	63.7	15.0	193
Woodward	63.7	15.2	186

Source: USDA County Soil Surveys

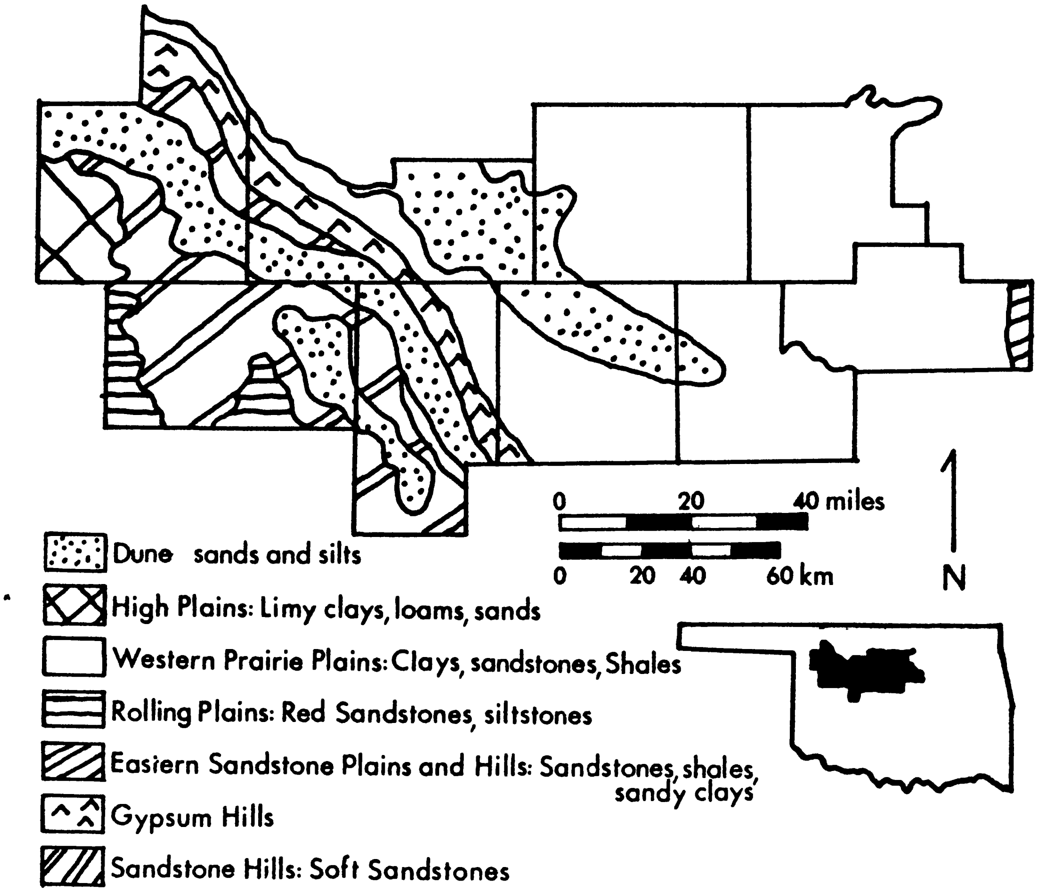

Figure 4. Study Area Transect Physiography

Source: Gray and Galloway, 1969

1969). The Sandstone hills result from the weathering of Pennsylvanian shales leaving low hills and resistant sandstone. The Gypsum Hills are also present in the mixed prairie environment as seen by the resistant gypsum escarpments in the area. The finely-textured soils of the High Plains support the short grass vegetation extending westward from the study area (Gray and Galloway, 1969).

On a broad scale, the physiography of the study area is diverse; however, physiographic characteristics at each site location are relatively uniform. The upland locations of silt-loam textured soils were chosen to minimize variations between sites resulting from differences in slope runoff, infiltration rates, and aspect. The 12 sample sites distributed along the transect are characterized by slopes of 0-3 degrees; however, one site is located on a slope of 5 degrees.

Vegetation

The vegetation of Oklahoma varies considerably because of the influences of topography, type of soil (parent material, texture, structure, and depth), and climatic regimes. The diverse nature of Oklahoma vegetation is illustrated by a range from grassland prairie associations of the western region of the state to the savanna/woodland and forest associations of the central and eastern regions, respectively (Gray and Galloway, 1969). A transition between alternating forestscrub and prairie cover to almost continuous grassland occurs across the central portion of the state because of a change in water content and water holding capacity with different soil types (Bruner, 1931). With decreasing aridity eastward, the grassland region itself grades from short to tall grass rangelands with a mixed grass transition between the two.

The vegetation of the study area (Figure 5) is characterized predominantly by the mixed native grass association with areas of timbers along streams and abundant cropland throughout. Though uniformity of site characteristics was a primary concern for area comparison, the environmental gradient with respect to precipitation affects the amount of moisture available for plants, therefore, the specific grass species at each site will vary accordingly. Absolute uniformity is relatively unobtainable given the inherent variability in nature. All sample sites are comprised of native grass vegetation, which had not recently been cultivated or grazed.

The west central region of Oklahoma has been designated as part of the mixed-grass association (Kelting, 1954). Perennial grass pastures are characteristic of the study area. Density and cover-type estimates were derived from direct field observation. The species which typify the sample sites are: (1) bromegrass, (2) bluestems, (3) grama grasses, (4) indiangrass, (5) switchgrass, and (6) buffalograss (Table IV). General descriptions and characteristics of these

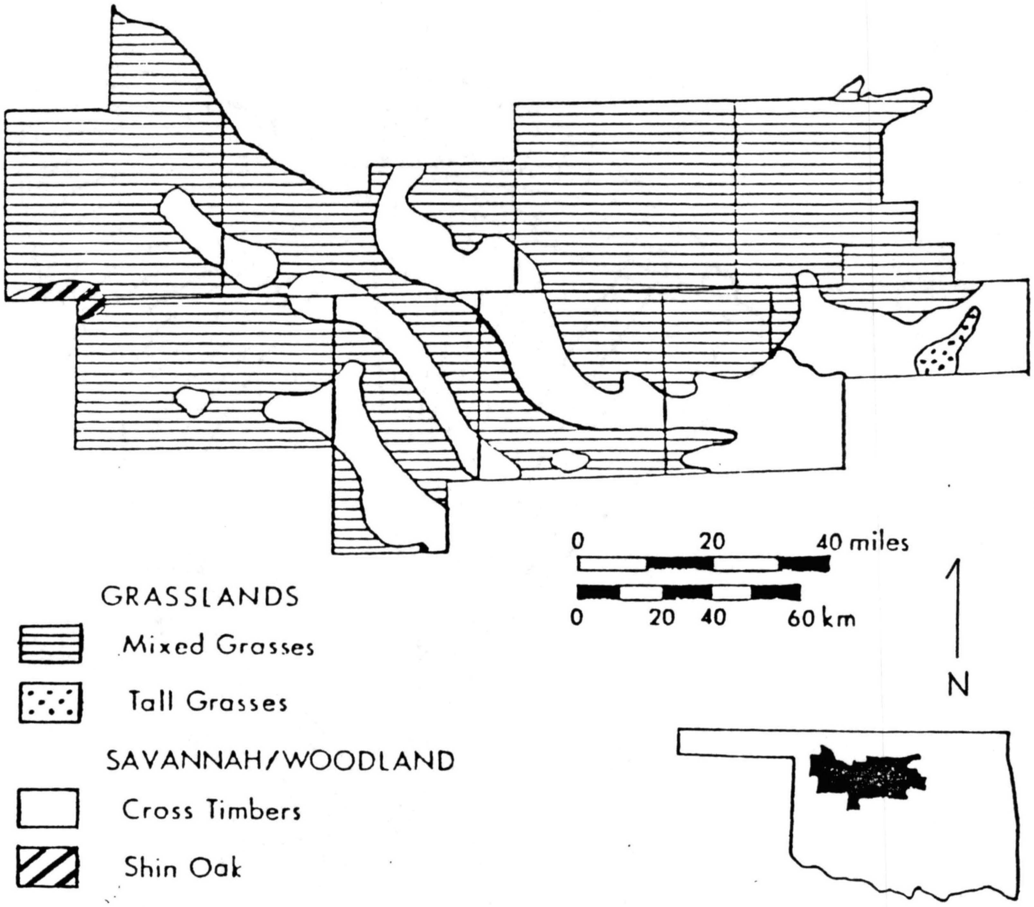

Figure 5. Natural Vegetation Types of the Area

Source: Gray and Galloway, 1969

TABLE IV

SAMPLE SITE VEGETATION COMPOSITION

Site	Grass %	Native Grass	Species Name	Type	Vegetation Density
1	40	Switch	(Panicium viragatum)	Tall	Dense
	30	Little Bluestem	(Andropogon scoparious)	Mid	
	20	Big Bluestem	(Andropogon gerardi)	Tall	
	10	Indiangrass	(Sorghastrum nutans)		
2	60	Little Bluestem	(Andropogon scoparius)	Mid	Medium
	30	Western Ragweed	(Ambrosia psilostachya)		
		Sage	(Artimisia)		
	10	Indiangrass	(Sorghastrum nutans)		
3	70	Little Bluestem	(Andropogon scoparius)	Mid	Medium
	10	Western Ragweed	(Ambrosia psilostachya)		
	10	Switch	(Panicium viragatum)	Tall	
	10	Buffalograss	(Buchloe dactyloides)	Short	
		Hairy Grama	(Boutelova hirsuta)	Short	
4	33	Silver Bluestem	(Andropogon saccharoides)	Mid	Dense
	33	Japanese Brome	(Bromus Japoniaes)		
	33	Western Ragweed	(Ambrosia psilostachya)		
5	40	Silver Bluestem	(Andropogon saccharoides)	Mid	Medium
	30	Japanese Brome	(Bromus Japoniaes)		
	20	Western Ragweed	(Ambrosia psilostachya)		
	10	Sideoats Grama	(Boutelova curtipendula)	Mid	
6	50	Japanese Brome	(Bromus Japoniaes)		Medium
	30	Silver Bluestem	(Andropogon saccharoides)	Mid	
	10	Hairy Grama	(Boutelova hirsuta)	Short	
	10	Snowy Partridgepea	(Chamaecrista fasciculata)		
		Blue Wildindigo	(Baptista australis)		
		Doted Grayfeather	(Liastris puncata)		
7	40	Japanese Brome	(Bromus Japoniaes)		Sparse
	30	Silver Bluestem	(Andropogon saccharoides)	Mid	
	20	Hairy Grama	(Boutelova hirsuta)	Short	
	10	Western Ragweed	(Ambrosia psilostachya)		

TABLE IV (Continued)

Site	Grass %	Native Grass	Species Name	Type	Vegetation Density
8	50	Sideoats Grama	(Bouteloua curtipendula)	Mid	Med-Sparse
	40	Japanese Brome	(Bromus Japoniaes)		
		Hairy Grama	(Boutelova hirsuta)	Short	
	10	Western Ragweed	(Ambrosia psilostachya)		
		Snowy Partridgepea	(Chamaecrista fasciculata)		
		Sand Sage	(Artimisia)		
9	60	Sideoats Grama	(Boutelova curtipendula)	Mid	Sparse
		Hairy Grama	(Boutelova hirsuta)	Short	
	20	Little Bluestem	(Andropogon scoparius)	Mid	
	10	Japanese Brome	(Bromus Japoniaes)		
	10	Bare Soil			
10	50	Japanese Brome	(Bromus Japoniaes)		Dense
	30	Hairy Grama	(Boutelova hirsuta)	Short	
		Buffalograss	(Buchloe dactyloides)	Short	
	10	Western Ragweed	(Ambrosia psilostachya)		
	10	Little Bluestem	(Andropogon scoparius)	Mid	
11	30	Little Bluestem	(Andropogon scoparius)	Mid	Medium
	20	Indiangrass	(Sorghastrum nutans)	Tall	
	20	Silver Bluestem	(Andropogon saccharoides)	Mid	
	10	Switchgrass	(Panicium viragatum)	Tall	
	10	Western Ragweed	(Ambrosia psilostachya)		
	10	Japanese Brome	(Bromus Japoniaes)		
12	60	Sideoats Grama	(Boutelova curtipendula)	Mid	Sparse
	10	Bare Soil			
	10	Little Bluestem	(Andropogon scoparius)	Mid	
	10	Japanese Brome	(Bromus Japoniaes)		
	10	Western Ragweed	(Ambrosia psilostachya)		
		Snowy Partridgepea	(Chamaecrista fasciculata)		

grasses that are important in understanding moisture/plant relationships include (Metcalfe and Elkins, 1980; Knapp, 1984; Anderson, 1985; Vankat; 1979):

(1) Bromegrass: *Bromus japanicus* is a leafy, cool-season perennial distributed throughout most of the United States. The native grass occurs as a sod-forming plant of varying height with close sheaths and flat blades. Distribution of this short grass is based on hardiness, drought resistance, wide climatic and soil adaptation, early season forage production, and wind/water erosion control properties. Growth begins in early spring.

(2) Bluestems: Many different species of bluestems exist, but only three native species, two of which are little bluestem (*Andropogon scoparius*) and big bluestem (*Andropogon gerardi*), are important forage plants in this country. Big bluestem (height approximately 1.8 m) is a native perennial, warm season, sod-forming grass with a distribution range in moist well-drained loams in the Central States and on the eastern edge of the Great Plains. Little bluestem (*A. scoparius*) is also a warm-season perennial, however, it is medium sized (0.6-1.2 m) bunchgrass with a widespread distribution across the Southwest Great Plains because of its

greater drought tolerance. Growth of bluestems begins in late spring and continues into the summer months.

(3) Gramagrasses: The warm-season gramas predominate throughout the Great Plains. Sideoats grama (*Bouteloua curtipendula*), a perennial bunch-type grass (approximate height of 0.6-0.9 m) is usually grown in association with bluestems. It is adapted to a wide range of climatic and soil conditions, however, a medium or course textured soil is preferable. The seed yield from this vigorous grass is good, with the seed maturing in late summer. Hairy grama (*Bouteloua hirsuta*) is a perennial short grass found predominantly in Central and Northern Great Plains on medium to fine-textured soils. It is a quickly-growing warm season grass, maturing in mid to late summer.

(4) Indiangrass: *Sorghastrum nutans* is a moderate to tall, erect perennial grass with narrow blades. This warm season bunch grass is well adapted to sandy plains sites of the Southwestern Great Plains. Indiangrass is often known to be a major constituent of prairie hay during late summer and early fall.

(5) Switchgrass: As a vigorous, sod-forming, warm season perennial, switchgrass (*Panicium virgatum*) occurs throughout the United

States; however, it is of greatest importance as a forage grass in the central and southern Great Plains. It is a tall-growing (0.9-1.5 m) grass of the sod-forming variety. Switchgrass not only produces well on dry, infertile, eroded soils, but also occurs naturally on fertile soils with adequate moisture (Metcalfe and Elkins, 1980; Knapp, 1984; Anderson, 1985; Vankat, 1979).

Soils

Soil type is an influential factor in the amount of moisture that is held in storage for plant utilization. Nearly all soils with deep, dark, relatively fertile topsoil are formed under grassland vegetation (Buol et al, 1980). Crockett(1964) also reported a significant correlation between vegetation and associated soil type. Available soil water is considered to be one of the principle determinants in shortgrass prairie productivity (Detling, 1979). Soil texture is a critical variable in controlling moisture availability for plant growth relative to water holding capacity, permeability, infiltration rates, runoff rates and internal redistribution of available moisture (Hillel, 1982). The finely textured clayey soils, for example, retain more water and for a longer period of time than the coarser sandy soils; therefore, moisture is retained for plant use and the infiltration rate is decreased.

The study sites are situated on relatively level upland locations with slopes ranging from 0-3 degrees to equalize slope aspect, runoff, and infiltration rates for area comparison. The western prairie soils of the region were originally developed from Pennsylvanian sedimentary shales, limestone, and clays. The dune sands and silts of the area occur as eolian and alluvial deposits of the North and South Canadian Rivers (USDA County Soil Surveys). The soils of the study plots were sampled and analyzed to establish soil type as indicated by texture classifications (Table V). Soil samples were collected from 15 cm, 61 cm, and 91 cm depths for texture classification. Particle size analysis contributes to a better understanding of the physical properties associated with infiltration, retention, and ease of water movement through the soil at each site. Clay loam textures tend toward decreased infiltration and movement of moisture because of an increase in retention with smaller particle sizes, in comparison to the slightly increased particle size, infiltration rates, and water movement associated with the silt loam textured soils. The many interrelated physical and chemical characteristics of the soil profile are incorporated by soil associations and series descriptions (White and Glenn-Lewin, 1984). Appropriate soil associations and series affiliations for the areas are described in Tables VI and VII, respectively.

TABLE V

SOIL CHARACTERISTICS FOR TRANSECT SAMPLE AREAS

Site	Depth	Percent Sand	Percent Silt	Percent Clay	Soil Texture
1	1	(not collected for this study)			loam/clay loam
2	1	39.5	35	25.5	loam/clay loam
	2				
	3	37	35	28	
3	1	39.5	38.75	21.75	loam
	2	42.0	37.5	20.5	
	3	22	42.5	35.5	
4	1				silty clay
	2	17	42.5	40.5	
	3	14.5	37.5	48.0	
5	1	37	45	18	clay loam
	2	38.25	31.25	30.5	
	3	37	30	33	
6	1	29.5	36.25	34.25	clay loam
	2	49.5	22.5	28	
	3	44.5	22.5	33	
7	1	32	40	28	clay loam
	2	29.5	32.5	38	
	3	33.25	46.25	20.5	
8	1	62.0	27.5	10.5	sandy loam
	2	49.5	35	15.5	
	3	53.25	36.25	10.5	
9	1	37	48.75	14.25	loam
	2	34.5	43.75	21.75	
	3	32	40	28	
10	1				sandy clay loam/ loam
	2	49.5	30	20.5	
	3	52	26.5	21.75	
11	1	52	28.75	19.25	loam/sandy loam
	2	54.5	26.25	19.25	
	3	39.5	35	25.5	
12	1	40.75	41.25	18	loam
	2	38.25	38.75	23	
	3	39.5	37.5	23	

TABLE VI

SOIL ASSOCIATIONS

SITE	SOIL ASSOCIATION	DESCRIPTION
1	Zanies	very gently sloping loamy soil on broad convex upland ridges, deep and well drained
2	Renfrow-Vernon-Kirkland	deep shallow prairie soils on red clay beds
3	Zanies-Lucien-Vernon	deep shallow very gently to steeply sloping soils of the uplands
4	Vernon-Renfrow	deep reddish silt loams and clay loams, nearly level to gently rolling
5	Bethany-Norge	deep, dark and nearly level to gently sloping
6	Norge-Kingfisher-Renfrow	deep, loamy, well-drained nearly level to sloping soils of the uplands, loamy and clayey subsoils
7	Bethany-Kirkland-Tabler	deep, well-drained and moderately well-drained nearly level soils of uplands, clayey subsoils
8	Woodward-Dill-Miles	sandy uplands and red bed hills
9	Quinland-Woodward	red bed hills
10	St. Paul-Carey-Holdrege	loamy uplands
11	St. Paul-Carey-Woodward	gently sloping loamy red beds
12	St. Paul-Carey-Woodward	gently sloping loamy red beds

Source: USDA County Soil Surveys

TABLE VII

SOIL SERIES DESCRIPTIONS

SITE	SOIL TYPE	DESCRIPTION
1,2	Rc	Renfrow silt loam, 3-6% slope, deep and nearly level to gently sloping soils of uplands, naturally well drained, internal drainage is medium, slow permeablility, high moisture retention, tall grass, gramas, and buffalograss are predominant native grass covers
3	KrB	Kirkland-Renfrow silt loams, 1-3% slope, nearly level to gently sloping uplands, adequate drainage, slow permeability and internal drainage caused by subsurface claypan, high moisture retention, mixed native grass cover
4	VeB	Vernon clay loam, 1-3% slope, shallow, very gently sloping soils of uplands, naturally well drained, internal drainage is medium, slow permeablility, mixed native grass cover
5,6,7	BeA	Bethany silt loam, 0-1% slope, nearly level uplands, slowly drained areas, friable granular structure, naturally well drained, internal drainage is medium, slow permeability, high water holding capacity, moderate moisture retention, native grass cover predominates
8	CeB	Carey silt loam, 1-3% slope, gentle upland slopes, subsoil readily penetrated by water and plant roots, granular to prismatic structure, native cover of mixed grasses
9	SpA	St. Paul silt loam, 0-1% slope, nearly level to very gently sloping soils of uplands, naturally well drained, internal drainage is medium, moderately slow permeability but easily penetrated by roots, ability to absorb and retain moisture is moderate, predominantly mid-grass cover
10	CeB	Carey silt loam, 1-3% slope, previously described above for Site 8
11	CaB	Carey silt loam, 1-3% slope, gently sloping soils, similar to CeB with silt loam surface layer, problems with surface crusting, moderately permeable, mixed native grass cover
12	CaC	Carey silt loam, 3-5% slope, moderately sloping with a subsoil of silt loam that absorbs water well, moderate permeability, roots penetrate with little difficulty, cover of mid to short native grass

Source: USDA County Soil Surveys

Summary

The description of the study area is important in considering factors that may prove influential in predicting biomass development. The upland sites with predominant silt loam texture and mixed native grass cover, positioned along a transect across an environmental precipitation and temperature gradient, provide appropriate characteristics to monitor and evaluate the variations in biomass over time. The preparation involved in research design and site investigation follows in the next chapter, along with corresponding sampling procedures and variable organization associated with quantitative vegetation analysis.

CHAPTER IV

METHODOLOGY

Preliminary Considerations

According to Daubenmire (1968), one of the most fundamental requirements for obtaining a valid statistic is that the sampled vegetation population must be homogeneous in order to reveal a valid representation for area comparison. Absolute homgeneity is relatively impossible given the complex character in natural communities. West et al (1921) demonstrated a need for material as uniform as possible in the investigation of environmental factors likely to affect plant growth and associated dry-weight measurements. Therefore, the basic sampling problem involves eliminating as much heterogeneity between sample sites as possible (Kellman, 1975). The sites chosen for this investigation were strategically located on the basis of grassland cover-type, soil type, and terrain orientation, with the overall aim of obtaining homogeneous study areas.

The particular species composition of a community may vary both in time and space, with a dynamic spatial character shifting through time (McNaughton, 1983). The relevance of the concept of spatial and temporal homogeneity to ecosystem organization has been increasingly questioned as dynamic relationships between spatial pattern and community organization have become apparant (McNaughton, 1983; Carpenter and Chaney, 1982; Tremlett et al, 1983). Spatial heterogeneity is a universal feature of plant communities and a long-standing problem for plant ecologists (Carpenter and Chaney, 1983). Spatial and temporal patterns reflect associated environmental patterns as well as demographic processes of plants within the dynamic community (Tremlett et al, 1983; Carpenter and Chaney, 1983). In comparison to the traditional technique in vegetation ecology to statistically measure homogeneous study areas, McNaughton (1983) recognized that spatial heterogeneity is an important attribute in the study of spatial pattern of plant species diversity. Spatial heterogeneity, however, varies on a regional scale with temperate locations exhibiting more uniform vegetation.

It was desirable to select sample areas of maximum homogeneity to minimize variations between sites. In the consideration of site selection, an attempt was made to control influential variables (i.e. those that may affect behavior of land cover and the availability of water over time and space). With the aid of the USDA Soil Conservation Service, associated USDA Soil Surveys, topographic maps, and subsequent field verification, upland locations with similar soil type and terrain orientation (slope angle, aspect, and elevation) were chosen to minimize the effect of factors such as the rate of infiltration and runoff at each site.

Vegetation is distributed differentially with respect to topographic position and subsoil permeability (White and Glenn-Lewin, 1984), therefore, lending supportive reasoning for maximizing site-uniformity characteristics. Similarly, areas of relatively uniform landcover type, specifically native rangeland grasses, were sampled for biomass content because plants of differing texture and composition may strongly affect comparisons on a dry weight basis (Knapp, 1984). Any locational history at each site, such as the occurrence of recent fires, plowing, and fertilization was also taken into consideration. Gulmon et al (1983) studied the water resource partitioning among three co-occurring grassland species and concluded that site fertility is an important interactive factor in available water utilization. Site fertility affects the competitive relations among species as well as overall timing of water use. Collins and Adams (1983) recognized that plowing and cropping alter soil structure and reduce soil organic matter, therefore, affecting vegetation composition.

In addition to the manipulation of parameters to maintain homogeneity, the control plots were fenced off in an attempt to eliminate any unnecessary local disturbances from grazing animals or vandalism. The abiotic effects of temperature and soil moisture may be modified by grazing, thus demonstrating that the trend of the grass production system can be severely altered by the pattern of grazing (French, 1979). Kelting (1954) indicated that the soil in the virgin prairie has a more desirable structure in that it is not as compact as the soil in grazed plots and moisture utilization by the plant is easier.

Site Preparation

Preliminary work involved in site preparation was essential before actual field measurements were conducted. Landowner permission for access and site inspection began the site selection process. Secondary weather stations close to the transect provide additional meteorologic variable information (mean daily air temperature and precipitation measures) to augment the rain gauge readings collected at each site on a weekly basis (previously represented on Figure 3).

First order meteorologic station measures (i.e. relative humidity, wind, and percent sunshine) were also utilized. The weather station point samples were interpolated into cell measures through the use of the Theissen polygon approach (Oliver, 1973). Construction of the polygons provided an appropriate method to obtain area values relative to each site. The meteorologic information was incorporated into the calculation of potential evapotranspiration (utilizing relative humidity, wind, and percent sunshine) and heat units (utilizing daily temperature values). Detailed calculations of derived variables may be found in Appendix A.

The objectives of vegetation analysis are to understand the form and function of vegetation, allowing predictions to be made about it in time and space (Kellman, 1975). The primary objective of this study is to measure plant biomass production at 12 sites along the transect and to correlate these measures with environmental factors that have been shown to have an affect on plant growth. At each site, an 8 x 10 meter plot was fenced off to protect the area throughout the duration of the study. A quadrat of 24 x 42 cm (0.1 m^2) area was constructed of a durable alloy to retain a uniform shape and size throughout the study. The quadrat was utilized as a sample boundary for weekly biomass evaluation. According to Pears (1977), if the area under examination is relatively uniform, then a small quadrat will provide a representative sample of the overall vegetation. Quadrats of 0.1 sq m prove sufficient to determine cover of a given area (Kelting, 1954).

The quadrat analysis technique is often employed in the collection of vegetation data. The systematic sampling of vegetation often takes the form of quantitative measures along transects utilizing the clipping of vegetation with uniform quadrats. Kelting (1954) demonstrated quantitative quadrat sampling of vegetation in a native tallgrass prairie in central Oklahoma. Each plot was analyzed by means of twenty-five 0.1 sq m quadrats throughout a growing season; the quadrats were spaced at intervals of ten paces along systematic lines of study (Kelting, 1954).

French (1979) also studied aboveground biomass by sampling and clipping ten 0.5 sq m quadrats, drying, and weighing the grass. He separated different plant species, however, because he was interested in classifiying types of grasslands in North America. Collins and Adams (1983) used a similar sampling method to study aerial vegetation coverage by evenly spacing twenty-five 0.1 sq m quadrats along randomly located transect lines in each study plot.

Area sampling is an accepted method in the study of vegeation trends. Areal cover measurement gives the best relationship between various components of a grassland community (Kelting, 1954; French, 1979). Kelting (1954) noted that it is coverage rather than numbers of plants, frequency, or other quantitative concepts used in the analysis of vegetation that determines dominance and gives character to a community. Coverage data is valuable and significant in the evaluation of quantitative vegetation relations (Collins and Adams, 1983).

Sampling Procedures

Pears (1977) suggested a regular pattern of plot location, emphasizing that quadrats distributed systematically throughout the stand give quite satisfactory results. A similar systematic sampling pattern was established in this study (Figure 6). Pears (1977) also stated that these practical considerations can outweigh the theoretical advantages of a random location.

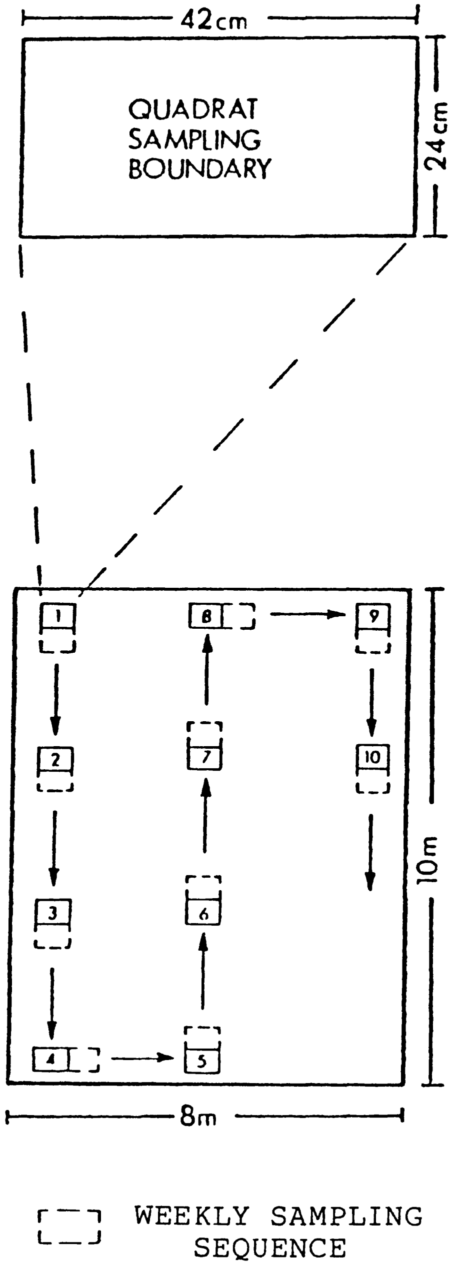

Figure 6. Systematic Quadrat Sampling

The use of random quadrats is limited because of the non-random distribution of plant species (Grieg-Smith, 1961). French (1979) demonstrated that methods of data collection should be similar at all study sites, as was incorporated into this study.

Wilm et al (1944) noted that it is necessary to obtain accurate estimates of grass produced; however, it is difficult simply because weight of plant material varies considerably with each species in a mixed grass population. Because all grass cannot be harvested and weighed individually, it is necessary to obtain a reasonable estimate of the true total weight by sampling (Wilm et al, 1944; Zar, 1974). Utilizing a standard method such as clipped plots, the sampling procedure is relatively simple in principle (Wilm et al, 1944; Sandland et al, 1982; Mohler, 1983). It is necessary to clip plots distributed over an area using an efficient, systematic scheme to provide an accurate estimate of average grass production (Wilm et al, 1944; Zar, 1974; Pears, 1977; Tremlett, 1984).

It is possible to concentrate on periodic variations by sampling at specified intervals through time (Daugherty, 1973). White and Glenn-Lewin (1984) also sampled along transects at intervals to represent the range in variation on the prairie vegetation under study. Sampling of grasses from within the plot area involved the weekly clipping of ten systematically placed quadrats of grass stands approximately two centimeters above ground level. Kelting (1954) used similar clipping techniques and supports clipping a new series of quadrats selected for each period of study, so no areas are clipped more than once. The samples were subsequently dried in shelved wall ovens of the Oklahoma Agricultural Experiment Station, and weighed five days later to measure the dry weight of the biomass.

Rain gauges were placed at each site to obtain weekly precipitation data in coordination with weather station information. Weekly relative humidity and temperature were also recorded at each site using a sling psychrometer as a comparable check for meteorologic station data.

Organization of Variables

Table lists the variables considered in the statistical assessment of significant influences on biomass growth. Table VIII summarizes the selected variables, collection methods and relevant data sources. The collection of these factors for subsequent analysis is explained here with detailed calculations available in Appendix A:

(1) Biomass ---direct field collection involving a systematic quadrat sampling technique with subsequent drying and weighing of aboveground live biomass to attain measures of dry mean biomass.

(2) Mean daily precipitation and mean daily temperature ---information obtained from associated

TABLE VIII

SELECTED VARIABLES WITH CORRESPONDING COLLECTION METHODS AND RELEVANT DATA SOURCES

Variable	Collection Method	Data Source
Biomass	Systematic quadrat sampling	Field Measurements
Air Temperature	Meteorologic station	Oklahoma Climatological Survey
Precipitation	Meteorologic station	Oklahoma Climatological Survey
Soil Moisture	Neutron-probe readings at 15,61, and 91 cm depths	Field Measurements
Soil Temperature	Thermocouple/ Microvoltmeter readings at 15,61, and 91 cm depths	Field Measurements
Soil Texture	Particle size analysis from 15, 61, & 91cm depths	Laboratory analysis
Potential Evapotranspiration	Calculated	Oklahoma Climatological Survey
Heat Units	Calculated	Oklahoma Climatological Survey
Relative Humidity Percent Sunshine Wind	Meteorologic station	Oklahoma Climatological Survey
Two-Week Accumulated Precipitation	Calculated	Oklahoma Climatological Survey
Elevation	Interpretation of topographic maps	U.S. Geological Survey
Universal Transverse Mercator coordinates	Interpretation of topographic maps	U.S. Geological Survey
Location	Site Location	Sample Site Number
Time	Week Number (1-15)	Date (May 07-Aug. 13, 1985)

Oklahoma cooperative weather stations. The derivation of the heat unit temperature factor involves the subtraction of an established base temperature (10°C) from daily mean temperature values to obtain daily heat units affecting the vegetation at each site and accumulated throughout the season (detailed in Appendix A).

(3) Relative humidity, percent sunshine, and wind ---obtained from first order weather stations to derive a weekly potential evapotranspiration value. The Christiansen method with appropriate meteorologic variables provided a satisfactory measure of the water loss associated with plant transpiration and atmospheric evaporation (Bordne and McGuinness, 1973).

(4) Soil moisture ---information provided by Panciera (1986). Galvanized pipes were inserted into the ground to allow for subsequent probe measurements. Weekly neutron-probe readings taken at the same sites over the same sample period allows for a measure of the available water (at the 15 cm depth) that ultimately controls many physiological plant processes (photosynthesis, respiration, leaf growth, and translocation) associated with moisture dynamics of grassland ecosystems (Detling, 1979). The relevant soil moisture values were then derived from appropriate computer analysis of the probe readings.

(5) Soil temperature ---information also provided by Panciera (1986). Tungsten thermocouple psychrometers were implanted at three depths of 15 cm, 61 cm, and 91 cm,

which correspond to soil moisture readings from similar soil horizon depths. Care was taken to secure the thermocouples in undisturbed soil to prevent variations in temperature resulting from arbitrary infiltration. Employing a microvoltmeter, the weekly soil temperatures were obtained and monitored.

Summary

Field research involves the design of appropriate methods for site selection and preparation, data collection, and sampling procedures. This chapter explained the basis of site selection, the systematic sampling pattern utilized to measure dry mean biomass, the collection techniques involved in attaining soil moisture and soil temperature data, and the source and derivation of selected environmental variables chosen for subsequent analysis. The results of the statistical analysis will allow for empirical modeling of significant variables associated with grassland development. The resultant relationships from the regression analysis will be interpreted and evaluated in response to environmental influences on vegetation growth.

CHAPTER V

ANALYSIS AND RESULTS

Introduction

This research focuses on the assessment of vegetation characteristics over time and space, in an attempt to evaluate the influence of selected environmental factors on plant biomass throughout the 15-week sampling period. Statistical analysis has been utilized in various research efforts to quantitatively describe changes in vegetation, as recognized in Chapter II. The complexity of the environmental interactions and resultant influence on vegetation growth warrant the interpretation of multivariate statistical procedures to enhance our understanding of dynamic vegetation response characteristics. When interest is primarily in estimation or prediction (modeling behavior changes) of dependent values from several other characteristic values, a need arises for an equation that relates the dependent response to the independent variables (Steele and Torrie, 1980). Multiple regression techniques will provide the necessary equation. Multiple correlation techniques will provide a measure of the degree of relation between the dependent variable and the set of independent variables.

Variable Manipulation

In lieu of the complex forces acting to influence ecological relationships between biomass and associated environmental factors, consideration of the independent variables, polynomial expressions (X^2, X^3, X^4), and cross products (X_1*X_2, X_1*X_3, etc.) of the independent variables are essential to evaluate the response of vegetation to combined environmental influences (Zar, 1974; Sims and Singh, 1978; French, 1979; Austin et al, 1984). In attempting to analyze factors affecting a logistic growth response, nonlinear provisions must allow for iterative, interactive variable interpretation (Zar, 1974; Steele and Torrie, 1980). Table IX shows the independent variables to be used and manipulated (cross products and polynomial expressions) in forthcoming statistical analyses.

Multiple Correlation Analysis

Initial attempts to evaluate the relationship between the dependent variable, dry mean biomass, and the selected set of independent variables involved correlation procedures. Correlations were performed to determine the significance, direction, and magnitude of the relationships which exist between the dependent biomass variable and the independent environmental variables. A standard confidence level of 95 percent was utilized to evaluate statistical significance.

TABLE IX

STATISTICAL VARIABLES

Variable Code	Description
SMOIS	Soil moisture at all depths
STEMP	Soil temperature at all depths
WEEK	Time
SITE	Location
MAI	Moisture Availability
PET	Potential evapotranspiration
UTM	Universal transverse mercator coordinate location
ELEV	Topographic elevation
HUNITS	Weekly total heat units
MTEMP	Weekly mean air temperature
W2PRECIP	Two-week cumulative precipitation
WPRECIP	Weekly total precipitation
SAND SILT CLAY	Soil textural classification

*Additional variables have been created by raising each variable listed above to the 2nd, 3rd, and 4th powers. Cross products have been derived for all variables for inclusion into the regression pool of available independent variables.

The correlation coefficient (r) resulting from the correlation procedure is not a measure of quantitative change of one variable with respect to the other, but it is a measure of the intensity of association between two variables (Zar, 1974; Hocking, 1976). The correlation coefficient has a range from a maximum of +1 (perfect positive correlation) to a minimum of -1 (perfect negative correlation). A positive r value implies that for an increase in the value of one of the variables, the other variable also increases in value; a negative r value indicates that an increase in the value of one of the variables is accompanied by a decrease in value of the other variable. Subsequent discussion of the statistical analyses will be presented in the results section of this chapter.

Multiple Regression Analysis

Multiple regression analysis is used in this research to assess the variation in plant biomass explained by independent variable influences. Theoretically, no limit exists to the number of independent variables which can be proposed to influence the dependent variable. The objective of the analysis technique is to develop an interactive model of the response variable as a function of the observed inputs and various functions of these inputs, in order to reveal relationships between the sets of variables (Hocking, 1976; Austin et al, 1984).

Multiple regression focuses on the basic assumption that one variable is functionally dependent on each of the other variables, and no single variable is independently responsible for explaining the variation in the dependent response variable. In ecological situations, the dependent variable (Y) is often a function of more than one independent variable (X). The general interrelationship observed from multiple regression analysis is represented by the equation:

$$Y = A + B_1X_1 + B_2X_2$$

where Y=the dependent varible, X= the independent variable, A=the Y-intercept or the value of Y when X is zero, and B=the partial regression coefficient used as an indication of relative importance of the various X's in determining the value of Y (Zar, 1974; Steele and Torrie, 1980). Though multiple regression analysis may include several independent variables, a significant effect on the magnitude of the dependent variable is not automatically implied. Appropriate techniques may be chosen to determine which of the independent variables have a significant effect on the dependent variable.

Stepwise (MAXR) Technique

The stepwise technique is useful when many independent variables are under consideration and it is necessary to find which variables should be included in the regression model. The technique provides an appropriate method to give insight into the relationships between the independent and dependent or response variable. The computational task of evaluating all possible regressions is accomplished by the stepwise procedure, proposed for evaluating the effect of each independent variable one by one or in combination with previously chosen variables.

The SAS Institute (1985) proposes a MAXR selection strategy that provides a forward selection with pair switching in choosing variables to apply to the stepwise model building procedure. This method does not settle on a single model, but attempts to find the best one-variable model, the best two-variable model, and so forth to explain the variation in the response variable. The MAXR stepwise technique begins by finding the one-variable model producing the highest r^2. Another variable, producing the greatest increase in r^2, is then added. Once the two-variable model is obtained, each of the variables in the model are compared to each variable in the pool not included in the model. For each comparison, MAXR determines if the r^2 would increase if one variable was replaced by another selection. The appropriate substitution is made, if deemed necessary, to produce the largest increase in r^2. The comparison process continues until MAXR finds that no remaining substitution would increase the r^2.

The user decides on an arbitrary number of steps to be included in the regression, usually based on a minimal increase in r^2 with additional steps or a minimal decrease in the sum of squares error. Table X provides the r^2 and the sum of squares corresponding to each step of the regression procedure to illustrate the increments of change. The r^2 is associated with an increase in variation of the dependent variable explained by the independent variables. The sum of squares error is associated with a reduction in error of the variable association.

The number of steps chosen as providing a significant combination of variables is often a function of the time and money available for research. One must consider the feasibility of the increase in r^2 relative to the additional cost of data collection. Table X reveals an r^2 increase of .38 associated with the first 7 steps and only an increase of .04 associated with the remaining 5 steps. Comparison of step 7 to step 12, however, shows that the specific variables selected as influential in the regression model do not change significantly. It is only the combinations of the textural, temporal, and spatial variable associations that fluctuate; therefore, the same amount of time and effort would be required for data collection and biomass analysis, whether the model was completed after the seventh or twelfth step.

The difference between the original stepwise technique and the maximum r^2 improvement method is that all substitutions are evaluated before any switch is made in the MAXR method. In the original stepwise procedure,

TABLE X

COEFFICIENTS OF DETERMINATION AND SUM OF SQUARES CORRESPONDING TO EACH REGRESSION STEP

Step Number	Coefficient of Determination	Sum of Squares Error
1	0.432	17250
2	0.648	10683
3	0.690	9417
4	0.716	8613
5	0.742	7837
6	0.794	6243
7	0.808	5830
8	0.816	5595
9	0.821	5447
10	0.835	4994
11	0.838	4910
12	0.845	4733

the "worst" variable may be removed without considering the consequence of adding the "best" remaining variable.

Coefficient of Determination (r^2)

The coefficient of determination is a measure of how much of the total variability in the dependent variable, dry mean biomass, is attributed to the independent variables as defined by the regression model. The r^2 value ranges from 0 to +1 and will be tested at the 95 percent confidence level for statistical significance.

F-test for Significance

The multiple regression is performed in an attempt to test the interrelated dependence of biomass on associated environmental factors. The F-statistic tests this relationship by dividing the treatment mean square by the error mean square. These calculated F values are compared to tabular F values for the degrees of freedom corresponding to each step of the regression procedure. Appendix C presents the detailed results of the stepwise MAXR regression procedure with associated F statistics. The calculated F obtained from the analysis is greater than the tabulated F corresponding to each step. The regression model, therefore, is significant and each variable in the model is significant at the 0.05 level.

Results

The intended research objectives of this study were analyzed and interpreted relative to correlation and regression analyses. Interpretation of the general environmental trends illustrated by graphical representations further added to the understanding of plant biomass changes throughout the sample period and along the transect. Figure 7 presents a three-space plot of dry mean biomass for sites 1, 6, and 12 for the 15-week sampling period. Figures 8 through 10 graphically illustrate relationships between weekly total precipitation, weekly mean air temperature, and weekly dry mean biomass associated with sites positioned along an environmental gradient. Sites 1, 6, and 12 represent the eastern, central, and western locations along the transect, respectively. Appendix B presents similar graphics for sites 2 through 5, and sites 7 through 11 not specifically discussed in the text.

The three-space plot (Figure 7) of biomass at the eastern (site 1), central (site 6), and western (site 12) locations over time illustrates a decreased dry mean biomass amount by weight (g/0.1 sq m) at the western extreme compared to the eastern extent of the transect. The intervening sites show similar growth trends and fluctuations throughout the sampling period. This decrease in dry mean biomass is partially a result of observed density differences associated with regional

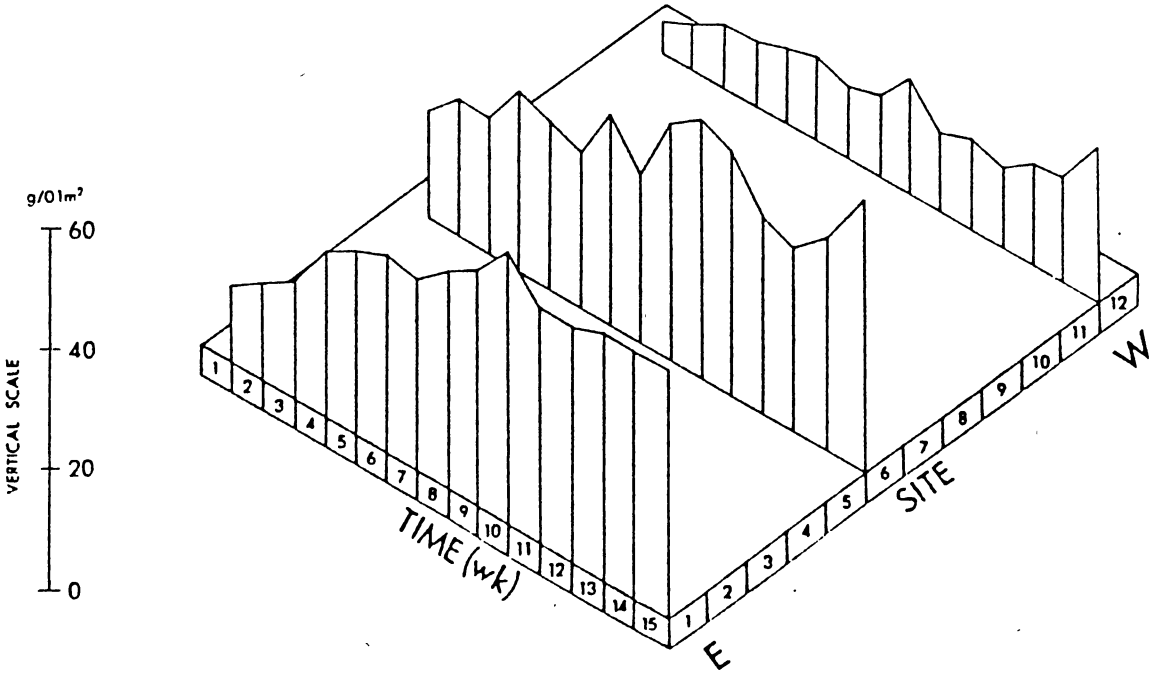

Figure 7. Three-Space Plot of Biomass at Site 1, 6, and 12 Over Time

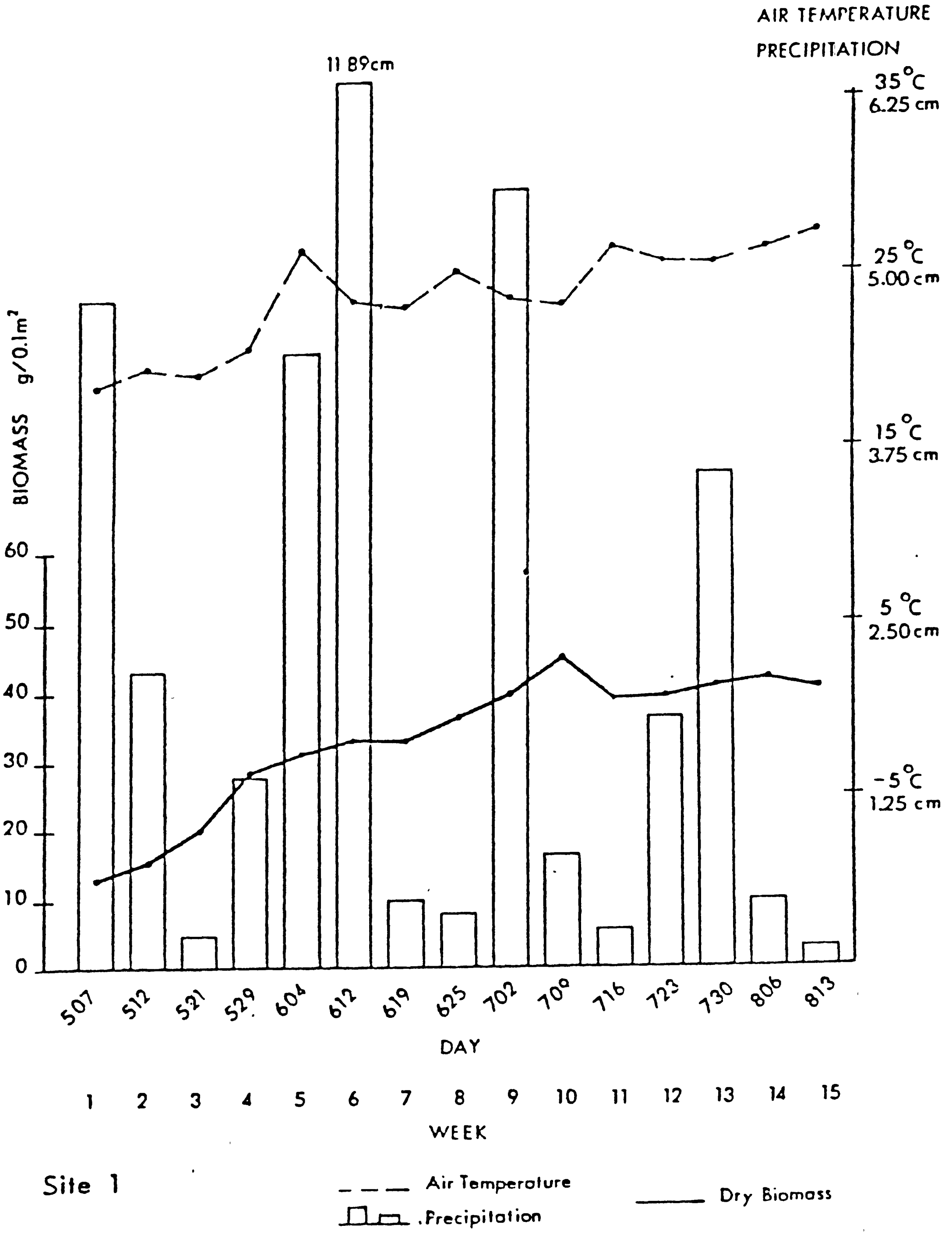

Figure 8. Dry Mean Biomass, Weekly Total Precipitation, and Weely Mean Air Temperature Over Time, for Site 1

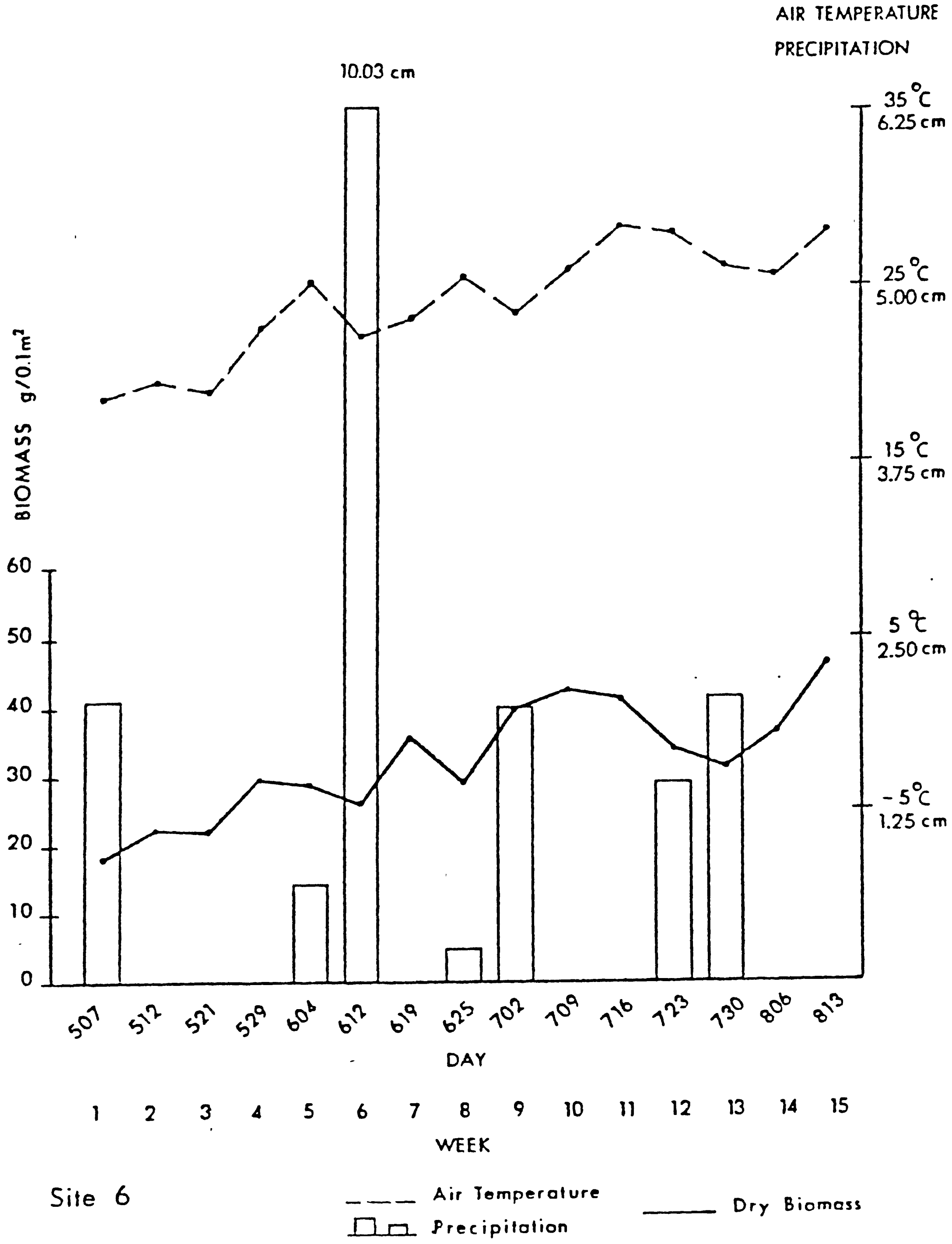

Figure 9. Dry Mean Biomass, Weekly Total Precipitation, and Weekly Mean Air Temperature Over Time, for Site 6

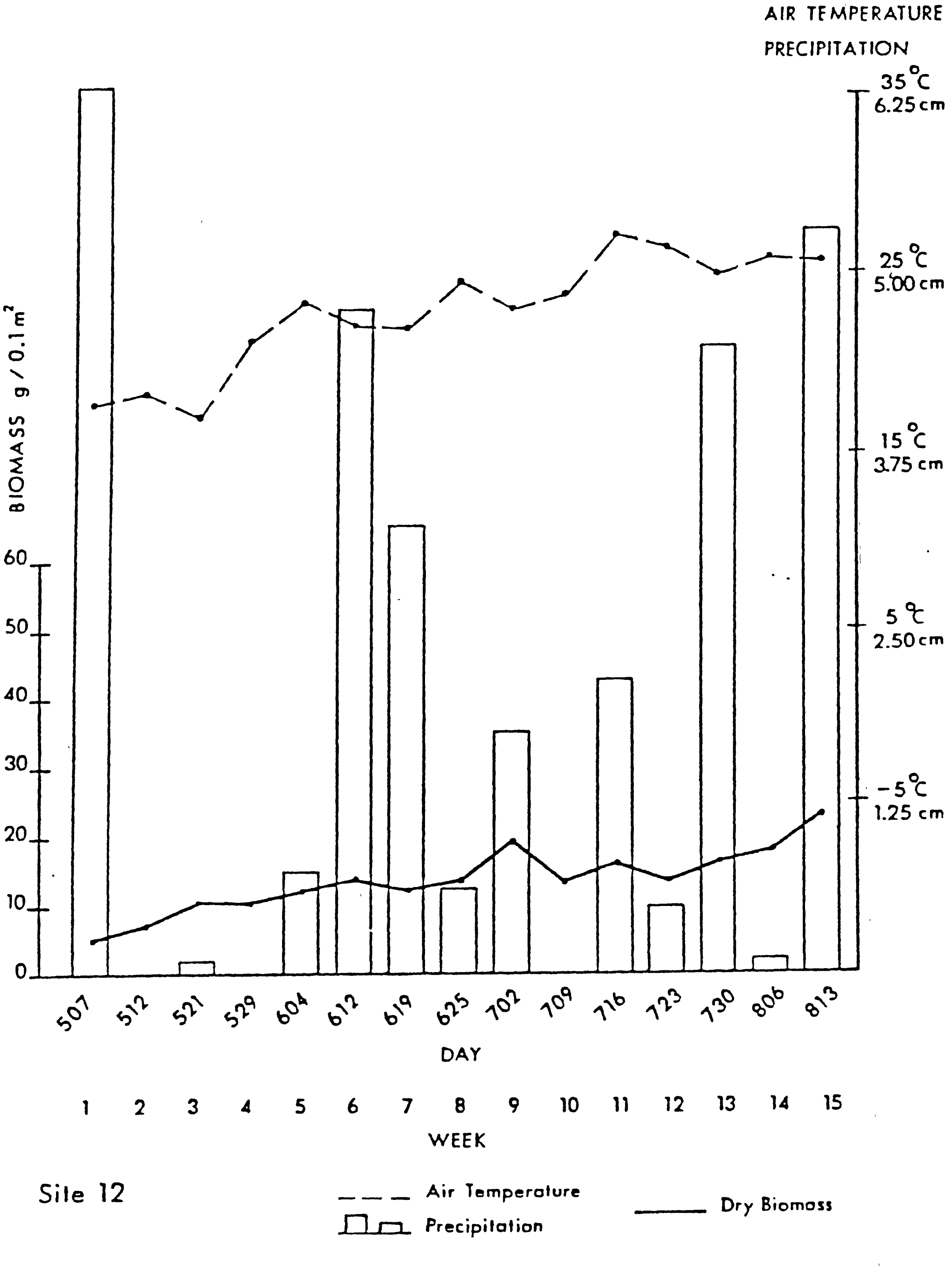

Figure 10. Dry Mean Biomass, Weekly Total Precipitation, and Weekly Mean Air Temperature Over Time, for Site 12

mixed-grass species comparisons (Table IV) at each site. Decreased environmental variables (i.e. monthly precipitaton and soil moisture) occurring in a westward direction also correspond to the east-west moisture gradient along the transect.

Interpretation of figures 9-11 provide a graphical representation of dry mean biomass, weekly total precipitation, and weekly mean air temperature throughout the 15-week growing season at sites 1, 6, and 12, respectively, to assess spatial and temporal trends. Biomass and mean air temperature appear to have corresponding seasonal trend increases over time, supported by the the correlation analyses (r=.42). The influence of temperature heat load on biomass growth relative to heat units also revealed a significant positive correlation with biomass (r=.42). However, the regression analysis did not reveal a significant independent temperature influence on biomass. Weekly precipitation also appears to fluctuate independently of dry mean biomass throughout the season. Robertson et al (1984) suggested that independent moisture and temperature effects are not significant alone. A combination of other factors must interact with precipitation and temperature to directly affect biomass growth rates (French, 1979).

Mixed-grass prairie sites sustain vegetation growth that is highly dependent on seasonal precipitation distribution (French, 1979; Lauenroth and Whitman, 1977). The weekly precipitation totals across the transect illustrate an erratic distribution independent of biomass trends; however, monthly precipitation totals do reveal decreasing spatial and temporal precipitation trends (Table XI). McNaughton (1983) recognized that monthly or annual effects have a greater influence on biomass than individual (weekly) effects. For the months of May, June, July, and the first half of August, a spatial decrease from site 1 to 12 revealed monthly trends from 8.64-7.77 cm, 17.2-9.60 cm, 11.83-8.91 cm, and 0.53-5.41 cm, respectively. A temporal decrease in monthly precipitation exists as the season progresses, from June to August, along the transect. Sites 8 and 11 do not follow this general trend, possibly a result of sporadic, heavy rainfall events during the month of July. Overall precipitation trends decrease westward, however, the erratic distribution of rainfall events in the western portion of the area introduces indiscriminant fluctuations (Albert and Wyckoff, 1984). Again, as recognized in Chapter III, annual precipitation averages also decrease westward across the transect for sites 1, 6, and 12 from 75 cm, 65 cm, to 64 cm, respectively.

Table XII provides results of the correlation analysis including the selected environmental variables, polynomial expressions, and cross products of these variables with corresponding correlation coefficients (r). Potential evapotranspiration (PET) may be recognized as a moisture variable indirectly indicating potential moisture loss from the soil resulting from the combined effects of

TABLE XI

TOTAL MONTHLY PRECIPITATION (CM) TRENDS ACROSS THE TRANSECT (EAST TO WEST)

	Month				
Site	May 5/7-5/29	June 6/4-6/25	July 7/2-7/30	August 8/6-8/15	Total 15-WK Precipitation
1	8.64	17.2	11.83	.53	15.04
2	11.33	10.95	8.46	.25	12.20
3	11.33	10.95	8.46	.25	12.20
4	10.67	7.78	5.95	1.24	10.98
5	10.67	7.78	5.95	1.24	10.98
6	2.11	11.05	5.56	0	7.37
7	2.11	11.05	5.56	0	7.37
8	3.05	8.81	10.52	.03	8.82
9	3.53	7.98	6.54	0	7.12
10	3.53	7.98	6.54	0	7.12
11	5.82	5.84	10.87	4.65	10.70
12	7.77	9.60	8.91	5.41	12.48

TABLE XII

SELECTED ENVIRONMENTAL VARIABLES, POLYNOMIAL EXPRESSIONS, AND CROSS PRODUCTS OF THESE VARIABLES WITH CORRESPONDING CORRELATION COEFFICIENTS (r)

Independent Variable	(r)	Polynomial Expressions x^2, x^3, x^4	(r)
SMOIS	+ 0.08927	SMOIS2	+ 0.09068
STEMP	+ 0.16170	SMOIS3	+ 0.08409
WEEK	+ 0.42265	SMOIS4	+ 0.07340
SITE	- 0.42691	STEMP2	+ 0.13963
MAI	- 0.13344	STEMP3	+ 0.11531
PET	+ 0.24973	STEMP4	+ 0.08975
UTM	+ 0.42773	WEEK2	+ 0.39520
ELEV	- 0.54369	WEEK3	+ 0.37970
HUNITS	+ 0.42044	WEEK4	+ 0.37223
MTEMP	+ 0.42060	SITE2	- 0.43830
W2PRECIP	- 0.14887	SITE3	- 0.42841
WPRECIP	- 0.10659	SITE4	- 0.41092
SAND	- 0.22082	SAND2	- 0.19495
SILT	- 0.16144	SAND3	- 0.16620
CLAY	+ 0.32329	SAND4	- 0.14243
		SILT2	- 0.16123
		SILT3	- 0.16075
		SILT4	- 0.16011
		CLAY2	+ 0.31336
		CLAY3	+ 0.30362
		CLAY4	+ 0.29648
		MAI2	- 0.07349
		PET2	+ 0.22618
		UTM2	+ 0.42203
		UTM3	+ 0.41531
		UTM4	+ 0.40770
		ELEV2	- 0.52757
		HUNITS2	+ 0.41238
		MTEMP2	+ 0.41850
		W2PRECI2	- 0.08670
		WPRECIP2	NS

TABLE XII (Continued)

Cross Products x_1, x_2, x_1, x_3	(r)	Cross Products x_1, x_2, x_1, x_3	(r)
SMOSTP	+ 0.16661	SLTCLY	+ 0.23020
SMOSND	NS	SLTWK	+ 0.35073
SMOSLT	NS	SLTST	- 0.48616
SMOCLY	+ 0.19427	SLTMAI	- 0.14700
SMOWK	+ 0.48770	SLTPET	NS
SMOST	- 0.32670	SLTUTM	+ 0.11120
SMOMAI	- 0.07516	SLTELE	- 0.58422
SMOPET	+ 0.18066	SLTHUN	+ 0.23319
SMOUTM	+ 0.15440	SLTMTP	+ 0.02732
SMOELE	- 0.25081	SLTW2P	- 0.17560
SMOHUN	+ 0.31218	SLTW1P	- 0.12176
SMOMTP	+ 0.17474	CLYWK	+ 0.52881
SMOW2P	- 0.07045	CLYST	- 0.27211
SMOW1P	NS	CLYMAI	- 0.08170
STPSND	- 0.12446	CLYPET	+ 0.40583
STPSLT	NS	CLYUTM	+ 0.41343
STPCLY	+ 0.38120	CLYELE	- 0.19209
STPWK	+ 0.39138	CLYHUN	+ 0.50245
STPST	- 0.37183	CLYMTP	+ 0.42142
STPMAI	- 0.11832	CLYW2P	NS
STPPET	+ 0.21237	CLYW1P	NS
STPUTM	+ 0.41848	WKST	- 0.06897
STPELE	- 0.38004	WKMAI	+ 0.07048
STPHUN	+ 0.34893	WKPET	+ 0.38814
STPMTP	+ 0.27255	WKUTM	+ 0.52287
STPW2P	- 0.12535	WKELE	+ 0.09693
STP1P	- 0.09278	WKHUN	+ 0.42257
SNDSLT	- 0.39773	WKMTP	+ 0.42418
SNDCLY	+ 0.10202	WKM2P	+ 0.11883
SNDWK	+ 0.23823	WKW1P	+ 0.07326
SNDST	- 0.37598	STMAI	- 0.22168
SNDMAI	- 0.15743	STPET	- 0.36975
SNDPET	- 0.10702	STUTM	- 0.41131
SNDUTM	- 0.07102	STELE	- 0.46730
SNDELE	- 0.39370	STHUN	- 0.25632
SNDHUN	+ 0.07223	STMTP	- 0.37489
SNDMTP	- 0.10951	STW2P	- 0.32528
SNDW2P	- 0.18767	STW1P	- 0.20441
SNDW1P	- 0.13151		

TABLE XII (Continued)

Cross Products x_1, x_2, x_1, x_3	(r)
MAIPET	- 0.10656
MAIUTM	- 0.10466
MAIELE	- 0.20707
MAIHUN	NS
MAIMTP	- 0.11013
MAIW2P	- 0.08798
MAIW1P	NS
PETUTM	+ 0.50148
PETELE	- 0.38769
PETHUN	+ 0.35221
PETMTP	+ 0.31400
PETW2P	- 0.11468
PETW1P	- 0.08051
UTMELE	- 0.60512
UTMHUN	+ 0.56049
UTMMTP	+ 0.57515
UTMW2P	- 0.09212
UTMW1P	- 0.07639
ELEHUN	- 0.16224
ELEMTP	- 0.42205
ELEW2P	- 0.29019
ELEW1P	- 0.18364
HUNMTP	+ 0.41710
HUNW2P	NS
HUNW1P	NS
MTPW2P	- 0.11676
MTPW1P	- 0.08401
W2PW1P	- 0.07410

NS - Not Significant at 0.05 level.

plant transpiration and atmoshperic evaporation. PET combined with a location (UTM) variable reveals a significant spatial correlation (r=.50) with dry mean biomass.

Table XIII provides results of the stepwise MAXR regression with corresponding regression coefficients (B) and associated independent variables. Again, the statistical results will be utilized in the interpretation of environmental influence. PET combined with a time (WEEK) variable provides a temporal influence (B=-.357) resulting from the regression equation (Table XIII). The negative relationship betweeen PET*WEEK and biomass corresponds to an increase in PET to a peak (week 11) over time with a decrease in biomass as illustrated in Figures 7 through 10. Inversely, an eventual decrease in PET to a minimum at the end of the sampling period corresponds to an increase in biomass.

The spatial aspect of total PET relative to sites 1, 6, and 12, indirectly reveals a decrease in available moisture with increasing distance. Calculated PET values of 83.94, 86.03, and 86.20 for sites 1, 6, and 12, respectively, show an increase in potential evaporative demand across the transect. Figures 7 through 10 illustrate decreases in biomass associated with week 11, corresponding to peak PET levels at all sites at this time. Table XIV reveals the PET values throughout the 15-week sampling period, with peak values late in the season (week 11) when evaporative demand is high.

TABLE XIII

RESULTS OF THE STEPWISE REGRESSION WITH CORRESPONDING REGRESSION COEFFICIENTS AND ASSOCIATED INDEPENDENT VARIABLES

Regression Coefficient	Independent Variable
+49.22830	Intercept
+ 0.00001	SAND614
- 0.00023	CLAY913
+ 0.00719	SN15SL15
- 0.02807	SN15WK
- 0.00001	SN61UTM
- 0.00037	SL91ELE
+ 6.79695	M15WK
- 0.03694	M15ELE
+ 0.19021	M61HUN
+ 0.05778	T61WK
- 0.35677	WKPET
+ 0.00001	WKUTM

$R^2 = .845$

TABLE XIV

POTENTIAL EVAPOTRANSPIRATION VALUES THROUGHOUT THE SAMPLING PERIOD ACROSS THE TRANSECT

	Site											
Week	1	2	3	4	5	6	7	8	9	10	11	12
1	4.31	4.49	4.50	4.22	4.24	4.32	4.32	4.44	4.69	4.71	4.37	4.46
2	4.71	4.98	4.99	4.67	4.70	4.78	4.78	4.73	4.56	4.57	4.48	4.58
3	4.85	4.97	4.97	4.59	4.62	4.79	4.79	5.23	5.14	5.15	4.96	4.67
4	5.06	5.43	5.45	5.03	5.06	5.32	5.32	5.60	5.41	5.43	5.43	5.44
5	5.92	6.12	6.14	6.10	6.14	6.23	6.23	5.78	6.15	6.17	5.98	5.81
6	5.07	5.09	5.10	5.16	5.19	5.19	5.19	5.34	5.88	5.63	5.54	5.55
7	5.54	5.65	5.67	5.33	5.37	5.64	5.64	5.56	5.66	5.67	5.39	5.50
8	5.88	5.90	5.92	5.94	5.97	5.97	5.97	5.82	5.92	5.93	5.75	5.95
9	5.93	6.05	6.07	5.88	5.92	6.02	6.02	6.00	5.70	5.72	5.92	5.84
10	5.91	6.32	6.35	6.01	6.04	6.04	6.04	6.57	6.57	6.59	6.49	6.50
11	6.63	6.85	6.87	6.65	6.69	6.89	6.89	6.96	6.85	6.87	6.98	6.89
12	6.71	7.05	7.07	6.40	6.44	6.73	6.73	6.85	6.95	6.97	6.87	6.99
13	5.83	5.85	5.87	6.04	6.07	6.26	6.26	5.96	6.24	6.26	6.09	6.18
14	5.54	5.72	5.73	5.73	5.77	5.59	5.59	5.61	5.44	5.45	5.72	5.82
15	6.08	6.09	6.11	6.09	6.13	6.31	6.31	6.06	6.06	6.08	5.90	5.83
	83.94	86.49	86.75	83.86	84.26	86.03	86.03	86.91	87.18	87.16	85.84	86.02

The interactive influences of soil moisture week reveal temporal moisture significance (r=.49; B=6.80) on dry mean biomass. The individual soil moisture factor does not reveal a strong correlation (r=.09) independently; however, the magnitude of the correlation coefficient increases significantly when combined with the time variable. Similarly, it is the interactive influence that is revealed in the regression model.

The final objective of the study was to assess the impact of selected environmental variables on biomass fluctuations throughout the growing season across the transect. Table XV provides the empirical ecological response model resulting from the stepwise (MAXR) regression procedure to best evaluate the influence of independent environmental variables on the dependent biomass variable, with appropriate correlation coefficients corresponding to similar interactive variables produced from the correlation analysis. The regression provides a statistically significant measure of the total variability in the dependent dry biomass variable attributed to the interactive influence of all independent environmental variables represented in the model. The coefficient of determination (r^2=.845) indicates that 84.5 percent of the fluctuations in dry mean biomass can be attributed to the combined impact of the modeled independent variables.

Again, the interactive influence of soil moisture and time revealed a strong relationship with biomass (r=.49;

TABLE XV

ECOLOGICAL RESPONSE MODEL

Regression Coefficient	Independent Variable	Correlation Coefficient
+49.22830	Intercept	
+ 0.00001	SAND614	-0.14
- 0.00023	CLAY913	+0.30
+ 0.00719	SN15SL15	-0.40
- 0.02807	SN15WK	+0.24
- 0.00001	SN61UTM	-0.38
- 0.00037	SL91ELE	-0.58
+ 6.79695	M15WK	+0.49
- 0.03964	M15ELE	-0.25
+ 0.19021	M61HUN	+0.31
+ 0.05778	T61WK	+0.39
- 0.35677	WKPET	+0.39
+ 0.00001	WKUTM	+0.52

$R^2 = .845$

B=6.80). Soil moisture also interacts with elevation (r=.25; B=-.04) and heat units (r=.31; B=.19) to influence biomass, the negative relationship signifying a decrease in biomass corresponding to an increase in the soil moisture elevation effect.

The other independent variables combining to have an impact on biomass growth emphasize temporal, spatial, and textural significance. Temporal influence (week) as a combined function with location (UTM), potential evapotranspiration (PET), soil moisture at 15 cm, soil temperature at 61 cm, and soil texture at 15 cm are apparent (r=.52, .39, .49, .39, and .24, respectively). Spatial and location characteristics are evident, relative to the combined UTM variable with time (r=.52), elevation with soil moisture at 15 cm (r=-.25; B=-.04), and elevation with silt at 91 cm (r=-.58). Soil textural influence is significant both in interactive combinations (i.e. silt at 15 cm with sand at 15 cm, r=-.38) and polynomial expressions (i.e. (clay at 91 cm)^3 ,r=.30; (sand at 61 cm)^4 ,r=-.14).

The edaphic textural influence is related to the physics of water movement and water holding capacity of the soil for plant utilization. The emphasis of the 15 cm and 61 cm depths is associated with both texture and upper reaches of the horizons influenced by atmospheric fluctuations in moisture and temperature (i.e. heat unit factor) over time; the 91 cm depth being significant only with respect to textural associations. The lower depths are not easily influenced by climatic fluctuations, but texture is still important in moisture available for plant roots at depth. The availability of soil water to the plant roots is determined by the potential of soil water in the boundary layer closely surrounding the roots; the finer the soil texture (i.e. clay at 91 cm), the higher the field capacity to retain water for plant utilization (Slavik, 1974; Hillel, 1982). Of the three textural variables, the independent clay variable correlates with biomass most significantly (r=.32), possibly because of the importance of high soil water retention and holding capacity for plant utilization indicative from small particle size. Texture is also influential in infiltration rates and evapotranspiration rates associated with increased ease of water movement with increased grain size (i.e. sand silt at 15 cm; r= -.40; B=+.01).

Summary

The results of the statistical analyses allowed for the empirical modeling of significant independent variables associated with grassland development. The interactive impact of soil moisture and time indicated the strongest influence on biomass fluctuations, with textural, spatial, and other temporal combinations also entering significant combined influences to the model on biomass development. General moisture trends were spatially and temporally analyzed relative to a decrease in monthly precipitation across the transect and increasing potential evapotranspiration across the transect throughout the growing season. The final chapter will coordinate the quantitative results with qualitative reasoning and interpretation into a summary of conclusions drawn from the investigation and recommendations for future vegetation research.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The original objectives of this investigation were to illustrate (1) a change in plant biomass relative to spatial and temporal variation in available moisture and (2) the impact of selected environmental variables on plant biomass fluctuations throughout a growing season across the transect. These objectives have been statistically assessed to reveal significant influences on biomass development over time.

Correlation analyses determined significant independent spatial and temporal relationships with dry mean biomass, as suggested by r values of -.43, +.43, and -.54, associated with location characteristics of site, UTM, and elevation, and +.42 associated with the temporal (WEEK) variable. The positive correlations of biomass with UTM and WEEK indicate an increase in biomass relative to an increase in distance eastward and time. The negative correlations of biomass with site and elevation indicate an increase in biomass as site number and elevation decrease eastward.

The correlation polynomial variable expressions (quadratic, cubic, and quartic) did not reveal increases in relationship significance with the dependent biomass variable; however, the interactive cross products revealed significant increases in correlation coefficients of all independent variables, especially recognized relative to the soil moisture and soil temperature variables. A combination of soil moisture with time (SMOIS*WEEK) showed an increase in correlation with biomass from +.09 to +.49, indicating a temporal variation in available moisture associated with a change in plant biomass. A combination of soil temperature with time (STEMP*WEEK) revealed a similar increase in correlation with biomass from +.16 to +.39.

A spatial variation in available moisture was suggested by a decrease in monthly precipitation westward across the transect. Total potential evapotranspiration increases westward across the transect indicative of a decrease in available moisture associated with increased evaporative demand. PET combined with a location (UTM) variable revealed a significant spatial correlation with biomass (r=+.50).

The stepwise (MAXR) regression evaluated the influence of selected environmental variables on biomass. This test proves useful for prediction and estimation, but it does not quantitatively describe a complicated physical relation between changes in the independent variable and responses in the dependent variable, only a relational influence between the two (Steele and Torrie, 1980). The regression analyses modeled significant independent variables associated with grassland development to reveal biomass growth as a function of the interactive influence of soil moisture and time, along with the textural, spatial, and temporal variable input combinations.

Recommendations and Limitations

To realize a regression function that describes a biological phenomena, the investigator should possess a good deal of knowledge about the interrelationship in nature among the variables in the model (Zar, 1974). Ideally, one may hope that a regression model implies a biological dependence (i.e. cause and effect) in nature and that this dependence confirms the mathematical relationship described by the resultant equation; however, regression equations are often solely useful as a means of predicting the value of a dependent variable, if the values of a number of associated independent variables are known (Zar, 1974). The resultant regression equations are not guaranteed to give the "best" model for ecological data or even the model with the largest coefficient of determination because no model developed by statistical means can be guaranteed to accurately represent real-world processes (SAS Institute, 1985).

In vegetation research, it is important to apply a logical basis for seeking to define nonlinear relationships and recognize the general logistic growth curve in the analysis of factors affecting biomass development (Zar, 1974). The three-space plot (Figure 7) of biomass illustrated growth over time. Successional vegetation stages are of initial growth (May), completed growth (end of June-beginning of July), with early reproductive stages in July, followed by August flower initiation. These stages represent a bimodal season growth pattern; grasslands dominated by both cool-season and warm-season species exhibit a bimodal growth pattern (Sims and Singh, 1978). Therefore, the general biomass trends are ideally associated with growth; fluctuations in the curve throughout the season, however, result from influences described in this investigation. Lauenroth (1979) suggested that as variation among sites increased, influence of soil properties, terrain orientation and elevation, site location and successional status increased in significance. Continual biomass fluctuations over time can be expected, corresponding to fluctuations in the climatic precipitation and temperature regime (Olson et al, 1985).

To further analyze the influence of environmental factors on biomass development, it is suggested that measurments be taken for an additional season. Cable (1975) and Webb et al (1978) supported a "carryover concept" referring to a significant influence of precipitation during a previous year on the performance of plant populations during the year of sampling. With additional sampling, similar conclusions and relationships may be analyzed. McNaughton (1983) also supports the significance of cumulative precipitation effects over successive seasons.

Cable (1975) and Ludlow et al (1980) described the difficulty in measuring and monitoring relatively small changes in biomass associated with rainfall events of short duration and magnitude, or erratic rainfall events of short duration but high intensity. In response to fluctuations in precipitation distribution across the transect, the number of sampling periods should be reduced to bimonthly instead of weekly to better evaluate the accumulated effect of climatic variables on biomass development over time.

It is essential to focus on key factors influencing grassland development and the resultant effects of independent input parameters on biomass in order to make predictions about the dependent biomass parameter. The results of this and associated vegetation research provide an appropriate basis for predictive management practices to economically employ in forage planning decisions. Management decisions for land use may be affected by changing vegetation conditions relative to influential environmental factors over time and space.

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APPENDIXES

APPENDIX A

CALCULATION OF DERIVED VARIABLES

APPENDIX A

CALCULATION OF DERIVED VARIABLES

HEAT UNITS

Wang, 1960

Daily

(Minimum Temperature + Maximum Temperature / 2)=

Average Temperature

Average Temperature - Base Temperature (10°C) =

Mean Daily Heat Units

Weekly

(Mean Weekly Temperature - Base Temperature) =

Mean Daily Heat Units for the Week

Mean Daily Heat Units for Week * 7 =

Weekly Accumulated Heat Units

POTENTIAL EVAPOTRANSPIRATION

Cristiansen Method

Bordne and McGuiness, 1973

PET = 0.473 * RT * CT * CW * CH * CS * CE * CM

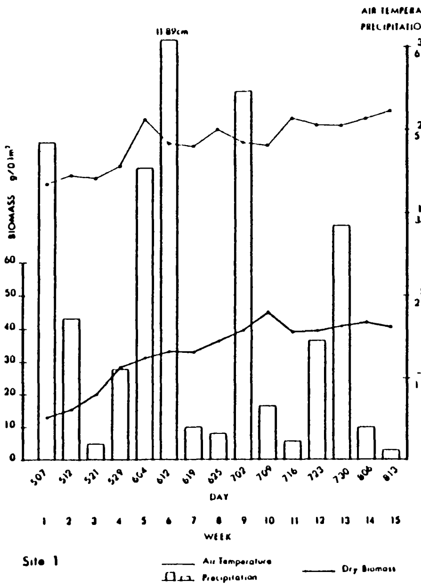
RT: solar radiation at the top of the atmosphere
CT: air temperature
CW: wind speed
CH: relative humidity
CS: percent available sunshine
CE: topographic elevation
CM: seasonal PET coefficient

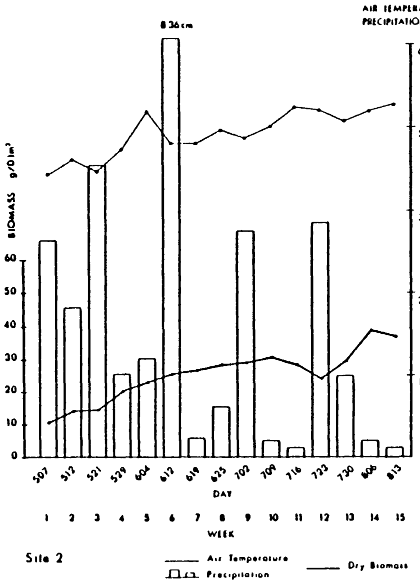
APPENDIX B

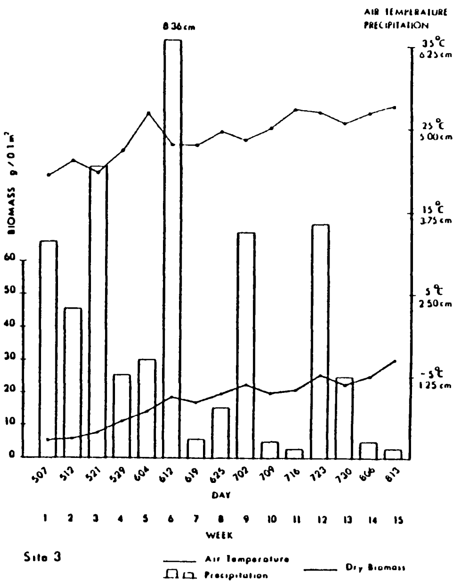
GRAPHIC REPRESENTATION OF THE WEEKLY PRECIPITATION, WEEKLY MEAN AIR TEMPERATURE, AND WEEKLY MEAN BIOMASS

APPENDIX B

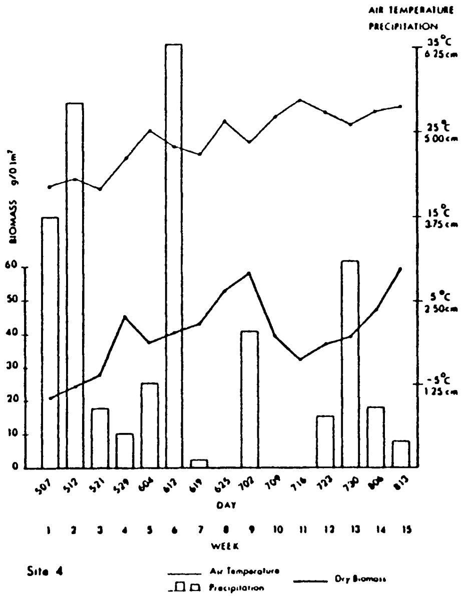
GRAPHIC REPRESENTATION OF THE WEEKLY PRECIPITATION, WEEKLY MEAN AIR TEMPERATURE, AND WEEKLY MEAN BIOMASS







APPENDIX B (Continued)



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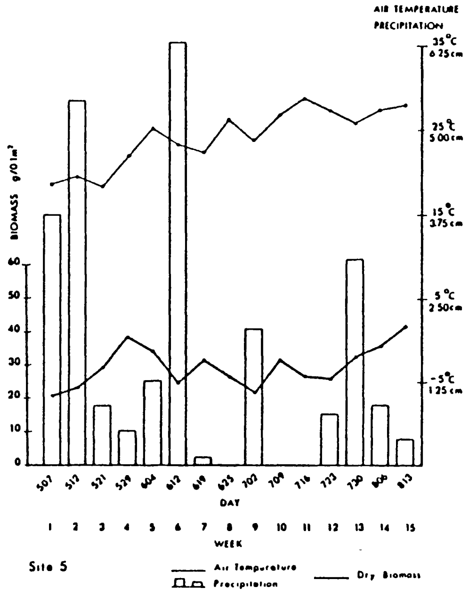

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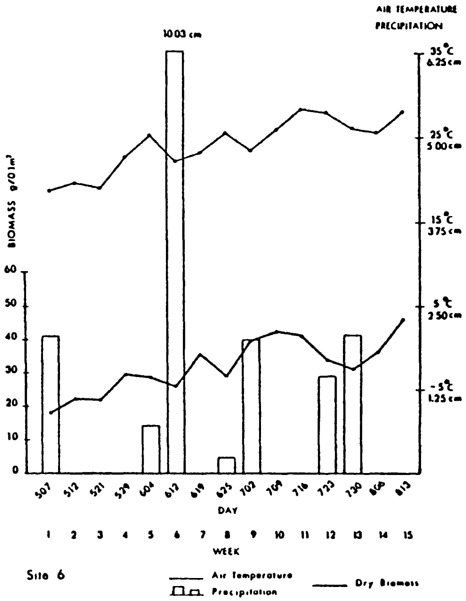
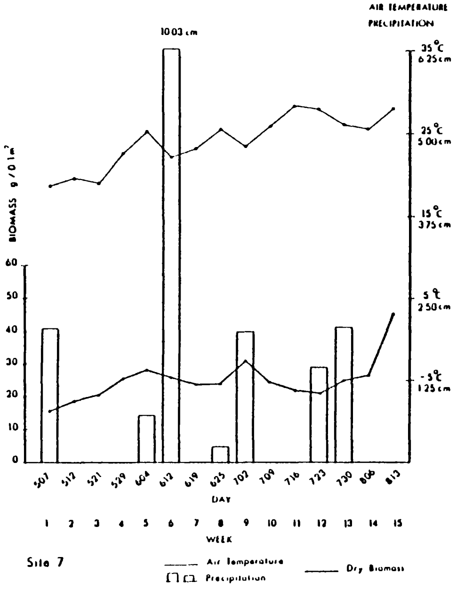
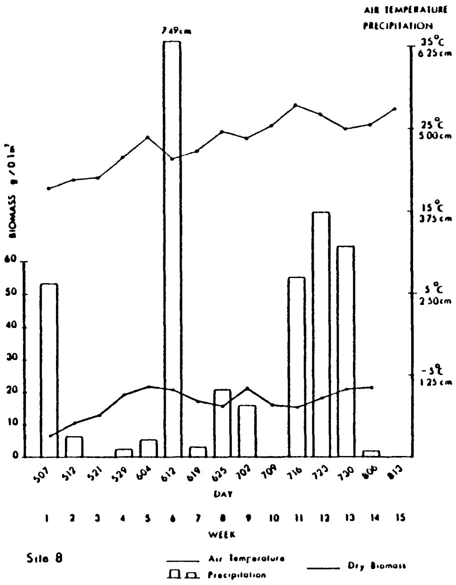


Site 6

APPENDIX B (Continued)



Site 7



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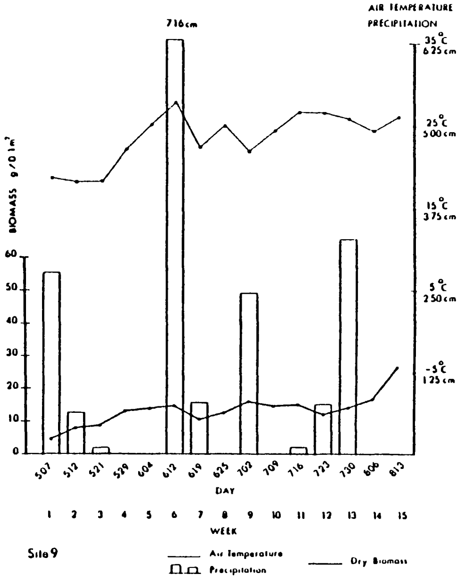
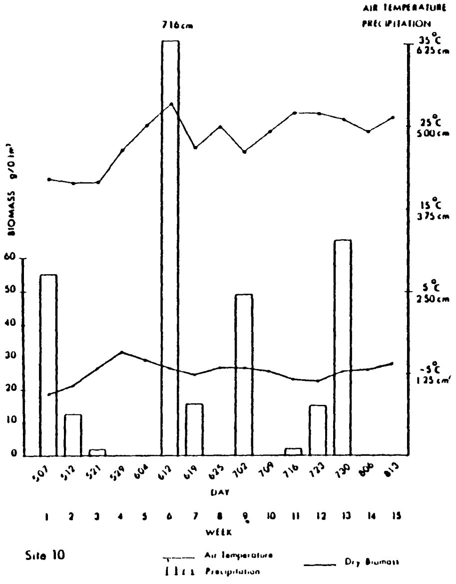
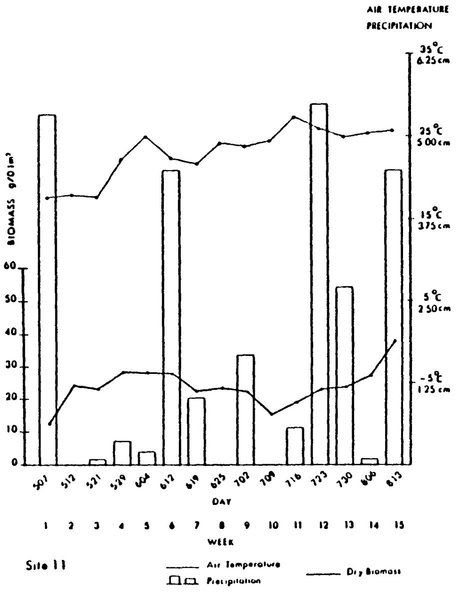


Site 9

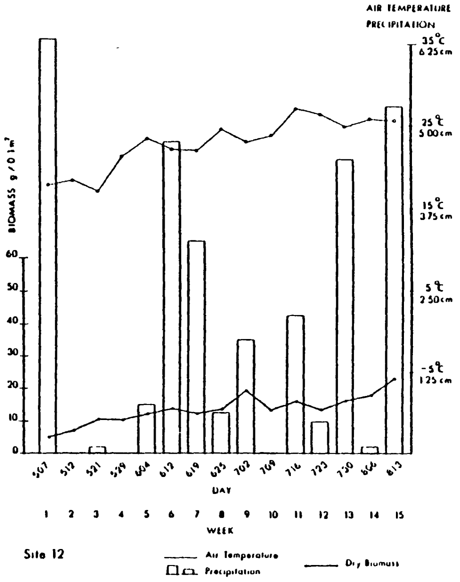
APPENDIX B (Continued)



Site 10



Site 11



Site 12

APPENDIX C

DETAILED RESULTS OF THE STEPWISE MAXR REGRESSION

APPENDIX C

DETAILED RESULTS OF THE STEPWISE MAXR REGRESSION

```
STEP 1    VARIABLE CL15WK ENTERED          R SQUARE = 0.43172345       C(P) =  3071.89840367

                      DF           SUM OF SQUARES         MEAN SQUARE              F       PROB>F

REGRESSION             1           13105.20882487      13105.20882487         203.60       0.0001
ERROR                268           17250.35500513         64.36699629
TOTAL                269           30355.56383000

                          B VALUE       STD ERROR         TYPE II SS               F       PROB>F

INTERCEPT        14.09015867
CL15WK            0.06125303           0.00429277      13105.20882487         203.60       0.0001

BOUNDS ON CONDITION NUMBER:             1,              2
------------------------------------------------------------------------------------------------

THE ABOVE MODEL IS THE BEST  1 VARIABLE MODEL FOUND.

STEP 2    VARIABLE SL91ELE ENTERED         R SQUARE = 0.64808715       C(P) =  1803.03823353

                      DF           SUM OF SQUARES         MEAN SQUARE              F       PROB>F

REGRESSION             2           19673.05075577       9836.52537789         245.86       0.0001
ERROR                267           10682.51307423         40.00941226
TOTAL                269           30355.56383000

                          B VALUE       STD ERROR         TYPE II SS               F       PROB>F

INTERCEPT        32.14514754
CL15WK            0.05063056           0.00348451       8447.04256403         211.13       0.0001
SL91ELE          -0.00033059           0.00002580       6567.84193091         164.16       0.0001

BOUNDS ON CONDITION NUMBER:      1.060009,      8.480073
------------------------------------------------------------------------------------------------
```

APPENDIX C (Continued)

```
STEP 3    VARIABLE CLAY914 ENTERED          R SQUARE = 0.68977871       C(P) =   1560.15358892

                    DF               SUM OF SQUARES          MEAN SQUARE                F       PROB>F

REGRESSION           3               20938.62164622         6979.54054874           197.15       0.0001
ERROR              266                9416.94218378           35.40203828
TOTAL              269               30355.56383000

                        B VALUE           STD ERROR           TYPE II SS                F       PROB>F

INTERCEPT         39.98358100
CLAY914           -0.00000540          0.00000090        1265.57089045            35.75       0.0001
CL15WK             0.04518876          0.00340176        6247.15654575           176.46       0.0001
SL91ELE           -0.00040520          0.00002729        7804.05069650           220.44       0.0001

BOUNDS ON CONDITION NUMBER:      1.340222,      22.63135
```

```
STEP 4    VARIABLE M91ST ENTERED            R SQUARE = 0.71626163       C(P) =   1406.60028721

                    DF               SUM OF SQUARES          MEAN SQUARE                F       PROB>F

REGRESSION           4               21742.52558582         5435.63139646           167 24       0 0001
ERROR              265                8613.03824418           32.50203111
TOTAL              269               30355.56383000

                        B VALUE           STD ERROR           TYPE II SS                F       PROB>F

INTERCEPT         39.28366317
CLAY914           -0.00000520          0.00000087        1171.95402083            36.06       0.0001
CL15WK             0.04912965          0.00335439        6972.21703896           214.52       0.0001
SL91ELE           -0.00050329          0.00003275        7674.00277747           236.11       0.0001
M91ST              3.23483286          0.65043667         803.90393960            24.73       0.0001

BOUNDS ON CONDITION NUMBER:      2.1027,      52.62771
```

APPENDIX C (Continued)

```
STEP 5    VARIABLE M61WK ENTERED          R SQUARE = 0.74182541        C(P) =  1258.44576002

                     DF           SUM OF SQUARES        MEAN SQUARE             F      PROB>F

REGRESSION            5           22518.52850331      4503.70570066        151.71      0.0001
ERROR               264            7837.03532669        29.68573987
TOTAL               269           30355.56383000

                  B VALUE              STD ERROR        TYPE II SS              F      PROB>F

INTERCEPT     38.72586145
CLAY914       -0.00000624             0.00000085    1592.02411768           53.63      0.0001
CL15WK         0.03148047             0.00471095    1325.60276336           44.65      0.0001
SL91ELE       -0.00048747             0.00003146    7129.55360036          240.17      0.0001
M61WK          2.96356762             0.57963834     776.00291749           26.14      0.0001
M91ST          3.85789462             0.63345075    1101.09017926           37.09      0.0001

BOUNDS ON CONDITION NUMBER:      2.90485,      110.6014
--------------------------------------------------------------------------------------------
STEP 5    CL15WK REPLACED BY SN91M91      R SQUARE = 0.75381998        C(P) =  1187.89296484

                     DF           SUM OF SQUARES        MEAN SQUARE             F      PROB>F

REGRESSION            5           22882.63057627      4576.52611525        161.68      0.0001
ERROR               264            7472.93325373        28.30656536
TOTAL               269           30355.56383000

                  B VALUE              STD ERROR        TYPE II SS              F      PROB>F

INTERCEPT     49.00522493
CLAY914       -0.00000835             0.00000078    3254.58205837          114.98      0.0001
SN91M91       -0.91457607             0.11837446    1689.70483632           59.69      0.0001
SL91ELE       -0.00056644             0.00003235    8680.66977993          306.67      0.0001
M61WK          6.20435307             0.38867631    7212.80267821          254.81      0.0001
M91ST          4.98026737             0.63747091    1727.71357973           61.04      0.0001

BOUNDS ON CONDITION NUMBER:      2.354643,     82.56251
--------------------------------------------------------------------------------------------

THE ABOVE MODEL IS THE BEST  5 VARIABLE MODEL FOUND.
```

APPENDIX C (Continued)

```
STEP 6    M91ST REPLACED BY SN61UTM        R SQUARE = 0.78082116       C(P) =   972.65833200

                    DF            SUM OF SQUARES          MEAN SQUARE              F      PROB>F

REGRESSION           6            24005.82221305        4000.97036884         165.72      0.0001
ERROR              263             6349.74161696          24.14350425
TOTAL              269            30355.56383000

                           B VALUE         STD ERROR          TYPE II SS              F      PROB>F

INTERCEPT         54.82407108
SAND614            0.00000227        0.00000021       2860.77376702          118.08      0.0001
CLAY914           -0.00000496        0.00000085        816.97113907           33.84      0 0001
SN61UTM           -0.00000099        0.00000011       1803.70560254           74.71      0.0001
SN91M91           -0.22488690        0.13115678         70.98182021            2.94      0.0876
SL91ELE           -0.00042940        0.00002394       7766.60823074          321.69      0.0001
M61WK              6.71435063        0.36989928       7955.02172742          329.49      0.0001

BOUNDS ON CONDITION NUMBER:       4.616819,       171.4121
------------------------------------------------------------------------------------------------

STEP 6    SN91M91 REPLACED BY M15ST        R SQUARE = 0.79433683       C(P) =   952.00828629

                    DF            SUM OF SQUARES          MEAN SQUARE              F      PROB>F

REGRESSION           6            24112.54224353        4018.75704059         169.30      0.0001
ERROR              263             6243.02158647          23.73772466
TOTAL              269            30355.56383000

                           B VALUE         STD ERROR          TYPE II SS              F      PROB>F

INTERCEPT         54.69532771
SAND614            0.00000254        0.00000020       3708.72630731          156.24      0.0001
CLAY914           -0.00000386        0.00000083        507.23797777           21.37      0.0001
SN61UTM           -0.00000116        0.00000010       3397.87717482          143.14      0.0001
SL91ELE           -0.00038819        0.00002650       5094.94809337          214.64      0.0001
M15ST             -1.80665303        0.66031068        177.70185069            7.49      0.0066
M61WK              6.63144172        0.36817648       7700.92559437          324.42      0.0001

BOUNDS ON CONDITION NUMBER:       3.3481,       158.4905
------------------------------------------------------------------------------------------------

THE ABOVE MODEL IS THE BEST  6 VARIABLE MODEL FOUND.
```

APPENDIX C (Continued)

```
STEP 7    VARIABLE M15WK ENTERED          R SQUARE = 0.80191373       C(P) =    909.50367576

                    DF        SUM OF SQUARES          MEAN SQUARE             F       PROB>F

REGRESSION           7        24342.54335145       3477.50619306         151.52       0.0001
ERROR              262         6013.02047855         22.95045984
TOTAL              269        30355.56383000

               B VALUE             STD ERROR          TYPE II SS              F       PROB>F

INTERCEPT  59.38657006
SAND614     0.00000273            0.00000021       3932.53718398         171.35       0.0001
CLAY914    -0.00000339            0.00000083        381.80006009          16.64       0.0001
SN61UTM    -0.00000135            0.00000011       3304.69565298         143.99       0.0001
SL91ELE    -0.00039192            0.00002608       5182.83736232         225.83       0.0001
M15WK       2.77325096            0.87603187        230.00110792          10.02       0.0017
M15ST      -3.41611275            0.82463733        393.84904863          17.16       0.0001
M61WK       4.74916129            0.69612598       1068.19254274          46.54       0.0001

BOUNDS ON CONDITION NUMBER:      5.419281,       349.814
```

```
STEP 7    CLAY914 REPLACED BY CL91PET      R SQUARE = 0.80346884       C(P) =    900.36840263

                    DF        SUM OF SQUARES          MEAN SQUARE             F       PROB>F

REGRESSION           7        24389.74953781       3484.24993397         153.02       0.0001
ERROR              262         5965.81429219         22.77028356
TOTAL              269        30355.56383000

               B VALUE             STD ERROR          TYPE II SS              F       PROB>F

INTERCEPT  63.40968221
SAND614     0.00000293            0.00000019       5198.91626848         228.32       0.0001
SN61UTM    -0.00000145            0.00000010       4663.33457722         204.80       0.0001
SL91ELE    -0.00037423            0.00002474       5209.17000435         228.77       0.0001
CL91PET    -0.04069549            0.00937559        429.00624645          18.84       0.0001
M15WK       3.31492060            0.85947468        338 72599401          14.88       0.0001
M15ST      -3.87876275            0.79046829        548.25925319          24.08       0.0001
M61WK       5.07799549            0.70470915       1182.31512493          51.92       0.0001

BOUNDS ON CONDITION NUMBER:      5.597689,       324.7908
```

APPENDIX C (Continued)

```
STEP 7    M15ST REPLACED BY M15ELE        R SQUARE = 0.80541984       C(P) =   888.90977608

                       DF           SUM OF SQUARES          MEAN SQUARE               F      PROB>F

REGRESSION              7           24448.97321761        3492.71045966          154.93      0.0001
ERROR                 262            5906.59061239          22.54423898
TOTAL                 269           30355.56383000

                          B VALUE        STD ERROR          TYPE II SS                F      PROB>F

INTERCEPT          62.89731254
SAND614             0.00000218        0.00000020       2561.73464656           113.63      0.0001
SN61UTM            -0.00000108        0.00000010       2732.19221789           121.19      0.0001
SL91ELE            -0.00040314        0.00002364       6557.55876890           290.88      0.0001
CL91PET            -0.05415663        0.00922458        777.04392508            34.47      0.0001
M15WK               4.14825612        0.94185419        437.32001999            19.40      0.0001
M15ELE             -0.02468688        0.00475573        607.48293298            26.95      0.0001
M61WK               4.49986078        0.75747066        795.61343625            35.29      0 0001

BOUNDS ON CONDITION NUMBER:      6.532109,      353.4309
```

```
STEP 7    M61WK REPLACED BY M61HUN        R SQUARE = 0.80792789       C(P) =   874.17757235

                       DF           SUM OF SQUARES          MEAN SQUARE               F      PROB>F

REGRESSION              7           24525.10967046        3503.58709578          157.44      0 0001
ERROR                 262            5830.45415954          22.25364183
TOTAL                 269           30355.56383000

                          B VALUE        STD ERROR          TYPE II SS                F      PROB>F

INTERCEPT          61.09588597
SAND614             0.00000245        0.00000022       2715.49841346           122.02      0.0001
SN61UTM            -0.00000118        0.00000010       3101.87629159           139.39      0 0001
SL91ELE            -0.00035134        0.00002694       3784.31024351           170.05      0.0001
CL91PET            -0.05532506        0.00917130        809.80985969            36.39      0.0001
M15WK               7.92947508        0.50023888       5591.58698828           251.27      0 0001
M15ELE             -0.04438693        0.00357719       3427.86644503           154.04      0.0001
M61HUN              0.19085202        0.03049308        871.74988910            39.17      0.0001

BOUNDS ON CONDITION NUMBER:      4.103792,      250.8711

THE ABOVE MODEL IS THE BEST  7 VARIABLE MODEL FOUND.
```

APPENDIX C (Continued)

```
STEP 8    VARIABLE CL15ELE ENTERED        R SQUARE = 0.81569403       C(P) =   830.56199899

                    DF              SUM OF SQUARES         MEAN SQUARE              F       PROB>F

REGRESSION           8              24760.85226627       3095.10653328         144.39       0.0001
ERROR              261               5594.71156373         21.43567649
TOTAL              269              30355.56383000

                         B VALUE           STD ERROR          TYPE II SS              F       PROB>F

INTERCEPT      71.86255128
SAND614         0.00000278          0.00000024       2893.47767795         134.98       0.0001
CL15ELE        -0.00018786          0.00005665        235.74259582          11.00       0.0010
SN61UTM        -0.00000124          0.00000010       3318.39628397         154.81       0.0001
SL91ELE        -0.00033549          0.00002687       3341.44924588         155.88       0.0001
CL91PET        -0.08918942          0.01361239        920.22713347          42.93       0.0001
M15WK           8.18896937          0.49715581       5815.81581978         271.31       0.0001
M15ELE         -0.04886191          0.00376014       3619.67553543         168.86       0 0001
M61HUN          0.20200102          0.03011567        964.40473025          44.99       0.0001

BOUNDS ON CONDITION NUMBER:       4.852893,        396.2696
------------------------------------------------------------------------------------------------

THE ABOVE MODEL IS THE BEST  8 VARIABLE MODEL FOUND.

STEP 9    VARIABLE CL15WK ENTERED         R SQUARE = 0.82055783       C(P) =   803.89342883

                    DF              SUM OF SQUARES         MEAN SQUARE              F       PROB>F

REGRESSION           9              24908.49545895       2767.61060655         132.10       0.0001
ERROR              260               5447.06837106         20.95026297
TOTAL              269              30355.56383000

                         B VALUE           STD ERROR          TYPE II SS              F       PROB>F

INTERCEPT      70.36311624
SAND614         0.00000275          0.00000024       2821 91511617         134.70       0.0001
CL15WK          0.01373181          0.00517272        147.64319267           7.05       0.0084
CL15ELE        -0.00025663          0.00006170        362.39385091          17.30       0.0001
SN61UTM        -0.00000115          0.00000010       2542.22596414         121.35       0.0001
SL91ELE        -0.00032024          0.00002718       2908.47687387         138.83       0.0001
CL91PET        -0.09753060          0.01381932       1043.51256277          49.81       0 0001
M15WK           6.54612869          0.79027766       1437.47117557          68.61       0.0001
M15ELE         -0.04064907          0.00483628       1480.02024065          70.64       0.0001
M61HUN          0.20177424          0.02977285        962.23264945          45.93       0.0001

BOUNDS ON CONDITION NUMBER:       4.965123,        625 6198
------------------------------------------------------------------------------------------------

THE ABOVE MODEL IS THE BEST  9 VARIABLE MODEL FOUND.
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APPENDIX C (Continued)

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STEP 10   VARIABLE SN15WK ENTERED          R SQUARE = 0.82831936      C(P) =    760.40432099

                    DF            SUM OF SQUARES          MEAN SQUARE               F       PROB>F

REGRESSION          10            25144.10128018        2514.41012802          124.96       0.0001
ERROR              259             5211.46254982          20.12147703
TOTAL              269            30355.56383000

                    B VALUE            STD ERROR          TYPE II SS               F       PROB>F

INTERCEPT       73.28372643
SAND614          0.00000298           0.00000024        3057.36824939          151.85       0.0001
SN15WK          -0.01163602           0.00340049         235.60582123           11.71       0.0007
CL15WK           0.02100605           0.00549704         293.82617411           14.60       0.0002
CL15ELE         -0.00035969           0.00006786         570.40818607           28.35       0 0001
SN61UTM         -0.00000114           0.00000010        2498.73419399          124.18       0 0001
SL91ELE         -0.00026926           0.00003052        1566.19324025           77.84       0 0001
CL91PET         -0.09771318           0.01354333        1047.40692105           52.05       0 0001
M15WK            8.12469769           0.90146914        1634.45343749           81.23       0 0001
M15ELE          -0.04804398           0.00520908        1711.64952155           85.07       0.0001
M61HUN           0.17164026           0.03047798         638.15464842           31.72       0.0001

BOUNDS ON CONDITION NUMBER:      8.269693,       910.3137
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```
STEP 10   CL15WK REPLACED BY WKUTM         R SQUARE = 0.83244131      C(P) =    736.19314293

                    DF            SUM OF SQUARES          MEAN SQUARE               F       PROB>F

REGRESSION          10            25269.22534512        2526.92253451          128.67       0.0001
ERROR              259             5086.33848488          19.63837253
TOTAL              269            30355.56383000

                    B VALUE            STD ERROR          TYPE II SS               F       PROB>F

INTERCEPT       74.33183824
SAND614          0.00000340           0.00000026        3364 84848588          171.34       0.0001
SN15WK          -0.02026533           0.00428223         439.81717235           22.40       0.0001
CL15ELE         -0.00036533           0.00006456         628.80469232           32.02       0.0001
SN61UTM         -0.00000127           0.00000010        3454 81150768          175.92       0 0001
SL91ELE         -0.00026843           0.00002962        1612.80199945           82.13       0 0001
CL91PET         -0.11310439           0.01426566        1234.47067740           62.86       0 0001
M15WK            6.75496861           1.01276881         873.63802287           44.49       0.0001
M15ELE          -0.04062879           0.00575742         977.95020414           49.80       0 0001
M61HUN           0.19306853           0.02996426         815.30744638           41.52       0 0001
WKUTM            0.00000190           0.00000041         418.95023905           21.33       0 0001

BOUNDS ON CONDITION NUMBER:      14.2162,       1220.67
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APPENDIX C (Continued)

```
STEP 10   CL18ELE REPLACED BY SN15SL15      R SQUARE = 0.83548099        C(P) =    718.33891974

                    DF             SUM OF SQUARES          MEAN SQUARE                F       PROB>F

REGRESSION          10            25361.49648438         2536.14964844           131.53       0.0001
ERROR              259             4994.06734562           19.28211330
TOTAL              269            30355.56383000

                       B VALUE           STD ERROR          TYPE II SS                F       PROB>F

INTERCEPT         53.87859570
SANO614            0.00000355          0.00000027       3430.81276693           177.91       0.0001
SN15SL15           0.00958002          0.00156658        721.07583157            37.40       0.0001
SN15WK            -0.03130443          0.00530127        672.36619301            34.87       0.0001
SN61UTM           -0.00000134          0.00000010       3640.39198929           188.80       0.0001
SL91ELE           -0.00038878          0.00002865       3550.35645993           184.13       0.0001
CL81PET           -0.09377681          0.01157463       1265.70069096            65.64       0.0001
M15WK              7.41824278          1.00484284       1050.89767403            54.50       0.0001
M15ELE            -0.04065760          0.00570325        979.82055008            50.82       0.0001
M61HUN             0.19711453          0.02972226        848.06342589            43.98       0.0001
WKUTM              0.00000235          0.00000044        549.59655350            28.50       0.0001

BOUNDS ON CONDITION NUMBER:      16.47216,      1341.268
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THE ABOVE MODEL IS THE BEST 10 VARIABLE MODEL FOUND.

STEP 11   VARIABLE CL18W2P ENTERED          R SQUARE = 0.83825729        C(P) =    704.03172124

                    DF             SUM OF SQUARES          MEAN SQUARE                F       PROB>F

REGRESSION          11            25445.77255547         2313.25205050           121.56       0.0001
ERROR              258             4909.79127453           19.03019874
TOTAL              269            30355.56383000

                       B VALUE           STD ERROR          TYPE II SS                F       PROB>F

INTERCEPT         56.39256844
SANO614            0.00000353          0.00000026       3386.39008042           177.96       0.0001
SN15SL16           0.00924306          0.00156453        664.21128713            34.90       0.0001
SN15WK            -0.03068488          0.00527475        644.00341937            33.84       0.0001
CL18W2P           -0.02132265          0.01013236         84.27607109             4.43       0 0363
SN61UTM           -0.00000136          0.00000010       3710.62015241           194.99       0.0001
SL91ELE           -0.00040448          0.00002943       3595.82197251           188.95       0.0001
CL81PET           -0.09912158          0.01177592       1348.30988618            70.85       0.0001
M15WK              7.61826331          1.00277204       1098.37552140            57.72       0.0001
M15ELE            -0.03716036          0.00590455        753.75298820            39.61       0.0001
M61HUN             0.18569849          0.02953513        835.48858937            43.90       0 0001
WKUTM              0.00000228          0.00000044        513.90727197            27.00       0 0001

BOUNDS ON CONDITION NUMBER:      16.5698,      1533 891
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THE ABOVE MODEL IS THE BEST 11 VARIABLE MODEL FOUND.
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APPENDIX C (Continued)

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STEP 12   VARIABLE WKPET ENTERED          R SQUARE = 0.84061887       C(P) =   692.16041542

                      DF          SUM OF SQUARES         MEAN SQUARE            F      PROB>F

REGRESSION            12          25517.45986317       2126.45498860       112.96      0.0001
ERROR                257           4838.10396684         18.82530726
TOTAL                269          30355.56383000

                         B VALUE         STD ERROR         TYPE II SS            F      PROB>F

INTERCEPT            87.72428431
SAND614               0.00000354        0.00000026     3385 90099546       180 38      0.0001
SN15SL15              0.00749738        0.00179490      328.46027993        17.45      0.0001
SN15WK               -0.02347070        0.00641798      251.76591755        13.37      0.0003
CL15W2P              -0.02685498        0.01046885      123.87786229         6.58      0.0109
SN61UTM              -0.00000143        0.00000010     3575.91386613       189.85      0 0001
SL91ELE              -0.00038632        0.00003042     3068.34016237       162.99      0.0001
CL91PET              -0.08645051        0.01339186      784.50468961        41.67      0.0001
M15WK                 7.38698457        1.00437640     1018.31808910        54 09      0.0001
M15ELE               -0.03448009        0.00603116      615.28650744        32.68      0.0001
M61HUN                0.18245810        0.03014910      689.47675712        36 62      0.0001
WKPET                -0.11919137        0.06107939       71.68730769         3.81      0 0521
WKUTM                 0.00000314        0.00000062      479.74474125        25.48      0.0001

BOUNDS ON CONDITION NUMBER:      40.16459,      3310.801
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STEP 12   CL91PET REPLACED BY CLAY912     R SQUARE = 0.84406700       C(P) =   671.80706071

                      DF          SUM OF SQUARES         MEAN SQUARE            F      PROB>F

REGRESSION            12          25622.12978314       2135.17748193       115 93      0.0001
ERROR                257           4733.43404686         18.41803131
TOTAL                269          30355.56383000

                         B VALUE         STD ERROR         TYPE II SS            F      PROB>F

INTERCEPT            55.79563636
SAND614               0.00000344        0.00000026     3289 95332849       178 63      0.0001
CLAY912              -0.00988437        0.00142258      889.17460959        48.28      0 0001
SN15SL15              0.00633711        0.00163256      277.51517838        15 07      0.0001
SN15WK               -0.02018128        0.00608676      202.47356922        10 99      0.0010
CL15W2P              -0.02768055        0.01035974      131 49070111         7.14      0 0080
SN61UTM              -0.00000143        0.00000010     3541 78775119       192.30      0 0001
SL91ELE              -0.00039948        0.00003045     3170 82719913       172.16      0 0001
M15WK                 6.60961458        1.00156875      802.11003464        43.55      0.0001
M15ELE               -0.02690420        0.00608123      360.49585158        19.57      0.0001
M61HUN                0 13907631        0.02889445      426 69792576        23.17      0 0001
WKPET                -0.26744330        0.05319829      465.49094479        25 27      0 0001
WKUTM                 0.00000437        0.00000062      815 36998562        49.70      0.0001

BOUNDS ON CONDITION NUMBER:      34.28626,      3013 792
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APPENDIX C (Continued)

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STEP 12   CL15W2P REPLACED BY T61WK        R SQUARE = 0.84454361        C(P) =   669.10759318

                     DF              SUM OF SQUARES          MEAN SQUARE               F     PROB>F

REGRESSION           12              25636.59751201        2136 38312600          116.35     0.0001
ERROR               257               4718.96631800          18.36173665
TOTAL               269              30355.56383000

                        B VALUE           STD ERROR          TYPE II SS               F     PROB>F

INTERCEPT        51.18001924
SAND614           0.00000372          0 00000027        3422 10830296          186.37     0.0001
CLAY912          -0.01030840          0 00143641         945.66980397           51.50     0.0001
SN15SL15          0.00834603          0.00161725         489.01154430           26.63     0.0001
SN15WK           -0.02869506          0.00620897         392.18318470           21.36     0.0001
SN61UTM          -0.00000140          0.00000010        3489 38778035          190.04     0.0001
SL91ELE          -0.00038936          0 00003001        3091.26039027          168.35     0.0001
M15WK             6.84244125          1 00732578         847.21963245           46.14     0.0001
M15ELE           -0.03618876          0.00589909         691 02059798           37.63     0.0001
M61HUN            0.19381182          0 03325707         623.60100369           33.96     0.0001
T61WK             0.05553151          0 01969617         145.95842997            7.95     0.0052
WKPET            -0.34960729          0 06786106         487.34156002           26.54     0 0001
WKUTM             0.00000322          0.00000069         401.59813649           21.87     0.0001

BOUNDS ON CONDITION NUMBER:       68.52867,       5364.098
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STEP 12   CLAY912 REPLACED BY CLAY913      R SQUARE = 0.84496193        C(P) =   666.65049264

                     DF              SUM OF SQUARES          MEAN SQUARE               F     PROB>F

REGRESSION           12              25649.29587819        2137.44132318          116.72     0.0001
ERROR               257               4706.26795182          18.31232666
TOTAL               269              30355.56383000

                        B VALUE           STD ERROR          TYPE II SS               F     PROB>F

INTERCEPT        49.22830536
SAND614           0.00000362          0.00000027        3303.36813945          180.39     0.0001
CLAY913          -0.00023743          0.00003282         958.36817015           52.33     0.0001
SN15SL15          0.00719987          0.00152129         410.17538090           22.40     0.0001
SN15WK           -0.02807574          0.00615962         380.45087274           20.78     0 0001
SN61UTM          -0.00000136          0 00000010        3222.74667091          175.99     0 0001
SL91ELE          -0.00037350          0.00002895        3047.31788977          166.41     0.0001
M15WK             6.78695028          1.00658606         834.96810825           45.60     0.0001
M15ELE           -0.03694473          0 00587666         723 74830684           39.52     0.0001
M61HUN            0.19021728          0 03316077         602.55164799           32.90     0.0001
T61WK             0.05778554          0.01971818         157 27077183            8 59     0.0037
WKPET            -0.35677299          0 06777966         507.37455912           27.71     0.0001
WKUTM             0.00000315          0.00000069         386 12509442           21.09     0.0001

BOUNDS ON CONDITION NUMBER:       69 8722,        5335.541
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THE ABOVE MODEL IS THE BEST 12 VARIABLE MODEL FOUND.
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VITA

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Master of Science

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