EC3025

Patterns and Magnitudes of Spatial and Temporal Changes in Precipitation and Aridity across 800 Great Plains Counties

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This extension circular provides information about the changes that have occurred in annual, growing season, and monthly precipitation and aridity in both space and time across the United States Great Plains region from 1968 to 2013. The data is based on the extensive and large scale studies conducted by Kukal and Irmak (2016a and b).

Precipitation refers collectively to rainfall, snowfall, and other forms of frozen or liquid water falling from clouds. Also, in this study we used the aridity index to represent aridity (or desertification) of a particular location, which is a quantitative indication of the degree of water vapor deficiency to meet the evaporation demand at that location. Specifically, we used the aridity index (AI) recommended by the Food and Agriculture Organization, which is expressed as the ratio of annual precipitation to annual potential (grass-reference) evapotranspiration.

Implications of a changing climate usually include changes in precipitation amounts, intensity, and frequency. A range of climate models has predicted that the increase in atmospheric greenhouse gases will lead to shifting of precipitation in a way that strengthens the existing precipitation patterns, i.e., the wet get wetter, and the dry get drier. There is a direct influence of temperature changes (warming/ cooling) on precipitation as this causes corresponding changes in evaporation and water-holding capacity of the atmosphere, and eventually the water cycle. Since the observations of surface warming/cooling are variable over space, the trends observed in precipitation, too, are anticipated to be spatially variable.

Precipitation is characterized by both natural inter-annual variation and decadal variations and human activity induced trends. Any of these changes can cause huge impacts on the environment and society, including both irrigated and rainfed agricultural production, hydrological functions in several ecosystems and wildlife and natural habitats in wetlands, riparian areas, etc. Other effects include water storage fluctuations in reservoirs, ponds, lakes, and other water bodies, and fluctuations in the water table for irrigation, municipal, recreation, and other uses. In this extension circular, all the analyses and discussions are presented in the context of agricultural implications of precipitation changes.

Variability in precipitation during the agricultural growing season can substantially affect soil water status and availability and hence impact crop productivity. This is true for precipitation change in either direction, i.e., positive or negative. Drought conditions can impose stress on freshwater resources in agricultural regions. An ideal example is the 2012 drought in the U.S. Central Plains. This drought exhibited the highest precipitation deficits since at least 1895. It surpassed even the dust bowl summers of 1934 and 1936 (Hoerling et al., 2014) and covered two-thirds of the continental United States. Economically, the 2012 drought was an agricultural disaster that caused $40 billion in agricultural losses (National Center for Environmental Information). Grain yields suffered substantial losses, which amounted to 4 billion bushels of corn, 170 million bushels of soybean, and 87 million bushels of sorghum, with more than one-quarter of the normal corn and sorghum crop lost to drought (Rippey, 2015). These losses were due to soil moisture not being able to keep up with high evapotranspiration rates under scarce precipitation. In irrigated production systems, these losses would be replaced by higher operational costs for greater pumping needed to maintain optimum levels of soil moisture.

Similarly, excess precipitation can be substantially damaging to agricultural production such as the 1993 U.S. Midwest floods, the North Dakota Red River floods of 1997, and the Mississippi floods of 2001. The damages caused by these floods to farmers were estimated at $6–8 billion, which was roughly 50 percent of the total damages from the floods (FEMA, 1995). Excess moisture is the key component of crop losses due to extreme precipitation events. Anoxic conditions (absence of oxygen) in extremely wet soils can directly damage crops both aboveground and below ground (Kozdroj and van Elsas, 2000). Other impacts can include increased risks of plant disease and insect infestation (Ashraf and Habib-ur-Rehman, 1999), delayed planting or harvesting due to inability to operate machinery, greater runoff, deep percolation and chemical leaching to groundwater, soil erosion, and other negative environmental impacts. Crop insurance data indicates that excess soil moisture has cost Iowa farmers five times more than direct flood damage from 1982–2002 (Rain and Hail Insurance Service, historic database). Hence, it is clear that the impacts of both positive and negative changes in precipitation can translate into substantial economic losses in agricultural production.

In addition to precipitation, it is also crucial to understand the relationship of agricultural productivity to atmospheric water demand. Reference evapotranspiration, which indicates atmospheric water demand, is often studied along with precipitation to represent aridity. Many farmers have conversations that include statements such as "Last year was so dry I thought we'd lose our crops, but the temperatures were not so bad, and it turned out great." This interaction of precipitation and temperature/atmospheric demand such as the weather being "dry and hot" or "cool and moist" is addressed by the aridity index (AI). The aridity index, which is the ratio of precipitation to reference evapotranspiration over a particular period, is expected to vary across the region as well as with time because of the changes in its driving factors. AI isn't expressed as units because both P and ET_o have units of inches. Studying these interactions (AI) across space and time can be crucial for interpreting large-scale and long-term dynamics of water supply and demand and their potential implications.

Moreover, seasonal variability exists in these spatial and temporal trends. Hence, it is beneficial to address these trends for different time scales, such as the annual, growing season, and monthly basis. Even though it changes with geographic location and from year to year and with cropping systems, in this publication, the growing season is considered as May 1 to September 30, which is a common period to represent the crop growing season throughout the region.

To conduct all of the above-mentioned analyses, precipitation and reference evapotranspiration data (derived from temperature data) from over 800 weather stations during a 46-year period (1968–2013) were used to represent 834 counties in nine states in the U.S. Great Plains region. Since the data involved in these analyses and their results are both extensive and arduous, the results are best represented using visual maps. Maps allow the reader to better observe the changes (trends) in a spatio-temporal manner and increase the comprehensibility of the research. Each variable and its associated trends, both in space and time, are shown via maps for the annual, growing season, and monthly temporal scales. This refereed extension circular can be a valuable resource for audiences involved in and concerned with water resources and agriculture. It can help to better understand change in climate variables (precipitation and aridity) at the location of interest and inter-compare these variables among multiple locations.

Study Region

Detailed study region characteristics are presented in Kukal and Irmak (2016a and b) and only basic information is discussed in this publication. As presented in Kukal and Irmak (2016a and b) and Kukal and Irmak (2017), the Great Plains region *(Figure 1)* refers to what is geographically the Central United States. Its boundaries extend from the Canadian border in the north to Texas in the south, Wyoming and Colorado on the west, and Iowa on the east. Specifically, the area consists of nine states (North Dakota, South Dakota, Nebraska, Iowa, Wyoming, Colorado, Kansas, Oklahoma, and Texas), which together comprise 834 counties.

The total land area enclosed by these states is 890,896 mi^2 (2,307,410 km^2). The area lies between dense forests on the east and mountains and deserts on the west. The common topographical characteristic of the area is the vast, flat-to-rolling plains. The highest elevation throughout the region is in the Rocky Mountains in Colorado, and the lowest elevation is at the southern coastline in Texas. Temperature and precipitation have an evident north-south and east-west gradient, respectively. The long-term (1968–2013) average annual precipitation ranges from 8.5 inches in the west to 57 inches in the southeast. Similarly, long-term (1968–2013) average growing season (May 1 to September 30) precipitation varies from 4.7 inches in the west to 27.5 inches in the southeast. Agricultural land use includes rangelands, prairies, irrigated and rainfed farming of agronomic row crops such as maize, soybean, sorghum, alfalfa, winter wheat, sugar-beets, and cotton.

Spatial Distribution of Annual, Growing Season, and Monthly Precipitation

Long-term (1968–2013) average annual, growing season, and monthly precipitation was calculated from daily weather data and results were analyzed on a spatial basis. Precipitation, irrespective of the period, showed a similar spatial na-

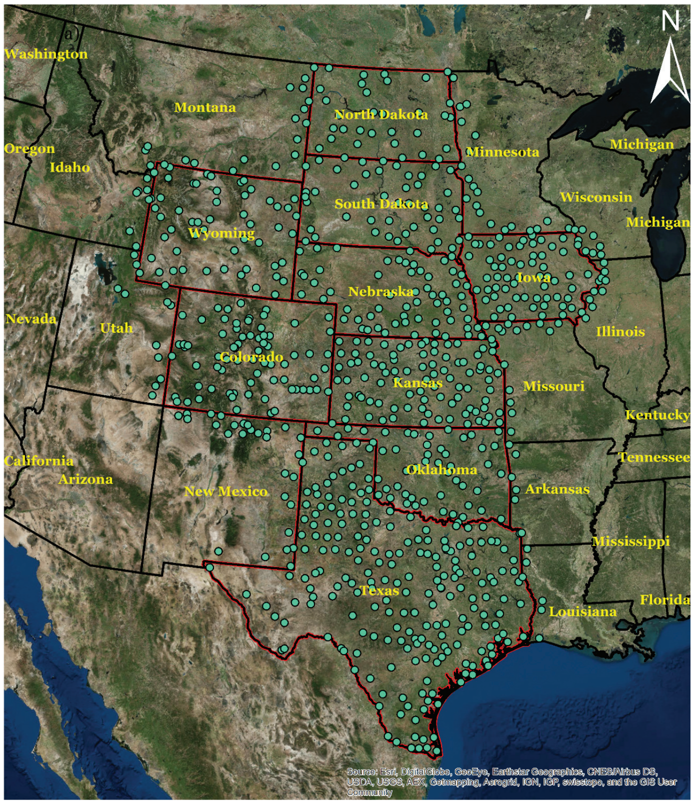

Figure 1. Study region (U.S. Great Plains) and the selected weather station sites used for analyses (Map: Kukal and Irmak, 2016 a, b).

ture where the amount increased gradually from west to east. This strong geographical trend can be seen in *Figures 2* and *3*.

These maps can be instrumental in determining average precipitation amounts in any geographical location in the region. Averaged across all the counties in the region, annual and growing season precipitation amounts were 24.3 and 13.7 inches, respectively. County-specific average precipitation amounts were calculated. These calculations indicated that the average annual precipitation ranged from 8.4 inches for Big Horn County, Wyoming, to 57.4 inches for Orange County, Texas. Similarly, the average growing season precipitation varied from 4.8 inches for Big Horn County, Wyoming, to 27.9 inches for Orange County, Texas.

The site-specific maximum and minimum precipitation amounts observed across the region were slightly different from the county-averaged amounts. The regional extremes in average annual precipitation were 6.4 and 58.5 inches, whereas those for average growing season precipitation were 3.9 and 29.3 inches, respectively.

Averaged by state, the maximum annual precipitation was observed in Oklahoma (35 inches), followed by Iowa (34.4 inches), while the minimum magnitude was observed in Wyoming (12.5 inches). Similarly, the state average maximum growing season precipitation was observed in Iowa (21 inches), whereas the minimum amount was observed in Wyoming (6.9 inches). The precipitation during the growing season months (May-September) contributes 56 percent towards annual precipitation when averaged across the region. This contribution of growing season precipitation is the highest in South Dakota and Nebraska (65 percent each) and least in Texas (49 percent). This is critical information, because at least some portion of the growing season precipitation would be used towards the water requirements of summer crops.

Table 2 shows the statistics, including mean and standard deviation for regional and statewide averaged monthly, annual and growing season precipitation amounts. Standard deviation (SD) is the measure of amount of variation from the average values of precipitation in each period. Higher SD indicates more variation or deviation of the precipitation data point from the average value in a given period, while the low SD indicates that the data points are close to the average value.

The timing (temporal change) of the peak precipitation amount varied significantly with geographic location. The maximum precipitation in Nebraska, Kansas, Wyoming, Oklahoma, and Texas occurred in May. In North Dakota, South Dakota, and Iowa, the peak precipitation occurred in June, while in Colorado, it occurred in July. The minimum precipitation was observed in January, both regionally and statewide. The minimum SD in both annual and growing season precipitation was observed in Colorado and Wyoming, whereas the highest SD was observed in Iowa, indicating that, generally, the precipitation is more variable in Iowa than other states. This also indicates a higher degree of spatial variability in precipitation in the eastern states compared with the western states in the Great Plains.

Temporal Changes in Annual, Growing Season, and Monthly Precipitation

Temporal trends in annual and growing-season precipitation amounts during the period 1968–2013 across the Great Plains region were calculated and their trends (whether increasing or decreasing) and statistical significance (whether a trend is large enough to be qualified as a trend by statistical definition) were investigated. These characteristics of temporal trends are reported in maps *(Figure 4* and *5)*. In these maps, the blue upright arrows represent increasing (positive) trends, while the red inverted arrows indicate decreasing (negative) trends. Counties with a green background indicate that the trend for the county is statistically significant at $\alpha = 0.05$, which distinguishes them from the counties with insignificant trends (counties assigned with a white background). Nevertheless, non-significant trends can still be crucial, because they have potential implications for agricultural crop production by affecting yields, irrigation requirements and timing, risk of diseases, pests, etc.

For annual precipitation, 61 percent of the counties in

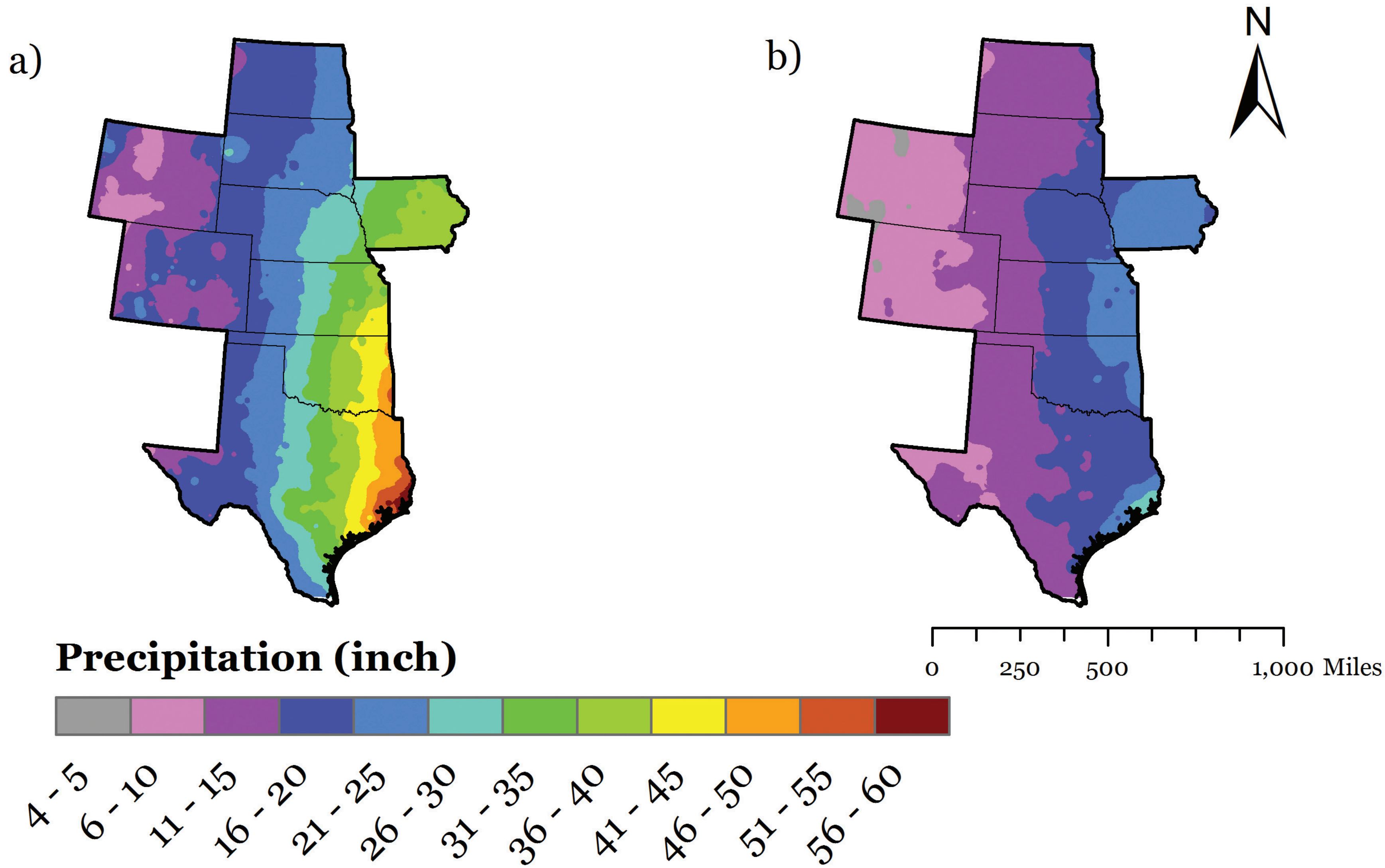

Figure 2. Spatial trends in a) annual and b) growing season precipitation across the U.S. Great Plains.

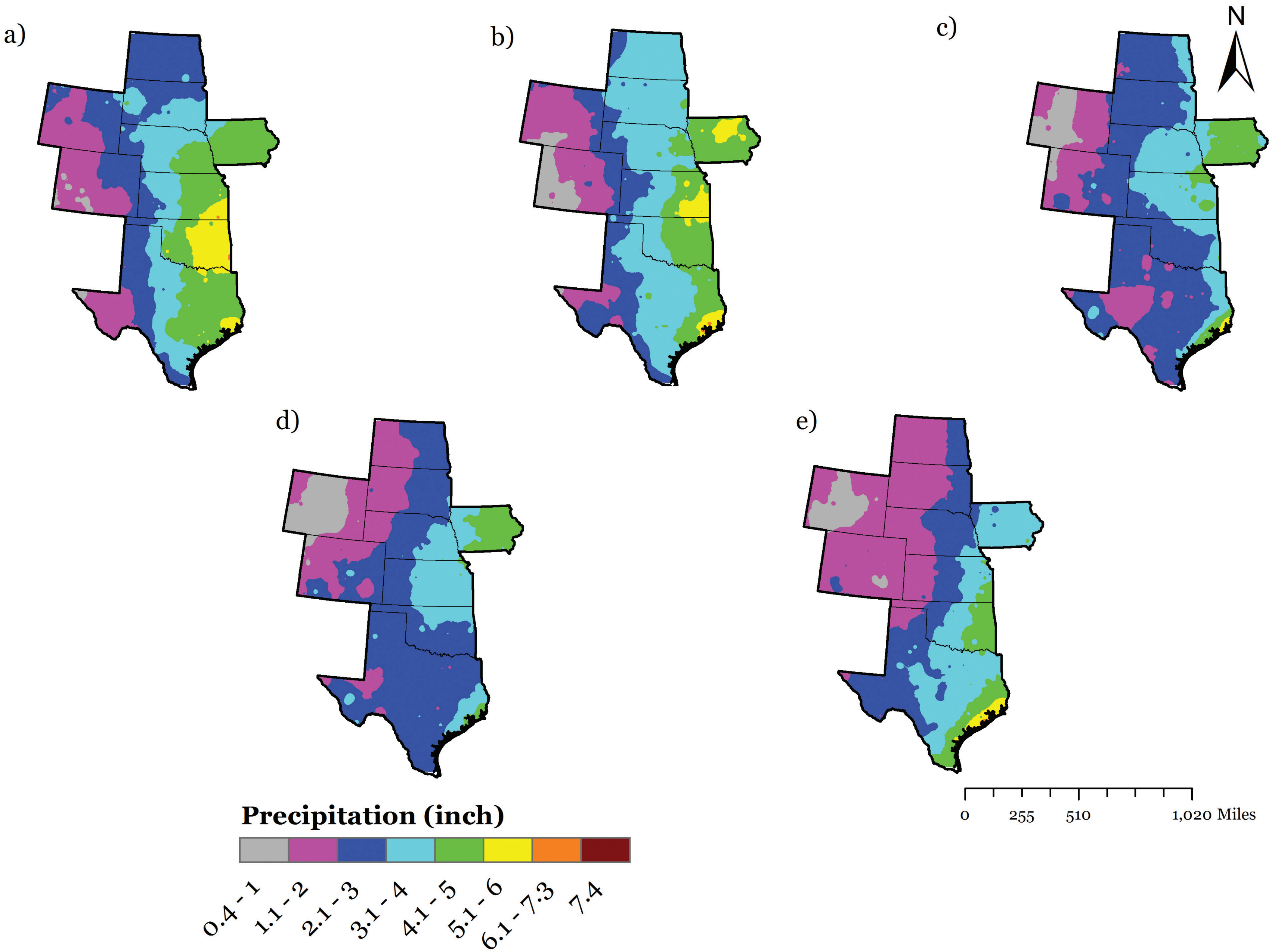

Figure 3. Spatial trends in growing season precipitation during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

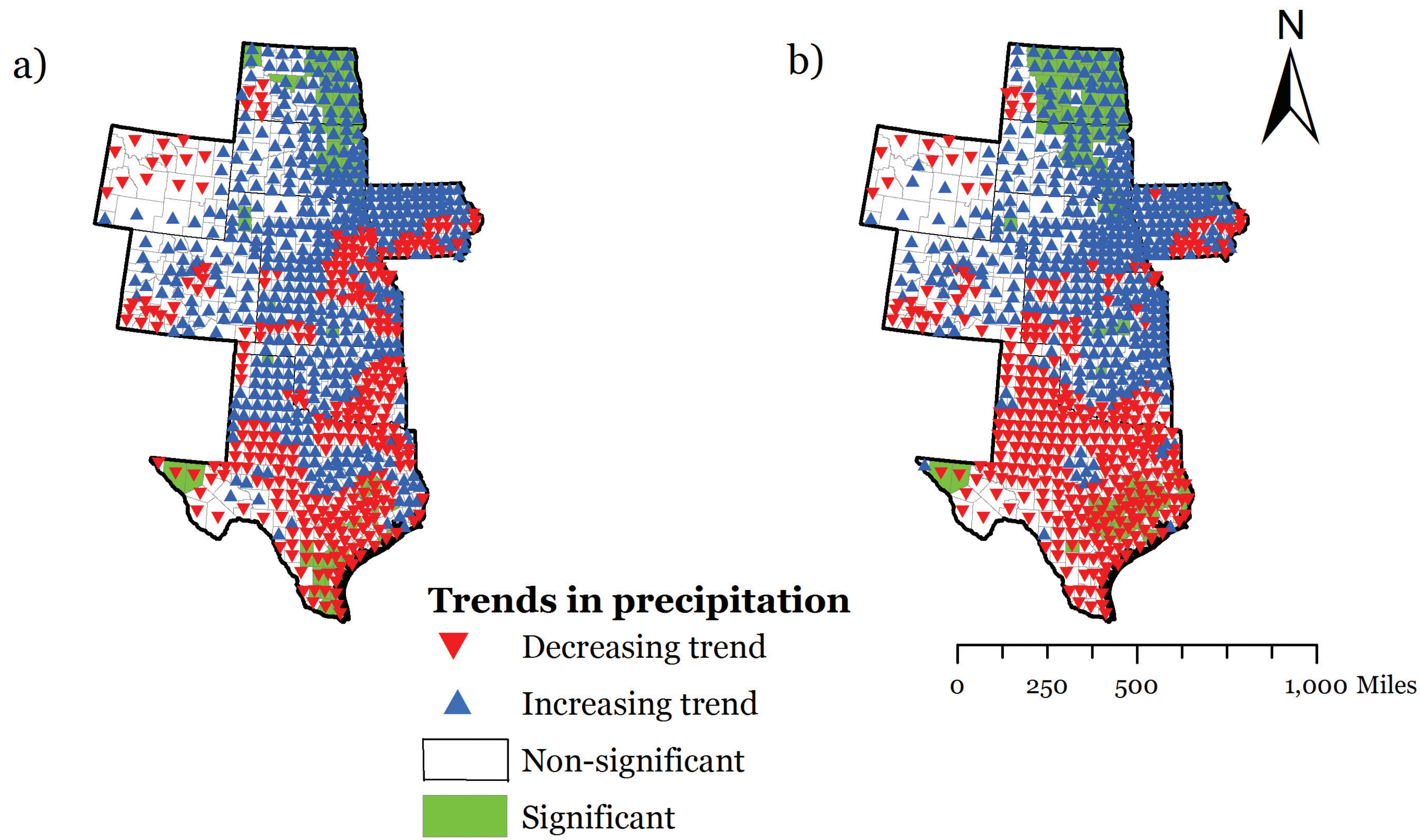

Figure 4. Temporal trends in a) annual and b) growing season precipitation across the U.S. Great Plains.

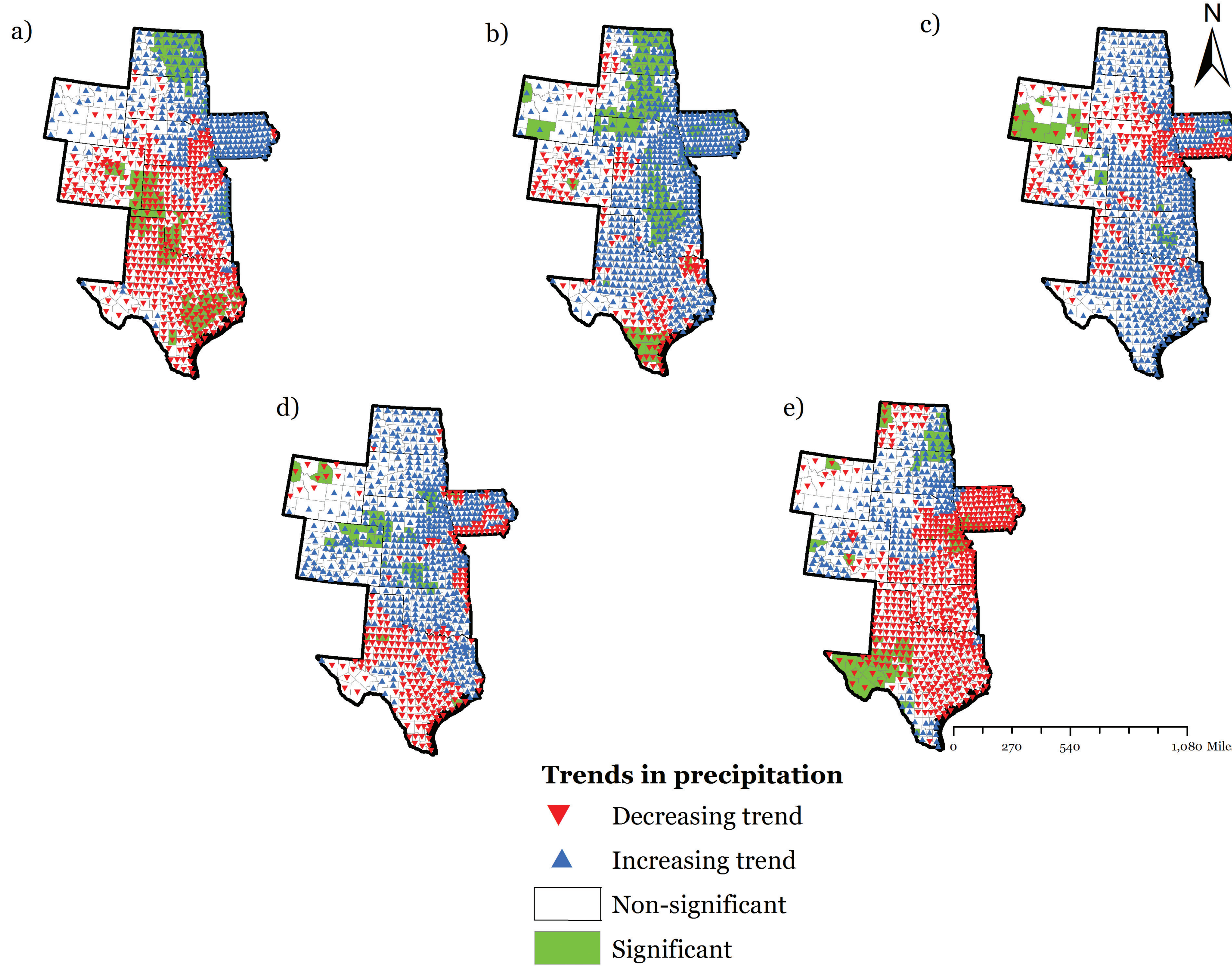

Figure 5. Temporal trends in precipitation during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

the region showed increasing trends and the rest (39 percent) showed decreasing trends. As shown in *Figure 4a*, all of the counties in North Dakota and South Dakota showed positive trends. In Nebraska, except for the east central and southeast regions, which showed negative trends, all other counties showed positive trends. Similarly, in Iowa, the majority of counties showed positive trends, although some counties in the southwest, south central, southeast, central and east central regions showed negative trends.

In Kansas, the north central, west central, central and south central regions showed positive trends, while the rest of the state showed negative trends. In Wyoming, the counties along the border of South Dakota, Nebraska, and Colorado showed positive trends, and the rest of the state was dominated by negative trends. Southwest and central Colorado have some counties that show negative trends, with the remainder of the state showing positive trends. Eastern Oklahoma showed negative trends, while western Oklahoma showed positive trends. Decreasing trends were found for counties in southern Texas, while northern Texas mostly showed positive trends.

Of the increasing trends, the ones in the western counties of North Dakota and South Dakota were statistically significant. Similarly, the western and southern counties in Texas showed statistically significant decreasing trends. On a regional average basis, the magnitudes of the annual increasing and decreasing trends observed in the region were 0.57 inches per decade and 0.53 inches per decade, respectively.

It should be noted that although the magnitudes of regional trends are gentler due to regional averaging, more aggressive magnitudes exist for individual counties with significant positive and negative trends. For instance, Pembina County in North Dakota showed the highest increasing trend in the region at 2.1 inches per decade, while San Patricio County in Texas showed the highest decreasing trend of 2.3 inches per decade. Both of these trends were statistically significant and can have significant implications in water resources, and agricultural practices, as well as in other natural resources functions and services in the respective regions.

The growing-season precipitation trends *(Figure 4b)* were also investigated for both their nature and significance for agricultural practices. About 57 percent of the counties in the region had positive (increasing) trends and almost all the counties in Texas showed negative trends, out of which the counties in the Trans Pecos, south central, and east Texas were significant. Nebraska also had dominant increasing trends in growing-season precipitation. The highest increasing trend in growing season precipitation was observed in Marshall County, South Dakota (1.5 inches per decade), while the highest decreasing trend was observed in Brazoria County, Texas (1.9 inches per decade). However, these magnitudes were considerably lower when increasing and decreasing trends were regionally averaged and were found to be 0.44 inches per decade and 0.46 inches per decade for precipitation increase and decrease, respectively.

Excess and deficit precipitation during different periods can inversely affect various crop production processes, including crop growth and development, irrigation water requirements, evapotranspiration, and their relationships to yield productivity. This implies that in addition to studying growing season precipitation trends, it is equally important to quantify and evaluate monthly trends during the crop season. Trends of monthly precipitation were quantified and are shown in *Figure 5* using maps for growing season months of the year.

There is considerable variability for temporal trends of precipitation in various months of the growing season. For instance, the significant increasing trends in North Dakota counties during May and June became insignificant during July and August, before again being significant during September. Similarly, decreasing trends are observed in western Kansas and Oklahoma and southeast Texas during May, southern Texas during June, and western Texas during September.

Observing the monthly trends, information about the county scale trends in precipitation for any month can be collected and interpreted. As an example, we chose one county (Clay County, Nebraska) from the 834 counties in the region to extract and tabulate all the temporal trends in precipitation during the 1968–2013 period. Detailed information for the observed precipitation trends in this county, Nebraska, is listed in *Table 1*. Trends were positive for February, June, August, and October, while negative trends were found during the rest of the year. However, the only significant decreases in monthly precipitation were in March. The trend in growing-season precipitation was positive, while the annual precipitation was negative. Irmak et al. (2012) calculated trends in annual precipitation and several other climate variables at the Platte River Basin in central Nebraska, and concluded that the annual precipitation increased significantly in the last 116-year period. In accordance, our results for Merrick County, Nebraska (Platte River Basin) show that the annual precipitation increased during the study period at a rate of 0.006 inches per decade.

Spatial Distribution of Annual, Growing Season, and Monthly Aridity

Using monthly summed precipitation and reference evapotranspiration (ET_o) records, the aridity index (AI) was calculated for annual, growing season, and monthly periods during the growing season from 1968 to 2013. The long-term average information about the aridity index is presented in this section. In a very similar way to precipitation, it was observed that the aridity index has a spatial nature as well. Specifically, the aridity index for all periods (annual, growing season, and monthly), increases from west to east as evident from *Figures 6* and *7*. The reasoning behind this spatial nature can be inferred from the spatial trends in both precipitation and reference evapotranspiration. As demonstrated in prior sections, precipitation has a west to east increasing trend.

Also, according to Kukal and Irmak (2016a), reference evapotranspiration has a southwest to northeast decreasing trend. Since aridity index is determined by the relative magnitudes of precipitation (P) and reference evapotranspiration (ET_o), the spatial trend in aridity index is a result of the spatial natures of both these factors. The trend in the aridity index represents the climate becoming more humid or less arid moving east.

According to UNEP (1997), any region can be classified into various aridity classes, depending on AI. These classes are: arid ($0.03 < AI < 0.2$), semi-arid ($0.2 < AI < 0.5$), dry sub-humid ($0.5 < AI < 0.65$), and humid ($AI > 0.65$). For example, a low AI of 0.1 in an arid region indicates that the precipitation in the region is only 10 percent compared with the ET_o. On the other hand, a high AI of 0.9 indicates that P is 90 percent of ET_o, making the region a humid climate.

Figure 8 represents the aridity classes that were delineated for the region based on the annual AI. When averaged across all the counties in the region, average annual and growing season AI was 0.49 and 0.44, respectively, which falls into the semi-arid class. This does not necessarily mean that the entire region is semi-arid, since a high degree of spatial variation was observed in the AI values in the region. For example, the average monthly AI calculated in Iowa was the highest for all months among all the states, as well as for annual and growing season AI. The AI in Iowa ranged from 2.21 in December to 0.74 in July, implying that the state falls into the humid class. The AI was the lowest in Wyoming and Colorado. The annual and growing season AI were 0.27 and 0.22 for Wyoming, while 0.29 and 0.25 for Colorado, respectively, meaning that the region is in the semiarid class. *Table 3* shows the statistics for region wide and statewide average monthly, annual, and growing season AI.

In terms of monthly AI magnitudes, the highest values were observed in December and January and the lowest during June and July. Although the seasonal trends in precipitation and ET_o amounts are similar (highest in summer and lowest in winter), the rates of increase and decrease are different, which results in the magnitude of summer ET_o being much higher than summer precipitation. However, this difference narrows during winter, resulting in higher ratios of monthly precipitation to ET_o, or AI.

The highest magnitudes of SD in annual and growing season AI were observed in Iowa, and the lowest were observed in Colorado and Wyoming. Due to variation in the monthly distribution of the two drivers of the AI (i.e., precipitation and ET_o), it is expected that consequently, considerable variation would occur in monthly AI magnitudes over the region. To visualize this variation, detailed maps depicting monthly AI were developed *(Figure 7)*. These maps indicate that the AI gradually increases towards the east, but magnitudes vary among various months.

By using the annual aridity index values calculated at each of the 800 weather station sites in the region, the map in *Figure 8* was developed to classify the region into four discrete aridity classes. This map is a useful tool to characterize regions with respect to water supply (precipitation) and demand (reference ET). For example, Nebraska consists of three discrete zones based on aridity, namely semi-arid, dry sub-humid, and humid from west to east. States such as Colorado and Wyoming are relatively drier as these states dominantly fall in the semi-arid class and some scattered regions fall in the arid class as well. In contrast, all of Iowa falls under the humid class. This explains, in part, the need and existence of irrigation infrastructure and irrigated crop production in the arid and semi-arid regions and primarily rainfed crop production in humid parts (Iowa and southeastern Nebraska).

Temporal Changes in Annual, Growing Season, and Monthly Aridity

AI trends in the region from 1968 to 2013 were computed in similar fashion as precipitation, and trends were tested for statistical significance and results were represented using maps. Trends in annual, growing season, and monthly aridity index are depicted visually in *Figures 9* and *10*. These maps are to be interpreted in the same way as explained for temporal maps that presented precipitation trends.

A majority of the Great Plains counties demonstrated that annual AI has increased over the 46 years, with 66 percent of the counties showing positive (increasing) trends in AI (getting more humid), and the rest (34 percent) of the region showing negative (decreasing) trends (getting drier or more arid). These increasing trends were largely found in the northern, central and eastern states. Specifically, North Dakota counties showed increasing trends, except for some counties in the southwest and west central regions. All counties in South Dakota showed positive trends. Nebraska was also dominated by counties that showed positive trends, except for the east central and southeast regions. Iowa, with the exception of the central and east central regions, showed positive trends.

Kansas had several counties scattered throughout the state that showed negative trends. Counties in western and central Wyoming showed negative trends, which surpassed the num-

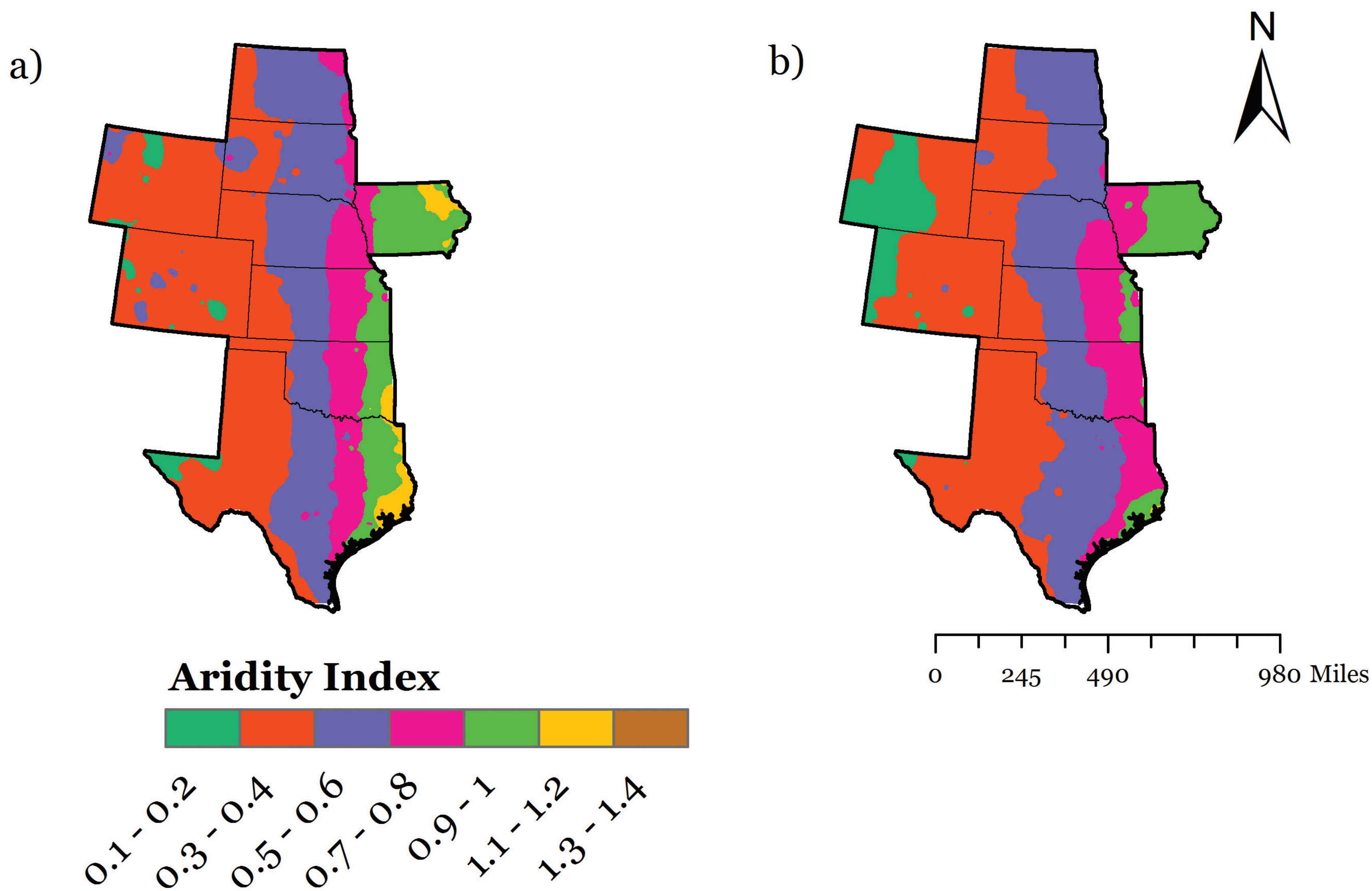

Figure 6. Spatial trends in a) annual and b) growing season aridity index (AI) across the U.S. Great Plains.

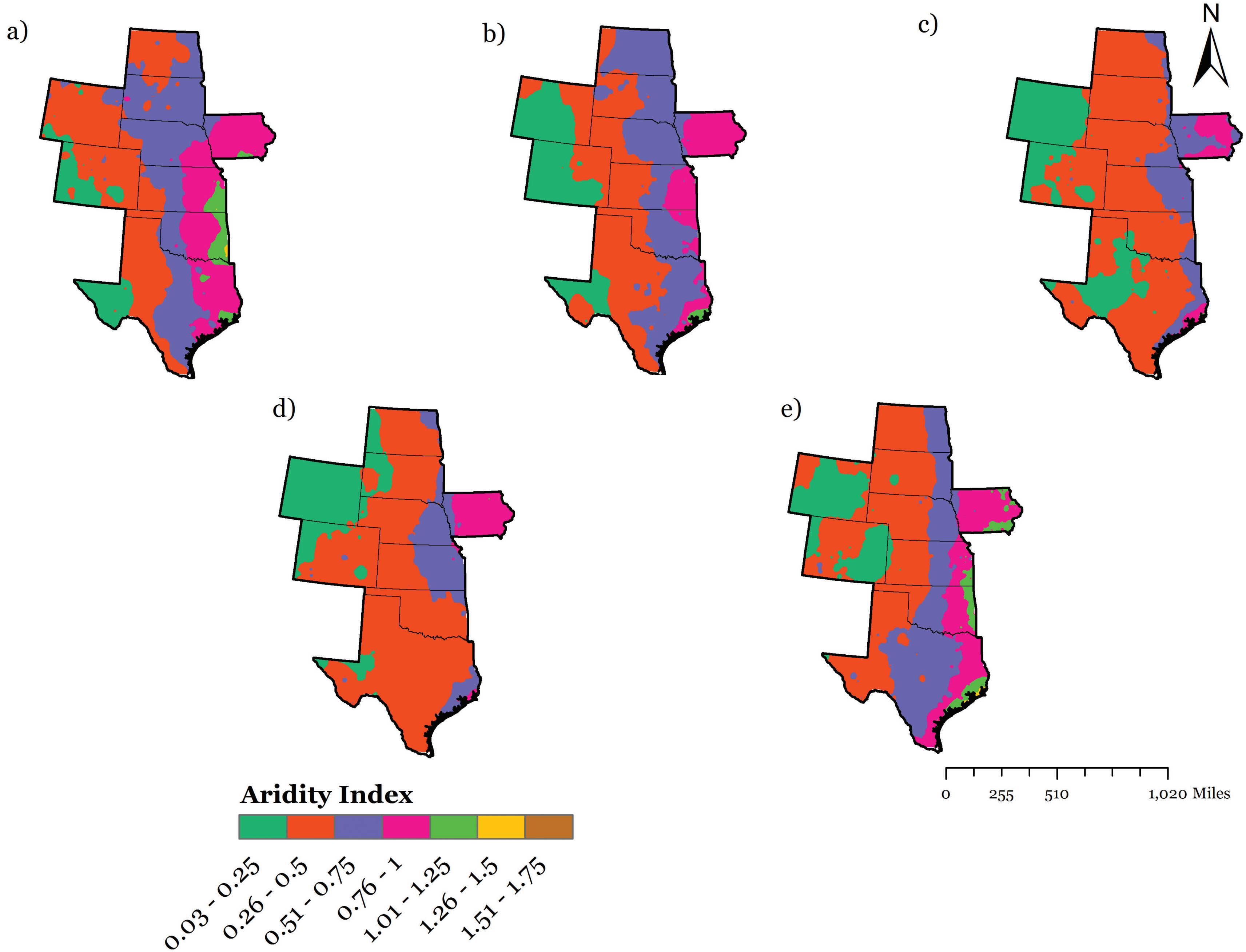

Figure 7. Spatial trends in aridity index (AI) during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

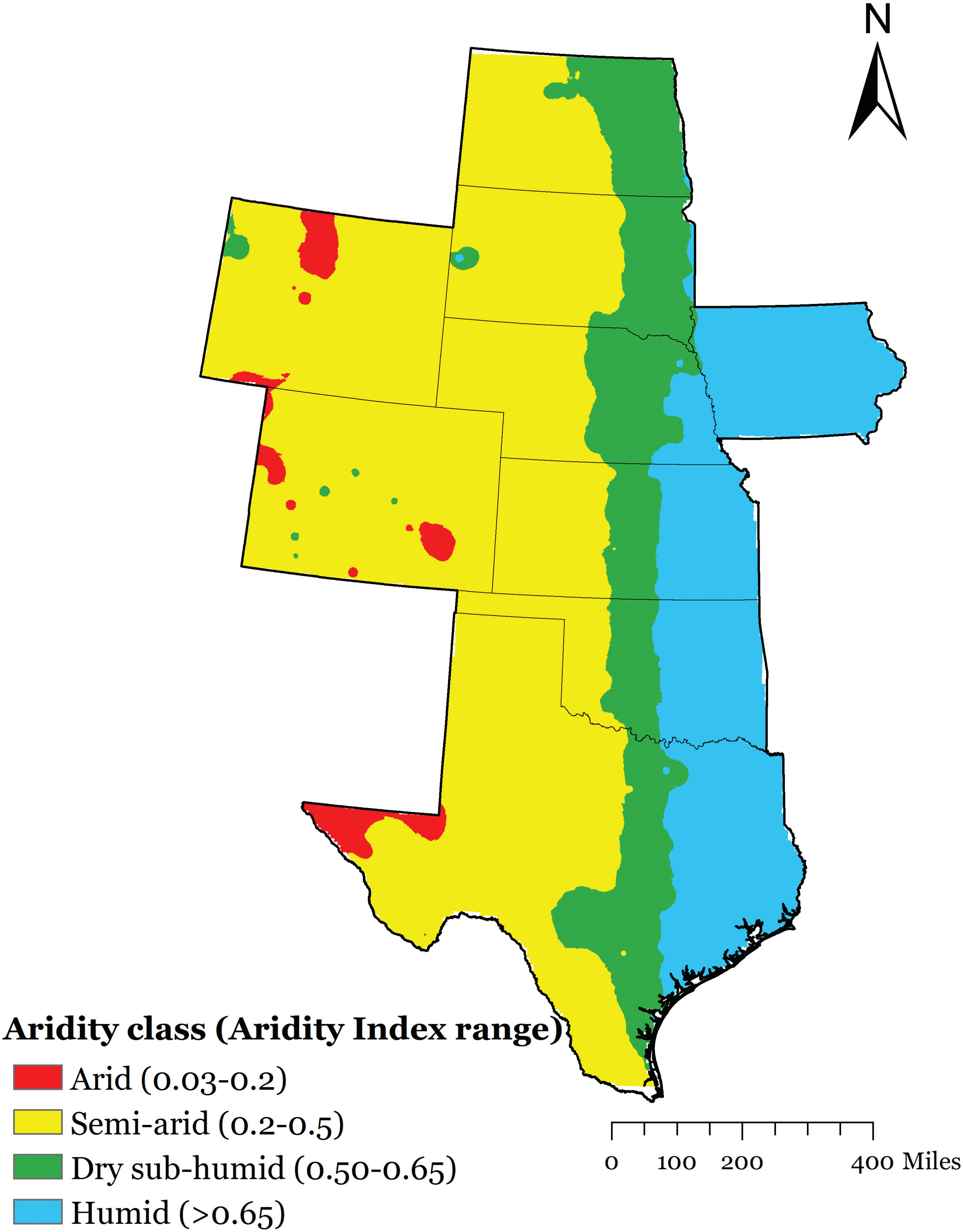

Figure 8. Classification of study region into aridity classes.

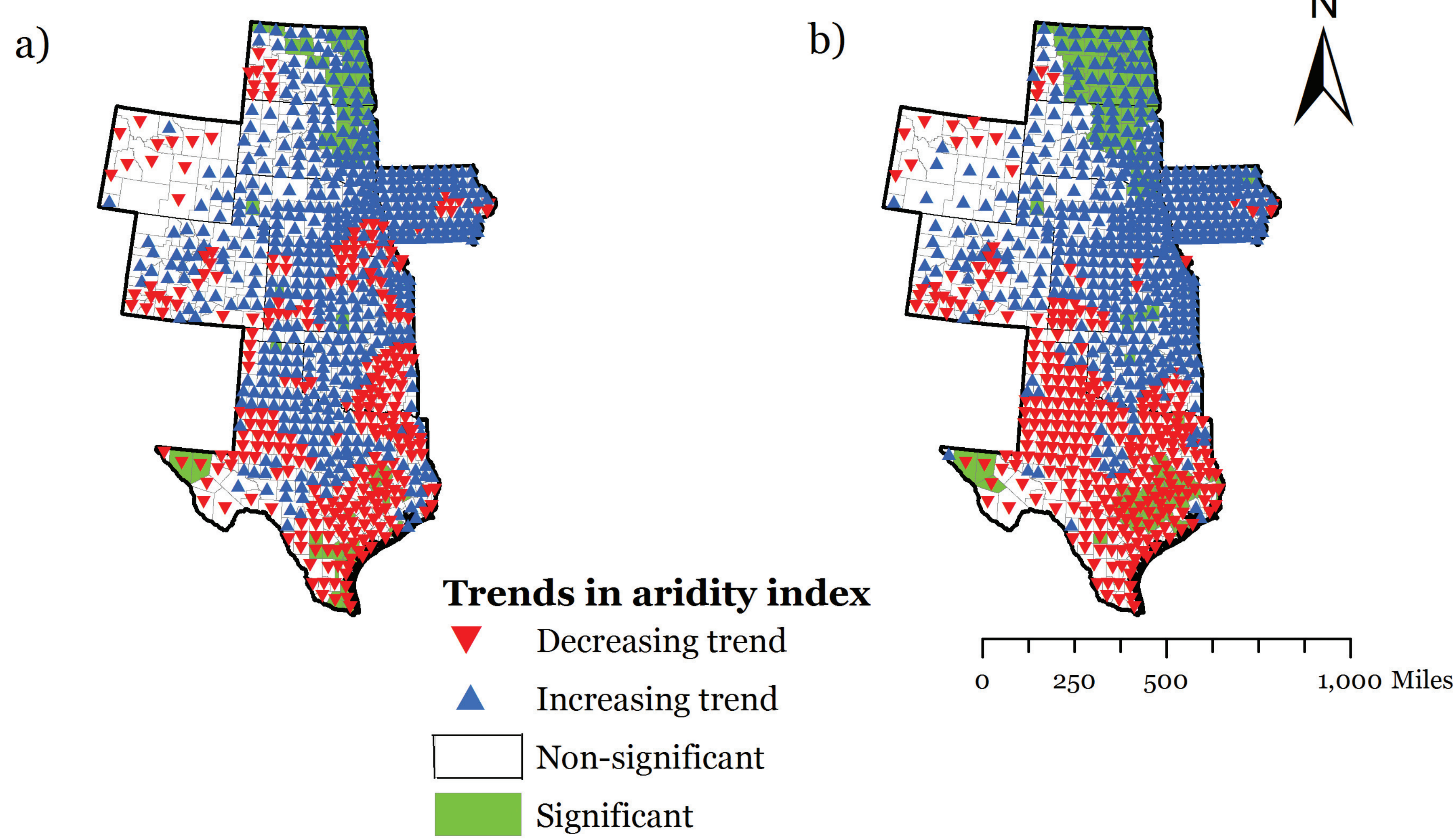

Figure 9. Temporal trends in a) annual and b) growing season aridity index (AI) across the U.S. Great Plains.

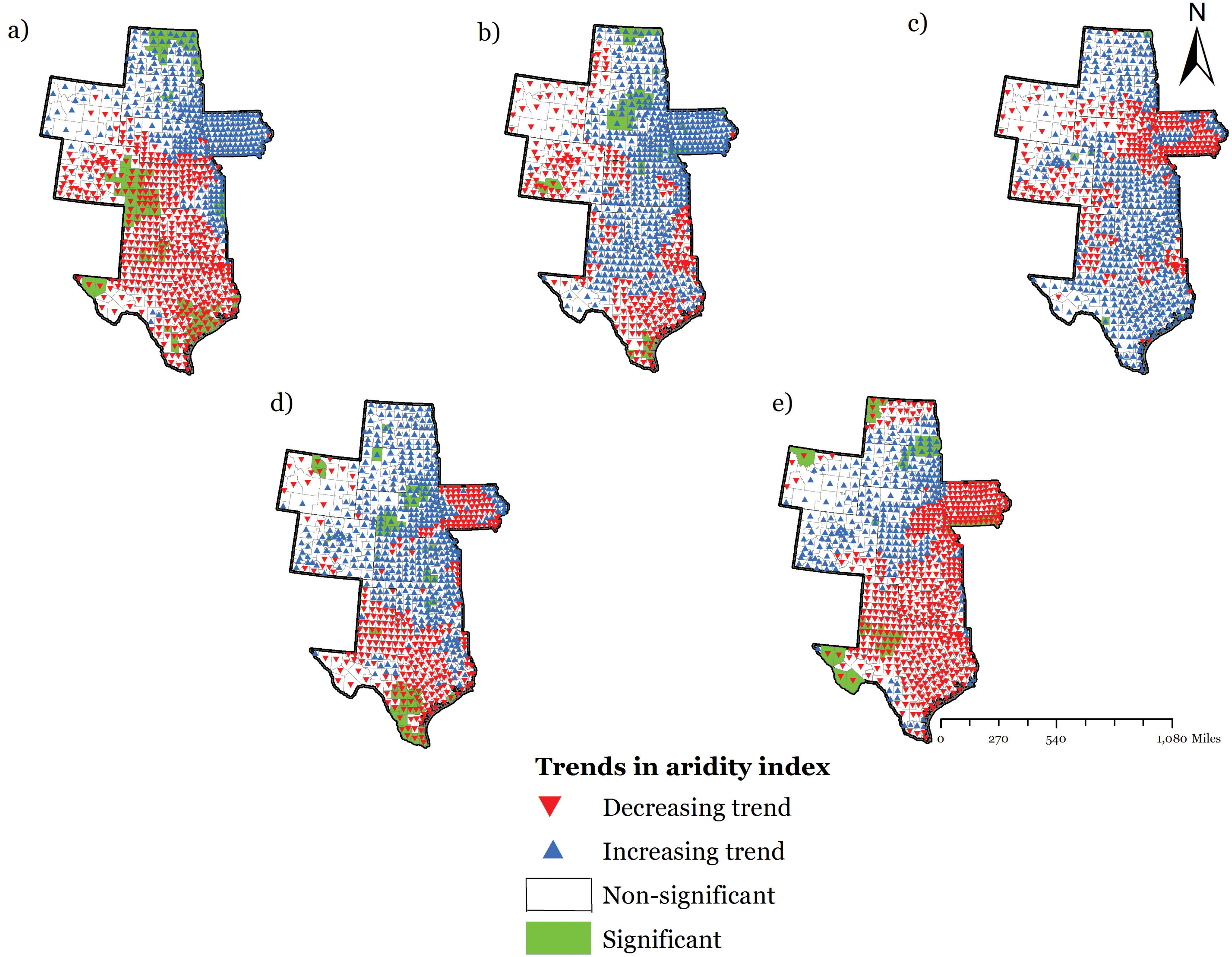

Figure 10. Temporal trends in aridity index (AI) during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

ber of positive trends in the state. Most of the counties in Colorado showed positive trends, except for some in the Colorado Drainage Basin. Counties in Oklahoma showed positive trends except for those in the eastern part of the state. Texas was dominated by positive trends in the northern region, while negative trends prevailed in the remainder of the state.

The significant positive trends, however, were only found primarily in North and South Dakota. Also, significant negative trends were only observed in Texas. The regional average magnitudes of the positive and negative trends in annual AI were 0.014 per decade and 0.010 per decade, respectively. The highest increasing trend in annual AI observed in the region was 0.067 per decade in Pembina County, North Dakota, while the highest decreasing trend was 0.043 per decade in San Patricio County, Texas.

The trends in growing season AI were similar to the annual trends with 63 percent of the counties in the region showing positive trends. North and South Dakota, Nebraska, Iowa, Kansas, and Oklahoma were predominantly occupied by counties that showed positive trends. Interestingly, the majority of North Dakota had significant positive trends, in addition to several counties in South Dakota.

The proportion and geography of the growing season AI trends in Wyoming and Colorado were very similar to those of annual AI. Another striking observation was that Texas showed negative trends throughout, with a considerable number of counties in south central and eastern Texas showing statistically significant negative trends. The regional average magnitudes of the positive and negative trends in growing-season AI were 0.020 per decade and 0.016 per decade, respectively.

The highest increasing trend in growing season AI observed in the region was 0.066 per decade in Marshall County, South Dakota, while the highest decreasing trend was 0.065 per decade in Brazoria County, Texas. Although these trends in AI appear to be very small, they are actually substantial (and statistically significant) considering that the usual range of AI is generally less than 2.0.

Different months of the growing season demonstrated different areas of increasing or decreasing trends in AI as evident from *Figure 10*. During May, the region demonstrates significant increasing trends in North Dakota and significant decreasing trends in eastern Colorado, western Oklahoma, and western and southeastern Texas. This pattern changes during June when increasing trends are observed in South Dakota and Nebraska, but no significant trends are found in July. In August, the significant increasing trends are only observed in Nebraska and decreasing trends are found in southern Texas.

In September the only significant trends are increasing trends. They are concentrated in northwestern and southeastern North Dakota, northeastern South Dakota, northwestern Wyoming, and western Texas. *Table 1* shows trend magnitudes in aridity for Clay County, Nebraska, which show that trends in monthly AI were positive for February, April, and June and negative for all other months. All of the monthly trends were insignificant, except the increasing trend in June, which was statistically significant. Also, the growing-season AI at Clay Center, Nebraska, had an increasing trend, while a negative trend was observed for the annual AI.

Table 1. Temporal trends in precipitation (P) and aridity index (AI) observed for Clay County, Nebraska. The values marked in red bold letters indicate that the corresponding trend is significant.

	Trend (change per decade)	
Period	**P (inch per decade)**	**AI (per decade)**
May	-0.02	-0.009
June	0.26	0.032
July	-0.02	-0.012
August	0.01	-0.006
September	-0.22	-0.017
Growing Season	**0.11**	**0.012**
Annual	**-0.33**	**-0.004**

Regional and Statewide Averages of Precipitation and Aridity Index

Tables 2 and *3* show the regional and statewide averages for annual, growing season, and monthly precipitation *(Table 2)* and aridity index *(Table 3)* to aid the interpretation of the discussed results for individual states.

Significance and Potential Implications of Precipitation and Aridity Trends for Agriculture and Water Resources

This extension circular presents and discusses the spatial and temporal variation in the long-term (46-year) precipitation and aridity index at the annual, growing season, and monthly basis for the 834 counties in nine states in the U.S. Great Plains region. The trends found in the precipitation amounts and aridity, whether increasing or decreasing, can have profound effects on agricultural crop production and the water cycle. For instance, the areas that show extreme positive (increasing) trends in precipitation can be vulnerable to experience increased disease pressure, runoff, flooding, and nutrient leaching to surface and groundwater resources. The amount and availability of water stored in the soil, which is a very important input to crop growth and yield, especially

Table 2. Regional and statewide average annual, growing season, and monthly precipitation (inches).

Months	Regional	ND	SD	NE	KS	CO	WY	IA	OK	TX
Monthly Means										
May	3.2	2.6	3.1	3.7	4.0	1.7	2.0	4.4	4.8	3.3
June	3.1	3.3	3.3	3.5	3.9	1.4	1.6	4.7	4.2	3.3
July	2.6	2.7	2.6	3.1	3.5	2.0	1.2	4.2	2.8	2.4
August	2.4	2.1	2.1	2.7	3.3	1.9	1.0	4.1	2.9	2.5
September	2.4	1.7	1.8	2.1	2.6	1.4	1.1	3.3	3.5	3.2
Annual										
Mean	24.3	18.6	20.6	23.5	28.5	15.0	12.5	34.4	35.0	29.0
Max	29.6	24.3	26.1	32.9	40.5	18.7	17.7	48.0	46.4	40.4
Min	18.3	11.8	13.3	13.6	19.8	9.6	7.6	21.9	25.4	15.2
SD	2.8	3.0	3.4	4.1	4.4	2.0	2.0	5.5	5.1	4.9
Growing Season										
Mean	13.7	12.7	13.5	15.4	17.5	8.6	6.9	21.0	18.2	14.3
Max	17.5	18.0	18.3	23.6	27.9	11.4	10.2	36.0	27.6	22.4
Min	9.4	7.6	8.2	6.6	9.8	5.2	3.3	11.8	10.7	5.4
SD	1.9	2.4	2.4	3.0	3.8	1.4	1.5	4.4	3.9	3.0

Table 3. Region-wide and statewide average annual, growing season, and monthly aridity index.

Months	Regional	ND	SD	NE	KS	CO	WY	IA	OK	TX
Monthly Means										
May	0.56	0.49	0.56	0.65	0.73	0.30	0.38	0.88	0.82	0.54
June	0.47	0.56	0.52	0.53	0.59	0.20	0.23	0.84	0.61	0.46
July	0.37	0.41	0.37	0.43	0.48	0.26	0.16	0.74	0.37	0.34
August	0.38	0.35	0.33	0.44	0.51	0.29	0.15	0.85	0.41	0.35
September	0.50	0.43	0.39	0.44	0.55	0.27	0.24	0.90	0.70	0.60
Annual										
Mean	0.49	0.48	0.46	0.50	0.58	0.29	0.27	0.91	0.66	0.50
Max	0.63	0.67	0.65	0.78	0.87	0.38	0.41	1.45	0.91	0.72
Min	0.34	0.27	0.27	0.25	0.36	0.17	0.15	0.52	0.45	0.24
SD	0.07	0.09	0.09	0.10	0.11	0.05	0.05	0.18	0.11	0.09
Growing Season										
Mean	0.44	0.44	0.42	0.49	0.56	0.25	0.22	0.82	0.55	0.44
Max	0.60	0.71	0.67	0.84	0.97	0.36	0.34	1.59	0.91	0.72
Min	0.30	0.24	0.24	0.19	0.28	0.15	0.10	0.42	0.31	0.15
SD	0.10	0.10	0.10	0.11	0.14	0.05	0.05	0.20	0.14	0.10

in arid and semi-arid areas, will be affected by changes in both precipitation and evapotranspiration. However, moderate increases in precipitation amounts (found in North Dakota and South Dakota) favors the soil moisture conditions and hence crop yields, while too little can be detrimental to crop yields (found in western and southwest Texas), especially if dry periods occur during critical crop development stages. For example, moisture stress during flowering, pollination, and grain-filling stages is especially harmful to maize, soybean, wheat, and sorghum (Decker et al., 1986). Also, the negative impacts of decreasing precipitation can be much worse for rainfed crop production. For irrigated fields, decreases in precipitation can be a major factor in affecting crop irrigation requirements. The amount and timing of the precipitation both play significant roles in determining the irrigation requirements.

Change in climate variables is likely to exacerbate the demand for irrigation water globally (Adams et al., 1990). Higher temperatures, increased evaporation, and yield decreases contribute to this projection. However, the supply of water resources for irrigation under changing climatic patterns is uncertain. Where and when water supplies are stressed or diminished, extra demand might require that some land be taken out of irrigation (Rosenzweig, 1990). Thus, information on regions that exhibit a precipitation deficit or surplus due to changes in climate variables can be combined with information on normal precipitation. This can help managers and practitioners to prepare for the potential implications of these changes on the crop production systems so that proper scientific and research-based mitigation strategies can be developed and implemented.

The aridity index quantitatively indicates the degree of atmospheric water vapor deficiency to meet the evaporation demand at a given geographical location. For example, *Figure 9b* implies that eastern and central North Dakota and eastern South Dakota, during the growing seasons of 1968–2013, became more humid and the ability to meet the evaporation demand was increased, whereas the opposite was true for the southwest Texas region. Decreases in aridity index, such as those observed in southwestern Texas, are of a high enough magnitude that they can translate into droughts.

The information provided in this publication can be useful to interpret what regions are experiencing increasing or decreasing trends in aridity index. This can help us to answer questions such as, "Are the arid regions approaching humid conditions or arid conditions and vice versa?" This information, along with those quantitative indicators presented in this publication, can be implemented into short- and long-term policy and decision-making to better prepare for the impact(s) of these changes. Also, it is recommended that precipitation patterns and magnitudes should be studied in conjunction with atmospheric water demand as it is a better indicator of how the region performs in these conditions rather than only concentrating on precipitation amounts.

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