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ENSO and PDO-related climate variability impacts on Midwestern United States crop yields

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Abstract An analysis of crop yields for the state of Missouri was completed to determine if an interannual or multidecadal variability existed as a result of the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Corn and soybean yields were recorded in kilograms per hectare for each of the six climate regions of Missouri. An analysis using the Mokhov "method of cycles" demonstrated interannual, interdecadal, and multidecadal variations in crop yields. Cross-spectral analysis was used to determine which region was most impacted by ENSO and PDO influenced seasonal (April–September) temperature and precipitation. Interannual (multidecadal) variations found in the spectral analysis represent a relationship to ENSO (PDO) phase, while interdecadal variations represent a possible interaction between ENSO and PDO. Average crop yields were then calculated for each combination of ENSO and PDO phase, displaying a pronounced increase in corn and soybean yields when ENSO is warm and PDO is positive. Climate regions 1, 2, 4, and 6 displayed significant differences (p value of 0.10 or less) in yields between El Niño and La Niña years, representing 55–70 % of Missouri soybean and corn productivity, respectively. Final results give the opportunity to produce seasonal predictions of corn and soybean yields, specific to each climate region in Missouri, based on the combination of ENSO and PDO phases.

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Introduction

Variations in climate, especially those related to the El Niño Southern Oscillation (ENSO), are commonly researched in the field of atmospheric science (Kung and Chern 1995; Lupo et al. 2005, 2012b). However, climate variability related to both ENSO and the Pacific Decadal Oscillation (PDO) is a growing topic after correlations were found with North American climate (Gershunov and Barnett 1998; Enfield and Mestas-Nuñez 1999; Ding and McCarl 2014), including Midwestern temperatures and precipitation (Berger et al. 2002; Lupo et al. 2007; Birk et al. 2010; Newberry et al. 2016). ENSO leads to changes in upper air conditions, specifically mid-tropospheric circulation and jet stream positioning across the USA (Keables 1992; Kung and Chern 1995; Lee and Kung 2000), which impacts surface temperature and precipitation (Lupo et al. 2008). A relationship has been found between temperature and precipitation and crop yields in Missouri (Hu and Buyanovsky 2003), but only a handful of studies have applied ENSO- and PDO-related climate variability to crop yields in the USA (Ding and McCarl 2014).

Crop yield variability understanding is important since it can lead to seasonal forecasts for field crop production. Seasonal forecasts of crop yields, on a time scale of 3 to 12 months, may become more useful to farmers or financial advisors if a link can be made to climate variability, specifically ENSO and PDO and their interaction. Knowing how the upcoming summer is going to potentially influence crops can help farmers plan which crop to plant, how much to plant, where to plant (for example, avoid flood prone fields or areas if the summer is expected to be wetter than average), how much irrigation will be needed, or even which fertilizer to use or how much. Loan companies can use these forecasts to decide whether or not to loan to a farmer for a certain crop and insurance companies can decide how much coverage is

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needed for the season. ENSO and PDO impacts on crops can impact the economy by leading to an increase or decrease in crop yields and influencing the crop value (Keppenne 1995; Hansen et al. 1998), making forecasts of yields a high priority and useful for consumers and the agricultural community in estimating their costs for the upcoming season (Adams et al. 1999).

ENSO events have been linked to interannual variations of 2 to 7 years in local and regional climates (Kung and Chern 1995; Enfield and Mestas-Nuñez 1999; Lupo et al. 2005), while PDO events have been linked to multidecadal variations of 20 to 30 years in North American climate (Lupo et al. 2007; Ding and McCarl 2014). A third signal occurs on an interdecadal time scale of roughly 10 to 15 years and is referred to as a PDO-modulated ENSO-related variability of Midwestern climates (Gershunov and Barnett 1998; Berger et al. 2002; Birk et al. 2010). Lupo et al. (2007) extended the work of Kung and Chern (1995) showing different clusters of monthly mean Pacific Region sea surface temperature (SST) anomalies corresponding to different phases of ENSO, as well as different phases of PDO. Results from Lupo et al. (2007) suggest that ENSO events are modulated by long-term SST variability associated with PDO; with strong El Niño and weak La Niña SST distributions occurring mostly during a positive PDO phase, weaker El Niño and stronger La Niña SST distributions common during the negative PDO phase, and El Niño events during the negative PDO phase featuring warm SST anomalies in the east-central Pacific.

More evidence of an interdecadal modulation is found in studies involving Australia and Asia rainfall and Arizona winter precipitation (Power et al. 1999; Goodrich 2004; Wang et al. 2008). Correlations between ENSO and PDO phases in the aforementioned studies strongly suggest that the PDO phase can contribute to the strength and frequency of the ENSO phase, therefore creating the climate interdecadal variability. It is acknowledged that the ENSO and PDO relationship is controversial in that research studies supporting the PDO dependence on ENSO, rather than the ENSO dependence on PDO, exist in atmospheric science literature (Newman et al. 2003; Zhang and Delworth 2015).

With crop yields in Missouri, specifically corn, showing a correlation to temperature and precipitation (Hu and Buyanovsky 2003), and Midwest temperatures and precipitation correlating to ENSO and PDO (Berger et al. 2002; Birk et al. 2010), the hypothesis stands that Missouri crop yields will also correlate to ENSO and PDO. Another question remains as to whether or not Missouri crop yield data will support the Gershunov and Barnett (1998) and Birk et al. (2010) findings of PDO-modulated ENSO events. Thus, the objective of this research is to determine if crop yield variability in Missouri is associated to ENSO and PDO variability and if such yield variability is supported by the theory of PDO-modulated ENSO-related variability (Gershunov and Barnett 1998; Birk et al. 2010).

Materials and methods

Data sources

Crop yield data were recorded from the United States Department of Agriculture (USDA)'s National Agricultural Statistics Service (NASS) using Quick Stats 2.0 (quickstats.nass.usda.gov). Crop yields were collected for the two most common field crops grown statewide in Missouri: corn and soybean. Corn was recorded as grain yield in bushels per acre, while soybean was recorded as a general yield in bushels per acre. Annual yields for each crop were downloaded by county in Missouri based on survey. From the collected data, an average yield representing each crop was calculated for each of the six climate regions in Missouri based on the counties located in each region. Yields were converted from bushels per acre (bu/acre) to kilograms per hectare (kg/ha) assuming corn to be a 56-lb bushel, soybean to be a 60-lb bushel, and 1 ha to equal 2.471 acres. Therefore, 1 bu/acre of corn equals 62.77 kg/ha and 1 bu/acre of soybean equals 67.25 kg/ha.

The six climate regions of Missouri (Fig. 1) are determined by the Climate Divisional Dataset, which is a long-term temporally and spatially complete dataset used by the National Oceanic and Atmospheric Administration (NOAA) to generate historical climate analyses for the continental USA. Missouri experiences regional differences in climate (NCDC 2006), so analyzing data by the climate regions will give the opportunity for more accurate results. A total of 95 years of data, from 1919 to 2013, were used for corn in each region, while only 70 years of soybean data were collected from 1944 to 2013.

Missouri is located in the center of the continental USA, as part of the Midwest Region, with a strong seasonal climate. Spring and fall are transitional seasons with sudden changes in temperature and precipitation due to sharp frontal boundaries between air masses. Missouri summers can be extremely wet or dry depending on the general circulation pattern of the Northern Hemisphere. Due to Missouri's size and orientation, a regional view of Missouri's climate is important to consider. During summer, temperatures reach 32 °C on an average of 30 to 40 days over the state, with the exception of southeastern Missouri (regions 5 and 6) where the temperature exceeds 32 °C for an average of 50 days. Summer precipitation in July is greatest for northeastern Missouri (region 2), with a mean 112 mm, and the least for southwestern Missouri (region 4), with a mean 81 mm, due to convectional precipitation

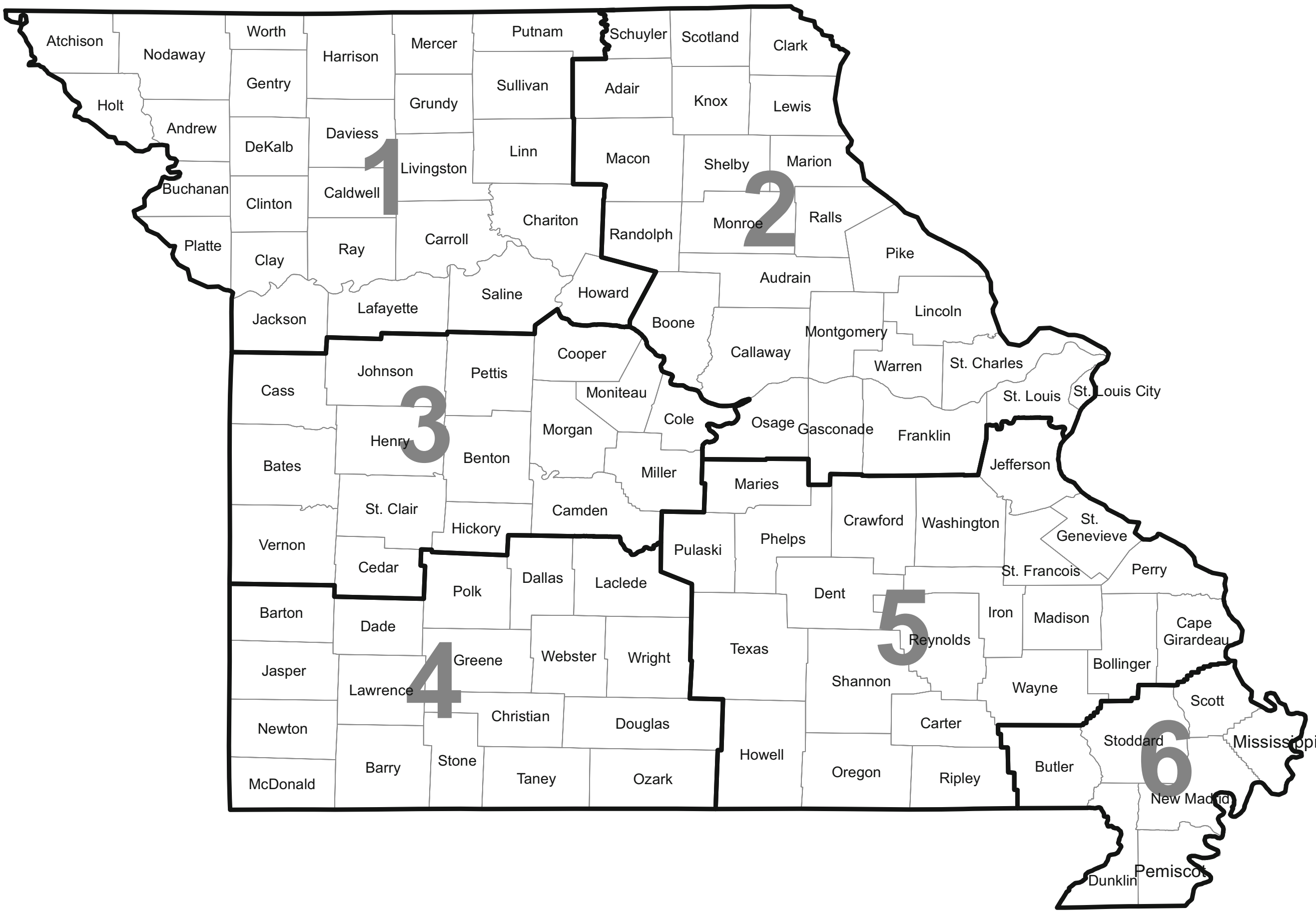

Fig. 1 A map of Missouri outlining the six climate regions, determined by the National Oceanic and Atmospheric Administration (NOAA) using the Climate Divisional Dataset. NOAA defines these regions as Climate Divisions of Missouri

systems in the northern central plains of the USA. The north-south orientation of Missouri also causes a difference in the number of days below freezing (0 °C), as well as snowfall amounts, in spring and fall, meaning northern regions (regions 1 and 2) have a much shorter growing season than that of the southeast (region 6).

Temperature and precipitation data were obtained from NOAA, via the Midwestern Regional Climate Center (MRCC) cli-MATE application (mrcc.isws.illinois.edu/CLIMATE). Temperature was recorded in degrees Celsius and precipitation in millimeters. Monthly averages for temperature and precipitation were downloaded directly for each climate region in Missouri, using the MRCC Climate Division Data. The number of years downloaded for temperature and precipitation depended on the number of years of data collected for each crop in each region. Thus, monthly average temperatures for each region were collected for the years 1919 to 2013 to match the corn dataset, while the same was collected for the years 1944 to 2013 to match with soybean yields. The monthly data were used to calculate average seasonal data, to represent values for each crop growing season of April to September.

Definitions

The climate variability this study is concerned with is related to the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The ENSO definition is provided by the Japan Meteorological Agency (JMA). The JMA ENSO Index was used in this study in order to stay consistent with previously referenced studies (Berger et al. 2002; Lupo et al. 2007, 2012b; Birk et al. 2010) and due to the fact that Hanley et al. (2003) found the JMA ENSO Index to be the most sensitive to La Niña events compared to five other ENSO indices. The JMA ENSO Index is described by the Center for Ocean-Atmospheric Prediction Studies (COAPS) and is a 5-month running mean of spatially averaged sea surface temperature (SST) anomalies over an area in the tropical Pacific (4° S–4° N, 150° W–90° W). There are three phases of ENSO: La Niña (cool phase) is based on SST anomalies at or below −0.5 °C, neutral is between −0.5 and 0.5 °C, and El Niño (warm phase) is based on SST anomalies at or above 0.5 °C. The JMA ENSO Index requires the index values for each phase to be observed for six consecutive months, including October, November, and December, in order to be classified.

The ENSO year for JMA starts on 1 October and continues through the following September. Corn and soybean mean growing season in Missouri runs from April to September, meaning the ENSO year begins at the end of the crop growing season, after harvest. For example, crop yields for 2012 are the product of the April 2012 to September 2012 growing season and are compared to the ENSO year for 2012, which JMA defines as beginning in October 2012 and ending in September 2013 (Fig. 2). Therefore, the crop-growing season falls in a period of possible ENSO transition. A list of years by ENSO phase, as defined by JMA, is available online from the Center for Ocean-Atmospheric Prediction Studies (coaps.fsu.edu/jma) and represented in Table 1.

PDO is often described as a long-lived ENSO-like pattern of SST anomalies (Mantua et al. 1997; Minobe 1997, 2000; Zhang et al. 1997). However, there are only two phases of PDO: the positive phase (phase 1) is characterized by cold western and north central Pacific waters with warm eastern and tropical Pacific waters, as well as an anomalously deep Aleutian low; the negative phase (phase 2) occurs during the opposite conditions (Gershunov and Barnett 1998; Mantua and Hare 2002). The PDO phase corresponding to each year examined in this study was adapted from Birk et al. (2010) and Lupo et al. (2012b). Table 1 organizes the years examined in this study by both ENSO and PDO phase.

For the summer growing season, April to September, ENSO and PDO phases have specific impacts on each region in Missouri. Overall, El Niño events are typically associated with above average spring precipitation, but below average precipitation with cooler than average temperatures in summer for Missouri. La Niña events are also associated with cooler and drier summers, while neutral ENSO events are associated with average to slightly above average summer precipitation and temperatures (Lupo et al. 2012b). However, regional and monthly specific ENSO impacts in Missouri differ and can be found online, Useful to Usable (U2U; mygeohub.org/groups/u2u/cpv). Positive PDO events are typically associated with cooler than average summer temperatures and average to slightly above average summer precipitation, with negative PDO events associated with average summer temperatures and precipitation. Again, PDO can impact each region of Missouri slightly different in each summer month; refer to NOAA's Earth System Research Laboratory (ESRL; www.esrl.noaa.gov/psd/data/usclimdivs/correlation/) for specific analyses.

Positive PDO events enhance El Niño impacts and negative PDO events enhance La Niña impacts (Birk et al. 2010). Therefore, a positive PDO with an El Niño event leads to cool summers with average precipitation, while a negative PDO with a La Niña event leads to slightly above average summer temperatures with dry conditions. Neutral ENSO events with a positive (negative) PDO are associated with wet (dry) summers (Birk et al. 2010). However, ENSO and PDO impacts are generally expected to be localized in nature (Ratley et al. 2002), so a regional analysis is very important to consider. Transition periods between ENSO phases also have certain impacts on summer temperature and precipitation in Missouri and can be referred to when creating forecasts (Ratley et al. 2002; Newberry et al. 2016).

Methodology

Agricultural techniques and equipment have advanced over the years causing an increasing trend in crop yields (Hu and Buyanovsky 2003). To account for the influence of these advancements, including seed genetics and the use of fertilizers, the trend was eliminated from the yield data for both crops. Using minimized squared error techniques, a simple linear trend in the data was defined and then removed. Removing the trend in the data allows for the opportunity to evaluate the climate effect on crop yields accurately. The annual crop yield data were plotted as a time series for each crop in each region in kilograms per hectare (Fig. 3), with the trend for each crop in each region represented by a dotted line. After removing the trend, the dotted line becomes representative of the mean yield, values above the dotted line represent a positive deviation from the mean yield, and values below the dotted line represent a negative deviation.

To identify interannual and multidecadal periodicities within each data set of detrended crop yields, the method of power spectra analysis was performed following the Mokhov et al. (2004) "method of cycles" (e.g., Birk et al. 2010; Lupo et al. 2012b). This method of amplitude and period calculation results in phase portraits $\dot{X}(X)$ for a given time series $X(t)$.

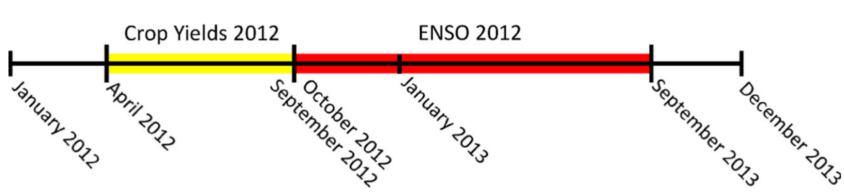

Fig. 2 Timeline representing the crop growing season of 2012 (Crop Yields 2012), which runs from April 2012 to September 2012, and the JMA defined ENSO year of 2012 (ENSO 2012), which begins in October 2012 and ends in September 2013

Table 1 The years examined in this study, corresponding to each El Niño Southern Oscillation (ENSO) phase, as defined by the Center for Ocean-Atmospheric Prediction Studies (COAPS, online at coaps.fsu.edu/jma), as well as each Pacific Decadal Oscillation (PDO) phase

Positive PDO (1)			Negative PDO (2)		
La Niña	Neutral	El Niño	La Niña	Neutral	El Niño
1938	1926–1928	1925	1922	1919–1921	1951
1942	1931–1937	1929	1924	1923	1957
1944	1939	1930	1949	1947	1963
1988	1941	1940	1954–1956	1948	1965
1998	1943	1982	1964	1950	1969
	1945	1986	1967	1952	1972
	1946	1987	1970	1953	1976
	1977–1981	1991	1971	1958–1962	2002
	1983–1985	1997	1973–1975	1966	2006
	1989		1999	1968	2009
	1990		2007	2000	
	1992–1996		2010	2001	
				2003–2005	
				2008	
				2011–2013	

Following Mokhov et al. (2004), the process can be fitted by a harmonic oscillator:

$$\ddot{X} + \omega^2 X = 0 \tag{1}$$

or

$$X(t) = A(t)\sin[\omega(t)t + \varphi(t)] \tag{2}$$

if there is a statistically significant linear regression of $\ddot{X}(t)$ on $X(t)$ with a negative regression coefficient $-\omega^2(t)$. The amplitude of the process $A(t)$, frequency $\omega(t)$, period $P(t) = \frac{2\pi}{\omega(t)}$, and initial phase $\varphi(t)$, are assumed to change sufficiently slowly over time (Mokhov et al. 2004). The variables $\dot{X}$ and $\ddot{X}$ are determined by taking the second-order finite difference of the original time series X. In this research, temperature, precipitation, and crop yield data are represented by X. The amplitude $A(t)$, frequency $\omega(t)$, and period $P(t)$ are calculated using a least-squares method (e.g., Mokhov et al. 2004). Equations (1) and (2) can be solved using empirical orthogonal functions (e.g., Fourier series).

Power spectra were constructed from the detrended crop data using Fourier coefficients. Fourier transforms convert data from Cartesian space to wave space and power is put into discrete wave numbers; resulting in a plot of wave power versus wave number that can then be analyzed for dominant periods in a time series. Spectral peaks represent periodicities in the time series and can be tested for significance against a red or white noise continuum (e.g., Wilks 2006), due to the expectation that low frequency would be dominant (red) or that all frequencies would be equally likely (white). The variability, or periodicities, in the detrended crop yields are recorded in years by dividing the time interval of the data used by the wave number of a significant spectral peak. Resulting power spectra for both crops in all six regions were analyzed for significant periodicities to determine if the resulting oscillations relate to ENSO and PDO variability.

The same method was used to create power spectra for seasonal (April to September) temperature and precipitation data for each climate region and time range, corresponding to the crop data. Resulting power spectra were not analyzed for periodicities, but rather used to perform a cross-spectral analysis (e.g., Lupo et al. 2012a). This analysis involves the convolution of power spectra to create a final power spectrum used for the examination of periodicities. Power spectra resulting from detrended crop data were cross-analyzed with power spectra resulting from seasonal temperature and precipitation, for the respective time range and climate region. The resulting covariance spectra were analyzed for dominant periods, which represent the periodicities shared by crop yields, temperature, and precipitation. The peaks found in the resulting spectra were tested for significance against a white noise continuum, assuming no particular frequency to be dominant (e.g., Wilks 2006).

In an effort to support the idea of an interaction between ENSO and PDO, annual detrended crop yields for each crop in each region were binned according to ENSO phase and ENSO-PDO phase combination. Averages were then calculated, resulting in an average crop yield for each crop in each region for each ENSO phase and each ENSO-PDO phase combination. Detrended crop yield averages are displayed as a positive or negative value, making it easy to see the impacts of each ENSO phase or ENSO-PDO phase combination on each crop and region in terms of productivity. A Mann-Whitney test was conducted on the phase-specific detrended crop yields to determine a statistical relationship between the calculated averages, using one-tail probability. Only data samples containing at least five values and resulting in a p value of 0.10 or less were considered to be of significance.

Results

Spectral analysis

Figure 3 represents 12 graphs created from the crop yield data collected from USDA NASS for each of the crops (corn and soybean) for all six climate regions in Missouri (Fig. 1). Figure 3a–f specifically represent annual corn yields in kilograms per hectare from 1919 to 2013 for each region, respectively, while Fig. 3g–l represent annual soybean yields in kilograms per hectare from 1944 to 2013 for each region,

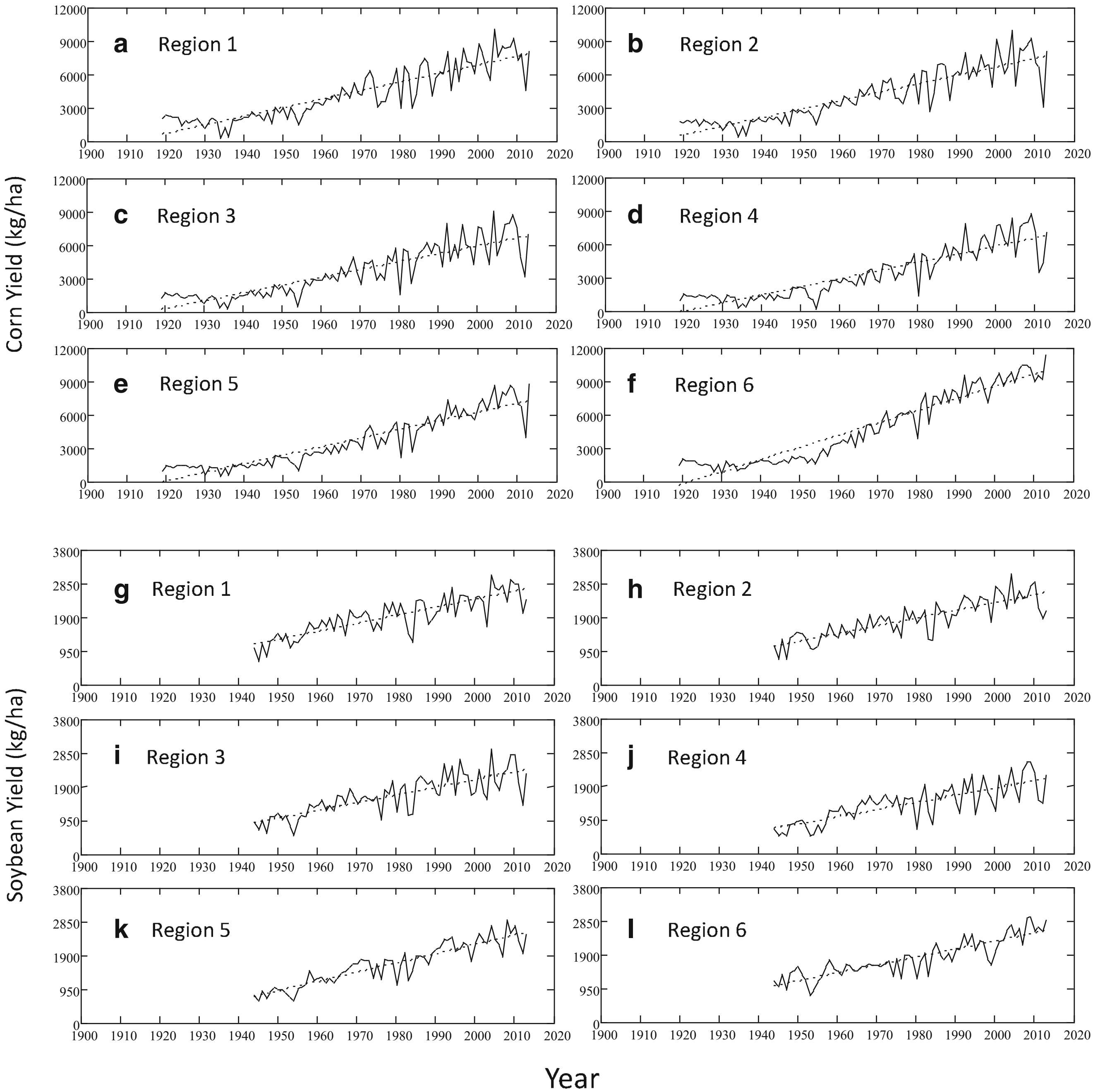

Fig. 3 Annual crop yields for each region in Missouri with the linear trend (*dotted line*) shown for *a–f*) corn yields from 1919 to 2013 and *g–l*) soybean yields from 1944 to 2013. Data provided by the United States Department of Agriculture (USDA), graphed as yield (kilograms per hectare) versus time (year)

respectively. The linear trend was then removed from the data in Fig. 3 and detrended crop yields for both crops in all six regions were used for the remaining methods in this study.

Figure 4a–f (m–r) represent the power spectra resulting from the Fourier transform of detrended corn (soybean) yields for each region, respectively. These spectra were analyzed for periodicities, represented by peaks, to determine a correlation to climate variability in the form of ENSO or PDO. For example, Fig. 4a displays a large peak on the right half of the graph at a wave number of roughly 20. The time interval of the data used in Fig. 4a is 1919 to 2013 for corn in region 1, which is 95 years of data. Therefore, the periodicity represented by the large peak is roughly 5, meaning corn yields in region 1 vary significantly every 5 years. With 5 falling into the interannual variability range of 2 to 7 years, this periodicity represents a possible relationship to ENSO phase. The same calculation was made for the remaining significant peaks shown in Fig. 4a, resulting in corn yields for region 1 having

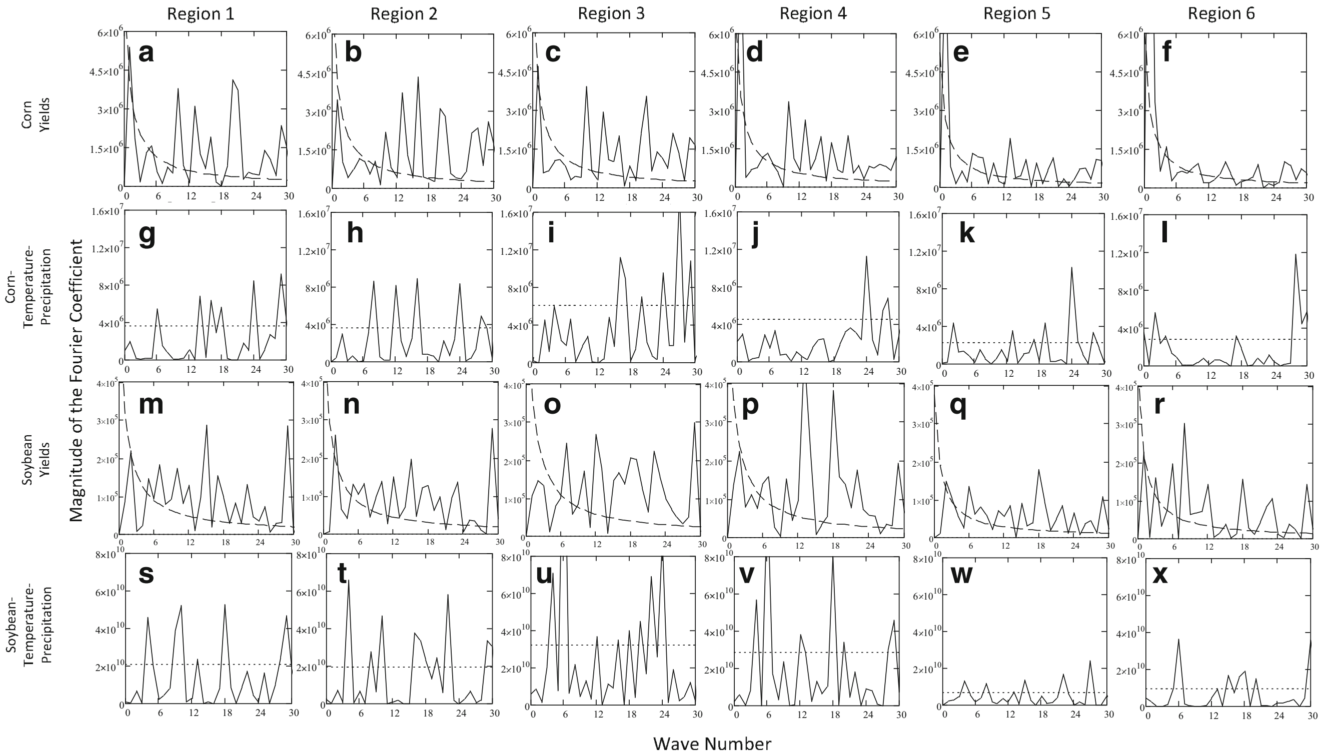

Fig. 4 Power spectra resulting from *a-f)* the Fourier transform of detrended corn yields for each region in Missouri, *g–h)* the convolution of the corn yield spectrum (*a–f*) with the spectra of seasonal temperature and seasonal precipitation data (not shown, *m–r*) the same as *a–f*, except soybean yields, and *s–x)* the same as *g–h* except soybean yield spectrum (*m–r*). The ordinate displays wave power, which is the magnitude of the Fourier coefficients, while the abscissa displays wave number. The *dashed* (*dotted*) *line* represents the 95 % confidence level against the *red* (*white*) noise background continuum (Wilks 2006)

interannual, interdecadal, and multidecadal variability. Thus, corn yields in region 1 have a possible relationship to ENSO, PDO-modulated ENSO, and PDO phase.

Figure 4g–l (s–x) display the power spectra representing the convolution of detrended corn (soybean) yields with seasonal temperatures and precipitation for each region over the period of 1919 (1944) to 2013 (corresponding to the time range of corn or soybean yields used). Using Fig. 4g as an example, dividing the time interval (again 95 years for corn) by the wave number of each significant peak results in the covariance of corn, temperature, and precipitation for region 1 displaying interannual and interdecadal variability. In other words, corn, temperature, and precipitation data from region 1 all vary at the same intervals as ENSO and PDO-modulated ENSO.

The same methods used for Fig. 4a, g were used for all power spectra involving both crops in all six regions with their corresponding time ranges of seasonal temperature and precipitation data. Each periodicity resulting from the analyzed spectra was associated with ENSO, ENSO-PDO (PDO-modulated ENSO), and PDO, depending on the variability range of interannual (2–7 years), interdecadal (10–15 years), or multidecadal (20 years), respectively. The final results are shown in Table 2 according to possible climate variability associations. Interannual variations were found in 24 out of 24 (100 %) analyzed spectra, while only 17 of the 24 (71 %) contained interdecadal variabilities and 10 of the 24 (42 %) contained multidecadal variabilities.

ENSO-PDO phase interactions

Table 3 displays the averages calculated for each set of detrended yields, in kilograms per hectare, for each crop in each region based on ENSO phase year, as defined by JMA. Corn and soybean yields display a positive value for El Niño years, meaning yields will most likely depart positively from the mean yield in future JMA El Niño years or years of El Niño transition. La Niña years display mostly negative values for corn and soybean yields based on region, meaning yields will likely depart negatively from the mean during La Niña transitions, referring to when La Niña events occur in the post-harvest winter. Statistical testing of yields in El Niño years versus yields in La Niña years determined regions 1, 2, and 6 to have significant differences (p values less than 0.10) for both crops, with region 4 for corn also included (Table 3). Testing of yields in La Niña years versus yields in neutral years determined regions 1, 5, and 6 to have significant differences (p values less than 0.10) for corn and only region 6 for soybean (Table 3). Further testing of yields in El Niño years versus neutral years concluded with no significant differences (p value of 0.10 or less).

Table 2 Regional Missouri crop yield variability resulting from each analyzed power spectrum

	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Corn	ENSO ENSO-PDO PDO	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO PDO
Corn-Temp-Precip Covariance (Season)	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO	ENSO	ENSO	ENSO PDO
Soybean	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO	ENSO ENSO-PDO PDO	ENSO ENSO-PDO PDO
Soybean-Temp-Precip Covariance (Season)	ENSO PDO	ENSO PDO	ENSO ENSO-PDO PDO	ENSO ENSO-PDO PDO	ENSO PDO	ENSO ENSO-PDO

Periodicities determined from each spectrum were compared to each climate variability and listed as ENSO, ENSO-PDO, or PDO. ENSO refers to an interannual variability of 2 to 7 years, corresponding to the El Niño Southern Oscillation. ENSO-PDO refers to an interdecadal variability of roughly 10 to 15 years, corresponding to PDO modulated ENSO-related variability. PDO refers to a multidecadal variability of roughly 20 years, corresponding to the Pacific Decadal Oscillation

Table 4 is similar to Table 3, only displaying average detrended crop yields based on ENSO-PDO phase combination years. El Niño and La Niña show the same impacts on the crops, but the impacts are enhanced when combined with a positive PDO phase and diminished when combined with a negative PDO phase. For example, detrended corn yields in climate region 1 have an increase in the average yield by 279.0 kg per hectare during El Niño years (Table 3). The average yield increases by 442.8 kg per hectare for El Niño and positive PDO years, and increases by only 131.5 kg per hectare for El Niño and negative PDO years (Table 4). Corn in region 6, while soybean in regions 3 and 6, resulted in significant differences (p values less than 0.10) in yields when comparing yields from El Niño/positive PDO years to yields from El Niño/negative PDO years (Table 4). Further testing of yields in La Niña/positive PDO years versus La Niña/negative PDO years determined there to be a significant difference (p value of 0.07) for soybean in region 3; however, this significance is not acknowledged due to a contribution from only three samples in one of the data sets involved. Testing of yields in neutral/positive PDO years versus neutral/negative PDO years concluded with no significant differences (p value of 0.10 or less).

Table 3 Departure from average (standard deviation) calculated from detrended crop yields in kilograms per hectare, for each crop in each climate region of Missouri, for the years associated with each El Niño Southern Oscillation (ENSO) phase, as defined by the Center for Ocean-Atmospheric Prediction Studies (COAPS, online at coaps.fsu.edu/jma)

	La Niña	Neutral	El Niño
Corn 1	***−330.6 (935.8)***	*29.9 (1195.4)*	**279.0 (922.3)**
Corn 2	**−263.5 (898.2)**	13.13 (1240.4)	**253.2 (874.3)**
Corn 3	−192.3 (931.8)	45.9 (1246.8)	79.6 (862.1)
Corn 4	**−189.9 (887.9)**	−10.8 (1142.1)	**241.2 (847.7)**
Corn 5	*−235.3 (732.0)*	*50.7 (1008.5)*	113.3 (685.8)
Corn 6	***−359.8 (943.3)***	*96.1 (1013.7)*	**119.5 (796.5)**
Soybean 1	**−59.4 (209.7)**	−15.9 (367.7)	**107.6 (221.2)**
Soybean 2	**−51.5 (262.5)**	−7.6 (345.6)	**77.6 (186.1)**
Soybean 3	−32.1 (220.3)	3.9 (389.6)	26.6 (336.4)
Soybean 4	21.1 (220.4)	−28.8 (369.2)	49.2 (340.2)
Soybean 5	−51.3 (264.1)	11.8 (254.9)	28.3 (166.5)
Soybean 6	***−117.8 (245.9)***	*45.6 (266.3)*	**18.0 (228.2)**

Bold values represent significant differences (p value of 0.10 or less) in yield between La Niña and El Niño years, while italic values represent significant differences in yield between La Niña and neutral years, with all data sets involved containing at least five samples (yield per ENSO phase year)

Discussion

Annual crop yields in Missouri were examined for periodicities, using the techniques of Mokhov et al. (2004) and Lupo et al. (2012a), to determine possible associations with the climate variabilities related to ENSO and PDO. The highly produced field crops of corn and soybean were studied by climate region in Missouri, in order to account for climate differences across the state (NCDC 2006). ENSO and PDO phases influence regional Missouri temperature and precipitation, therefore impacting regional Missouri corn and soybean. Corn (soybean) in Missouri reaches the reproductive stage in July (August), making that time of summer the most impactful for the crop. The ENSO and PDO impact on July and August temperature and precipitation is the most important to consider, but the entire growing season influences crop growth because temperature and precipitation can shorten or lengthen each stage of crop growth (Hu and Buyanovsky 2003). Average seasonal temperature and precipitation ranging from April to September, to cover Missouri's corn and soybean

Table 4 Departure from average (standard deviation) calculated from detrended crop yields in kilograms per hectare, for each crop in each climate region of Missouri, for the years associated with each El Niño Southern Oscillation-Pacific Decadal Oscillation (ENSO-PDO) phase combination (Table 1)

	Positive PDO (1)			Negative PDO (2)		
	La Niña	Neutral	El Niño	La Niña	Neutral	El Niño
Corn 1	−360.0 (894.3)	−137.0 (1144.5)	442.8 (631.3)	−321.4 (976.7)	230.1 (1247.5)	131.5 (1138.4)
Corn 2	−495.3 (966.3)	−92.8 (992.6)	455.1 (650.0)	−191.1 (925.7)	140.3 (1496.8)	71.6 (1037.2)
Corn 3	−50.1 (258.1)	22.4 (1127.7)	213.3 (743.3)	−236.7 (1063.5)	74.2 (1399.8)	−40.8 (980.4)
Corn 4	−175.7 (274.7)	−35.1 (985.6)	389.5 (636.7)	−194.3 (1015.4)	18.3 (1326.5)	107.7 (1017.3)
Corn 5	−309.7 (290.3)	−1.2 (863.8)	137.6 (515.2)	−212.0 (830.4)	113.0 (1174.5)	91.4 (838.7)
Corn 6	−573.1 (522.6)	129.2 (891.9)	**429.0 (686.8)**	−293.1 (1045.8)	56.3 (1160.9)	**−158.9 (817.1)**
Soybean 1	−135.3 (283.2)	−33.6 (398.1)	92.5 (186.0)	−43.1 (200.5)	−1.6 (350.5)	115.2 (246.1)
Soybean 2	−107.0 (300.9)	−14.4 (339.1)	100.9 (66.5)	−39.6 (264.6)	−2.2 (359.1)	66.0 (226.8)
Soybean 3	78.9 (69.6)	39.8 (403.7)	**174.3 (263.1)**	−55.9 (235.7)	−25.3 (385.3)	**−47.2 (356.5)**
Soybean 4	14.2 (127.7)	−80.3 (374.5)	90.5 (394.8)	22.6 (239.3)	12.8 (368.7)	28.5 (330.7)
Soybean 5	−83.3 (154.9)	−10.1 (280.3)	91.5 (96.8)	−44.5 (286.2)	29.5 (237.8)	−3.3 (188.8)
Soybean 6	−145.8 (318.3)	−15.5 (292.0)	**−56.6 (124.4)**	−111.8 (242.1)	95.0 (239.3)	**55.4 (263.7)**

Bold values represent significant differences (p value of 0.10 or less) in yield for El Niño years of different PDO phases, with both data sets involved containing at least five samples (yield per phase year combination)

growing season, were used for the analysis of each crop. Spectral analysis of each crop in each region displayed different variabilities of interannual, interdecadal, and/or multidecadal time scales in each set of data, suggesting slightly varied ENSO and PDO impacts across Missouri. Regional differences in ENSO and PDO impacts are not extreme, possibly due to the fact that Missouri's regional climates grade inconspicuously into each other (NCDC 2006).

With results varying for each crop in each region, including each power spectrum analyzed, the best way to choose the basis for seasonal forecasts is specifically with each crop and region. Table 2 displays all possible associations to ENSO and PDO phase, as well as to PDO-modulated ENSO variability, for every power spectrum analyzed. Therefore, results from Table 2 allow for an analysis of each region, specific to each crop. Corn results suggest the most climate variability associations to be found in regions 1, 2, and 6, while soybean yields display the most variability related to climate in regions 3 and 6. After determining if each crop and region is impacted by certain climate variabilities, the question of how they are impacted becomes a factor.

Comparing crop yield averages from each ENSO phase (Table 3) to crop yield averages from each ENSO-PDO phase combination (Table 4) gave the opportunity to assess how ENSO and PDO phases impact crop yields. Table 3 displays a positive departure from average of corn and soybean yields for El Niño years and a negative departure from average for La Niña years. Table 4 displays similar results and is described in section "ENSO-PDO phase interactions". Results suggest that ideal conditions of adequate precipitation with no extreme temperatures are more likely to occur in growing seasons prior to El Niño events, which can be referred to as El Niño transition periods. Since a negative departure from average yields is found for La Niña years, it is possible that extreme temperatures and drought are common during La Niña transition periods, which represent the crop growing seasons prior to La Niña events. Ratley et al. (2002) and Newberry et al. (2016) concur that summer months are typically hot and dry in Missouri during an ENSO transition towards La Niña.

ENSO years in this study begin after the harvest of the crops used in this study (Fig. 2). It is realized that the growing season of the crop falls in a time period that could display either similar index values to the JMA ENSO year or values that represent a transition into the phase defined by the JMA ENSO year. For either situation, the growing season should not experience drastically different impacts or resulting yields than what the JMA ENSO year phase would suggest. July and August weather has the greatest impact on crop yields and those months fall slightly before the JMA ENSO year begins. Similar strategies have been used involving the time period before an ENSO phase occurs, which can be referred to as the summer transition period (Ratley et al. 2002; Lupo et al. 2008, 2014; Mokhov et al. 2014; Newberry et al. 2016).

The JMA ENSO year was chosen for this study based on the resulting statistical relationships. Tables 3 and 4 were recreated using the ENSO year prior to the crop production year, which begins in the winter before and continues through the crop growing season. For example, the JMA ENSO year of 2011 was compared to the crop yields produced in 2012. However, the recreated tables displayed no statistical relationships (not shown), meaning all p values were well above 0.10. Therefore, the results used in this study display the relationship of crop yields to the ENSO phase beginning after the crop harvest, which means the predictability of crop yields will depend on the advanced predictability of ENSO. Thus, crop yield forecasts will be seasonal, on the order of 3 to 12 months.

Seasonal forecasts may be more accurate for the regions displaying significant differences in yield between ENSO phases or ENSO-PDO phase combinations, which are displayed in Tables 3 and 4, respectively. Eighty-five percent of Missouri corn productivity (regions 1, 2, 4, 5, and 6) from 1919 to 2013 and 55 % percent of Missouri soybean productivity (regions 1, 2, and 6) from 1944 to 2013 exhibit a significant difference (p values less than 0.10) in yields either between El Niño and La Niña years and/or La Niña and neutral years. It is fair to say ENSO has an impact on Missouri crops and has the possibility to be used as an aid in creating crop yield predictions. Table 4 displays less impressive results than Table 3, with only one region for corn and two for soybean exhibiting a significant difference in yields between El Niño/positive PDO years and El Niño/negative PDO years. However, the averages in Table 4 are still compelling evidence of a possible interaction between ENSO and PDO, with PDO contributing to ENSO impacts on Missouri crop yields.

Out of all six of the Missouri climate regions, region 6 is most promising for accurate crop yield predictions. Corn and soybean yields differ significantly between El Niño and La Niña years, La Niña and neutral years, as well as between El Niño/positive PDO and El Niño/negative PDO years, showing high potential for accurate forecasts of yields based on ENSO and PDO phases. These results are very impressive, especially because region 6 produces roughly 20 % of both corn and soybean yields for the state of Missouri. Regions 1, 2, and 6 display statistical relationships (p values less than 0.10) for both crops, while region 3 is only significant for soybean and regions 4 and 5 for corn. Therefore, regions 1 and 2 show the most promise after region 6. However, regions 1 and 2 only have significant differences (p values less than 0.10) in yield when dealing with ENSO phase differences. When considering the PDO phase, only regions 3 and 6 show significant differences (p values less than 0.10). The likelihood of accurate yield predictions based on ENSO and PDO phase depends on the specific crop and climate region in question.

The statistical analysis displayed more impressive results based on ENSO phase only, rather than both ENSO and PDO phases. Five climate regions showed statistical relationships when dealing with ENSO phase, while only two regions showed relationships after including PDO phase. The power spectra analysis also reveals a less apparent PDO influence on Missouri crop yields, compared to the ENSO influence. Only 42 % of the analyzed spectra represented a multidecadal variability, while 100 % displayed an interannual variability. However, PDO still has an impact on Missouri crops through an interdecadal variability found in 71 % of the analyzed spectra, associated with a possible ENSO-PDO interaction.

Comparing averages from each ENSO phase alone (Table 3) to averages from each ENSO-PDO phase combination (Table 4), highly suggests that PDO influences ENSO impacts. An example was provided in the aforementioned results, supporting the conclusions from Lupo et al. (2007) that strong El Niño signals occur during years of positive PDO, while strong La Niña events occur during years of negative PDO (Gershunov and Barnett 1998; Birk et al. 2010). Therefore, the findings in this study support the theory of PDO-modulated ENSO-related interdecadal variability found in Midwestern climates (Gershunov and Barnett 1998; Berger et al. 2002; Birk et al. 2010).

The results in this study provide a solid foundation for future seasonal forecasts of corn and soybean yields, specific to each climate region in Missouri, based on both ENSO and PDO phases. ENSO and PDO affect Missouri temperature and precipitation, while temperature and precipitation impact Missouri corn and soybean yields. Thus, ENSO and PDO impact Missouri crops and provide an opportunity for creating crop production outlooks. Forecasts of both corn and soybean yields can help farmers who rotate crops in their fields decide which crop to plant for the upcoming season or even help them prepare for a season in need of irrigation. Further, these forecasts can inform insurance or loan companies and agricultural consumers of the projected crop yields for their use in financial planning or coverage agreements. Knowledge of crop yield changes in relationship to ENSO and PDO phase can greatly benefit the agricultural community and economics through the use of accurate forecasts on the seasonal time range of 3 to 12 months.

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