**Spatiotemporal Relationships of Crop Yield and Growing Season**

**Climate Anomalies in the Southeastern United States**

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**Introduction**

Agricultural production in the United States (US) is highly sensitive to interannual climatic variability and will likely experience significant adverse impacts as a result of anthropogenically enhanced climate change (Reilly et al., 2003; Lobell & Asner, 2003; Adams et al., 1995). Farmers across the US have been adapting to and coping with extreme meteorological hazards for centuries but future projections of increased warming and volatility in precipitation suggest increased pressure on the agricultural industry (Cho & McCarl, 2017; Doll et al., 2017). Techniques to manage the effects of climatic change and coping mechanisms for short-term meteorological “shocks” differ across the unique agricultural regions of the United States (Reyes & Elias, 2019; Nelson et al., 2014). In more vulnerable regions, such as the southeastern United States (SEUS), the impacts and associated response differs considerably based on the crop type, hazard, and the time in which the event occurred during the growing season.

Despite being more heavily associated with the Midwest, agriculture remains a primary economic driver for the SEUS. Accounting for nearly 17% of the total agricultural production in the country, the SEUS provides some of the highest diversity of cultivated crops of any region in the U.S. (Asseng, 2013),with much of this variety in agricultural productivity attributable to the unique geographic and climatic subregions that compose the SEUS (Knox et al., 2014). In the coastal plain of Georgia and the Carolinas, the sandy soil and long growing season allow for peanuts and sweet potatoes to flourish, with Georgia and North Carolina being the top producing states for these crops respectively (USDA, 2018). Along with these regional crops, the SEUS is also a large contributor to the national yield of maize, soybeans, and other major crops.

Annual fluctuations in agricultural production and loss are highly influenced by year-to-year variability in the local climate (Wolfe et al., 2018; Hansen et al., 1997). Agriculture in the southeast is highly vulnerable to extreme heat, with many crops in the region already being grown near their thermal limits (Hatfield et al., 2011). One prominent example is soybeans, which has an ideal daytime temperature of ~290C and can experience pollen sterility and reduced seed sets during periods of heat stress (Annan & Schlenker, 2015). The impacts of heat can be intensified when coupled with drought conditions. Such was the case during the southeast drought of 1993, when South Carolina lost 25% of their tobacco crop, 70% of their soybean crop, and 95% of their corn crop as a result of record heat and extended periods without precipitation (Lott, 1993). Although irrigation techniques may offset some of the impacts of heat stress and drought, the SEUS is more susceptible to these impacts than the western U.S. and Midwestern U.S. as the soils in the region have a lower water-holding capacity (McNider et al., 2011).

Frequently considered an afterthought as an agricultural deterrent, excess precipitation ranks among the top two causes of crop loss for nearly every agricultural region in the U.S. and is the primary contributor to loss in the SEUS (Reyes & Elias, 2019). In fact, even crops typically associated with resilience to excess moisture, such as maize, have been found to suffer losses of comparable magnitude to periods of extreme drought (Li et al., 2019). In the SEUS, many extreme precipitation events are associated with tropical cyclone activity from the Atlantic Basin (Knight & Davis, 2013; Konrad et al., 2002). The timing and duration of these extreme precipitation events has a considerable influence on the overall agricultural impact. For example, Hurricane Hugo, despite being a Category 4 storm at landfall, had relatively minimal impacts on South Carolina agriculture as it made landfall in late September after much of the state’s crop had been harvested (Janiskee, 1990).

Despite significant advancements in linking climate extremes to agricultural production at national and state levels, there remain significant gaps in understanding the relationships between climatic extremes and crop yields at finer spatial and temporal scales (Zipper et al., 2017; Lobell & Asner, 2003). Namely, research concerning the relationships between agriculture and meteorological hazards have historically focused on the major global crops of wheat, rice, corn, and soybeans (Asseng et al., 2013; Lobell et al., 2011; Adams et al., 1998). As a result, there is a limited understanding of the impact regarding more regional and specialty crops. Secondly, nationwide studies on the climate-crop connection focus considerable attention on the agricultural belt of the Midwest (Li et al., 2019; Lobell et al., 2014). Although important, this hyper focus has led to a considerable knowledge gap in other agricultural regions, many of which are comprised of smaller farms and are more vulnerable to large-scale hazards. Lastly, studies to date have used seasonal anomalies to identify threats to crop productivity across the U.S., but high resolution spatiotemporal analysis could further enhance our understanding of when and where crops are most vulnerable to climatic extremes.

In this study, we seek to address these prominent knowledge gaps by assessing the impact of seasonal and monthly climate anomalies on annual crop yield for regional (cotton, peanuts, sweet potatoes) and major (corn, soybeans) crops in the SEUS. By creating county-level thresholds of extreme precipitation and temperature for each month of the growing season, we are able to better identify what stage of the crop production process is most vulnerable to the known meteorological hazards of extreme heat and precipitation. Our findings provide a deeper spatiotemporal understanding of the inherent relationships between the local climate and crop productivity in the region. More importantly, our findings provide tangible results for local farmers, who face severe challenges in preparing for and adapting to climate extremes in the era of anthropogenic climate change.

**Data & Methods**

**Crop Yield Data**

County-level records of crop yields, which are measured in units of weight harvested per acre planted, were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Quick Stats survey database for corn (grain), upland cotton, peanuts, soybeans, and sweet potatoes from 1981 through 2017 for the three-state (Georgia, North Carolina, South Carolina) region (USDA NASS, <https://quickstats.nass.usda.gov/>). NASS agricultural statistics are collected through annual surveys carried out by the USDA, including area-frame survey, stratified, sampling farm surveys, and farmer interviews (NASS, 1999; O’Neal et al., 2005; Peng et al., 2018; Li et al., 2019).

We restricted our analysis to counties which had at least thirty years of crop yield data between 1981 and 2017, which was determined separately for each crop (Figure 1). Each crop is represented by at least one county in every state, except for sweet potatoes, which is confined to the state of North Carolina. Spatially, the eastern counties of Georgia and the Carolinas provide the greatest amount of data for analysis in this study and are historically known for being part of the southeastern agricultural belt. Although some foothill and mountain counties meet the 30-year threshold for analysis, much of the region’s crop productivity is confined to low-lying and coastal reaches of the study area.

**Detrending Crop Yield**

County-level linear trend analysis revealed significant increases in yield for each of the crops across the entire study area. These trends can primarily be linked to improvements in technology, management, and other modern agricultural practices. In order to more accurately associate climatic extremes to changes in crop yield, a new variable was created that compared the annual observed crop harvest to the expected yield as quantified by the linear trend. Using methods applied by Li et al. (2019), the difference between the observed and expected yield (YieldDiff), divided by the trend yield (YieldTrend) provides a new metric known as the yield percentage change (YieldChange). Yield percent change represents the departure of the observed yield from the long-term trend and better reflects the impacts of interannual variability in the local climate. Yield percent change was then tabulated for every county in the study area by individual crops.

(1)Where Y­c is the percent yield change, Yd is the yield difference, and Yt is the yield trend.

**Climate Data**

Daily data for precipitation and maximum temperature were downloaded for each year from 1981 through 2017 from the PRISM Climate Group. The PRISM model outputs a national 4km gridded raster of climatic variables including total precipitation, maximum temperature, and minimum temperature for each day. PRISM data for years prior to 1981 are considered less reliable since they were created using significantly fewer in-situ observations (PRISM Climate Group, 2019; Daly et al., 2008) and were thus not considered in this study. PRISM data were then subset into the traditional growing season of the southeast, which we define as May 1 to October 31.

Using R statistical software, we overlaid counties onto the 4km gridded climate data and extracted the spatial means to return daily average precipitation and average maximum temperature for each county (Figure 1). For each county that met both the climate and crop yield data thresholds, we calculated the mean and standard deviation of maximum temperature and precipitation by month and the growing season, enabling us to analyze crop yield variability across distinct categorizations of climatic anomalies. For the purposes of this study, climate categories for precipitation and temperature were simplified to represent near normal (-0.5 σ – 0.5σ), below normal (< -0.5σ), or above normal (>0.5 σ) conditions by month and across the entire growing season. By outlining monthly and seasonal climate anomalies, we are better able to pinpoint what combination of temperature and precipitation patterns are most harmful to crops in the SEUS and identify what time period within the crop development process is most vulnerable to these extremes.

The creation of county-level norms and anomalies reveals the climatic diversity seen in the SEUS (Figure 2). Average growing season maximum temperatures range from 31.7ºC in southern Georgia to 21.5ºC in the southern Appalachian Mountains of western North Carolina. Much of the variance in average growing season temperature in the SEUS is related to latitudinal and topographic differences. Precipitation norms are also varied within the southeast, with counties along the coast of North and South Carolina averaging upwards of 937mm of precipitation across the growing season. Average precipitation generally decreases as one moves further inland with the exception of the southern Appalachian Mountains, where orographic lifting enhances the amount of rainfall seen over a given year. It is important to note that precipitation anomalies are especially variable for the coastal reaches of the study area as tropical cyclone activity (or inactivity) play an important role in annual precipitation totals.

**Statistical Analysis**

For each crop, separate analyses were performed by state and county to determine the effect of climatic variability on yield for each month of the growing season for the entire study period (1981-2017). Pearson and spearman’s rank correlation coefficients (p < 0.05) were used to quantify the relationship between detrended crop yield for temperature and precipitation anomalies at both the monthly and seasonal (May-Oct) timescale. Differences in detrended yield were tested by crop and climate anomaly categorization (Below Normal, Near Normal, Above Normal) using the non-parametric Kruskal-Wallis method. When finding significant (p < 0.05) differences between the three categorizations, the Mann-Whitney U test was used to assess whether above or below normal climate anomalies were more detrimental (negative detrended yield) to crop productivity. Lastly, comparisons were made between climate anomaly couplings. For example, within the “Above Normal Maximum Temperature” categorization, we test for significant differences of detrended crop yield when also associated with below, near, or above normal precipitation.

**Results & Discussion**

**Extreme Heat is Particularly Harmful to Southeastern Crops**

Above normal maximum temperatures over the course of the growing season are detrimental to agriculture in the SEUS, especially for surface crops corn, cotton, and soybeans (surface crops). The negative association between maximum temperatures and crop yield becomes stronger moving north through the study area, with counties in the Midlands of South Carolina seeing the greatest differentiation from expected yield during years of warmer than normal temperatures. In fact, South Carolina counties average a 12.5% decline from expected cotton yield during years in which maximum temperatures are categorized as above normal and suffers similar declines for corn (-24.7%) and soybeans (-14.4%) for growing seasons with above normal temperatures. Interestingly, counties located directly along the coast have much weaker and, in some cases, positive relationships with maximum temperature for these surface crops. Sweet potatoes and peanuts (Subsurface crops) exhibit little to no significant relationship with maximum temperature anomalies over the course of the growing season.

Analyzing crop yield and temperature relationships at a finer temporal scale reveals marked spatial variations in the association between monthly maximum temperature anomalies and crop yields (Table 1). Overall, the strength of the negative relationship between monthly temperature anomalies and yield is greatest for the months of July, August, and September. This finding is logical as normal maximum temperatures for some counties in the SEUS match or exceed the ideal conditions for corn and soybeans. Even in more heat-adapted crops, such as peanuts, above normal maximum temperatures from July to September produce significantly lower yields. Cotton yields have distinct temporal and geographic relationships with monthly temperature anomalies. In Georgia, above normal temperatures from May to August produce significantly lower yields. However, in the Carolinas, above normal temperatures in May produce significantly higher yields than expected and experience a significant negative association from June to September. This finding likely hints at differences in planting time and thus different timing in peak vulnerability to heat for the crop across the study area. Sweet potatoes however, experience no significant negative effects as a result of extreme heat. Rather, warmer than normal temperatures in both May and June signal significant increases in expected yield for the crop in North Carolina.

**Influence of Precipitation Varies by Crop**

Although drought may be more commonly associated with crop loss in the U.S., in the SEUS both an excess and lack of moisture can be harmful to agriculture. County-level relationships between growing season precipitation and yield is heavily dependent on crop type and local geography. Notably, corn and soybeans thrive in wetter conditions as they share a significant positive relationship with growing season precipitation anomalies for much of the study area. The exception being the coastal counties of North Carolina which exhibit a significant negative relationship between precipitation and yields. Although the association is relatively weaker than with the other surface crops, cotton yields in the southeast favor excess moisture except for coastal counties in the Carolinas. Similar to temperature, the relationships between precipitation and yield differ considerably between surface and subsurface crops. In particular, the negative relationship between precipitation and sweet potato yield suggests that excess moisture is more damaging to the crop than drought conditions. This is especially the case in eastern North Carolina, where sweet potato yields average 5.7% less than expected during wet growing seasons. Lastly, although relationships were found to be statistically insignificant for peanuts, there is a distinct spatial pattern to the association (positive in Georgia and negative in eastern North Carolina).

Parsing the analysis down into a monthly timescale reveals distinct temporal patterns in the relationship between precipitation and crop yield in the SEUS (Table 2). For corn and cotton, above normal precipitation in May and June favor increased yields for the study area. This association begins to break down in August and shifts completely during September and October. During these latter months, higher than normal precipitation produces much lower than expected yields, especially for coastal reaches of North and South Carolina. Soybean yields exhibit a similar temporal pattern, however, the relationship with higher than normal precipitation does not become evident until October and is highly concentrated in the Carolinas. Monthly precipitation relationships with peanuts and sweet potatoes are much weaker than surface crops until September and October, when both crops experience significant declines in response to above normal precipitation.

**Importance of Recognizing Temperature-Precipitation Relationship**

Results from the Kruskal-Wallis test reveal distinct differences among the most and least ideal conditions for individual crops in the region. As expected, corn and soybeans flourish in years when growing season average maximum temperatures are below normal and precipitation is above normal. Conversely, these crops experience their greatest negative deviations from expected yield when above normal temperatures and below normal precipitation are recorded. Cotton farmers in the southeast enjoy greater than normal yields during near or below normal temperature growing seasons, no matter the amount of precipitation. Cotton can also be successful with above normal temperatures but begins to suffer losses when associated with excess precipitation. Peanuts are most sensitive and experience the greatest deviation from expected yield when higher than normal temperatures are paired with above normal precipitation. As expected, sweet potatoes suffer significant declines as a result of increased precipitation, no matter the associated temperature anomaly.

**Timing of Extremes**

Deviations from expected yield as a result of climatic extremes can be directly linked to the timing of meteorological events and the development of individual crops within their main phenological stages (e.g. emerging, silking, mature). During each of these stages, crops face a variety of different sensitivities to the local environment. For example, corn has been found to be most vulnerable to drought conditions during early development as the lack of moisture leads to a lack of pollination and dries out the crop grains (Wu et al., 2004). Our results highlight similar meteorological timing-yield relationships, but also reveal the spatial complexities of agriculture in the SEUS. For example, corn is generally planted in early May across Georgia and the Carolinas and thus suffers the greatest negative deviation from expected yield when temperatures are much above normal in the month of July when the crop is beginning to silk. In contrast, cotton shares a unique spatiotemporal relationship with maximum temperature in the study area. For Georgia, above normal temperatures are detrimental throughout most of the growing season. However, because the Carolinas have a later average planting date for cotton, there is a positive relationship in the month of May. This is likely as a result of farmers being able to plant earlier and taking advantage of a longer than average growing season for the crop. There is also a delay to the negative effects of maximum temperatures with July (-0.31) and August (-0.46) ranking worst for Georgia and the Carolinas respectively.

Despite being a critical ingredient to crop success, an excess amount of precipitation during the latter portion of the growing season can result in significant negative deviations from expected crop yield. Although more resilient to drought conditions in the mature stage of development, excess moisture in September and October makes harvesting particularly difficult for farmers. As a result of a delayed harvest, some crops begin to deteriorate in quality and in some cases become unsalvageable as the product begins to rot in the field. Such was the case in North Carolina following Hurricane Florence in September 2018. The record rainfall associated with the storm resulted in flooded fields and made harvesting impossible for weeks. Root crops, such as sweet potatoes, suffered the greatest losses with a 37% decline in yield from 2017 and the lowest average yield statewide since 2002. As mentioned previously, differences in planting and harvest time in Georgia and the Carolinas results in varied monthly responses. This is most evident in the cotton crop, with excess moisture in September resulting in significant declines in yield for Georgia, whereas heavier precipitation in October leads to higher losses of the Carolinas.

**Tropical Cyclones**

Compared to other agricultural regions of the US, the southeast faces a significant threat from tropical cyclones on an annual basis. However, geographic differences in coastline and proximity to areas favored for tropical cyclone development means that there are significant differences in the average expected impact of tropical cyclones. This is particularly evident in our study area, as the Outer Banks of North Carolina average a tropical cyclone impact once every 2 years, whereas return periods in Georgia are as low as one cyclone every ten years, which is more aligned with New England than it is the SEUS (Keim et al., 2007). These distinct differences in tropical cyclone frequency are evident within our findings as North Carolina crops experience far more frequent negative deviations from expected yield in all crops when associated with excessive moisture when compared to Georgia.

**Limitations and Future Work**

Within this work, it is important to recognize the limitations in both data and analysis. Namely, there are inconsistencies within the crop yield data collected from the USDA which limits the ability to analyze a broader scope of counties. Secondly, data collected by the USDA is primarily harvested from larger farms, which means that many smaller operations that have less capacity to respond to heat, drought, or excess moisture may not be adequately captured. Similarly, for some counties in the SEUS, there are large temporal gaps within the data. This made a regional analysis of sweet potatoes particularly difficult and investigation into impacts in climatically diverse areas, such as the southern Appalachian Mountains, impossible.

Future climate-agricultural work in the southeast must consider the uncertainties regarding future change in the region. Recognized as a “warming hole,” the SEUS experienced a slight cooling trend in the second half of the twentieth century (Ellenburg et al., 2016; Meehl et al., 2015). Much debate surrounds the possible attributable factors that have caused this anomalous regional phenomenon with explanations ranging from increased aerosols and clouds (Weber et al., 2007) to internal variability in sea surface temperatures and atmospheric circulation patterns (Kumar & Wang, 2015; Kunkel et al., 2006). However, recent studies suggest a reversal in the regional warming trend beginning in the 1970s (Meehl et al., 2015; Kunkel et al., 2013). Similar uncertainties remain regarding trends in southeastern precipitation (Knox et al., 2014). Research suggests that the southeast has experienced distinct seasonal trends in overall precipitation and an increase in the frequency of extreme precipitation days with events becoming more intense, albeit with shorter durations (Powell & Keim, 2015; Groisman et al, 2001). *Mention here how our findings suggest that with future warming and an end to the “warming hole” will mean even more damage for crops in the southeast going forward…...*

**Conclusion**

Understanding responses of major and regional crop yields to climate variability is crucial to addressing the future needs of farmers and the agricultural industry at a finer spatial scale. Our study helps further this effort by assessing the relationship between temperature and precipitation anomalies over the growing season for a variety of regional (cotton, peanuts, sweet potatoes) and major (corn, soybeans) crops at a county-scale in the SEUS. Our findings help reaffirm the associations between excess heat and precipitation extremes within the growing season but also illustrate the substantial spatiotemporal variability in the magnitude of these effects. Notably, our results highlight that excess moisture associated with higher than normal temperatures in the growing season can be equally detrimental to crop success in the SEUS as seasons associated with drought-like conditions. The timing of meteorological and climatic “shocks” to the agricultural industry are critical to furthering the understanding of the inherent relationship shared between crop yields and interannual climate variability. Moving forward, research would benefit from considering these climatological complexities, especially when analyzing agriculture at a finer spatial scale.

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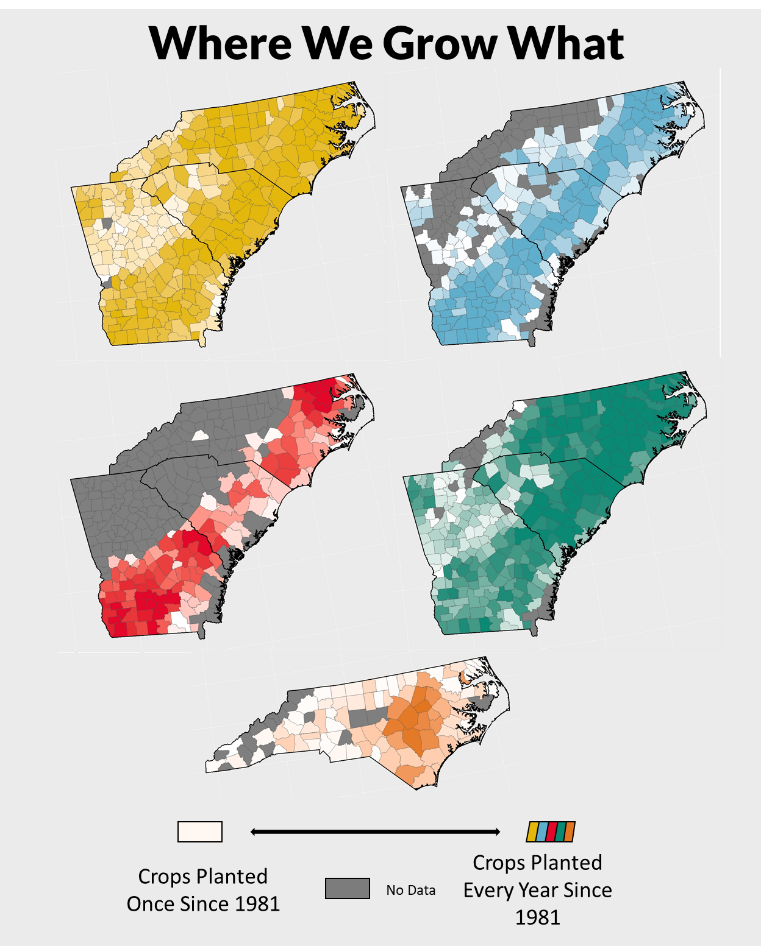
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*Figure 1*: Years of county-level crop yield data. Crops were analyzed for climatic relationships only when meeting the 30-years’ worth of data threshold.



**Corn**

**Cotton**

**Peanuts**

**Soybeans**

**Sweet Potatoes**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Georgia | |  |  |  | | S. Carolina | |  |
| Month | Corn | Cotton | Peanuts | Soybeans |  | | Corn | Cotton | Peanuts | Soybeans |
| May | **-0.14** | **-0.11** | **-0.05** | **-0.09** |  | | **-0.15** | **0.09** | 0.16 | 0.04 |
| June | **-0.27** | **-0.15** | 0.02 | **-0.22** |  | | **-0.51** | -0.01 | 0.03 | **-0.14** |
| July | **-0.41** | **-0.31** | **-0.30** | **-0.41** |  | | **-0.54** | **-0.37** | **-0.36** | **-0.28** |
| August | **-0.26** | **-0.28** | **-0.37** | **-0.42** |  | | **-0.34** | **-0.47** | **-0.43** | **-0.43** |
| September | **-0.21** | -0.03 | **-0.25** | **-0.43** |  | | **-0.25** | **-0.11** | **-0.35** | **-0.44** |
| October | 0.05 | 0.01 | **0.16** | **-0.13** |  | | 0.00 | 0.08 | 0.13 | **-0.17** |
|  |  |  |  |  |  | |  |  |  |  |
|  |  |  |  | N. Carolina | | | |  |  |  |
|  |  | Month | Corn | Cotton | Peanuts | | Soybeans | Sweet Potatoes |  |  |
|  |  | May | -0.03 | **0.18** | **0.11** | | **0.06** | **0.18** |  |  |
|  |  | June | **-0.34** | 0.00 | **0.12** | | **-0.11** | **0.23** |  |  |
|  |  | July | **-0.51** | **-0.26** | **-0.15** | | **-0.28** | 0.05 |  |  |
|  |  | August | **-0.36** | **-0.45** | **-0.42** | | **-0.53** | -0.13 |  |  |
|  |  | September | **-0.36** | **-0.10** | **-0.21** | | **-0.45** | -0.06 |  |  |
|  |  | October | 0.03 | 0.08 | -0.01 | | **-0.16** | 0.13 |  |  |

Table - Relationship between monthly temperature anomalies and crop yield by state

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | | Georgia | | | |  | | |  |  | | S. Carolina | | | |  |
| Month | Corn | Cotton | | Peanuts | | Soybeans | | |  | | | Corn | | Cotton | Peanuts | | Soybeans |
| May | **0.22** | **0.26** | | **0.18** | | **0.13** | |  | | | | **0.18** | | **0.25** | -0.03 | | **0.13** |
| June | **0.29** | 0.02 | | **0.06** | | **0.23** | |  | | | | **0.55** | | 0.06 | -0.11 | | **0.20** |
| July | **0.29** | **0.22** | | **0.18** | | **0.29** | |  | | | | **0.42** | | **0.42** | **0.24** | | **0.23** |
| August | **0.08** | **0.17** | | **0.21** | | **0.28** | |  | | | | -0.03 | | 0.02 | 0.09 | | **0.22** |
| September | **-0.15** | **-0.33** | | **-0.15** | | -0.02 | |  | | | | **-0.14** | | **-0.14** | -0.01 | | **0.13** |
| October | **-0.11** | 0.01 | | **-0.23** | | **-0.06** | |  | | | | **-0.10** | | **-0.24** | -0.08 | | -0.04 |
|  |  | |  | |  | |  | | |  |  | |  | | |  |  |
|  |  | |  | |  | | N. Carolina | | | | | |  | | |  |  |
|  |  | | Month | | Corn | | Cotton | | | Peanuts | Soybeans | | Sweet Potatoes | | |  |  |
|  |  | | May | | **0.15** | | **0.14** | | | **0.14** | **0.14** | | 0.04 | | |  |  |
|  |  | | June | | **0.48** | | -0.04 | | | **-0.12** | **0.11** | | -0.12 | | |  |  |
|  |  | | July | | **0.37** | | **0.23** | | | **0.17** | **0.29** | | -0.06 | | |  |  |
|  |  | | August | | 0.03 | | **0.12** | | | **0.25** | **0.28** | | 0.03 | | |  |  |
|  |  | | September | | **-0.06** | | **-0.26** | | | **-0.24** | **0.07** | | **-0.24** | | |  |  |
|  |  | | October | | **-0.08** | | **-0.34** | | | **-0.32** | **-0.28** | | **-0.29** | | |  |  |

Table 2- Relationship between monthly precipitation anomalies and crop yield by state.

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Figure . Example of the spatial mean technique used to identify count-wide averages of maximum temperature and total daily precipitation. (A) showcases the raw PRISM data and (B) illustrates the newly created county-mean of total precipitation on May 31, 2018.



Figure 2. Growing season average of maximum temperature and precipitation by county in the SEUS study region.

