PATTERNS AND TRENDS OF SOIL CLIMATE REGIMES AND DROUGHT EVENTS IN THE NORTHERN GREAT PLAINS

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1.1 INTRODUCTION

Drought is the dominant process of crop loss nationally and within Nebraska. Nearly two-thirds of the 18.6 million harvested acres are covered by crop insurance (USDA/RMA, 2003; USDA/NASS, 2003). For the most part, Nebraska's crop losses range from $50 to 75 million in non-drought years, but the losses approach nearly $200 million in drought years, such as 2000. The past growing season (2002) crop losses are projected to greatly exceed $375 million in Nebraska and more than $4 billion nationally (USDA/RMA, 2003). The analysis and understanding of drought processes in the Great Plains is an important component to developing drought mitigation strategies and reducing agricultural risks on the landscape. In building a drought decision support system for Nebraska, we have proposed a suite of drought indices linked to geospatial databases describing the agricultural statistics or infrastructure to identify drought regions and potential impacts. Most approaches to visualizing drought indices, such as the traditional Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Precipitation Index (SPI; McKee et al., 1993; 1995), and the Drought Monitor (Svoboda et al., 2002) are small-scale maps that provide a regional (climate divisions) or national perspective, emphasizing current conditions. Most mapping approaches do not integrate thematic overlays of the agricultural infrastructure or provide the historical context, relative to agroecosystems, cropping systems, or the potential economic liabilities. In our research, we are describing the geography of agriculture, its vulnerabilities, and the drought characteristics at multiple temporal and spatial scales to enhance the understanding of drought risks.

In this paper, we will introduce new applications of soil moisture regimes as a drought risk indicator of patterns and trends within an agricultural drought decision support system. The Enhanced Newhall Simulation Model represents a longer-term time window (growing season; 6 to 9 months) and historical context that can compliment SPI, PDSI, and the Drought Monitor, in describing different parameters of drought events.

The Enhanced Newhall Simulation Model (ENSM) is a modified version of Van Wambeke et al. (1992), originally intended for classification of soil climate regimes. Soil climate regimes (Van Wambeke et al., 1992; Soil Survey Staff, 1999) describe the pattern of days when soils are above 5^{o}C or 8^{o}C and moist, moist to dry, and provide a classification of growing season environments. Although the Newhall Simulation Model has been run on individual weather stations with 30 year normals for classifying soil moisture and temperature regimes, it has not been extended to describing or classifying drought events and their historical context.

1.2 OBJECTIVES

Our research is designed to build a suite of geospatial risk assessment tools within a drought decision support system that assists USDA programs and the National Drought Mitigation Center's ability to: 1) compute and map drought metrics, such as soil moisture regimes (Enhanced Newhall Simulation Model) across multiple time windows and spatial scales, 2) develop new drought interpretations and vulnerability maps through integration of national USDA databases with those from the automated weather network of the High Plains Regional Climate Center and the NWS cooperative station network, and 3) develop new thematic maps and interpretations to better visualize the potential exposure of the agricultural infrastructure to drought events.

2. MATERIALS AND METHODS

2.1 SOIL CLIMATE REGIMES

Soil climate regimes were modeled for long-term weather stations, as well as University of Nebraska-Lincoln Research and Extension Centers (see Figure 1) in Nebraska to detect and characterize shifts through time. Weather stations were modeled on an annual time-step using the Enhanced Newhall Simulation Model (ENSM) and summarized to develop frequencies and probabilities of soil moisture regimes, as well as identify major drought and wet cycles. The root zone available water-holding capacity for each weather station was spatially derived through the State Soil Geographic Database (STATSGO; Soil Survey Staff, 1994; 1999) and Soil Ratings for Plant Growth (SRPG; Soil Survey Staff, 2000), and used as the primary soils input for the soil water balance calculations within ENSM. Key to our new efforts is the inclusion of "Centennial Stations", with weather records extending more than 100 years, which provides a unique archive to apply data mining and knowledge discovery algorithms for pattern associations between soil moisture regimes, crop yields, and oceanic parameters (Multivariate ENSO Index; MEI).

The Newhall Simulation Model (NSM) has long been used by the USDA Natural Resources Conservation Service to estimate soil moisture regimes as defined in *Soil Taxonomy* (Soil Survey Staff, 1975, 1999; Newhall and Berdanier, 1996). Van Wambeke et al. (1992) modified the original model and introduced new subdivisions of soil moisture regimes (Figure 2) and variable soil moisture storage. Van Wambeke (1981, 1982, and 1985) applied the model to map soil moisture regimes across Africa, South America, and Asia. Our research follows these earlier definitions, concepts, and applications, but it attempts to improve the temporal and spatial resolution of the ENSM and generate probabilities from long-term records that can be used to interpret crop production risks.

The NSM was developed to run on monthly normals for precipitation and temperature; generally 30 year normals were most reasonable and appropriate. However, the ENSM can also be run on monthly records of individual years to develop frequency distributions of soil moisture regimes. Both the original NSM and ENSM rely upon a modified Thornthwaite (1948) approach for the calculation of potential evapotranspiration (PET). Although the ENSM still shares inherited routines and concepts from the Palmer Drought Severity Index (Palmer, 1965), it provides reasonable estimations of soil moisture and temperature regimes, which can yield the historical perspective of shifts in soil climate regimes across the Northern Great Plains.

2.2 RASTER SURFACES AND MAPS

A raster interpolation (Thin-Plate Spline) procedure was used in conjunction with the ENSM results to map the frequencies of soil climate regimes at multiple scales--subcounty, county, watershed, and major land resource area (MLRA). Soil climate parameters were interpolated using “s.surf.tps” (Mitasova, 1992; Mitas and Mitasova, 1999) in GRASS 5.0 to derive a 200 m resolution grid. Similarly, sub-calculations behind the soil climate regime classification can be mapped to produce ancillary themes of growing season precipitation, potential evapotranspiration, annual water balances, mean summer soil water balance (Precipitation-PET)$_{\text{June-July-August}}$, and soil biological windows (cumulative days that the soil is above 5^{o}C and moist). The web-based, ENSM can be reached at http://nadss.unl.edu and run on National Weather Service (NWS) Cooperative Weather Station sites throughout the conterminous U.S. .

FIGURE 1
THE DISTRIBUTION OF NWS COOPERATIVE WEATHER STATIONS ACROSS NEBRASKA.

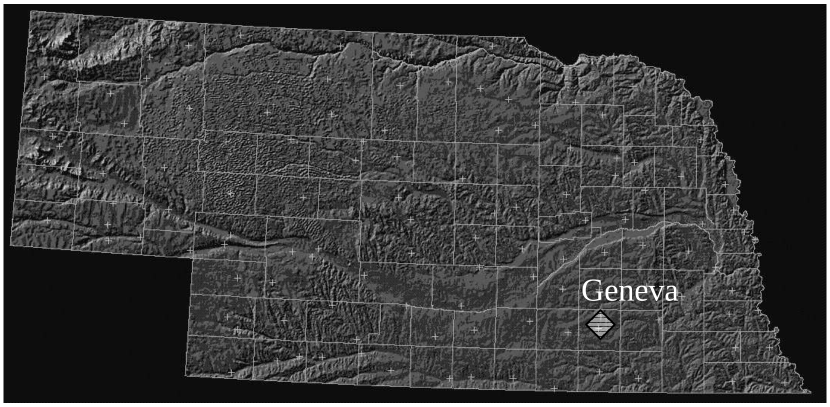
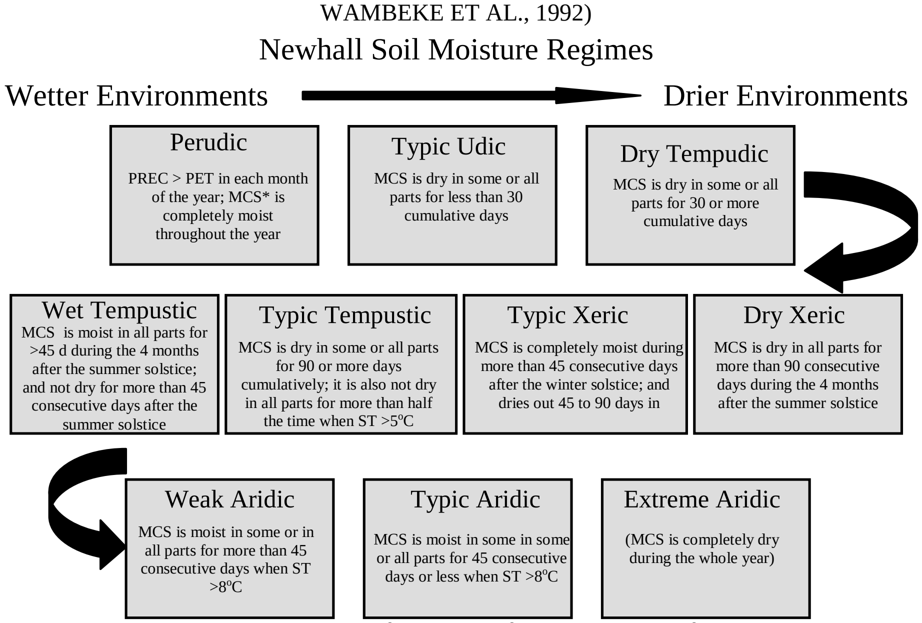


FIGURE 2
THE CLASSIFICATION OF SOIL MOISTURE REGIMES (VAN WAMBEKE, 1985; VAN WAMBEKE ET AL., 1992)



*MCS is the Moisture Control Section of the soil profile which extends from 25 cm to 100cm below the soil surface.

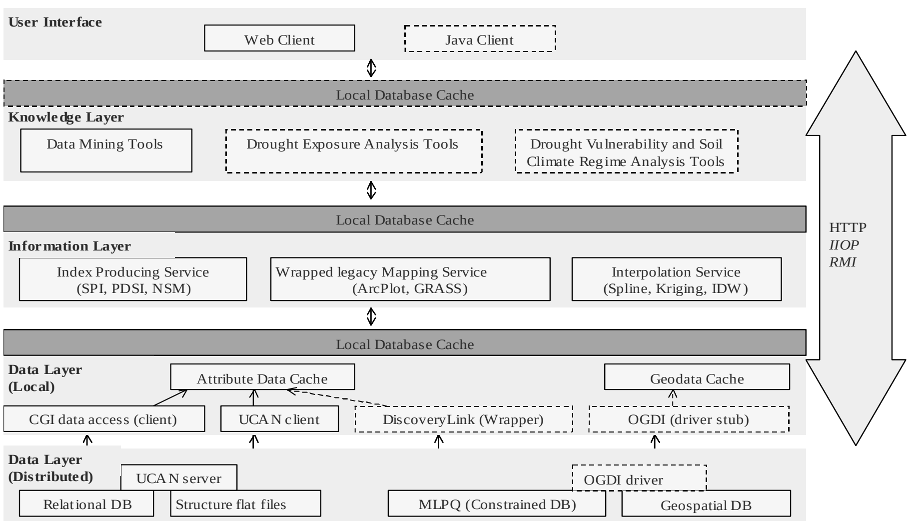
Statewide and national maps of soil moisture regime frequencies can be generated for specific temporal windows as a continuous raster surface and re-summarized to a county-level or physiographic interpretation.

3. RESULTS AND DISCUSSION

3.1 WEB-BASED TOOLS

The Enhanced Newhall Simulation Model is part of a suite of drought indices to characterize the historical context of events and explore their relationships to crop yields and ENSO cycles. The drought indices are part of a 4-tier architecture in the National Agricultural Decision Support System (NADSS; Figure 3) that integrates exposure analysis, risk assessment, knowledge discovery, and geospatial analysis tools operating across a coherent framework of climate (High Plains Regional Climate Center, HPRCC; and the Unified Climate Access Network, UCAN) and USDA databases, such as soils (Natural Resources Conservation Service), crop insurance (Risk Management Agency), and agricultural statistics (National Agricultural Statistics Service).

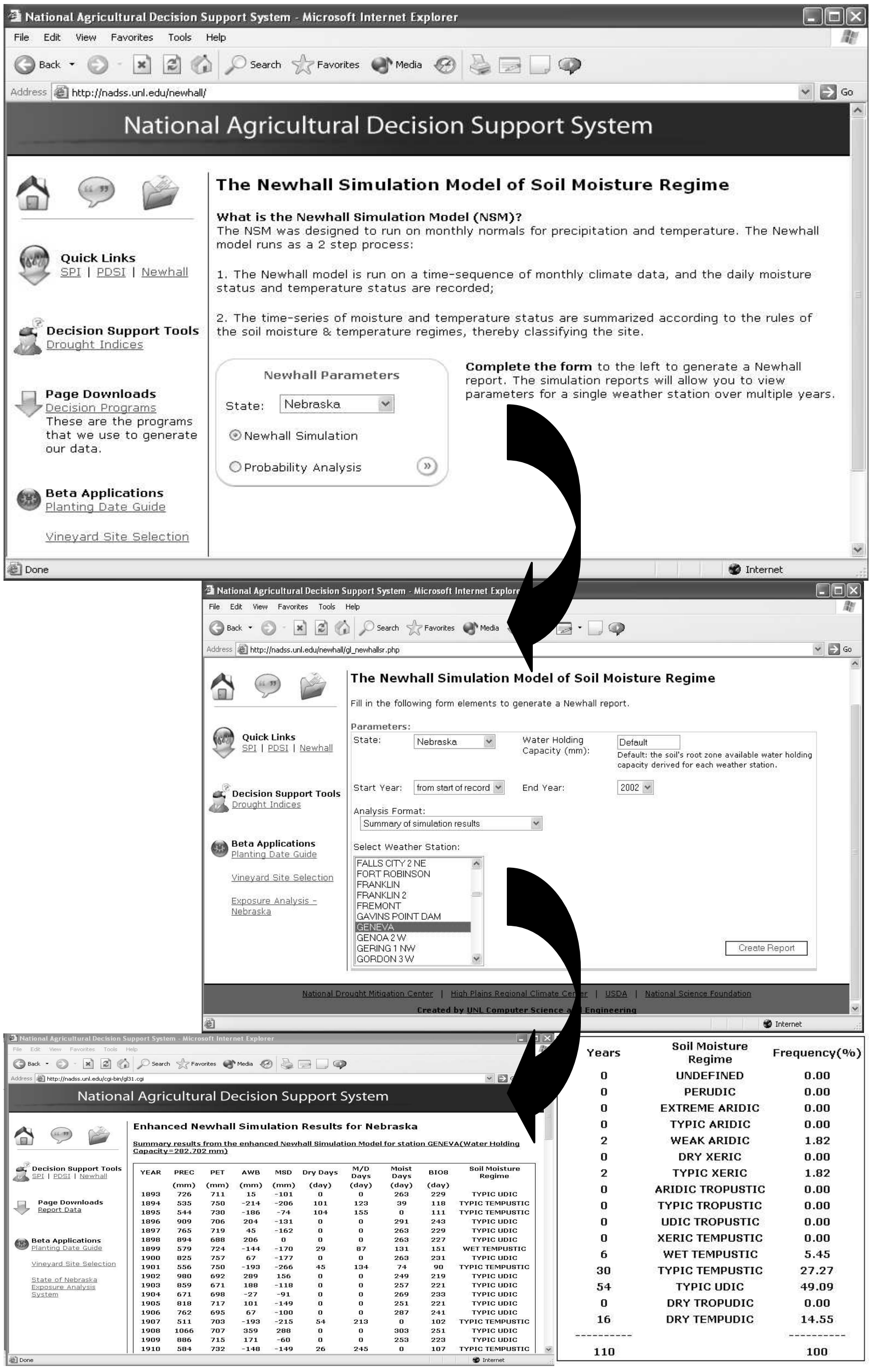
FIGURE 3
FOUR-TIER ARCHITECTURE OF THE NADSS



The new version of the Newhall Simulation Model is part of the "Information Layer" in this architecture and draws upon the climate information from UCAN and the State Soil Survey Geographic Database (STATSGO) for the root zone available water-holding capacity (RZAWHC). Thus, the model runs are tailored to the dominant soil associations surrounding the weather station. However, a user-defined estimate of RZAWHC can replace these default values assigned to the weather stations.

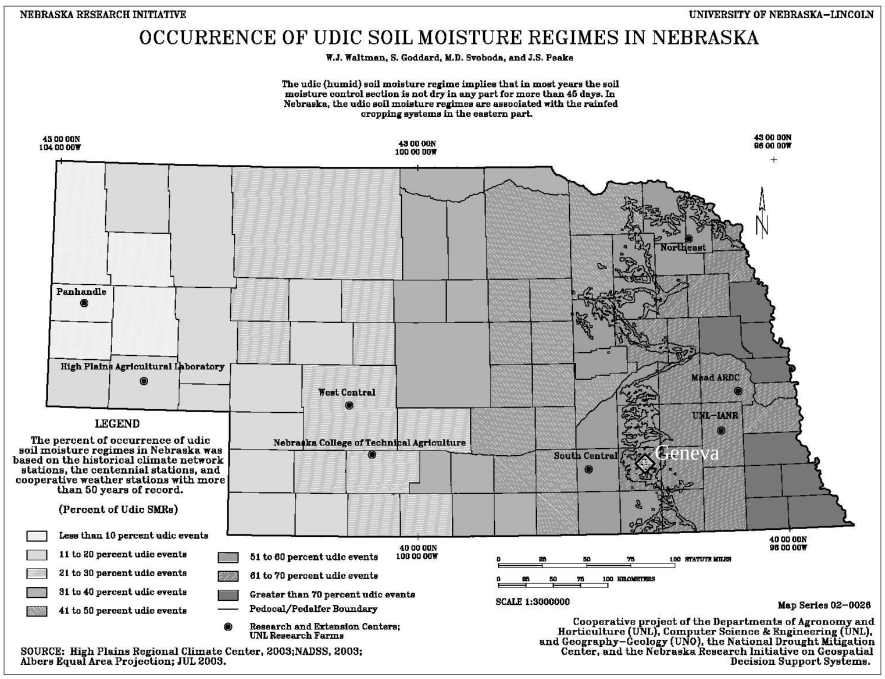
Figure 4 presents the user interface for running the ENSM to derive model results for a single station, across its entire length of record or for a specified period of record. As a case study, the Geneva, Nebraska station was selected as an example for model runs from 1894 to the present and illustrates the changes in soil moisture regime through time associated with the western edge of the Corn Belt. For the 110 years of record, the dominant soil moisture is Typic Udic (54 of 110 years; 49%) and the major drought events are represented by Typic Tempustic, Typic Xeric, and Weak Aridic regimes. The Geneva station occurs near an important soil

FIGURE 4
WEB-BASED TOOL FOR THE ENHANCED NEWHALL SIMULATION MODEL



boundary known as the “Pedocal-Pedalfer” line, the zero point where the mean annual precipitation and evapotranspiration are equal (Marbut, 1935; Jenny, 1941). As Figure 5 illustrates, the percent occurrence or frequency of soil moisture regimes can be interpolated and summarized to county boundaries from the population of weather stations available. The “Pedocal-Pedalfer Boundary” represents the landscape position where mean annual precipitation equaled potential evapotranspiration over the period of 1961 to 1990, which is derived as a sub-calculation of the ENSM.

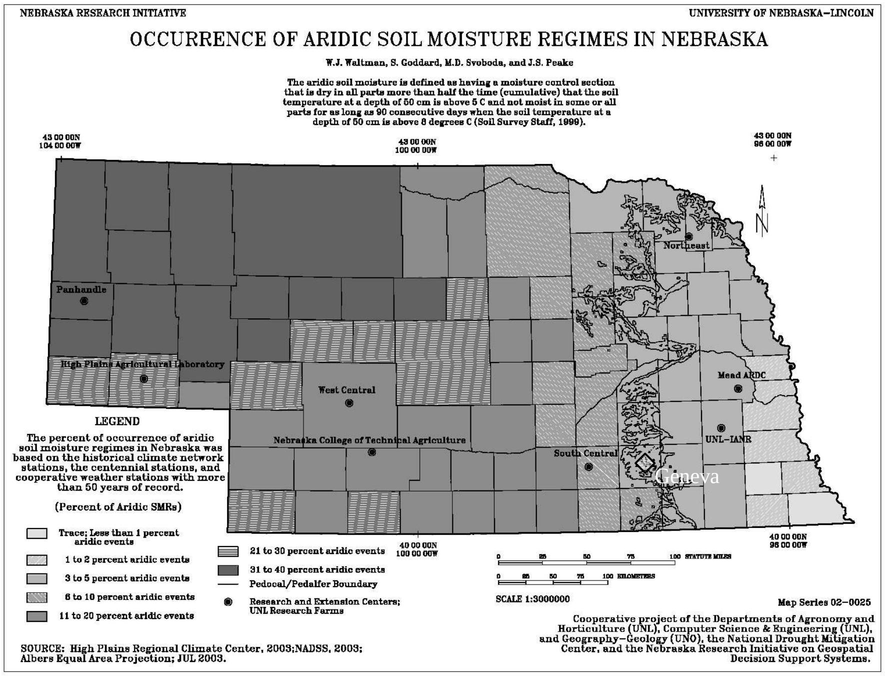
FIGURE 5
MAPPING OF UDIC SOIL MOISTURE REGIMES ACROSS NEBRASKA



Similarly, NADSS will produce soil moisture maps for Ustic and Aridic regimes to identify natural boundaries for the oscillation of these occurrences through time. From the Geneva station, Weak Aridic events have occurred only twice in the past 110 years, as a multi-year drought in 1936 and 1937 during the Dust Bowl period. Recent drought events are represented by less severe shifts to Typic Tempustic soil moisture regimes during 2000 and 2002.

Figure 6 shows the occurrence of Aridic events across Nebraska, given the entire length of weather record available. Aridic (Weak, Typic, or Extreme) soil moisture regimes do occur in eastern Nebraska at 1 to 2 events per 100 years and the majority of the occurrences were associated with the “Dust Bowl” years. In reviewing the occurrence of Aridic soil moisture regimes, the Missouri River Valley seems to be natural eastward boundary for these events, since long-term weather stations in Iowa lack any modeled occurrences even during the Dust Bowl period. Although Aridic soil moisture regimes are dominant (but less than 50% frequency) in the panhandle region of Nebraska, it remains an area of high variability. The Udic soil moisture regimes can extend westward to a higher frequency than Aridic events reaching the eastern humid region of Nebraska. The soil moisture regimes of the panhandle region clearly suggest a polyclimatic environment with a wide range of Typic Udic to Extreme Aridic regimes.

FIGURE 6
FREQUENCY OF ARIDIC SOIL MOISTURE REGIMES ACROSS NEBRASKA

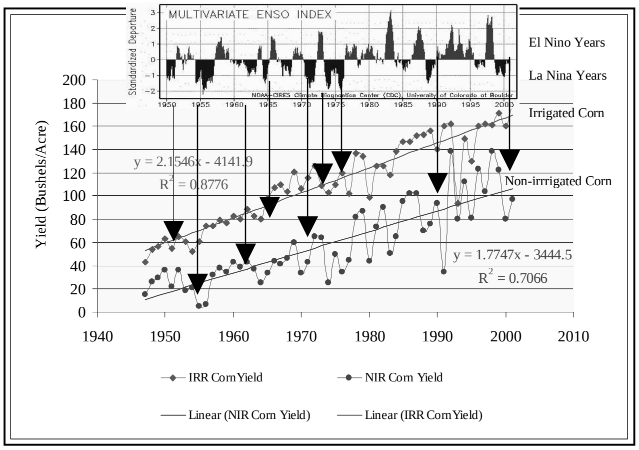


3.2 SOIL MOISTURE REGIMES, CROP YIELDS, AND ENSO

From NASS crop yield data at the state and county, we see patterns associated with El Nino and La Nina events and soil moisture regimes that often elude traditional statistical approaches. Figure 7 presents the patterns between irrigated and non-irrigated corn yields and the Multi-variate ENSO Index (Wolter and Timlin, 1993) in Fillmore County, Nebraska, which is associated with the Geneva weather station. The major La Nina (blue lines and areas) events show a connection to droughts and reduced corn yields in Fillmore County, whereas the El Nino phases (red areas) are largely associated with higher nonirrigated corn yields. As illustrated, both irrigated and non-irrigated (NIR) corn yields show the typical yield progression through time, that is a function of improved genetics and field-level management of conservation practices. The slopes of the yield trendlines can serve as an indicator of high versus low yielding environments.

When the sum of $MEI_{(July\ to\ December)}$ is compared with the following growing season characteristics, the La Nina phases (negative MEI indices) were associated with lower nonirrigated corn yields (Mean = 60 Bu/A) and higher variability (Standard Deviation = 35 Bu/A; CV = 58%) over 29 years. The El Nino phases (positive MEI indices) were followed by growing seasons with higher and more positive annual water balances (+25 mm versus -11 mm), 20 more days that the soil profile will be moist throughout and above 5^{o}C, and higher NIR corn yields (Mean = 64 Bu/A), with less annual variability (Table 1). Through data mining and knowledge discovery algorithms, we are searching for ENSO rules that can be mapped and serve as forecast tools to describe drought risk at county levels, recognizing the phase lags between ENSO episodes and consequent growing seasons. The rule structures can serve as conditions for decision-making prior to spring planting and commitment to crop insurance. We anticipate that coupled parameters, such as crop yields, soil biological windows, and soil moisture regimes will yield ENSO signals, especially with targeted episodes, but the rule structures vary with physiographic regions.

FIGURE 7
DROUGHT EVENTS AND CORN YIELDS THROUGH TIME



Geneva, Fillmore County

Recent Drought Events

1955-1956 Typic Tempustic
1963-1964 Typic Tempustic
1974 Typic Tempustic
1988-1989 Typic Tempustic
1991 Wet Tempustic
1995 Typic Tempustic
1999-2000 Typic Tempustic

TABLE 1
SUMMARY OF ENSO CHARACTERISTICS IN FILLMORE COUNTY, NEBRASKA

ENSO Phase	Mean MEI	NIR Corn Yield (Bu/A)	Yield CV (%)	AWB* (mm)	BIO5** (d)
$MEI_{(July-Dec)}$ Negative	-4.11	60	58%	-11	195
$MEI_{(July-Dec)}$ Positive	5.47	64	51%	+25	215

*Annual Water Balance = Mean Annual Precipitation – Potential Evapotranspiration
** BIO5 = Cumulative Days when Soil is Moist and Above 5 ^{o}C

4. SUMMARY AND CONCLUSIONS

The Enhanced Newhall Simulation Model can provide the historical context of drought events during growing seasons through the classification of soil moisture regimes. Soil moisture regimes can be mapped at multiple scales to identify counties and ecological regions with higher probabilities of drought events, or polyclimatic environments. The distribution of soil moisture regimes can also help us visualize those geographic regions of higher climatic variability or where soil moisture regimes may be co-dominant. The Enhanced Newhall Simulation Model results can be coupled with MEI indices, along with USDA NASS and RMA databases to derive new drought interpretations and forecasts prior to the next growing season. In Fillmore County, Nebraska, La Nina events during the July to December window are followed by greater yield variability and an average yield reduction of 4 Bu/A in the next growing season. Future research will focus on development of new data mining algorithms to extract rule structures that can describe relationships between oceanic parameters (MEI, SOI, PDO, and NAO), soil moisture regimes, and crop yields in the Northern Great Plains.

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