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CLIMATE VARIABILITY AT MULTIPLE TIME SCALES: IMPLICATIONS FOR PRODUCTIVITY IN TALLGRASS PRAIRIE

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1. INTRODUCTION

Although climate is recognized as a fundamental driver of ecosystem structure and function, the response of ecosystems to climate variability depends on the time scale over which the variability occurs. Historically, large-scale geographic fluctuations of vegetation biomes have occurred in response to climate variability on time scales of centuries to millennia (Axelrod, 1985; Ritchie, 1986). Climatic variability on decadal scales can effect community composition and structure (Weaver, 1968). However on shorter time scales, climate variability is more likely to affect net primary productivity (NPP; Knapp et al.,1998, Briggs and Knapp, 2001). This is especially true in grasslands, which have been shown to display greater variability in NPP in response to interannual climate variability than forest, desert, or arctic/alpine ecosystems (Knapp and Smith, 2001).

While the basic relationships between interannual variability in temperature, rainfall, and grassland NPP are well studied (Sala et al., 1998; Knapp et al., 1998; Alward et al., 1999), linkages to major modes of climatic variability at quasiquintennial (≈ 5 years) and interdecadal (≈10 year) time frames are less well understood. Climatologists have identified a number of atmospheric circulation patterns with modes of variability at quasiquintennial/ interdecadal time scales, including the El Niño / Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation, and the North Pacific (NP) pressure pattern. In this paper, we examine how variations in annual precipitation and mean temperature at a tallgrass prairie site may be related to large scale circulation patterns, how these circulation patterns interact at multiple time scales, and how the resulting annual patterns of precipitation and temperature may relate to productivity at the Konza Prairie Biological State (KPBS) a tallgrass prairie site in the Flint Hills of Kansas.

2. CLIMATIC REGULATION OF PRODUCTIVITY IN TALLGRASS PRAIRIE

Climate is one of several biotic and abiotic factors regulating Aboveground Net Primary Productivity (ANPP) in tallgrass prairie, including fire, grazing, nutrient availability, and topography. The simultaneous presence of multiple interacting controls mean that there is considerable temporal variation in limitations on ANPP in tallgrass prairie, and that ANPP depends strongly on the degree to which these multiple interacting controls either reinforce or cancel each other (Knapp et al., 1998). Climatic variability can best be viewed as the backdrop against which these other productivity limiting factors operate.

The presence of multiple interacting controls means that climate/productivity relationships will rarely be strong or straightforward. For example, Briggs and Knapp (1995) using 20-year record of ANPP harvested from several sites at KPBS found that correlations between ANPP and climate indices derived from temperature and precipitation varied from as low as 0.40 to 0.87 depending on the topographic location and treatment of the site at which the productivity was measured, and the time frame over which the climate data were derived (i.e. growing season vs. total annual data).

More recent work suggests that the seasonal timing as well as the magnitude of precipitation and temperature is a critical element in determining ANPP in the trallgrass prairie (Fay et al., 2000). Accumulation of biomass over the growing season is not a monotonic function of time (Figure 1a) Calculation of the rate of biomass accumulation (in g m^{-2} d^{-1}) at each harvest interval over a 14 year period at two sites on KPBS with air temperature and available soil moisture (a function of precipitation) indicates that biomass accumulates in two distinct phases; 1) a phase of rapid accumulation from the beginning of the growing season (late April) through early summer (late June), 2) a slower accumulation phase through the hotter, drier portion of the growing season (July-September) (Goodin et al., 2002). Regression analysis indicates that the rate of biomass accumulation during the faster first phase correlates most strongly with air temperature (Figure 1b), while the slower second phase was correlated with soil moisture (Figure 1c). This suggests that ANPP accumulation in tallgrass prairie is limited by a temporally shifting set of climatic factors. If further implies that investigation of the links between climate process and vegetation response in the tallgrass prairie must consider both the seasonal behavior and temporal scale of the various climatic processes known to effect annual precipitation and temperature, and thus vegetation canopy response.

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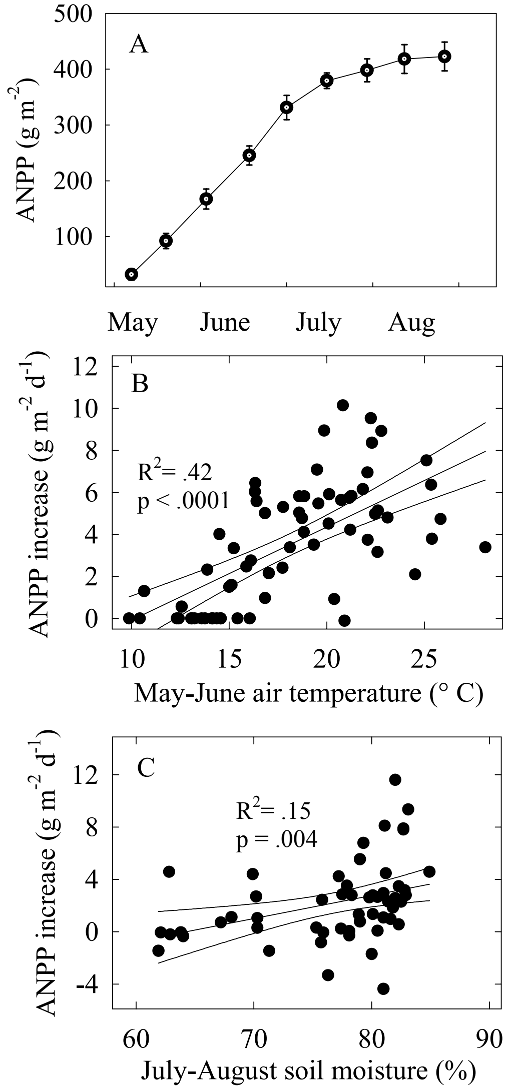

Figure 1. Growing season biomass accumulation and climatic correlates in tallgrass prairie. A) Seasonal course of aboveground biomass accumulation based on a 14 years of biweekly ANPP sampling (1984-1997) at Konza Prairie (means ± 1 SE). B) Linear regression analysis of May-June NPP increase (in g $\text{m}^{-2}\ \text{d}^{-1}$) versus air temperature (± 95% confidence intervals). C) Linear regression of July-August ANPP increase versus soil moisture

3. CLIMATIC VARIABILITY AND PRODUCTIVITY

Regression results (see Figure 1) suggest that investigations of the links between climate process and biomass production in tallgrass prairie should focus on two periods of the growing season; springtime -- the period of rapid biomass accumulation correlated with air temperature, and summer -- the time of slower biomass accumulation correlated to precipitation and soil moisture. Our analysis used two methods to characterize the time scale and drivers of climate and ANPP variability in the tallgrass prairie; 1) period-spectrum analysis to characterize the predominant time scales of temperature and preciptation variability during the two critical periods of the growing season, and 2) correlation analysis to relate observed climate variables with quantitative indices of various climatic variability modes.

3.1 *Observed Climatic Variability*

Characteristic time scales of observed climate variability were determined by period-spectrum analysis of a 108-year weather record (1891-1999) from Manhattan, KS, USA ($\approx$12 km north of KPBS). We performed spectral analysis on two subsets of these data, May-June air temperature and July-August precipitation. Data were expressed as anomalies for both analyses.

May-June temperature and June-July precipitation values between 1891 and 1999 show interannual variability typical of a continental interior site. Prominent peaks in precipitation occur between 1900 and 1920, and in the 1940 and early 1950s (Figure 2). Periods of drought were apparent in the 1930 and mid- to late 1950s. Temperature values are generally the inverse of temperature, with hotter periods associated with drought and cooler temperatures with wetter periods. The periodogram for May-June temperature (Figure 3a) shows two prominent peaks, a highly significant one at $\approx$3.1 yr ($p<0.05$) and less significant peak ($p<0.10$) at $\approx$7.5 yr. The periodogram for May-June precipitation (Figure 3b) shows only one significant peak, at $\approx$6.9 yr ($p<0.10$).

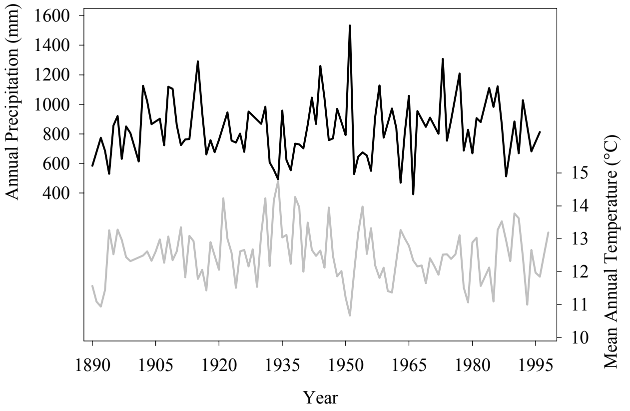

Figure 2. Time series of climate variables used in this chapter, 1891-1998. Annual precipitation is shown by the dark line, mean annual temperature by the lighter line.

3.2 *Correlation with Circulation Indices*

The periodicities observed in the temperature and precipitation spectra suggest correspondence to several atmospheric circulation patterns characterized by periodic fluctuations on time scales varying from 3 to 10 years. These circulation patterns are generally characterized by changes in pressure, upper atmosphere

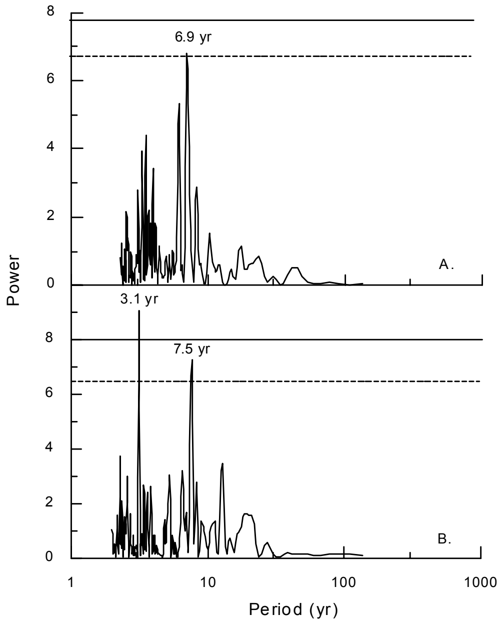

Figure 3. Power spectra of the 108-year record of July-August precipitation (A.) and May-June temperauture (B.) anomalies. Horizontal lines indicate the 90% (dashed) and 95% (solid) significance levels.

winds, or sea-surface temperature over specific regions of the earth's surface, and are quantified by a number of indices typically derived from global pressure measurements. These circulation indices include the Southern Oscillation Index (SOI), an index of the El Niño-Southern Oscillation phenomenon with significant periodic at about 3.5 and 7.0 years (Philander, 1990), the Pacific Decadal Oscillation (PDO), an El Niño-like pressure pattern across the Pacific (Zhang et al., 1997) with significant periodicity at ≈ 5.5 and 10.0 yr. the North Atlantic Oscillation (NAO) an index of pressure differential over the Atlantic with prominent oscillations at ≈5.0 and ≈9.0 yr (Hurrell, 1995), and the North Pacific index (NP), a measure of surface pressure in the northern Pacific exhibiting periodicities at ≈3.2, ≈5.5, and ≈13 yr. Each of these indices quantifies complex variability in temperature, pressure, and wind patterns that can impose teleconnection patterns at locations far removed from the region of direct effect.

We used correlation analysis to test for associations between the various teleconnection indices and Manhattan seasonal temperature and precipitation over the 108-year data record (Table 1). Of the four circulation indices considered, two correlated significantly with May/June temperature The NP index showed the strongest correlation (r=0.24, p=0.0011), but PDO was also significantly related to temperature. Note that both of these significant correlations are positive, indicating increased temperature during the positive phase of these circulation patterns. Among the indices, the North Atlantic Oscillation showed a significant inverse relationship with July/August precipitation (r=-0.19. p=0.09). Note that there was little association between ENSO related indices (e.g. SOI) and weather observations at KPBS. This supports earlier work by Greenland (1998), who also found little ENSO influence at KPBS.

Table 1. Seasonal correlations between teleconnection indices and climate variables. (Format: r(p), *=r-value significant at p<0.10).

Index	Temperature (May/June)	Precipitation (July/August)
SOI	-0.04	0.06
NAO	-0.09	-0.19 *
NP	0.24 *	-0.02
PDO	0.18 *	0.05

3.3 *Interaction of Circulation Indices*

Although the correlation analysis does reveal some links between atmospheric circulation indices and temperature/precipitation response at Manhattan, it is clear that none of the teleconnection patterns exerts an overwhelming influence. This is especially apparent for July/August precipitation, which did not correlate significantly with any index. Correlation assumes a simple, univariate relationship between the circulation indices and climatic response. Given the complexity of the climate system and the number of variables simultaneously influencing response at any given place or time, it is likely that some of the empirical variability observed at a given location is the result of interaction between various teleconnection patterns.

To test whether interannual variability of May/June temperature and July/August precipitation can be attributed to interactions of teleconnection processes, we created a series of composite indices by weighted additive or subtractive combinations of the four teleconnection indices listed in Table 1. We then correlated these composite indices with May/June precipitation and July/August temperature.

Table 2. Seasonal correlations between composite teleconnection indices and climate variables. (Format:r(p), *= r-value significant at p<0.10)

Index	Temperature (May/June)	Precipitation (July/August)
NAO+NP	-0.18 *	0.02
SOI-NP	-0.13	0.17*
NAO-PDO	-0.17*	-0.07
NP-PDO	0.00	-0.16*
SOI+PDO	-0.06	0.20*

Generally, correlations with the composite indices were less than those of the original teleconnection indices, however a few of the combined indices did result in relative strong correlations, some of them significant at p<0.10 (Table 2). An additive combination of NAO and NP resulted in a significant negative relationship with

May/June temperature, despite the higher correlation with NP alone. This suggests that the influence of a high value of the NP index would tend to override the effect of other, less correlated indices. The significant positive correlation between SOI+PDO and July/August precipitation indicates that these two teleconnection act in concert to effect summertime rainfall.

4.0 SYNTHESIS

Results of this analysis suggest that the historic spring temperature and summer precipitation records at Konza Prairie displays periodic fluctuations similar to those in frequency to those of the Pacific Decedal Oscillation, the North Pacific pressure pattern, and to less extent, the Southern Oscillation. A key question, then, is how might these atmospheric teleconnection patterns be linked to productivity at this tallgrass prairie site? Clearly, given the complex nature of the productivity/climate interaction, compounded by the additional complexity of the climate system, we would not expect to see any "iron clad" links between atmospheric process and ecosystem response. Nevertheless, the relationships described above can be interpreted in terms of climate-canopy interaction.

Periods of stronger NP (i.e. larger positive index values) tend to be associated with greater springtime temperatures, and thus with greater early season productivity. Years with positive phase PDO events would also tend to warm earlier and stimulate greater early ANPP production, but there seems to be little composite effect of the two indices. The period spectra of PDO and NP both show significant peaks at about 6.5 yr ($p<0.05$), a frequency very close to the most significant periodicity in the May-June temperature data (see Figure 2). We can conclude from this that years of high PDO or high NP would associate with the fastest early season accumulation of ANPP.

In contrast to spring, NAO was negatively correlated with summer precipitation. Thus years with positive phase NAO would have inhibited productivity later in the season when precipitation is the dominant control. Interaction effects between circulation processes appear to be a more important regulator of summer precipitation, and thus later-season biomass production. The subtractive SOI-NP index is positively correlated with July/August precipitation, suggesting that these two indices exert an inhibiting effect on each other, and when the two indices are out of phase, greater summer precipitation and biomass accumulation will occur. The negative correlation with the NP-PDO effect also indicates the complexity of relationships between precipitation and circulation at this site. The subtractive nature of this index indicates that in years when the NP is especially strong relative to PDO, precipitation in the July/August period will be less. In these years, rapid spring biomass production driven by heat accumulation would give way to slower, rainfall-limited biomass addition in summer. The significant positive correlation between an additive combination of SOI+PDO and rainfall suggests dependence between these two teleconnections with effects most readily apparent when the two indices are "in-phase." This observations supports earlier findings indicating a connection between PDO and ENSO phenomenon (Gershunov and Barnett, 1999).

5.0 CONCLUSIONS

This analysis concentrated on controls on the rate at which ANPP accumulated during the growing season. Controls on the annual magnitude of ANPP are probably similar, but would need to account for variables such as beginning soil moisture and the interaction of precipitation and temperature throughout the growing season. The relationships between climatic variability and biomass accumulation proposed here are speculative. The brevity of the available ANPP data precludes any direct comparison between climatic variability and ecosystem response at any except the briefest time spans. Nevertheless, the results we present are important for two reasons. First, they provide insight into interpreting current patterns of ANPP. The tallgrass prairie (and grasslands in general), more so than other ecosystems (forest, desert, arctic/alpine), are poised in a dynamic equilibrium that makes them especially sensitive to both biotic and abiotic disturbances, including climate variability. Increased understanding of climatic effects on the system provides a framework for posing specific hypotheses about climate-ecosystem interactions at all temporal scales.

Second, our results might form the basis for prediction of response to climatic change in tallgrass prairie. Climate change scenarios that predict changes in periodic circulation phenomena can be linked to probable changes in productivity patterns. Although we detected periodicities in temperature and precipitation at frequencies of about 3.5 and 7-8 yr, in fact these different periods occur as part of a hierarchical system of climatic variation. Focusing on the degree to which these hierarchical regimes of temperature and precipitation variability reinforce (or oppose) each other may shed more light on the regulation of variability in ANPP or other ecosystem characteristics than considering them independently. Clearly, much more research will be needed before these complex links can be fully understood. In particular, better characterization of the interaction of circulation processes (beyond the simple combinations of indices used here) are needed but are beyond the scope of this brief paper. However, the results presented here provide direction for future research.

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