CFIRE

Estimating the Future of Agriculture Freight Transportation Network Needs due to Climate Change

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16. Abstract

A reoccurring challenge with increasing fuel prices is optimization of multi- and inter-modal freight transport to move products most efficiently. Projections for the future of agriculture in the United States (U.S.) combined with regional climate models indicate a shift in warm temperatures northward and potential shift in agricultural growing seasons and conditions for optimized crop yield which leads to a potential change in how much and where freight to move these crops will be needed in the future. Given recent history, we are already experiencing changes in regional weather trends and growing seasons likely due to climate change and these can be used as indicators of future changes. It would be beneficial for freight carriers to have an awareness of where and to what extent fleets will be needed to continue export of grains from the upper Midwest to the rest of the U.S. and the world. This project seeks to use recent historical climate and crop information combined with regional climate modeling and other tools to project forward the demands on freight transportation for the upper Midwest grain distribution in the future.

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Agricultural products; Climate change; Forecasting; Freight traffic; Grain; Intermodal transportation; Multimodal transportation; Optimization; Remote sensing; United States; Data and Information Technology; Freight Transportation; I15: Environment

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CFIRE 09-20: Estimating the Future of Agriculture Freight Transportation Network Needs due to Climate Change

FINAL REPORT

Paul Johnson[1] and Janey Camp[2]

"The impact of climate change on agriculture is the most carefully studied area of impact analysis."
William Nordhaus, *The Climate Casino*

INTRODUCTION

The United States is one of the world's largest exporters of grain, and in particular corn. In 2012 through 2013, the U.S. corn production amounted to 32.1% of all the corn grown in the world, and approximately one fifth of that amount was exported[3,4]. The vast majority of this corn is grown in the Midwestern U.S. due to the region's favorable growing conditions. However, several studies indicate that climate change may alter these favorable conditions and potentially shift the optimal growing region and in turn, demands for commodity transportation.

In general, temperatures in the Midwest are expected to increase with elevated levels of carbon dioxide in the atmosphere stemming from fossil fuel emissions, which would shift the currently ideal conditions of the Corn Belt region northward. This effect would most likely benefit farms in the Upper Midwest due to longer growing seasons and harm areas in the Lower Midwest due to shortened periods of the corn's reproductive development period. Additional heat strain in the relatively warmer south could also be detrimental to yields. Extreme weather events, like heat waves, are also anticipated to be more likely under future climate scenarios, which severely hurt crop yields.

Compared to temperature, the relationship between precipitation and increased carbon dioxide levels is not as exact and much harder to establish. As such, studies have projected various precipitation scenarios for the Midwest, with the majority anticipating increased precipitation during winter months and decreased precipitation during the growing season. The already dryer western region is generally projected to become dryer as well. Impacts on agriculture are difficult to assess because winter precipitation helps create more soil moisture for spring planting, but less rain during the crucial, summer development stages would strain yields. Although, irrigation practices help offset the latter. Extreme flood events are also expected to be more likely in projected climates, which would severely damage crops. Overall, precipitation projections under future climates are largely unknown, but in all likelihood, more strain will be placed upon the crops as a result of more extreme weather.

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[3] USDA. (2013) Crop Production (August 2013). National Agricultural Statistics Service. http://usda01.library.cornell.edu/usda/current/CropProd/CropProd-08-12-2013.pdf
[4] National Corn Grower's Association 2013 Report. 11 Feb. 2013. http://www.ncga.com/upload/files/documents/pdf/WOC%202013.pdf. Accesssed 22 August 2013.

The U.S. has a widely spanned irrigation system that helps manage the soil moisture content across much of the Midwest. Most studies suggest soil moisture will follow similar patterns as precipitation, increases in the winter and decreases in the summer, placing a greater system demand during crucial growing seasons. Increased evapotranspiration from elevated temperatures adds to further volatility and pressure. Additionally, increased likelihood of droughts and floods is expected to degrade conditions even more.

Carbon dioxide fertilization and solar radiance also affect agriculture. However, being a C4 crop that is already relatively energy efficient, corn is not expected to greatly benefit from increased levels of carbon dioxide. Radiation from the sun is not largely affected by climate changes here on earth, except for the indirect and largely unknown impacts of cloud coverage. As a result, future projections are difficult and largely futile to establish.

Overall, the optimal growing conditions for corn are largely believed to shift northward over the next few decades as a result of increased temperatures in the south. As a result, transportation demands could largely be altered. A study at Texas A&M expects to see a shift from barge to rail and truck, as shipments along the Mississippi River to the Gulf of Mexico are replaced by more commodities coming out of the Upper Midwest to the Pacific Northwest and Great Lake areas[5].

However, the majority of these agricultural impact studies imply that climate factors have the biggest influence on corn yield. A handful of others attribute major trends in crop yield to vaguely defined, all-encompassing categories that include technology and crop management improvements. We have not found a study that explicitly defines these improvements, quantifies their respective impacts, and determines how they relate to climate factors. As such, this study seeks to infer what phenomena, both environmental and other, are causing the major trends and variations in corn yield over the past few decades. It is wise to establish such an interpretation before making predictions about what's to come.

METHODOLOGY

To infer the most influential trends in Midwest corn yield through time, three approaches are followed. First, county-level corn yield data is looked at over the past 35 years to establish general spatiotemporal trends. The county-level corn yield data was derived from the US Department of Agriculture's (USDA's) National Agricultural Statistical Service (NASS)[6] for states of Illinois, Indiana, Iowa, Kansas, Michigan, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Second, regional climate factors are observed in concurrence with crop trends to establish correlations between environmental factors and yield. Third, an exploratory statistical analysis method, Principal Component Analysis (PCA), is employed to discern potentially concealed trends.

For the first two approaches, ESRI's ArcGIS suite is used to visually examine climate and yield trends. A multiple linear regression is then performed to assess the significance that temperature, precipitation, and soil moisture have on corn yield during the growing season. Based on scientific literature, these

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[5] Attavanich, W., Bruce A. McCarl, Zafarbek Ahmedov, Stephen W. Fuller, and Dmitry V. Vedenov (2013). *Effects of climate change on US grain transport*. Nature Climate Change. (3). 638-643

[6] USDA's National Agricultural Statistical Service (NASS) - https://www.nass.usda.gov/Surveys/.

three are the most influential climate factors affecting corn yield. The results of this approach help establish general trends between climate means and annual crop yield.

The PCA results in a set of eigenvectors and eigenvalues that describe the underlying arrangement of variance in the corn yield data. The magnitude of the eigenvalue reveals how much of the relative variance can be explained by its corresponding eigenvector, or component. The eigenvectors are arranged so that the first one, the one with the largest eigenvalue and known as the first principal component, explains most of the variance in the data; the second explains the second most variance orthogonal to the first, and so forth. Because the components are orthogonal to one another, they should infer underlying processes that are uncorrelated with each other. With the case of this particular analysis, the dimensions of the PCA correspond to the calendar year, so the eigenvectors form time series that reveal temporal trends over the span of the data. As such, we can see what phenomena moving through time has the greatest impact on corn yields.

Additionally, the original yield data can then be rotated by each eigenvector to infer how yield values map to each principal component, known as principal component scores. In this case, as the data are county-level values, the scores will yield spatial patterns mapping to each of the time series. As a result, we can observe how spatial patterns interact with the temporal ones. The results of the PCA help identify underlying, sometimes hidden, processes and their respective impacts.

The data for all of these approaches is obtained from the following two sources:

- Corn Yield Data – United States Department of Agriculture (USDA) National Agricultural Statistics Survey (https://quickstats.nass.usda.gov/)
- Climate Data (temperature, precipitation, and soil moisture) – National Oceanic and Atmospheric Administration (NOAA) North American Region Reanalysis (https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html)

RESULTS

As see below in Figure 1, annual corn yield has steadily increased over the last 35 years. This result is consistent with other agricultural studies. Additionally, as seen in Figure 2, mean centers of corn yield have spatially shifted only slightly, 13km northwest, over the same time period. This result also aligns with several studies and predictions of how climate change may shift the Corn Belt region northward.

Figure 1: Annual Corn Yield in the Midwestern U.S.

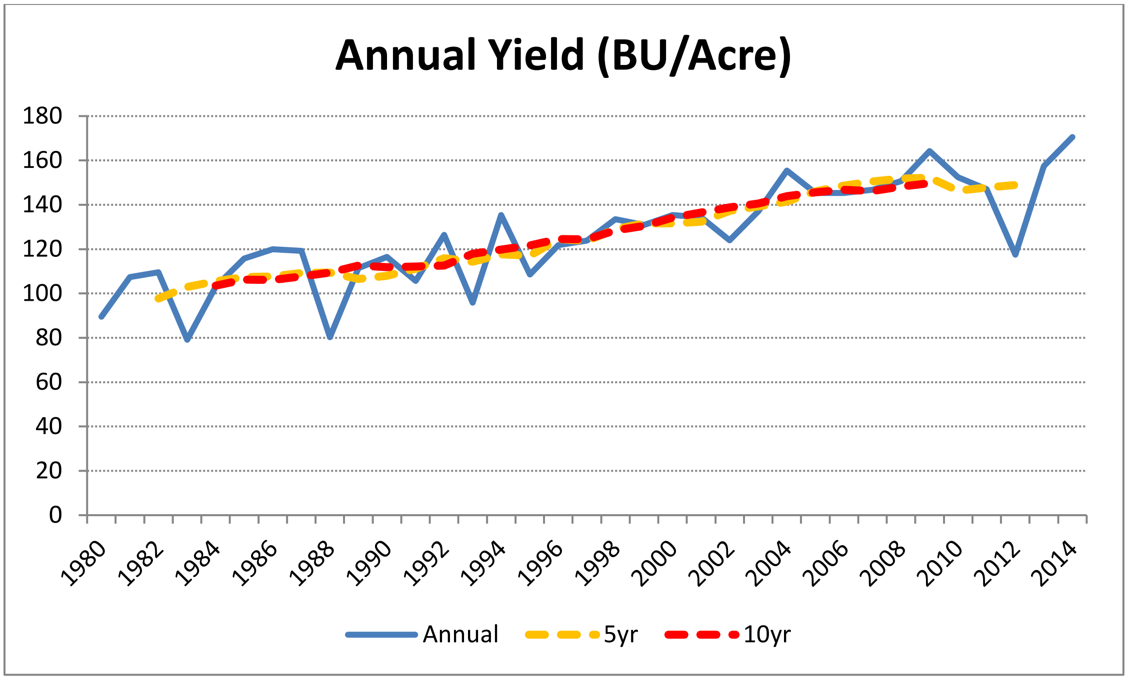


Figure 2: Spatial Patterns of Midwest Corn Yield

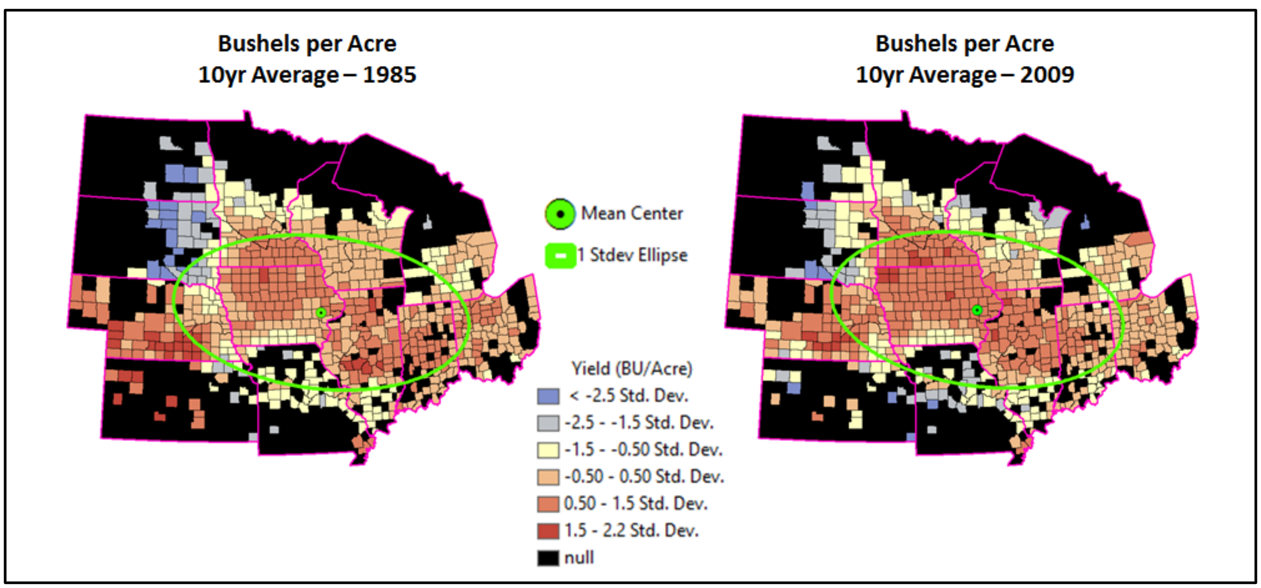


Figure 3 below shows that growing season temperatures have increased slightly over the last 35 years. Figure 4 reveals that most of this slight increase involves regions of the Upper Midwest. Both results are consistent with expected impacts from climate change.

Figure 3: Mean Growing Season Temperatures by Year

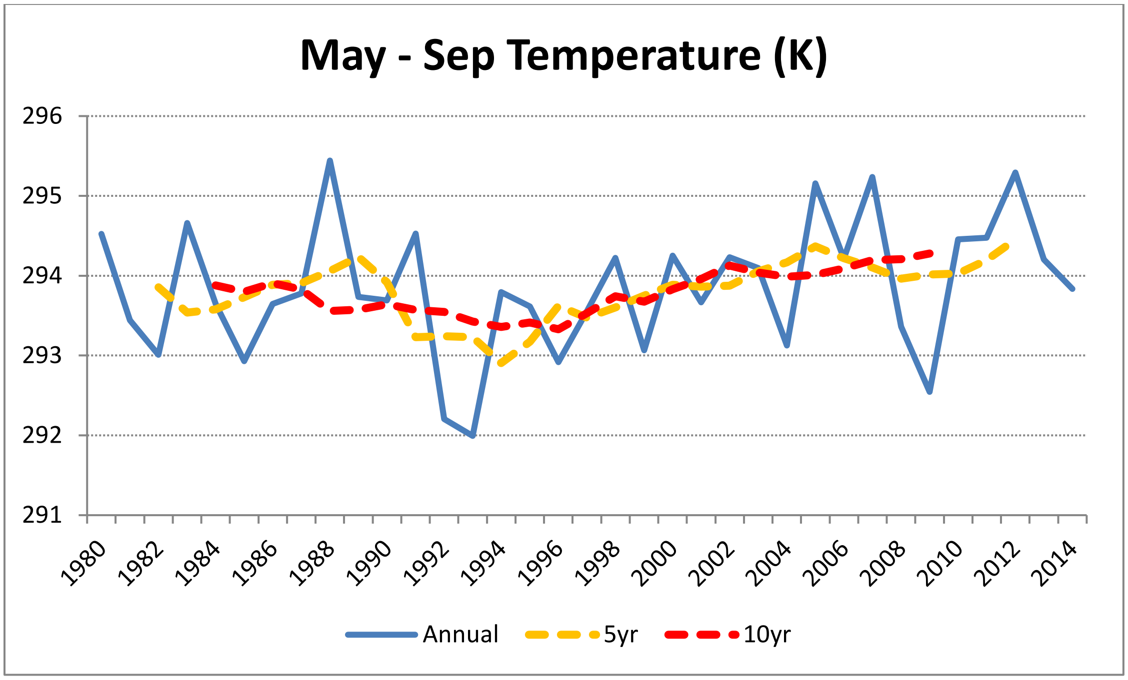
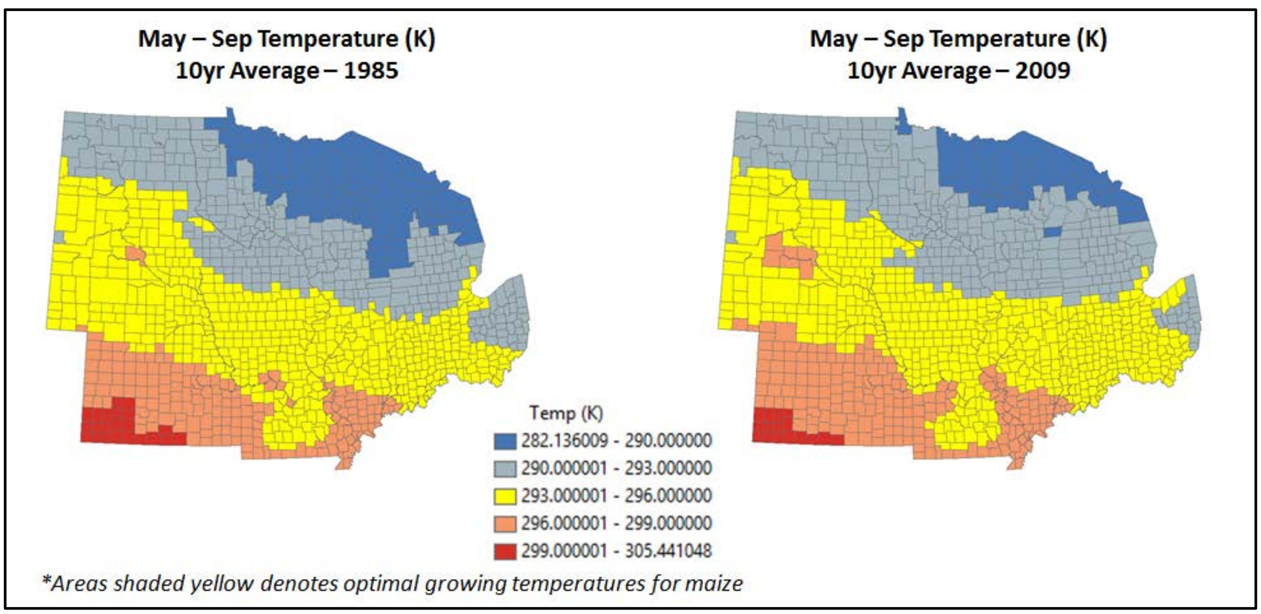


Figure 4: Spatial Patterns of Growing Season Temperatures



Below, Figure 5 shows that mean precipitation during growing season has remained constant over the past 35 years. Figure 6 indicates that slight increases in participation in the west offset decreases in the north. As mentioned in the introduction, while precipitation plays a vital role in corn development, the effects climate change has on it are difficult to project since the relationship between carbon dioxide and precipitation is not as exact as with that of temperature. Results here differ from most expectations, where Midwest growing season precipitation is expected to decrease, especially in the west.

Figure 5: Mean Growing Season Precipitation by Year

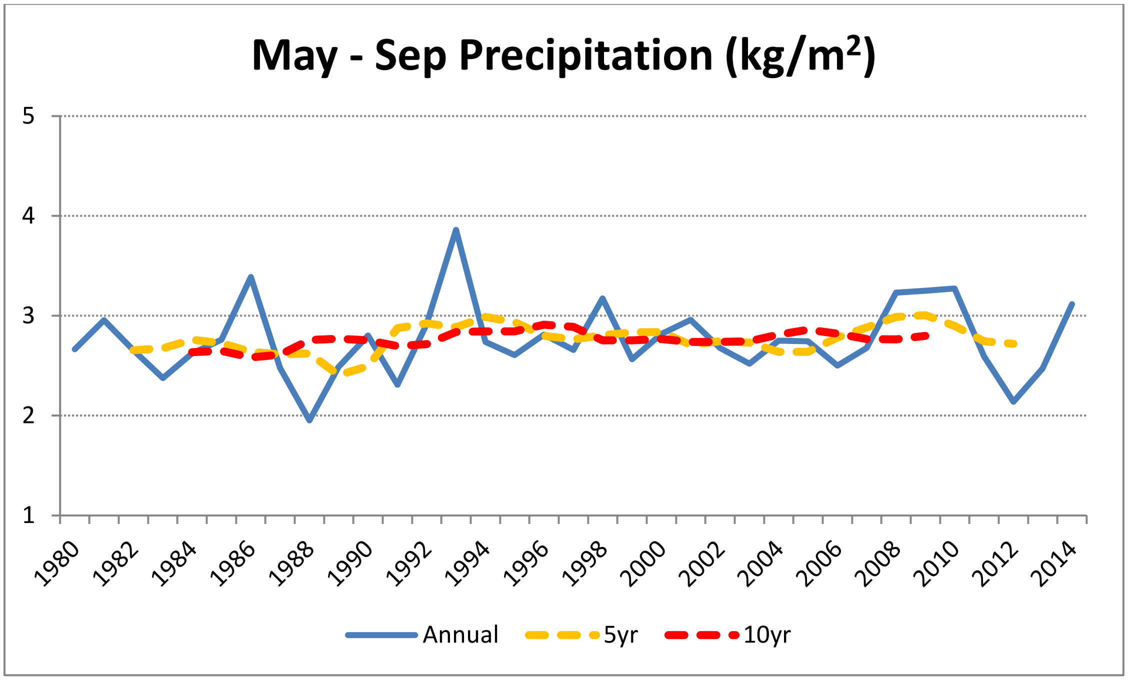
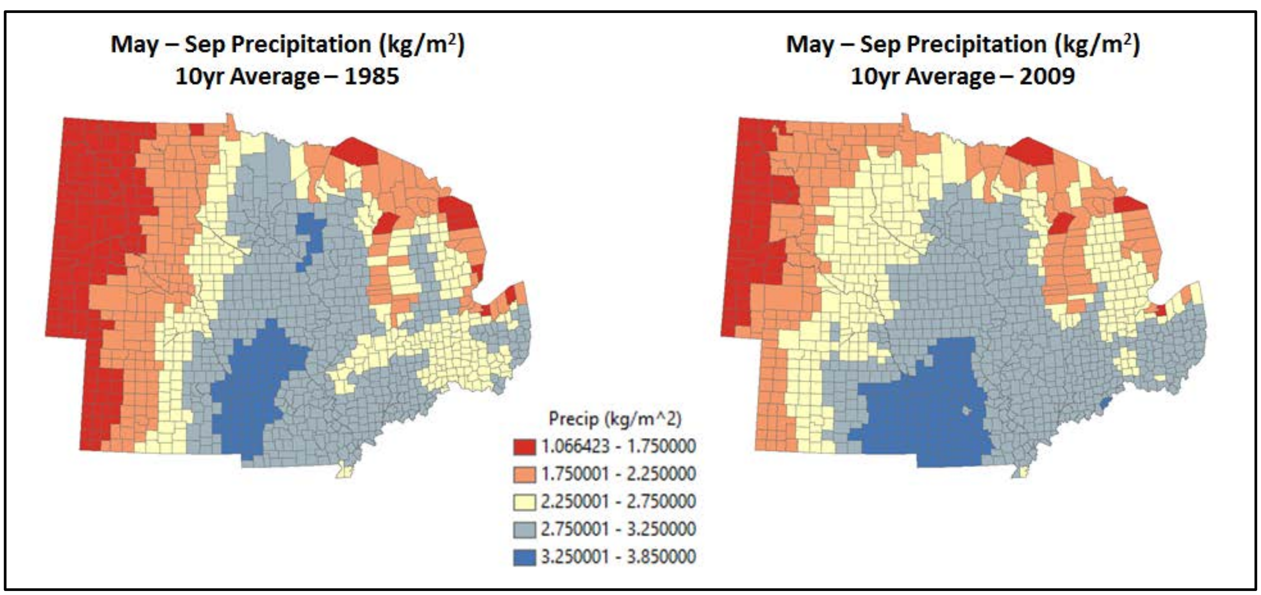


Figure 6: Spatial Patterns of Growing Season Precipitation



Soil moisture has decreased in recent decades, predominantly in the eastern Midwest, as seen in Figures 7 and 8 respectively. The decline is due to improved farming practices that help manage detrimental over-inundation. The eastern Midwest traditionally receives the most rainfall and much of it is unneeded, and at times damaging.

Figure 7: Monthly Liquid Soil Moisture Fraction during Growing Seasons in the Midwest

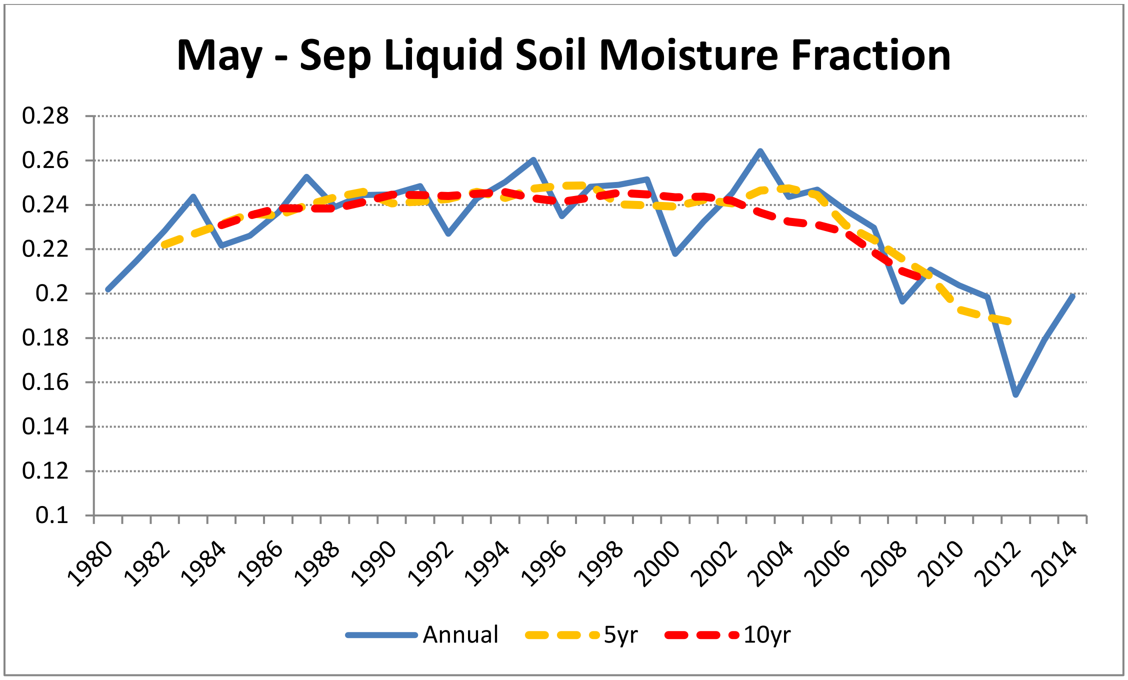
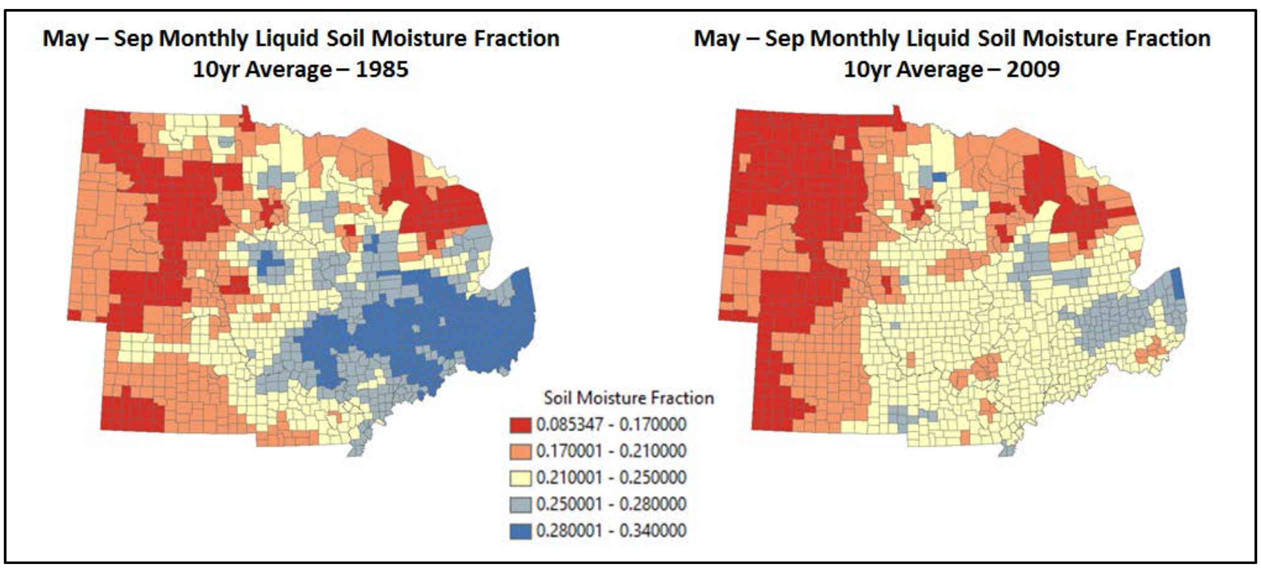


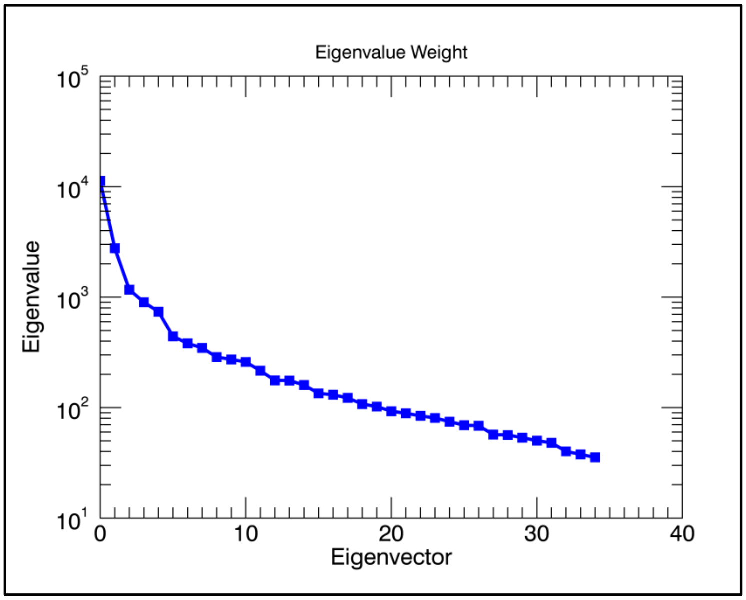
Figure 8: Spatial Patterns of Growing Season Soil Moisture



Overall, these results suggest that temperature is increasing in the Midwest and that regions of highest corn yield could be shifting northward with it, albeit slowly. Mean precipitation and soil moisture trends don't appear to have much of an impact on crop placement or yield in the Midwest, most likely due to the U.S.' advanced irrigation system. However, none of these climate factors explain what is causing the steady increase in crop yield (Figure 1).

Regarding the PCA, Figure 9 shows the weights of the resulting eigenvalues, and Table 1 lists the explained variances that correspond to the first ten principal components.

Figure 9: Skree Plot of Eigenvalue Weights



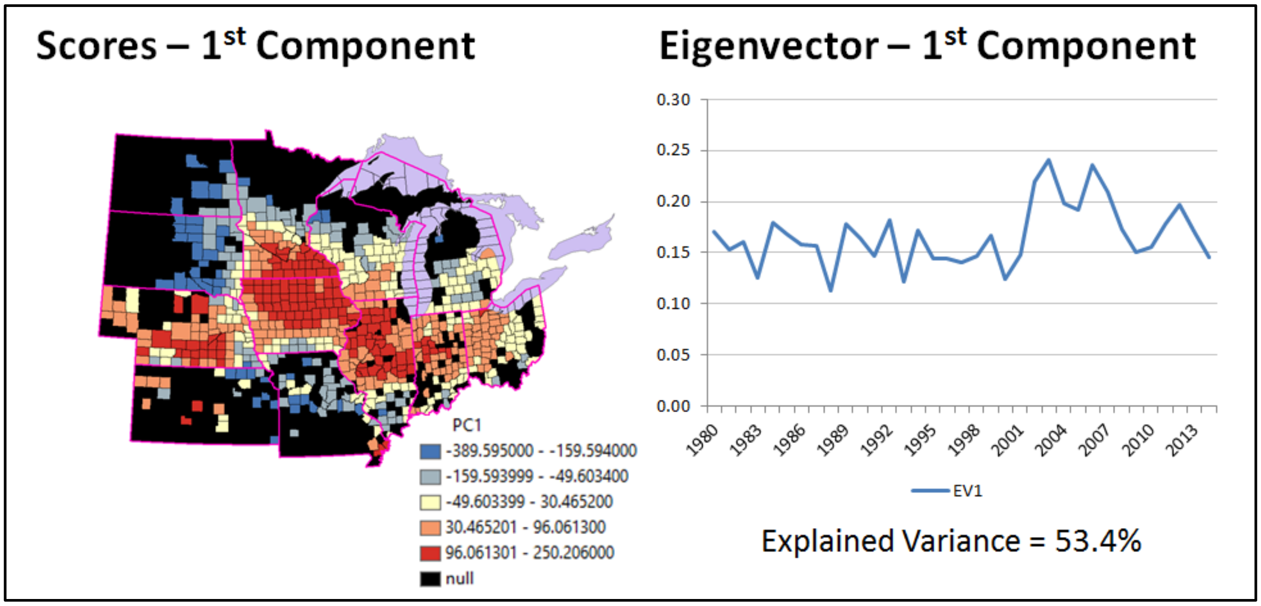
PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
53.4%	13.1%	5.5%	4.3%	3.5%	2.1%	1.8%	1.6%	1.4%	1.3%

Table 1: Explained Variance of Each Component

As seen, there is one factor that dominates the underlying variation in crop yield with 53.4% explained variance. A second significantly affects outcomes, with 13.1%. A third contributes to a modest 5.5%. The fourth and fifth components contribute even less, and anything beyond these is negligible, as demonstrated by the exponential decay like curve in the plot above. Over 70% of the entire variation in crop yield over the past 35 years can be explained by three underlying factors.

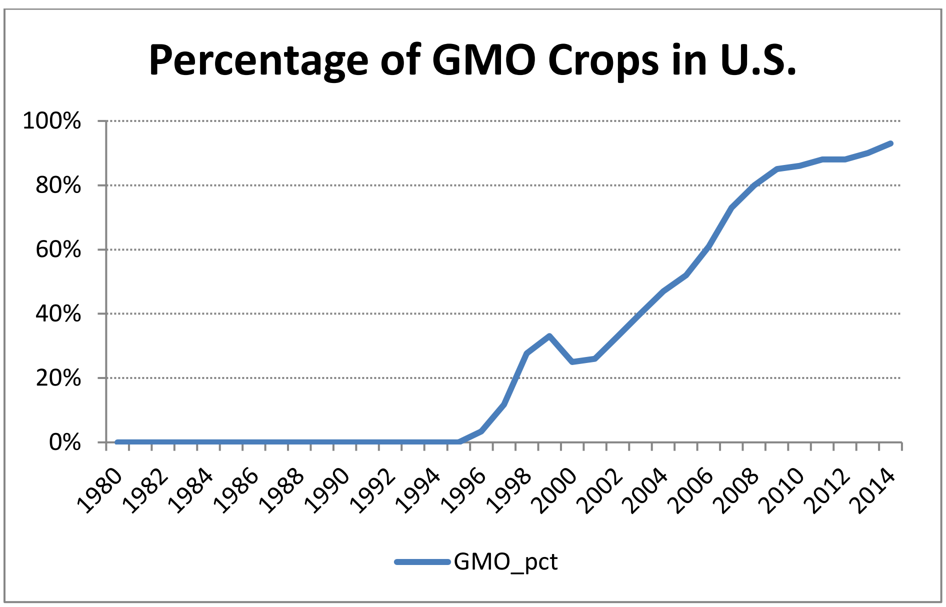
Figure 10 below shows the scores (spatial mappings) and eigenvectors (time series) of the first principal component. The time series infers that whatever phenomena is causing 53.4% of the variance in crop yield is relatively constant up until the late 1990s, and then something happens. The sign of the eigenvector is arbitrarily determine, so we do not yet know whether the increase in the time series corresponds to an increase or decrease in yield amount. We do know that whatever happened in the 1990s spatially maps directly to the Corn Belt region, as seen in the score plot. The higher the score, the more closely related the county is to whatever happened in the late 1990s.

Figure 10: 1st Principal Component



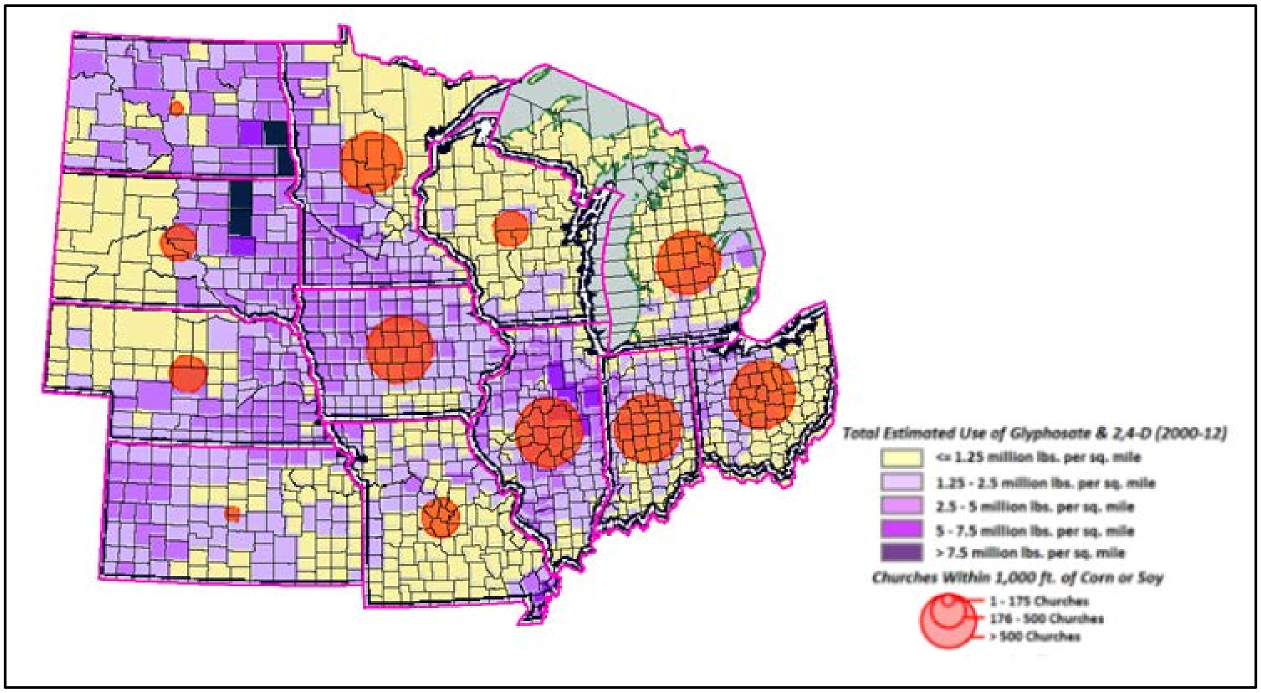
In 1996, genetically modified organisms (GMOs) started being used as herbicides for crops. In the next few years, the agricultural community began using them profusely as herbicides and pesticides to combat weeds and pests that were damaging crops. Figure 11 below shows this trend, and currently, around 90% of all crops in the U.S. use some sort of GMO.

Figure 11: Percentage of GMO Crops to Total Crops in the U.S.



Additionally, the majority of GMO use centered around the Corn Belt and northwest regions of the Midwest, as seen by the dark purple regions in Figure 12 below.

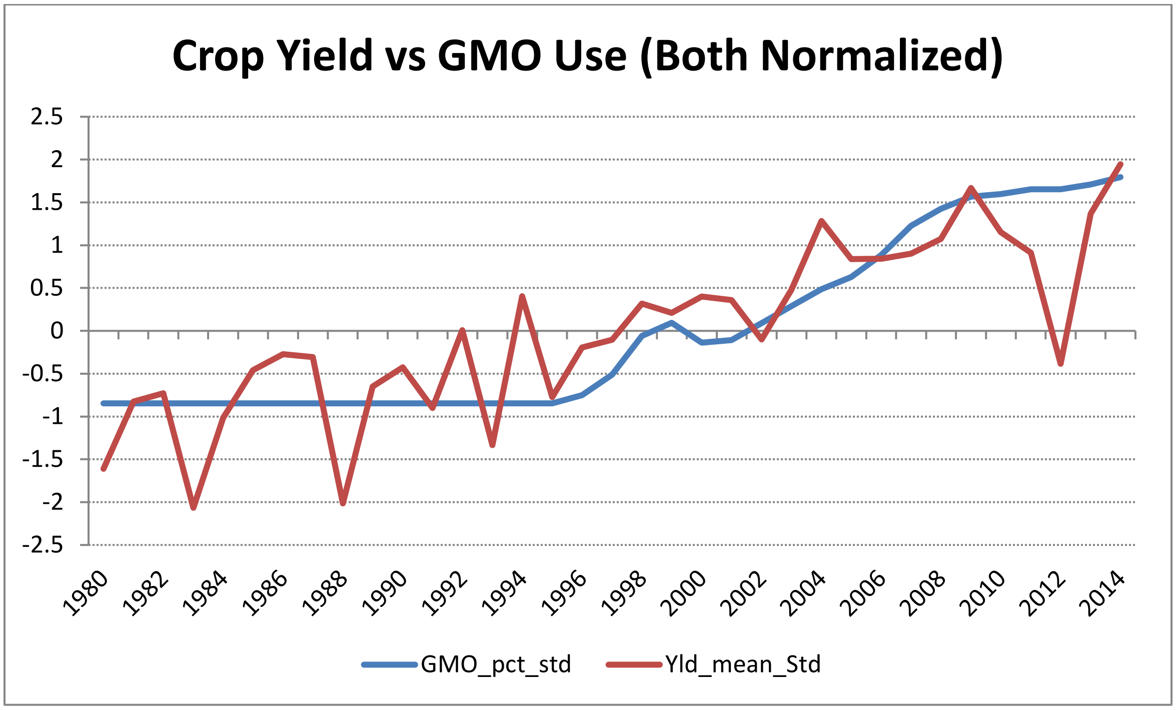
Figure 12: Spatial Patterns of GMO Crops[7]



Because the GMO use aligns both temporally and spatially with the eigenvectors and scores of the first principal component, these findings suggest that GMOs correspond to the underlying process that explains 53.4% of the variation in crop yield over the last 35 years. Figure 13 plots the percentage of GMO use (Figure 11) against Mean Crop Yield (Figure 1) on a normalized scale, and the two align very well with a correlation of 0.79. The GMO usage appears to be responsible for the steady increase in crop yield.

[7] EWG Agricultural Magazine (2015) http://www.ewg.org/agmag/2015/07/monsanto-s-gmo-weed-killer-sprayed-fields-close-12000-churches

Figure 13: Crop Yield vs GMO Use (Normalized Scale)



Additionally, when the PCA is repeated on a dataset that is de-trended based GMO use, the first principal component is equivalent to the second principal component of this analysis, as seen in Figure 14 below.

All these findings combined conclusively lead to the interpretation that the first principal component, and the factor that has historically contributed to the greatest variation in annual corn yield, is the introduction of GMOs to crops.

Figure 14: 2nd Eigenvector vs 1st Eigenvector (de-trended GMO)

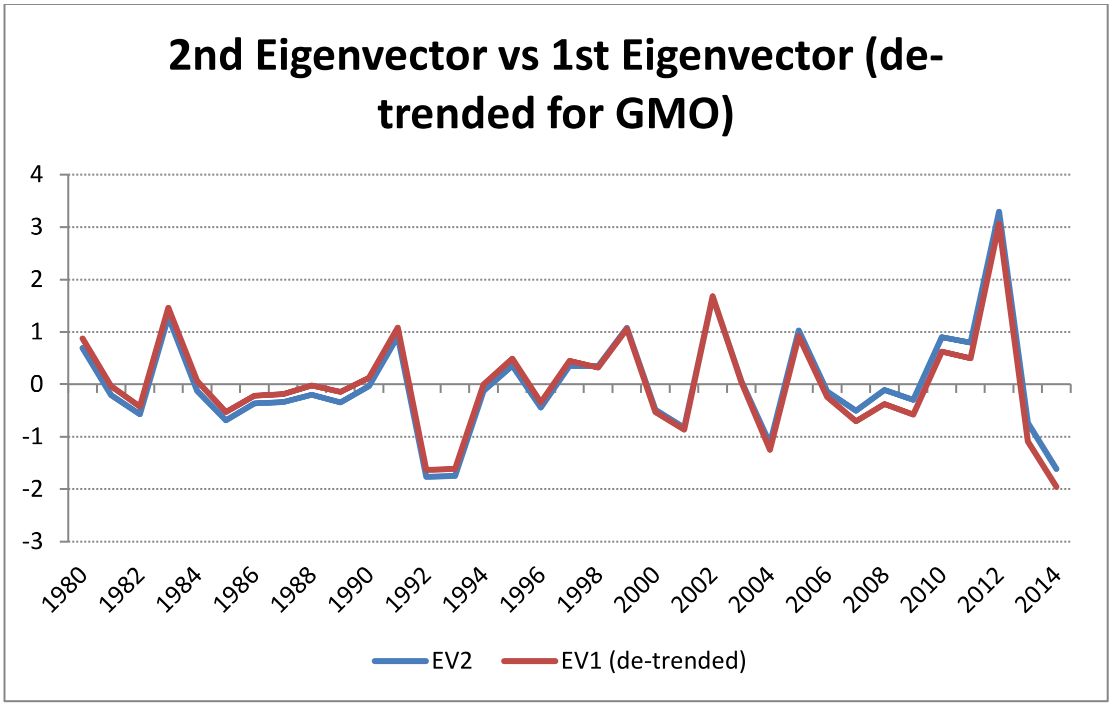
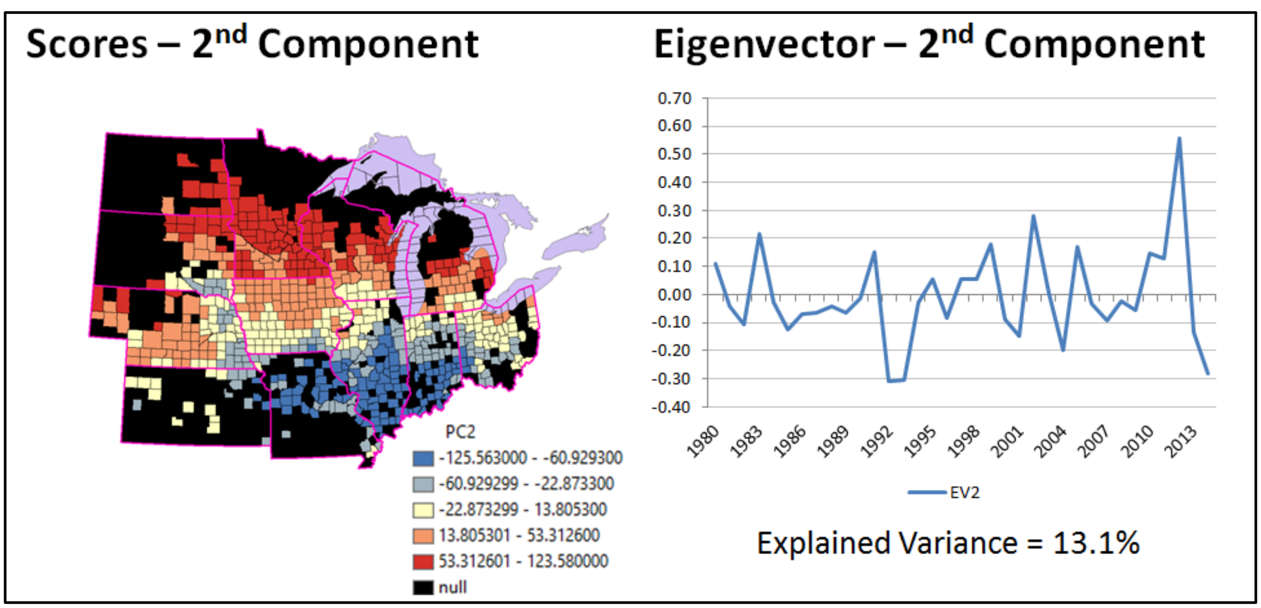


Figure 15 below shows the scores and eigenvectors pertaining to the second principal component. Temporally, the trend remains fairly level across the 35 years, with intermittent peaks and troughs. Spatially, a striation between northern and southern regions in the Midwest is apparent. The two infer that whatever process contributes to around 13.1% of the variation in corn yield occurred heavily in the year 2012, the highest peak, and somewhat less so in the other peak years, and that this process is out of phase with the southern region of the Midwest.

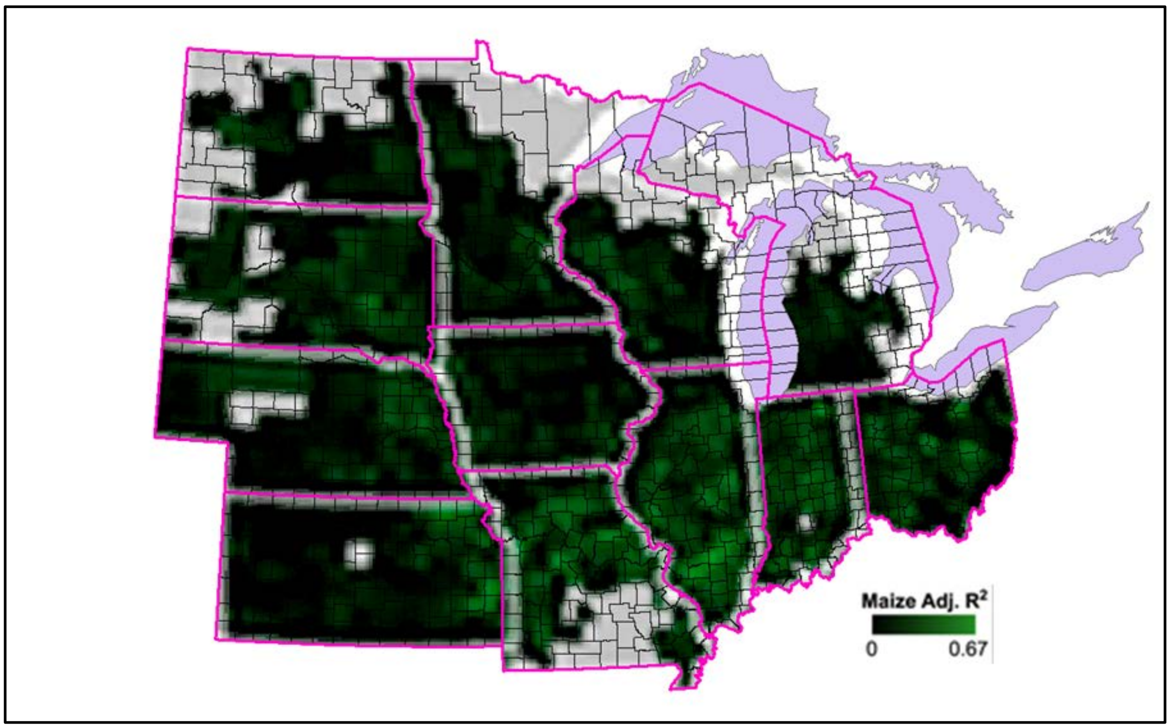
Figure 15: 2nd Principal Component



In the year 2012, one of the most sever droughts on record struck the U.S., crippling agriculture production. The area most significantly affected in the Midwest was the southeastern regions that are already subject to relatively warmer conditions and have less irrigation systems in place than in the west due to its naturally dryer climate. Furthermore, a drought has been documented in the Midwestern U.S. for the years 1980, 1983, 1995, 2002, 2005, 2010, and 2011, all timepoints that correspond to peak years of the eigenvector.

Figure 16 below shows the standardized precipitation evapotranspiration index (SPEI) calculated for regions in the Midwest and its relationship to crop yield. The higher the relationship infers the greaer impact heat waves and droughts have on the region. Regions with the highest correlation overlap with the ares of low scores from the PCA. The study[8] that conducted the SPEI analyis also estimated that droughts are associated with approximately 13% of yield variability, which is exactly the amount variance explained by the second principal component in this analyis. The two methodologies are disparate in concept and execution yet offer equivalent interpretations.

Figure 16: SPEI Correlations on Yield[9]



Additionally, when the original corn yield data is reconstructed using only the second principal component, the same striation pattern occurs for years when there is a drought. Much lower than expected yields are found in the southeastern region of the Midwest. For normal years, the striation pattern is flipped and higher yields are found in this gernally fertile region of the Corn Belt. All of these fidings lead to the conclusion that droughts are the second most influential phenomena affecting corn yield.

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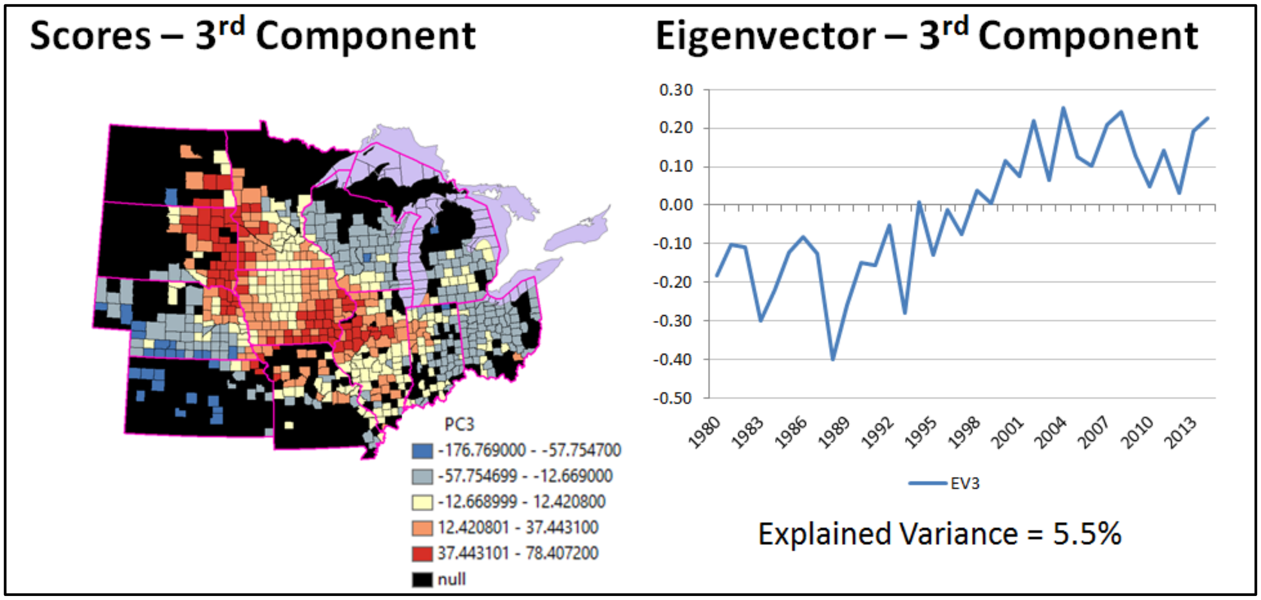
[8] Zipper, Samuel C., Jiangxiao Qiu, and Christopher J Kucharik (2016). *Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes.* Environmental Research Letters. (11). 9.

[9] Ibid

The scores and eigenvector of the thrid principal component can be seen in Figure 17 below. The temporal pattern here is similar to that of the first component, relatively flat until the mid-1990s when something picks up. Spatially, the regions most related to this increase are the northwestern states (North and South Dakota) and southern Iowa and Illinois.

Figure 17: 3rd Principal Component



The interpretation of the third principal component is a mixture of GMO crop usage and noise, which starts becoming more apparent as explained variance decreases. Similar logic from component one is applied here.

Temporally the trend aligns extremely well (Figure 11). Spatially, the Dakotas were among the heaviest users of GMOs (Figure 12). Additionally, when the PCA is repeated for GMO de-trended data, the resulting second and third principal components map to the initial fourth and fifth components respectively; it is a difference of two because the GMO trend is attributed to both the first and third original components. These results can be seen below in Figures 18 and 19.

The reason that GMO is present two components when they should be uncorrelated factors due to the orthogonality of the eigenvectors is two-fold. First, the third component predominately corresponds to areas of the northwest while the first one was associated with the Corn Belt. The two regions have drastically different yield amounts, with the latter being much higher, and the PCA picked up this difference. Second, if there is an underlying trend present in the data, as is the case here, “then it is likely that it [the trend] will be spread over more than one PC”[10].

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[10] Hannachi, A., I.T. Joliffe, D.B. Stephenson. (2007) *Empirical orthogonal functions and related techniques in atmospheric science: A review*. International Journal of Climatology 27: 1119-1152

Figure 18: 4th Eigenvector vs 2nd Eigenvector (de-trended for GMO)

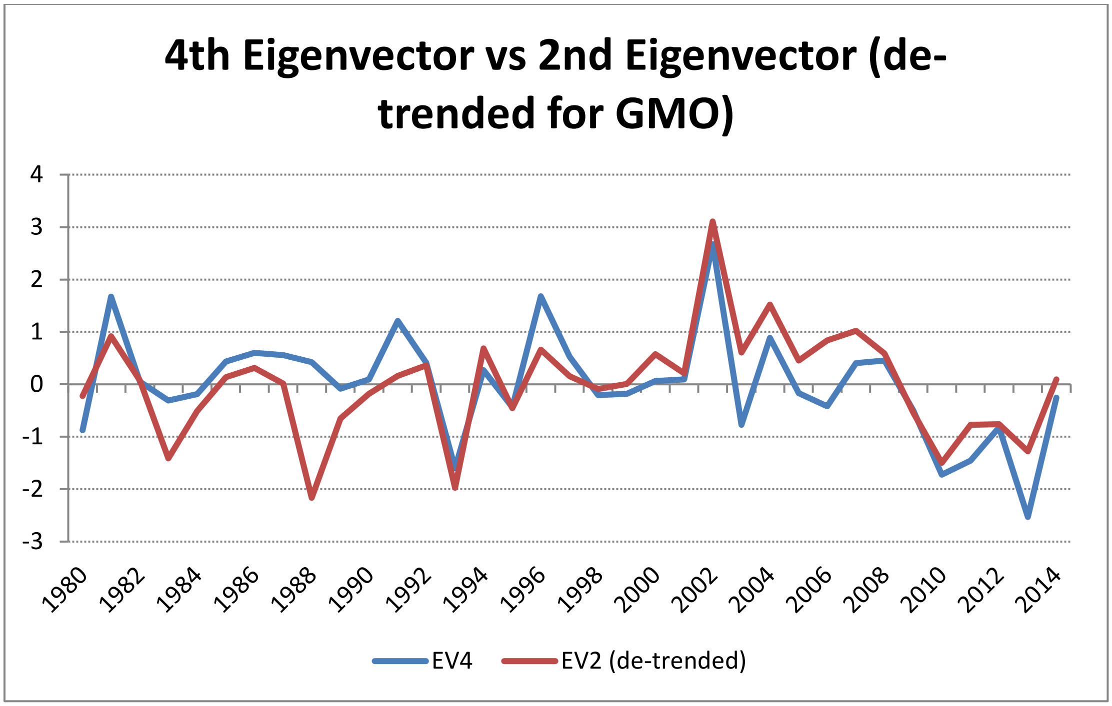
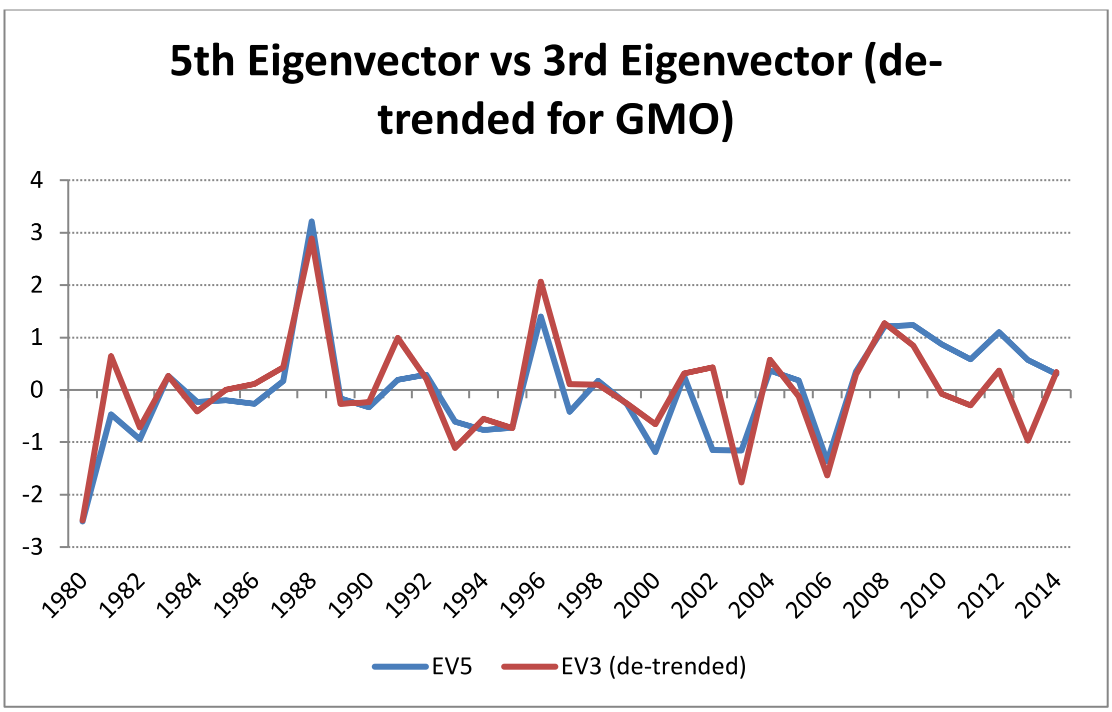


Figure 19: 5th Eigenvector vs 3rd Eigenvector (de-trended for GMO)



Figures 20 and 21 below show the results of the fourth and fifth principal components respectively. Currently, we are not able to figure out their underlying processes. Potentially, the PCA could just be picking up noise mixed in with some small, unidentifiable factor, or perhaps we just haven't been able to discern a pattern yet. We do know they do not align with any of the abovementioned environmental factors: temperature, precipitation, and soil moisture, and that their contribution to the overall variance in corn yield is much smaller than the aforementioned components.

Figure 20: 4th Principal Component

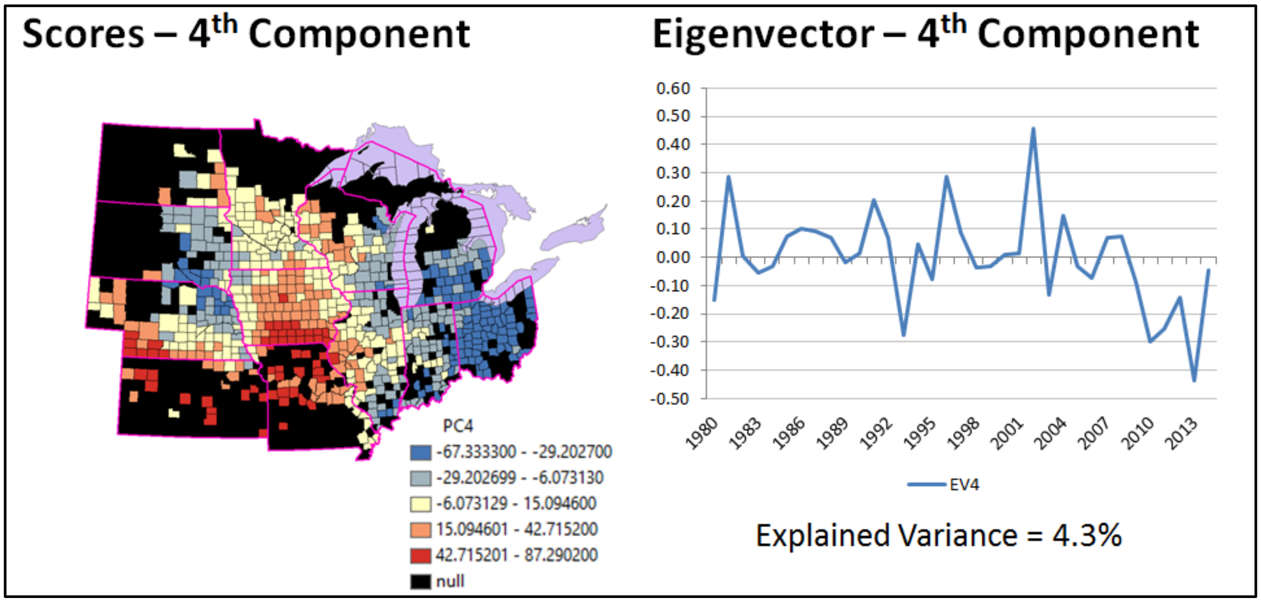
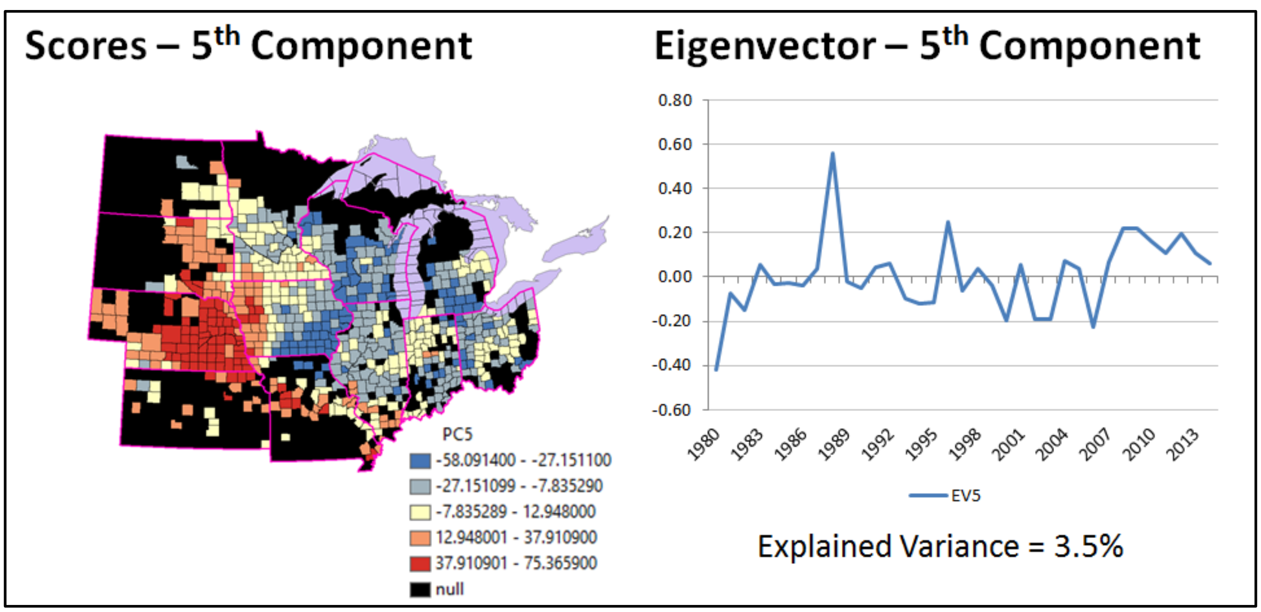


Figure 21: 5th Principal Component



Lastly, a multiple linear regression is performed on the original corn yield data using the following as regressors: percent GMO usage (national-level), temperature (county-level), precipitation (county-level), and soil moisture (county-level). Table 2 below shows the results.

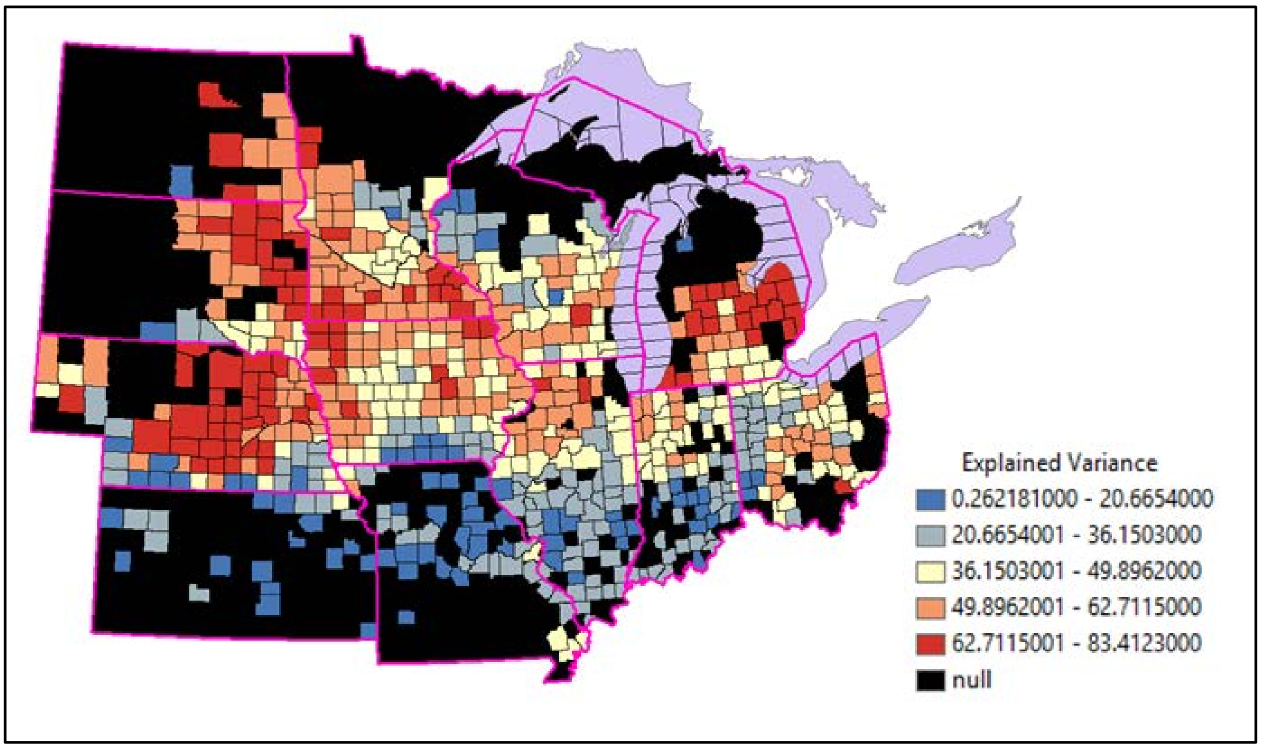
	y_gmo	y_temp	y_precip	y_soilm	y_all
R2	0.436768	0.061518	0.078995	0.066595	0.589359
R	0.660884	0.248028	0.28106	0.258061	0.767697

Table 2: Multiple Linear Regression

As seen, even at a broad, national granularity, the overall GMO trend dominates all of the climate factors. Temperature, precipitation, and soil moisture offer similar fits, which suggests in the Midwestern U.S., they have had similar impacts on crop yield over the past 35 years. This makes sense if we consider that droughts are responsible for much of the variance as explained by PCA; droughts generally entail periods of correlated temperature, precipitation, and soil moisture stress.

Spatially, the analysis is in line with results from the PCA interpretation as well. Figure 22 below shows that the GMO regressor generally fits county-level yield data better in areas where there was high use of GMOs, the Corn Belt and northwestern Midwest.

Figure 22: GMO Regressor Spatial Plot



Figures 23-25 show similar plots for the temperature, precipitation, and soil moisture regressors respectively. As seen, these factors, especially the first two, carry more weight in the southeastern region that tends to be more heavily influenced by drought conditions.

Figure 23: Temperature Regressor Spatial Plot

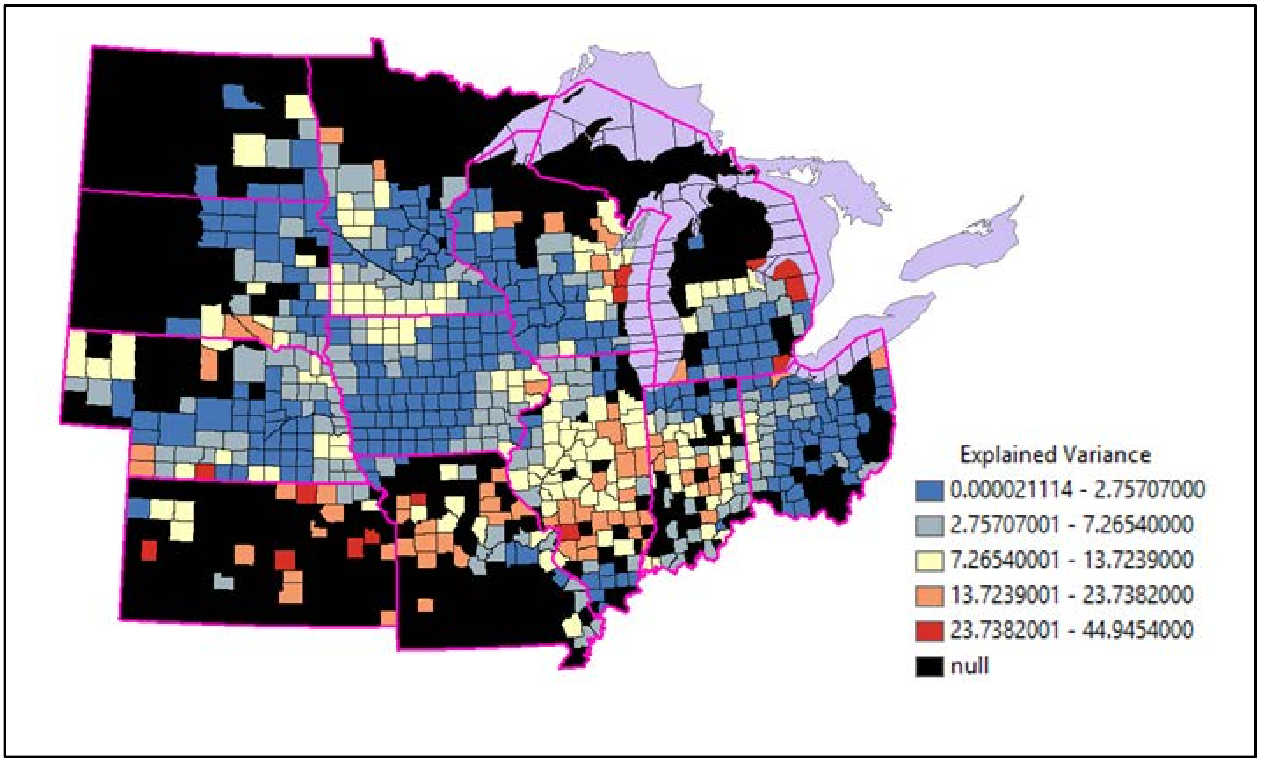


Figure 24: Precipitation Regressor Spatial Plot

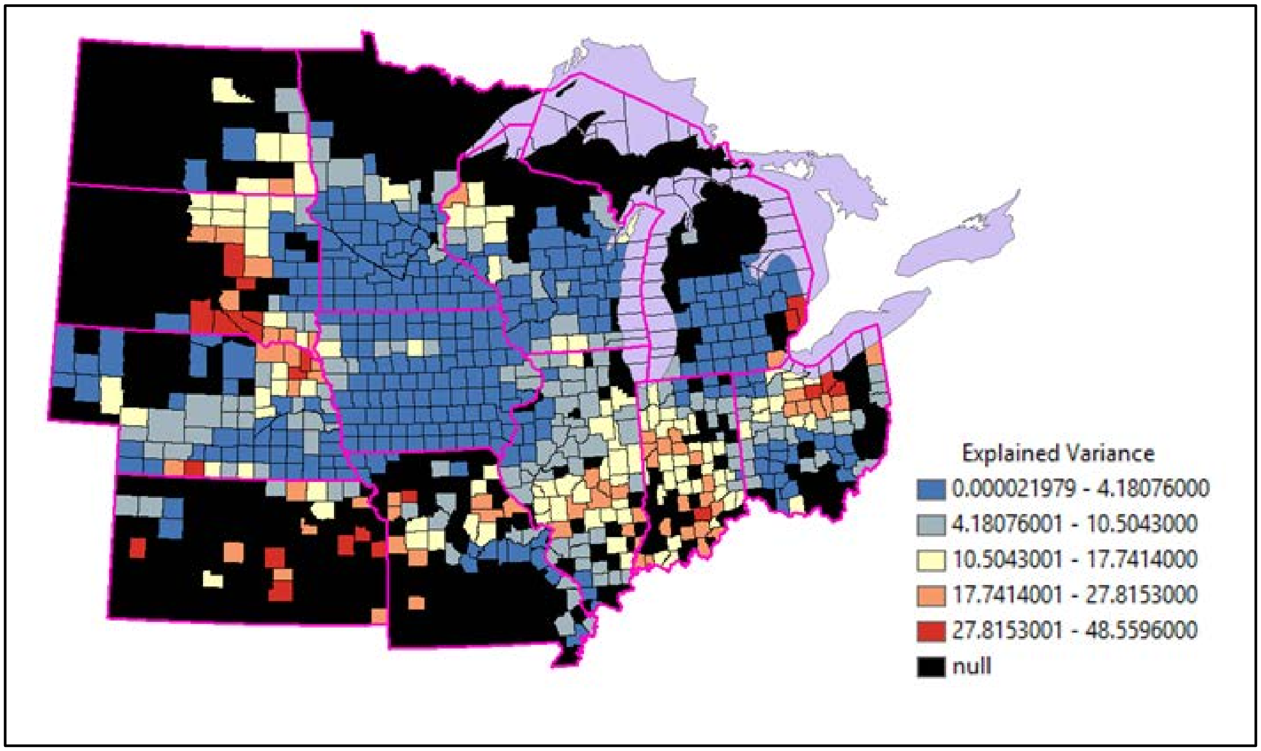
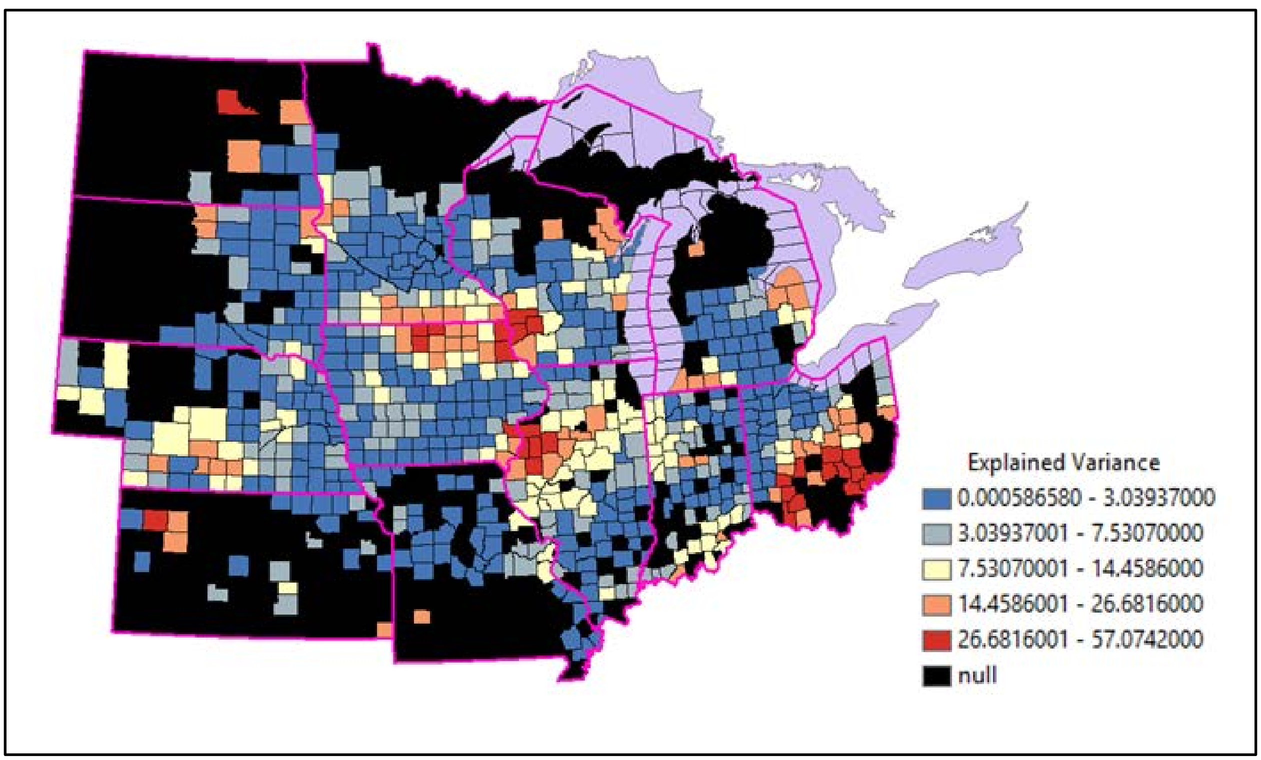


Figure 25: Soil Moisture Regressor Spatial Plot



Ultimately, all but one of the climate factors can be dropped from the regression and yield similar overall fits. In this particular case, the combination of GMO usage and precipitation offers the most effective combination, but temperature can easily be substituted. Both precipitation and temperature offer nice spatial compliments to the GMO use; areas where the GMO regressor performs relatively poorly tend to be regions where the precipitation and temperature regressors perform well. Soil moisture has too much overlap in the Corn Belt and performs not as well in the southeastern regions compared to the previous two.

CONCLUSIONS

Agriculture, especially in the Midwestern U.S., is an important sector that is expected to be heavily affected by climate change. Most studies anticipate ideal growing conditions for corn to shift northward, along with transportation demands for grain commodities. However, the majority of these studies imply that climate factors are the most significant variables influencing grain yield.

This analysis infers that although recent climate trends seem to align with predictions, climate factors themselves do not paly as important of a role in corn yield as manmade ones. Specifically, the introduction of GMOs in crop management has accounted for by far the most variation in corn yields over the last 35 years and adroitly explains its underlying increasing trend.

Additionally, it is extreme climate conditions, droughts in particular, that affect corn yield more than simply mean temperatures, precipitation, and soil moisture. This finding is consistent with previous research and foreboding when combined with the general expectation that future climates will be subject to more extreme weather.

With these results, **it is difficult to anticipate and unwise to forecast changes in crop landscape and resulting transportation needs.** Although favorable growing conditions may shift northward due to increased temperatures in the south, based on this analysis, it is just as plausible that heat resistant crops could be developed before that occurs, nullifying the need to relocate. Over the last 35 years, one manmade technological innovation influenced corn yields more than all climate factors combined. It is not dumbfounding that something similar could likely occur in future climates.

The most important thing to keep in mind is that in a highly complex, non-linear system such as the earth's climate and the impacts it has on agriculture, all forecasts need to be taken with a grain of salt. By no means should we ignore climate change and wait for revolutionary technologies to shape our landscape, but we also cannot ignore uncertainty in predictions either. Agile and effective adaptation will be crucial in navigating these complex systems under future climates.

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