Climate induced reduction in U.S.-wide soybean yields underpinned by region- and in-season-specific responses

Spyridon Mourtzinis, Department of Agronomy, University of Wisconsin-Madison

James E. Specht, Department of Agronomy, University of Nebraska

Laura E. Lindsey, Department of Horticulture and Crop Science, Columbus

William J. Wiebold, Department of Plant Sciences, University of Missouri

Jeremy Ross, University of Arkansas Division of Agriculture

Emerson D. Nafziger, Department of Crop Sciences, University of Illinois

Herman J. Kandel, Department of Plant Sciences, North Dakota State University

Nathan Mueller, Department of Plant Sciences, South Dakota State University

Philip L. Devillez, Director of the Purdue Crop Performance Program

Francisco J. Arriaga, Department of Soil Science, University of Wisconsin-Madison

Shawn P. Conley, Department of Agronomy, University of Wisconsin-Madison

Introduction

Global annual temperatures have increased by 0.4 °C since 1980 with several regions exhibiting even greater increases[5]. Climate change appears to have affected crop yields in some countries[4], and these effects are expected to continue[6]. Crop management strategies could help to mitigate the potential negative impacts of climate change on crop yields. Strategies include the development of new cultivars and hybrids, altered maturity groups, changes in planting dates, the use of cover crops, and greater management of previous crop residues. However, it is important to understand in-season weather variability before any specific adaptation strategies are proposed.

Site- and region-specific variations in climate can be missed in historical analyses of weather variations over large areas. Equally important in studies looking at the effect of weather on agriculture is the period of time used to quantify climate trends[3], as the impact of weather deviations on yield will depend on the timing of the deviation. For instance, crops will exhibit different sensitivities during vegetative and reproductive development[7]. Because of this crop developmental sensitivity (reflected in final yield) to site-specific precipitation events and regional temperature episodes[8], it is important to quantify the effects of climatic variations on crop yields on a region and month-specific basis rather than aggregating the data to look at seasonal and nation-wide average effects[9]. For this study, soybean yield from non-irrigated cultivar performance trials conducted at sites within each of twelve states for periods ranging from 18 to 80 years (depending on the state) were assembled.

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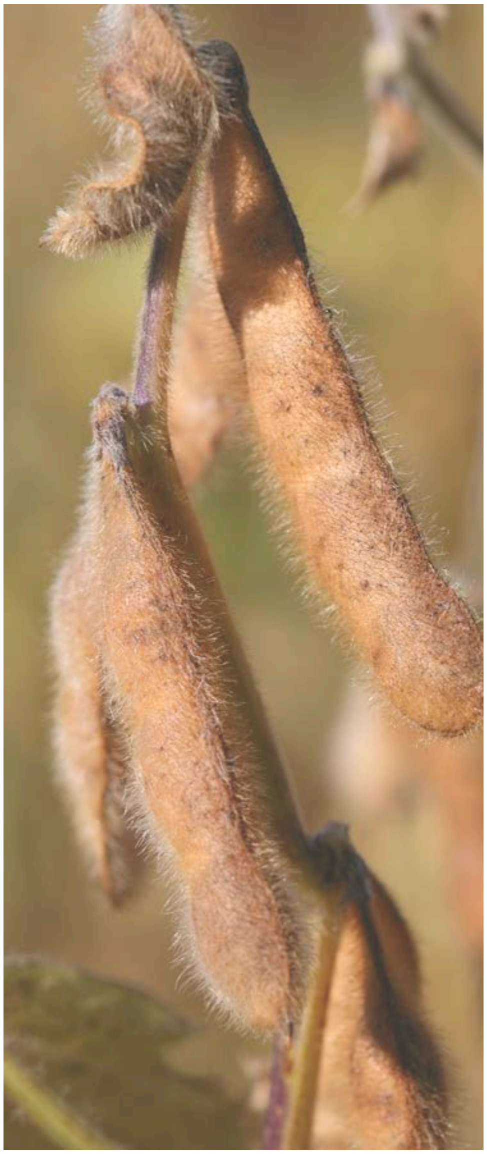


Results and Discussion

Over the past 20 years, monthly precipitation trends varied among states (Table 1). Northern states experienced positive rainfall trends in May, June and September, but negative trends in July and August, while lower Midwestern and Southern states generally experienced a negative rainfall trend in June and July. Across the U.S. as a whole, positive rainfall trends were apparent at the start and the end of the growing season, but negative trends were evident in June, July and August. Temperature trends were more consistent among states and months within the crop growing season. Apart from Wisconsin, Minnesota, and Mississippi, the rest of the states studied experienced a warming trend in every month of the growing season, which resulted in a collective U.S. warming trend for all months from May to September between 1994 and 2013. Among states and growing season months, trends in precipitation and temperature were not generally similar in magnitude and in fact were not always in the same direction (Table 1). For example, early season (May-June) precipitation and temperature trends were similar among northern states (N. and S. Dakota, Minnesota, and Wisconsin). In contrast, lower Midwestern states (Indiana, Ohio, and Illinois) experienced negative rainfall trends but positive temperature trends. These results point to spatial variations in climate change variability and thus highlight the importance of examining region- and month-specific climate trends rather than generalizing over the entire U.S. and averaging weather data over the entire growing season.

Table 1. Summary of monthly precipitation and temperature trends within each state and aggregated into acre-adjusted USA values (1994-2013).

The number in each cell is the month-specific yearly linear trend and was independently generated by holding constant the variation in all other cells.

	Precipitation trend					Temperature trend				
State	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
	---------- mm $year^{-1}$ ----------					---------- °C $year^{-1}$ ----------				
N. Dakota	0.516	0.971	-2.762	-0.067	1.047	0.001	-0.027	0.113	0.019	0.047
S. Dakota	1.490	0.784	-0.887	-0.124	0.100	0.033	0.021	0.124	0.032	0.041
Minnesota	0.380	0.550	-1.850	-1.630	0.510	0.028	-0.015	0.075	-0.008	-0.005
Wisconsin	1.263	0.110	0.614	-1.552	0.435	0.058	-0.010	0.070	-0.001	-0.037
Iowa	0.989	0.760	-0.132	0.756	-0.644	0.058	0.005	0.057	0.002	0.011
Illinois	-0.790	-0.094	1.620	-0.602	1.822	0.094	0.048	0.048	0.011	0.031
Indiana	-0.533	-0.261	-1.366	-0.345	1.847	0.111	0.011	0.043	-0.014	0.013
Ohio	-0.833	-1.450	0.415	-1.320	2.350	0.136	0.041	0.070	0.040	0.038
Missouri	0.860	-1.660	-3.990	0.400	-1.584	0.021	0.063	0.047	-0.010	0.040
Arkansas	5.760	-3.828	-1.063	0.876	2.190	0.074	0.145	0.046	0.062	0.093
Kentucky	-2.640	-3.800	2.530	0.960	1.350	0.058	0.100	0.050	0.019	0.048
Mississippi	0.310	-2.950	-0.690	-0.520	1.200	-0.043	0.060	-0.033	0.042	0.005
†USA (adjusted for state-acres)	**0.484**	**-0.402**	**-0.628**	**-0.270**	**0.758**	**0.062**	**0.030**	**0.060**	**0.011**	**0.026**

†USA is used because these 12 states accounted for 79% of the average USA acres from 1994 to 2013.

State-specific climate-yield models based on monthly cumulative precipitation and average temperature accounted for a large amount (53-95%) of the variability in soybean yields. Of 60 state-month parameters measured, 19 (~30%) were significant for rainfall and 12 (~20%) were significant ($P<0.1$) for temperature (Table 2). Of the regression coefficients significant for rainfall in June, five (out of six) were positive; four (out of four) were positive in August. The results suggest that for every 10 mm of additional rainfall in June, yields would rise by ~1.3%, and for every 10 mm of additional rainfall in August, yields would rise by 1.4%.

In the case of average temperature, one of the four significant regression coefficients for July were positive and three were negative (Table 2). The effect of temperature change on yield varied among regions. Positive temperature trends in May, July and/or September increased yields in the northern states. According to our estimates, 1 °C of warming in May in N. Dakota increased soybean yields by 1.8 bu ac^{-1}. The yield increase associated with 1 °C of warming in July was 3.7 bu ac^{-1} in Wisconsin and 1 °C of warming in September raised yields by 2 bu ac^{-1}in Iowa soybean. Surprisingly, 1 °C of warming in June appeared to increase yields in Mississippi by 8.2 bu ac^{-1}. However, in the remaining states, soybean yields fell by 1.8-5.9

Table 2. Summary of statistically significant soybean yield responses ($P<0.1$) for a one unit increase in monthly precipitation and temperature.

The coefficients were estimated fitting linear regression models between first year differences (year-to-year changes) of de-trended yield (bu ac^{-1}), of monthly cumulative precipitation (left), and monthly average temperature (right) generated for each of the 12 states and each of the five growing season months from 1994-2013. The number in each cell is the month-specific yearly linear trend and was independently generated by holding constant the variation in all other cells. The state-data were aggregated to generate a acre-adjusted USA average for the same five months. Dashes denote non-significant soybean yield responses ($P>0.1$).

	Precipitation					Temperature				
State	May	Jun	Jul	Aug	Sep	May	Jun	Jul	Aug	Sep
	bu ac^{-1} mm^{-1}					bu ac^{-1} C^{-1}				
N. Dakota	-	-	-	-	-0.05	1.75	-	-	-	-
S. Dakota	-	0.12	-	0.13	-	-	-	-	-	-
Minnesota	-	0.16	-	-	-	-	-	-	-	-
Wisconsin	-	0.08	-	-	-	-	-	3.64	-	-
Iowa	-0.07	-	-0.17	0.11	0.11	-2.13	-	-	-	1.96
Illinois	-	0.09	-	-	-	-	-	-	-1.77	-
Indiana	-	0.17	-	0.24	-	-	-	-	-	-
Ohio	0.09	-0.13	-	-	-0.11	-	-	-2.61	-	-
Missouri	-	-	0.13	-	-	-	-	-	-	-
Arkansas	-	-	-	-	-	-	-	-	-3.44	-
Kentucky	-	-	-	0.14	-	-	-	-5.9	-	-
Mississippi	-0.09	-	0.1	-	-	-	8.14	-5.84	-5.52	-4.18
†USA bu ac^{-1} (adjusted for state-acres)	**-0.008**	**0.05**	**-0.02**	**0.05**	**0.01**	**-0.29**	**0.26**	**-0.44**	**-0.69**	**0.22**
% effect on USA average yield (adjusted for state-acres)	**-0.02**	**0.13**	**-0.04**	**0.14**	**0.02**	**-0.75**	**0.65**	**-1.11**	**-1.74**	**0.55**

†These 12 states accounted for 79% of the average USA acres from 1994 to 2013.

bu ac^{-1} with a 1 °C rise in average temperature, depending on the month and state.

These results reveal the significant potential impact of in-season weather variability associated with climate change on state soybean yields. Depending on the state, the climate change contribution (when measured as the yield impact of a one unit change in in-season rainfall (mm) and temperature (°C)) ranged from -22 to +9% of total annual yield over the 20 years examined. Averaging across the U.S., soybean yields fell by around 2.2% due to climate change over the studied period. The suitable temperature range for soybean is 15-22 °C at emergence, 20-25 °C at flowering, and 15-22 °C at maturity[10]. According to these temperature ranges it appears that the cooler conditions in N. and S. Dakota, Minnesota, and Wisconsin during the last 20 years favored soybean yields compared to the warmer in-season conditions in the rest of the states. When state data were aggregated into a U.S. average, 1°C of warming in May was associated with a decrease in soybean yields of about 0.75%. Using the same temperature change in June, July, and August, yields were estimated to change by +0.65%, -1.1% and -1.74%, respectively. The large, negative effects of increasing temperatures in July and August are detrimental to production

Table 3. Summary of statistically significant (P<0.1) observed soybean yield trends due to the realized monthly precipitation and temperature anomalies.

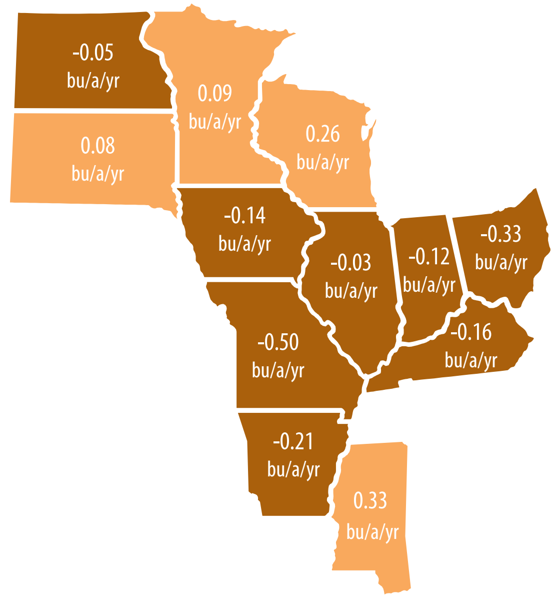
The estimates were calculated by multiplying the observed monthly precipitation and temperature trends (mediated by climate change) that are documented in Table 1 and the estimated potential impacts on yield that are documented in Table 2 for each of the 12 states over the past 20 years (1994-2013). The state data were aggregated to generate an acre-adjusted USA average for each of the five months. Dashes denote statistically non-significant observed soybean yield trends (P>0.1).

	Precipitation					Temperature				
State	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
	bu ac^{-1} year^{-1}					bu ac^{-1} year^{-1}				
N. Dakota	-	-	-	-	-0.05	0.002	-	-	-	-
S. Dakota	-	0.09	-	-0.02	-	-	-	-	-	-
Minnesota	-	0.09	-	-	-	-	-	-	-	-
Wisconsin	-	0.01	-	-	-	-	-	0.25	-	-
Iowa	-0.07	-	0.02	0.08	-0.07	-0.12	-	-	-	0.02
Illinois	-	-0.01	-	-	-	-	-	-	-0.02	-
Indiana	-	-0.04	-	-0.08	-	-	-	-	-	-
Ohio	-0.08	0.18	-	-	-0.25	-	-	-0.18	-	-
Missouri	-	-	-0.5	-	-	-	-	-	-	-
Arkansas	-	-	-	-	-	-	-	-	-0.2	-
Kentucky	-	-	-	0.13	-	-	-	-0.3	-	-
Mississippi	-0.03	-	-0.07	-	-	-	0.5	0.19	-0.23	-0.02
†USA bu ac^{-1} (adjusted for state-acres)	**-0.02**	**0.03**	**-0.04**	**0.01**	**-0.04**	**-0.02**	**0.015**	**-0.012**	**-0.02**	**0.003**
% effect on USA average yield (adjusted for state-acres)	**-5.5**	**7.7**	**-12.7**	**2.5**	**-10.9**	**-6.5**	**4.6**	**-3.5**	**-6.8**	**0.9**

†These 12 states accounted for 79% of the average USA acres from 1994 to 2013.

Figure 1. Annualized yield impacts of climate-driven changes in precipitation and temperature during the past 20 years (1994-2013).

The impacts were estimated on a state-specific basis for the 12 soybean-producing states that combined accounted for 79% of the total USA acreage in 2013. The depicted regression coefficients were calculated by summing the statistically significant yield impacts reported in Table 2.

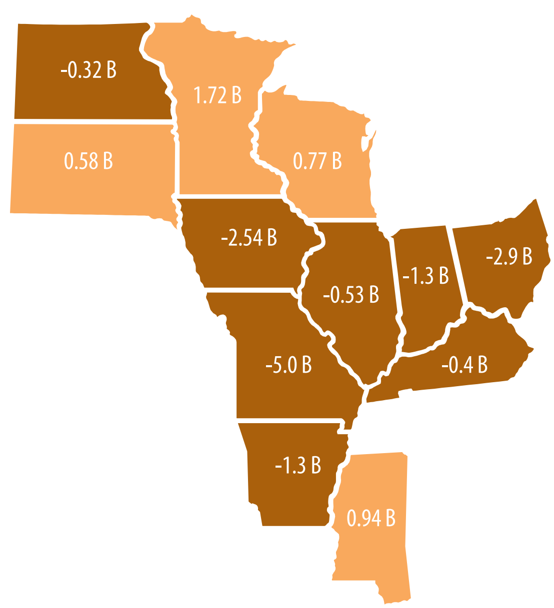


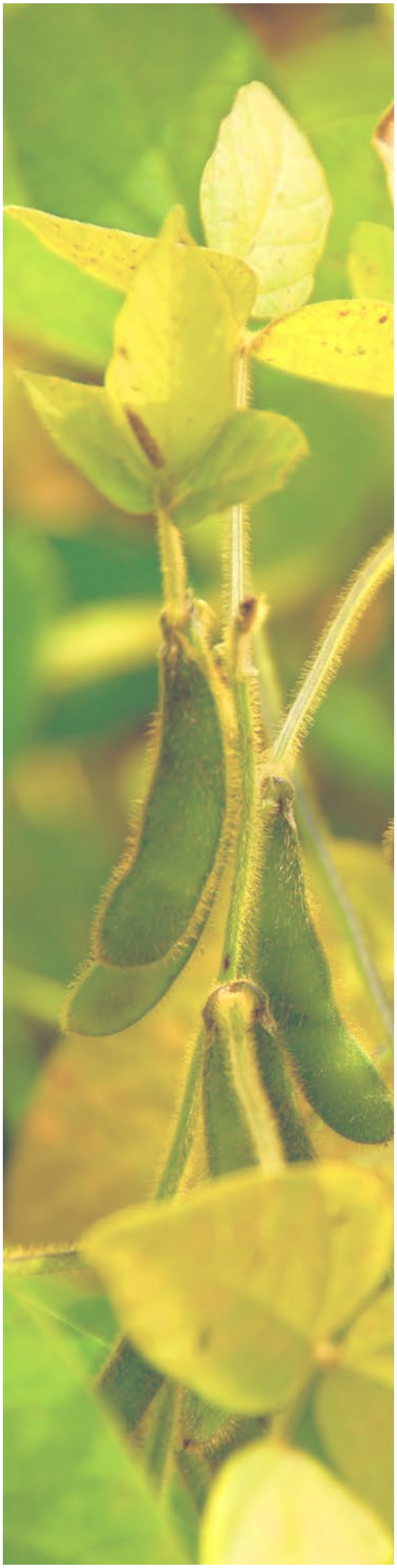
because they occur in states with large harvested areas. For example, the positive effect of warming in July in Wisconsin exceeds the negative effect on yield in Ohio, but the harvested area in Ohio is some 3-fold greater than that of Wisconsin, hence overall production is negatively impacted. While these results represent theoretical scenarios (that is, a month-specific unit change in temperature while holding temperature and precipitation in all other months constant), they demonstrate that, over the past 20 years, monthly temperature anomalies have had a greater impact on soybean yields than monthly precipitation anomalies, even though both temperature and precipitation vary widely with state and month.

On average, U.S. soybean yields rose by 0.35 bu $ac^{-1}year^{-1}$ between 1994 and 2013[1]. Month-specific precipitation anomalies since 1994 (holding all other examined parameters constant) had a variable effect on the 20-year soybean yield trend within the 12 states studied (Table 3). Averaging data

Figure 2. Monetary impacts associated with the annualized effects of changes in monthly precipitation and temperature on state-specific soybean yield trends.

The values are inflation-adjusted estimates of the dollar value (in billions of 2013 dollars) and reflect the impacts over the 20-year period 1994 to 2013.





from across the U.S., May, July, and September rainfall fluctuations reduced the average yield trend by 5.5, 12.7, and 10.9%, respectively. Rainfall fluctuations in June, and August increased the soybean yield trend by 7.7, and 2.5%, respectively. Holding precipitation trends constant, the U.S. on-farm soybean yield gain might have been 18.9% higher than the yield gain realized by producers.

The impact of temperature fluctuations on production trends varied among months and states for the 20-year data set. Overall, May, July, and August temperature anomalies (holding all other examined parameters constant) had a negative effect on yield trend, while warming in June and September had a positive effect. The greatest impact was observed due to warming in August (-6.8%). When holding temperature constant, the U.S. on-farm soybean yield gain might have been 11.3% greater than the realized yield gain and the total climate-adjusted soybean yield trend (holding precipitation and temperature constant) might have been 30% greater than that realized by producers between 1994 and 2013.

The overall effect of climate on soybean yield varied significantly among the examined states (Figure 1). Among northern states of S. Dakota, Minnesota, and Wisconsin and the southern state of Mississippi, climate change favored soybean yields by 0.08 to 0.33 bu $ac^{-1}year^{-1}$ (0.21-0.98% $year^{-1}$ of total yield). In central and mid-south states, yield trends were suppressed as a result of rainfall and temperature changes, with losses of 0.03 to 0.5 bu $ac^{-1}year^{-1}$ (0.06-1.38 %$year^{-1}$ of total yield). The effect of the estimated climatic change on individual state economies is shown in Figure 3. Minnesota showed the greatest climatic-change-related monetary gain over the period, with +0.09 bu $ac^{-1}year^{-1}$ in yield and an economic gain of approximately $1 billion. In Missouri, the estimated economic loss was $5 billion. The overall effect on the U.S. farm economy was negative, and soybean producer income lost was estimated at about $11 billion over the 20 years.

The analysis of longer-term time-series (available for some states) indicates that the influence of climate change on soybean yields has shifted over time. Climatic changes in Ohio since 1970 are estimated to have suppressed the yield trend by 0.03 bu $ac^{-1}year^{-1}$ while the loss during the last 20 years was 10-fold greater, at 0.33 bu $ac^{-1}year^{-1}$. Climatic changes in Wisconsin favored yields by 0.035 bu $ac^{-1}year^{-1}$ since 1943, by 0.06 bu $ac^{-1}year^{-1}$ since 1973, and by 0.26 bu $ac^{-1}year^{-1}$ in the last two decades. Climatic trends in Illinois favored yields from 1969 to 1993 by 0.03 bu $ac^{-1}year^{-1}$. However, in the last 20 years the effect was negative, suppressing yield by 0.03 bu $ac^{-1}year^{-1}$. In Missouri, during the last 35 years, climatic changes suppressed yields by 0.1 bu $ac^{-1}year^{-1}$, while the loss during the last 20 years was 5-fold greater, at 0.5 bu $ac^{-1}year^{-1}$. In N. Dakota, yield trends since 1984 were negative (-0.13 bu $ac^{-1}year^{-1}$), while the last two decades the yield suppression due to climatic anomalies was reduced to -0.05 bu $ac^{-1}year^{-1}$. Overall, the effect of in-season temperature trends on U.S. soybean yields was greater when considering the last 20 years alone, than when accounting for mid-century eras, probably due to an increased warming trend during the last two decades (Figure 3). The recent climactic warming appears to have favored soybeans in northern states, but not in the central Midwest, where it further suppressed yields. These results are consistent with those of previous studies showing that soybean yields before 1982[11] were favored by cooler and wetter years in the Midwest, and by warmer years in the Northern Great Plains[2].

We show that the impact of month-specific temperature and precipitation anomalies on soybean yields varies with region and time of the year. We therefore suggest that the development of regional adaptation strategies to mitigate the impacts of climate change on crop yields is imperative. Biotechnology and classical breeding can be used to develop crops that not only survive increased water saturation during establishment but also increased heat stress tolerance during the reproductive stages of the plants that usually occur in July-August. Shifts in the seasonality of monthly in-season rainfall and air temperatures, as reported here, can be used by the climatologists as a diagnostic tool when evaluating climate simulations. Using region-based predictive early-, mid-, and late-season weather projections, plant scientists must develop region-specific adaptation practices that target sensitive regions. For example, in locations where yield is suppressed due to climate warming, the use of cover crops could assist in mitigating excessive soil warming and water evaporation. Planting

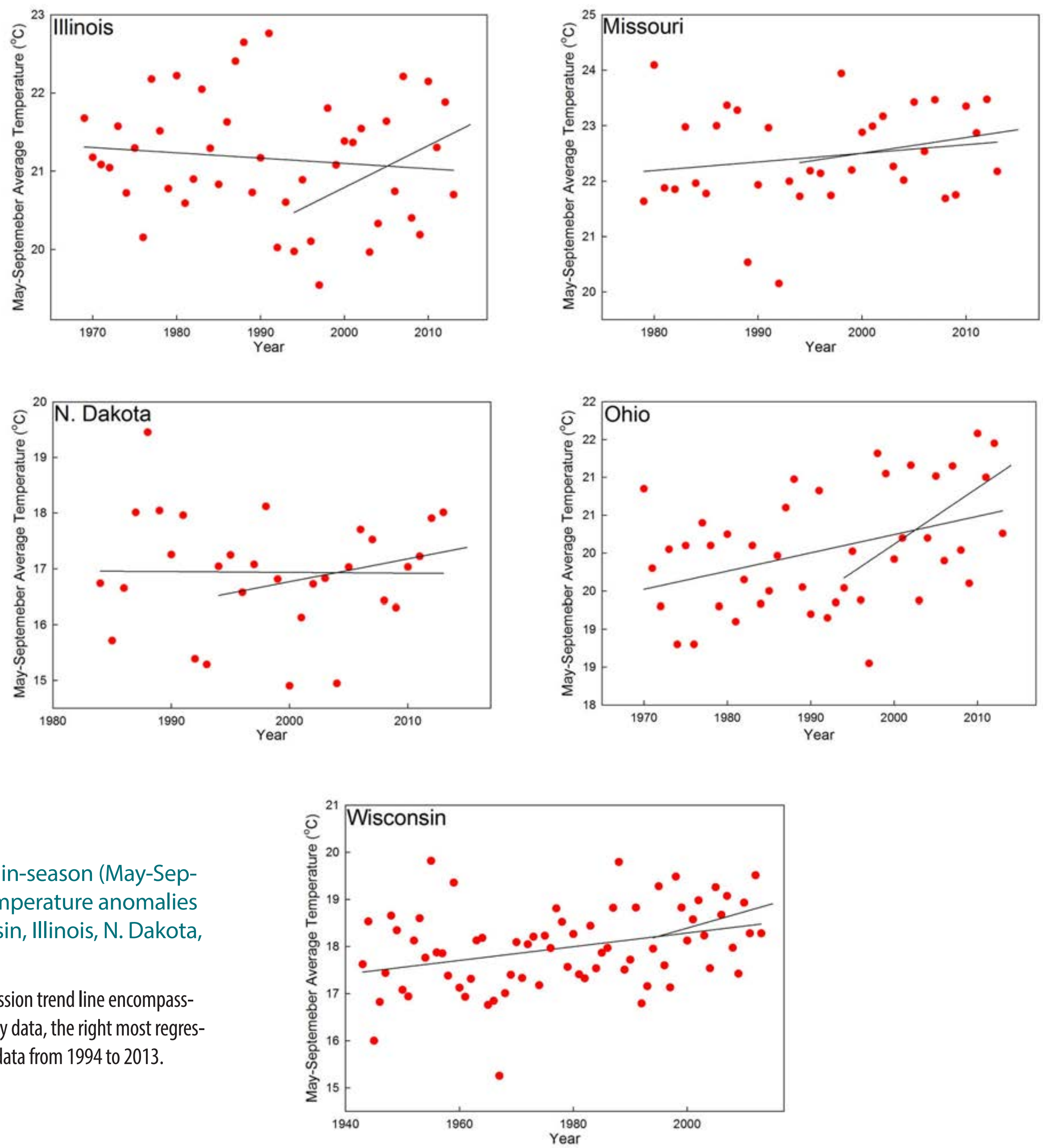
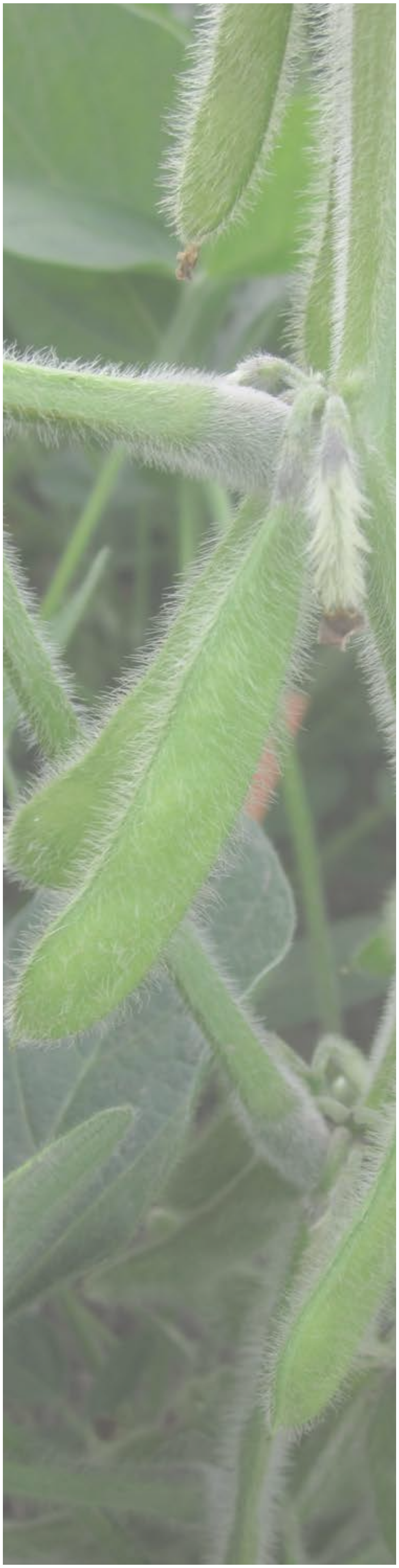


Figure 3. Historical in-season (May-September average) temperature anomalies (°C) in Ohio, Wisconsin, Illinois, N. Dakota, and Missouri.

In addition to a linear regression trend line encompassing all of the available yearly data, the right most regression line encompasses the data from 1994 to 2013.



dates or soybean maturity groups could be adjusted so that the sensitive reproductive development stages of the crop, which currently occur in August, take place at a different time in the year, for instance in September in the northern states, to take advantage of warming trends. Additionally, row spacing and seeding rate could be altered to allow for adequate light interception to minimize in-season water loss due to evaporation or mitigate excessive soil temperatures.

Although there are many factors that affect agricultural commodity prices, the results of our study suggest that long-term economic returns are sensitive to regional climatic changes. These changes will impact trade policy, consumer food prices and national food security. Targeted monies should be used to improve infrastructure and direct research priorities to meet future needs. In short, failure to acknowledge and develop region based strategies to mitigate climate change impacts would greatly weaken the competitive ability of U.S. soybean farmers and subsequently impact food security for U.S. consumers.

Notes

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