COMPARISON OF NOAA AVHRR NDVI TO PALMER DROUGHT INDICES IN NORTH CENTRAL OKLAHOMA

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CHAPTER I

INTRODUCTION

Physical geography is a science which studies the patterns of spatial distribution and variation of the physical phenomena on the surface of the earth through time. Until recently, much research by physical geographers entailed the acquisition and assessment of principally geomorphological, biogeographical or climatological data, derived by a combination of manual, mechanical or electronic equipment, through actual field reconnaissance, occasionally supported by ancillary data sources such as aerial photographs. However, with the dawning of the 'space-age', much of this data has been augmented by or even replaced by information derived by a multitude of operational space-based remote sensing satellite systems recording the electromagnetic characteristics of the earth's surface at varying resolutions.

Purpose

This research will attempt to measure how changes in weather conditions, as assessed through various point aggregated Palmer indices, namely, the Palmer Drought Severity Index (PDSI), the Crop Moisture Index (CMI), and Z-Index -- based upon weekly deviations from the long term precipitation and temperature averages -- condition the remotely sensed spectral returns over a largely homogeneous winter wheat growing area of north central Oklahoma.

Objective

The main objective of this study is to determine which of the aforementioned Palmer indices is the most related to winter wheat NDVI spectral returns, during the critical 'greening-up' and 'browning-out' phases of the crop, from March through June, over north central Oklahoma. Furthermore, this study will consider whether the data from the 11 climate stations used in the calculation of the relationships, interpolated into representational Theissen polygon areas, when compared to NDVI values per polygon, have any advantageous benefits over the averaged values for the various Palmer variables and NDVI data for the entire study area as a whole.

Literature Review

Drought has been cited as a scourge of mankind since biblical times. It still is a major menace to food supplies and human survival, particularly in fragile ecological zones, as recently illustrated by the frequently severe droughts, and their horrifying impacts, experienced in sub-Saharan Africa during the early 1970s and mid 1980s. Drought is defined as a prolonged or abnormal moisture deficiency (Palmer, 1965). Much research into drought's causes and consequences has naturally been place-specific, but unfortunately subjective, in assessment. However, one of the most significant publications in drought research was Palmer's (1965) paper which presented a numerical approach to the problem. Palmer's research permits an objective evaluation of droughts as it varies both spatially and temporally , with the proviso that drought is considered as a strictly meteorological phenomenon.

Since the publication of Palmer's (1965) drought research and particularly over the last 15 years, there has been a veritable explosion in the amount of valuable environmental resource information being acquired from an ever growing series of satellite remote sensing systems. As such, remote sensing has supported investigation in subjects of scientific interest to agriculturalists in many geographic locales worldwide, through allying ground aggregated data (e.g. weather variables, wheat yield parameters) to spectral information on many occasions. Despite much large area research in the agrarian central portion of the United States, pioneered by the Large Area Crop Inventory Experiment (LACIE) (Erb, 1979) carried out as part as part of the Landsat program to predict winter wheat yield for the 1976-77 growing season, there has been little attempt within the literature to analyze similar subject material for smaller areas.

Increasingly, environmental researchers, particularly in relation to vegetation growth, have begun to utilize the Normalized Difference Vegetation Index (NDVI) spectral data, acquired by the National Oceanic and Atmospheric Administration's (NOAA) Advance Very High Resolution Radiometer (AVHRR), aboard a series of polar-orbiting meteorological satellites. This is advantageous because the AVHRR provides worldwide coverage on a daily basis. Despite both AVHRR vegetation index data and Palmer indices being used to investigate vegetation growth and drought conditions, respectively, in regional, national and international settings, little attempt has been made to integrate these two types of valuable environmental indicators.

The sections which follow group all the important literature for this thesis into similar topical categories, as they vary in time and space of interest, utilizing Palmer and/or NDVI variables in turn.

<u>Palmer Indices</u>

Droughts are, by nature, regional phenomena. Palmer's pioneering research in the 1960s into drought phenomenon evaluated this poorly defined event in terms of a meteorological anomaly condition, as assessed through three indices, namely, the Palmer Drought Severity Index (PDSI), the Crop Moisture Index (CMI) and the Z-Index. The overall purpose of Palmer's research was to establish geographically comparable deviations of the weather situation from normal in terms of indices. Palmer's drought analysis utilized, amalgamated and built upon previous supportive empirical research, carried out by Thornthwaite (1948) and Palmer and Havens (1958), who had estimated potential evapotranspiration rates; the soil moisture research carried out by Marlatt et al (1961); and Kohler and Richards' (1962) computations of drainage basin runoff.

Each of Palmer's drought indices, use the concept of the amount of precipitation required for the near-normal operation of the established economy of the area during some stated period, which is dependent on the average climate of the area and on the prevailing meteorological conditions, both during and preceding the week in question (Palmer, 1965 and 1968). Ultimately, the Palmer indices can be calculated for points, or areas, allowing temporal and spatial comparisons (Palmer, 1965). The

USDA/NOAA use maps of these indices to determine the spatial and temporal extent of drought within the U. S., which are published bi-monthly in their Weekly Weather and Crop Bulletin.

Palmer Drought Severity Index. The Palmer Drought Severity Index (PDSI), or more commonly called Palmer Index, is a measure derived in 1965 to analyze the nature, and regional phenomena, of moisture crop stress, caused by either deficit or inundation of precipitation. The PDSI is calculated from a combination of meteorological and hydrological data, and is based upon the principles of water balance computations, (Alley, 1984) principally a moisture supply and demand, giving a moisture departure value (index) from normal for recent weather conditions. The supply is composed of precipitation and stored soil moisture. The demand is the potential evapotranspiration, and the amount needed to keep the rivers, lakes and reservoirs at a normal level. Via a series of equations, which require the input of long term hydrological constants which define the moisture characteristics of the climate in the area of interest, this computation gives a numerical standardized index which evaluates the occurrence of meteorological drought/moisture excesses conditions on a weekly, monthly, and longer, time framework for recent weather conditions (Equation 1).

$$PDSI(X)_i = X_{i-1} + Z_i/3 - 0.103X_{i-1} \quad (1)$$

where : $PDSI(X)_i$ = index of drought severity for week i,

Z_i = moistute anomaly for week i

Source : Palmer, 1965

Palmer indices can be calculated for any area worldwide where there is a long enough climate record to generate the input coefficients. The PDSI ranges from greater than 4.00 for extremely wet conditions to less than - 4.00 for extreme drought. A value of zero indicates normal moisture conditions (Table I).

Alley (1984) has recognized that Palmer's PDSI and Z-Index employ rather arbitrary rules and assumptions in quantifying the intensity of periods of drought and their beginning and ending times. As such, Alley catalogs his misgivings regarding the computation of these indices which overlook the fact that, (a) there is no universally accepted way of computing potential evapotranspiration, (b) vegetation cover and root development change annually which affects soil water capacities, and (c) Palmer's runoff term incorporates no lag time between generation of excess water and its appearance as runoff. Furthermore, Alley noted that more information is needed on the relationship between variables

TABLE I

CLASSIFICATION OF RECENT WEATHER
ACCORDING TO PDSI (X)

X	Class
>= 4.00	Extremely Wet
3.00 to 3.99	Very Wet
2.00 to 2.99	Moderately Wet
1.00 to 1.99	Mildly Wet
0.99 to 0.50	Incipient Wet Spell
0.49 to - 0.49	Near Normal
- 0.50 to - 0.99	Incipient Drought
- 1.00 to- 1.99	Mild Drought
- 2.00 to - 2.99	Moderate Drought
- 3.00 to - 3.99	Severe Drought
<= - 4.00	Extreme Drought

Source : Karl, 1986.

simulated by water balance and actual conditions, and economic consequence. However, Alley realized that without this information, it is difficult to derive drought indices not based on relatively arbitrary operating rules.

Despite Alley's misgivings, the PDSI has been used extensively by various researchers to illustrate the areal extent and severity of dry conditions in the continental United States. Felch (1978) used the PDSI to compare droughts of the 1930s, 1950's and mid-1970s across the continental United States. Lawson et al (1971) studied the spatial and temporal characteristics of droughts in Nebraska. Similarly, Skaggs (1975) appraisal of the severe widespread drought in the United States during the period 1931- 40 details its spatial and temporal patterns through an identification by a PDSI eigenvalue/ eigenvector analysis. Skaggs study showed that there were "waves" of drought occurring during that particular decade. Moreover, the area affected by each subsequent drought episode differed in each instance. Karl and Koscielny (1982) and Diaz (1983) used the PDSI to study dry and wet episodes over the coterminous United States between 1895 and 1981. Their results showed that the interior and western portions of the United States are found to be more drought-prone than other parts of the country as indicated by the monthly PDSI values. By contrast, the likelihood of drought occurrence in states near coastal areas is considerably less. Moreover, prolonged abnormalities also tend to occur over drought-prone states indicating a tendency toward "biomodality" (i.e. either "too dry" or "too wet"). Given the above, it is safe to point out that the PDSI method has been used extensively and it currently remains the most popularly utilized drought index.

Crop Moisture Index. Since it would be impractical to devise an index system for all drought effects, Palmer created the Palmer Drought Severity Index (PDSI) and Crop Moisture Index (CMI) to consider different situations. The PDSI was devised to measure all aspects of drought whereas the much more sensitive CMI was developed to measure drought effects on mature, fully rooted crops. The CMI developed as a derivative from moisture accounting procedures used in calculation of the PDSI (Palmer, 1965), to measure the degree to which moisture requirements of mature, fully rooted crops were met during the previous week. The short-term CMI gives the status of purely agricultural drought, or moisture surplus, affecting warm season crops versus available water in a 5-feet soil profile and can change rapidly from week to week.

The index is the sum of the evapotranspiration anomaly, which is negative or slightly positive, and the moisture excess (either zero or positive). Both terms take into account the value of the previous week. The evapotranspiration anomaly is weighted to make it comparable for different climates and times of year. If the potential moisture demand exceeds available moisture supplies, the index is negative. If moisture meets or exceeds demand, the index is positive. (Equation 2)

$$CMI = Y + G \qquad (2)$$

where : Y = index of evapotranspiration defecit

G = index of excessive moisture

Source : Palmer, 1968

Until recently, the use of the CMI had been much overlooked by researchers, however, Janowiak et al (1986) and Gallo and Heddinghaus (1989) were able to employ it in their respective studies. Janowiak et al (1986), during the development of their Precipitation Anomaly Classification, listed its accuracy against the well known PDSI and CMI, indicating that their new technique compared favorably with the aforementioned indices on a global scale. In a similar study, Gallo and Heddinghaus' (1989) 'Corn Belt Analysis - 1987 - 88' for eastern Illinois, related a satellite derived biomass estimate to a seasonally accumulated CMI within their study area. They were able to establish that greater amounts of precipitation and thus larger values of Crop Moisture Index, in 1987 compared to 1988, were associated with greater amounts of seasonally cumulated NDVI. However, their results showed that only 33 percent of the variation in cumulative daily NDVI was explained by changes in seasonal CMI.

<u>Z-Index</u>. Palmer's Z-Index (the weekly moisture anomaly index) has been seldom used. Exceptions are Karl (1986), Karl and Young's (1987),

Sakamota's (1978) , Easterling et al (1988) and Isard and Easterling's (1989) research. Each Z expresses on a weekly bases, and from a moisture standpoint, the departure of the weather of a particular week from the average moisture climate of that week. Only two basic meteorological inputs are required to calculate the Z-Index, namely the mean temperature and total precipitation on a weekly basis (Karl, 1986). As such, the Z-Index is a precursor to the calculation of PDSI (Isard and Easterling, 1989) (Equation 3).

$$\text{Z-Index} = dK \qquad (3)$$

where : d = moisture departure for a particular week

K = the climatic characteristic or weighting factor

Moreover, Karl's (1986) investigation for the United States suggested that the Z-Index is a better indicator of agricultural drought than the accumulated PDSI, since the Z-Index, by virtue of its discrete weekly calculation, is more reflective than the PDSI of short-term moisture shifts during sensitive crop development stages at a given location. Karl's, 1986, statement is a result of the fact that the Z-Index exclusively includes the moisture anomaly of the current week, whereas the PDSI statistically weights the moisture of the previous week more heavily than the current week, slowing down the reaction time, and muffling the change, of the PDSI value as it reacts to a new regime. As a result, the Z-Index is much more sensitive than the PDSI to unusually wet (or dry) weeks even in an extended period of drought (or wet) weather. Given the above, Karl (1986) concludes that most agricultural interests should find the Z-Index more useful than the PDSI.

Sakamoto's (1978) use of the Z-Index as a variable for crop yield estimation in South Australia, together with mean temperature departures during selected months, provided a significant variable in his winter wheat yield model. Karl and Young (1987) utilized the Z-Index to assess the severity of the agricultural drought of 1986 in the Southeastern region of the United States, which they concluded was the most severe on record for this area.

Easterling et al (1988) used results of an Illinois corn-climate analysis to weight a Palmer Z-Index to reflect how different types of moisture conditions interact with crop phenology and crop management decisions. The weighted Z-Index for various parts of the growing season, such as moisture sensitive and anthesis/ grainfill periods, was shown to correlate ($r^2 = 0.54$) with final yields more closely than the use of the Z-Index which are simply averaged over the growing season.

Isard and Easterling's (1989) county-based corn yield modeling analysis, employed transformed (weighted) Z-Index calculations from the records of 12 climate stations in Illinois for 24 years (1960-82). They compared their weighted Z-index against eventual county aggregated yield data for the entire study period, and found this model to be a reliable predictor of corn yield, particularly during periods of benign or stressful climate during the growing season.

Comparison of Palmer Indices

The aforementioned Palmer indices outlined above are dependent on a common, but fairly complex, water budget bookkeeping system system based on potential evapotranspiration, soil water recharge, potential runoff and potential loss from the soil profile. It is important to note that each index possesses distinctive differences and associated operating regimes.

Palmer's principle index, the PDSI, and the precursor in its calculation, namely the Z-Index, both measure the aspects of drought, whereas the CMI was specifically designed to measure the effects of drought on mature, fully rooted crops. As such, the CMI is designed to react much quicker in comparison to the other two indices to dry or wet events, since it is principally agricultural in focus. Furthermore, as previously noted, the Z-Index is much more sensitive than the PDSI with the onset of dry or wet events, since the latter index's measurement is conditioned by the strict statistical weighting technique, which considers the previous weeks condition more than in the Z-Index calculation.

Comparing the three indices, it is evident that they react at different rates to wet (or dry) events, with the most sensitive CMI, increasing (decreasing) at the greatest speed, while the Z-Index reacts quicker in turn when compared to the most lethargic of Palmer's indices, namely, the PDSI, under the same moisture event. Given that Oklahoma experiences extreme ranges and abrupt changes in the weather regime, particularly in regard to sudden, wet and dry events, one would expect the CMI to react most quickly, while the Z-Index and PDSI in turn would be more lethargic under the same moisture and dry influences.

Normalized Difference Vegetation Index

The spectral reflectance of chlorophyll pigment in the visible and near infrared part of the electromagnetic spectrum provides a means of monitoring growth, density and vigor of green vegetation from afar. Leaf pigments and cells structure are the dominant factors controlling leaf reflectance in the visible and near infrared portions of the electromagnetic spectrum (Walsh, 1987). Chlorophyll in green leaves has a reflectance in the 0.5 to 0.7 micrometer spectral interval of less than 20 percent, but about 60 percent in the 0.7 to 1.3 micrometer range (NOAA/NESDIS, 1986). NOAA's (National Oceanic and Atmospheric Administration) AVHRR satellite system's Channel 1 (Red - 0.58 to 0.68 micrometers) and Channel 2 (Near infrared - 0.724 to 1.10) can be used for vegetation monitoring, in that various mathematical combinations of Channels 1 and 2 data have been found to be sensitive indicators of the presence of green vegetation and are referred to as vegetation indices (Perry and Lautenschlager, 1984). At this juncture, it is important to realize that the AVHRR spectral channels were primarily designed for cloud, atmospheric and sea-surface temperature analyses, although, as outlined above, the visible and near-infrared channels have proven to be suitable for vegetation studies (Holben, 1986).

The Normalized Difference Vegetation Index is computed by subtracting radiance measured in the visible region from that measured in the reflective infrared region and then dividing the result by the sum of the radiances in the visible and reflective infrared regions using AVHRR data (Equation 4).

$$NDVI = (Channel\ 2 - Channel\ 1) / (Channel\ 2 + Channel\ 1) \qquad (4)$$

where Channel 1 = 0.58 - 0.68 micrometers

Channel 2 = 0.724 - 1.10 micrometers

Source : NOAA/NESDIS, 1986

In theory, derived NDVI measurements range between - 1.0 and + 1.0. However, in practice, the measurements generally range between - 0.1 and + 0.7 (NOAA/NESDIS, 1986). Clouds, water, snow, and ice give negative NDVI values. Bare soils and other background materials produce NDVI values between - 0.1 and + 0.1. In scenes with vegetation, NDVI ranges from + 0.1 to + 0.6 and is very sensitive to the underlying vegetation conditions to the exclusion of other surface coverages, which possess categorically different spectral signatures. Large NDVI greenness-oriented values represent areas containing higher amounts of standing green vegetation rather than the common, but misleading and erroneous inference of biomass production (Tucker and Sellers, 1986). Dividing by the sum of the channels normalizes the numerical index by reducing the effects of changes in soil color, or brightness, changes in levels of solar illumination intensity and cloud contamination. Therefore, NDVI values representing different locations, or times, can be mapped and compared. In general, high values correspond to greater coverage of healthy plant material (NOAA/NESDIS, 1986).

Weekly accumulated NDVI data include differences in atmospheric conditions, positions of the sun, view angles of the sensor, and sensor calibration. These differences constitute the radiometric disturbances present in remotely sensed data and reduce the quality of the data. Any of these variables can cancel or reinforce the variability (Van Dijk et al, 1987).

The radiometer on board the various NOAA polar-orbiting meteorological satellites, which scans across a 2700 Km ground swath, records the spectral response characteristics of the viewed underlying surface in 5 channels, at a ground resolution of of 1 km. The 1 km data is sampled down to nominally 4 km resolution and recorded on board the satellite for subsequent transmission. AVHRR Global Area Coverage (GAC) at 4 km resolution in thus available, but it is normally resampled to a 13 Km cell size which is produced as a standard product by NOAA/NESDIS. This coverage is supplemented by 1 km resolution (LAC for Local Area Coverage) coverage of selected areas by means of direct readout 1 km data and the limited amount of 1 km that can be recorded (NOAA/NESDIS, 1986). As such, GAC data are routinely available while LAC is very scarce.

On any single day about half the Earth is obscured by clouds. To remove cloud contamination from NDVI products, seven-day maximum vegetation index composites are produced for the daily arrays. For each composite period of seven days, the pixel from the daily data having the greatest Channel 2 - Channel 1 difference is retained at each array location. That is, the greenest of the seven daily values of each array location is retained in the composite. This eliminates clouds from the composite except for areas which were cloudy for all seven days.

Since the early 1980s, a significant number of research papers have employed Normalized Difference Vegetation Index products. These research studies have been used in land cover classification and to monitor vegetation dynamics. Sahelian Africa and the North American Continent have received the most extensive treatment. Therein, this technique has been used successfully to monitor and study vegetation trends on regional, state and continental scales, while utilizing combinations of both Local Area Coverage (LAC) and Global Area Coverage (GAC).

Despite some interest in vegetation monitoring in the Nile Delta (Tucker et al, 1984; 1986) and for the African continent as a whole (Tucker et al, 1985), the principal thrust to NDVI utilization and interest in Africa has been associated with seasonal land-cover dynamics and classification, which are affiliated with the seasonal movement of the Intertropical Convergence Zone in the Sahel. The principal research has focussed on the spectral returns related to the much publicized drought conditions experienced during 1983 - 1985. Tucker et al (1985), Tucker et al (1986), Hielkema et al (1986), Justice and Hiernaux (1986), and Tucker and Choudhury (1987) are examples of work in this area. In Tucker et al (1985) study of herbaceous biomass production in the Senegalese Sahel, 1980-1984, the NOAA AVHRR satellite data were compared to sampled above ground biomass data. The calculated mathematical integral of the satellite data over time was found to be strongly correlated ($r^2 = 0.62$) with end-of-season above-ground total dry biomass.

Throughout most of the aforementioned research, the controlling factor as regards NDVI values derived from spectral returns were considered to be the availability of precipitation. Precipitation amounts can affect vegetation productivity and, therefore, the spectral response from remote sensors sensitive to biomass and other vegetation characteristics (Walsh, 1987). All the Sahel researchers analyzed how the lack of moisture effected plant growth and 'apparent' and 'potential' biomass production in this highly fragile, and important, ecological zone. For instance, Hielkema et al (1986) successfully correlated NDVI values with rainfall for parts of the 1983 and 1984 growing seasons in order to assess the possibility of predicting eventual biomass / net primary productivity in the savanna zone of the Democratic Republic of Sudan.

Turning to the North American Continent, there are five particularly noteworthy papers on AVHRR NDVI which will he herein considered as they progress from larger to smaller areas of focus in turn.

Goward et al (1985) analysis of North American NDVI scenes, extending from April and November, 1982, showed that the vegetation index patterns observed correspond to the known seasonality of North American natural, and cultivated, vegetation. With particular reference to the study area of this thesis, these authors illustrated that the winter wheat growing area extending from north central Texas to Kansas stands out as an island of high NDVI values in the April images whereas the cornbelt shows up as an area of low values at the same time. Moreover, like the Tucker et al (1985) African work mentioned above, Goward et al (1985) research has further shown that the mathematical integration of the remote sensing observations over the growing season produced measurements, directly related to net primary productivity patterns of the major North American natural vegetation formations.

Owe et al (1988) utilized NDVI in conjunction with remotely sensed - microwave-brightness temperatures in order to calibrate a physically based soil moisture model. Soil moisture values were estimated from a space based microwave sensor over six test sites of dimensions of 1.5 longitude by 1.5 latitude in northern Texas and Oklahoma, and were shown to compare favorably with actual ground surface observations of soil moisture in these areas. These vegetation index values varied as a result of the marked temperature-precipitation changes noted from east to west in the U. S. Southern Great Plains. As a result, these authors projected that with further refinement that, their soil moisture model appeared to be valid, at least for similar arid or semiarid conditions.

Norwine and Greegor's (1983) paper considered the feasibility of utilizing AVHRR imagery for vegetation classification when allied to climatological variables along an east-west environmental transect across Texas. Therein, the authors utilized a term called the "Hydrological Factor" (derived by Trenchard and Artley (1981a, 1981b) which is a water availability variable based on precipitation, evaporation and daily maximum and minimum temperatures. When the NDVI values were regressed against the Hydrological Factor, it was found that the latter explained 86 percent of the variation in the NDVI for the 12 sample study sites. Thus, Norwine and Greegor showed that precipitation, evapotranspiration and daily temperature range, collectively were significant in controlling NDVI values.

Miller and Moore (1983) used NOAA'S AVHRR NDVI to successfully monitor the growth and accumulation of green herbaceous vegetation in northwestern Arizona. The major focus of this time-series analysis was in the spring growth cycle pattern of the vegetation during winter dormancy through the senescence of annual grasses during March and April, in order to locate remote areas with large standing green NDVI biomass values, which were pinpointed as being highly susceptible to wildfires.

Of all of these North American studies, the most helpful with regard to this thesis is Walsh's (1987) paper, which investigated the relationship between AVHRR data and three meteorological drought measures, namely, the Crop Moisture Index (CMI), the Palmer Drought Severity Index (PDSI) and the Hydrological Deficit (HD)-- which is not a Palmer Index --, for 181 climate stations in Oklahoma for four weekly study periods extending from late June through August, 1980, during a severe summer drought. It is essential to note that Walsh's statewide analysis during this summer drought period did not attempt to temporally analyze the entire winter wheat growing period in Oklahoma, which spans from its planting in September/October to eventual harvest in May/June. Instead, Walsh's research generally considered the spectral returns from the heterogeneous landcover types in which each of the 181 climate stations were located.

Multiple regression analysis was used to assess the level of explanation of each of the three meteorological drought indices through the use of remote sensing measures of vegetation conditions input as independent variables to a model building process. Walsh's multiple regression analysis explained 80, 57, and 44 percent of the variation in the CMI, PDSI, and HD, respectively, when regressed against AVHRR spectral channels and derived vegetation indices.

A criticism of Walsh's research lies in the fact that NDVI returns over the climate stations represented a multitude of landscape coverages, and thus varying spectral signatures. Furthermore, these spectral values were further confused during 1980 by the reversal of the normally traditional east to west transitional nature in precipitation across the state. Nevertheless, for the purposes of this research, Walsh significantly notes that while the regression models do relatively well in estimating the three investigated drought indices, the r^2 (coefficient of determination) could be increased if a smaller geographic study area having less diversity was tested.

Winter Wheat (*Triticum aestivum* L.)
and Moisture Availability

Analysis on how water availability influences winter growth in the Great Plains is lacking from an AVHRR remote sensing perspective. However, in a winter wheat Great Plains Landsat study carried out by Thompson and Wehmanen (1979), they investigated how the spectral response measured through a Green Index Number (GIN) -- a ratioing technique of Landsat's visible and infrared channels representing growing vegetation similar to the AVHRR NDVI calculation -- changed for this crop during its spring 'greening-up' and 'browning-out' phases, as conditioned by water stress over 36, 5 by 6 nautical mile sampling frames, as assessed through Palmer's (1968) weekly calculated Crop Moisture Index (CMI). These authors, reasoned that if drought was experienced within an area, the effects upon the plant would cause a change in its usual spectral signature, and that change would be reflected in a decrease in the GIN. As a result, through a chi squared test of association, it was found that 85 percent of the variation in GIN was associated with a change in the values of the weekly calculated ground-based CMI values. It is important to note that AVHRR NDVI is recognized as superior to the Landsat GIN because of the narrower bandwidths utilized, which reduce the atmospheric effects inherent in Landsat returns.

Given the guidance of the literature, it is essential to realize that in order to understand NDVI values associated with winter wheat are determined by the winter wheats' condition. As the spectral signature of the winter wheat changes through the progression of the various phenological growth stages, the success of which is ultimately dependent upon the soil moisture availability situation. Moreover, with in situ data, it has been shown by authors such as Day and Intalap (1970), Fischer (1973), Davidson and Birch (1978) and Johnson and Kanemasu (1982), that different wheat yield components are affected by water deficits depending on the growth stage at which water stress develops and its temporal duration.

Day and Intalap (1970) found that when field winter wheat (*Triticum aestivum* L.) was water stressed at joining, yields were reduced about 50 percent compared with wheat under an optimum irrigation schedule, and the reduction was related to fewer heads per square meter and kernels per head.

In a growth chamber experiment, Fisher (1973) found that reductions in kernels per spikelet were severest when moisture stress occurred just before heading of winter wheat.

Johnson and Kanemasu's (1982) field experiments were conducted comparing yield and yield components of winter wheat (*Triticum aestivum* L.) grain under different soil water conditions. Soil water was controlled by excluding precipitation from a 150 square meters plot area with an automatic rain shelter. A neutron probe was used to periodically monitor soil water to the 150 cm depth in each regime. Their results indicate that, if drought develops before grain filling in the spring, improved tiller survival and/or floret fertility could increase yields, even if some stress continued through grain filling. Under nonstress conditions, yield appears limited most by the amount of assimilate required to fill a higher number of kernels per square meter.

Conclusion

From the above resume of the literature, it is obvious that very little interaction has occurred between AVHRR studies of vegetation growth and water availability as assessed by Palmer indices, with the exception of Walsh's (1987) Oklahoma - based NDVI / Palmer research and Gallo and Heddinghaus' (1989) paper.

Since there is no index system to measure the unique effect of water availability in the spring months, the various Palmer indices have advantages and disadvantages with regard to their use in the Oklahoma winter wheat environment under consideration. An advantage of Palmer indices, is that they can all be applied to a region of the size of the study area in this thesis, and therein consider precipitation and temperature and their combined influences on evapotranspiration, soil moisture and runoff as they vary spatially. On the other hand, there are disadvantages based on the water balance model's simplistic representation of hydrologic phenomena, especially runoff. For instance, the simulation of runoff by the water balance model is very crude, and it is difficult to account for the lag between moisture surplus and stream flow (Alley, 1984).

Assuming that when a drought (or rain) event is experienced within any part of the study area as assessed through the various Palmer variables, that this would impact upon the growth of winter wheat and cause a change in the expected spectral signature of the crop. However, it remains unclear at this juncture, which Palmer variable will best represent, and correspond to, changes in the spectral signature recorded. Therefore, one of the goals of this thesis will be to assess which measure(s) is/are the most appropriate for use here with AVHRR NDVI data.

This thesis represents a significant change in focus from the large area analyses reported within much of the AVHRR NDVI remote sensing literature to date. In addition, this combination of NDVI data and weekly ground-based Palmer indices during the spectrally significant 'greening-up' and 'browning-out' phases of winter wheat remains unexplored when considering such smaller sized study areas in which almost monocultural winter wheat farming is practiced. Thus, this analysis forwards a projectedly useful reorientation for remotely sensed agricultural research in geography.

CHAPTER II

STUDY AREA

Introduction

The principle reason for focusing in on a 'T-shaped' study area (Figure 1) emanates from the fact that within Oklahoma, the counties of Alfalfa, Canadian, Garfield, Grant, Kay, Kingfisher and Woods, have consistently remained within the 15 top counties of the State in terms of acreage of dry land (non-irrigated) winter wheat planted, harvested and/or yield returns over the last 15 years (Weekly Weather and Crop Bulletin, 1973-1988). Simultaneously, winter wheat has consistently accounted for in excess of 40 percent of the total land area under agriculture in the study area as a whole. At this county level, only Canadian, at 33 percent, and Woods counties, at 27 percent, have recorded lower acreages of land under winter wheat farming over the same period, and these lesser acreages are mainly conditioned by urban encroachments and physiographic-environmental controls therein, respectively. These physical controls limit the winter wheat acreages in these counties, but otherwise the crop is virtually spatially ubiquitous throughout the study area.

It has been historically recognized that winter wheat accounts for the main crop of the Southern Great Plains area, with this zone being considered part of the 'breadbasket' wheat belt zone. Evidently, with winter wheat growth dominating agricultural land in this study area and

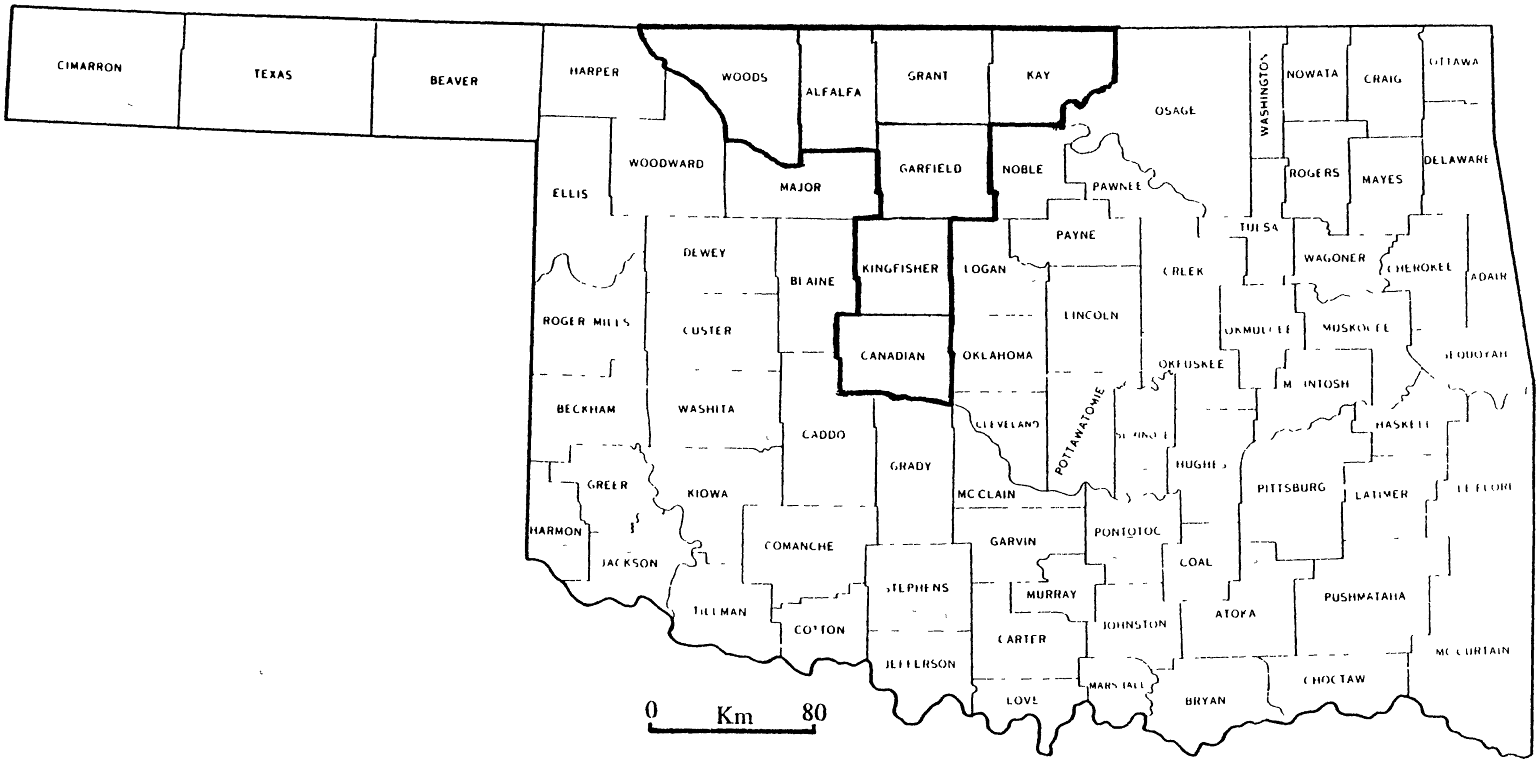


Figure 1. Study Area

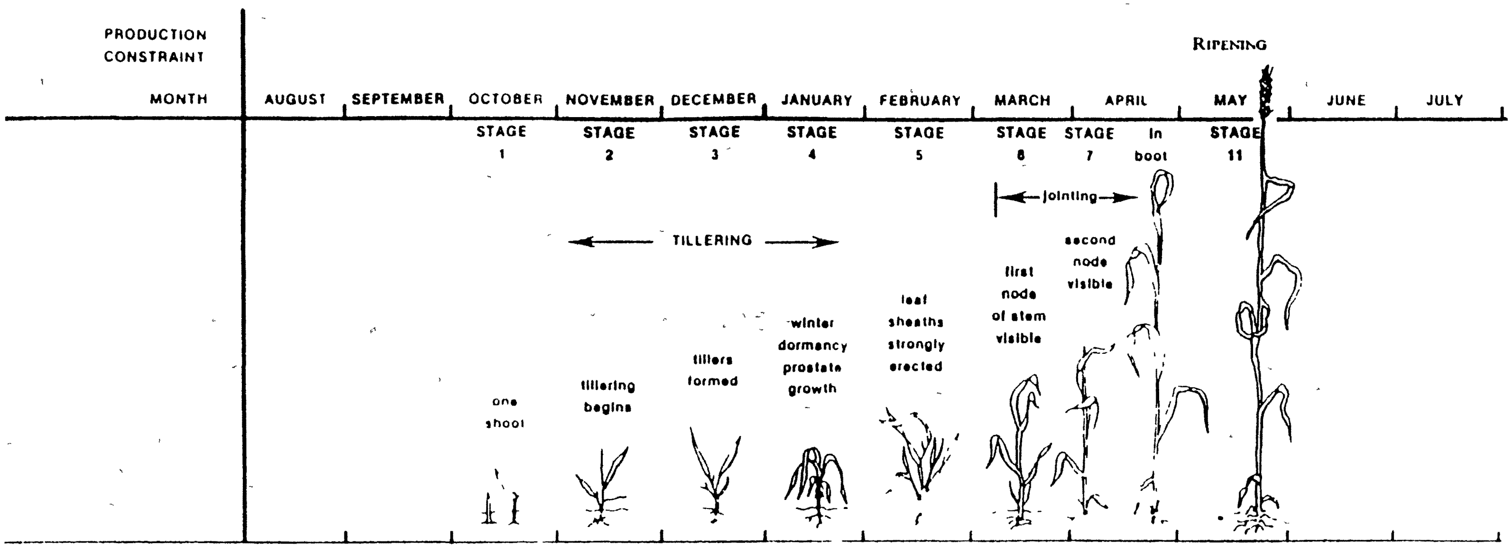
the associated spectral returns during its spring 'greening-up' and 'browning-out' phases, as winter wheat emerges from winter dormancy around the beginning of March (Week 9 of the year) through to its eventual harvest before the end of June (Week 26), it should stand out when compared to the surrounding landcover associations significantly higher NDVI values. As a result, this study area forwards an excellent research focus with regard to the exploration of the relationship between almost ubiquitous winter wheat-oriented NDVI values and Palmer drought indices within a small area.

Before considering the agricultural development of the winter wheat culture area, and the simultaneous demographic trends therein, it is essential to outline the climate, physiography and geology, soils, vegetation and history of the region, since they have all significantly impacted on, or have been conditioning factors in, the initiation, growth, development and eventual flourishing of the winter wheat culture in the study area.

Climate

The climate of the study area is mainly under continental controls, common to the Great Plains region as a whole. The continental effects on climate caused by the clash of contrasting air masses, can result in pronounced daily and seasonal changes in temperature and precipitation and considerable interannual variation in the amount of precipitation.

In outlining the climatic characteristics of the study area, it is important to focus in on those periods which are critical within the growing season for winter wheat (Figure 2). The crop is planted in north



Source : Cuperus and Johnston, n.d.

Figure 2. Crop Calendar for Winter Wheat in Oklahoma

central Oklahoma from September through to early October, depending on if winter wheat is to be utilized for pasture and grain, or grain only, respectively. Having emerged, it undergoes tillering until eventual winter dormancy through December and January. On average, winter wheat resumes growth in February, and then, particularly from the beginning of March (Week 9 of the year), it enters into the jointing period which lasts until mid April (Week 15/16), as the crop undergoes the rapid 'greening-up' phase. Following this, winter wheat usually 'browns-out' from mid-late April (Week 16/17) onwards and is harvested in the study area from late May (Week 21), until the end of June (Week 26). The timing of these events are largely dependent upon the amount and timing of rainfall recorded throughout the entire growing season.

The mild fall season normally alternates between sunny days and periods of moderate to soaking rains, which greatly aids the recently planted winter wheat grains. Following this, the winters are generally short and comparatively mild. The winter periods of cold and snow last only a few days and occur when northern air tracks south. However, extreme cold snaps (≤ 0 °F / ≤ -17 °C) can punctuate these winters, and prolonged periods of cold and dry weather can freeze-dry the winter wheat.

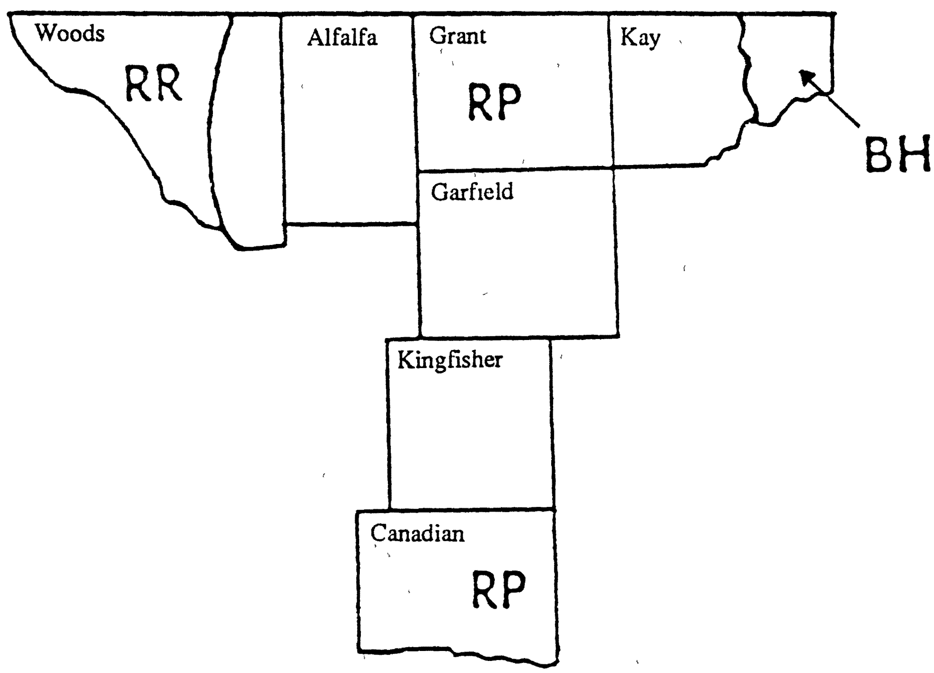
Spring, which is the most variable of seasons, is characterized by frequent precipitation, out of large thunderstorms. This season is crucial for the successful growth, development and kernel filling of the winter wheat during its 'greening up' and 'browning-out' phases. As a result, if drought conditions occur during the jointing phase or kernel-filling stages it can severely impede growth and low yields will result. Winter wheat is harvested before the hot summer strikes since the crop is unable to withstand high evapotranspiration rates.

Given the elongated shape of the study area, it is only along the four northwesternmost branch of counties -- paralleling the Kansas-Oklahoma State Line -- that Oklahoma's characteristic longitudinal and latitudinal controls on temperature and especially precipitation become evident. Along the northernmost counties the mean annual temperature varies little from west to east, recording a difference of less than 1° C (from 64.9 °C to 65.8 °C, respectively). However, for the same zone, the annual precipitation gradient shows a significantly greater variation from around 813 mm in the east in Kay County to around 610 mm in Woods County. The central column of the study area, namely, the Grant through Canadian county region, has on average, around 737 mm of rainfall per year, associated with little, if any annual temperature variation (Morris, 1977). Apart from the spatial variability, it is important to note that Oklahoma's climate is characterized by a large annual precipitation variability.

Physiography and Geology

For the most part, this study area lies within the Reddish Prairies (RP) resource region of central Oklahoma (Figure 3). Moreover, under Gray and Galloway's (1959) classification, the western three-quarters of Woods and the eastern two-fifths of Kay counties were shown to be encompassed within parts of the Rolling Red Plains and the Bluestem Hills, respectively.

The general geological associations of the seven counties largely conditions their physiographic classifications (Figure 4). The Reddish

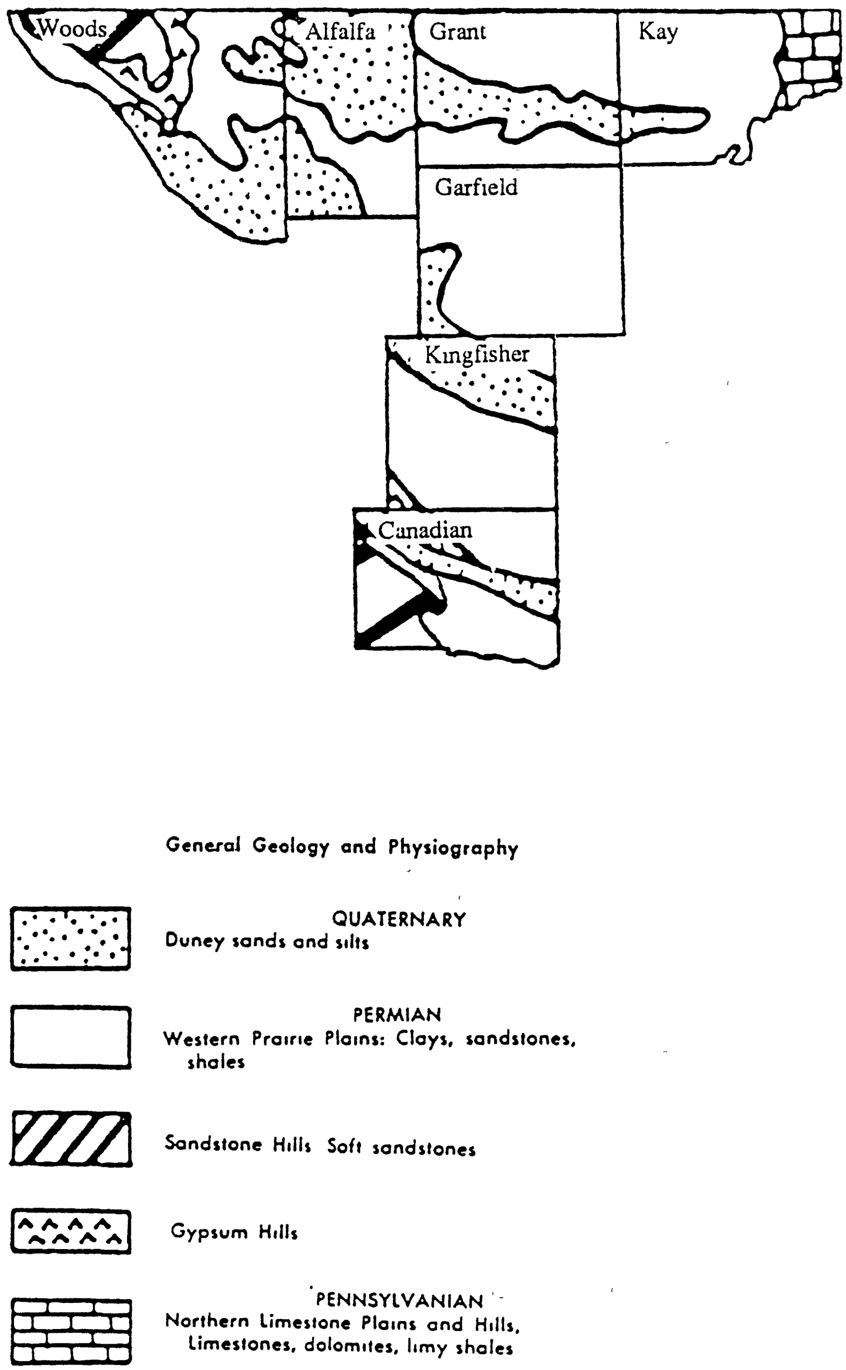


Resource Areas - Elevation Variability

RR	Rolling Red Plains 3000'-1000'
RP	Reddish Prairies 1400'-1000'
BH	Bluestem Hills 1100'-700'

Source : Gray and Galloway, 1959.

Figure 3. Elevation Variability by Broad Land Resource Areas in the Study Area



Source : Gray and Galloway, 1959.

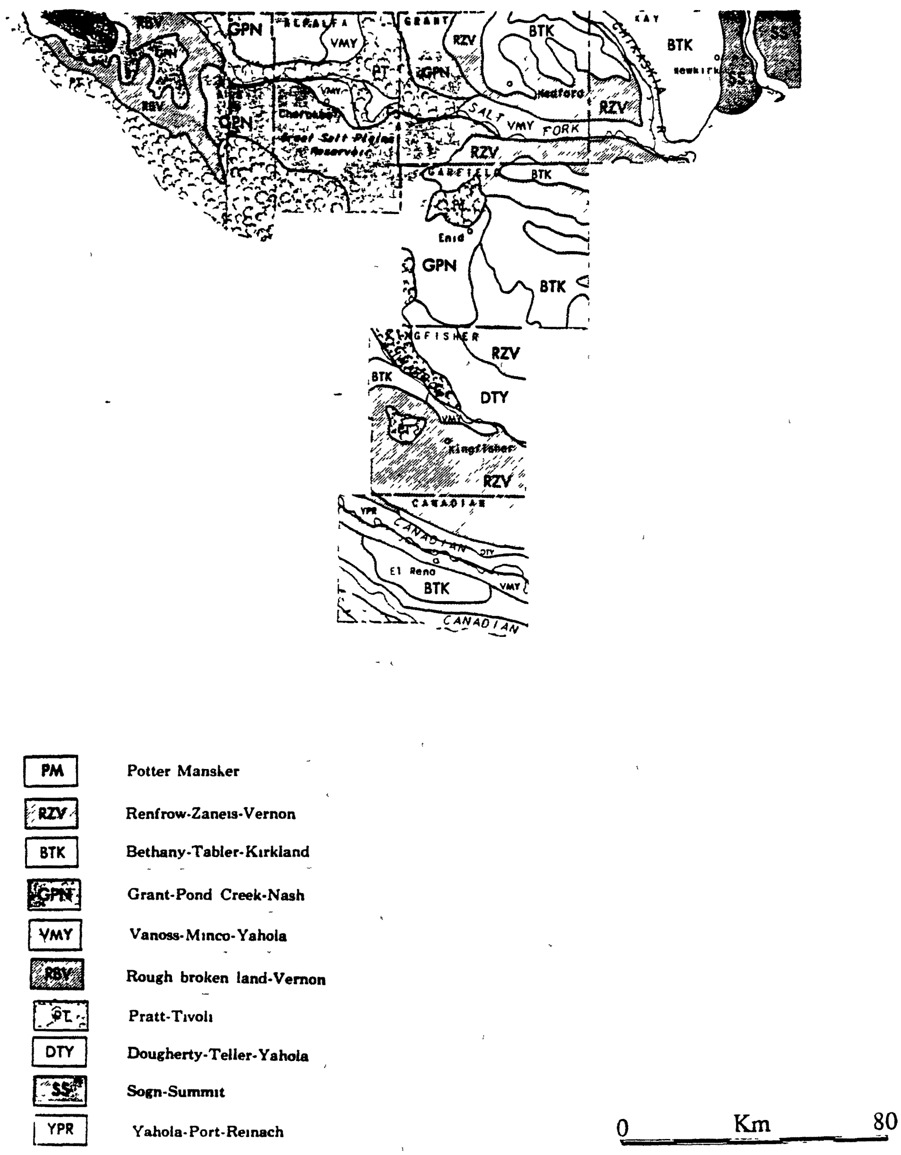
Figure 4. General Geology and Physiographic Areas of the Study Area

Prairies region is located primarily across an area of gently undulating Permian clays, sandstones and shales, and Quaternary duney sand and silt deposits, which forwards a large amount of level to slightly undulating land of less than 3°, determining the dominant winter wheat orientation of the 'heartland' of the study area. In the easternmost sections of Kay County, Pennsylvanian limestones occasionally outcrop at the surface to produce steep slopes in this otherwise Cuesta Plain area dominated by range and pastureland having little, if any, winter wheat farming. In addition, the western part of Woods County records a mixed variety of geological associations including Permian sandstone and gypsum hill areas juxtaposing clays, sandstones and shales of the same geological age, with duney sands and silts from the Quaternary era, conditioning its livestock orientation on land unsuitable for winter wheat growth.

Soils

From the highly generalized map of the soils of the study area (Figure 5), four main associations are evident, namely : Renfrow-Zaneis-Vernon, Bethany-Tabler-Kirkland, Grant-Pond Creek-Nash, and Pratt-Tivoli. These soil associations, like all soils, are largely determined by the geologic fundament as the soils developed from the weathering of the underlying bedrock through climatic influences, and the soil record largely parallels the general geological patterns outlined above.

The soils of the Renfrow-Zaneis-Vernon (RZV) association range from clay to loam, principally occurring within the southern half of Kingfisher and along the northern portion of Canadian County. The other major areas where RZV soils exist are in distinctive bands within Grant



Source : Soil Conservation Service, U.S.D.A., 1959.

Figure 5. Soil Map of the Study Area

County with smaller areas in eastern Kay and northern Garfield counties. All areas where these associations occur are marked by a predominance in winter wheat cultivation.

Bethany-Tabler-Kirkland (BTK) soils which encompass silt loams through gray clays, form the highly regarded north central portion of Oklahoma's winter wheat belt. This association mainly occurs in eastern Garfield, northeastern Grant and the west central portion of Kay counties.

The Grant-Pond Creek-Nash (GPN) soils, which are found in western Garfield, western Grant, Alfalfa, and in northeastern and eastern Woods counties, range from clay and silt loams. All these soils have fairly heavy subsoils that collect and retain a considerable portion of the rainfall. It is essential to realize that soil type is an influential factor in the amount of moisture that is held in storage for plant utilization. Given these characteristics, soils in this association are fertile, productive, and highly prized for farming. Moreover, they are considered the 'breadbasket' of north central Oklahoma for they are used mainly to grow winter wheat, grain sorghums, and alfalfa (Gray and Galloway, 1959).

The undulating Pratt-Tivoli (PT) soils range from loamy soils to sandy loams in composition, located next to riverine areas in most counties. For the most part, these soils are used for a mixture of crops including winter wheat and/or livestock grazing. However, winter wheat is grown selectively in isolated pockets where less sandy formations occur (Gray and Galloway, 1959).

Of the other seven soil associations represented in the study area, the Rough Broken Land-Vernon Association and Sogn-Summit type play a major role in conditioning their landuse utilization within the parts of the counties where they occur.

Soils of the Rough Broken Land-Vernon Association (RBV) are mainly clayey in nature and are found along drainageways, principally in western Woods County. These clay soils remain largely unproductive and are entirely used for cattle rearing here (Fitzpatrick, et al., 1950).

The Sogn-Summit (SS) soil association has developed on an undulating to sloping terrain on the limestone escarpment area of eastern Kay County. Given their poor quality, Sogn-Summit soils are best suited to native pastures, with little winter wheat grown.

Vegetation

Much of Oklahoma's original vegetation no longer is evident, largely due to the effect of man on the environment through burning, overgrazing, erosion, timber cutting, and cultivation, which have left very few climax areas (Gray and Galloway, 1959).

The Reddish Prairie resource zone, which encompasses most of the study area, records a semi-natural grass dominated environment (Bruner, 1931). Moreover, this area is largely treeless except for narrow strips along streams and on some upland areas adjacent to stream bottoms. The occurrence of this grassland has been determined by the local and regional interdependedness and interrelatedness of the elements of the environment, namely, the atmosphere, biosphere, hydrosphere, and lithosphere. However, overseeing all of these interactions is the overriding influences of humans.

The peripherally located regions of this study area, namely the eastern half of Kay County, and the areas including western Woods and the southeasternmost extremities of Canadian counties exhibit different human-modified vegetation covers. The section of Kay County, in the Bluestem Hills physiographic region, lies on an easterly facing limestone escarpment associated with low butte-like knobs. Accordingly, this area has evolved a limestone/limy clay soil type supporting the development of tall grasses producing a range farming landscape (Gray and Galloway, 1959). The aforementioned parts of Woods and Canadian counties, included in the Rolling Red Plains physiographic region, show less vegetation growth than in comparison to the wetter adjacent Red Plains area. This native vegetation cover, is as result of the occurrence of a drier climate with sandier soils preventing tall grasses from existing, but enabling short drought-resistant species to secure a foothold, producing a mixed prairie landscape.

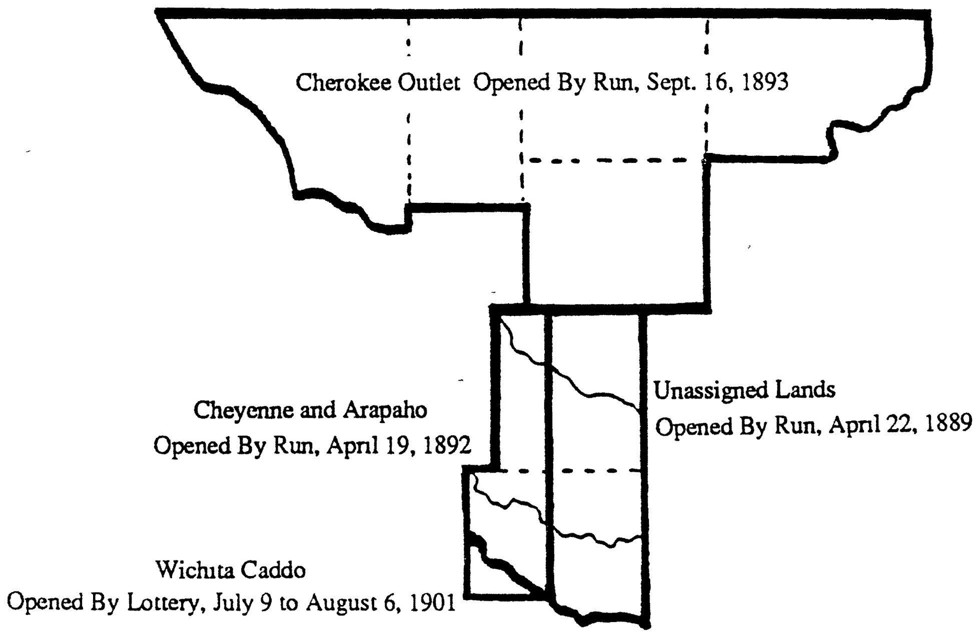
Historical Overview of the Study Area : 1828-1893

The historical evolution of the study area -- which was once mainly found within the Cherokee Outlet marking the westward extension from Indian Territory (including present day Woods, Alfalfa, Grant, Kay and Garfield counties), while the remaining two study counties, (Kingfisher and Canadian) were located in the northern regions of the Unassigned Lands ('Old Oklahoma') -- is inextricably bound up with the general Indian Policy of the United States.

From 1828 until 1840, the Five Civilized Tribes, namely, the Seminoles, Choctaws, Creeks, Chickasaws, and Cherokees, were actively relocated to eastern Oklahoma (i.e. Indian Territory). Morris (1977) has noted that as a result of this influx of population into this area, the process of land clearance in eastern Oklahoma was greatly intensified. Subsequently, fields of maize appeared along with tracts of cotton, wheat, oats, barley and potatoes, with some livestock raising occurring.

The Cherokee Outlet was finally established by 1835 in a general agreement between commissioners of the U. S. and leaders who spoke on behalf of the Cherokees. This agreement for a "home in the west" (Pierce, 1926), guaranteed this perpetual outlet of around seven million acres for hunting and fishing grounds lying westwards from 96° to 100° (Figure 6). Moreover, this area -- which measured approximately 71 km wide and more than 285 km long from west to east -- could be used for expansion of tribal reservation space if required. However, this land remained largely unused, except for a few isolated Indian settlements, until the Cherokees agreed to lease this area as 'pasturelands' *en bloc* for cattle to the Cherokee Strip Livestock Association from 1883 until 1890 (Pratt, 1929). At this time the area was relinquished to the U.S. Government, due to the increasing demand for white settlers for farmland. Eventually, the Outlet was opened up -- via a 'Land Run' -- for permanent agricultural settlement in 1893.

In the geographic center of the land which was to become Oklahoma, there were 2 million acres called the Unassigned Lands. From the Unassigned Lands (opened up for settlement in 1889) and the Cheyenne-Arapaho area (opened in 1892), the 2 southernmost counties of the study area, namely, Canadian and Kingfisher counties, were carved, except for the southwestern part of Canadian County which was added in 1901, from the Wichita Caddo Lands, when this area was opened by



Source : Mc Reynolds, 1953.

Figure 6. Study Area Land Openings

lottery.

Undoubtedly, one of the most significant historical events within the study area was the use of the Chisholm Trail which existed between 1866 and 1884. This cattle artery, roughly paralleling the 98 th Meridian, was used by Texas cattlemen seeking the most direct route north to the Kansas railheads at Caldwell and the markets beyond. Evidently, this trail almost bisected the study area in half since its route passed almost through the heart of the presently existing Canadian, Kingfisher, Garfield, and Grant counties (Figure 7). The choice of this particular route has been elucidated by Thompson (1962) who considers that this track was taken due to the inhospitable factors for cattle trailing in the western shortgrass country and the eastern Cross Timbers which flanked the trail to the west and east, respectively. It could be argued that the environmental knowledge acquired by passing traders raised the publics' awareness of the suitability of this land for agriculture. Moreover, Thompson (1962) claims that despite the short duration of the Chisholm Trails existence, it provided a basis for, and subsequent development of, the various cultural establishments which are in existence and operation today, in terms of towns, rail and road placements.

Agricultural Development of the Study Area : 1889-1987

At the outset, it is essential to realize that the pattern of agricultural, namely, winter wheat, land utilization in Oklahoma has been dependent upon a myriad of factors associated with climate, soils and the impact of man, to mention but a few. Moreover, it is obvious that although

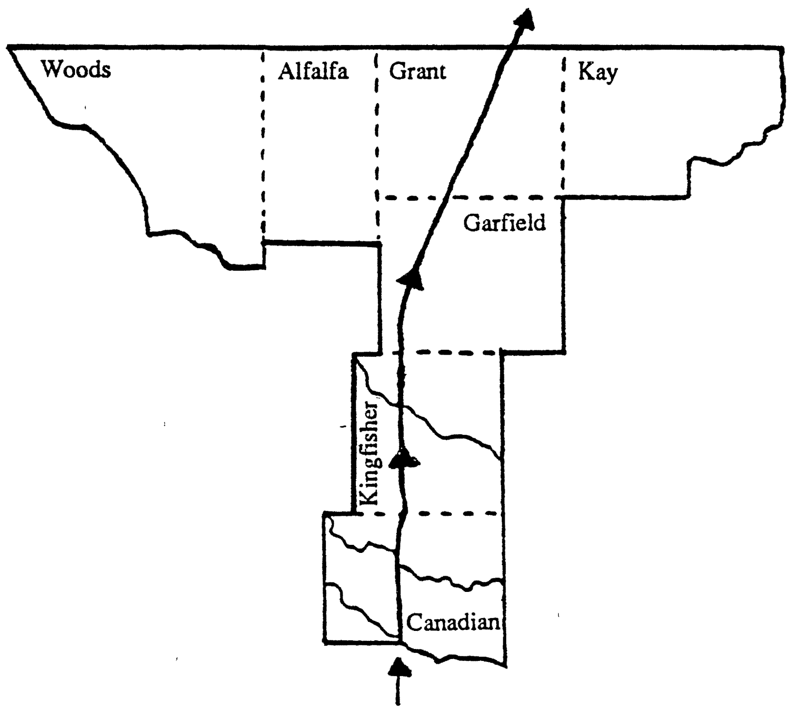


Figure 7. The Route of the Chisholm Trail
Through the Study Area

the five Civilized Tribes who were relocated into Oklahoma, brought wheat culture with them into the Indian Territory adjacent to the study area long before the opening of land for settlement, that it was only with the opening up of the Unassigned Lands (1889) and Cherokee Outlet (1893) to white settlers that significant agricultural development occurred herein.

Initially the white settlers, who were primarily interested in agriculture, practiced largely unsuccessful subsistence farming on these unbroken lands with their traditional combination of hard and soft wheats, corn, and cotton, and some livestock rearing during the drought years from 1885 to 1896. In addition, Carney et al (1988) have noted "often the agricultural activities of these pioneers resulted in failure because the settlers did not know how to farm the environment into which they had moved" : as illustrated by the use of soft wheat varieties which could not withstand the occasional cold and dry winters. Therefore, it was not until the abundant fall and winter moisture of 1896 and subsequently wet years, aided by the provision of much needed varieties of winter-hardy hard-red Russian wheat seeds by railroad companies, -- principally in the form of the Turkey Red variety, which was imported into Kansas from the steppes of southwestern Russia, from the early 1880s onwards -- that the winter wheat culture experienced its growth from its subsistence nature through the transformation to an agribusiness.

Allied to this wet year cycle, aided by the realization of the suitability of hard-red winter wheats in this plains environment, there was a corresponding increase in bushel price from $ 0.48 in 1895 up to $ 0.76 in 1897, causing the elevation of Kay County to be known as "The

Banner Wheat County of the U. S." (Boone, 1968). It is important to realize that if soil moisture is adequate and wheat pasture is required, it is possible for this crop to be sown as early as September or into October in north central Oklahoma. As a result, this symbiotic relationship, where wheat can generally be pastured from November to March if conditions are favorable for its growth, can be set up. Harvesting of the crop is usually accomplished in late May through June, just before the damaging high evapotranspiration rates strike, which are associated with the hot summer temperatures and winds.

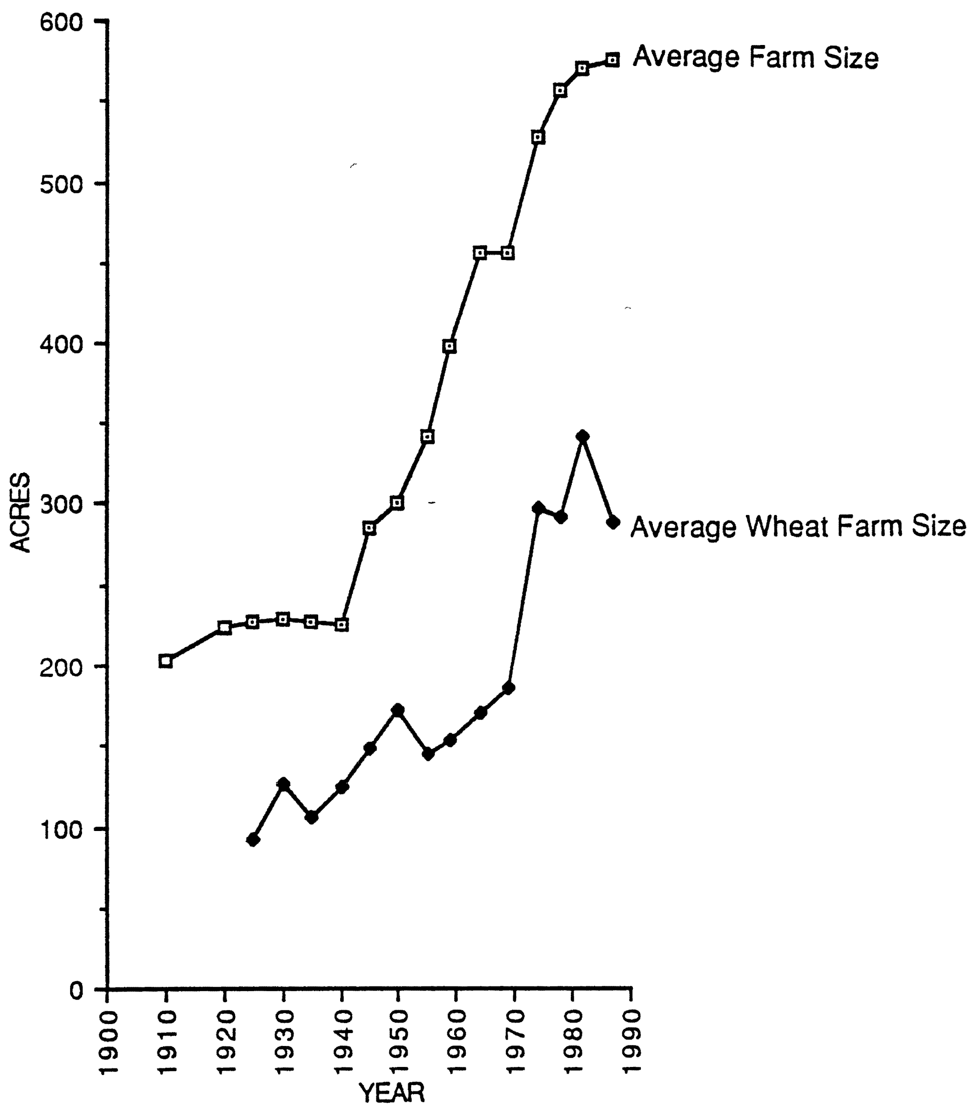
Wheat is an ideal cash crop for many Oklahoma farmers, particularly in the drier north central part of the State. Moreover, it is essential to note that wheat farming is practiced ubiquitously throughout the study area, except in western Woods and eastern parts of Kay County where the rigors of the environment in terms of the clay and limy soil types preclude wheat agriculture.

World War I caused a surge in wheat prices from $ 0.76 in 1913 to $ 1.40 in 1919. However, the War prosperity was shortlived and prices for wheat plunged downward with a highly fluctuating trend in the 1920s, which was paralleled by a decline from 40 percent of the entire study areas' land being under wheat in 1920, to around 29 percent in 1925. These actions significantly impacted a host of far reaching changes throughout the study area, namely the switch to organization and mechanization.

In the early 1920s, wheat farmers banded together to form the Oklahoma Wheat Growers Association -- an affiliate of the National Wheat Growers Association -- which sought an escape from the dilemma of low market prices (Brown, 1939). Simultaneously, the impact of mechanization -- through tractors, trucks and combined harvesters -- was felt throughout the wheat culture farming zone, with changes in disc, plowing and drilling techniques, through to harvesting and eventual transportation of the crop to market.

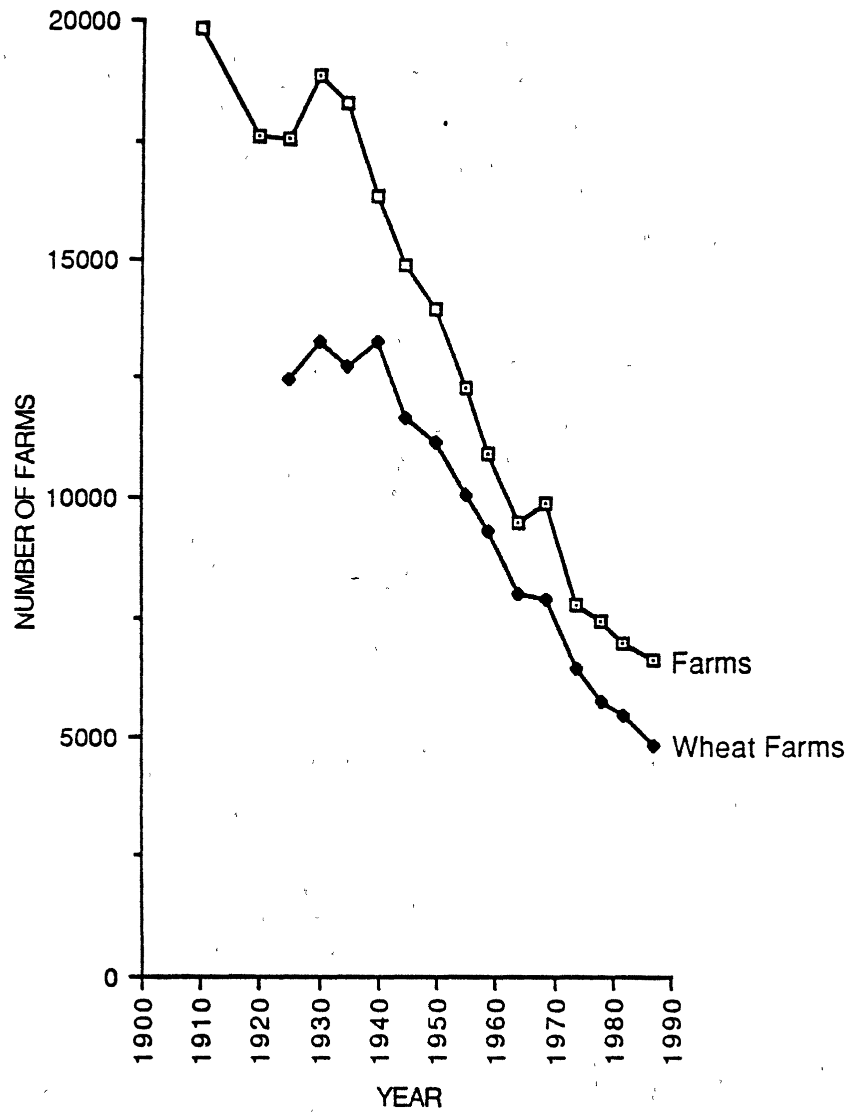
As a result, Green (1971) has noted that "the movement of wheat farmers to power farming was symptomatic of a significant but slow change in the wheat belt - the decline in the number of farmers and the appearance of larger farms." Thus, by the mid 1920s trends had already been established in the wheat belt which would continue to the present : the growth of larger farms, a decline in the number of farms, and more mechanization (Figures 8 and 9). These processes were somewhat accelerated by the drought and economic depression of the 1930s which selectively hurt both the larger and smaller farmers (Carney et al, 1988). In fact, during the the severest drought years of the 'Dust Bowl Era' the study area experienced a loss in wheat acreage of around 20 percent between 1930 and 1935.

By the 1940s, of the 3 major cash crops, namely, corn, cotton and winter wheat, which were dominant in north central Oklahoma farms earlier in the century, only winter wheat retained its importance. This partially occurred as a result of the nutrient-sapping nature of cotton and its economic crash in the 1930s. Furthermore, it became clear to farmers that cotton did not possess enough growth days in the northern part of the state which undermined its viability. The vulnerability of corn's nondrought resistant characteristics were deemed unsuitable in the highly fluctuating and unpredictable Oklahoma environmental regime. As a



Source : Computed by Author from United States Agricultural Census (1910-1987)

Figure 8. Change in Study Area's Farm and Wheat Farm Sizes



Source : Computed by Author from United
States Agricultural Census
(1910-1987)

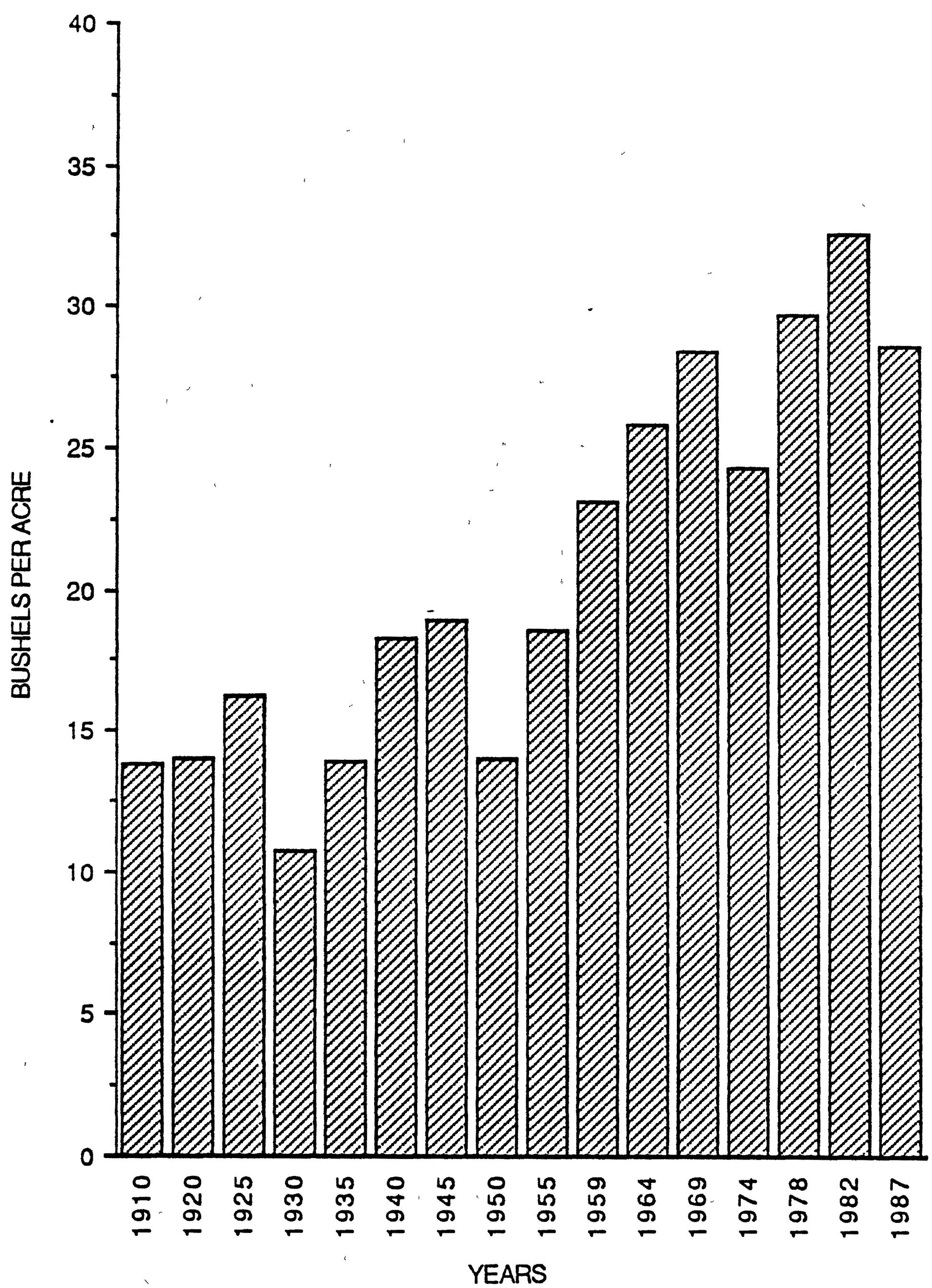
Figure 9. Change in the Number of Farms and Wheat Farms in the Study Area.

result, winter wheat was pushed to the forefront in terms of acreage.

The aforementioned trends continued in the 1940s and were increasingly supported thereafter by a continuing revolution in the development of shorter, sturdier, and earlier maturing winter wheat varieties. One of the principal and most influential new varieties introduced to the study area was Danne's Triumph variety (Green, 1971). Since then, higher world prices, increasing demand, mechanization and the introduction of new and improved wheat strains have dictated the continued growth and flourishing of the wheat culture throughout the study area.

In the 40 year period from the late 1940s to present day, the study area has seen improved varieties of winter wheat which have yielded greater returns through time (Figure 10). Despite the obvious increase in yields over time, aided by mechanization and fertilization, it is essential to realize that one of the main contributing factors in regard to yield is the amount of rainfall received and its timing through the growing season. The much publicized droughts of 1930, 1935, 1959 and 1974 all showed a corresponding decrease in yield returns. However, for the most part, it is noteworthy to realize that the seasonal distribution of precipitation "fits well" with the growing season of winter wheat.

This transformation of winter wheat yields returned from farms in north central Oklahoma, has been coupled with the trend towards larger acreage farm sizes from fewer and fewer farms specializing in winter wheat, particularly since 1940. From the early 1940s onwards, until the present, the acreage under wheat has remained largely unchanged in the study area with around 1.4 to 1.6 million acres of land being under wheat



Source : Computed by Author from United States Agricultural Census (1910-1987)

Figure 10. Winter Wheat Yields in the Study Area

annually. However, by 1987, only 36 percent (at 4837) of the farms growing winter wheat in 1940 remained, and thus the average winter wheat farm size -- given the stabilized acreage under growth -- has correspondingly increased by around 275 percent, from around 124 to 341 acres, over the same period (United States Agricultural Census, 1940-1987). Furthermore, it is important to note that the increase in winter wheat yields from the mid 1950s was associated with increased fertilizer application.

Given the large acreages of winter wheat recorded throughout the study area, annually constituting in excess of 40 percent of the farm land coverage during the 1980s, it could be argued that this area is virtually a monoculture, with little internal crop variation. Areas where winter wheat does not grow within the study area, particularly in the western three-quarters of Woods and the eastern two-fifths of Kay counties, are well documented in regard to their physiographic and geologic situation, and thus should be spectrally different within remotely sensed AVHRR NDVI satellite data. Areas which are non-wheat are largely devoted to grazing and thus possess different spectral curves. Otherwise, the spectral returns over the study area should be dominated by winter wheat growth, especially during the spring 'greening-up' and 'browning-out' phases within north central Oklahoma. Since the study area illustrates an almost ubiquitous winter wheat surface, its spectral signal should take precedence over background 'noise' associated with other heterogeneous land covers. As a result, this area forwards an excellent place to study the effects of moisture differences -- through Palmer drought variables -- on AVHRR NDVI spectral returns over winter wheat agricultural lands.

Demographic Evolution of the Study Area : 1907-1980

In studying the demographic evolution of the study area, it is essential to note that it was only with the establishment of statehood in 1907 that the present day county boundaries were established and have remained constant thereafter, thereby conditioning the temporal focus herein. Table II charts the demographic characteristics of each of the study areas counties, in terms of their total population and percentage of rural population therein, from 1907 up until 1980. It is evident on the whole that Alfalfa, Grant and Kingfisher counties have lost large absolute numbers of population, but have sustained their rural natures throughout -- due in part to the Census classification schemes employed -- whereas Canadian, Garfield, and Kay counties have increased their total populations over the last 70 years, while the associated rural depopulation forces have acted throughout, giving the decreased percentage returns. However, singularly, Woods county has registered declines in both the absolute number of people there, and those classified as rural. Cumulatively, these figures for the study area somewhat parallel the national trend towards a decrease in absolute rural population (Morris, 1977), while the percentage of people classified as rural dwellers was noted to fall from 46 percent in 1910 to 24 percent in 1980. Over roughly the same period, there has been a three-fold increase in the average size of winter wheat farms to over 300 acres in the study area, as more and more land was acquired by fewer landowners.

The loss of people from the rural setting and winter wheat agriculture in particular, can be accounted for by a myriad of factors

TABLE II

STUDY AREA'S TOTAL AND RURAL POPULATIONS, 1907-1980

YEAR	ALFALFA	% RURAL	CANADIAN	% RURAL	GARFIELD	% RURAL
1907	16070	N.A.	20110	N.A.	28300	N.A.
1910	18138	100	23501	67	33050	58
1920	16253	100	22288	65	37500	56
1930	15228	100	28115	67	45588	42
1940	14129	82	27329	63	45484	38
1950	10699	75	25644	57	52820	32
1960	8445	100	24727	42	52975	27
1970	7224	100	32245	19	56343	20
1980	7077	100	56452	24	62800	19

YEAR	GRANT	% RURAL	KAY	% RURAL	KINGFISHER	% RURAL
1907	17638	N.A.	24757	N.A.	18010	N.A
1910	18760	100	26999	79	18825	87
1920	16072	100	34097	62	15671	100
1930	14150	100	50186	36	15960	83
1940	13128	100	47084	39	15617	68
1950	10464	100	48892	32	12860	74
1960	8140	100	51042	27	10635	69
1970	7117	100	48791	22	12857	69
1980	6518	100	49852	23	14187	70

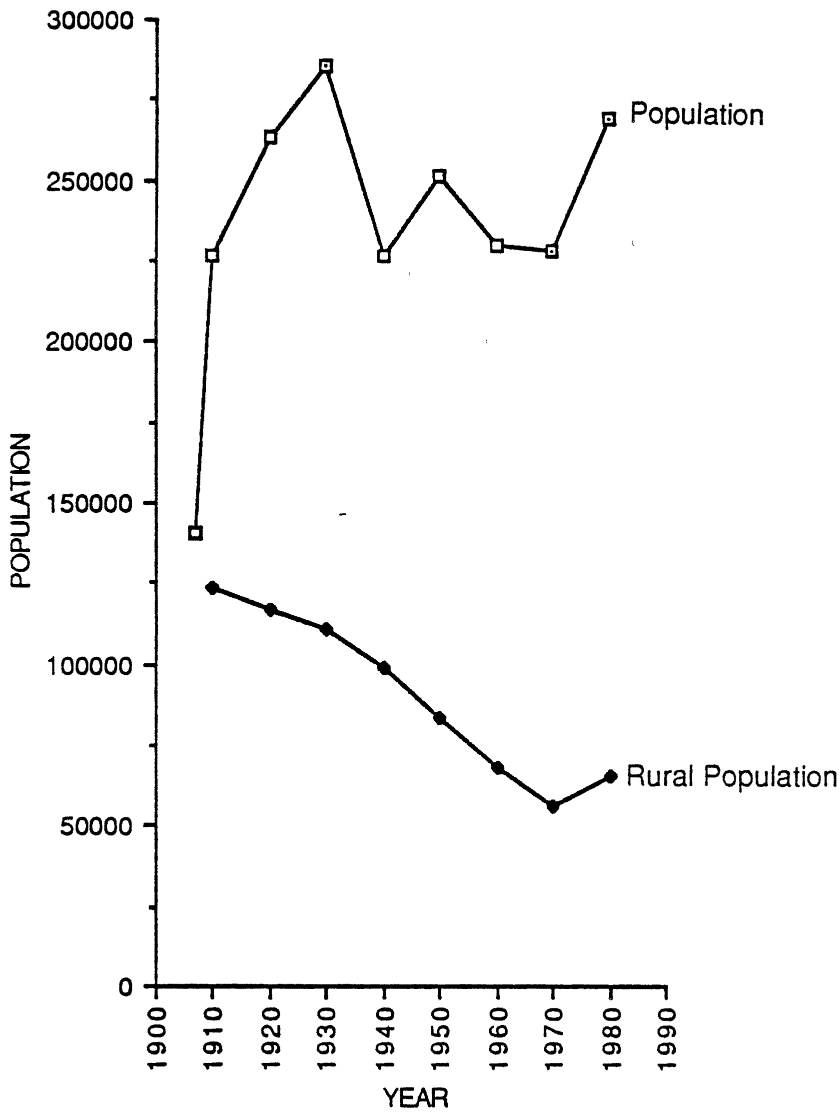
YEAR	WOODS	% RURAL	TOTAL	% RURAL
1907	15517	N.A.	140402	N.A.
1910	17567	79	266607	46
1920	15939.	75	262992	44
1930	17005	71	285341	39
1940	14915	66	266671	37
1950	14526	55	251642	33
1960	11932	48	230414	29
1970	11920	38	228354	25
1980	10923	41	268920	24

Source : Computed by Author from United States Population Census (1907-1980) including the trends towards fewer farms (and thus farmers) -- given that the original allotments were too small to be economically viable -- with larger acreages, the planting of better yield varieties, and the associated development of mechanization in the rural locations from the early 1920s onwards. This trend was exacerbated in the 1930s economic depression which caused an absolute decrease of over 12,000 people from the study area alone, who were classified as rural dwellers.

Despite the obvious, but fluctuating, growth of population in the study area through time (Figure 11), this population gain has been associated with settlements classified as urban. However, it is interesting to note that the rural population, which has been showing a steady decrease from 1910 through 1970, began to pick up thereafter in terms of absolute numbers from 228,354 in 1970 to 268,920 in 1980 (i.e. an increase of over 40,500). This 'anomaly' can be accounted for by the movement of workers "into the field" during Oklahoma's boom oil period during the 1970s (Carney, personal communication). Nevertheless, the number of people in winter wheat agriculture during the 1970s and 1980s within the study area, at best remained steady, or possibly declined, as some farmers diversified their agricultural focus into the 'booming' oil related pursuits, with many ventures ultimately failing with the onset of the 1980s crash, causing farm property loses. Nevertheless, these property losses did not cause any reorientation in the overall landuse or the winter wheat spectral signatures expected over the study area.

Conclusion

In the final analysis, through conditioning factors such as climate,



Source : Computed by Author from United States Agricultural Census (1910-1987)

Figure 11. Population and Rural Population Changes in the Study Area

physiography and geology, soils, vegetation, and the internal and external effects of humans through time in this region, it is evident that the importance of the winter wheat culture has been demonstrated for the study area. The process of continual farm mechanization and the general trend towards the eventual agribusiness nature of the winter wheat concerns of today in this study area are evident from yield increases, farm size changes, and acreages under cultivation. As a result, all of these variables have significantly impacted upon the demographic characteristics recorded through time and space within this study area, which is located at the heart of the winter wheat plains environment of the Great Plains. In addition, given that winter wheat accounts for a large proportion of the agriculturally oriented land within the study area, then this location forwards an excellent large scale region to examine the conditioning relationships between the various Palmer drought indices and the simultaneously acquired spectral vegetation signatures.

CHAPTER III

METHODOLOGY

Introduction

Remote sensing, which is the observation of a target by a device separated from it by some distance, is primarily a technique used in physical geography and the other physical sciences for the location, classification and estimation of the features of the environment. (Richason, 1983) Despite the increasing environmental focus within the remote sensing literature utilizing spectral data acquired from a multitude of space-based satellite systems, little integration with ground aggregated Palmer climatological indices has been investigated. Nevertheless, the coarse resolution of Normalized Difference Vegetation Index products acquired on board NOAA's AVHRR, compared to the other finer resolution satellite based systems, forwards a useful medium for analyzing vegetation growth and monitoring crop development through the growing season in areas of largely homogeneous plant/crop associations, which might be related to Palmer indices calculated through time and space.

Study Period

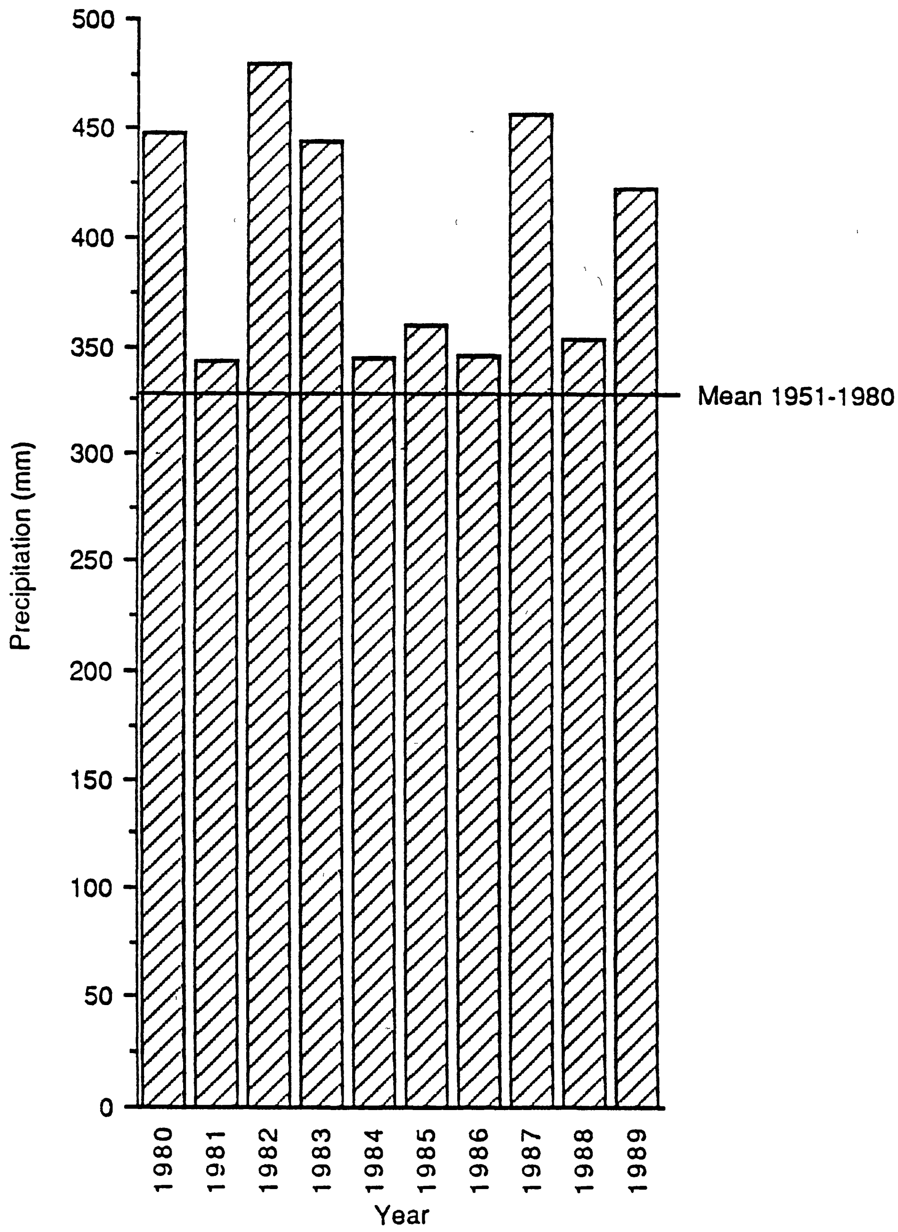
The temporal research focus herein was principally determined by the availability of weekly NOAA AVHRR NDVI satellite imagery, which became an operational product from April, 12, 1982 onwards. Since

Oklahoma's winter wheat crop remains, for the most part, dormant annually from December to February, it was decided that this study should include only the 'greening-up' and 'browning- out phases. The start of the 'greening-up' period usually coincides with the beginning of March (Week 9 of the year). The 'browning-out' is normally finished before the end of June (Week 26). Throughout this time period when winter wheat undergoes post-dormancy growth to senescence until harvest time, the crop spectrally changes (Cuperus and Johnston, n.d.). Another critical consideration in this temporal analysis was that Palmer's calculated indices stipulate that for their appropriate use that vegetation/crops must be actively growing (Palmer, 1965). Therefore, the March through June time focus was herein chosen for the study years under investigation.

Having established the above criteria, a systematic analysis of daily meteorological variables, namely, precipitation and temperature -- on which Palmer indices are based -- for the 11 weather stations recording both these required measures within the study area, were aggregated and averaged for monthly, and four-monthly periods (March through June), from 1980 onwards.

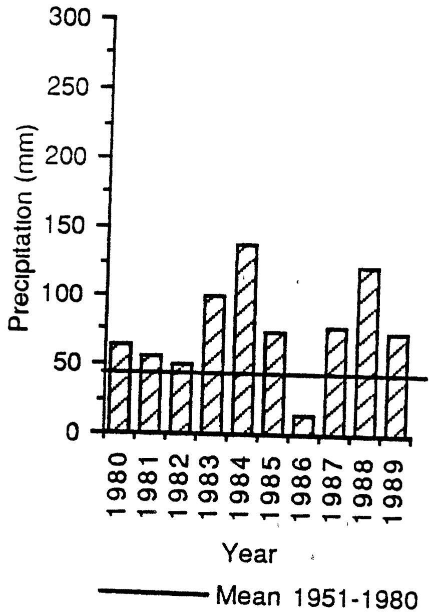
Comparing four-monthly aggregates of rainfall to the long term record (1951-1980) at 328 mm, it was noteworthy that throughout the 1980s each of these four-monthly time periods recorded values above this averaged value (Figure 12). Principally from this graph, and the accompanying monthly precipitation and temperature graphs, (Figures 13 through 20) it was decided to focus upon the study years of 1982, 1985 and 1989.

The four-monthly period from March to June, 1982, was distinguished



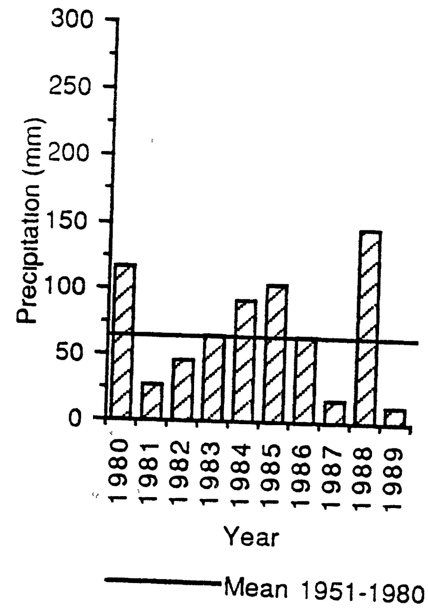
Source : Oklahoma Climatological Survey

Figure 12. Cumulative Yearly Precipitation (March-June)



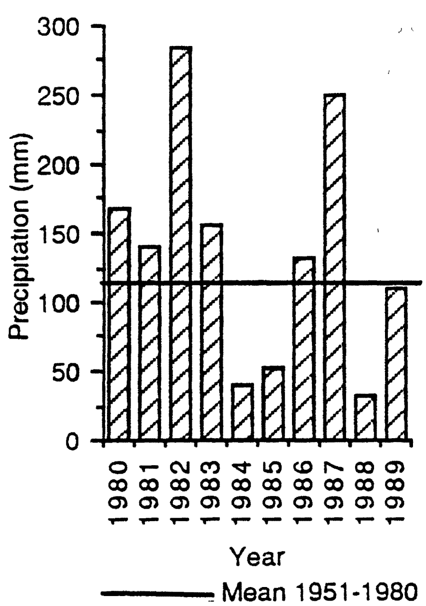
Source : Oklahoma Climatological Survey

Figure 13. March Precipitation



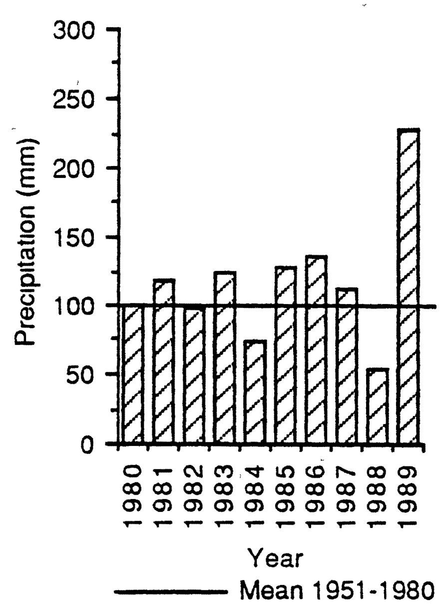
Source : Oklahoma Climatological Survey

Figure 14. April Precipitation



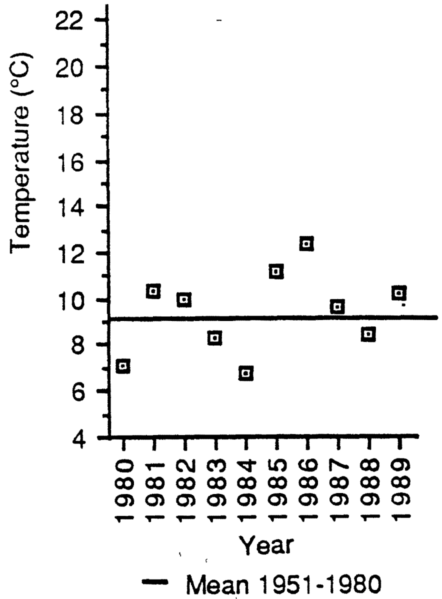
Source : Oklahoma Climatological Survey

Figure 15. May Precipitation



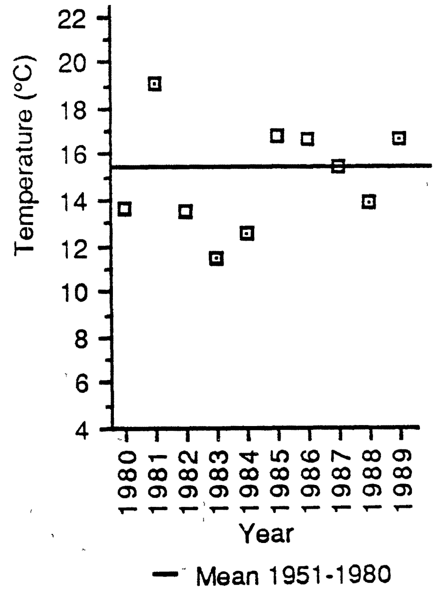
Source : Oklahoma Climatological Survey

Figure 16. June Precipitation



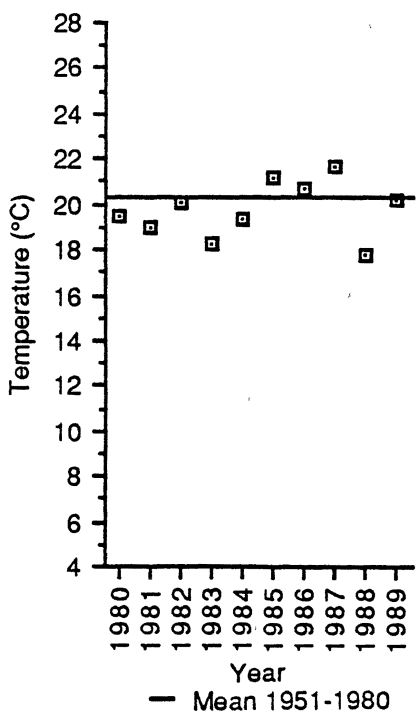
Source : Oklahoma Climatological Survey

Figure 17. March Temperature



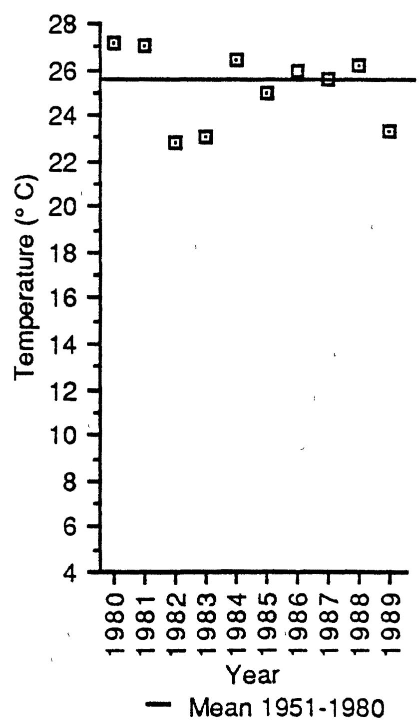
Source : Oklahoma Climatological Survey

Figure 18. April Temperature



Source : Oklahoma Climatological Survey

Figure 19. May Temperature



Source : Oklahoma Climatological Survey

Figure 20. June Temperature

in that it recorded 480 mm of rainfall outstripping all the other illustrated years' cumulative precipitation amounts. Undoubtedly, the elevation of 1982 to the status to the wettest 'year' was conditioned by the high average rainfall in May that year throughout the study region at 285 mm, which was associated with the passage of three exceptionally strong cold fronts through Oklahoma during Weeks 18, 20 and 21 respectively (Daily Weather Maps, 1982). In addition, all months, with the exception of March, recorded average temperatures below the 1951-1980 long term monthly averages.

The four-monthly period from March to June, 1985, was shown to be just above the average precipitation conditions and was taken to represent the cumulative 'near-normal' conditions. Importantly, the actual analysis of the daily synoptic situation allied to average monthly aggregated conditions showed that March (359 mm), April (103 mm) and June (128 mm) recorded rainfall amounts at least 28 mm above their usual monthly normals, while May experienced much drier conditions with less than one half of its usual amount of rainfall at 53 mm. March's wet spell was determined by stationary fronts over the study area during Weeks 12 and 13 (Daily Weather Maps, 1985). April's above normal rainfall here was a result of a cold front (Week 15) and two stationary fronts (Weeks 16 and 17), while June had early (Week 23) and late (Week 26) rain events associated with a stationary and cold front, respectively (Daily Weather Maps, 1985). The March through May study period recorded mean monthly temperatures at least 1 °C above the long term mean, with only the month of June, at 25 °C, recording an average temperature below the long term 'normal' of 25.6 °C.

At first impressions, it appeared that the aggregated rainfall, and the individual monthly temperature, data for this March through June period, 1989, illustrated the occurrence of fairly wet, and somewhat cool, conditions throughout the entire study area. Nevertheless, the principle reason for choosing this study 'year' lay in the fact that April received only 12 mm of rainfall, which was a shortfall of over 51 mm from the long term average, allied to an average temperature of 16.6 °C, that is 1 °C above the long term mean. In fact, this period proved to be the driest April in Oklahoma since meteorological records began, and the crop was undergoing the critical jointing phase (Figure 2) ,which when coupled with previously recorded fall and early spring drought conditions exacerbated the already serious winter wheat growth situation (Webster, 1989). This dry weather was caused by the stabilizing influence of anticyclonic conditions over the Gulf of Mexico and the south-western region in general. The month of April, 1989, recorded the most serious spring dryness since the AVHRR NDVI record began. The other months of the study period remained at, or slightly above, the normal expected rainfall totals, with the principle exception being during the month of June which remarkably received 227 mm of precipitation which is 127 mm above the long term rainfall average, associated with a significant decline of 2.4 °C below the long term June temperature average of 25.7 °C. The general synoptic situation over Oklahoma at this time showed a warm front (late in Week 22), two rapid cold front passages (in Week 24) and a stationary frontal situation (Week 25/26) cumulatively delivering the bulk of this unseasonably high rainfall, thus suppressing the mean monthly temperature (Daily Weather Maps, 1989).

Data Acquisition

Palmer Indices

Following the identification of the study area and years for investigation under the aforementioned criteria, the required weekly calculated Palmer indices, namely, the PDSI, CMI, and Z-Index, were calculated for the present author by Oklahoma Climatological Survey, for each of the 11 cooperative observation stations within the study area for Weeks 9 through 26 of the year, for 1982, 1985, and 1989.

Normalized Difference Vegetation Index

The standard archived data sets of NOAA AVHRR NDVI spectral returns over both the northern and southern hemispheres, comprehensively mapped to a polar-stereographic projection with a nominal 13 km resolution (Chapter I) and stored on the Computer Compatible Tape (CCT) form, were purchased from the National Climate Data Center, Satellite Services Division, Washington D. C., for weeks 15 through 26, 1982, Weeks 9 through 26, 1985 (no data were recorded during Week 13), and 1989.

Data Processing

Palmer Indices

The Palmer weather station point variables were interpolated into cell measures through the use of the Theissen polygon approach (Oliver, 1973). Construction of these representational polygons was based on a nearest-neighbor analysis for 41 mapped weather stations located in -- 11 stations -- and around the study area -- 9 stations being in southern Kansas -- which was accomplished by employing a Symap graphing routine

(Dougenik and Sheehan, 1975). Following this, it was concluded that the 11 climate reporting stations within the study area could be used to areally represent a large proportion of the study region (Figure 21), thereby avoiding the use of meteorological variables recorded at stations outside the study area to represent areas therein.

After digitizing these 11 polygons through the Atlas Graphics Package (1987) boundary file manipulation, these coordinates were thereafter transferred to a Mapmaker (1988) program. Using an Excel (1988) program, spread sheets of the Palmer variables were created for each of the 11 polygon areasand imported into the Mapmaker boundary file, so that weekly based choropleth maps of the data could be visually inspected and temporally analyzed.

Normalized Difference Vegetation Index

A computer compatible tape (CCT) of AVHRR data supplied the digital data for the scene analyses performed at the Center for Applications of Remote Sensing (CARS), Oklahoma State University. The uncalibrated digital pixel data were processed on a Perkin-Elmer 8/32 computer utilizing the Earth Resources Laboratory Applications Software (ELAS), interfaced with a Comtal image display device for visual analysis, and a Versatec electrostatic plotter.

To fit the 1600 bpi format of the CARS Perkin-Elmer 8/32 system, it was necessary to convert this tape from the 6250 bpi base which was carried out at the University Computing Center, Oklahoma State University. Subsequently, each file of uncalibrated spectral pixel data, arranged on a weekly basis, was visually checked (46 files) on the Comtal

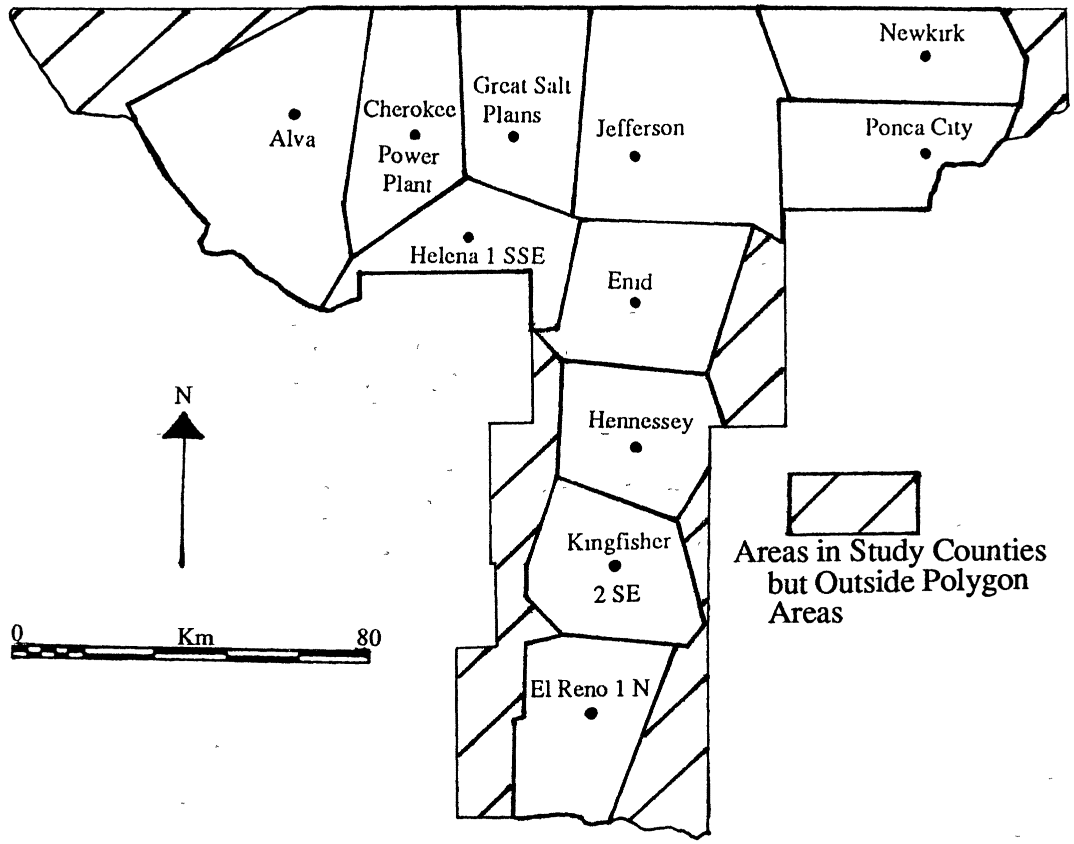


Figure 21. Cooperative Observation Stations and Polygon Areas

visual display device at CARS, to ensure that reformatting had not introduced any distortions or inaccuracies into the global mpolar-stereographic projections.

Given the coarse resolution of this globally mapped pixel data, with a cell size of approximately 13 km in the central region of the United States (NOAA/NESDIS, 1986), it was first necessary to focus upon the North American Continent to begin georeferencing the study area. At this scale, only features such as the Great Lakes and the panhandle of Florida were visibly distinct. However, by knowing the latitude and longitude coordinates of the 'corner' points from the Mapmaker digitized 'T-shaped' study area, enabled a SAS (Statistical Analysis System) program to be written -- following a NOAA directive (personal communication) -- to forward the appropriate georeferenced element and line number of the 'corner' pixels located within the mapped arrays.

At this juncture, it is essential to realize that despite the NOAA AVHRR satellite systems' inherent off-nadir pixel distortions which vary with latitudinal differences (Holben and Fraser, 1984), it is considered that with this study area having a latitudinal variation of less than 2°, that pixel distortions therein are minimal and therefore can be overlooked (Stadler, personal communication).

Following the successful georeferencing of these 'corner' points within each of the 46 mapped files, a matrix of pixels with their associated element and line numbers, inclusive of the entire study area and the surrounding environs, were printed for each of these weekly files on the Versatec electrostatic plotter.

A graphic matrix of pixels -- with their corresponding element and line numbers -- were then overlaid on a mapped image of the study area including the representative Theissen polygons, with the aforementioned georeferenced 'corners' acting as anchor points for the pixels located within the entire study area (Figure 22). A visual systematic search was then undertaken to to record the element and line number of each of those pixels, where at least 50 percent of their area was considered to be contained within any of the 11 outlined polygons. As a result, 44 pixels were adjudged as being within the polygons of the entire study area, with a minimum of 3 and a maximum of 7 pixels per area identified (Table III). Having identified these pixels, SAS files of this recorded uncalibrated spectral information from the required pixel arrays output via the Versatec electrostatic plotter, were then manually created for each of the polygon areas on a weekly basis.

Since each of the 46 created SAS files contained unscaled polygon georeferenced pixel information, another SAS program following a scaling NDVI equation (NOAA/NESDIS, 1986) was written to calculate the scaled NDVI values on a weekly basis, for each of the 44 pixels used. Following the successful completion of this task, all the derived georeferenced NDVI values were then averaged by polygon, so that a single number was able to represent the entire polygon area per week and which could then be compared to the various corresponding Palmer values therein. Furthermore, weekly average values for the aggregated data over the 44 pixels included within the 11 polygons were also calculated.

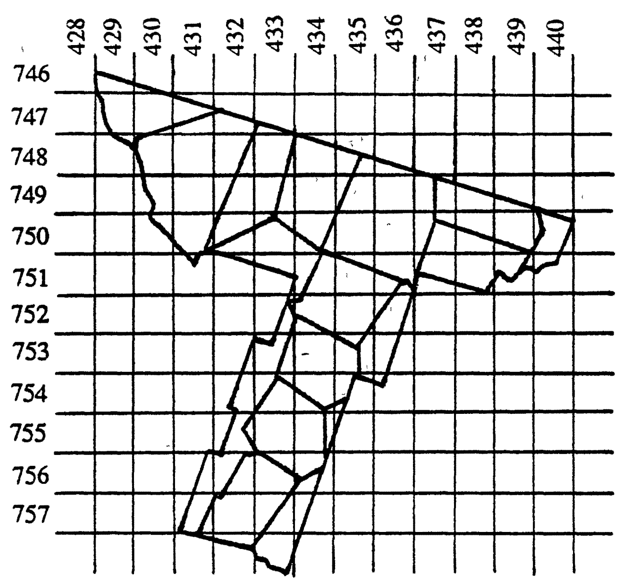


Figure 22. Georeferenced AVHRR NDVI Pixel Matrix Over Study Area

TABLE III

GEOREFERENCED PIXEL DATA

POLYGON NAME	NUMBER OF PIXELS PER POLYGON	ELEMENT AND ROW NUMBERS						
ALVA	7	430,749	430,748	431,748	431,749	431,750	432,747	432,748
CHEROKEE POWER PLANT	3	433,748	432,750	433,749				
EL RENO 1N	4	433,756	433,757	432,757	432,756			
ENID	3	435,751	435,752	434,752				
GREAT SALT PLAINS	3	434,748	434,749	434,750				
HELENA 1 SEE	3	433,750	433,751	434,751				
HENNESSEY	4	433,753	434,753	435,753	434,754			
JEFFERSON	5	435,749	436,749	436,750	435,750	436,751		
KINGFISHER 2 SE	4	433,754	433,755	434,755	434,756			
NEWKIRK	4	437,749	438,749	439,750	438,750			
PONCA CITY	4	437,750	437,751	438,751	439,751			
TOTAL NUMBER OF PIXELS	44							

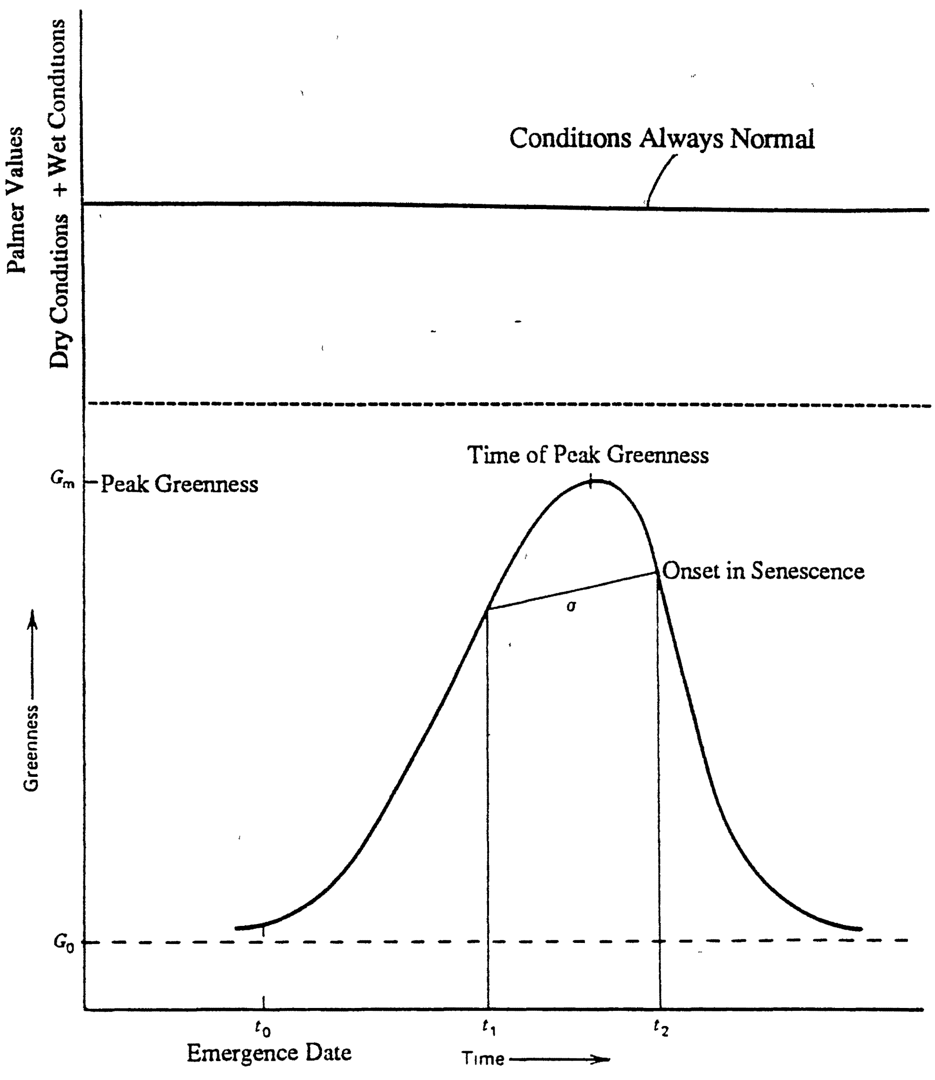
Statistical Manipulations

Background Information

In order to statistically test the previously unexplained relationship between weekly calculated PDSI, CMI, and Z-Index measures and the derived averaged NDVI values for each of the 11 polygon areas under investigation, it was necessary to investigate, and understand, the idealized behavior of the Palmer variables and this spectral data over the 'greening-up' and 'browning-out' phases under 'normal' conditions. The characteristic patterns for each of the investigated variables ultimately determined the appropriate choice of a meaningful statistical procedure herein.

Since all of the Palmer indices record deviations from the long term conditions at each of the climate reporting stations, then under 'normal' conditions throughout the temporal duration of the study period -- Week 15 through Week 26, 1982, Week 9 to Week 26, 1985 and 1989 -- these calculated indices would record a value of zero, following Palmer's (1965) scheme. Evidently, under these 'idealized' conditions, if these zero deviations were plotted through time, the distribution would be categorized by a horizontal line (Figure 23).

On the other hand, under an idealized growth pattern for winter wheat as it progresses through the 'greening-up' and 'browning-out' phases until eventual harvest, it has been previously shown that the time behavior of the 'greenness' curve -- which NDVI essentially measures -- for this crop is sigmoidal (Bauer, 1985) (Figure 23). The sigmoidal nature of spectral returns was evident within the derived NDVI curves for the



Source : Part adapted from Bauer, 1985

Figure 23. Idealized Temporal Profiles for Palmer Values and Greenness

three growing seasons under study (Chapters IV and V).

As a result, under a 'normal' growing season, the Palmer variables and the NDVI would show categorically different plots (Figure 23). Given the form of this data it would be inappropriate to relate thase variables through a simple linear regression technique. In order to attempt to statistically test the underlying relationships between the various Palmer indices and how they condition the NDVI spectral returns over winter wheat in north central Oklahoma, and thereby identify the most suitable Palmer variable to be utilized in conjunction with this 'greenness' data, transformations of the original data sets were necessary.

Palmer Indices

With all three Palmer indices recording both weekly negative, and positive, deviations from 'normal' during the times under investigation, it was decided to transform this data so that all represented values would be positive -- like NDVI values -- throughout this part of the growing season. A search through the Palmer data found the lowest weekly negative PDSI, CMI and Z-Index values for each of the polygons per study year. When the lowest negative values therein were located, all these points were set to a value of zero, thereby transforming all the remaining Palmer variables into the positive oriented range, through adding this appropriate amount to all the other recorded values. Thereafter, these entirely positive Palmer indices were cumulatively added by week for each of the Theissen polygons for each of the study years under a Statview and Graphics (1987) transformation routine, thus reducing the Palmer values to approximate linear functions.

Normalized Difference Vegetation Index

Following the methodology employed by Gallo and Heddinghaus (1989), the NDVI 'greenness' data were accumulated for each of the Theissen polygons on a weekly basis, and for the entire study area therein, over the weeks under consideration, to overcome the sigmoidal nature of spectral returns through this part of the growing season, thus reducing these curves to approximate linear functions. These accumulations, carried out by importing Excel files containing the NDVI values into the Statview and Graphics package, considered Weeks 9 (or Week 15 in the case of 1982) until Weeks 22, 23 or 24 for each of the study periods, when the winter wheat was observed to have spectral senescence, as illustrated by the lowest NDVI values as vegetation completes its' 'browning-out' before harvest. This scheme eliminated the spectrally significant 're-greenning' of the landscape afterwards, but before harvest, which are not associated with winter wheat growth, but are determined by the growth of weeds and Bermuda grasses within early harvested winter wheat fields, and other crops growing within the study area (Stone, personal communication).

Conclusion

The linearized transformed Palmer and NDVI data, as defined in this chapter, were now in a form suitable for comparison through a simple linear regression technique. The analysis of these statistical tests are discussed in the following chapters.

CHAPTER IV

YEARLY ANALYSIS

Introduction

In order to determine if the PDSI, CMI or Z-Index is the most associated with the NDVI spectral returns over winter wheat in north central Oklahoma during the critical 'greening-up' and 'browning-out' phases of the crop, for each of the 11 polygon areas under investigation, the following systematic approach was undertaken for the 1982, 1985 and 1989 crop growing periods.

First, the general synoptic situation effecting the study area will be outlined, since it principally determines the value and tendency of each of the weekly calculated Palmer indices, while simultaneously effecting the growth and development of the winter wheat crop. Following this, the spatial and temporal pattern of the values associated with each of these weekly indices will be considered with reference to drought and/or rainfall episodes within the study area. Next, the characteristics of the simultaneously acquired winter wheat NDVI sigmoidal curves will be highlighted. Finally, the statistical analyses -- in terms of the coefficients of determination (r^2) expressed as percentages, where Palmer indices were considered independent variables and the NDVI input as the dependent variable in this model -- will be forwarded and explained on a polygon basis per study year, and for the averaged values for all the variables per annum for the entire study area therein.

1982

Synoptic Situation

On the whole, Oklahoma's 1981-82 winter wheat growing season was one of the wettest in this century and thus chosen as the 'wet' year within the satellite record. The only moisture stress of consequence was experienced in April (Week 14 through 16) during the stem elongation phase of growth, and was due to anticyclonic conditions over the study area (Johnston et al., 1982). However, rains received in early May, during Weeks 18 and 19, effectively eliminated any drought effects, with a cold front and a cyclonic passage affecting this area. In fact during May, around 285 mm of precipitation was recorded as a succession of three frontal passages over Weeks 20 and 21. Allied to the earlier precipitation events of Weeks 18 and 19, this amounted to record rainfall over the study area. Winter wheat growth benefited from these showers but dry weather was desperately needed to ripen wheat and allow harvest to begin (Oklahoma Crop-Weather Summary, 1983). The compounding effects of these rains which continued into June (Weeks 22 and 24) with cold front passages, caused a delayed and difficult harvest which was ultimately a bumper harvest averaging around 34 bushels per acre for the study area. At this point it is important to note that by convention in the U. S., the English bushel will be employed herein when considering yields of winter wheat, rather than metric liters.

Palmer Indices - Spatial and Temporal Comparison

Although NDVI was not available before Week 15, 1982, some notion of the spatial and temporal variations within and between the various Palmer indices from Week 9 onwards is required within this analysis, since they ultimately effect the winter wheat growth situation as recorded by NDVI 'greenness' values, obtainable later within the 1982 growth season. Comparing the averaged PDSI, CMI and Z-Index variables for the entire study area from Week 9 through Week 24 (Figure 24), it is evident that they react at different rates to the determining synoptic situation, with the most sensitive CMI, increasing/decreasing at the the greatest rate under wet/dry events, while the Z-Index reacts quicker in turn when compared to the most lethargic of Palmer's indices, namely the PDSI, under the same event. Furthermore, the precipitation effectiveness decreases as temperatures increase and the same amount of water may mean drought conditions later in the growing season.

Palmer Drought Severity Index. From Week 9 until Week 18, 1982, the majority of the study area recorded a near normal PDSI classification (Figure 25), with occasional incipient wet spells, particularly during Week 11, being noted in the north central area consisting of the Cherokee Power Plant, Great Salt Plains, Helena 1 SSE and Jefferson polygons, and in the southernmost part of the study area around El Reno 1 N (Figure 26), as a result of the cyclonic precipitation events during Week 11. Furthermore, it is noteworthy that while both Week 15 and 16 recorded near normal conditions, the PDSI illustrated negative values -- thus deficit (i.e. drought) values from the long term average conditions -- for all of the study area, with the exception of the El Reno and Helena 1 SSE polygons which returned positive, near normal conditions.

The remainder of the study period from Week 19 onwards, until Week

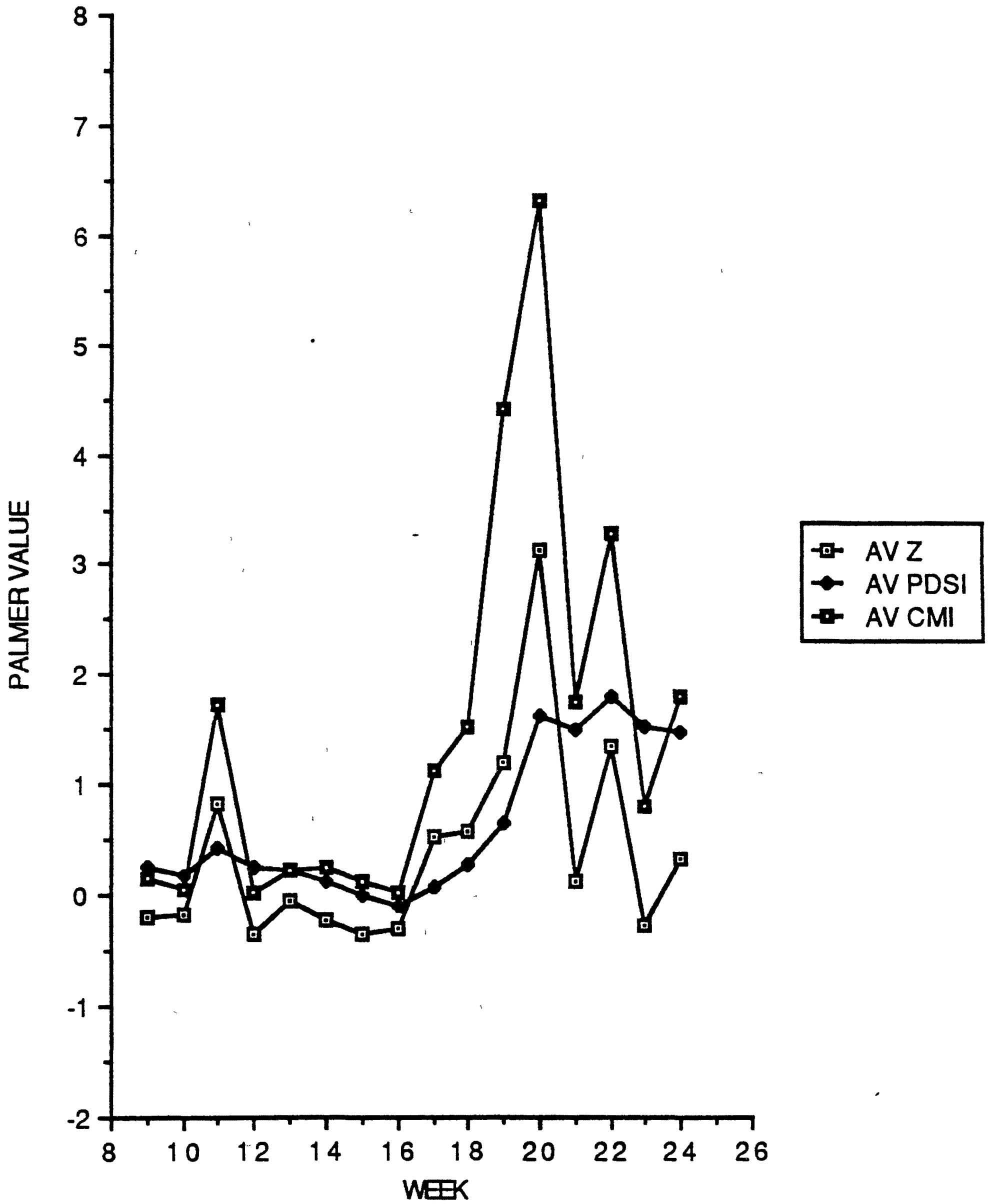


Figure 24. Comparison of Weekly Average PDSI, CMI and Z-Index Values, 1982

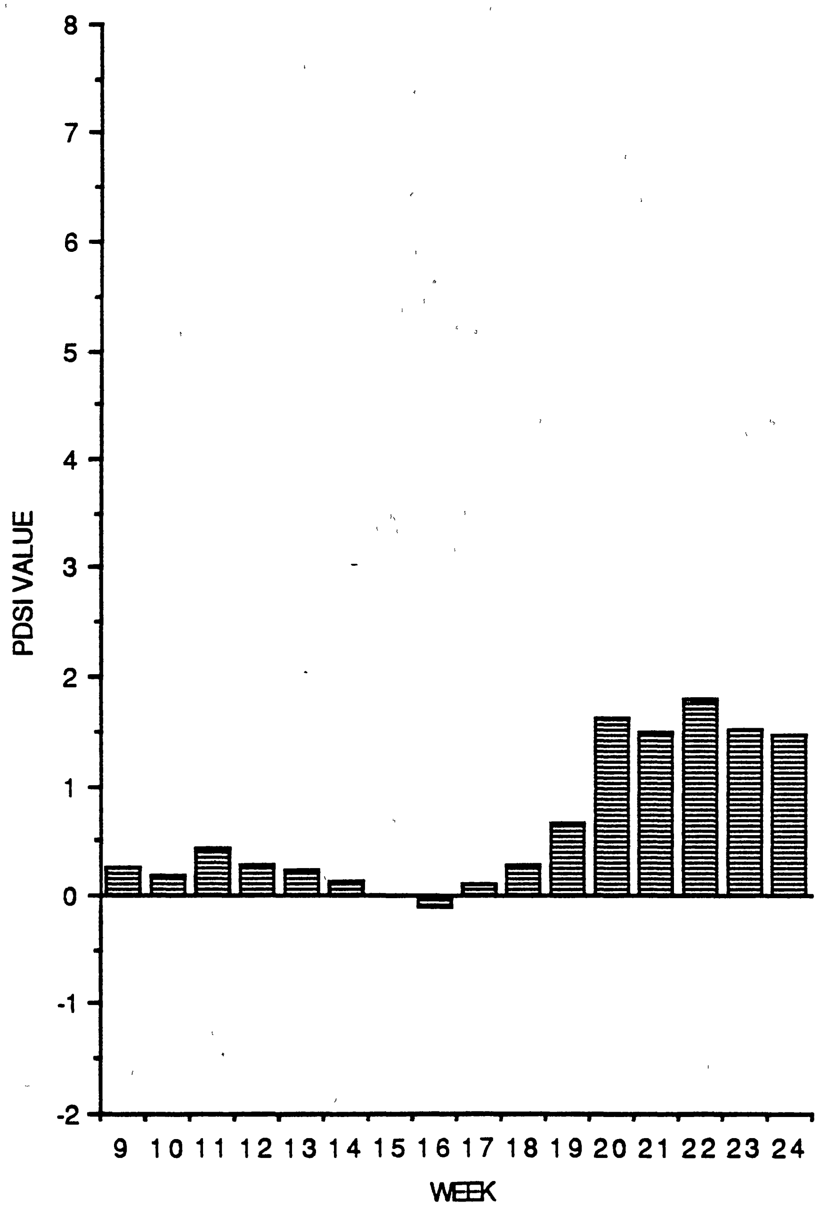


Figure 25. Weekly Average PDSI, 1982

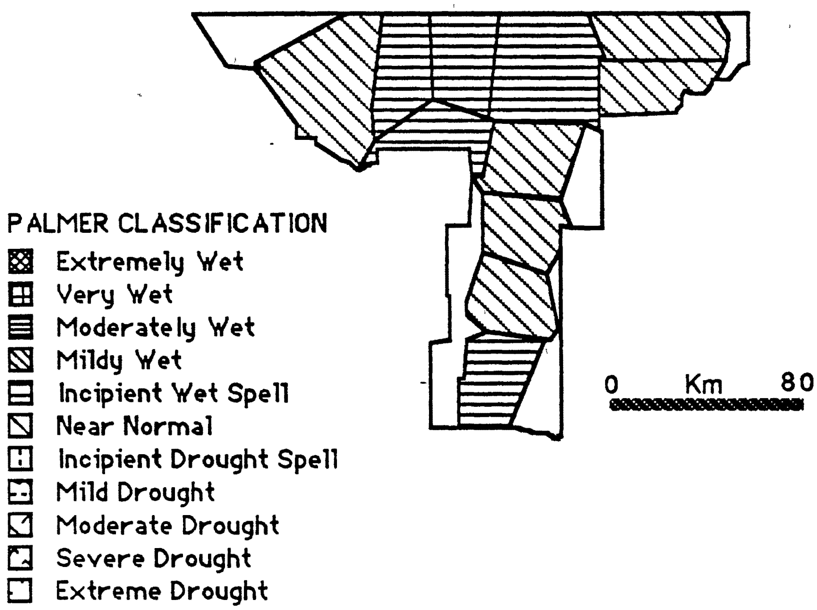


Figure 26. PDSI Week 11, 1982

24, was characterized by the averaged PDSI value exhibiting incipient wet spells (Week 19) and a mildly wet conditions thereafter. This can be explained by the previously outlined May and early June cyclonic synoptic situation. From Week 20 through until Week 24, the Great Salt Plains and Helena 1 SSE areas remained the wettest places throughout the entire study area for this five-week period from mid May until mid June recording constant, moderately wet, Palmer classifications.

Crop Moisture Index. The average CMI value for the study area underwent rapid fluctuations as determined by wet and relatively 'drier' phases recorded from Weeks 9 through 24, 1982 (Figure 27). With the exception of Kingfisher (Weeks 12 and 14) and the majority of the polygon areas exhibiting negative (i.e. drought), near normal classifications during Week 16, the entire study period illustrated much wetter conditions, principally from Week 19 onwards. On the whole, the CMI showed rapid increases during Weeks 11, 17, 19, 20, 22 and 24, corresponding to frontal or associated cyclonic precipitation events, delivery the bulk of the recorded rainfall amount at 480 mm over this approximately four months study period.

Over the first two weeks (Weeks 9 and 10), the entire study area recorded near normal conditions with only traces of precipitation received. With three days rains events during Week 11, the CMI increased in the Helena 1 SSE, Jefferson and Newkirk areas which now exhibited moderately wet readings. Simultaneously, with the exception of the Alva and El Reno polygons showing incipient wet spells, all the remaining areas recorded mildly wet Palmer conditions (Figure 28). Afterwards, the CMI quickly returned to near normal conditions up until the 'droughty' events of

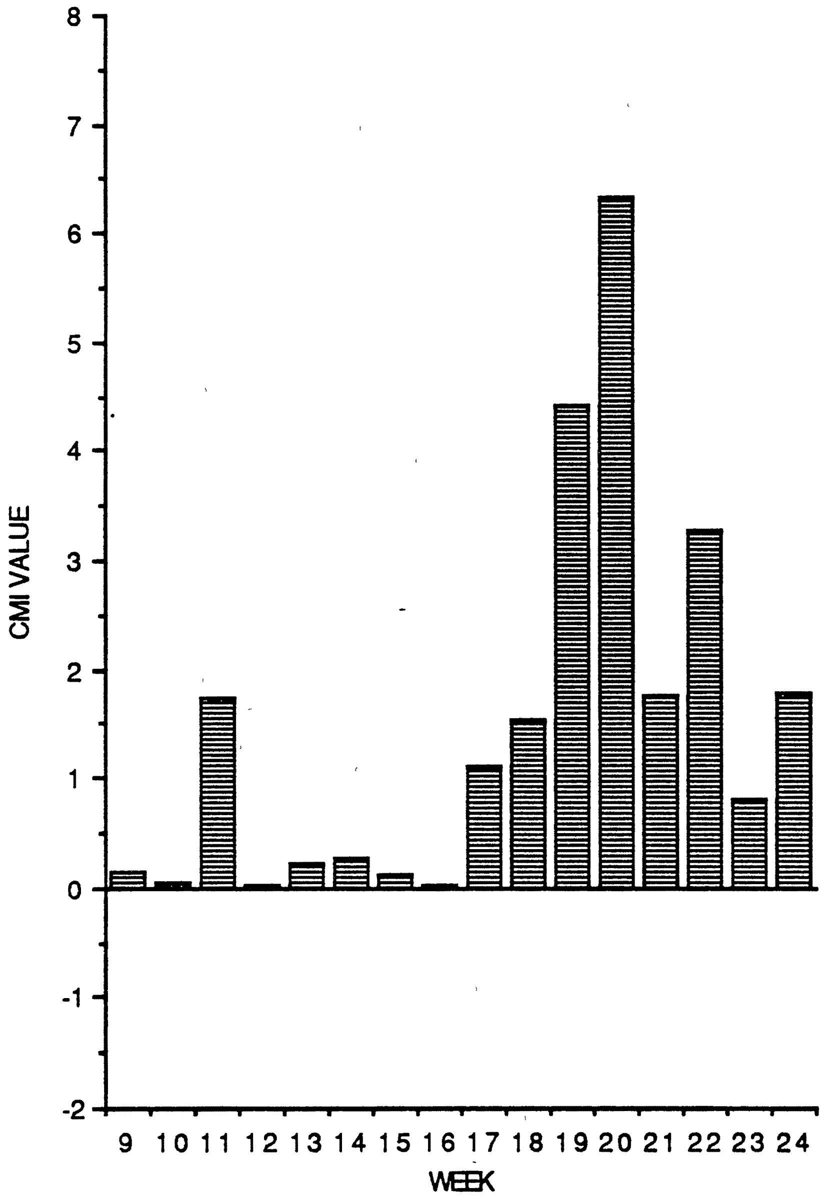


Figure 27. Weekly Average CMI, 1982

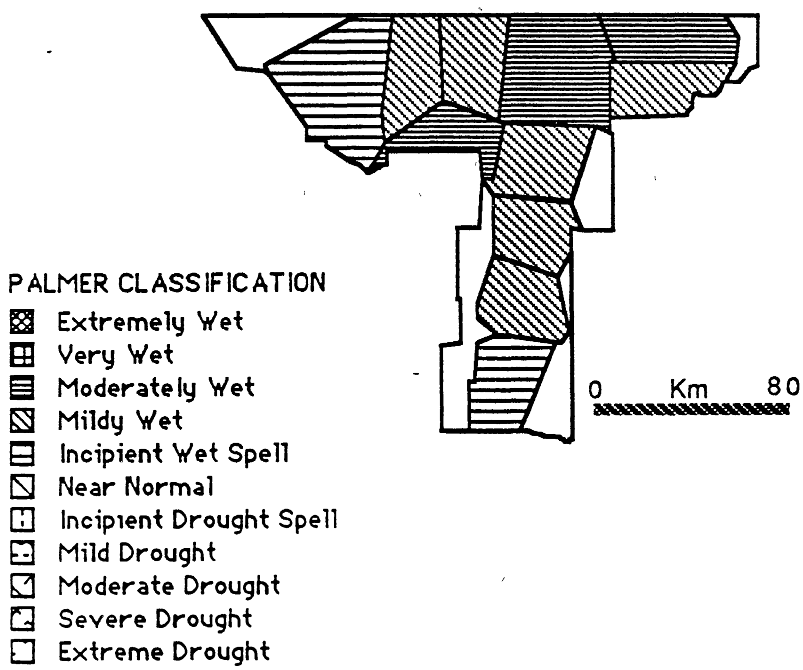


Figure 28. CMI Week 11, 1982

Week 16, as outlined above. These conditions were superseded by average mildly wet conditions for Weeks 17 and 18, and extremely wet conditions for most of the polygon areas during Week 19 and 20, in response to the high May precipitation.

Although it was a little drier over Weeks 21 through 23, the entire study area remained under extremely wet, very wet, moderately wet and mildly wet classifications. Finally, Week 24 showed the northern tier of the study area encompassing the Alva, Cherokee Power Plant, Great Salt Plains and Jefferson areas recording moderately wet conditions, while the remaining areas returned mildly wet and incipient wet spells during this week (Figure 29).

Z-Index. For the most part, the average Z-Index values largely paralleled the recorded fluctuations exhibited by the average CMI from Weeks 9 through 24, although the former did not undergo the extreme range and as abrupt changes which the CMI values experienced (Figure 30).

During Weeks 9 and 10, each of the 11 polygon areas recorded near normal, although negative (i.e. drought), conditions. The passage of a cold front in Week 11 resulted in the Z-Index climbing to mildly wet categorizations throughout the Great Salt Plains, Helena 1 SSE and the Kingfisher areas, while the remaining polygons recorded incipient wet spells (Figure 31). Over the next five weeks, namely Weeks 12 through 16, the Z-Index returned to near normal conditions. However, it is important to note that this phase, from late March until late April coincided with a period when little precipitation was received, ultimately causing small negative values to be recorded throughout the study area over this time period. Furthermore, the Alva area exhibited an incipient drought spell

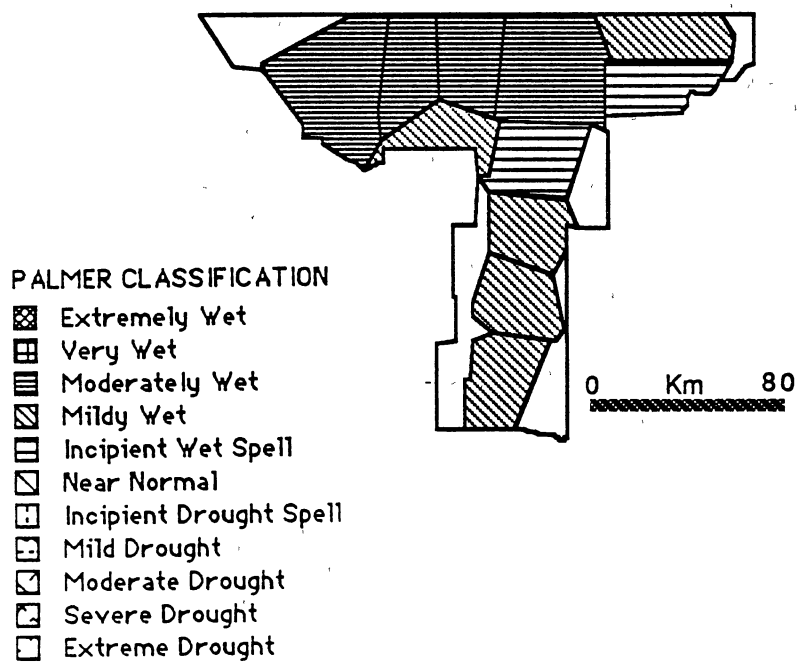


Figure 29. CMI Week 24, 1982

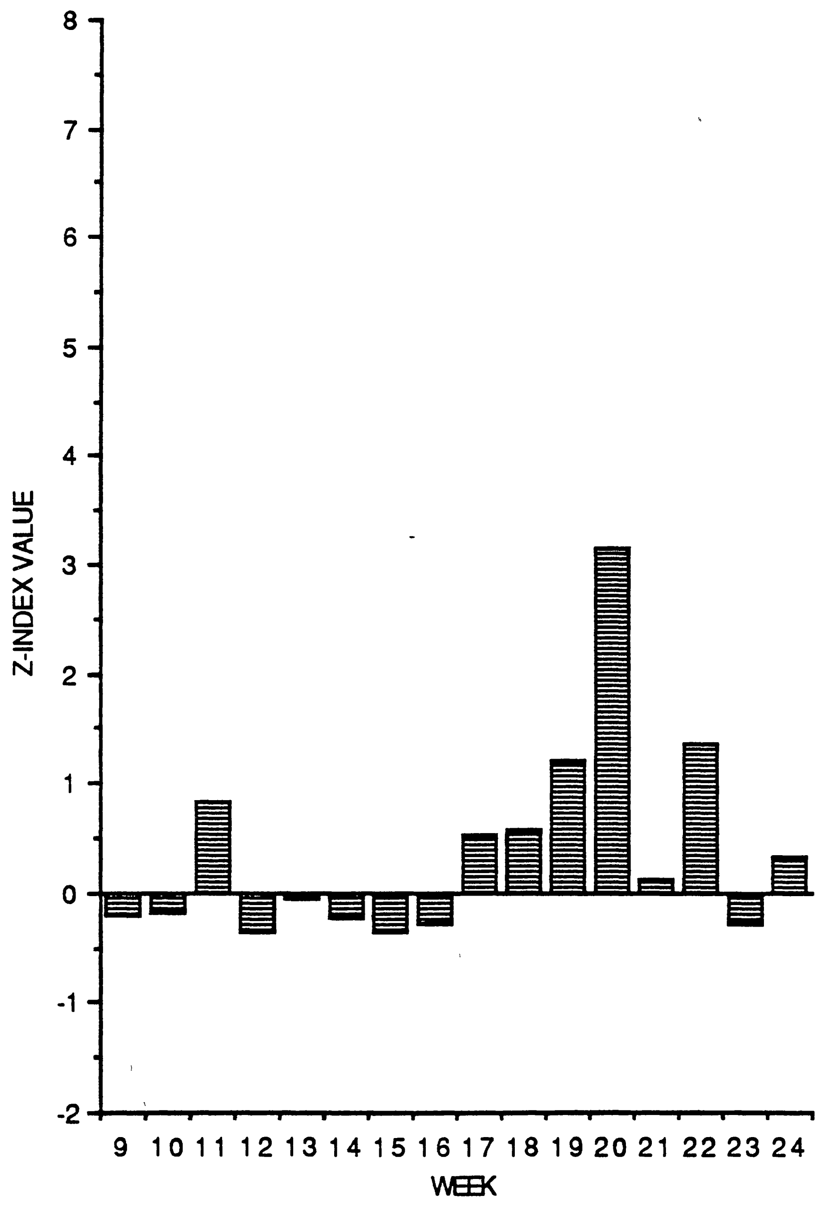


Figure 30. Weekly Average Z-Index, 1982

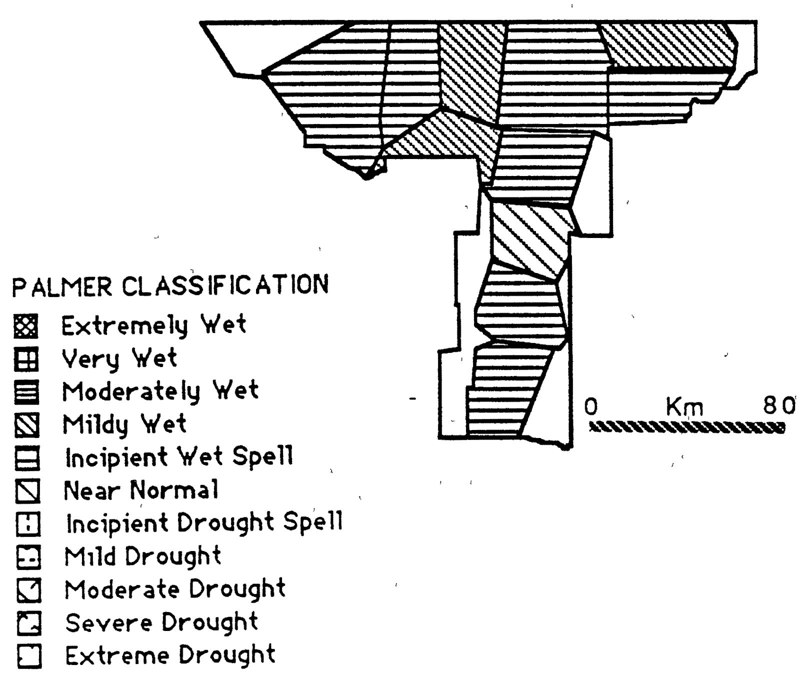


Figure 31. Z-Index Week 11, 1982

during Weeks 12 and 13 (Figures 32 and 33).

The movement of a cyclone through the study area during Week 17 impacted a slight change in conditions along the area running south east from the Alva region, through the Cherokee Power Plant, Great Salt Plains, Helena 1 SSE and Enid polygons, which now as a result, recorded incipient wet spells (Figure 34). Although Week 18 saw many of the areas forwarding the identical conditions as the previous week, the two southernmost areas of Kingfisher 2 SE and El Reno 1 N, were recategorized to mildly wet and incipient wet spell regions, respectively, because of the effect there of the precipitation events associated with a cold front passing directly overhead.

During Weeks 19 and 20, the Z-Index for each of the 11 polygons underwent reclassifications to wetter categories. Week 19 illustrated increases in the Palmer values throughout the eastern half of the study area, in a contiguous zone encompassing Jefferson and Newkirk in the north to El Reno 1 N in the south, which at least recorded mildly wet classifications (Figure 35). Following this, due to two cold fronts passing through Oklahoma during Week 20, the Cherokee Power Plant and the Great Salt Plains areas recorded extremely wet conditions, while Alva, Helena 1 SSE and Newkirk in the north, and Hennessey and Kingfisher 2 SE in the south central portion of the study area exhibited very wet categorizations (Figure 36).

The entire study area essentially 'dried-out' during Week 21, with all areas recording near normal conditions with the exception of El Reno 1 N and Jefferson, which returned incipient wet spell categorizations (Figure 37). These drier conditions were superseded by moderately wet

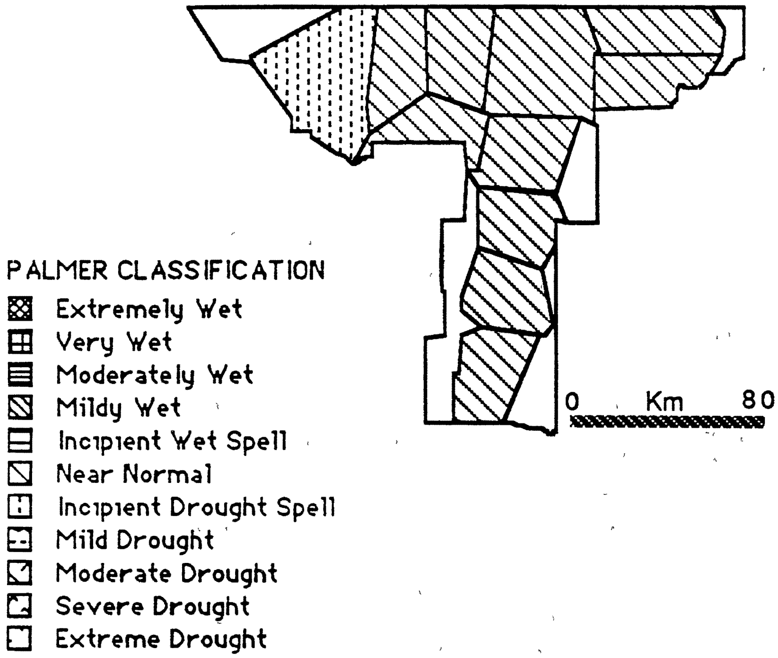


Figure 32. Z-Index Week 12, 1982

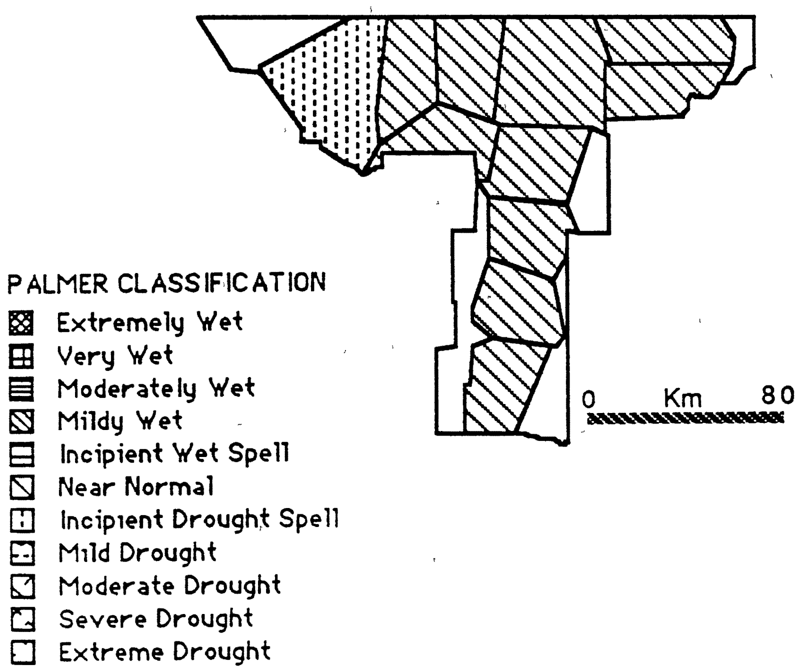


Figure 33. Z-Index Week 13, 1982

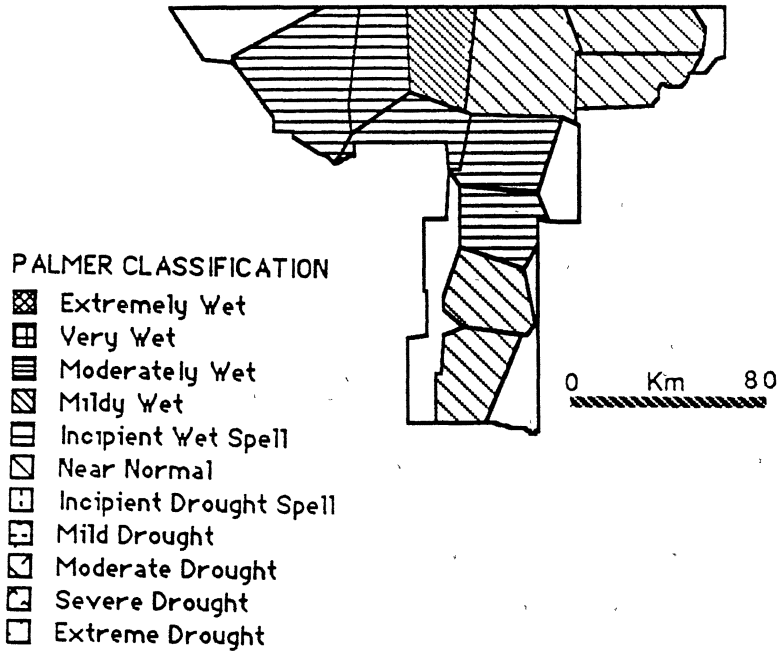


Figure 34. Z-Index Week 17, 1982

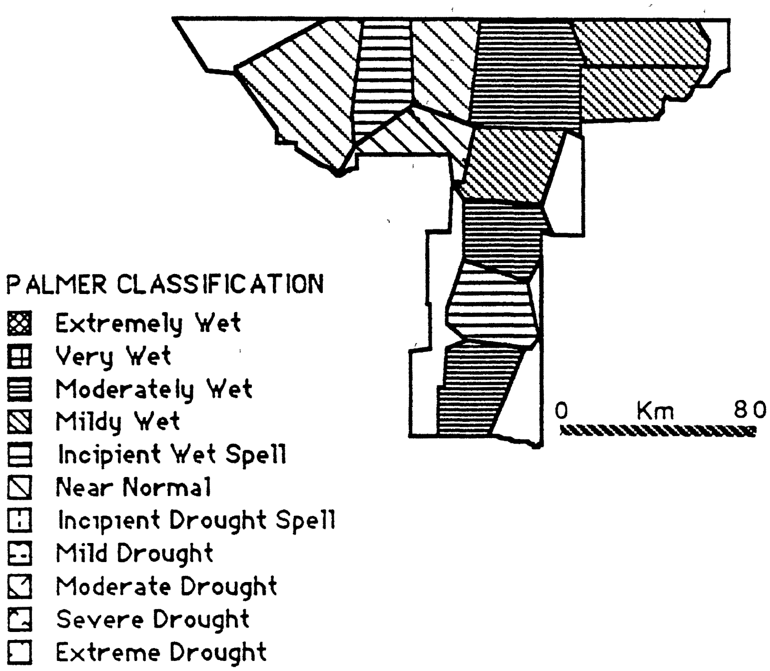


Figure 35. Z-Index Week 19, 1982

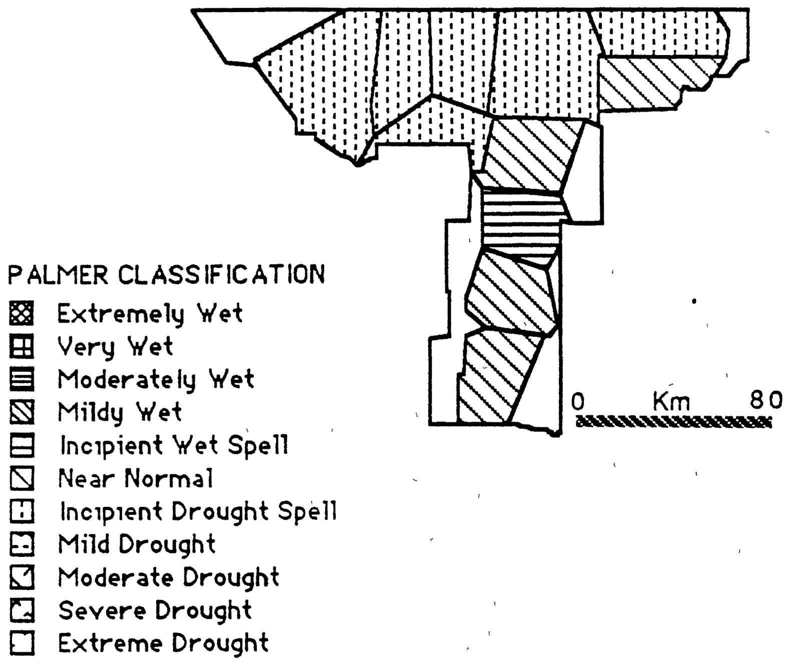


Figure 36. Z-Index Week 20, 1982

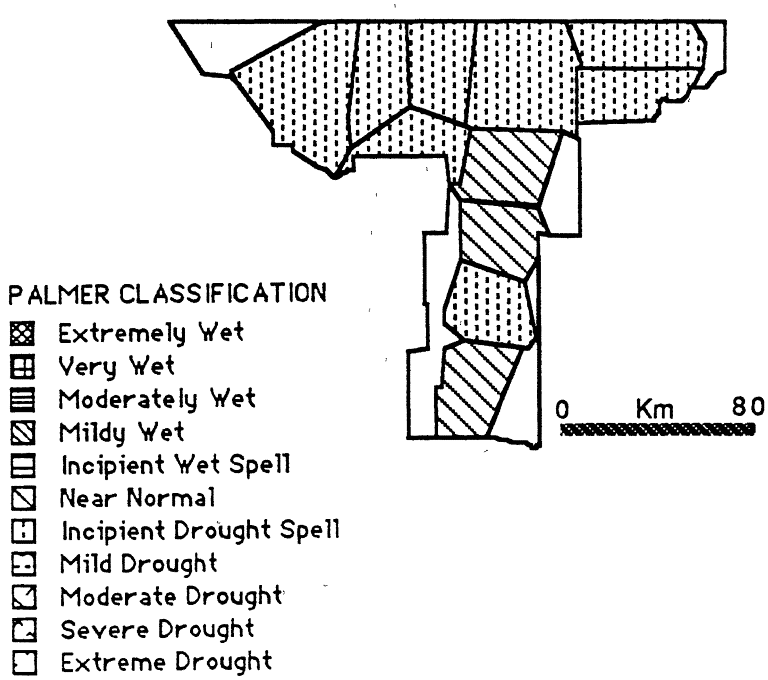


Figure 37. Z-Index Week 21, 1982

conditions during Week 22, which were focussed on the northwesternmost part of the study area encompassing the Alva, Cherokee Power Plant and Great Salt Plains areas, while the other polygons illustrated the intermingling of mildly wet and incipient wet spell conditions.

Throughout Week 23, each region within the study area forwarded negative (i.e. drought), near normal conditions, excluding the Enid and Newkirk polygons which returned incipient drought classifications. Finally, during Week 24, the Alva and Great Salt Plains areas recorded incipient drought spell categorizations despite the frontal precipitation received, while the remaining areas now entirely showed positive, near normal conditions (Figure 38).

Normalized Difference Vegetation Index

The spectral information for the 1982 analysis is considered for the last 10 weeks of the growing season, that is, from Week 15 -- when the operational NDVI first became available -- through the 'browning-out' phase up to Week 24, for seven of the polygon areas, whereas the Alva, Cherokee Power Plant, Jefferson and Kingfisher 2 SE regions are examined herein for Weeks 15 through 26, when the lowest NDVI values were returned.

The average NDVI values over winter wheat during this 'browning-out' / senescence period (Figure 39), and for each of the individual polygon returns, exhibited a somewhat gradual, although fluctuating, decrease in spectral returns over time and space. It is particularly noteworthy that the peak 'greenness' returns from the available data coincided during Week 15 for the majority of the study

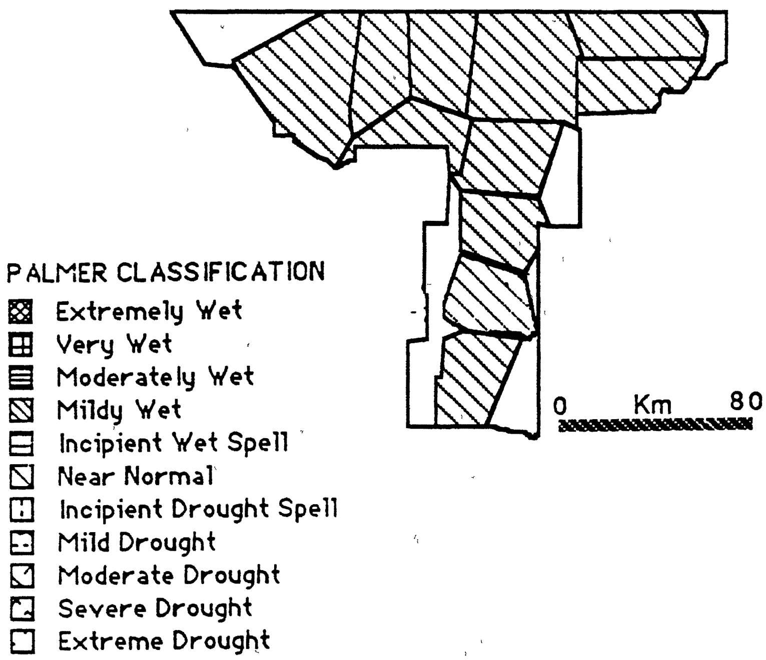


Figure 38. Z-Index Week 24, 1982

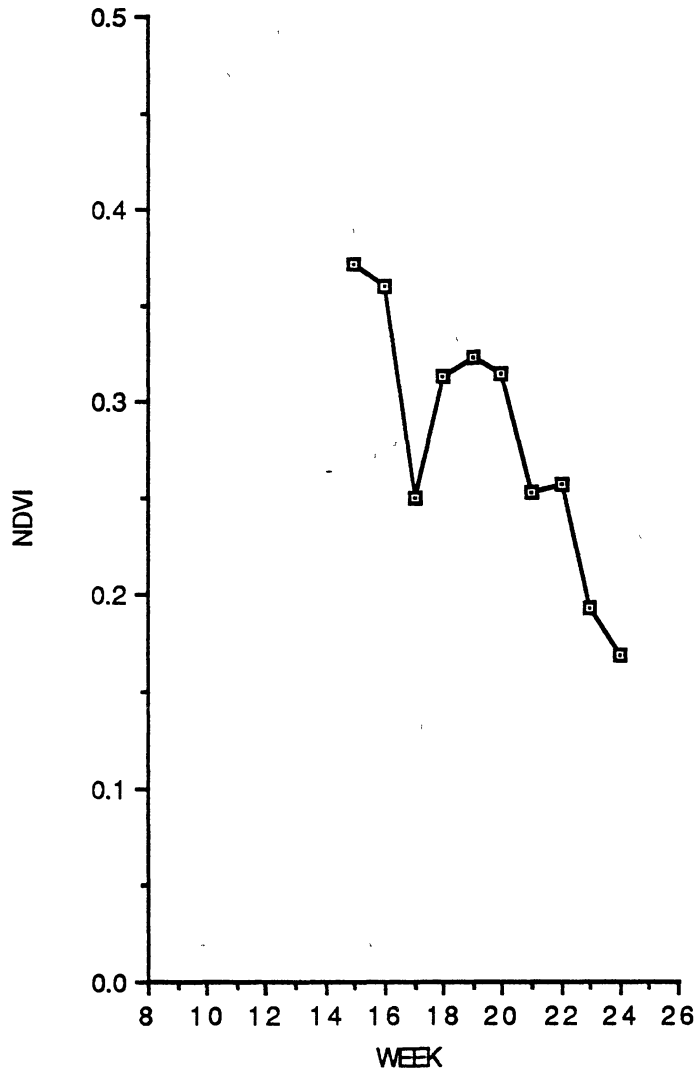


Figure 39. Weekly Average NDVI Spectral Returns Over Winter Wheat in North Central Oklahoma, 1982

areas, while the Great Salt Plains, Ponca City (both Week 16) and Newkirk (Week 17) areas quickly followed. The only area apparently peaking later was Alva during Week 20.

For the individual polygons, the spectral NDVI values portrayed some perturbations between late April (Week 17) through until early June (Week 22), at a time when the entire study area experienced record high precipitation. As such, each area illustrated a decline in this 'greenness' value either during Week 17 or 18, followed by a 're-greening' of the landscape over the next two weeks, which was superseded by the final 'browning-out' of the crop until the eventual harvest. However, this senescent period was largely interrupted by small, but nevertheless noticeable, increases in NDVI values during Week 22. These increases probably were a result of background spectral 'noise' associated with the growth of other surface coverages rather than the 're-greening' of the winter wheat crop, which by this time in mid June was under, or at least near, harvest.

Statistical Analysis

The linear regression analyses performed between each of the transformed Palmer variables, namely, the PDSI, CMI and Z-Index, and the transformed NDVI information, provided the coefficients of determination (r^2). These r^2 values, expressed as percentages, are associated with increases in the variation of the dependent transformed NDVI variable being explained by the independent transformed Palmer (PDSI, CMI or Z-Index) variable, and can range from 0 percent (i.e. no relationship) to 100 percent (i.e. a perfect relationship). High r^2 values are taken to imply a biological dependence, that is cause and effect, between the transformed Palmer variable under investigation and the observed transformed NDVI 'greenness' signature.

Table IV illustrates the high coefficients of determination (r^2) between each of the transformed Palmer indices and the transformed NDVI values, for all of the polygon areas and for the averaged values for the entire study area. These high r^2 values, which were all significant at the 0.01, may appear surprising, but it is essential to reiterate that all the Palmer indices are calculated for points -- interpolated to Theissen polygons here -- and combine influencing environmental factors which not only just take into consideration the daily recorded precipitation and temperature in their calculation, but also their deviations from the long term normal, soil types, time of the year, potential evapotranspiration and soil water runoff, to mention but a few. As a result, the calculated r^2 values could be envisaged as the integration of many factors that are amalgamated within the spectral signal that is the NDVI, which are individually input as the independent variable.

From Table IV, it appears that the changes in the transformed PDSI values during 1982 compared to the transformed CMI and Z-Index readings, were the least influential when considering the spectral NDVI returns of the 'browning-out' winter wheat. The lowest r^2 value at 83.2 percent, was determined for the Great Salt Plains area which experienced a moderately wet PDSI classification over a five week span from mid May (Week 20) until mid June (Week 24), and as such, consistently remained the wettest area throughout the study area during this 'browning-out' time when the other indices experienced fluctuating, and sometimes categorically

TABLE IV

PERCENTAGE COEFFICIENTS OF DETERMINATION (r^2) BETWEEN THE PALMER INDICES AND NDVI, 1982 *

POLYGON NAME	PDSI r^2 (%)	CMI r^2 (%)	Z-INDEX r^2 (%)
ALVA	92.1	98.2	91.4
CHEROKEE POWER PLANT	85.8	94.4	95.2
EL RENO 1N	91.5	94.5	95.7
ENID	89.8	94.8	97.6
GREAT SALT PLAINS	83.3	93.3	92.9
HELENA 1 SEE	86.4	94.9	94.8
HENNESSEY	90.6	96.2	95.9
JEFFERSON	85.9	95.2	95.7
KINGFISHER 2 SE	87.3	96.1	96.0
NEWKIRK	85.1	93.5	94.1
PONCA CITY	86.1	95.2	95.8
AVERAGE	87.1	95.3	95.8

* All significant at the 0.01 level

different, classifications. Furthermore, largely steady PDSI categories were also monitored within the Cherokee Power Plant, Helena 1 SSE, Jefferson, Kingfisher 2 SE, Newkirk and Ponca City areas, over the last five to seven weeks of the study period and as a result these polygons showed weaker relationships. During this particularly wet spell around the latter half of the study period, the statistical weighting of the previous week's condition more than the current in the PDSI calculation, caused this index to forward a somewhat lower determination of the NDVI spectral returns over winter wheat in many of the areas, which apparently reacted much quicker than the PDSI to the current environmental conditions experienced.

On a polygon by polygon basis, the r^2 values for the CMI and Z-Index with NDVI were virtually inseparable, except within the Alva area where the r^2 for CMI at 98.2 percent appeared a little more closely related to accumulated NDVI values, that the Z-Index at 91.4 percent. This difference is probably a result of the comparative slowness of the Z-Index in registering an extended period of droughty near normal values from the second last Week in March (Week 12) up until the third Week in April (Week 16) in the Alva region, while incipient drought classifications were recorded over Weeks 12 and 13 here, which nevertheless did not appear to be severe enough to drastically alter the NDVI spectral returns.

For 1982, the Z-Index marginally proved to be the best predictor of the observed NDVI returns in six out of the 11 polygon areas, while the remaining regions' winter wheat signatures' were most influenced by the CMI values. In addition, the average calculations provided a similar pattern as recorded within individual polygons with the coefficients of determination being virtually identical for the CMI and Z-Index at 95.3 and 95.8 percent, respectively, while the lethargic, and largely constant, nature of the PDSI term over the last five to seven weeks of the study period -- depending on the polygon under investigation -- was less elucidating throughout this 'wet' study year when considering NDVI returns over winter wheat.

1985

Synoptic Situation

Although 1985 was primarily chosen to represent cumulative 'near normal' conditions, from Week 9 through until the harvest which was largely completed by Week 24, the cyclical nature of the precipitation events (Week 12, 13, 16, 17 and 23) and a particularly dry phase (Week 20 through 22) recorded therein, will be highlighted since these fluctuations were determining of the winter wheat's growth regime.

The months of March and April, 1985, were characterized by precipitation amounts 28 mm and 36 mm above the 1951-1980 mean, respectively, while the average monthly temperatures were both simultaneously at least 1 °C above the long term normals. The bulk of March's rainfall was delivered during Weeks 12 and 13, which was conditioned by a stationary front during each week being positioned over north central Oklahoma, associated with a cyclonic passage. Weeks 16 and 17 of April, again saw the study area register rainfall concurrent with the positioning of a stationary front during this two week period, allied to a cold front passing overhead towards the end of Week 17, which cumulatively accounted for the bulk of this month's precipitation.

Collectively, these comparatively warmer and wetter conditions of March and April, resulted in winter wheat making excellent growth and development following its emergence from winter dormancy.

In May, warm, dry weather determined by anticyclonic conditions during Weeks 20 and 21, helped winter wheat make further progress, with the crop heading for a banner year. However, the winter wheat growth situation deteriorated in late May and early June (Week 22) when hot daily high temperatures ranging from 28 °C to 38 °C during the critical kernel-filling stage, severely reduced the expected yields, principally in north central localities (Oklahoma Crop-Weather Summary, 1986). Furthermore, the torrential precipitation events experienced the following week in June (Week 23) -- associated with a stationary and warm front -- caused winter wheat growth to be irrecoverably effected by this cumulative period of inclement conditions, during the late development stages of the crop. As a result, yields of winter wheat averaging only 22 bushels per acre for the study area were eventually realized, which is around 20 percent below the long term normal of 27 bushels per acre.

<u>Palmer Indices</u> - <u>Spatial and Temporal Comparison</u>

Comparing the average weekly PDSI, CMI and Z-Index values spanning the 16 week study period from Weeks 9 through 24 (Figure 40), it is evident that the reaction rates per index differed with respect to the recorded wet and dry synoptic events. These different reaction rates were determined by the original statistical weighting techniques employed in the various Palmer index calculations. The PDSI experienced

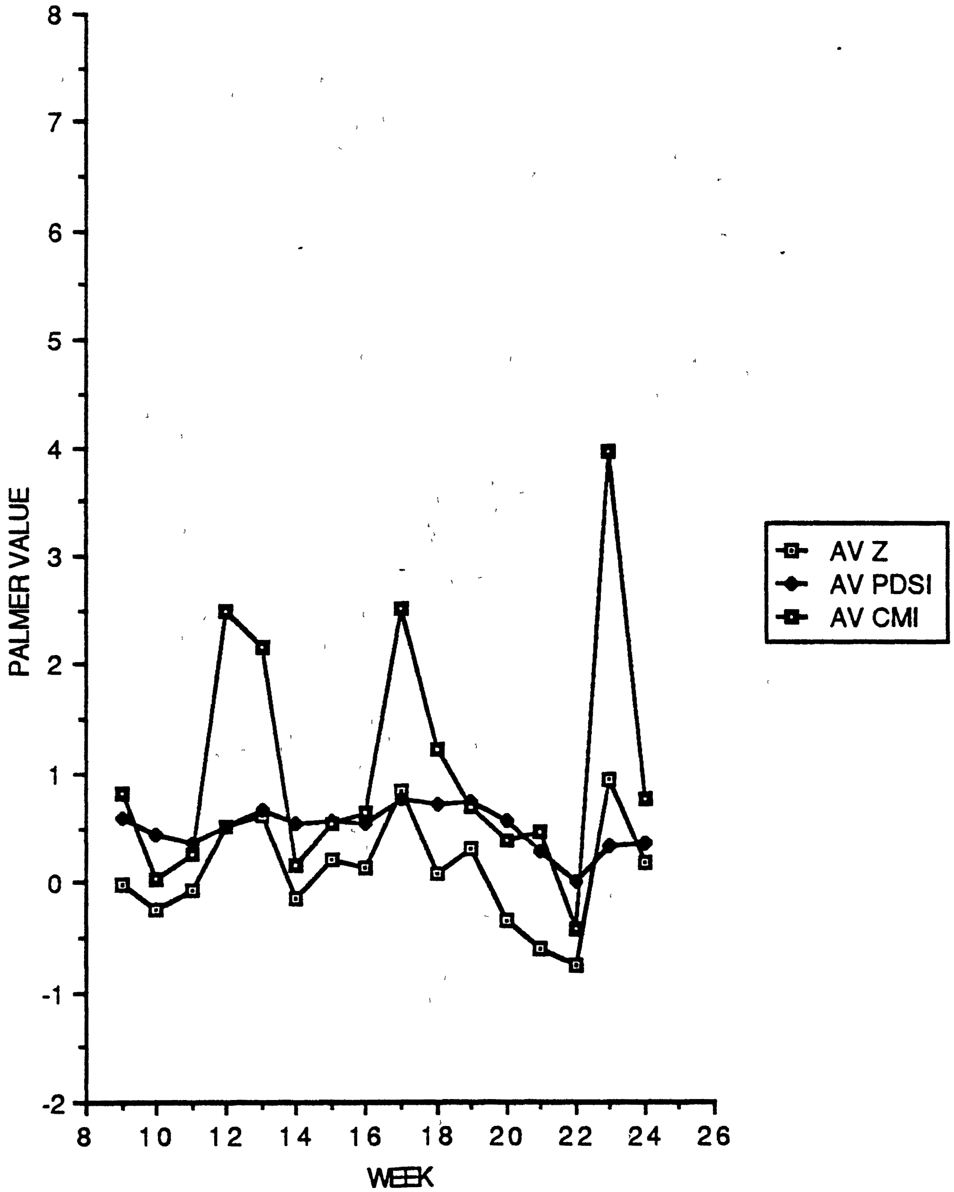


Figure 40. Comparison of Weekly Average PDSI, CMI and Z-Index Values, 1985

the slowest rate of change to a new regime as it exhibited almost stabilized conditions, which only recorded either near normal or incipient wet spell categorizations, throughout the entire period under investigation. Alternatively, the Z-Index simultaneously illustrated a greater range of classifications inclusive of the most common near normal conditions, through to brief, but critical, phases of incipient wet, and especially incipient dry, spell categorizations. Furthermore, as expected, the CMI experienced the greatest rate of change of all the indices on a week to week basis, and therein exhibited the whole range of categories from very wet to negative (i.e. drought), near normal conditions, as determined by rainfall and dry events recorded during the 'greening-up' and 'browning-out' phases of the winter wheat crop in north central Oklahoma. Finally, it is noteworthy that like 1982, the recorded average Z-Index values appeared to accentuate periods of drought conditions, whereas the average CMI highlighted times of high weekly rainfall at various intervals during the duration of the study period.

Palmer Drought Severity Index. Over the entire 16 week study period from Week 9 through 24, 1985, the average PDSI registered either near normal or incipient wet spell categorizations, with little recorded variation from week to week (Figure 41). However, the precipitation events of Weeks 13, 17 and 23, and the hot, dry weather experienced in late May and early June (Week 22) were nevertheless detectable.

An examination of the PDSI values for the individual polygons over the first three weeks of March (Weeks 9 through 11), illustrated very few deviations from the characteristic average near normal and incipient wet spell classifications. During Week 9, the entire study area returned these

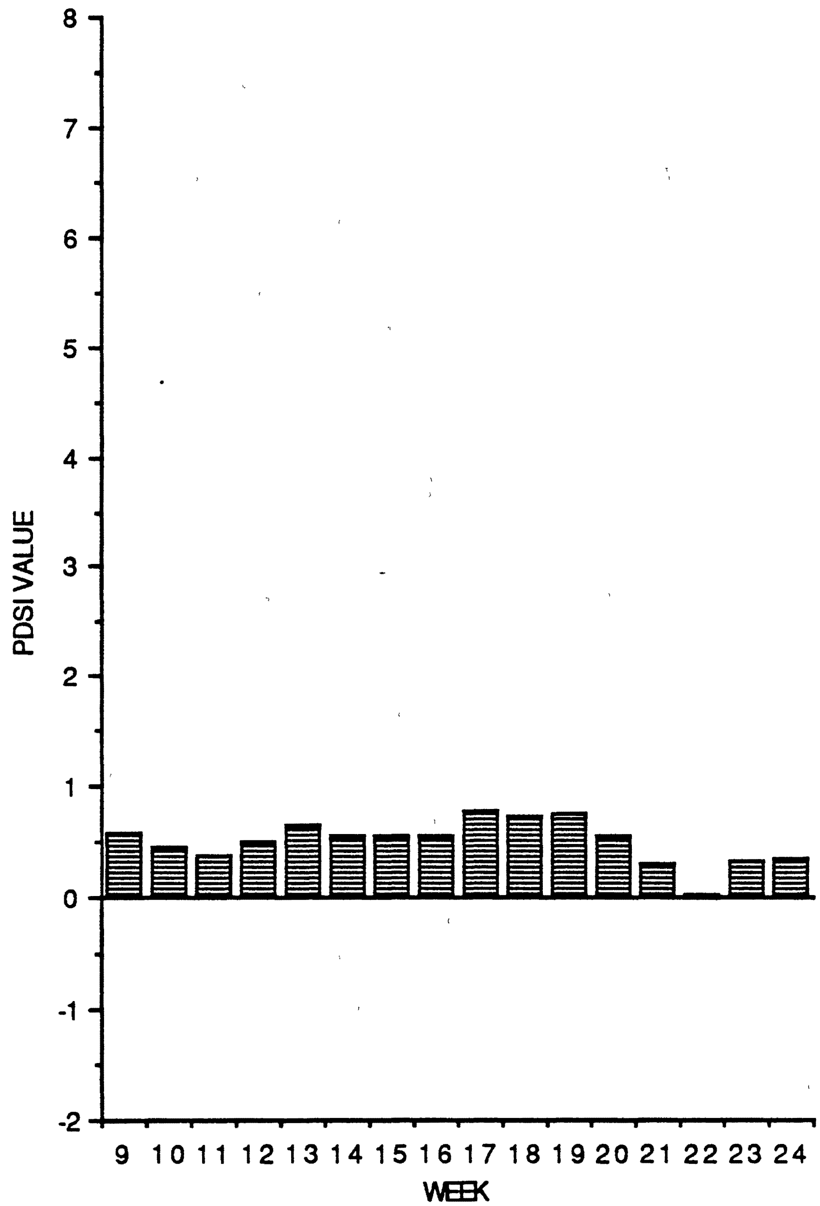


Figure 41. Weekly Average PDSI, 1985

aforementioned conditions, excluding the El Reno 1 N and Newkirk regions which forwarded mildly wet classifications (Figure 42). The comparatively drier conditions recorded during Week 11 resulted in the whole area again being designated under near normal and incipient wet spells.

The rain events of Week 13 impacted the greatest change with mildly wet conditions being cataloged in the two southernmost areas of El Reno 1 N and Kingfisher 2 SE (Figure 43). Over the next four weeks, namely Weeks 13 through 16, there were few recorded changes in the PDSI classifications in any of the 11 investigated polygons, although by Week 16, it is safe to point out that the southern parts of the study area exhibited moister Palmer classifications in comparison to the somewhat drier northern areas (Figure 44).

The rainfall associated with a stationary front positioned over the study area during Week 17, caused the greatest change in the Alva, Enid and Jefferson areas which now came under mildly wet conditions, and retained these classifications over the following four weeks until the drier events of Week 21, which caused siccative categories principally in parts of the northeastern, and southernmost reaches of the study area.

The hot, dry weather of Week 22 registered declines in the PDSI values for the Alva, Helena 1 SSE and Hennessey areas from the previous week (Figure 45). Negative (i.e. drought), near normal conditions were concentrated in four northern areas, namely, the Cherokee Power Plant, Great Salt Plains, Newkirk and Ponca City, while the Helena 1 SSE region illustrated an incipient drought spell. The torrential rains of Week 23, impacted only changes in the Newkirk (incipient wet spell), El Reno 1 N

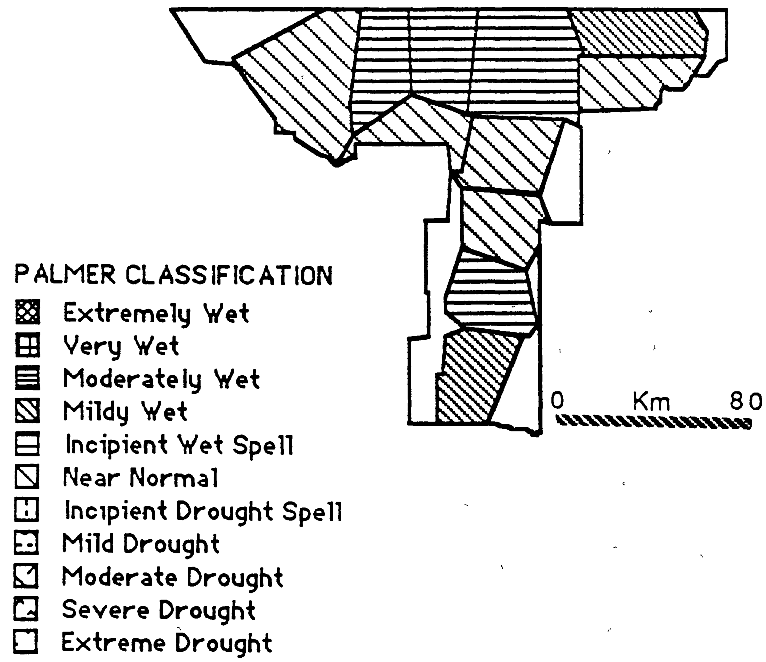


Figure 42. PDSI Week 9, 1985

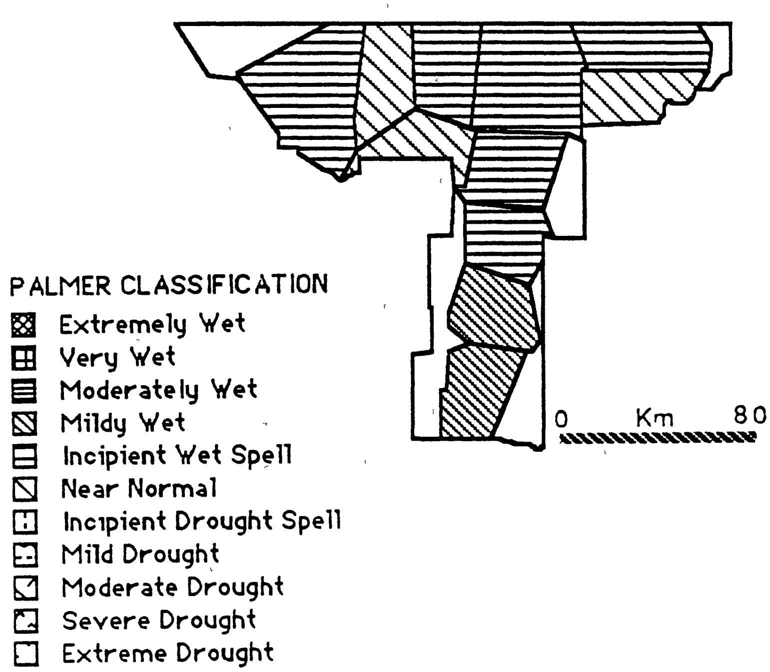


Figure 43. PDSI Week 13, 1985

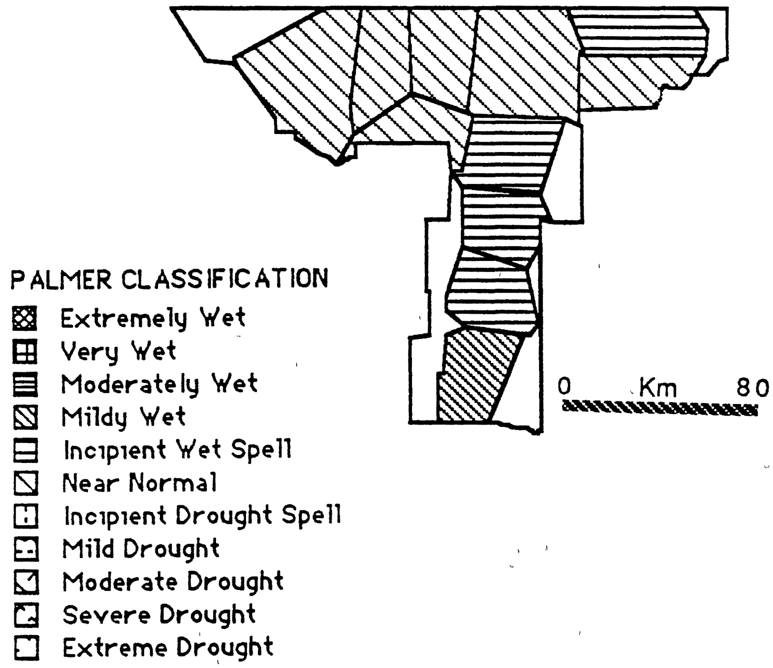


Figure 44. PDSI Week 16, 1985

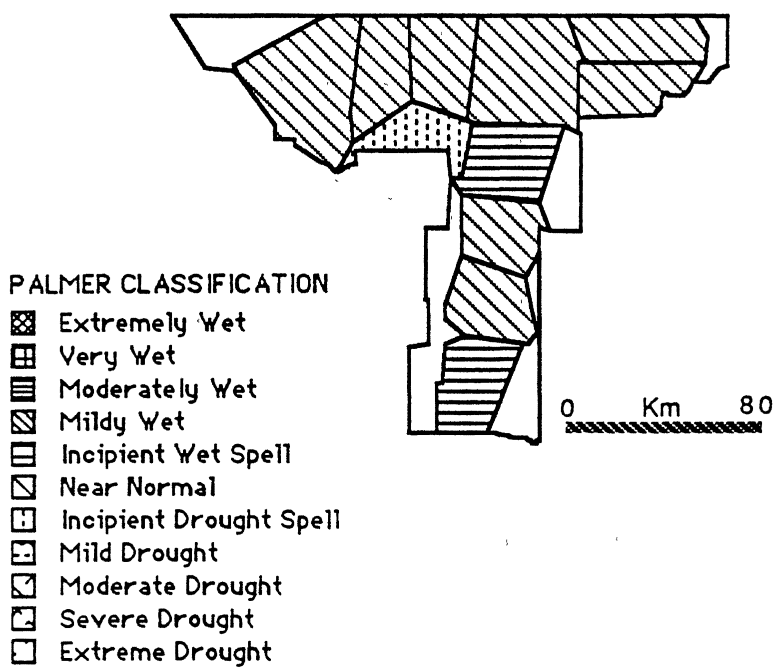


Figure 45. PDSI Week 22, 1985

and Enid (both mildly wet) areas (Figure 46). The entire study area registered the same categories, up to, and including, Week 24, although the Alva area received some localized rainfall as it was reclassified from a near normal to an incipient wet spell condition.

Crop Moisture Index. The averaged weekly CMI values were characterized by an extreme range and very abrupt changes, which were coincident with the aforementioned precipitation and hot, dry events experienced during particular times within this 16 week study period (Figure 47). Undoubtedly, the greatest overall change occurred when the average incipient drought conditions of Week 22 were superseded by an average wet classification during Week 23.

At the outset (Week 9), the majority of the study area was characterized by incipient wet spells, except for the near normal conditions experienced in the northern areas of the Great Salt Plains and Newkirk, and the Hennessey polygon in the center of the study area, while El Reno 1 N in the extreme south registered moderately wet CMI values (Figure 48). Week 10 illustrated relative CMI value declines in nine of the 11 polygons, with the entire region recording near normal conditions, which largely continued into Week 11, with only the north central Enid and Jefferson areas being reclassified under incipient wet spells.

The rain events of Week 12 impacted changes in the CMI values throughout the study area (Figure 49). El Reno 1 N bore the brunt of this precipitation, given its extremely wet categorization. In fact, while the Cherokee Power Plant, Jefferson, Newkirk and Ponca City polygons experienced mildly wet classifications, all the remaining areas returned greater CMI values. By Week 13, the areas of Alva, Cherokee Power Plant

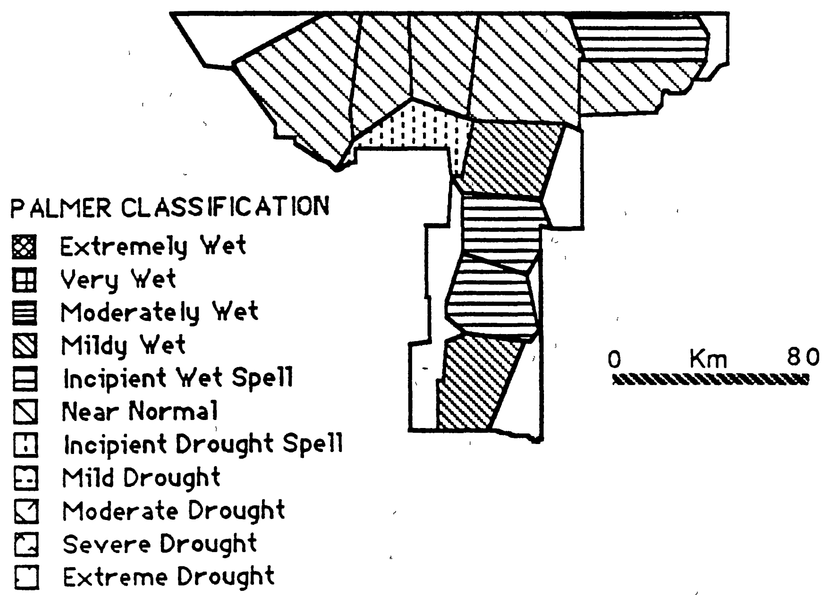


Figure 46. PDSI Week 23, 1985

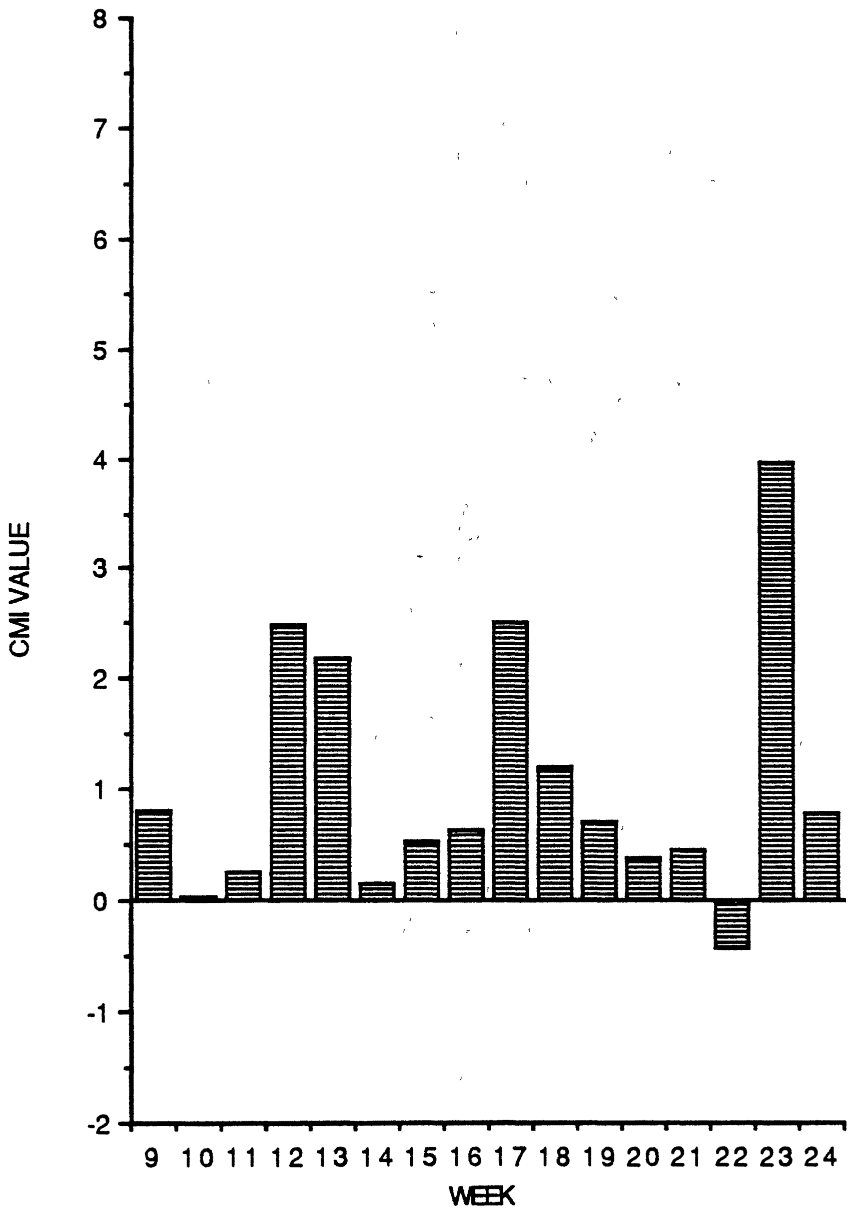


Figure 47. Weekly Average CMI, 1985

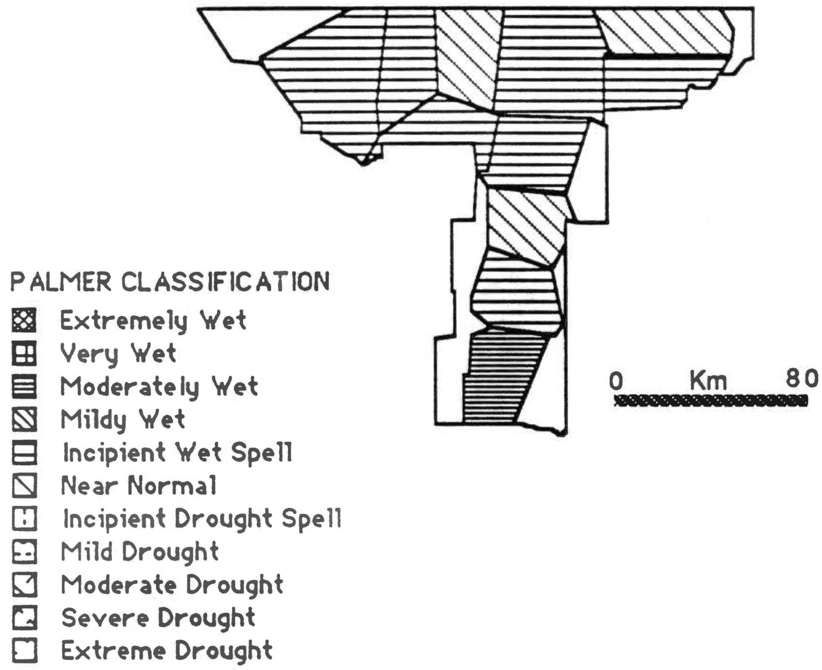


Figure 48. CMI Week 9, 1985

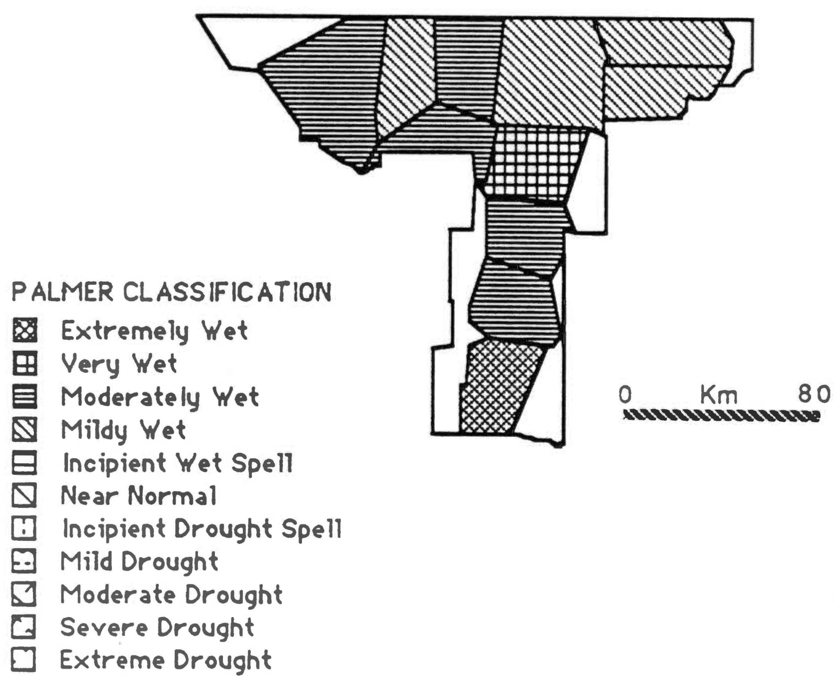


Figure 49. CMI Week 12, 1985

and Jefferson recorded relatively wetter classifications, while the remaining eight polygons returned identical or decreased CMI returns. Week 14 cataloged a return to near normal conditions throughout the study area. Incipient wet spells were noted in six of the 11 polygons during Week 15, while the other areas of Alva, Helena 1 SSE, Jefferson, Kingfisher 2 SE and Ponca City returned near normal classifications (Figure 50). The following week (Week 16), exhibited little change, with only the Enid and El Reno 1 N areas undergoing a change to a mildly wet situation.

The documented frontal precipitation events of Week 17 caused all areas, excluding El Reno 1 N and Enid, to register much wetter CMI classifications, with Alva and Jefferson 2 SE recording extremely wet classifications (Figure 51). All areas, except the El Reno 1 N, Enid, Kingfisher 2 SE and Ponca City polygons, dried out somewhat during Week 18, while rainfall events were experienced in El Reno 1 N causing a very wet classification. This drier phase continued into Week 19, although Alva continued as very wet.

Week 20 was classified by near normal conditions, with only the Enid and Hennessey areas illustrating incipient wet, and moderately wet, classifications, respectively. During Week 21, precipitation events were localized in the Helena 1 SSE and Ponca City areas in the north with incipient wet and mildly wet conditions, respectively, while the two southernmost areas of El Reno 1 N and Kingfisher 2 SE both exhibited incipient wet spells.

The extremely hot, dry events of Week 22 forwarded a concentration of mild drought conditions in the northeastern sections of the study area

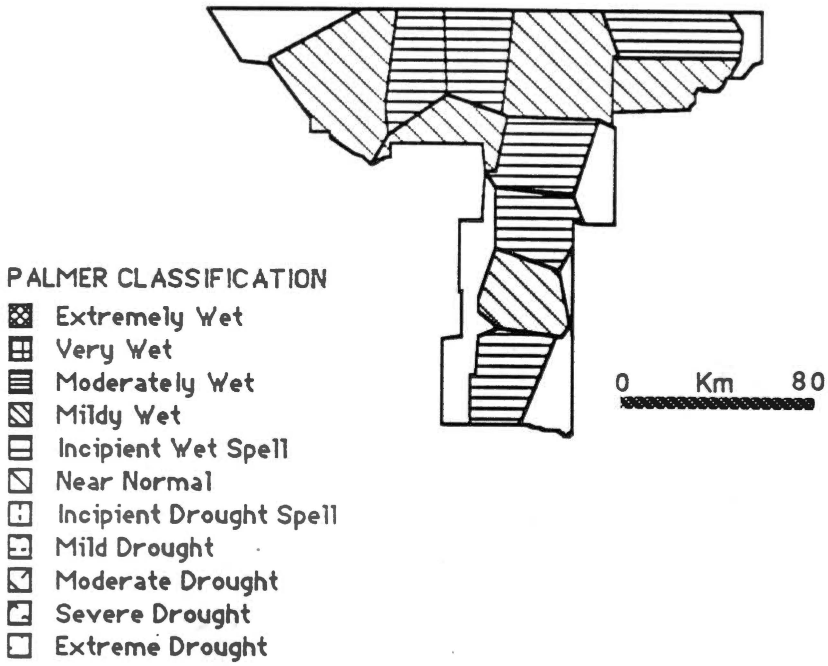


Figure 50. CMI Week 15, 1985

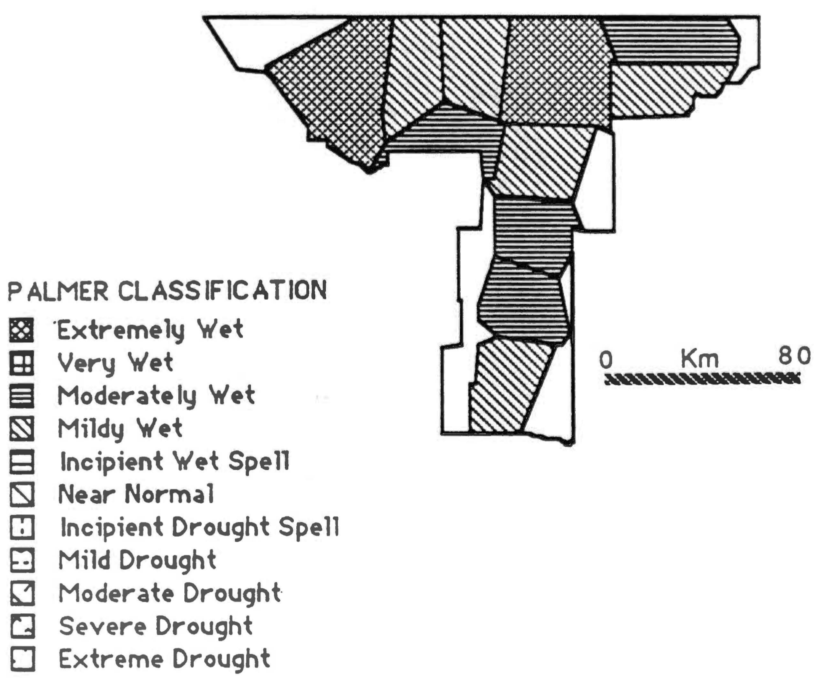


Figure 51. CMI Week 17, 1985

and Kingfisher 2 SE in the south, while the remaining polygons registered incipient drought spells (Figure 52).

The torrential rains of Week 23, caused six of the 11 polygons to be reclassified as very wet, while the remaining areas at least registered mildly wet classifications (Figure 53). The study area became much drier during the final week (Week 24) with only the north central area, including the Cherokee Power Plant, Enid and Great Salt Plains, recording mildly wet classifications, at a time when the remaining polygons, excluding Jefferson, returned incipient wet spells and near normal conditions, respectively.

Z-Index. The greatest fluctuations in the average Z-Index values (Figure 54) coincided with the large precipitation events during Weeks 12, 13, 17 and 23, and the drought conditions of Weeks 21 and 22. Otherwise, the study area was characterized by near normal classifications -- recording either positive and/or negative values therein -- throughout the other 10 weeks of this 16 week focus.

The initial week of the study period (Week 9) saw near normal conditions throughout the whole area, with the exception of the southernmost El Reno 1 N area which exhibited a mildly wet classification (Figure 55). However, it is important to note that eight of the 11 polygons simultaneously recorded negative (i.e. drought), near normal conditions during this week, which thereafter continued and were reinforced by comparatively dry conditions experienced in the study area during Week 11, causing the Alva region to register an incipient drought spell categorization.

Frontal precipitation events during Week 12 impacted wetter returns

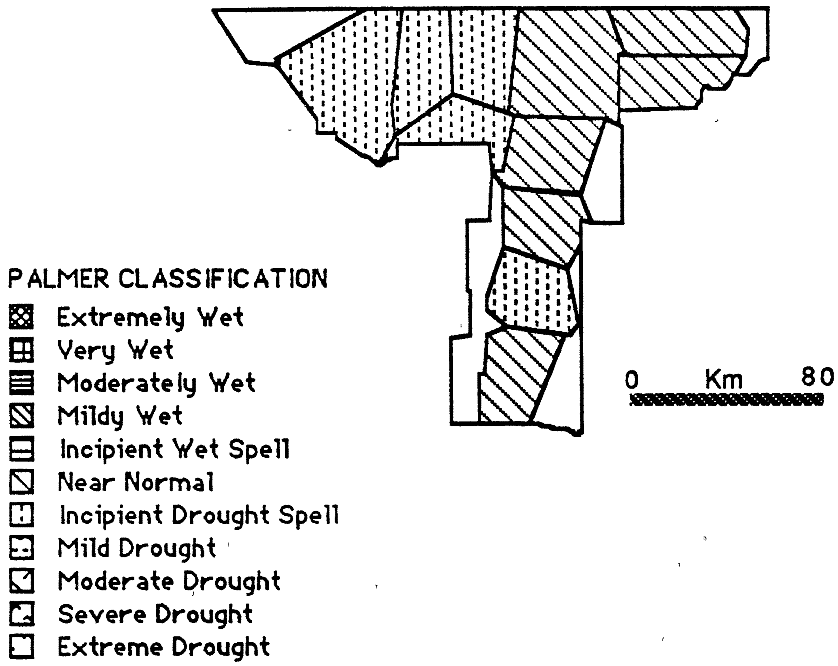


Figure 52. CMI Week 22, 1985

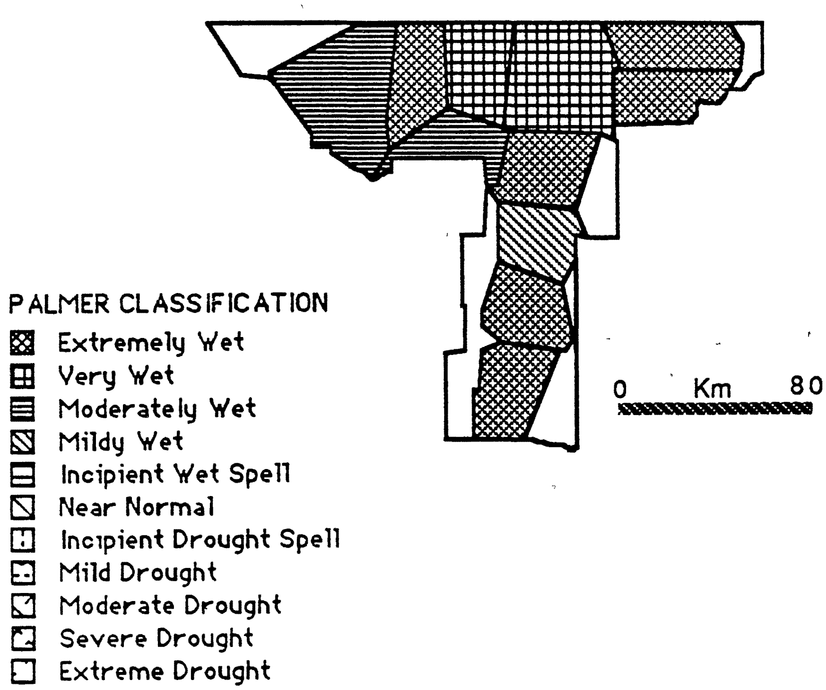


Figure 53. CMI Week 23, 1985

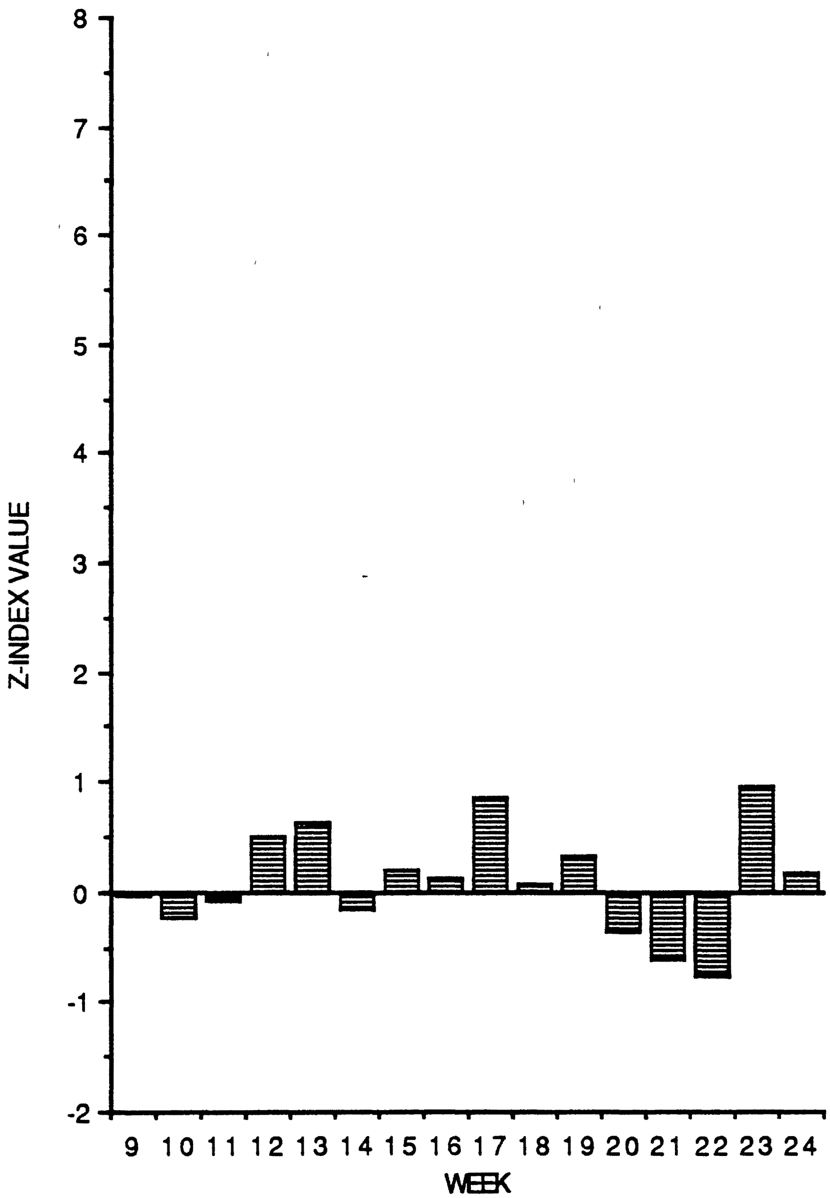


Figure 54. Weekly Average Z-Index, 1985

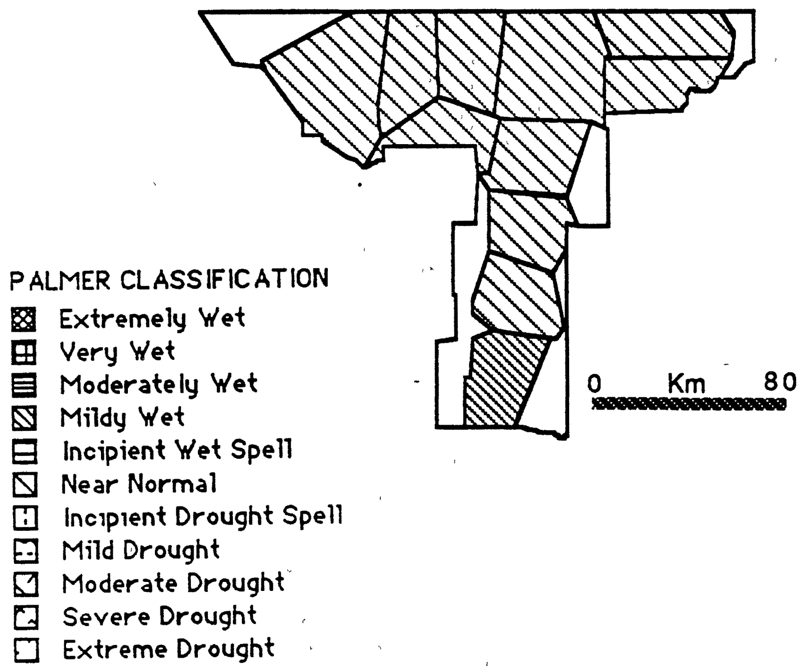


Figure 55. Z-Index Week 9, 1985

in the north central areas of the Great Salt Plains and Enid, which both illustrated incipient wet spells, while the south central areas of El Reno 1 N, Hennessey and Kingfisher 2 SE exhibited mildly wet classifications (Figure 56). The south central area essentially dried out during Week 13 despite the precipitation events associated with a stationary front existing over the study area. The impact of this rain focused a categorical change in the Alva region which recorded very wet conditions (Figure 57).

Week 14, illustrated negative (i.e. drought), near normal conditions throughout the entire study area, which was followed by precipitation events during Week 15 when all areas, with the exception of Alva and Kingfisher 2 SE, recorded increases in their absolute Z-Index values, with the Cherokee Power Plant and Hennessey areas forwarding incipient wet spells (Figure 58). Largely similar polygon classifications existed until the precipitation events of Week 17 which impacted the greatest changes in the Alva (moderately wet) , and Enid and Jefferson (both mildly wet) regions. All areas during Week 18, experienced absolute declines in their Z-Index values, with the exception of El Reno 1 N in the extreme south of the study area which registered an incipient wet spell.

The hot, dry weather of the last two weeks in May and the first week in June (Weeks 20 through 22) exhibited increasingly droughty conditions throughout the study area. In fact, by week 22, all areas north of the negative, near normal regions of Kingfisher 2 SE and El Reno 1 N, and west of the Newkirk and Ponca City areas (both negative, near normal), illustrated either mild or moderate drought Z-Index values (Figure 59). The final week of the 1985 study period was characterized by the rapid return to near normal conditions throughout the whole area, despite the

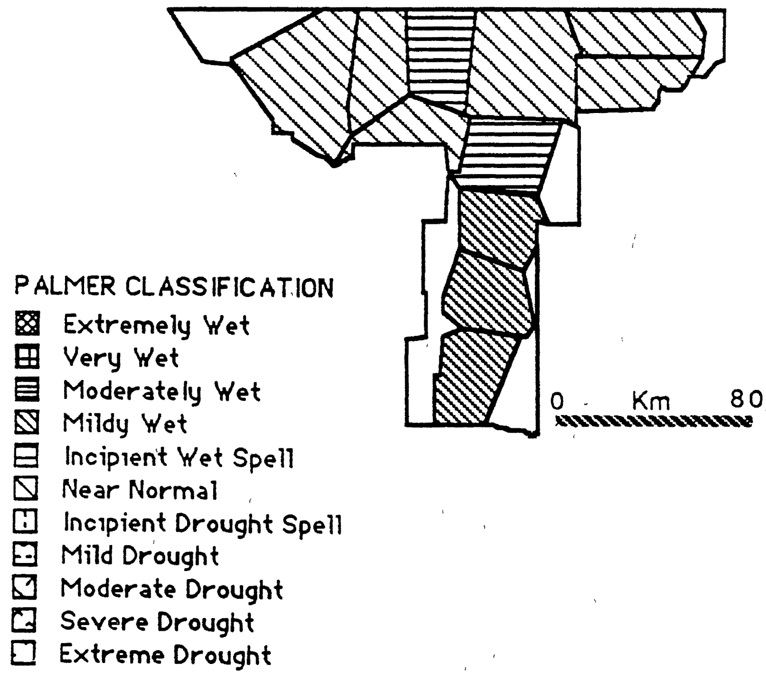


Figure 56. Z-Index Week 12, 1985

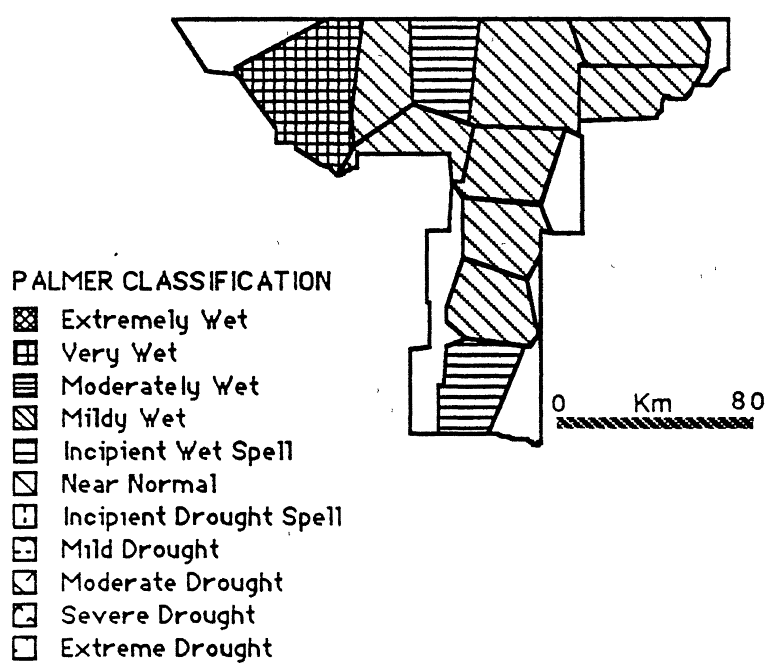


Figure 57. Z-Index Week 13, 1985

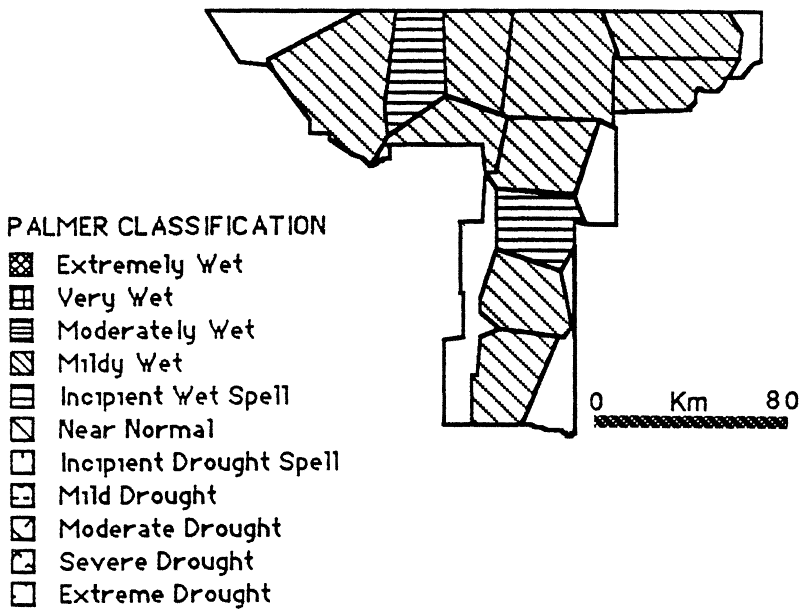


Figure 58 Z-Index Week 15, 1985

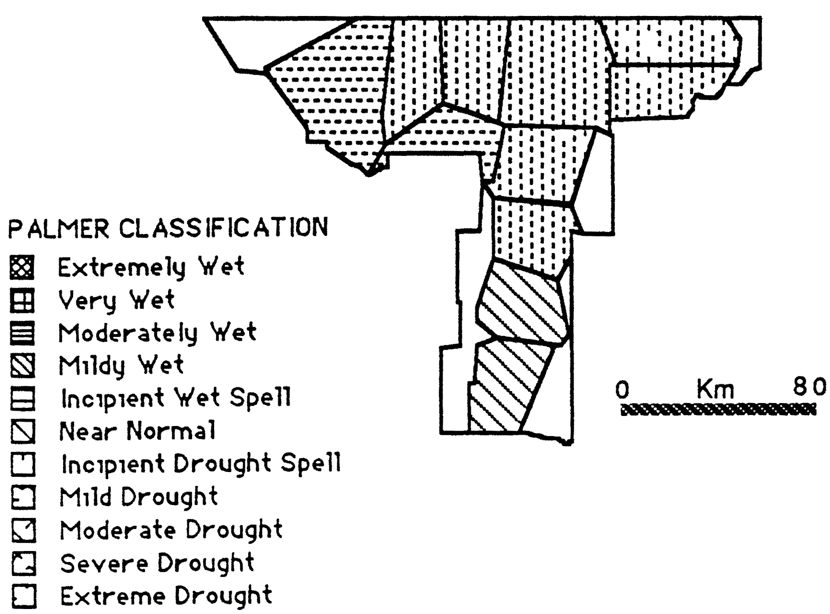


Figure 59 Z-Index Week 22, 1985

torrential precipitation of Week 23, illustrating the rather quick reaction time of this weekly moisture anomaly index.

Normalized Difference Vegetation Index

The largely sigmoidal nature of the average spectral signature over the 'greening-up' and 'browning-out' phases of winter wheat for the entire study area (Figure 60), illustrated a steady increase from early March (Week 9) to the third week in April (Week 16) when the peak 'greenness' value was registered, and thereafter decreased until the harvest time during early to mid June, 1985 (Week 23/24). On a polygon by polygon basis, the northwestern area, inclusive of the Alva, Cherokee Power Plant and Helena 1 SSE regions, registered similar 'greening-up' phases with somewhat sooner peak returns around early April (Week 14), while the Enid, Great Salt Plains, Hennessey, Kingfisher 2 SE and Ponca City areas all coincided with the average peak 'greenness' values during Week 16. Otherwise, the two remaining polygons, lying at the extreme southern and northeasternmost parts of the study area, namely, the El Reno 1 N and Newkirk areas, respectively, registered their highest returns during the last week in April (Week 17).

Characteristically, despite the variance in the peak 'greenness' times, eight of the 11 polygon areas registered a slight downturn in NDVI values during mid April (Week 15) -- with the exception of the Great Salt Plains, Newkirk and Ponca City areas -- at a time when the entire study area was essentially drying out following the rain events of the last two weeks in March (Weeks 12 and 13). Nevertheless, thereafter, all the 11 polygon areas received frontal precipitation which appeared to impact a

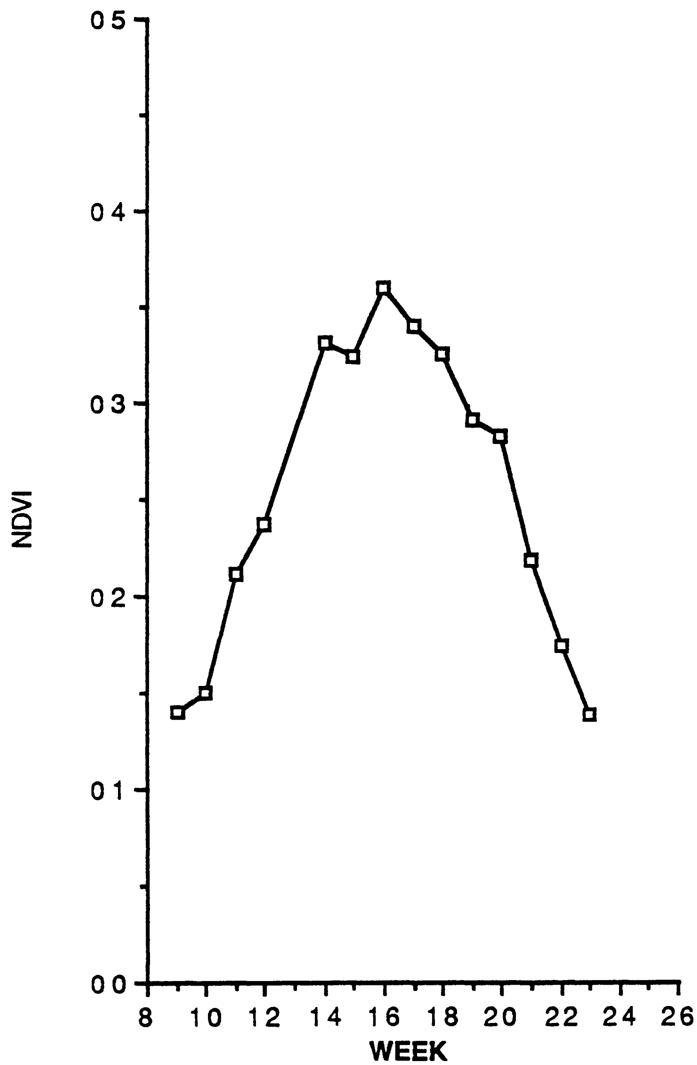


Figure 60 Weekly Average NDVI Spectral Returns Over Winter Wheat in North Central Oklahoma, 1985

're-greening' of the landscape over Weeks 16 and 17 Following this, on average, each of the areas then exhibited decreasing NDVI spectral returns until harvest time, which was generally timed around early June (Week 23) throughout the study area, except for the Enid and Jefferson areas, which largely completed their harvest a little later by mid June (Week 24)

Statistical Analysis

Very high coefficients of determination (r^2) ranging from 93 1 to 99 8 percent, which were all significant at the 0 01 level, were derived for each of the transformed Palmer indices and the associated transformed NDVI values for each of the 11 individual areas under investigation (Table V) On the whole, the least fluctuating PDSI proved the most elucidating with regard to NDVI spectral returns over winter wheat within seven of the 11 polygons Otherwise, the Z-Index was marginally advantageous in the remaining Alva, Enid and Hennessey areas, while for the Helena 1 SSE region the Z-Index and PDSI r^2 values tied at 98 7 percent

Given these mixed results, it is safe to point out that despite the large precipitation phenomena during Week 12, 17 and 23, and the occurrence of a critical hot, dry spell spanning from the end of May to the beginning of June (Week 22) -- with the latter event impacting severely on the kernel-filling stage of winter wheat development causing reduced yields -- as largely outlined by the CMI and Z-Index values These events did not cause any peculiar fluctuations within the expected sigmoidal nature of NDVI winter wheat returns when assessed through the PDSI,

TABLE V

PERCENTAGE COEFFICIENTS OF DETERMINATION (r^2) BETWEEN THE PALMER INDICES AND NDVI, 1985*

POLYGON NAME	PDSI r^2 (%)	CMI r^2 (%)	Z-INDEX r^2 (%)
ALVA	94 9	98 1	98 3
CHEROKEE POWER PLANT	98 8	97 5	98 7
EL RENO 1N	99 8	94 5	96 4
ENID	97 2	93 1	98 5
GREAT SALT PLAINS	97 1	97 6	97 1
HELENA 1 SEE	98 7	98 5	98 7
HENNESSEY	99 4	98 9	99 4
JEFFERSON	97 3	95 5	97 3
KINGFISHER 2SE	96 5	96 7	96 5
NEWKIRK	94 6	92 5	94 6
PONCA CITY	97 0	94 2	97 0
AVERAGE	99 6	97 5	98 7

* All significant at the 0 01 level

except within the Alva, Enid and Hennessey areas.

The Alva area's coefficients of determination (r^2) at 98.1 and 98.3 percent for the transformed CMI and Z-Index, respectively, forwarded marginally greater results than the transformed PDSI at 94.9 percent. The CMI and Z-Index values simultaneously recorded the greatest Palmer values of the entire area over Alva, during Weeks 13, 17 and 19 and the droughtiest conditions herein during Week 22. However, these important extreme values were not replicated within the PDSI -- illustrating its lethargic nature caused by the weighting of the previous weeks' situation more than the current weeks' in its calculation -- which ultimately resulted in the PDSI variable underestimating the influence that these wet and dry periods had on the recorded NDVI spectral returns over winter wheat in the Alva area within particular parts of this 16 week study period.

For the Enid area, the transformed Z-Index returned the highest coefficient of determination (r^2) at 98.5 percent, which was slightly greater than the r^2 value for the transformed PDSI and the CMI at 97.2 and 93.1 percent, respectively. The slight difference between the Z-Index and PDSI r^2 values here was probably a result of Week 14 and 22 illustrating Z-Index values which were classified as near normal but negative and as an incipient drought spell, respectively, while the PDSI simultaneously recorded an incipient wet spell during Week 14, and Week 23 was characterized by a near normal condition. Undoubtedly, the lower r^2 value for the transformed CMI, when compared to the other two indices, was associated with the Week 12 and Week 23 readings. During Week 12, Enid experienced a very wet CMI classification at a time when the other indices returned drier values, while this area in early June (Week 23) bore the brunt of the torrential rains received with an extremely wet classification, when both the PDSI and Z-Index returned mildly wet classifications. Evidently, the rapid changes in the moisture situation as presented by the CMI, were not mirrored by any similarly severe fluctuation within the simultaneously acquired NDVI winter wheat spectral returns.

In considering the transformed PDSI's, CMI's and Z-Index's coefficients of determination (r^2) derived for the Hennessey area at 97.2, 98.9 and 99.4 percent, respectively, the only perceivable explanation for the transformed PDSI returning a slightly lower r^2 value was primarily a result of the nature of the first four weeks' readings (Weeks 9 through 12) Over this period the PDSI registered near normal conditions throughout, while the CMI and Z-Index were similarly classified up until the mild and moderately wet readings during Week 12, respectively. In this instance, the effect of Hennessey being in receipt of amongst the heaviest rainfalls during Week 12 for the entire study area from the CMI and Z-Index values, while the PDSI underestimated this precipitations impact in regard to NDVI values recorded herein over winter wheat.

For the most part, the averaged values for the transformed Palmer and NDVI variables for the entire study area replicated, and slightly improved upon, the individual polygon results, with the transformed PDSI marginally returning a very high r^2 value of 99.8 percent for this 'near normal' year. As a result of the process of averaging all the indices values on a week to week basis, those values representing extreme wet and/or dry returns, such as outlined above for the Alva, Enid and

Hennessey areas were removed, thus causing slightly higher r^2 values.

1989

Synoptic Situation

On the whole, the winter wheat growth situation for the 1988-89 crop was bedeviled by extreme weather conditions. The winter and early spring drought of April, coupled with severe February freezes, and finally, the heavy June rainfalls before the harvest, resulted in the state returning an average yield of 27.0 bushels per acre (Bartlett and Cole, 1989). The 1989 growing season was chosen because it illustrated the driest month (April- when jointing was under way) in the NDVI record. However, the entire 1980s were characteristically wet and there was no extremely dry year within the satellite record which could be studied.

On a month by month basis, March through June, 1989, illustrated extreme fluctuations in terms of the precipitation amounts received within the study area. Both March and June experienced above average rainfall amounts totaling 73 mm and 227 mm, which were 26 mm and 100 mm above their long term normals, respectively. As a result of June's extremely high rainfall, the mean monthly temperature registering at 23 °C was 2 °C below the long term average. On the other hand, April received very warm, dry conditions with a record low precipitation amount of only 12 mm, which was 55 mm below the long term average of 77 mm, while May returned near normal precipitation and temperature averages.

March's precipitation was mainly concentrated within the first and last weeks of the month, namely Weeks 9 and 13, respectively, following the frontal passages associated with the easterly movement of mid latitude cyclones over Oklahoma then. The very dry weather which critically persisted throughout the entire month of April, namely, Weeks 14 through 17, when winter wheat was undergoing jointing, was determined by the occurrence of settling anticyclonic conditions throughout the southern Great Plains, which accordingly raised the mean monthly temperature from 15 °C to 16 °C within the study area.

The rain events of May were mostly focussed during Weeks 19 and 20, as determined by cold fronts passing over the study area, delivering the bulk of this month's precipitation. During the month of June, from the latter half of Week 22 up until the end of Week 25, the study area registered repeated cold front passages, causing periods of large rainfall events. The majority of this monthly precipitation was delivered during the first half of the month during Weeks 23 and 24.

<u>Palmer Indices</u> - <u>Spatial and Temporal Comparison</u>

Characteristically, each of the averaged Palmer indices reacted at different rates to the aforementioned, highly fluctuating, nature of the weather conditions experienced throughout the 'greening-up' and senescent periods of winter wheat growth, namely, from Week 9 through until Week 22 (Figure 61). However, for the purposes of this part of the investigation, some consideration of the Palmer variables up until Week 26 will be outlined, since the recorded high precipitation amounts during June, ultimately delayed the harvesting of the crop within north central Oklahoma, despite senescence being considered spectrally accomplished

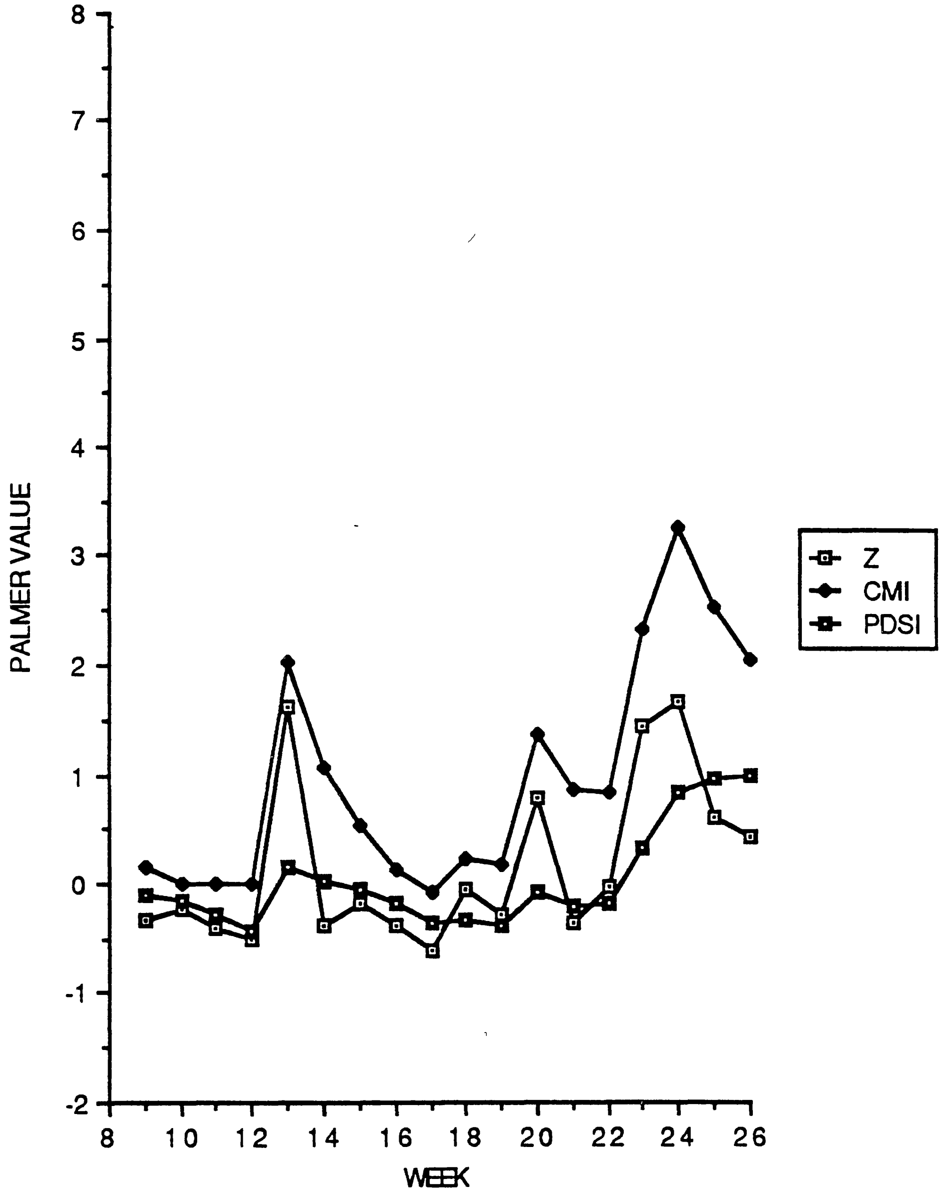


Figure 61. Comparison of Weekly Average PDSI,
CMI and Z-Index Values, 1989

by Week 22.

From Figure 61, it is noteworthy that the CMI values returned the wettest Palmer classifications when compared to the simultaneously acquired PDSI and Z-Index values. The PDSI, given that it statistically weights the previous week's weather condition more than the current in its' calculation, illustrated the slowest change over time of all the indices. Alternatively, the Z-Index increased and decreased the most rapidly of all the indices, and therein accentuated the times of the droughtiest conditions.

The frontal rain events of late March (Week 13), mid May (Week 20) and early to mid June (Weeks 23 and 24), impacted the greatest increases within all the Palmer indices. During Weeks 9 through 19, on average, the PDSI, CMI and the Z-Index, were all characterized by near normal classifications, excluding Week 13, when the CMI and Z-Index shot up to record moderately and mildly wet conditions, respectively. Furthermore it is important to note that from Week 9 up until the precipitation recorded during mid May (Week 20) -- excluding the rain events of Week 13 -- all the indices returned near normal but negative spells, with the average CMI value during Week 17 registering incipient drought conditions throughout the study area.

On the whole, Weeks 20 through 26 included much wetter conditions, as the Palmer indices reacted to the frequently occurring precipitation events within the study area at that time. From late May / early June (Week 22) until mid June (Week 24), all the indices exhibited increases, with the CMI undergoing the greatest categorical change when compared to the lower Z-Index value and, in turn, the most lethargic of Palmer indices, namely, the PDSI, during this particularly wet spell.

Palmer Drought Severity Index. The entire study period from early March (Week 9) through until the end of June (Week 26) was characterized by the average PDSI values registering near normal but negative conditions, which were only punctuated by the rainfall events of late March (Week 13) and throughout June (Week 23 through Week 26), which impacted average increases into the positive, near normal and incipient wet scales, respectively (Figure 62). Before going on to elucidate the week by week PDSI situation, it is essential to highlight that this averaged value throughout this 18 week period, was undoubtedly influenced by the Alva area consistently returning droughty conditions.

During Week 9, the majority of the areas were under negative, near normal classifications, while the Alva and Kingfisher 2 SE areas registered mild drought and incipient wet spells, respectively (Figure 63). Although there were no categorical changes during the following week, Week 10 was characterized by more areas now exhibiting negative, near normal Palmer conditions. By Week 12, the northwestern tier of polygons inclusive of Alva, Cherokee Power Plant, Great Salt Plains and Jefferson indicated drought values, with Alva's PDSI value plummeting to record a moderate drought, while these other areas illustrated incipient drought spells (Figure 64). The frontal precipitation events of Week 13, caused these drier areas to register near normal conditions, although the Alva region still exhibited a mild drought value (Figure 65). In fact, these same drought conditions in the Alva area persisted until mid June, Week 24.

As the month of April progressed, more of the individual polygons began to register negative, near normal classifications in response to the

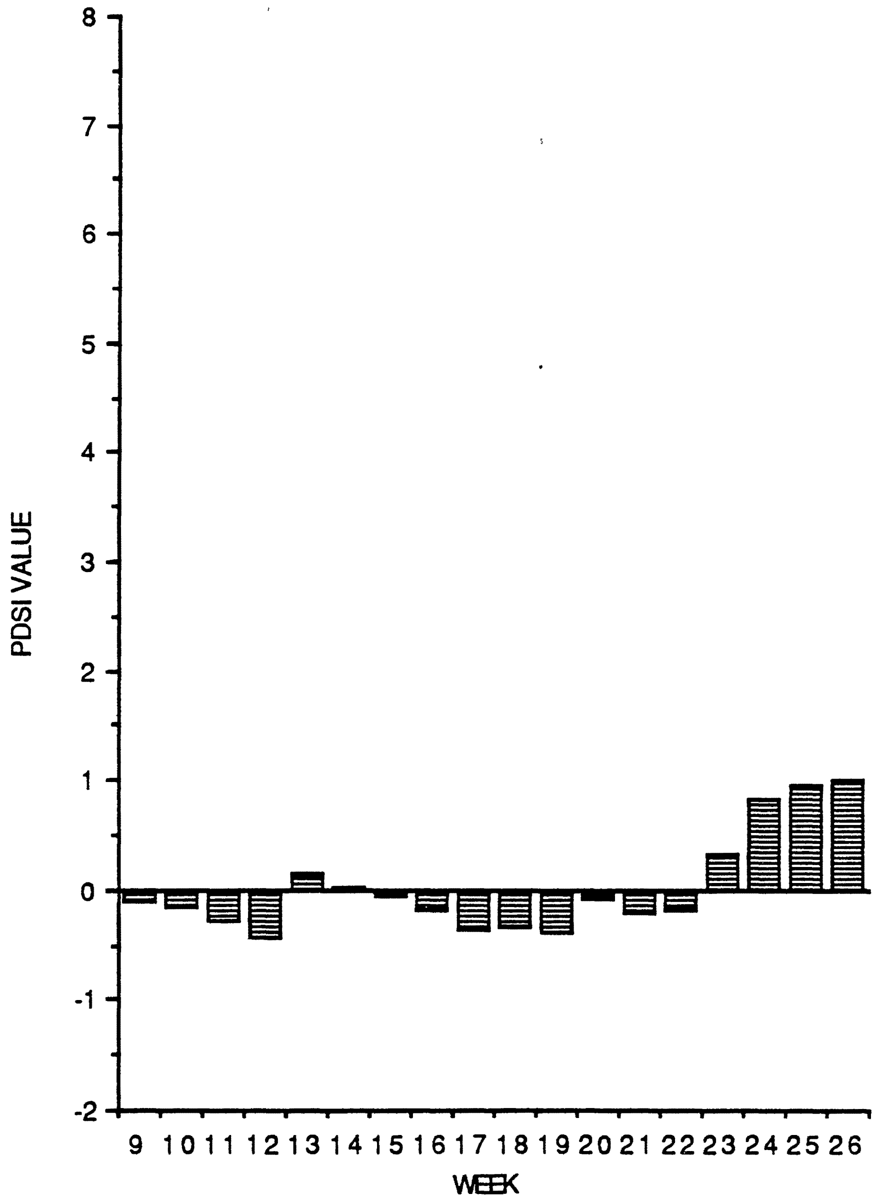


Figure 62. Weekly Average PDSI, 1989

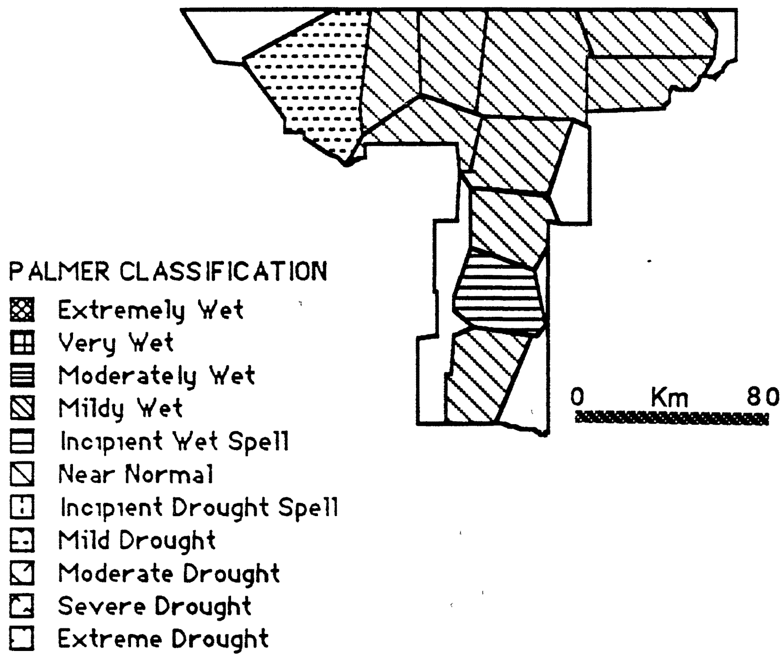


Figure 63. PDSI Week 9, 1989

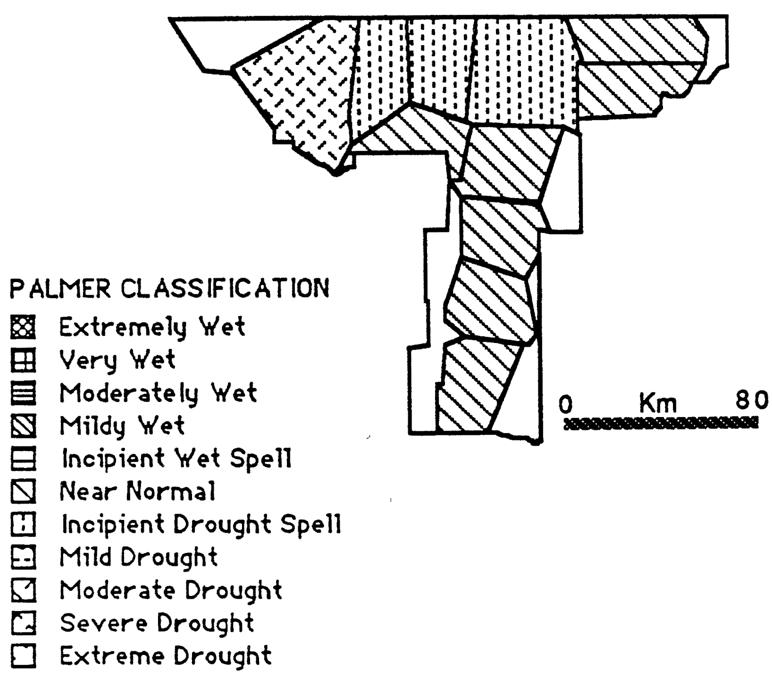


Figure 64. PDSI Week 12, 1989

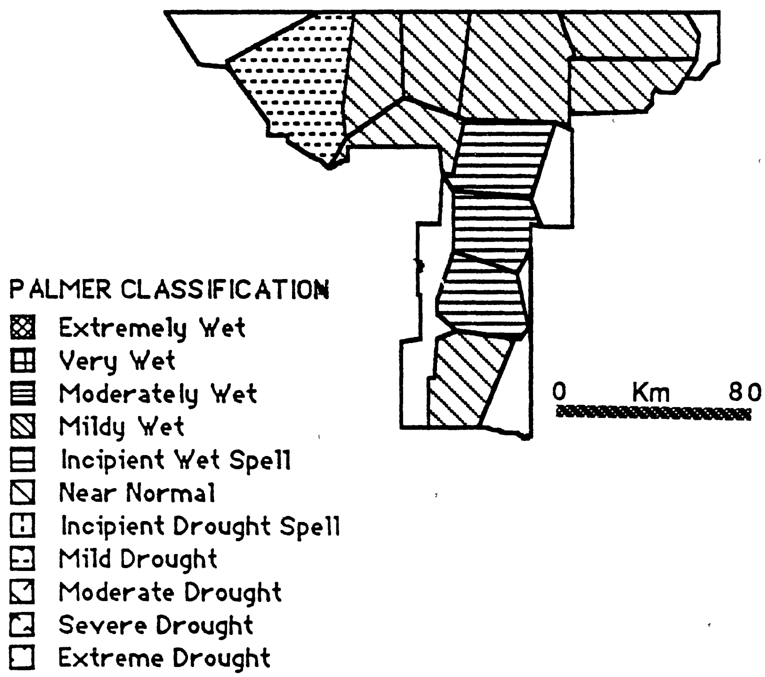


Figure 65. PDSI Week 13, 1989

dry conditions associated with the stabilizing anticyclonic conditions experienced over the entire southern Great Plains (Daily Weather Maps, 1989). By the end of the month, Week 17, the Alva and Ponca City areas returned mild drought and incipient drought values, respectively, while of the remaining nine polygons, all but the central areas of Enid and Hennessey with near normal conditions, exhibited near normal but negative classifications. During early May, Week 19, the areas inclusive of Cherokee Power Plant, Newkirk and Ponca City illustrated incipient drought values, while Alva returned its usual mild drought categorization (Figure 66). Thereafter, most areas continued to return negative, near normal conditions until the start of June's record rainfall, spanning Week 23 through 26, causing all areas to return comparatively wetter PDSI classifications. In fact, by Week 25 (Figure 67), the study area registered PDSI values inclusive of near normal (Alva and Helena 1 SSE) through to moderately wet categories (El Reno 1 N) which hampered the harvesting of the winter wheat crop.

Crop Moisture Index. Since the CMI is designed to react quickly to the onset of rain events, the average CMI values over the study period, highlighted the influence of the precipitation received here during Weeks 13 and 20, and the record rainfall during the month of June as a whole (Weeks 23 through 26) (Figure 68). Over the first four weeks of this investigation, namely, Weeks 9 through 12, the average CMI fluctuated closely around zero, the climatic normal. The impact of Week 13's rain resulted in the CMI increasing to a moderately wet classification, and over the following three week period, it steadily decreased back to near normal conditions (Week 16), which continued throughout the

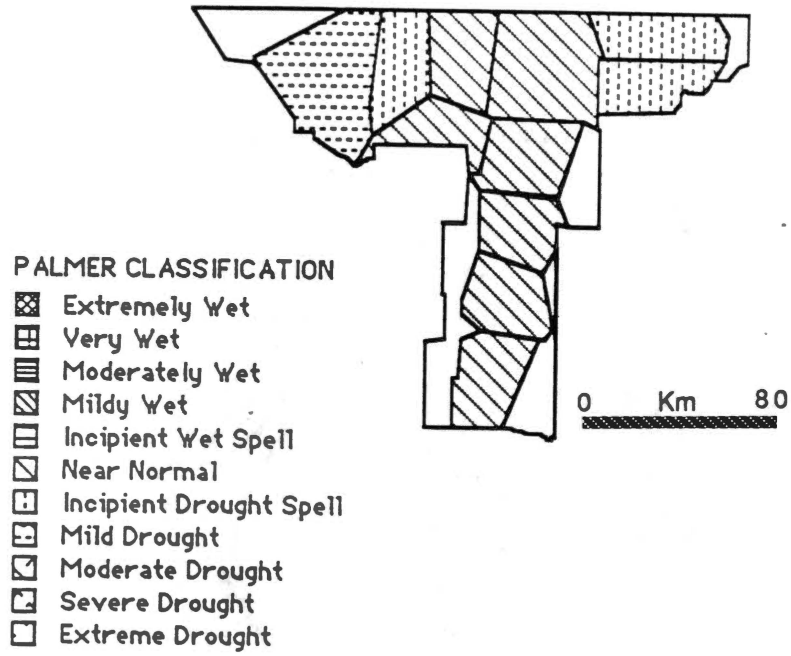


Figure 66. PDSI Week 19, 1989

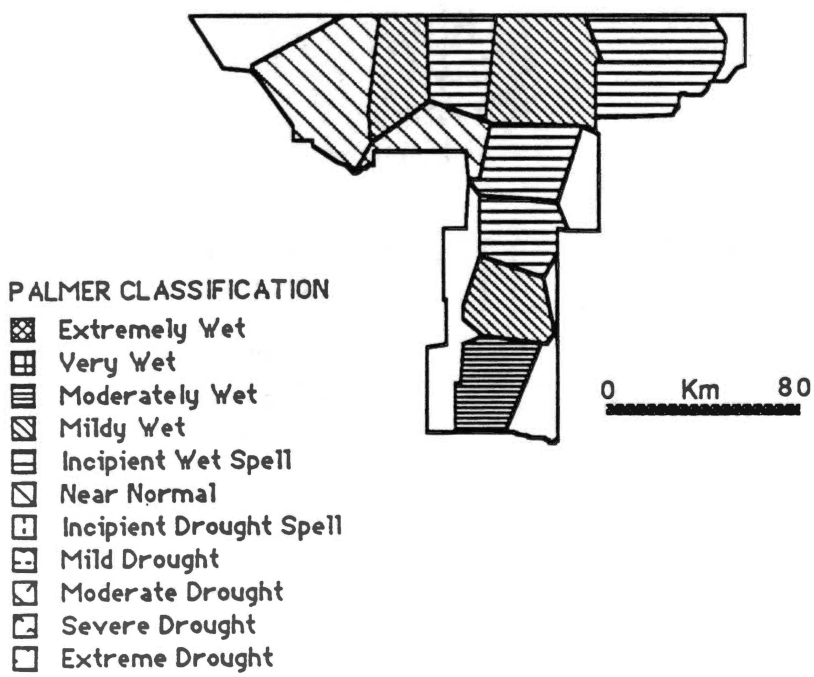


Figure 67. PDSI Week 25, 1989

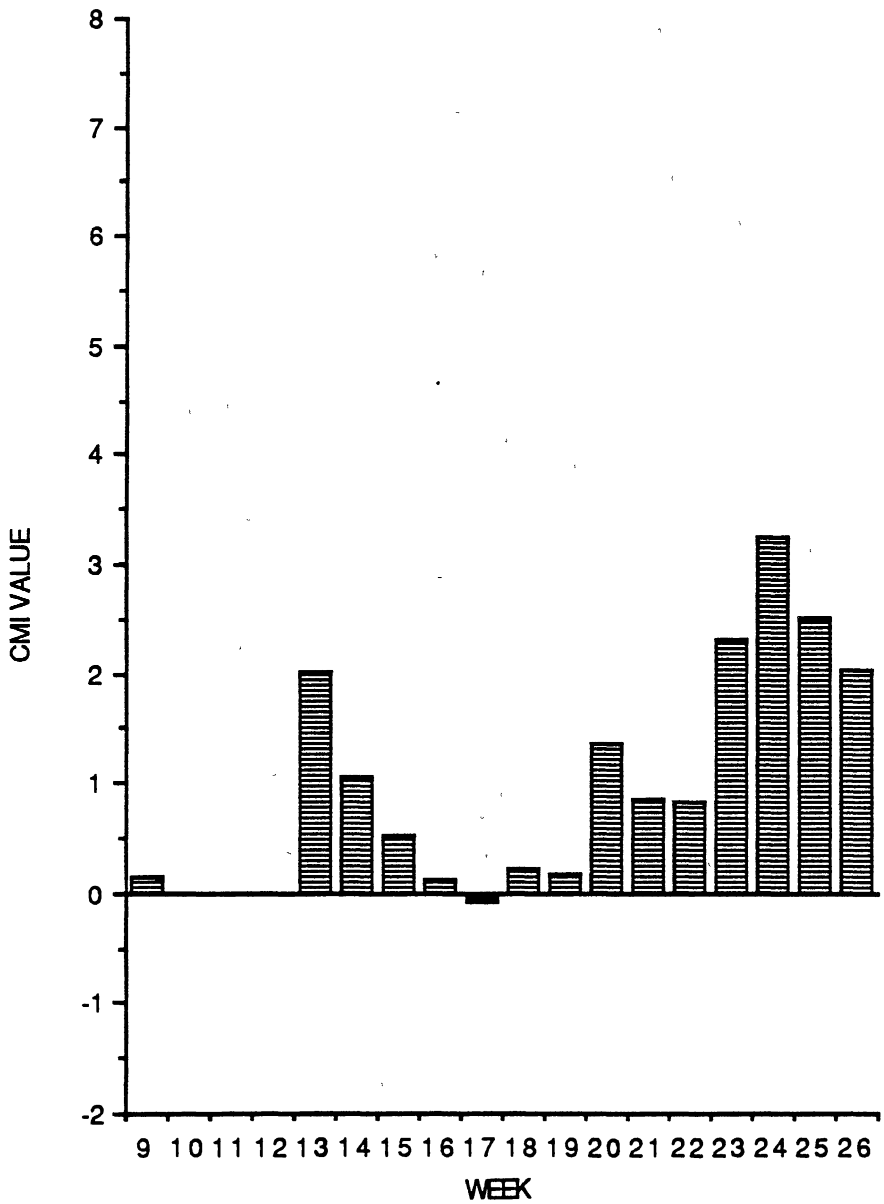


Figure 68. Weekly Average CMI, 1989

comparatively dry month of April until Week 19 in early May. From then on, until the end of June, the average Palmer classifications, experienced the greatest increases during Weeks 20 and 24, with average mildly wet and very wet classifications, respectively.

The beginning of the study period, Week 9 (Figure 69), saw all areas, excluding the two southernmost polygons, namely, El Reno 1 N and Kingfisher 2 SE, exhibiting near normal conditions. However, an analysis of the absolute values forwarded the northern band of areas inclusive of Alva, Cherokee Power Plant, Great Salt Plains, Helena 1 SSE, Jefferson and Ponca City to return slightly negative (i.e. drought), near normal returns. In fact, these near normal but negative CMI classifications encompassed the entire area by Week 11. The precipitation during the last week in March (Week 13) impacted the greatest changes in the central areas of Enid and Hennessey elevating them to very wet categories, while all the remaining areas registered incipient wet spells or above (Figure 70).

April' s dry, anticyclonic conditions resulted in the CMI quickly returning to near normal conditions throughout the study area, and by Week 17 (Figure 71), eight of the 11 polygons exhibited near normal but slightly negative conditions. It is interesting to note that the CMI did not illustrate April's drought very well, and exhibited near normal conditions. Given the April situation, it is safe to point out that the CMI main weakness is that it underplayed a short, but agriculturally significant, drought period. The CMI values increased throughout the study area during Week 20, with the rainfall events being mainly focussed within the northern areas, which returned mildly wet Palmer classifications, excluding the Ponca City area which exhibited an incipient wet spell

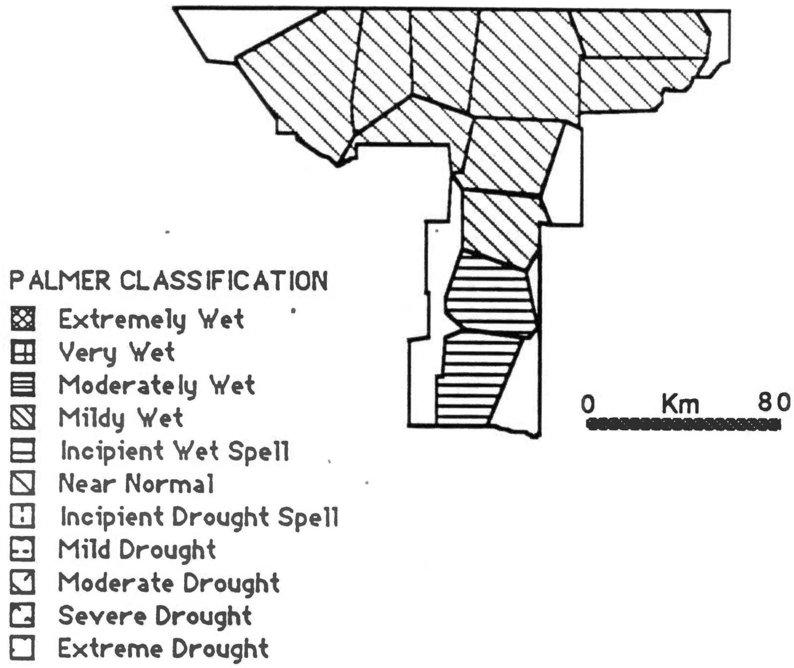


Figure 69. CMI Week 9 , 1989

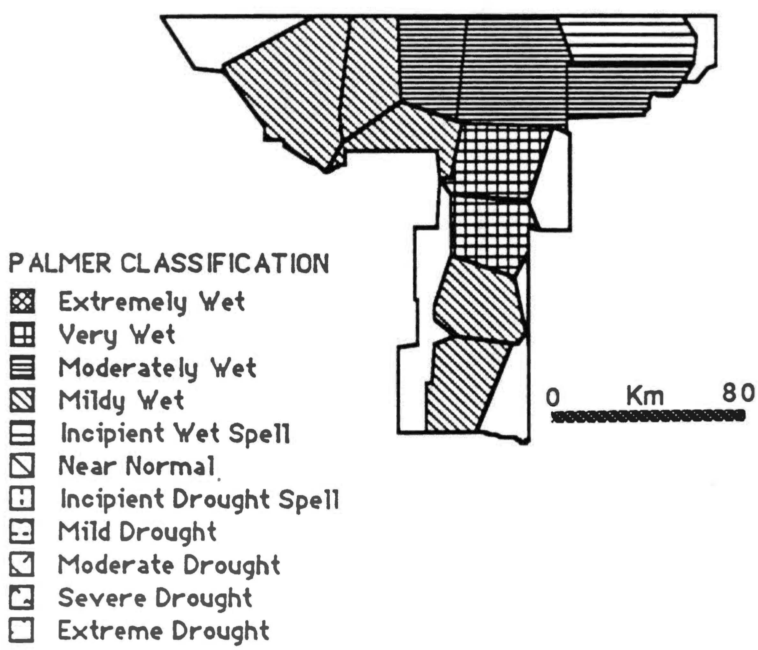


Figure 70. CMI Week 13, 1989

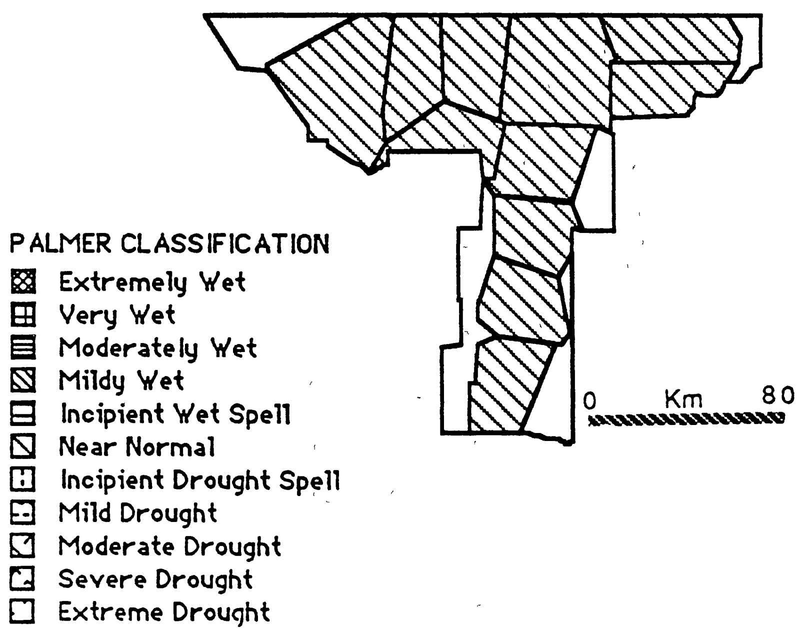


Figure 71. CMI Week 17, 1989

(Figure 72). The last two weeks in May, namely, Weeks 21 and 22, illustrated a somewhat general drying out within the study area.

The first week in June, Week 23, saw the precipitation events being focussed in the central band of the study area, particularly in the Jefferson and El Reno 1 N areas which returned extremely wet conditions (Figure 73). These rain events continued during Week 24, which resulted in eight of the 11 polygons recording greater PDSI values, with only the north central area inclusive of Helena 1 SSE and Enid (both mildly wet), and the Jefferson area with a moderately wet condition, retaining or decreasing their CMI values (Figure 74). On the whole, these conditions continued throughout the remainder of the study period until Week 26, therein illustrating the severity of the rain events throughout the study area during June.

Z-Index. The average Z-Index values illustrated droughty conditions for 12 of the 18 weeks under focus (Figure 75). From Weeks 9 through 12, the average Z-Index values exhibited near normal but negative conditions, which were interrupted by the frontal precipitation events during late March, Week 13, causing a reclassification to a mildly wet value. The following week, Week 14, the Z-Index rapidly returned to a negative near normal classification. These conditions continued throughout the anticyclonic events of April, with its' last week, Week 17, returning an average incipient wet spell. The first two weeks in May, namely, Weeks 18 and 19, illustrated a slight upturn in the averaged Z-Index value, although the negative, near normal conditions were again evident.

The frontal passages during mid May (Week 20) caused the Z-Index to increase to a incipient wet spell value. Following this upturn, the Z-Index

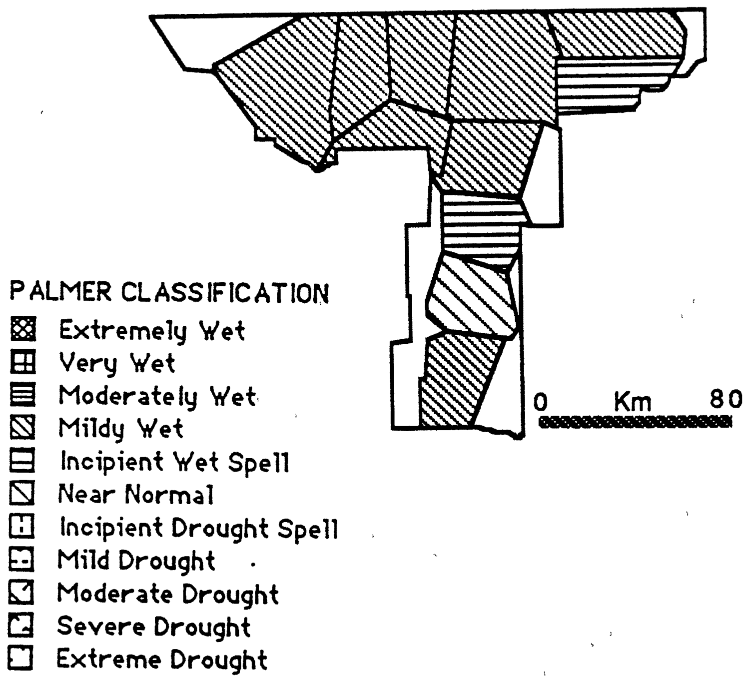


Figure 72. CMI Week 20, 1989

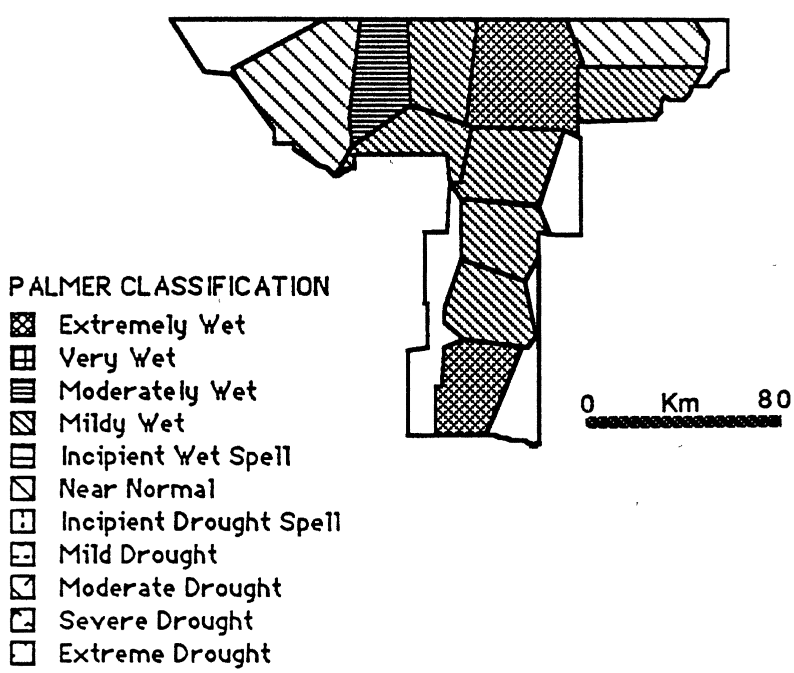


Figure 73. CMI Week 23, 1989

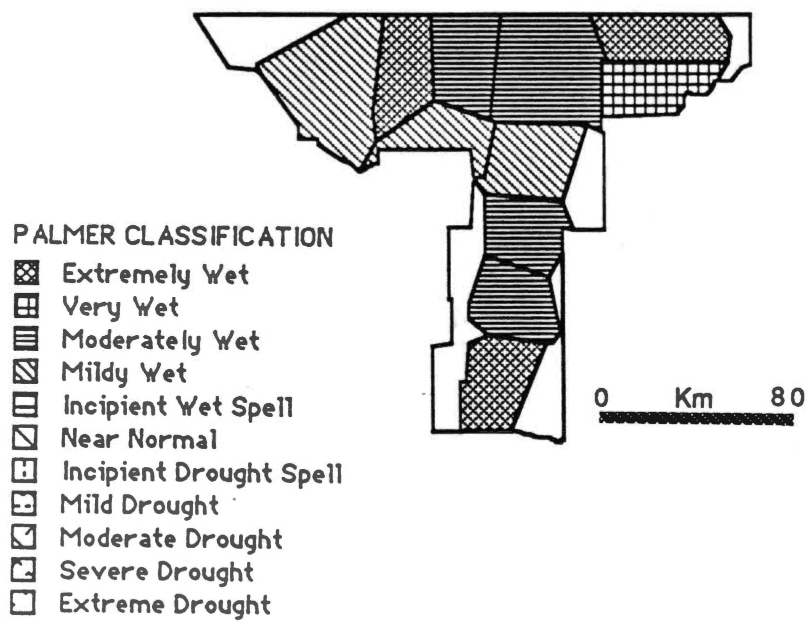


Figure 74. CMI Week 24, 1989

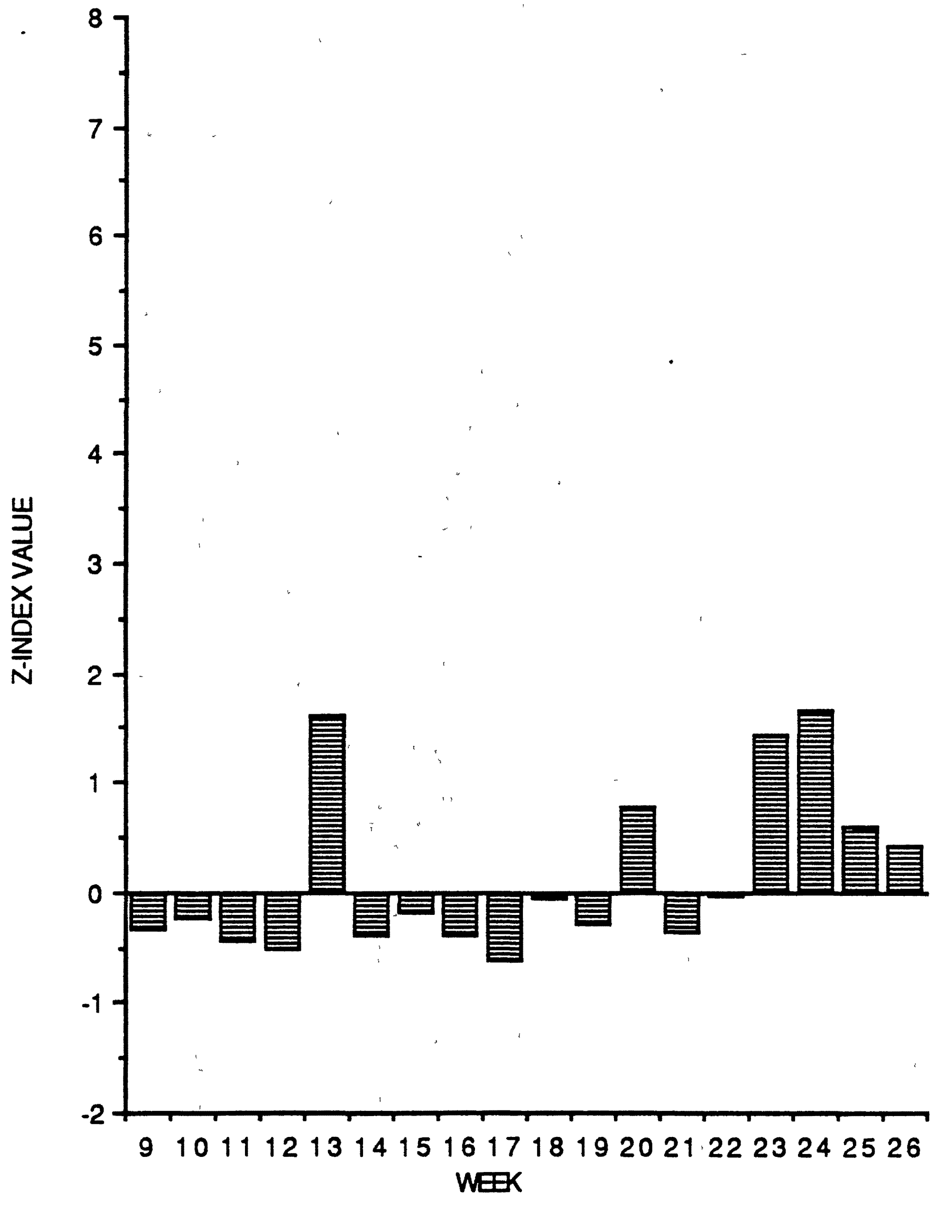


Figure 75. Weekly Average Z-Index, 1989

decreased during the next two weeks to return negative, near normal values. Throughout the month of June, the Z-Index illustrated much wetter Palmer classifications, peaking during Week 24 with an average mildly wet value.

During the initial study week, Week 9, the Z-Index returned near normal but negative values, with the exception of the Alva area which exhibited a mild drought situation (Figure 76). These negative, near normal conditions were replicated throughout the entire study area during Week 10, until Week 12, when the Alva and Cherokee Power Plant areas returned moderate drought and incipient drought spells, respectively (Figure 77). The rapidly changing nature of the Z-Index is highlighted by the impact of the frontal precipitation received during Week 13, causing the north and central areas, inclusive of the Great Salt Plains, Enid and Hennessey, to exhibit moderately wet Palmer values, while the remaining polygons, with the exception of the Newkirk area with a near normal classification, returned mildly wet categories (Figure 78).

The near normal but negative values returned within the study area during early April, Week 14, persisted until the end of April, Week 17, by which time incipient drought spells were recorded in nine of the 11 polygon regions, while the remaining areas of the Cherokee Power Plant and Helena 1 SSE, experienced near normal but negative values (Figure 79). Evidently, the Z-Index picked out April's reported drought condition better when compared to the CMI, with the former simultaneously returning lower absolute Palmer values. This situation prevailed until Week 19, by which time the Alva, Cherokee Power Plant and Ponca City areas in the north, exhibited incipient drought conditions, while localized rainfall had

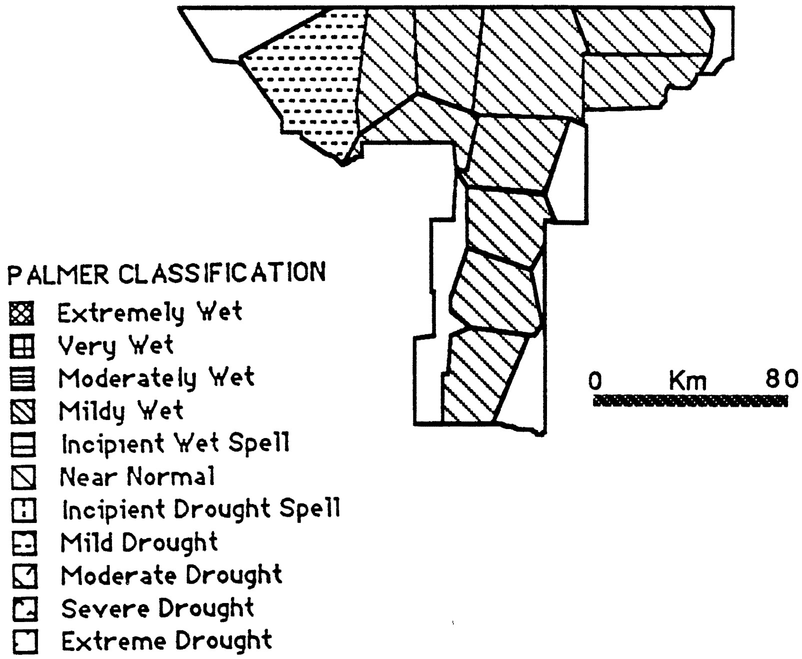


Figure 76. Z-Index Week 9, 1989

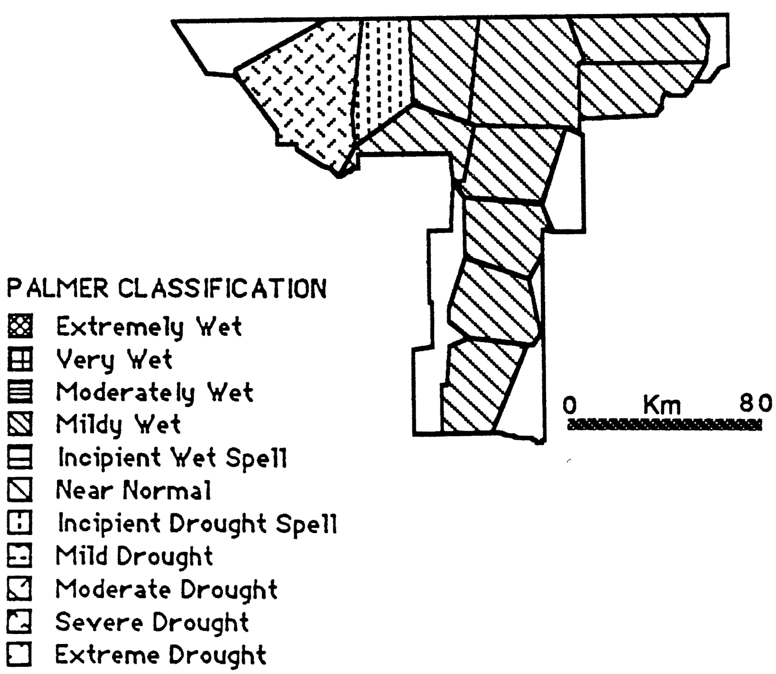


Figure 77. Z-Index Week 12, 1989

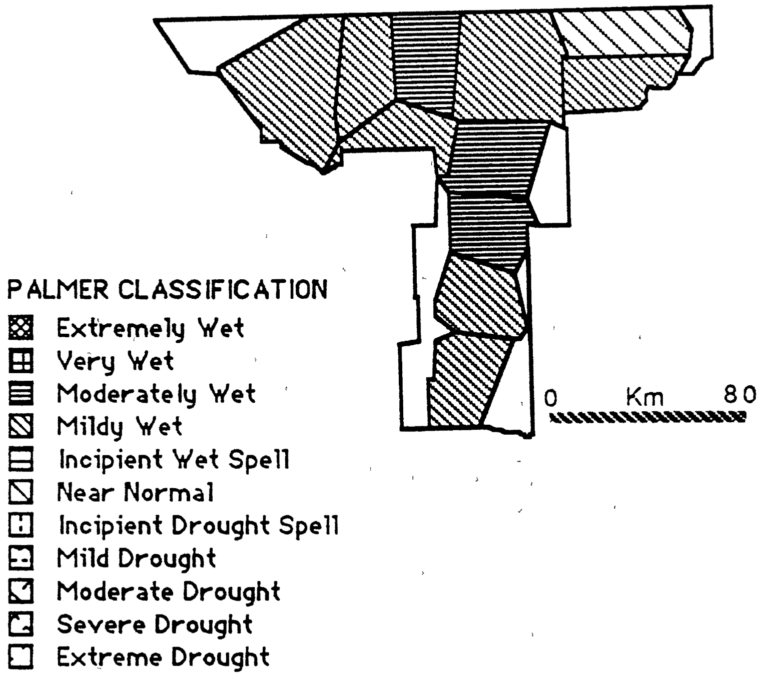


Figure 78. Z-Index Week 13, 1989

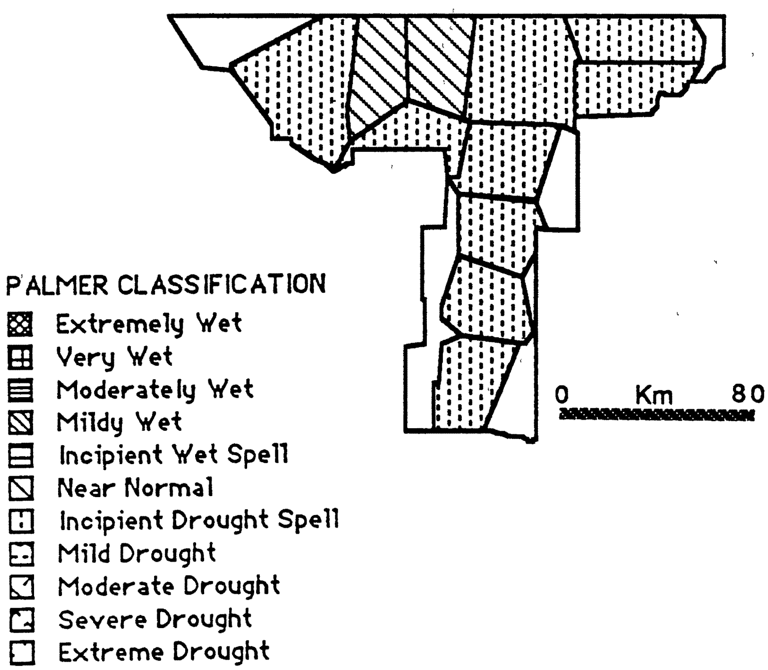


Figure 79. Z-Index Week 17, 1989

elevated El Reno 1 N in the southern extremities of the study area to a mildly wet situation, while the remaining polygons all simultaneously illustrated negative, near normal classifications.

The rainfall events of Week 20 saw each polygon increase its absolute Palmer value. The northwestern area inclusive of Alva, Cherokee Power Plant and Great Salt Plains exhibited mildly wet classifications, while the remaining polygons illustrated a combination of near normal and incipient wet spells (Figure 80). These wetter conditions were superseded by a return to negative Z-Index values throughout the entire study area during Week 21. Week 22, saw a band of mild drought and incipient drought conditions encompassing the Alva, Enid and Helena 1 SSE areas, while the remaining areas developed a combination of near normal, incipient wet and mildly wet values (Figure 81). The entire study area to the west of the Newkirk and Ponca City areas underwent reclassifications to greater Z-Index values during Week 23, especially within the El Reno 1 N and Jefferson areas which recorded very wet Palmer values (Figure 82). These wetter Palmer classifications increased the following week, Week 24, as a result of rainfall being focused upon the northwestern Alva (moderately wet) and Cherokee Power Plant (Very Wet) areas and within the Newkirk and Ponca City polygons, returning extremely wet and mildly wet values, respectively. Thereafter, the Z-Index values declined gradually to register the intermingling of near normal and incipient wet spells throughout the area during Week 25 and 26.

<u>Normalized Difference Vegetation Index</u>

The average NDVI spectral response over winter wheat, spanning the

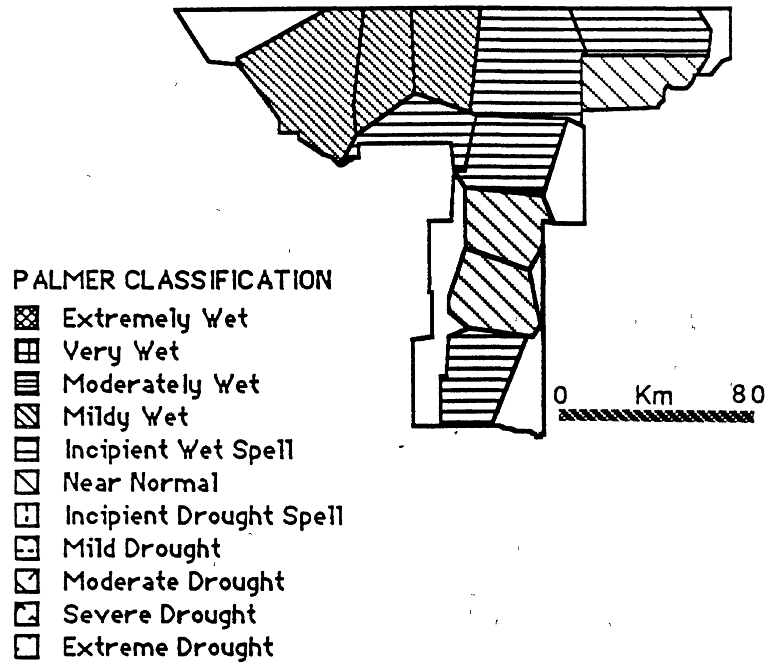


Figure 80. Z-Index Week 20, 1989

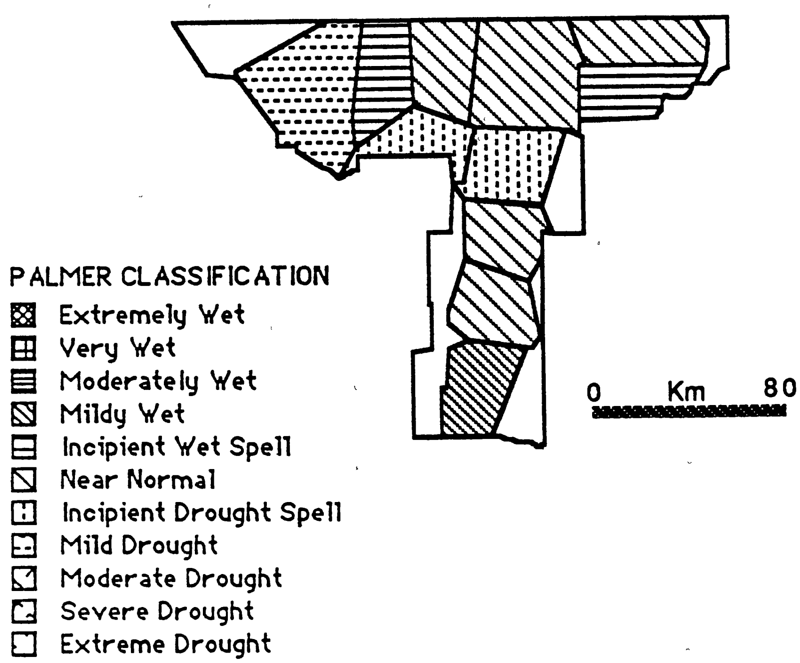


Figure 81. Z-Index Week 22, 1989

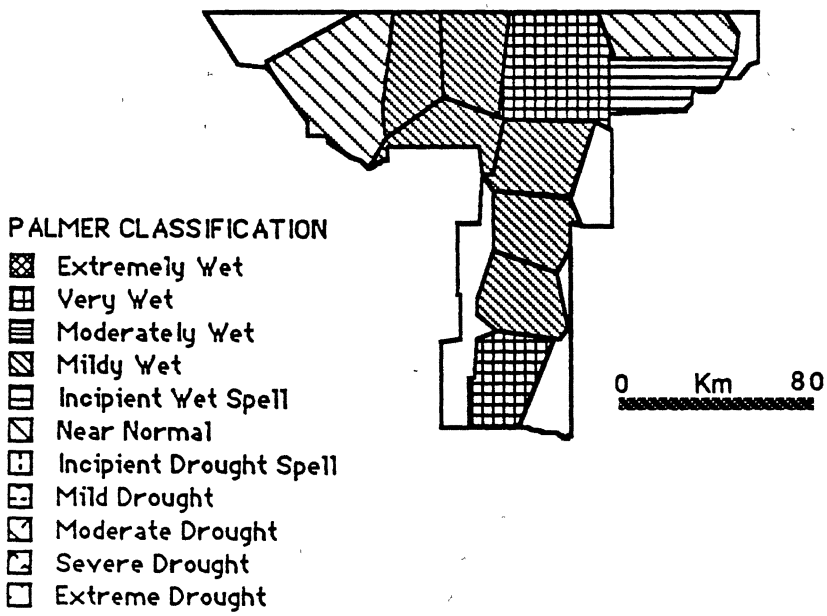


Figure 82. Z-Index Week 23, 1989

'greening-up' and 'browning-out' phases from early March (Week 9) until late May / early June (Week 22), illustrated the expected sigmoidal returns (Figure 83), although the period occurred at a faster rate than in the earlier study years. From these averaged values, it is obvious that the Week 17 exhibited the peak return time, while an inspection of the NDVI values on a polygon by polygon basis, showed that seven of the eleven investigated areas simultaneously returned their peak greenness values. However, the Great Salt Plains and Hennessey areas registered their peak NDVI values earlier during Week 16, while the Cherokee Power Plant and Enid areas reported their 'greenest' values in Week 18.

In considering the largely steady 'greening-up' phase over Week 9 through 17, it is obvious that in early April, namely, Week 14, that the recorded dry conditions determined a rapid greening of the winter wheat crop throughout the study area. However, these continuing hot, dry conditions took their toll on the 'greenness' values during Week 15, as the average rate of increase slowed down, principally in response to the cataloged decreases in the NDVI in all areas excluding El Reno 1 N, Great Salt Plains and Newkirk.

During the accelerated senescence period of the winter wheat from late April (Week 17) through until late May / early June (Week 22), before the rain delayed harvest carried out during mid to late June, there was a noticeable slowing down within the the 'browning-out' returns during Week 21. This event was a result of the apparent 're-greening' of the surface in Alva, Cherokee Power Plant, Helena 1 SSE, Jefferson and Newkirk areas, as the vegetation cover there responded to rain events of mid May during Week 20 and 21. Most probably, this 're-greening', and the

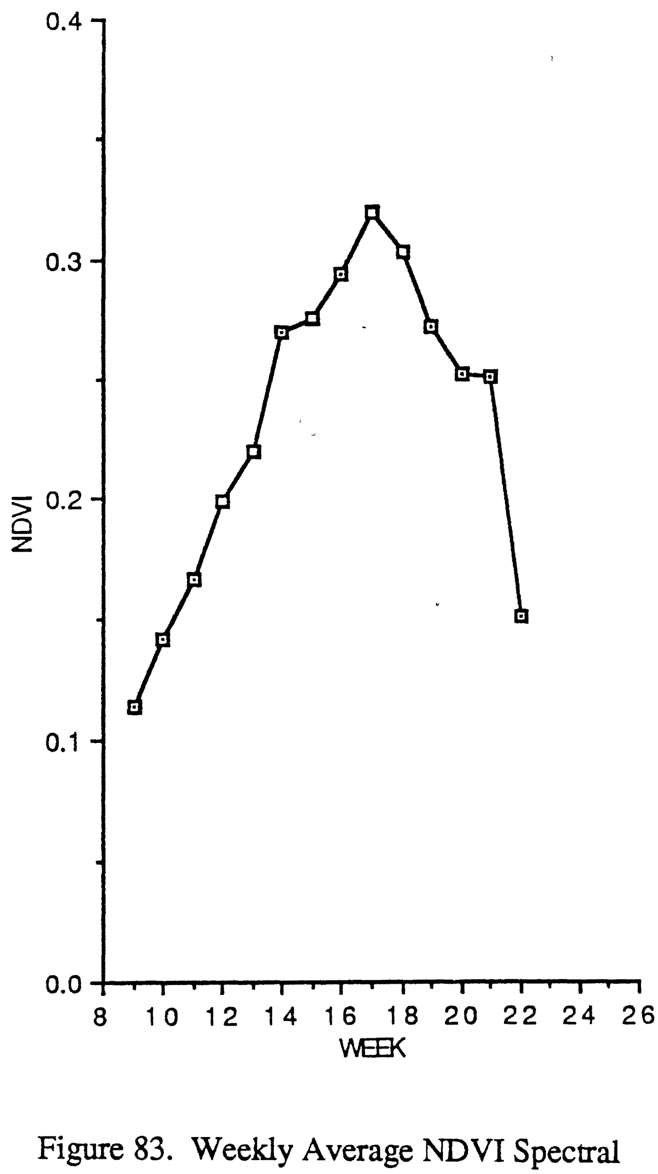


Figure 83. Weekly Average NDVI Spectral Returns Over Winter Wheat in North Central Oklahoma, 1989

increasing NDVI values during the month of June resulted from the growth of other planted and natural vegetation within these areas, rather than the 're-greening' of the senescent winter wheat crop.

Statistical Analysis

The results of the linear regression analyses between each of the individual transformed Palmer indices and the transformed NDVI values are shown in Table VI. The coefficients of determination (r^2) ranged between 80.8 and 99.2 percent and were all significant at the 0.01 level for the indices under consideration during the study period, which spanned Week 9 through until Week 22/23, depending on the area analyzed.

On the whole, the transformed PDSI proved to be the most influential of the three Palmer indices with the transformed NDVI values, with nine of the 11 polygon areas registering the highest r^2 percentage values with the PDSI measure. Evidently, the lethargic nature of the PDSI values, which exhibited little week to week variation, despite the aforementioned dry, anticyclonic period during April and the cyclonic passages of May and early June, registered mostly negative and positive, near normal categories, were the most closely related to spectral signatures over the crop in most areas. Simultaneously, the fluctuating nature of the CMI and Z-Index, as they varied in response to the weather situations which impacted the area during the 'greening-up' and senescent phases of the winter wheat crop were less associated with the spectral returns. However, the Z-Index did return the highest coefficients of determination in the Kingfisher 2 SE and Newkirk area with values of 94.7 and 95.1 percent, respectively.

TABLE VI

PERCENTAGE COEFFICIENTS OF DETERMINATION (r^2) BETWEEN THE PALMER INDICES AND NDVI, 1989 *

POLYGON NAME	PDSI r^2 (%)	CMI r^2 (%)	Z-INDEX r^2 (%)
ALVA	99.2	93.2	93.7
CHEROKEE POWER PLANT	97.1	92.0	93.4
EL RENO 1N	90.0	80.6	86.7
ENID	95.6	92.7	95.1
GREAT SALT PLAINS	98.0	93.2	89.1
HELENA 1 SEE	97.6	93.9	95.1
HENNESSEY	94.9	89.9	92.0
JEFFERSON	91.9	82.7	82.7
KINGFISHER 2SE	87.1	91.3	94.7
NEWKIRK	90.1	86.3	95.1
PONCA CITY	94.6	90.4	93.5
AVERAGE	94.9	93.3	94.0

* All significant at the 0.01 level

The Alva region undoubtedly experienced the most severe drought conditions throughout the study area during this period, with all the indices categorically returning negative Palmer values. Throughout the entire 'greening-up' and 'browning-out' phases, the PDSI registered mild drought values on a week by week basis, with Week 12, being the only exception with a moderate drought situation. Despite the rain events of Week 13 and 20 producing mildly wet values for the CMI and Z-Index, the drought nature of the landscape was still recognized within the PDSI term, and resultantly, the PDSI, with an r^2 value of 99.2 percent was most indicative of the winter wheat spectral signature.

In the other eight polygons which recorded the PDSI as having the greatest coefficients of determination with the NDVI values, the PDSI classifications were noted to range between values inclusive of incipient drought to incipient wet categories, principally registering negative (i.e. drought), near normal values. The simultaneously calculated CMI and Z-Index collectively experienced greater weekly variations than the PDSI, especially within the El Reno 1 N and Jefferson areas causing lower r^2 values there.

The last five weeks of the winter wheat's senescence, namely, Week 19 through 23, in the El Reno 1 N area, which received the greatest overall rainfall amounts of all areas therein, illustrated increasing CMI and Z-Index values which peaked with extremely wet and very wet values, respectively. However, at the same time, the PDSI values increased from near normal through to a mildly wet classification. Therefore, it is safe to point out that the slower reacting PDSI values were more indicative of the 'browning-out' NDVI returns with an r^2 value of 90.0 percent, when the

Z-Index and CMI returned 86.7 and 80.6 percent, respectively.

The Jefferson area was largely under negative, near normal PDSI conditions throughout its' entire 'greening-up' and senescent period up until the end of May / beginning of June (Week 22), which were only interrupted by near normal values following Week 13s rainfall. This dry situation, was largely replicated within both the CMI and Z-Index, although the Week 13 precipitation causing the CMI and Z-Index to simultaneously illustrate mildly wet classifications. Furthermore, the frontal rainfall during Week 20 resulted in the CMI and Z-Index values increasing from negative, near normal conditions, to mildly wet and incipient wet categories, respectively, while the PDSI continued to register a drought, near normal value. Evidently, despite these rainfall events, they did not appear to play any significant role within the 'greening-up' and 'browning-out' periods of winter wheat throughout the Jefferson area.

The Z-Index proved to have the greatest influence over the NDVI in the Kingfisher 2 SE and Newkirk areas, with r^2 values of 94.7 and 95.1 percent, respectively, in comparison to the PDSI and CMI there. On inspection of the PDSI values for Weeks 9 through 22 in the Kingfisher area, it was obvious that this index registered amongst the greatest absolute values throughout the month of March, at a time when the average Z-Index consistently returned near normal but negative values. In fact, negative Z-Index values continued throughout the study period, except following the rain events of Weeks 13 and 22, while the PDSI and CMI illustrated the continuation of relatively wetter and drier classifications, respectively, throughout this period until final senescence of the crop here. The combination of negative, near normal and incipient drought PDSI values throughout the study period, forwarded a r^2 value of 90.1 percent for the Newkirk area. Simultaneously, the much more fluctuating CMI value gave a r^2 value of 86.3 percent. However, the Z-Index proved to have the greatest coefficient of determination at 95.1 percent, in response to a combination of negative and positive near normal values ranging through to incipient wet spells during the the 'greening-up' and 'browning-out' phases. Evidently, the PDSI and CMI overestimated the impact upon the NDVI values over winter wheat during the droughty April and wetter, early June events here, respectively, than the more stabilized Z-Index during these critical stem extension and kernel-filling phases, respectively.

Utilizing the average transformed NDVI returns from the 44 pixels over the study area's polygons, and averaged transformed PDSI, CMI and Z-Index values, the coefficients of determination were virtually indistinguishable at 94.9, 93.3, and 94.0 percent, respectively. However, given the internal variation in the severity of the drought and / or wetter phases, particularly in the El Reno 1 N, Jefferson, Kingfisher and Newkirk areas as outlined above, these averaged values mask these important environmental differences from place to place.

CHAPTER V

INTERANNUAL COMPARISONS

Introduction

In order to address if size of study area plays a role in the relationships between NDVI and the Palmer indices, a single polygon, namely, Alva will be considered for the 1982, 1985 and 1989 crop growing seasons. Following this, a brief, but nevertheless critical, systematic comparison of how each of the Palmer variables and the NDVI spectral returns over winter wheat, varied between 1982, 1985 and 1989 during the post winter dormancy growth phases in north central Oklahoma will be developed.

Alva : Interannual Comparisons

The Alva polygon was primarily chosen for study here as it illustrated some of the greatest weather extremes within the 11 polygon areas for the study 'years'. During mid May through until the end of June, 1982, Alva experienced very wet episodes and in the 1989 winter wheat growing season the area exhibited an almost continual drought condition.

Palmer Indices

The 1982 Palmer values (PDSI, CMI and Z-Index) for the Alva area (Figure 84) largely paralleled the average situation (Figure 24), exhibiting noticeable categorical increases for all these indices following the

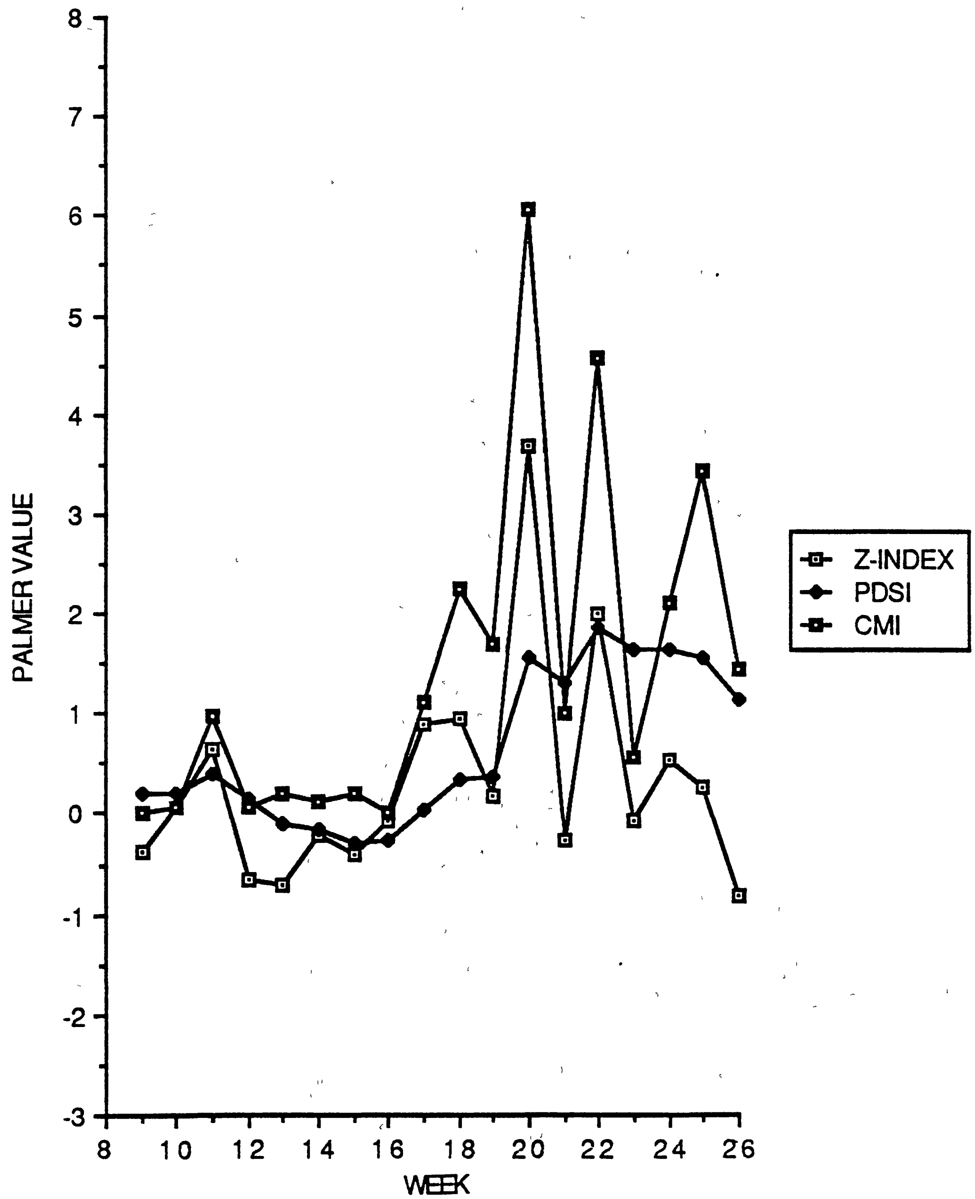


Figure 84. Weekly PDSI, CMI and Z-Index Values
in Alva, 1982

frontal rain events of mid March (Week 11), and particularly from early May (Week 18) onwards. As such the CMI experienced the greatest week to week variations, while being illustrative of wet periods, especially from early May (Week 18) onwards ranging from near normal through to extremely wet conditions. The Z-Index highlighted the droughtier times during the 1982 growing season, particularly from late March (Week 12) with an incipient drought spell through until mid April (Week 16) which registered near normal but negative conditions.

Like 1982, the Palmer indices for the 1985 growing season in Alva (Figure 85) largely replicated the overall average situation (Figure 40). Nevertheless, Alva experienced a greater range in the absolute Palmer values calculated. Although, somewhat mirroring the average 1985 growing season situation, all Palmer indices portrayed wet situations during Weeks 12, 13, 17 and 23 following frontal passages over the Alva area, it is evident that early May (Week 19) (Figure 85) illustrated significant upturns in Alva's PDSI, CMI and Z-Index returns. These values, which ranged between moderately wet and very wet classifications, must have been associated with a localized thunderstorm event herein.

Although, the Palmer variables in the Alva area during 1989 (Figure 86) registered identical perturbations as the average situation, it is striking that the PDSI illustrated continual drought values from early March (Week 9) through until mid June (Week 24). These values fluctuated between a mild and a moderate drought situation, which illustrated the driest returns from all polygons during 1989.

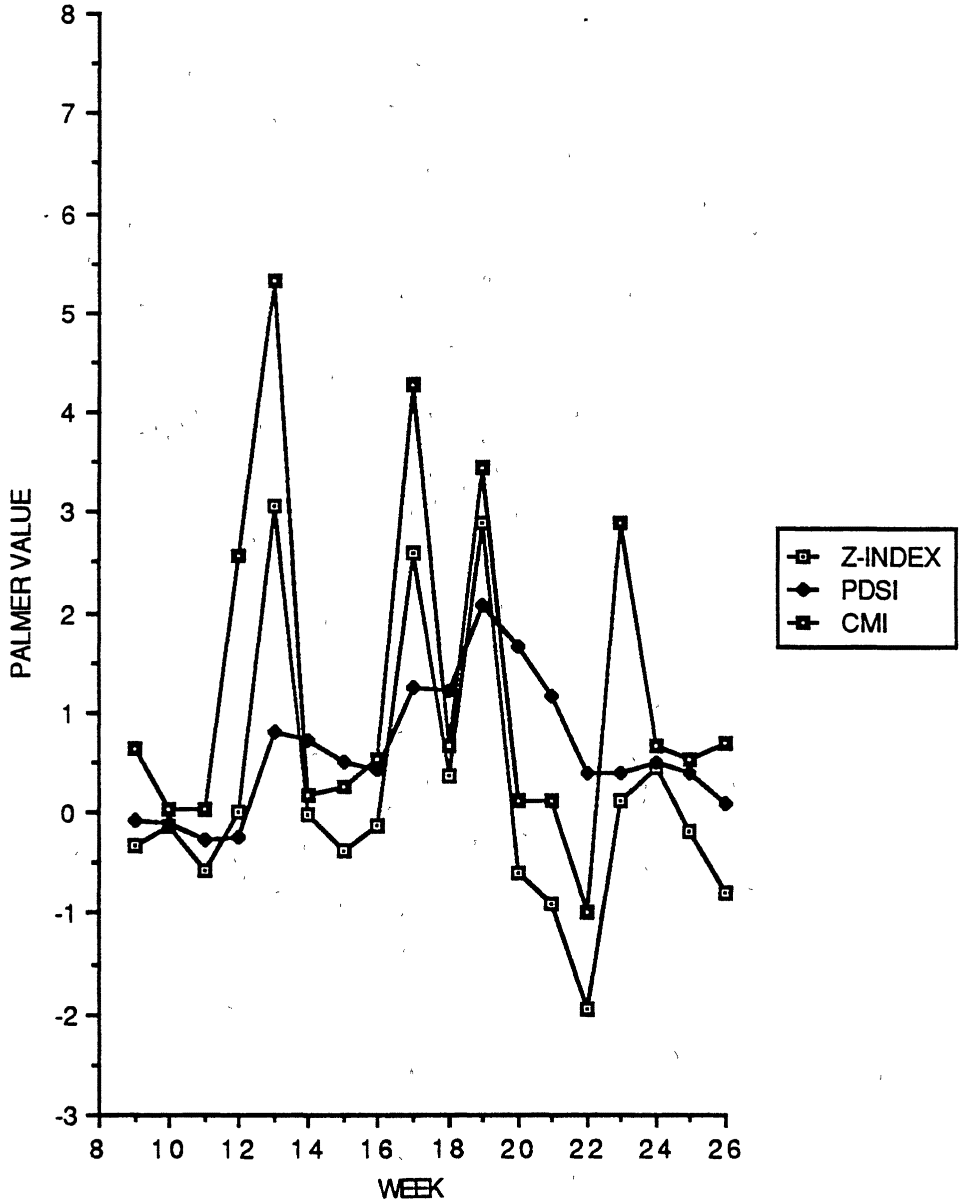


Figure 85. Weekly PDSI, CMI and Z-Index Values in Alva, 1985

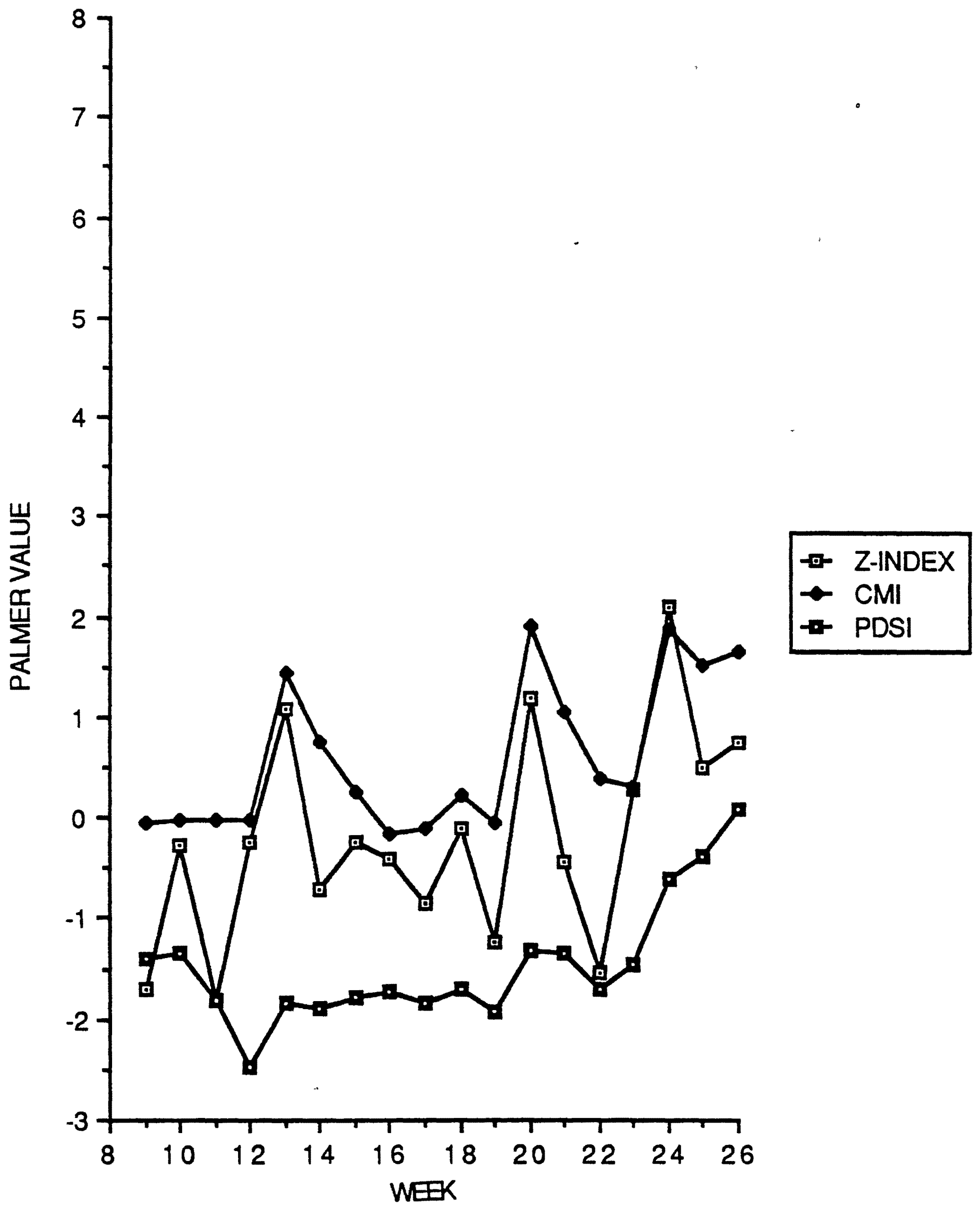


Figure 86. Weekly PDSI, CMI and Z-Index Values in Alva, 1989

Normalized Difference Vegetation Index

The weather situation, as outlined by the values and tendency of the Palmer indices, significantly impacted upon the winter wheat spectral returns for the Alva polygon over 1982, 1985 and 1989. The wettest 'year', namely, 1982, produced the highest NDVI values which peaked around mid May (Week 20) (Figure 87) which was coincident with the end of season precipitation events. For Woods County -- which the polygon area of Alva essentially encompasses -- the winter wheat harvest for 1982 returned a record yield at 40 bushels per acre. The two other study 'years', namely, 1985 and 1989, illustrated comparatively lower NDVI values, with both 'years' having earlier, and much lower, peak 'greenness' returns during early April (Week 14) and late April (Week 17), respectively. The 1985 yield in Alva was 24 bushels per acre, while in 1989 a value of 27 bushels was returned for the entire state as a whole (Krenzer, pers. comm. -- no county estimates were available).

During the senescent phase for the 1982 winter wheat, from Weeks 20 through 26, in the Alva area, it is particularly noteworthy that there was a noticeable 're-greening' of the landscape during late May / early June (Week 22) at a time of large frontal precipitation. This upturn in the NDVI value was probably a result of the growing of other surface coverages, rather than the 're-greening' of the winter wheat crop, which had began to 'brown-out' by this time.

The 1985 NDVI values over winter wheat exhibited senescence beginning from mid April (Week 15) onwards, although the frontal precipitation of Week 17 and the thunderstorm of Week 19, impacted a increase in the NDVI of the underlying surface (Figure 87). Apparently, the

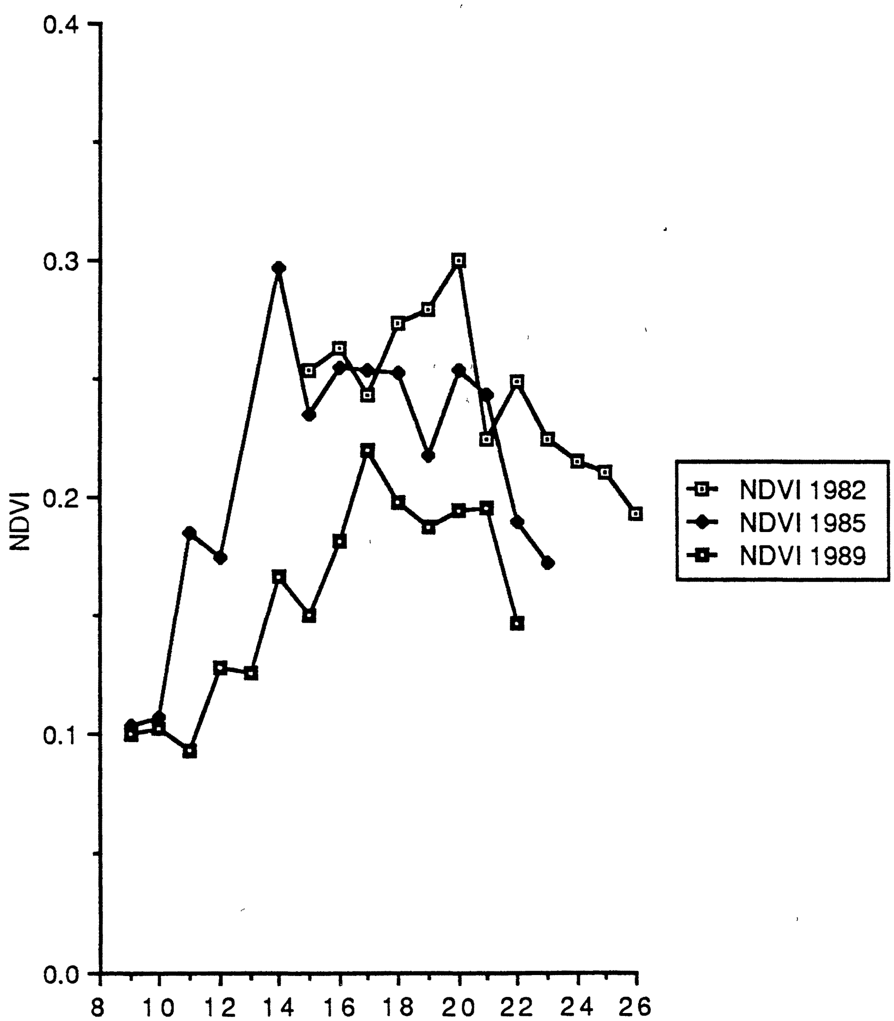


Figure 87. Comparison of NDVI Spectral Returns
Over Winter Wheat in Alva,
1982, 1985 and 1989

NDVI value illustrated a lag time between the thunderstorm of Week 19 and the noticeable 're-greening' during the following week (Week 20).

The 1989 spectral NDVI returns over Alva's winter wheat illustrated an increasing nature, punctuated by some declines, until peak 'greenness' by early May (Week 18). These declines were apparently a result of the drought stressed returns during the growing season. Comparing the various NDVI values for 1982, 1985 and 1989, it is apparent that the wet nature of 1982 resulted in greater returns, while the drought conditions of 1989 suppressed the NDVI throughout the growing season. Therefore, it is safe to point out that winter wheat stress, as illustrated the spectral returns, is observable from satellite, even when dealing with such a small area, which was borne out for the eventual yields realized.

Statistical Results

The coefficients of determination (r^2) for the Alva area over the 1982, 1985 and 1989 growing seasons -- following the outlined transformation-linearization procedures -- returned similarly high values between the transformed Palmer and NDVI, as illustrated in Tables IV, V and VI. The wet situation during the later half of the 1982 growing season from late May / early June in Alva -- for which AVHRR NDVI was available -- was best represented by the CMI, which was closely related to the accumulated NDVI with an r^2 value at 98.2 percent. This result is not surprising given that the CMI is designed to quickly react to periods of precipitation, at a time when this area received a record late May and June rainfall.

The 1985 Alva area's coefficients of determination (r^2) at 98.1 and

98.3 percent for the transformed CMI and Z-Index, respectively, forwarded marginally greater results than the transformed PDSI at 94.9 percent. The CMI and Z-Index values simultaneously recorded the greatest Palmer values of the entire area over Alva, during Weeks 13, 17 and 19 and the droughtiest conditions herein during Week 22. However, these important extreme values were not replicated within the PDSI -- illustrating its lethargic nature caused by the weighting of the previous weeks' situation more than the current weeks' in its calculation -- which ultimately resulted in the PDSI variable underestimating the influence that these wet and dry periods had on the recorded NDVI spectral returns over winter wheat in the Alva area within particular parts of this 16 week study period.

The Alva region undoubtedly experienced the most severe drought conditions throughout the study area during 1989, with all the indices categorically returning negative Palmer values. Throughout the entire 'greening-up' and 'browning-out' phases, the PDSI registered mild drought values on a week by week basis, with Week 12, being the only exception with a moderate drought situation. Despite the rain events of Week 13 and 20 producing mildly wet values for the CMI and Z-Index, the drought nature of the landscape was still recognized within the PDSI term, and resultantly, the PDSI, with an r^2 value of 99.2 percent was most indicative of the winter wheat spectral signature.

Study Area : Interannual Comparisons

Palmer Indices

Tracing the PDSI, CMI and Z-Index on a week by week basis over the three study 'years' under investigation, the expected pattern of the reaction rates were borne out within the observed data, as determined by the different calculations involved in their derivation.

The most operationally sensitive index, that is, the CMI, was noted to increase at the most rapid rate in both time and space within the study area, and therein was particularly elucidative of the periods of high weekly precipitation amounts (Figures 27, 47 and 68). During the 'wet' year, 1982, the CMI indicated a maximum average value of around 6.5 -- an extremely wet classification -- during mid May (Week 20), cataloging a time when the study area received a record monthly precipitation at 285 mm. The lowest CMI returned from throughout all of the study areas was registered during Week 22, 1985, when the study area illustrated a combination of mild drought and incipient drought conditions on a polygon basis. These droughty CMI values were determined by this week experiencing dry, hot daily maximum temperatures ranging from 28 °C to 38 °C, during the critical kernel-filling stage of the winter wheat crop at that time. Up until then, a bumper harvest had been envisaged, but this short, although highly important, period literally decimated the eventual yield with only 22 bushels per acre realized.

The Z-Index, the mean weekly moisture anomaly index, reacted at a comparatively slower rate than the CMI to the onset of wet and/or dry events, although the Z-Index proved categorically to be the most illustrative of droughty conditions experienced within the study area (Figures 30, 54 and 75). The continuing drought nature of the 1989 winter wheat growth regime (Figure 75) was in fact only finally broken with the record torrential rainfall received during the month of June.

The characteristically most lethargic of the Palmer indices used, namely, the PDSI, was observed to undergo the least week to week variation over the three study 'years' (Figures 25, 41 and 62). Comparing these graphs, it is obvious that the periods just before and/or during the harvest in June (Weeks 22 through 26), for 1982 and 1989 crops, signified the relatively wettest deviations from the long term normals, with average mildly wet conditions. It is particularly noteworthy, that the average PDSI illustrated the nature of the droughty situation which developed and remained within the study area from early March (Week 8) until the first week in June (Week 23), 1989, despite rain events during Week 13 and 20, which never overturned the long term situation.

The timing and amount of precipitation experienced within the various parts of the study area, allied to the mean weekly calculated temperature, as outlined by the relative values and tendencies of the three Palmer indices, were obviously determinant in the eventual winter wheat yields obtained.

Normalized Difference Vegetation Index

The NDVI values over the study area roughly exhibited similar 'greening-up' -- except for 1982 when the data was unavailable until Week 15 -- and 'browning-out' phases (Figure 88). It is particularly noteworthy that the wettest 'year', namely, 1982, exhibited the 'greenest' peak value for the NDVI during early April, Week 15, while 1985 crop peaked one week later, during Week 16. The environmentally plagued 1989 crop exhibited the greatest NDVI value during the last week in April, namely, Week 17. Evidently, the conditioning weather situation experienced during

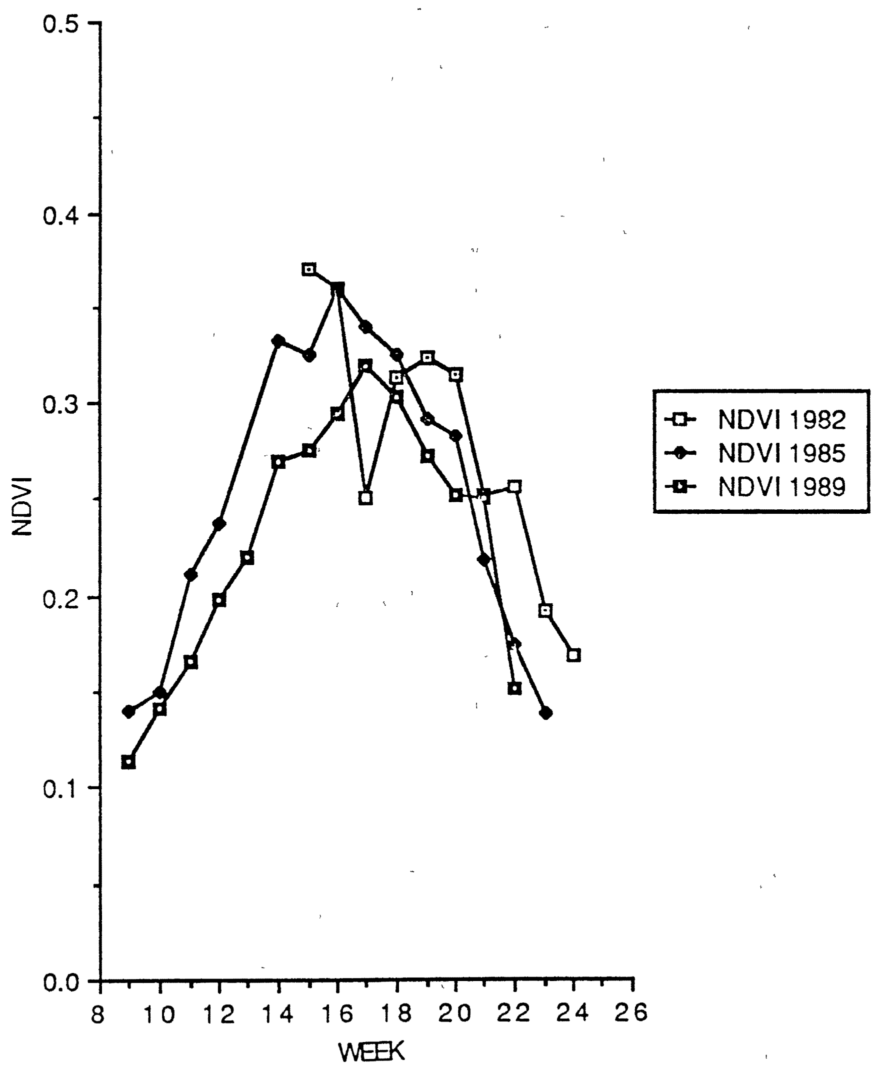


Figure 88. Comparison of Weekly Average NDVI Spectral Returns Over Winter Wheat in North Central Oklahoma, 1982, 1985 and 1989

the 'greening-up' phase, resulted in a lag in the timing of the peak returns before the onset of senescence. Moreover, compared to the 1982 and 1985 crops, the NDVI value over this drought-affected crop zone during 1989 was consistently lower than the other 'years' weekly NDVI values throughout the post dormancy growth season. In addition, the 1989 crop experienced spectrally senescence from Week 17 to Week 22, while the lowest NDVI values for the 1985 and 1982, followed during Week 23 and 24, respectively.

It is striking that the wettest 'year', namely, 1982, exhibited the greatest week by week NDVI values over the senescencent period for which remotely sensed data was available. On the whole, the average NDVI values for 1989, were consistently the lowest within almost all of the weeks considered throughout the 'greening-up' and senescence periods. This resulted in less vegetation development, although the yield at 27 bushels per acre was not as low as the 1985 value despite 'greener' returns. The 1985 low yield was a determined by sustained, extremely hot temperatures which undermined the crops' previous vitality and resulted in a low kernel-filling amount, thus suppressing the eventual yield, although this event was not spectrally distinct within the 'browning-out' winter wheat. In addition, it is important to realize that despite the study area being spectrally homogeneous, eventual yield cannot be reliably related to the NDVI spectral signature since yield is not available on a polygon basis. Moreover, yield is a parameter which is integrated over the entire growing season and is largely determined by fertilizer application.

Statistical Results

Comparing Tables IV, V and IV, it is obvious that high coefficients of determination (r^2) registering greater than 80 percent for all the transformed indices with cumulative NDVI, which were all significant at the 0.01 level. However, the tendency of the Palmer values were not necessarily replicated within the NDVI values, and thus positive, cumulative transformations were carried out on these variables to overcome the problem of negative Palmer values. As a result, on the whole, through a linear regression technique on a polygon by polygon basis, the transformed PDSI proved to be the most closely related to the accumulated NDVI during the 'normal' 1985 and 'dry' 1989 times for their 'greening-up' and 'browning-out' phases. Although the transformed CMI and Z-Index were virtually inseparable in regard to the r^2 values during the 'wet' 1982, it is essential to reiterate that these results were representative of this exceptionally wet senescent period over winter wheat.

It is safe to conclude, that the PDSI was the most closely related to of NDVI spectral returns over winter wheat, particularly during stabilized weather conditions. Where short spells of drought or particularly wet weather afflicted an area, the Z-Index and CMI were noted to register accordingly, respectively, although, with the exception of a few areas in 1985 and 1989 analyses, the stabilized PDSI was the most enlightening therein. Therefore, the NDVI spectral returns, despite naturally progressing from week to week, it is obvious that they never underwent rapid changes, and its' developments were mirrored best by the PDSI term.

There was no reported significant advantage in using average Palmer and NDVI values as an alternative to the individual polygon values. It could be claimed that, depending on the scale of interest that the averaged values may have hidden more than they elucidated, since they had a tendency to ignore the influence of localized wet (e.g. thunderstorms) and/or dry events in individual polygon areas, and the effect on the spectral signature of the crop therein, as illustrated by the Alva results outlined above.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main objective of this study was to determine whether the PDSI, CMI or Z-Index was the most associated with, and conditioning of, winter wheat oriented NDVI spectral returns in north central OKlahoma. The principle reason for focussing in on this particular part of the Southern Great Plains 'Wheat Belt' zone emanated from the fact that winter wheat growth dominates the landscape here, with in excess of 40 percent of the total farmland devoted to its cultivation annually. Resultantly, this area was spectrally distinct during the crops critical 'greening-up' and 'browning-out' phases spanning March through June annually. Furthermore, due to the NDVI data only being publicly available from April, 1982, onwards, then this determined the temporal research focus herein.

Due the almost ubiquitous nature of winter wheat over the surface, this study area forwarded an excellent basis from which to test the strength of the previously, largely unexplained temporal and spatial relationships between Palmer indices and NDVI values during post dormancy winter wheat growth. Bearing this in mind, it was decided to simultaneously investigate the Palmer indices and NDVI returns over recorded 'wet', 'near normal' and 'dry' 'years', namely, 1982, 1985 and 1989, to see if the variations within and between these years would return different results. In addition, it is important to note that 1989 winter wheat growing season as a whole was not 'dry', but there have been no totally dry 'years' over the satellite NDVI record. In order to test the relationships between each of the Palmer variables and the NDVI herein, a series of linear regression analyses were performed, forwarding the coefficients of determination (r^2), through transformations of the original data sets, following the developed methodology.

The coefficients of determination (r^2), which were derived between the various transformed Palmer indices and accumulated NDVI, returned consistently high percentage results, which ranged from 80.6 to 99.2 percent for areas within the three periods studied and were all significant at the 0.01 level. Importantly, for the 1985 and 1989 crops, the transformed PDSI proved to be the most closely associated with transformed NDVI values on a polygon by polygon basis for the majority of these areas, during these 'near normal' and 'dry' 'years'. Alternatively, for the 1982 crop, the PDSI did not as strongly mirror the development of the NDVI values over the 'browning-out' winter wheat phase, and therein the Z-Index and CMI consistently returned higher r^2 associations. These lower PDSI r^2 values during 1982, resulted from an extended period of stabilized wet Palmer conditions being noted over the latter half of the spectral senescent phase, when the other indices characteristically reacted at much quicker rates to the perturbations of the weather situations experienced.

Although Karl's (1986) research claimed that for most agricultural interests that the Z-Index would be found to be more useful than the PDSI, this investigation found that the comparatively lethargic nature of the PDSI -- accounted for by its statistical weighted calculating technique --

was more illustrative of, and associated with, the winter wheat's spectral progression as assessed during the 'near normal' (1985) and 'dry' 'years' (1989). It can be concluded that the NDVI values on the whole did not undergo the extreme fluctuations that the CMI and Z-Index sometimes experienced on a week to week basis.

The NDVI, which measured the vigor and density of the 'viewed' green vegetation, illustrated the annual sigmoidal nature of the winter wheat crop as it progressed through the 'greening-up' and 'browning-out' phases for the 1982 (senescence only) , 1985 and 1989. It is particularly noteworthy that the 1989 crop consistently returned the lowest week by week NDVI values as determined by the droughty nature of the growth regime then. Furthermore, the categorically 'wet' year, 1982, returned much higher greenness values than during the other two study years over the senescence phase, and in the end, it exhibited the greatest average yield at 34 bushels per acre for the three seasons studied. Therefore, at this scale and at the polygon level as outlined for the Alva area, it is possible to monitor winter wheat growth and stress during the post dormancy 'greening-up' and 'browning-out' phases. Nevertheless, given that the entire winter wheat agricultural area in the southern Great Plains is human modified through the application of fertilizers, it is impossible to relate the NDVI to the eventual yields realized.

Given the distinct spectral nature of the post-dormancy spring growth period of the winter wheat in the study area, the employed methodology could be utilized in either regional or global settings which record monocultural crop dominated signals. In addition, within this homogeneous cropland area, the remotely sensed NDVI returns over winter wheat proved to be more illustrative of the crops growth situation than the calendar date as a result of the interannual variation in the weather situation as indicated by the Palmer indices.

Recommendations

With the PDSI, CMI and Z-Index being indices which are derived from a series of different water balance computations based on the collection -- weekly precipitation and mean weekly temperatures -- and estimation -- evapotranspiration and runoff -- of the variables used in their calculations, it would be interesting to address how in fact rainfall and temperature individually affect the value and tendency of the the NDVI values. Moreover, although Alley (1984) has documented some of the problems inherent in Palmer's (1965) assumptions in regard to potential evapotranspiration and the runoff terms, no index is currently available which specifically measures the effect of spring water availability on winter wheat's growth regime in the southern Great Plains.

In this light, research is needed within the NDVI literature in regard to the quantitative and qualitative assessment of the spectral returns over cropland. This could be accomplished through the integration of simultaneously measured and observed ground based phenomena, such as rainfall amount, degree growing days, total dry matter production and biomass, to mention but a few, if the remote sensing spectral observations are to be better understood. Furthermore, due to the spectral data only being available for the comparatively wet 1980s, it would be beneficial to be able to measure the relationships between the NDVI and PDSI, CMI and Z-Index over a continuously drought-stressed crop.

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