Impact Analysis of Decadal Climate Variability on Crop Yields in the Marias River Basin

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Selected Paper prepared for presentation at the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-28

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Abstract: Natural climate variability and change, including decadal climate variability (DCV), can influence different crop production in different ways. Signals on climate variability may provide farmers important information and further affect their decision making. In this paper, we use an econometric method to estimate the DCV effects on yields of five crops in the Marias river basin in Montana. We find strong DCV effects on barley, spring/winter wheat. And the DCV phase combination PDO-TAG+WPWP+ has the strongest effect. Adaptive decision making is allowed in terms of acreage changes in crops under different DCV phases.

1 Introduction

Natural climate variability ranging from inter-annual to inter-decadal timescales influences agricultural production and water resources. Decadal climate variability (DCV) is one form of variability and stands for regional variations in weather and climate patterns on the time scale of seven to twenty years (Hurrell et al., 2010). A priori information on climate variability including DCV signals may provide farmers crucial information with which they may improve crop production, water usage, and land allocation (Fernandez, 2013).

[1] This research is supported by the U.S. Department of Agriculture-National Institute of Food and Agriculture under grant 2011-67003-30213 in the NSF – USDA – DOE Earth System Modelling Program, and by the NOAA – Climate Programs Office - Sectoral Applications Research Program under grant NA12OAR4310097.

Analyses of inter-seasonal and inter-annual climate phenomena, such as El Niño-Southern Oscillation (ENSO), have been done in numerous studies (Solow et al., 1998; Adams et al., 1999; Chen et al., 2005; Power et al., 2013). Little attention has been focused on DCV impacts. This paper does an econometric analysis of the DCV effect on yields for five different crops in a Montana region - the Marias river basin, which accounts for a large proportion of agricultural production in Montana. And identifiable DCV signals in precipitation and temperature can be found in this area. Following Mehta, Rosenberg, and Mendoza (2011, 2012), the DCV phenomena analyzed here include the Pacific Decadal Oscillation (PDO), the Tropical Atlantic Gradient (TAG) and the West Pacific Warm Pool (WPWP).

2 DCV Background

The PDO is a long-lived El Nino-like pattern of Pacific climate variability (Mantua, 1999). The PDO manifests itself in a decadal pattern of change in sea surface temperatures (SSTs) in the Pacific Ocean. During a positive PDO phase, the western Pacific becomes cool and part of the eastern Pacific becomes warm. The opposite pattern occurs during a negative PDO phase.

The TAG is defined as the difference between North (5°N-25°N) and South (5°S-25°S) Atlantic SSTs (Huang, Robertson, and Kushnir, 2005). The TAG is known to potentially influence the rainfall anomalies over the Nordeste region of South America (Huang et al., 2009). The TAG usually persists for a period of 12-13 years across the equator and is associated with rainfall in the southern, central, and mid-western U.S. (Murphy et al., 2010). The WPWP is characterized by a SST consistently higher than

28℃, which is around 2-5℃ above that of other equatorial waters (Yan et al., 1992; Wang and Mehta, 2008).

Mehta, Rosenberg, and Mendoza (2011, 2012) showed that oceanic phenomena such as PDO, TAG, and WPWP were highly correlated with temperature and precipitation anomalies in the Missouri river basin (MRB). They used the Erosion Productivity Impact Calculator (EPIC) model to simulate the impacts of these DCV phenomena on yields of dryland corn, spring wheat, and winter wheat in the MRB region. They showed that the DCV impacts varied in spatially specific scales and ranged as great as 40-50% of average yield. Fernandez (2013) used a price endogenous agricultural and non-agricultural model (RIVERSIM) to examine the economic value of DCV information to agriculture and water users in the MRB region. He showed that the value of the DCV information for perfect forecast was about $5.2 billion per year, of which 86% can be gained based on transition probabilities. He also found that under different DCV states, there existed differential responses in the acreage of major crops and water allocation among agricultural, residential, and industrial users.

3 Marias River Basin

Marias river basin is a Montana sub-basin contained within the MRB. The MRB as a basin produces about 46% of US wheat, 22% of US grain corn, and 34% of US cattle. In the MRB region, around 117 million acres are in cropland, of which 12 million acres are irrigated, thus nearly 90% of the MRB cropland depends on precipitation. In 2008 the economic value of crops and livestock production in the MRB region was over $100 billion (Mehta et al., 2013). Marias river basin is located in the upper MRB (see

Figure 1), which is an important agricultural region, accounting for a large portion of Montana's agriculture.

In our study area, there are 14 counties: Broadwater, Cascade, Chouteau, Gallatin, Glacier, Hill, Jefferson, Judith Basin, Lewis and Clark, Liberty, Meagher, Pondera, Teton, and Toole. Only Pondera, Teton, and Cascade are entirely located in the Marias river basin, with other counties partially within the basin boundaries.

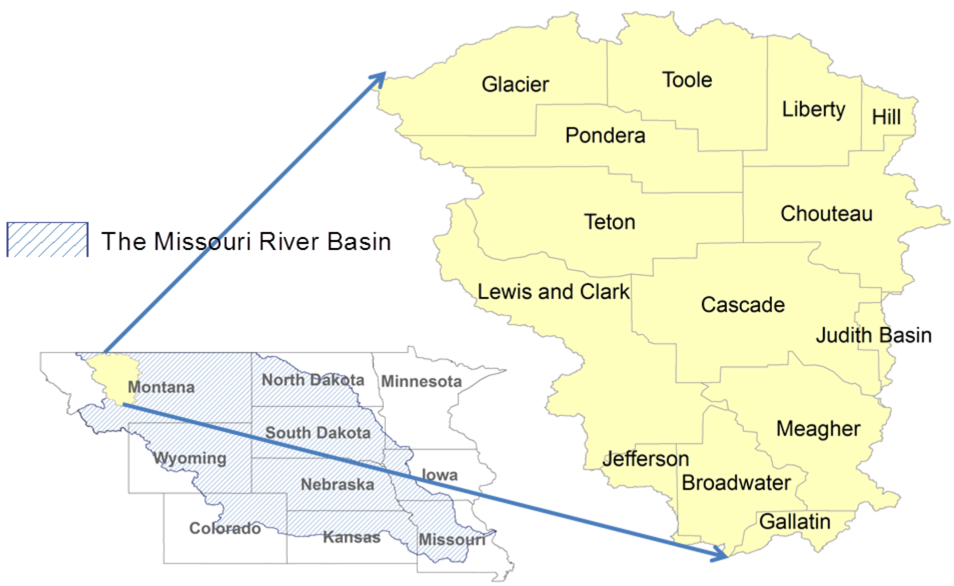

Figure 1 Geographic Location of the Marias River Basin

In the Marias river basin, we can also find substantial and identifiable DCV signals in precipitation and temperature (see Figure 2). DCV signals are most obvious in precipitation. From February to October, average monthly precipitation under a positive PDO phase is greater than that under a negative PDO phase. Average monthly precipitation is higher under a positive TAG phase from February to July, while under a positive WPWP phase the level of monthly precipitation is lower from July this year to

May in the following year. In terms of average monthly temperature, the difference between a positive DCV phase and a negative phase is small, but we still can see some DCV signals, e.g., under positive PDO phases, monthly temperature is higher from January to July, while from August this year to February next year, average monthly temperature is greater under positive TAG and WPWP phases.

4 Econometric Analysis of DCV Impacts on Crop Yields

4.1 Econometric Model

The effect of climate variability on crop yields can be simulated through a simulation-based model, e.g., EPIC (Solow, et al., 1998; Adams et al., 1999; Mehta, Rosenberg, and Mendoza, 2012), or a historical data-based approach, e.g., estimation over historical yield outcomes using an econometric model (Kim and McCarl, 2005; Jithitikulchai, 2014). Mehta, Rosenberg, and Mendoza (2012) used the EPIC model to simulate the yields of dryland crop under average climatic conditions and examine how the DCV impacts on the MRB hydro-meteorology alter these yields. However, the counties in the Marias river basin were not covered in their study.

In this essay, econometric analysis will be applied to estimate the effects of DCV information on the yields of five different crops in the Marias basin. Direct DCV effects will be estimated through the regression of crop yields on time trend, climate variables, DCV phase combination, and ENSO. Indirect DCV effects will be done through the impacts of DCV on climate, which further influences the crop yields.

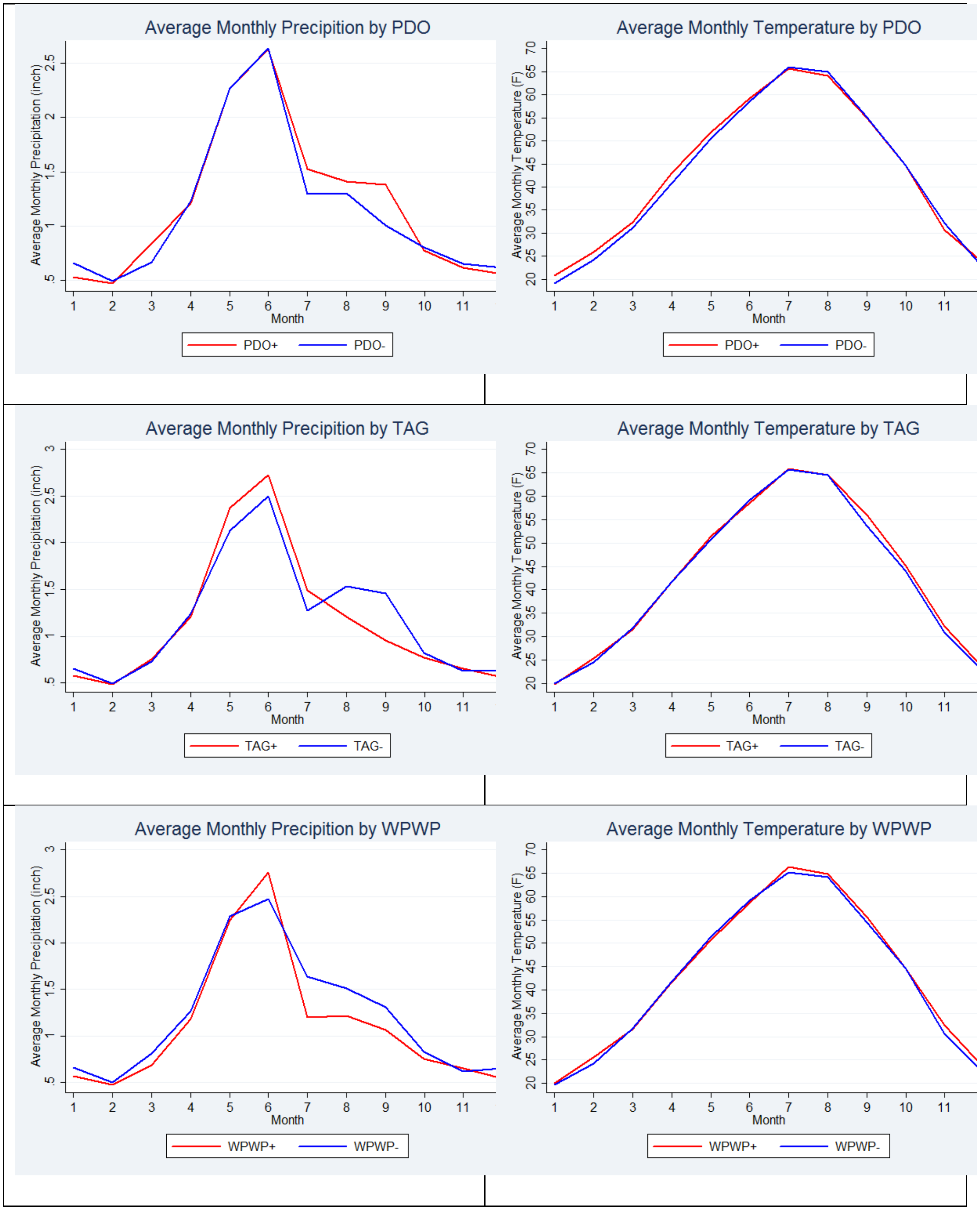

Figure 2 Monthly Changes of Precipitation and Temperature under DCV

A nonlinear relationship has been found in a number of cases between temperature and crop yields (Schlenker and Roberts, 2009). Following McCarl, Villavicencio, and Wu (2008) and Cai (2009), we use the following functional form to estimate the DCV impacts on crop yield,

$$(1) \qquad \log(Yield) = f(Time, Climate, DCV, DCV * County, ENSO) + \varepsilon$$

where function f is in linear form, $\log(Yield)$ is the log of crop yields. $Time$ denote the year and its corresponding squared terms collectively used to account for technological change. $Climate$ contain three types of climatic variables: monthly total precipitation, monthly mean temperature, and monthly Palmer Drought Severity Index (PDSI). These climatic variables have also been defined based on the consideration of seasonality, e.g., spring total precipitation, summer total precipitation, and fall total precipitation. DCV denote dummies of 8 DCV phase combinations, which are used to estimate the effect of DCV phases on crop yields. $County$ are dummies identifying 14 counties in the Marias basin allowing spatially differential effects. To take into account of the heterogeneity of DCV impacts among counties, we add an interaction term between DCV and the county dummies. $ENSO$ is included to capture the short-term effect of climate variability on the yields of crops. We assume that ε is a normally distributed error term with zero mean.

To investigate the DCV impact on climate, we define the following functional form,

$$(2) \qquad Climate = g(Time, DCV, DCV * County, ENSO) + \mu$$

where function g is in linear form, μ is also assumed to be an error term following a normal distribution with zero mean.

Based on equations (1) and (2), we can calculate the total DCV impacts on log crop yields as follows,

(3) $$\frac{\Delta \log(Yield)}{\Delta DCV} = \frac{\Delta \hat{f}}{\Delta DCV} + \sum_{Climate} \frac{\Delta \hat{f}}{\Delta Climate} * \frac{\Delta \hat{g}}{\Delta DCV}$$

where $\frac{\Delta \hat{f}}{\Delta DCV}$ is the direct DCV effect on log crop yields, and $\sum_{Climate} \frac{\Delta \hat{f}}{\Delta Climate} * \frac{\Delta \hat{g}}{\Delta DCV}$ is the indirect DCV effect on log crop yields.

From equations (1) and (2), we know that the error terms ε and μ would be highly correlated since both equations have the same regressors (*Time, DCV, DCV*County* and *ENSO*) and *Climate* also enters equation (1) as an independent variable. We cannot regress the crop yield function f and climate functions g separately. Since functions f and g used here are in linear form, we can change all the regression functions from structural form to reduced form, that is, only exogenous variables exist in the right-hand-side of the equation. Then we can estimate all the equations as a system. In the new crop yield function, the estimated coefficients of DCV are just the total marginal effects of DCV on crop yields, including both the direct and indirect DCV effects. The interaction terms of DCV and county dummies $DCV * County$ are absorbing the DCV effects particular to each county.

In equation (3), we only know the total marginal effect of DCV on the log of the crop yields, which is not extremely interesting. Suppose the estimated coefficient for DCV in the reduced form crop yield function is $\hat{\beta}$, that is $\frac{\Delta \log(Yield)}{\Delta DCV} = \hat{\beta}$. We want to know the marginal effect of DCV on crop yields. Since DCV is the dummy variable, in the log scale, $\hat{\beta}$ is the difference in the expected geometric means of log crop yield between DCV=1 and DCV=0. In the original scale of crop yield, $e^{\hat{\beta}}$ is the ratio of the geometric mean of crop yield for DCV=1 over the geometric mean of crop yield for DCV=0[2]. With some algebraic transformation, we know that from DCV=0 to DCV=1, we expect an increase of $\left(e^{\hat{\beta}}-1\right)*100$ in the geometric mean of crop yield (detailed derivation can be found in the Appendix).

4.2 Data Specification

The data used here is in the form of a panel across counties and years. There are 14 counties in the study area. We mainly focus on the DCV impact analysis of five crops due to data availability. The crops considered here are dryland barley, alfalfa hay, oats, spring wheat, and winter wheat. All the crop yield data were obtained from Quick Stats (NASS, USDA). Yield data for barley and oats range from 1949 to 2008, alfalfa hay data cover from 1964 to 2008, and spring/winter wheat data range from 1949 to 2011.

Monthly mean temperature, monthly total precipitation, and monthly PDSI are drawn from the National Climatic Data Center, National Oceanic and Atmospheric Administration (NCDC-NOAA). Those reported data are in station-level, and monthly mean temperature is measured in °F and total precipitation is measured in inches. Temperature and precipitation can be calculated based on the average across the data for all weather stations in each county as NOAA data on each weather station contains latitude and longitude of its location. Monthly PDSI data are at the climate division level. Using the definition of division and county in Montana, we have the PDSI data for each county in the division. In addition, we divide the monthly climate data into four seasons

[2] How do I interpret a regression model when some variables are log transformed?. UCLA: Statistical Consulting Group. From http://www.ats.ucla.edu/stat/mult_pkg/faq/general/log_transformed_regression.htm (accessed July 21, 2015).

to take into account of seasonality effect, that is, March, April, and May in Spring, June, July, and August in Summer, September, October, and November in Fall, and the rest in Winter. Table 1 reports summary statistics for the crop and climatic data set.

Table 1 Summary Statistics of Crop and Climatic Factors

	Mean	Std. Dev.	Min	Max
Crop Yield				
Barley (bu/acre)	33.91	11.36	8.6	71
Alfalfa Hay (tons/acre)	1.39	0.42	0.3	3.1
Oats (bu/acre)	32.32	13.35	10	85
Spring Wheat (bu/acre)	23.67	8.68	4	63
Winter Wheat (bu/acre)	31.33	10.10	8.8	69
Precipitation (inch)				
Spring	3.97	2.20	0	28.42
Summer	5.12	2.50	0	15.99
Fall	2.44	1.55	0	11.17
Temperature (°F)				
Spring	41.53	3.74	29.09	49.82
Summer	63.13	2.92	47.66	71.66
Fall	43.70	3.44	31.28	54.32
PDSI				
Spring	0.005	2.06	-6.68	5.87
Summer	0.154	2.66	-6.58	7.02
Fall	0.148	2.68	-6.54	7.53

DCV data are gotten from Fernandez (2013) and Jithitikulchai (2014). We use data on three types of DCV phenomena, that is, PDO, TAG, and WPWP, with each having positive and negative phases. Based on work of Mehta, Rosenberg, and Mendoza (2011, 2012) and Fernandez (2013), we look at the combinations of those phases, with 8 DCV phase combinations considered herein (see Table 2). We also calculate the historical probability distribution of DCV phase combinations.

Table 2 Years in DCV Phase Combinations

DCV Phase Combinations	Years in Each DCV Phase Combination							
PDO- TAG- WPWP-	1949	1965	1971	1972	1974	1975	1989	1991
	1994	2008						
PDO- TAG+ WPWP-	1955	1966	1967	2001				
PDO- TAG- WPWP+	1959	1963	1968	1973	1999	2000	2009	
PDO+ TAG+ WPWP-	1976	1978	1979	1980	1982	1983	1987	1992
	1997	2006						
PDO- TAG+ WPWP+	1950	1951	1952	1953	1954	1956	1961	1962
	1964	1969	1970	1990	2007	2010	2011	
PDO+ TAG+ WPWP+	1957	1958	1960	1981	1998	2004	2005	
PDO+ TAG- WPWP-	1977	1984	1985	1986	1993			
PDO+ TAG- WPWP+	1988	1995	1996	2002	2003			

Source: DCV data from 1949 to 2010 is gotten from Fernandez (2013). DCV information in 2011 is updated from Jithitikulchai (2014).

ENSO data are drawn from the Japan Meteorological Agency (Solow et al., 1998; Chen et al., 2005). The index is defined as a spatially 5-month mean of SSTs anomalies in the region of tropical Pacific. If values of the index are 0.5℃ or greater for consecutively 6 months (including October, November and December), the ENSO year of October through the following September is set as El Niño, if the index values are less than or equal -0.5℃, then it is categorized as La Niña year, otherwise, it is neutral year.

4.3 Estimation Results Discussion

In reduced form, the crop yield function and the climate functions are estimated as a system. We report the econometric results of log crop yield regression in two tables (Table 3 and Table A1), since we need to do a linear combination of the coefficients for DCV and the coefficients for the interaction terms of DCV and county dummies to get the exact effect of DCV in each county. Table 3 shows the econometric results of log crop yield regression without the interaction terms of DCV and counties dummies. The linear combination results will be shown in Table A1 in the Appendix.

Table 3 Econometric Results of Log Crop Yield Regression

	Barley	Alfalfa Hay	Oats	Spring Wheat	Winter Wheat
Time	0.021***	-0.007	0.018***	0.015***	0.016***
	(0.003)	(0.005)	(0.004)	(0.004)	(0.003)
Time_sq	-0.000***	0.000	-0.000***	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
C1	-0.178	-0.211	-0.413**	-0.099	-0.111
	(0.138)	(0.136)	(0.177)	(0.148)	(0.113)
C2	0.070	0.085	0.174	-0.209	-0.149
	(0.153)	(0.213)	(0.177)	(0.164)	(0.126)
C3	-0.050	-0.154	0.054	-0.089	-0.148
	(0.137)	(0.173)	(0.178)	(0.125)	(0.096)
C4	0.008	0.008	-0.122	0.168	0.048
	(0.100)	(0.099)	(0.111)	(0.107)	(0.082)
C5	-0.288**	0.109	-0.142	-0.213	-0.165
	(0.138)	(0.136)	(0.216)	(0.148)	(0.113)
C6	-0.155*	0.050	-0.123	-0.006	-0.211***
	(0.093)	(0.151)	(0.097)	(0.093)	(0.069)
C7	0.144	0.405***	-0.107	-0.007	0.003
	(0.118)	(0.151)	(0.155)	(0.126)	(0.096)
El Niño	0.143***	0.047	0.119***	0.083***	0.070***
	(0.029)	(0.033)	(0.031)	(0.030)	(0.023)
La Niña	-0.034	-0.068**	-0.092***	-0.047	0.026
	(0.029)	(0.035)	(0.034)	(0.032)	(0.023)
Constant	3.124***	0.471***	3.277***	2.813***	3.015***
	(0.058)	(0.058)	(0.062)	(0.063)	(0.046)
R_sq	0.334	0.269	0.303	0.325	0.461
Obs.	749	593	637	752	790

Note: 1) C1~C7 are dummies for eight DCV phase combinations. C1=PDO+TAG-WPWP-, C2=PDO-TAG+WPWP-, C3=PDO-TAG-WPWP+, C4=PDO+TAG+WPWP-, C5=PDO+TAG-WPWP+, C6=PDO-TAG+WPWP+, C7=PDO+TAG+WPWP+, PDO-TAG-WPWP- is excluded due to the consideration of collinearity. 2) El Niño is the dummy for the year of El Niño, and La Niña is the dummy of La Niña year. 3) Values in parentheses are standard errors with * for p<0.1, ** for p<0.05, and *** for p<0.01, respectively. 4) Time_sq denotes the squared term of time. R_sq denotes R squared value. And Obs. is the observation number.

The results in Table 3 indicate that the yields of most crops increase with time, which is a proxy for technical advancement. The coefficients of the squared term of time show a small diminishment in technical progress over time. The coefficients on DCV in this table show the marginal DCV effect on log crop yields in the county of Broadwater. We find that in year PDO-TAG+WPWP+, barley yield significantly decreases by 14.36% relative to the base year PDO-TAG-WPWP-, and winter wheat yield decreases by 19.02%. DCV phase combination PDO-TAG+WPWP+ also shows yield declines and is known to be associated with persistent droughts (Mehta, Rosenberg, and Mendoza, 2012; Fernandez, 2013). In terms of ENSO effects, under an El Niño year, yields of barley, oats, spring wheat, and winter wheat significantly increase by 5-15% relative to a neutral year, while in a La Niña year, the yield of alfalfa hay decreases by 6.57%, and oats yield decreases by 8.79%.

The estimated coefficients for the DCV effects on log crop yields in each county are shown in Table A1 in Appendix. There we see that most of the significant DCV impacts arise under PDO-TAG+WPWP+, PDO+TAG-WPWP-, PDO+TAG-WPWP+, and PDO-TAG-WPWP+. After some algebraic transformation, the values can be explained as the crop yield percentage change under each DCV phase combination relative to the base case PDO-TAG-WPWP-. For example, the yield of barley in Gallatin is expected to significantly increase by 20.2% under PDO-TAG+WPWP+ relative to the year of PDO-TAG-WPWP-, while decrease by 19.8% in Hill. Comparing the DCV effects by crops, we can see that barley, winter wheat, and spring wheat are highly statistically significant.

In order to explain the DCV effects more intuitively, we transform the results in Table A1 into percentage yield changes and add the case of PDO-TAG-WPWP- expressing all the results as deviations from the mean using the historical probabilities of the DCV phases. In doing this, we only use estimation results that are significant in the

90% confidence interval. We use the ArcGIS to display the final results which are shown in Figures 3-7.

Results in Figure 3 show that yields of barley under PDO-TAG+WPWP+ decrease by 5-20% in southwestern and northeastern Marias basin (including counties Broadwater, Lewis and Clark, Meagher, liberty, and Hill). In year with the phase combination PDO+TAG+WPWP+, barley yields increase for all the counties in the Marias basin. Similarly under PDO+TAG+WPWP- and PDO-TAG+WPWP-, barley yields increase by 2.5-20% almost everywhere in the Marias basin except counties Glacier, Pondera, and Teton in the northwest. And in year of PDO+TAG-WPWP+, yields of barley decrease in most of the counties except in the northeastern part of the Marias basin, e.g., Hill, Liberty, and Toole, and in the southwestern Marias, e.g., Lewis Clark.

For alfalfa hay, under PDO+TAG+WPWP+, PDO-TAG+WPWP+, and PDO+TAG+WPWP-, there are significant increases in yields in most of the counties except some counties in the southern Marias basin (see Figure 4). Similar results can be found under PDO-TAG-WPWP- and PDO-TAG+WPWP-. And in year of PDO-TAG-WPWP+, changes of alfalfa hay yields are mostly negative, ranging from -5% to -35% of average yield.

For oats, changes in yields are mostly negative from -2.5% to -35% of average yield in year of PDO+TAG-WPWP- (see Figure 5). In the year with the phase combination PDO-TAG+WPWP+, the changing pattern of oats yields is quite similar to that of barley under the same phase combination. Under DCV phase combinations PDO-TAG+WPWP- and PDO-TAG-WPWP+ changes in oats yields are negative in the north of Marias basin and positive in south. Similar results can be seen from the phase combinations PDO-TAG-WPWP-, PDO+TAG+WPWP+, and PDO+TAG-WPWP+. Note there are no significant changes in oats yield in Chouteau andGlacierfor all DCV phase combinations.

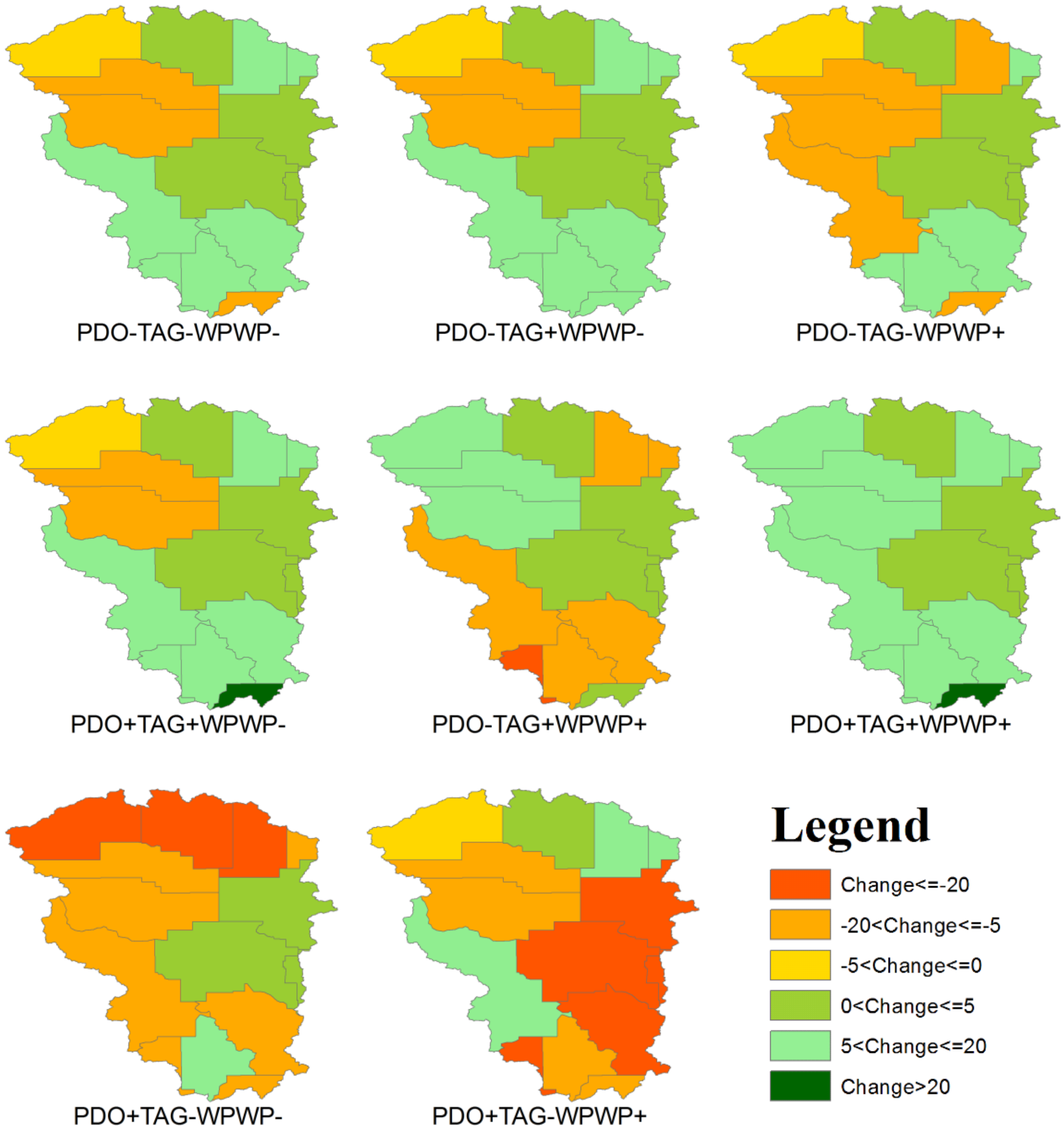

Figure 3 Yield Changes of Barley under DCV Phase Combinations (% Change)

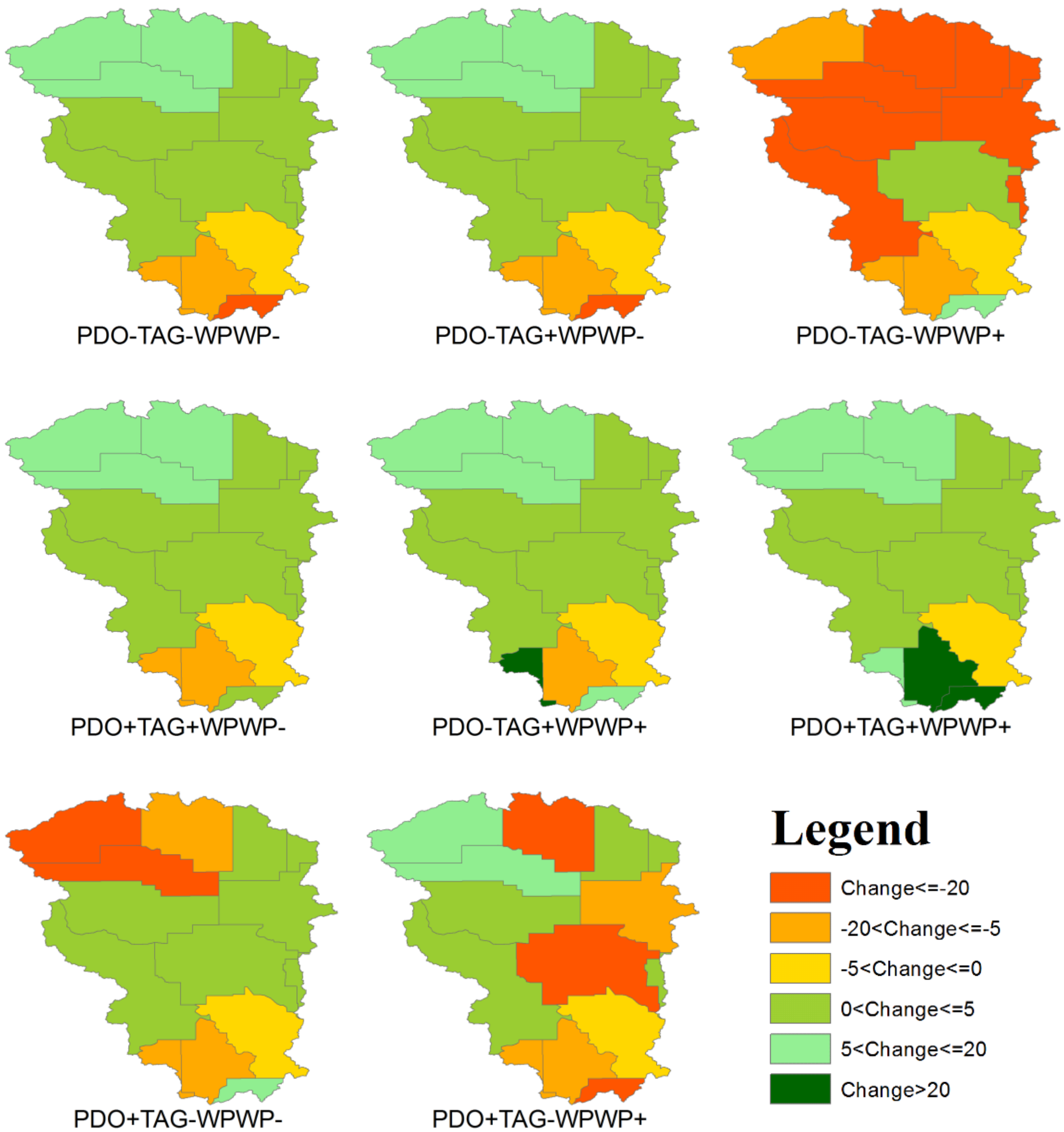

Figure 4 Yield Changes of Alfalfa Hay under DCV Phase Combinations (% Change)

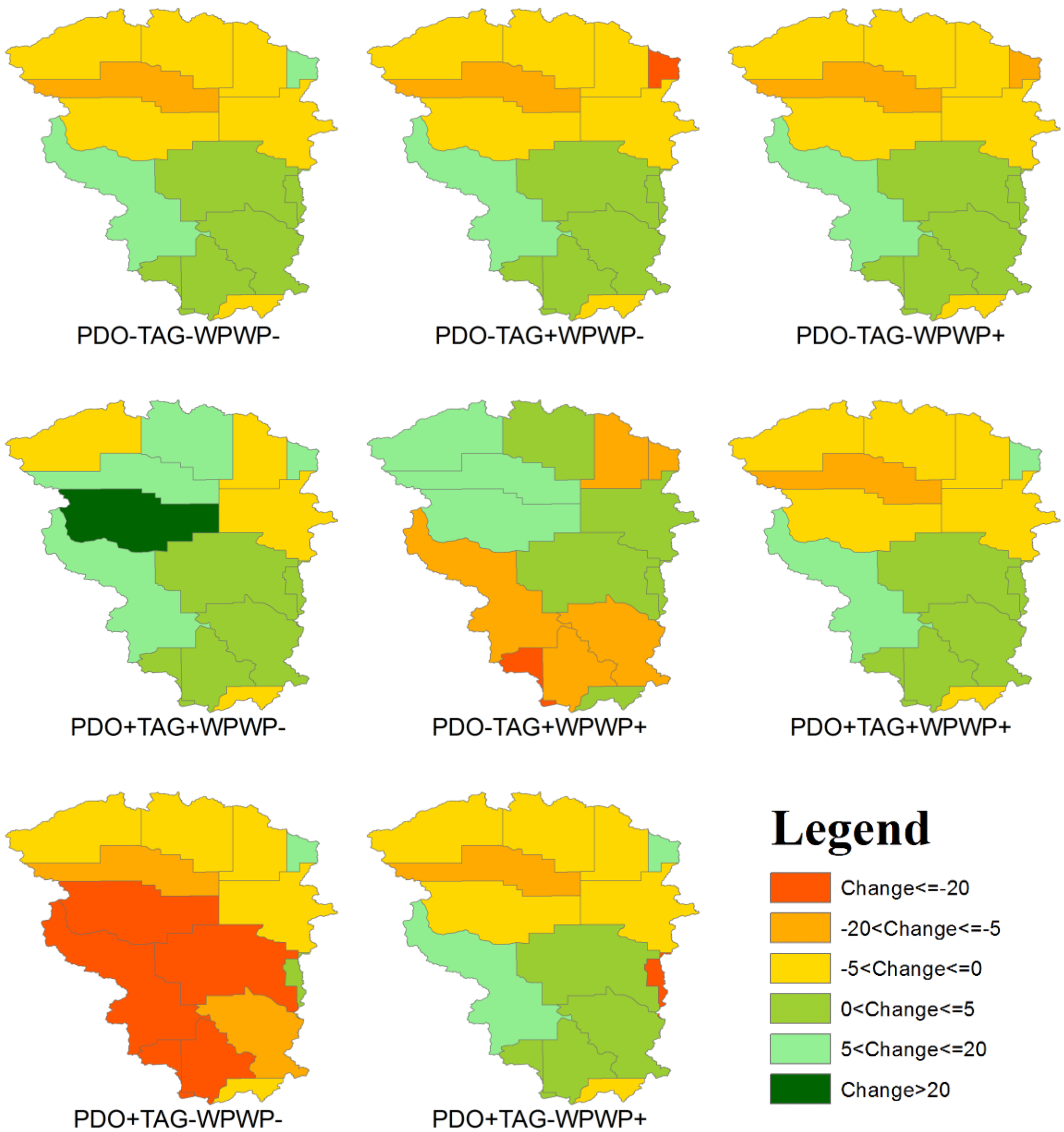

Figure 5 Yield Changes of Oats under DCV Phase Combinations (% Change)

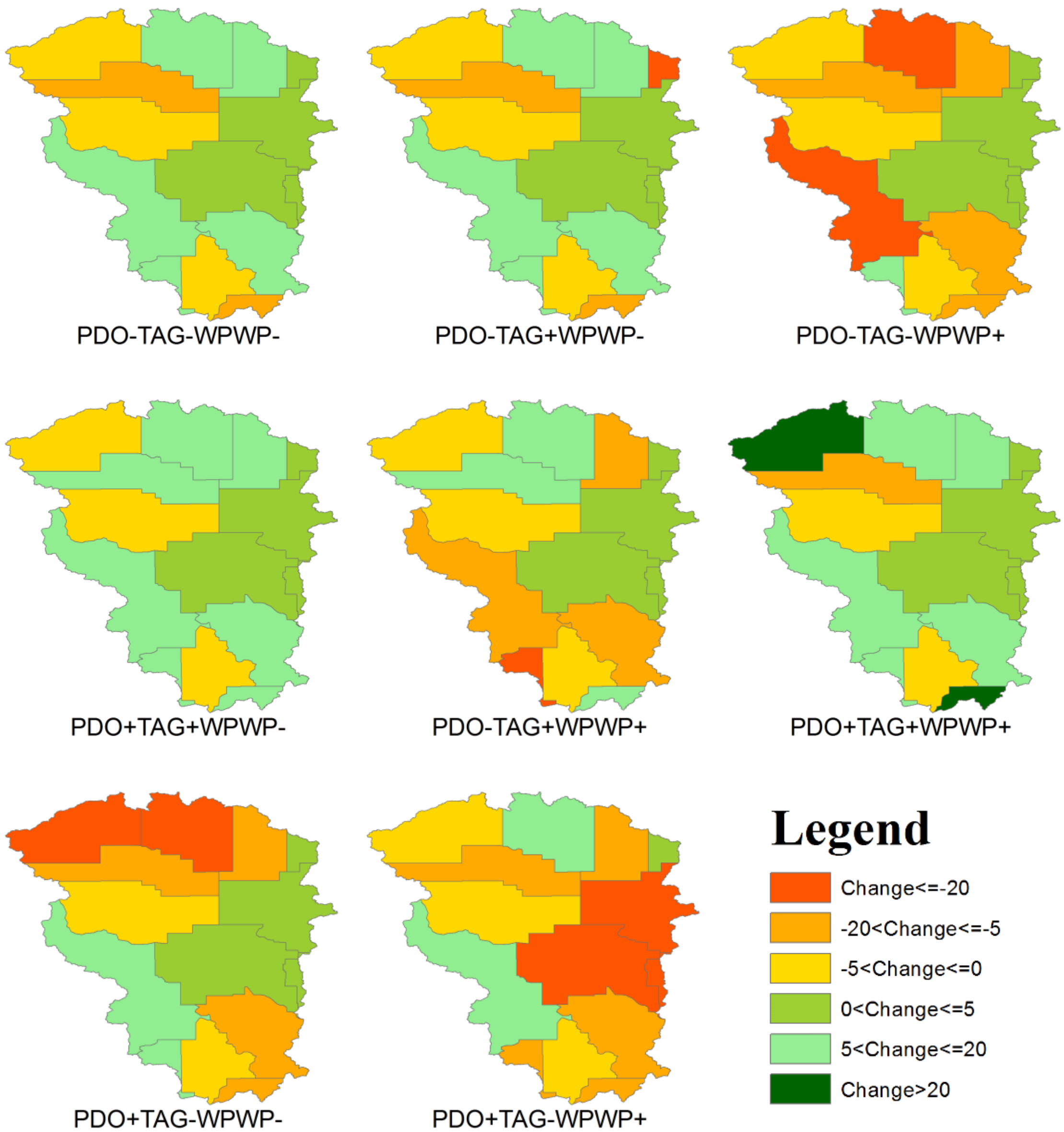

Figure 6 Yield Changes of Spring Wheat under DCV Phase Combinations (% Change)

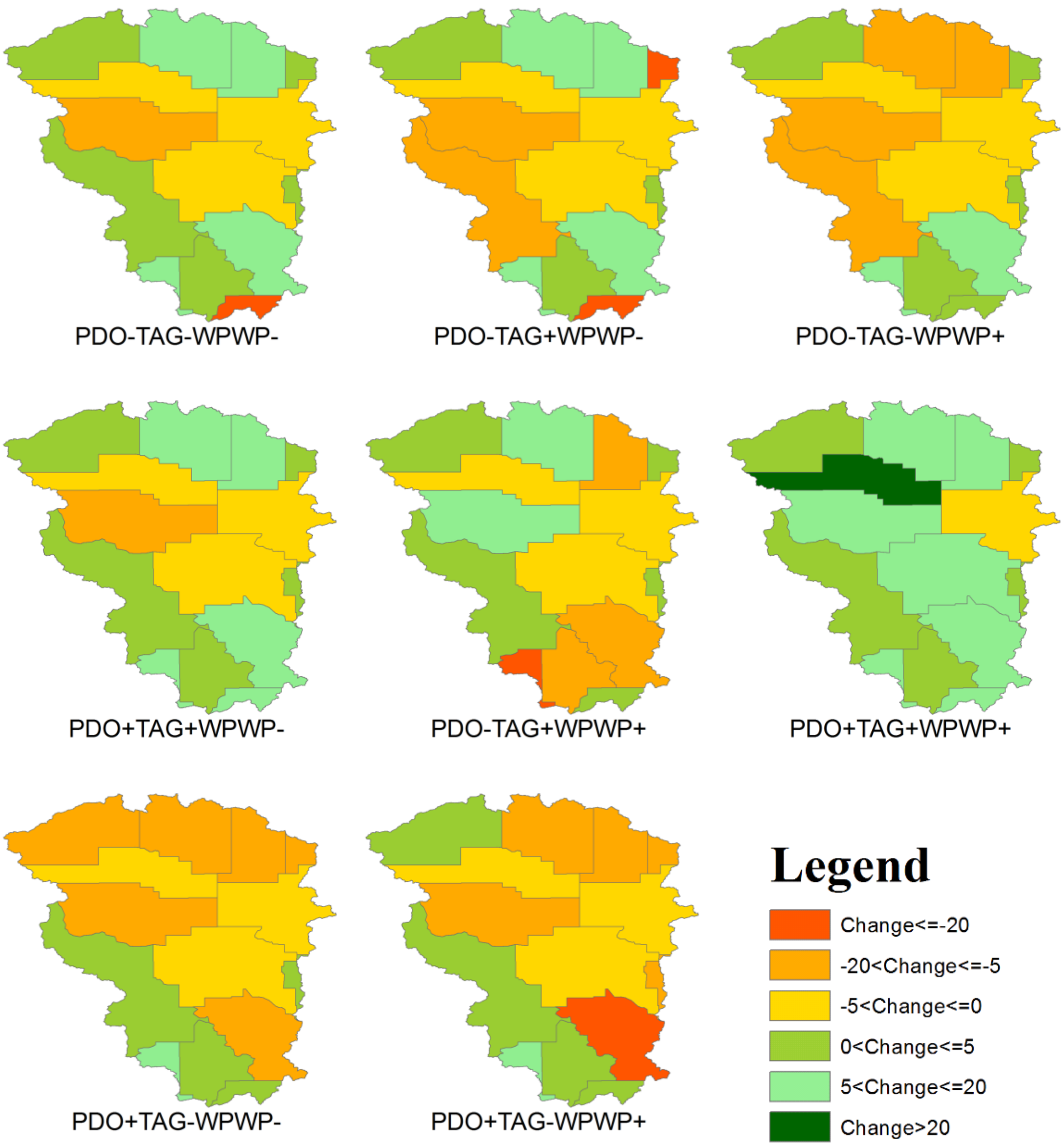

Figure 7 Yield Changes of Winter Wheat under DCV Phase Combinations (% Change)

In terms of spring wheat, there are no significant yield changes in Broadwater and Teton under all DCV phase combinations (see Figure 6). And under PDO+TAG+WPWP- and PDO+TAG+WPWP+, yields of the spring wheat increase by 2.5-25% in most of the counties, while under PDO+TAG-WPWP+, changes in spring wheat yields are mostly negative, ranging from -10% to -25%. According to Mehta, Rosenberg, and Mendoza (2012), there were significant increases of 5-20% in yield of spring wheat in Montana under positive PDO. Under negative TAG, spring wheat yields increase significantly 5-15% in northeast Montana. And there are small significant increases in spring wheat yield in a few locations in Montana under negative WPWP. Since we have these three DCV phenomena combined together to have 8 DCV phase combinations, each DCV phase may enhance or weaken each other, in some cases some DCV phase might dominate. For instance, in our results, yield changes of spring wheat range from 2.5% to 25% under PDO+TAG+WPWP- and PDO+TAG+WPWP+, which is consistent with the results under positive PDO in Mehta, Rosenberg, and Mendoza (2012), probably because positive PDO dominates in the phase combinations of PDO+TAG+ WPWP- and PDO+TAG+WPWP+.

For winter wheat, there are no yield changes in Chouteau under all DCV scenarios (see Figure 7). Most yields of winter wheat decrease by 2.5-25% under PDO+TAG-WPWP- and PDO+TAG-WPWP+ in the Marias basin except the southwestern part. While under PDO+TAG+WPWP+, significant yield changes are positive almost everywhere except Chouteau, ranging from 2.5% to 20%. In the simulation results of Mehta, Rosenberg, and Mendoza (2012), in eastern Montana winter wheat yields decrease by 5-15% under PDO+. And changes of winter wheat yields are 5-10% below average in eastern Montana under TAG- and WPWP+, respectively. Our results under PDO+TAG-WPWP- and PDO+TAG-WPWP+ are consistent with the results of Mehta, Rosenberg, and Mendoza (2012) under positive PDO and negative TAG, except with a little larger range of yield changes.

After discussion on the crop yield change anomalies associated with different combinations of DCV phase phenomena, we can look at Table 4 to get a summary statistics of the total DCV effects on crop yields. Changes in yields of barley and alfalfa hay range from -39.06% to 44.38%, meaning DCV effects on yields of barley and alfalfa hay varying a lot in different counties. And the variation range of wheat yield is between -32.10% and 24.55%, which is quite consistent with the results in Mehta, Rosenberg, and Mendoza (2012), especially for winter wheat.

Table 4 Statistics of Total DCV Effects on Crop Yields by Crop (% Change)

	Observation Number	Mean	Standard Deviation	Minimum Value	Maximum Value
Barley	112	-0.61	13.05	-39.06	22.74
Alfalfa hay	112	-1.31	12.90	-35.63	44.38
Oats	112	-1.05	9.16	-40.05	20.54
Spring Wheat	112	-0.70	11.74	-32.10	24.55
Winter Wheat	112	-0.42	9.24	-23.21	21.88

Note: Here the total DCV effects data are recalculated by subtracting the average impact data from the original estimated DCV impact data at the 90% confidence interval.

Table 5 Average DCV Effects on Crop Yields over All Marias Counties (% Change)

	PDO- TAG- WPWP-	PDO- TAG+ WPWP-	PDO- TAG- WPWP+	PDO+ TAG+ WPWP-	PDO- TAG+ WPWP+	PDO+ TAG+ WPWP+	PDO+ TAG- WPWP-	PDO+ TAG- WPWP+
Barley	2.46	4.59	-1.19	5.16	-2.82	10.43	-11.28	-12.26
Alfalfa Hay	-0.29	-0.29	-17.00	1.54	6.05	9.58	-4.21	-5.85
Oats	0.65	-2.92	-0.89	5.51	0.81	0.65	-11.20	-0.96
Spring Wheat	2.76	0.40	-5.35	7.12	-2.52	7.12	-5.79	-9.35
Winter Wheat	1.14	-2.13	-1.60	3.91	-2.36	7.87	-4.39	-5.75

Note: Here the total DCV effects data are recalculated by subtracting the average impact data from the original estimated DCV impact data at the 90% confidence interval.

Moreover, we discuss some adaptation possibilities given DCV information. We take the average value of DCV effects on crop yields over all the 14 counties (see Table 5). We find that under PDO+TAG+WPWP- and PDO+TAG+WPWP+ all the average yield changes are positive, which can be explained due to the dominance of positive PDO and positive TAG. And in years with DCV phase combinations PDO-TAG-WPWP+, PDO+TAG-WPWP-, and PDO+TAG-WPWP+, all the average changes in crop yields are negative. For the scenario of PDO-TAG+WPWP+, average yield changes of barley, spring/winter wheat are negative while yield changes of alfalfa hay and oats are positive. In this case, under year of PDO-TAG+WPWP+, which is probably associated with droughts, more land can be used to plant alfalfa hay and oats. However, under PDO-TAG+WPWP-, acreage of oats, winter wheat, and alfalfa hay decreases, while the acreage of barley and spring wheat can be increased due to their positive changes in yields.

5 Conclusions

The Marias river basin is a very important agricultural production region in Montana. The basin is locating in the upper Missouri River Basin. Simulation studies have been done in the basin as a Missouri whole that showed decadal climate variability was associated with anomalies in precipitation and temperature, with substantial influences on the yields of dryland corn, spring wheat, and winter wheat. The area of the Marias basin was not covered in those DCV impact studies. However, DCV phases are associated with changes in precipitation and temperature in the Marias basin. Hence, in this essay, we used econometrics to estimate the total DCV effect on yields of five different crops in the Marias river basin.

We find that DCV effects are strong on barley, winter wheat, and spring wheat. We also observe that the DCV phase combination PDO-TAG+WPWP+ has the strongest effects. Under PDO-TAG+WPWP+, average yield changes of barley, spring/winter wheat are negative, while changes of yields in alfalfa hay and oats are positive. These results permit adaptive decision making land increases in alfalfa hay and oats under certain phases. We also found the econometric results on DCV effects on yields of winter/spring wheat are quite consistent with the simulation results in Mehta, Rosenberg, and Mendoza (2012).

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Appendix:

If we know that $\frac{\Delta \log(Yield)}{\Delta DCV} = \hat{a}_4 + \hat{a}_3\hat{b}_3$, since DCV is the dummy variable, we have

$\log Yield\big|_{DCV=1} - \log Yield\big|_{DCV=0} = \hat{a}_4 + \hat{a}_3\hat{b}_3$.

Then, $\log \frac{Yield\big|_{DCV=1}}{Yield\big|_{DCV=0}} = \hat{a}_4 + \hat{a}_3\hat{b}_3$

With exponential transformation, we have $\frac{Yield\big|_{DCV=1}}{Yield\big|_{DCV=0}} = \exp\left(\hat{a}_4 + \hat{a}_3\hat{b}_3\right)$.

Then, $\left(\frac{Yield\big|_{DCV=1} - Yield\big|_{DCV=0}}{Yield\big|_{DCV=0}}\right)*100 = \left(\exp\left(\hat{a}_4 + \hat{a}_3\hat{b}_3\right) - 1\right)*100$.

The final equation shows that switching from DCV=0 to DCV=1, the mean of crop yield will increase by $\left(e^{\hat{a}_4 + \hat{a}_3\hat{b}_3} - 1\right)*100$.

Table A1 Total DCV Impacts on Log Crop Yield by County

	PDO- TAG+ WPWP-	PDO- TAG- WPWP+	PDO+ TAG+ WPWP-	PDO- TAG+ WPWP+	PDO+ TAG+ WPWP+	PDO+ TAG- WPWP-	PDO+ TAG- WPWP+
BARLEY							
Broadwater	0.070	-0.050	0.008	-0.155*	0.144	-0.178	-0.288**
	(0.153)	(0.137)	(0.100)	(0.093)	(0.118)	(0.138)	(0.138)
Cascade	-0.003	-0.079	0.003	0.016	0.044	-0.174	-0.325**
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Chouteau	-0.045	-0.054	0.021	0.042	0.137	-0.157	-0.383**
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.153)
Gallatin	0.261*	0.189	0.321***	0.184**	0.336***	0.220	0.116
	(0.153)	(0.126)	(0.105)	(0.090)	(0.118)	(0.138)	(0.138)
Glacier	0.111	-0.050	0.134	0.157*	0.193*	-0.365***	-0.077
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Hill	-0.267	-0.128	-0.025	-0.221*	0.156	-0.306**	-0.085
	(0.176)	(0.126)	(0.100)	(0.126)	(0.138)	(0.138)	(0.153)
Jefferson	0.070	-0.050	-0.078	-0.875***	0.336	-0.298*	-0.551*
	(0.153)	(0.137)	(0.127)	(0.302)	(0.302)	(0.176)	(0.302)
Judith Basin	-0.002	-0.043	0.018	-0.163	0.092	-0.191	-0.481***
	(0.176)	(0.153)	(0.105)	(0.176)	(0.154)	(0.138)	(0.138)
Lewis and Clark	-0.226	-0.299**	-0.045	-0.166*	-0.038	-0.309**	-0.099
	(0.153)	(0.126)	(0.105)	(0.093)	(0.126)	(0.138)	(0.138)
Liberty	-0.218	-0.292**	0.013	-0.159*	0.080	-0.359***	-0.126
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Meagher	-0.200	-0.075	-0.066	-0.354***	-0.164	-0.312**	-0.527***
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Pondera	0.155	0.006	0.159	0.225**	0.248**	-0.181	-0.026
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Teton	0.141	-0.019	0.121	0.148*	0.201*	-0.220	-0.113
	(0.153)	(0.126)	(0.100)	(0.090)	(0.118)	(0.138)	(0.138)
Toole	0.042	-0.111	0.130	0.041	0.181	-0.303**	0.051

	PDO- TAG+ WPWP-	PDO- TAG- WPWP+	PDO+ TAG+ WPWP-	PDO- TAG+ WPWP+	PDO+ TAG+ WPWP+	PDO+ TAG- WPWP-	PDO+ TAG- WPWP+
	(0.153)	(0.126)	(0.111)	(0.093)	(0.118)	(0.138)	(0.138)
ALFALFA Hay							
	0.085	-0.154	0.008	0.050	0.405***	-0.211	0.109
Broadwater	(0.213)	(0.173)	(0.099)	(0.151)	(0.151)	(0.136)	(0.136)
	-0.229	0.107	0.062	0.113	0.140	-0.116	-0.293**
Cascade	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.159	-0.293*	0.006	0.129	0.047	-0.149	-0.234*
Chouteau	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	0.071	0.276*	0.229**	0.267**	0.430***	0.250*	0.223*
Gallatin	(0.174)	(0.151)	(0.103)	(0.136)	(0.151)	(0.151)	(0.136)
	-0.130	-0.263*	0.019	-0.153	0.132	-0.404***	-0.116
Glacier	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.198	-0.443***	-0.158	0.062	-0.009	-0.224*	-0.148
Hill	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	0.085	-0.154	0.111	0.459**	0.296*	-0.071	-0.043
Jefferson	(0.213)	(0.173)	(0.116)	(0.212)	(0.174)	(0.174)	(0.212)
	-0.278	-0.342**	0.041	0.105	0.012	-0.219	-0.137
Judith Basin	(0.174)	(0.151)	(0.099)	(0.150)	(0.151)	(0.136)	(0.136)
Lewis and	-0.091	-0.267*	-0.016	-0.055	0.085	-0.096	-0.207
Clark	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.200	-0.318**	-0.074	-0.054	-0.022	-0.184	-0.111
Liberty	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.046	-0.009	-0.064	-0.242	0.076	-0.154	-0.006
Meagher	(0.213)	(0.151)	(0.099)	(0.151)	(0.151)	(0.136)	(0.136)
	-0.205	-0.350**	-0.021	-0.077	0.161	-0.312**	0.025
Pondera	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.244	-0.512***	0.072	0.051	0.141	-0.088	0.007
Teton	(0.174)	(0.151)	(0.099)	(0.136)	(0.151)	(0.136)	(0.136)
	-0.159	-0.388***	-0.093	-0.164	-0.022	-0.263*	-0.378***
Toole	(0.174)	(0.151)	(0.109)	(0.136)	(0.151)	(0.136)	(0.136)
OATS							
	0.174	0.054	-0.122	-0.123	-0.107	-0.413**	-0.142
Broadwater	(0.177)	(0.178)	(0.111)	(0.097)	(0.155)	(0.177)	(0.216)
	-0.051	-0.201	-0.062	-0.045	-0.086	-0.259*	-0.187
Cascade	(0.177)	(0.126)	(0.101)	(0.094)	(0.119)	(0.139)	(0.178)
	-0.111	-0.052	0.089	0.040	0.030	-0.052	-0.212
Chouteau	(0.154)	(0.138)	(0.111)	(0.094)	(0.119)	(0.139)	(0.178)
	0.222	0.150	0.159	0.167*	0.103	0.143	0.156
Gallatin	(0.177)	(0.138)	(0.111)	(0.094)	(0.155)	(0.139)	(0.216)
	0.081	-0.122	0.154	0.045	-0.009	-0.139	-0.225
Glacier	(0.177)	(0.154)	(0.111)	(0.094)	(0.139)	(0.139)	(0.155)
	-0.693***	-0.242*	-0.019	-0.204*	0.122	-0.057	0.018
Hill	(0.177)	(0.138)	(0.105)	(0.118)	(0.140)	(0.139)	(0.155)
	0.174	0.054	0.067	-0.288	0.004	-0.445**	-0.142
Jefferson	(0.177)	(0.178)	(0.139)	(0.304)	(0.304)	(0.177)	(0.216)
	-0.179	-0.023	0.050	-0.103	-0.083	-0.099	-0.256*
Judith Basin	(0.177)	(0.177)	(0.105)	(0.176)	(0.179)	(0.139)	(0.155)
Lewis and	-0.113	-0.121	0.028	-0.223**	-0.198	-0.366**	-0.189
Clark	(0.177)	(0.154)	(0.111)	(0.094)	(0.155)	(0.154)	(0.216)
	0.051	-0.158	0.100	-0.073	0.089	-0.192	0.066
Liberty	(0.177)	(0.138)	(0.106)	(0.094)	(0.138)	(0.139)	(0.177)

	PDO- TAG+ WPWP-	PDO- TAG- WPWP+	PDO+ TAG+ WPWP-	PDO- TAG+ WPWP+	PDO+ TAG+ WPWP+	PDO+ TAG- WPWP-	PDO+ TAG- WPWP+
	-0.156	-0.214	0.028	-0.113	-0.100	-0.241*	0.054
Meagher	(0.216)	(0.154)	(0.111)	(0.094)	(0.178)	(0.139)	(0.216)
	0.129	-0.102	0.223**	0.203**	-0.067	-0.005	0.014
Pondera	(0.177)	(0.154)	(0.111)	(0.094)	(0.139)	(0.139)	(0.155)
	0.122	-0.052	0.202*	0.059	0.072	-0.240*	-0.034
Teton	(0.154)	(0.138)	(0.106)	(0.094)	(0.155)	(0.139)	(0.216)
	0.116	-0.169	0.187*	0.055	0.202	0.002	0.137
Toole	(0.177)	(0.154)	(0.112)	(0.094)	(0.127)	(0.139)	(0.178)
SPRING WHEAT							
	-0.209	-0.089	0.168	-0.006	-0.007	-0.099	-0.213
Broadwater	(0.164)	(0.125)	(0.107)	(0.093)	(0.126)	(0.148)	(0.148)
	-0.093	-0.128	0.066	-0.023	0.100	-0.144	-0.349**
Cascade	(0.164)	(0.125)	(0.107)	(0.093)	(0.126)	(0.148)	(0.148)
	-0.101	-0.149	0.126	-0.009	0.068	-0.056	-0.331**
Chouteau	(0.164)	(0.125)	(0.107)	(0.093)	(0.126)	(0.148)	(0.148)
	0.152	0.167	0.283**	0.172*	0.309**	0.210	0.197
Gallatin	(0.164)	(0.125)	(0.112)	(0.091)	(0.126)	(0.148)	(0.148)
	-0.033	-0.074	0.160	0.060	0.221*	-0.384***	-0.007
Glacier	(0.164)	(0.125)	(0.107)	(0.096)	(0.126)	(0.148)	(0.148)
	-0.401**	-0.236	0.026	-0.218	0.080	-0.184	-0.203
Hill	(0.188)	(0.147)	(0.107)	(0.135)	(0.165)	(0.148)	(0.164)
	-0.209	-0.089	0.153	-0.592*	0.041	-0.085	-0.391*
Jefferson	(0.164)	(0.125)	(0.135)	(0.323)	(0.323)	(0.188)	(0.230)
	-0.054	-0.106	0.057	-0.120	-0.026	-0.189	-0.338**
Judith Basin	(0.188)	(0.188)	(0.107)	(0.188)	(0.189)	(0.148)	(0.164)
Lewis and	-0.202	-0.344**	-0.005	-0.191*	0.012	-0.177	-0.071
Clark	(0.164)	(0.135)	(0.107)	(0.100)	(0.126)	(0.148)	(0.148)
	-0.254	-0.304**	0.069	-0.217**	0.027	-0.316**	-0.262*
Liberty	(0.164)	(0.135)	(0.107)	(0.096)	(0.136)	(0.148)	(0.148)
	-0.095	-0.361***	-0.135	-0.396***	-0.126	-0.366**	-0.326**
Meagher	(0.164)	(0.135)	(0.112)	(0.100)	(0.126)	(0.148)	(0.148)
	0.045	-0.054	0.250**	0.195**	0.196	-0.235	0.028
Pondera	(0.164)	(0.125)	(0.107)	(0.100)	(0.126)	(0.148)	(0.148)
	0.002	-0.106	0.170	0.140	0.191	-0.231	-0.094
Teton	(0.164)	(0.125)	(0.107)	(0.096)	(0.126)	(0.148)	(0.148)
	-0.055	-0.327**	0.061	-0.019	0.090	-0.359**	-0.189
Toole	(0.164)	(0.135)	(0.118)	(0.100)	(0.136)	(0.148)	(0.164)
WINTER WHEAT							
	-0.149	-0.148	0.048	-0.211***	0.003	-0.111	-0.165
Broadwater	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
	0.042	0.008	0.096	0.011	0.175*	-0.017	-0.093
Cascade	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
	-0.037	-0.005	0.037	0.024	0.143	-0.068	-0.129
Chouteau	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
	0.201	0.234**	0.328***	0.230***	0.257***	0.241**	0.228**
Gallatin	(0.126)	(0.103)	(0.086)	(0.069)	(0.096)	(0.113)	(0.113)
	-0.070	-0.031	-0.044	0.021	0.035	-0.224**	-0.072
Glacier	(0.126)	(0.096)	(0.082)	(0.071)	(0.096)	(0.113)	(0.126)
	-0.312**	-0.076	-0.117	-0.126	0.071	-0.205*	-0.213*
Hill	(0.144)	(0.096)	(0.082)	(0.085)	(0.113)	(0.113)	(0.113)

	PDO- TAG+ WPWP-	PDO- TAG- WPWP+	PDO+ TAG+ WPWP-	PDO- TAG+ WPWP+	PDO+ TAG+ WPWP+	PDO+ TAG- WPWP-	PDO+ TAG- WPWP+
Jefferson	-0.149	-0.148	0.015	-0.316*	-0.010	-0.231	-0.030
	(0.126)	(0.096)	(0.104)	(0.176)	(0.248)	(0.145)	(0.144)
Judith Basin	-0.006	-0.036	0.026	-0.136	0.100	-0.107	-0.211*
	(0.144)	(0.113)	(0.082)	(0.104)	(0.126)	(0.113)	(0.113)
Lewis and Clark	-0.210*	-0.257***	-0.088	-0.119	0.079	-0.169	-0.052
	(0.126)	(0.096)	(0.082)	(0.073)	(0.103)	(0.113)	(0.144)
Liberty	-0.167	-0.238**	-0.068	-0.205***	0.011	-0.284**	-0.308***
	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
Meagher	-0.179	-0.073	-0.078	-0.258***	-0.081	-0.197*	-0.395***
	(0.126)	(0.103)	(0.082)	(0.073)	(0.103)	(0.113)	(0.126)
Pondera	-0.043	0.045	0.113	0.107	0.220**	-0.020	0.028
	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
Teton	0.000	0.017	0.080	0.119*	0.193**	-0.003	0.028
	(0.126)	(0.096)	(0.082)	(0.069)	(0.096)	(0.113)	(0.113)
Toole	-0.206*	-0.234**	-0.142	-0.049	0.075	-0.265**	-0.283**
	(0.126)	(0.096)	(0.091)	(0.069)	(0.096)	(0.113)	(0.126)

Note: Values in parentheses are standard errors with * for p<0.1, ** for p<0.05, and *** for p<0.01, respectively.