

AN ASSESSMENT OF SOCIAL AND PHYSICAL VULNERABILITY TO  
HYDROCLIMATE EXTREMES IN APPALACHIA

A Thesis  
by  
LEAH R. HART HANDWERGER

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LEAH R. HART HANDWERGER  
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APPROVED BY

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Margaret M. Sugg, Ph.D.  
Chairperson, Thesis Committee

---

Elizabeth D. Shay, Ph.D.  
Member, Thesis Committee

---

Kara E. Dempsey, Ph.D.  
Member, Thesis Committee

---

Saskia L. van de Gevel, Ph.D.  
Chairperson, Department of Geography and Planning

---

Michael J. McKenzie, Ph.D.  
Dean, Cratis D. Williams School of Graduate Studies

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## **Abstract**

### **AN ASSESSMENT OF SOCIAL AND PHYSICAL VULNERABILITY TO HYDROCLIMATE EXTREMES IN APPALACHIA**

Leah R. Hart Handwerger  
B.S., Appalachian State University  
M.A., Appalachian State University

Chairperson: Margaret M. Sugg, Ph.D.

Appalachia is a culturally and economically distinct region in the southern and central Appalachian Mountains. Although the region receives consistent precipitation throughout the year, climate projections indicate that precipitation and drought variability will increase in both severity and frequency in future decades. This projection suggests that an increase in hydroclimate extremes will elevate the risk of experiencing natural hazards related to these events. Disadvantaged populations are most severely impacted by natural disasters, and Appalachia lags behind the nation in several social vulnerability indicators. The purpose of this study is to investigate the spatial patterns of drought and precipitation, and determine how these trends overlap with vulnerable communities across Appalachia. The study utilizes trend analysis through Mann-Kendall calculations and a Social Vulnerability Index, resulting in a bivariate map that displays areas most susceptible to adverse effects from hydroclimate extremes. Results show the southwestern portion of the region as most vulnerable to

increased precipitation, and the central-southeast most vulnerable to an increase in drought-precipitation variability. This study is among the first to utilize the boundaries defined by the Appalachian Regional Commission from a climatological perspective, which will assist policymakers in designing more effective mitigation strategies that span from the local to federal levels.

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I would like to thank Ronald Leeper of NOAA's National Centers for Environmental Information, who had generously compiled and shared the drought data used in this study. I also thank the Appalachian Regional Commission and the U.S Census Bureau for providing the necessary data to complete this study. Finally, I would like to acknowledge the Geography & Planning Department at Appalachian State University for their passionate support of their graduate students and mission to create a strong community within the department.

I owe thanks to my friends and family for their constant support and assistance in helping me achieve this goal. My parents, Nancy Hart and Norman Handwerger, have made

many sacrifices in order for me to pursue my dreams. I am eternally grateful for their unending love and support.

Finally, I dedicate this thesis to one of my closest friends, Mason Moldoven, who was taken from us in August of 2020. We were inseparable for most of my formative years and the impact of her loss cannot be overstated. She has become my strongest motivator for completing this study to the best of my ability, as she had always unconditionally supported my endeavors. Her memory continues to drive me to be the best version of myself, which I will carry with me as I move forward into a professional career.

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## **Forward**

The main body of this thesis is formatted to the manuscript submission guidelines for *Natural Hazards*, an official journal of the International Society for the Prevention and Mitigation of Natural Hazards.

## **Introduction**

Appalachia is a geographic region in the Appalachian Mountains that exhibits unique cultural and economic characteristics. However, the boundaries of what constitutes the region are ambiguous and ill-defined. Past environmental studies have arbitrarily drawn borders with little consistency (e.g., Clark et al. 2001; Konrad 1994; Gaertner et al. 2019). The Appalachian Regional Commission defines the region as spanning across 420 counties and 13 states from southern New York to northern Mississippi. As a federal economic partnership, the commission unites the region based on similar demographic and economic needs. In an effort to provide regional consistency and with the intent to reach wider audiences, this study utilizes this boundary for the study area.

Appalachia experiences consistent precipitation throughout the year, with some areas receiving the highest precipitation values in the U.S after the Pacific Northwest (Reinhardt and Smith 2007). The region is an essential water source for millions east of the Mississippi River, with dozens of major rivers originating in the forests of Appalachia. The region's saturated reputation has piqued the interests of researchers, where past studies have primarily focused on precipitation (e.g., Gaffin and Hotz 2000; Kelly et al. 2012; Konrad 1994). However, there is a substantial lack of research examining how drought impacts the region, despite the fact it occurs rather frequently. Moreover, climate projections show that the region will experience an increase in precipitation and drought variability in both severity and frequency in future decades (Carter et al. 2018; Dupigny-Giroux et al. 2018). This signifies the need for further research exploring the spatiotemporal relationships that exist between precipitation and drought in Appalachia.

These climate projections pose several challenges for the region. Drought can destroy crops, reduce water yields, and elevate wildfire risk (Andersen 2016; Caldwell et al. 2016). Inversely, heavy precipitation may lead to flooding, landslides and debris flows, and contaminated runoff can decrease the quality of drinking water (CCES; NSSL; Trenberth 2008; Wooten et al. 2016). Moreover, the impacts from both hydroclimate extremes are more likely to disproportionately impact disadvantaged populations (Cutter et al. 2003).

Appalachian communities are those with many struggles. Appalachia exceeds the national average in poverty, unemployment, and disability rates, and lags behind in educational attainment and having access to internet and phone services (Pollard and Jacobsen 2020a). Rural Appalachia is also more disadvantaged when compared to other parts of rural America. These factors make the region more susceptible to impacts from extreme weather events. Understanding the spatial relationships between hydroclimate extremes and vulnerable populations is crucial for decision-makers to better prepare for potential risks.

The purpose of this study is to identify vulnerable populations that are most susceptible to an increase in drought or precipitation. Using the longest available record of the Palmer Drought Severity Index (PDSI) from 1895 to 2016, the study employs Mann-Kendall calculations to examine long-term trends for the entire time period as well as trends at 30-year intervals. I designed a Social Vulnerability Index based on Dr. Susan Cutter's vulnerability indicators to identify clusters of at-risk communities (Cutter et al. 2003). A bivariate mapping technique was utilized to represent areas that are most susceptible to adverse effects from hydroclimate extremes. The results from this study highlight how current weather trends overlap with disadvantaged populations across Appalachia. This study is among the first to use the boundaries defined by the Appalachian

Regional Commission from a climatological perspective, and therefore has the potential to influence decisions up to the federal level. The study provides valuable information that will assist policymakers in designing more effective mitigation strategies to better protect at-risk communities.

# **An Assessment of Social and Physical Vulnerability to Hydroclimate Extremes in Appalachia**

Leah R. Handwerger<sup>1</sup>, Margaret M. Sugg<sup>1</sup>, Elizabeth D. Shay<sup>1</sup>, Kara E. Dempsey<sup>1</sup>

<sup>1</sup>Department of Geography and Planning, Appalachian State University, Boone, NC, USA

## **Abstract**

Appalachia is a culturally and economically distinct region in the southern and central Appalachian Mountains. Although the region receives consistent precipitation throughout the year, climate projections indicate that precipitation and drought variability will increase in both severity and frequency in future decades. This projection suggests that an increase in hydroclimate extremes will elevate the risk of experiencing natural hazards related to these events. Disadvantaged populations are most severely impacted by natural disasters, and Appalachia lags behind the nation in several social vulnerability indicators. The purpose of this study is to investigate the spatial patterns of drought and precipitation, and determine how these trends overlap with vulnerable communities across Appalachia. The study utilizes trend analysis through Mann-Kendall calculations and a Social Vulnerability Index, resulting in a bivariate map that displays areas most susceptible to adverse effects from hydroclimate extremes. Results show the southwestern portion of the region as most vulnerable to increased precipitation, and the central-southeast most vulnerable to an increase in drought-precipitation variability. This study is among the first to utilize the boundaries defined by the Appalachian Regional Commission from a climatological perspective, which will assist policymakers in designing more effective mitigation strategies that span from the local to federal levels.

## 1. Introduction

Appalachia is a geographic region in the Appalachian Mountains with distinct cultural and economic characteristics. The Appalachian Regional Commission defines Appalachia as spanning across 13 states and 420 counties from northern Mississippi to southern New York. There are five subregions that will be used throughout this paper: Southern, South-Central, Central, North-Central, and Northern (Fig. 1).

Appalachia experiences consistent precipitation throughout the year, with some areas receiving the highest precipitation values in the U.S after the Pacific Northwest (Reinhardt and Smith 2007). Dozens of major rivers originate in the forests of Appalachia, making the region an essential water source for millions east of the Mississippi River. Although the region is considered to be ‘water-rich’, climate projections suggest that precipitation and drought variability is likely to increase in both severity and frequency in future decades (Carter et al. 2018; Dupigny-Giroux et al. 2018). This projection poses several challenges for the region. Drought can destroy crops, reduce water yields, and elevate wildfire risk (Caldwell et al. 2016; Dale et al. 2001; Mitchell et al. 2014). Inversely, heavy precipitation can lead to dangerous hazards such as flooding, landslides, debris flows, and contaminated drinking water (CCES; NSSL; Trenberth 2008; Wooten et al. 2016). The impacts from both hydroclimate extremes are more likely to disproportionately impact underprivileged populations (Cutter et al. 2003).

Appalachian communities are more disadvantaged when compared with the rest of the nation. Appalachia exceeds the national average in poverty, unemployment, and disability rates, and lags behind in educational attainment and having access to internet and phone services (Pollard and Jacobsen 2020a). These factors make the region more susceptible to

impacts from extreme weather events, highlighting the need to improve our understanding of how hydroclimate extremes affect at-risk communities in Appalachia.

The purpose of this study is to identify vulnerable populations that are most susceptible to increased drought or precipitation. Using the longest available record (1895-2016) of the Palmer Drought Severity Index (PDSI), the study employs Mann-Kendall calculations to examine long-term trends for the entire time period as well as trends at 30-year intervals. A Social Vulnerability Index was designed based on the established literature by Dr. Susan Cutter and her vulnerability indicators (e.g., Cutter et al. 2003) to identify clusters of at-risk communities. A bivariate mapping technique was utilized to combine both social and physical vulnerabilities, displaying areas that are most susceptible to adverse effects from hydroclimate extremes.

## **2. Background**

### *2.1 Drought*

Drought is most commonly defined by the extended absence of rainfall (NCEI). Drought is the most expensive natural disaster in the U.S, costing \$248.7 billion from 1980 to 2019 (Smith 2020). As climate change continues to progress, drought is projected to become more widespread and costly in upcoming decades. However, drought is still among the least understood weather events due to its irregular spatiotemporal scales, slow onset, and variability associated with local climate (NCEI).

While drought has been widely studied across arid regions, there is significantly less research in wetter areas despite the fact that it can occur in any ecosystem. This is especially true in Appalachia, where the vast majority of research is centered around precipitation (e.g., Gaffin and Hotz 2000; Kelly et al. 2012; Konrad 1994). However, drought can still have disastrous consequences regardless of Appalachia's reputation for being a saturated region. An increase in drought frequency threatens agriculture and water resources. According to the NOAA Storm Events Database (1950-2019), drought and related events (i.e., dust devils and wildfires) were responsible for \$869.7 million in crop damages across the region (NCEI 2018). Recent studies have also shown that water yields are already declining in the Appalachians by as much as 18%, and projections suggest this will continue to decrease in future decades (Caldwell et al. 2016). Drought also has the potential to cause significant wildfires across the region. Unprecedented wildfires in 2016 decimated the southern Appalachians, causing millions in property damage and leading to 14 fatalities and hundreds of injuries (Andersen 2018; Boddy 2017; NCEI 2018). Severe drought can also reduce decomposition processes, which leads to the build-up of organic matter and increases the risk

for more significant wildfire and debris flow (Dale et al. 2001). Therefore, understanding the patterns of drought in Appalachia will be a critical part of preparing for and mitigating future challenges throughout the region.

## *2.2 Precipitation*

Heavy precipitation may lead to the destruction of crops, flooding, landslides, debris flows, and contaminated drinking water (CCES; NSSL; Trenberth 2008; Wooten et al. 2016). According to the National Oceanic and Atmospheric Association (NOAA), floods in the U.S claim more lives than tornadoes, hurricanes, or lightning (NSSL). The Appalachian landscape harbors particular risk factors conducive to flooding, such as: 1) steep mountainous slopes that produce rapid runoff, 2) close proximity to rivers and low-lying areas, and 3) densely populated urban areas that experience increased runoff along impervious surfaces (NSSL). Moreover, heavy rainfall can saturate the ground and reduce slope stability, causing landslides and debris flows. Appalachia is particularly susceptible to these hazards due to its steep slopes and frequent rainfall (Wooten et al. 2016). Heavy precipitation and polluted stormwater runoff can degrade water quality, which can impact both aquatic ecosystems and human health (CCES).

According to the NOAA Storm Events Database (1950-2019), flooding and flash floods resulted in \$5.4 billion in property damage and \$85.2 million in crop damage. Landslides and debris flows caused \$62.4 million in property damage and \$802,600 in crop damage. Heavy rainfall and related events (including all types of winter weather, hurricanes, and hail) resulted in \$1.1 billion in property damage and \$36.2 million in crop damage

(NCEI 2018). While this study does not directly examine the effects of these hazards, trends of increased precipitation represent a higher likelihood of experiencing these risks.

### *2.3 Socioeconomic Vulnerability*

Cutter (2003) defines vulnerability as potential loss. Vulnerability is inherently geographical, as the degree of loss varies over different social groups, time, and space (Cutter et al. 2003). There is substantial literature that shows the risk of impact by a natural disaster disproportionately affects disadvantaged populations (e.g., Cutter et al. 2003; Rufat et al. 2015; Yoon 2012). Four primary indicators that most strongly correlate with heightened vulnerability include poverty, race/ethnicity, gender, and age (Yoon 2012).

Poverty is one of the strongest indicators for vulnerability; simply put, individuals with less access to resources will have more difficulty recovering from a natural disaster. Poverty is also closely linked to educational attainment and having access to information that would provide advanced warning of impending hazardous weather (Cutter et al. 2003). Race and ethnicity is an important variable to consider, as minority (nonwhite) populations are less likely to have access to resources due to limited employment options, lower wages, and political marginalization (Cutter et al. 2003). If individuals are not proficient in English, they may have additional challenges staying informed about potential hazards and evacuation processes. Women are typically more vulnerable than men due to more limited employment opportunities, lower wages, and family care responsibilities (Cutter et al. 2003). Elderly and disabled populations are also at increased risk due to challenges with mobility and required care (Rufat et al. 2015).

Many of these indicators highlight Appalachia's vulnerability to natural hazards. Appalachia exceeds the national average in poverty, unemployment, elderly populations, and disability rates, and lags behind in educational attainment and having access to internet and phone services (Pollard and Jacobsen 2020a). Rural Appalachia is also more disadvantaged when compared to other parts of rural America.

There are also some variables in which Appalachia exceeds the national average, implying that the region as a whole may be less vulnerable in some arenas. For example, Appalachia generally has smaller populations of nonwhite minorities compared to the rest of the nation, as well as small populations with low English proficiency. Residents are also more likely to have health insurance, and having access to a vehicle is only slightly lower than the national average (Pollard and Jacobsen 2020b). However, these averages fail to acknowledge the uneven distribution of these populations. There are 166 counties where lacking health insurance exceeds the national average (9.4%), and there are more than a dozen counties where nonwhite minorities make up more than 40% of the population.

#### *2.4 Gaps in the Literature*

Although the study area is united by the Appalachian Regional Commission, very few studies focus on this area as a whole. The vast majority of those that do are grounded in the social or political sciences (e.g., Bradshaw 1992; Isserman and Rephann 1995; Ulack and Raitz 1981). To my knowledge, there are no published studies that focus on the environmental or climatological sciences for the entire region. Using these boundaries as a study area could provide benefits by reaching wider audiences that extend up to the federal level.

Additionally, there is substantially more literature focusing on the southern Appalachians compared to the central and northern subregions (e.g., Caldwell et al. 2016; Elliott et al. 2015; Gaffin and Hotz 2000; Henson et al. 2014; Kelly et al. 2012). This is most likely due to the fact that these subregions are considered to be climatologically different from their southern counterparts. For example, northern West Virginia, New York, Ohio, and Pennsylvania exhibit a climate that is more similar to that of the Northeast (Hayhoe et al. 2007), experiencing much cooler temperatures and more frequent snowfall. Counties that border the Great Lakes may experience significantly different precipitation patterns as a result of the lake effect (Niziol et al. 1995).

Finally, there is a lack of research examining drought across the region, even though Appalachia has experienced numerous severe drought events within the last decade. In 2016, severe drought conditions were responsible for unprecedented wildfires throughout the southern Appalachians (Andersen 2018). Moreover, there is growing evidence that indicates Appalachia will experience more frequent drought (e.g., Elliott et al. 2015; Mitchell et al. 2014), highlighting the need for further research exploring the spatiotemporal relationships that exist between precipitation and drought in Appalachia.

### **3. Methods**

#### *3.1 Data*

The Palmer Drought Severity Index (PDSI) was used to measure physical vulnerability. PDSI compiles precipitation, surface air temperature, soil moisture, and evapotranspiration rates, and is most commonly used to assess long-term meteorological or hydrological drought (Alley 1984; Dai et al. 2019). The dataset contained the longest available record of monthly values from January 1895 to December 2016. PDSI values range from -10 to 10, with values  $>4$  indicating a severe moist spell and  $<-4$  representing intense drought.

To measure social vulnerability, the following socioeconomic variables were compiled using American Community Survey (ACS) 2015-2019 Census percentages: poverty status by age (under 18, 18-64, over 65); nonwhite minorities; aging population (over 65); individuals with high school or less education; single-parent households; low English proficiency; no vehicle access; no health insurance; no internet access; and no phone service (U.S. Census Bureau). These variables were compiled into a spreadsheet and imported into IBM SPSS 27 to be computed for Principal Component Analysis.

#### *3.2 Statistical Analyses*

Physical vulnerability was evaluated by calculating trends of PDSI values using the Mann-Kendall test (Hipel and McLeod 1994; Libiseller and Grimvall 2002). The Mann-Kendall calculates the *tau* value, which reveals the strength and direction (+ or -) of trends in each county. Negative *tau* values reveal trends of increased drought frequency and positive values indicate movement towards more frequent precipitation. Trends with

$p$ -values < 0.05 were deemed statistically significant. The test was conducted using the entire time period available (1895-2016) and also at 30-year intervals. Thirty-year intervals were chosen based on the established recommendations for Climate Normals by the World Meteorological Organization (WMO 1989). The objective was to examine long-term trends, as well as uncover patterns at shorter time scales.

Next, a Social Vulnerability Index was designed, consisting of fifteen variables based on Dr. Susan Cutter's vulnerability indicators. These values were standardized and a Principal Component Analysis (PCA) was applied, retaining five components that met Kaiser's criterion (Kaiser 1960) (Table 3). The results from this process were totaled and mapped across the region using the standard deviation classification method to represent overall social vulnerability (Fig. 4). The five components were also mapped individually to explore unique themes of each component (Fig. 5).

Finally, hydroclimate trends and social vulnerability maps were combined using a bivariate mapping technique. This method used quantile classifications to reveal high, moderate, and low rankings of vulnerability (Table 5). The output displays the counties that are most susceptible to adverse effects of hydroclimate extremes (Fig. 6).

## 4. Results

### 4.1 Physical Vulnerability

Long-term trends (Table 1, Fig. 2) revealed increased precipitation in the southwest, especially in Mississippi. Counties gradually grew drier moving east, with negative *tau* values peaking in the Carolinas. A total of 62.6% counties reported precipitation (positive) trends and 6.2% with drought (negative) trends, while the remaining 31.2% of counties showed no significant movement in either direction. The strongest *tau* values ranged from  $-0.08$  ( $p$ -values $<0.001$ ) in Alexander and Davie counties in North Carolina to 0.19 in Tompkins and Schuyler counties in New York ( $p$ -values $<0.001$ ).

Trends at 30-year intervals (Table 2, Fig. 3) revealed patterns of alternating wet and dry periods. *Period A* (1895-1924) was a predominantly wet period, especially in the central and southern subregions, with 70.5% (297 of 420 counties) showing positive trends. Counties were drier in the north, though few of these (14 counties, or 3.3%) were statistically significant. Conversely, *Period B* (1925-1954) was notably drier with negative *tau* values in 182 counties, though only 9.7% of these were statistically significant. 22.5%, or 95 counties, reported statistically significant positive trends. Georgia and North Carolina displayed the strongest positive *tau* values, where these counties were neutral or negative in the previous segment. The central subregion also had the highest rate of insignificant trends (94%), though it reported 100% of counties with positive trends in *Period A*.

Similarly, *Period C* (1955-1984) was an extremely wet period, with almost exclusively positive trends (e.g., less drought periods). Only 2 counties reported negative, but insignificant, trends, while 85.2% of counties were statistically significant in the positive direction. The strongest *tau* values were concentrated in the southern subregion, grew

steadily weaker moving north to Kentucky and Virginia, then rose once more in the north-central and northern subregions. *Period D* (1985-2016) follows with another dry period, though only 5 counties reported significant drought trends. The majority of the region displayed much weaker and insignificant *tau* values, with only 40.9% (or 172 counties) showing significantly positive trends. The southern subregion reported the highest rate of insignificant trends (95.2%), where it had repeatedly been among the wettest subregions for all previous periods.

#### *4.2 Social Vulnerability*

Following principal component analysis, the remaining five components were totaled and mapped in ArcGIS Pro to visualize overall social vulnerability across the region (Fig. 4). This map did not reveal many obvious clusters of vulnerability, though Mississippi had the highest proportion of vulnerable counties than any other state (70.9%). When the three highest vulnerability classifications were compiled (Extreme-High, High, Moderate-High), the southern, south-central, and central subregions exceeded 30% vulnerable counties (Table 4). The northern and north-central subregions were deemed least vulnerable, as well as counties that surround metropolitan areas.

*Component 1* contained the highest variance for variables Disability, No Internet, Education Attainment, Poverty Status, and Unemployment (Table 3, Fig. 5); variables which most prominently affect rural Appalachia (Pollard and Jacobsen 2020b). There were two clusters with high vulnerability: 1) extremely high values in Kentucky, and parts of Virginia and West Virginia; and 2) the southernmost counties in Mississippi and western Alabama. The northern subregion and counties surrounding metropolitan areas showed low

vulnerability. *Component 2* contained the highest variance for No Health Insurance and moderately high variance for Low English Proficiency. While this component contained few counties in the highest vulnerability ranking, there were large clusters with high and moderately high levels in the southern and south-central subregions. The remaining subregions had rather low vulnerability. *Component 3* contained the highest variance for Female Population, Single-Parent Households, and moderate variance for Nonwhite Minorities. There were two small clusters of elevated vulnerability in Mississippi/Alabama and in the Carolinas. Where New York and Pennsylvania have previously been presented as least vulnerable, this subregion has notably shifted to having higher vulnerability. Metropolitan areas also exhibited higher rates of vulnerability. *Component 4* had the highest variance for Elder Populations. Most of Virginia was deemed moderately vulnerable, and there was also a small cluster of vulnerable counties along the North Carolina/Georgia border. Metropolitan areas, eastern Kentucky, and a small handful of counties in New York and Pennsylvania were least vulnerable. *Component 5* contained the highest variance for lacking access to phone services and vehicles. This component displayed clusters of elevated vulnerability in the central, north-central, and northern subregions, while the southern and south-central subregions were least vulnerable.

#### *4.3 Bivariate Mapping*

The bivariate map (Fig. 6) displayed counties that are most vulnerable to both hydroclimate extremes and socioeconomic factors. The map identified the central-southwestern portion of the study area as most vulnerable to increased precipitation, especially in Mississippi, Alabama, Tennessee, and western Kentucky. A handful of counties

in northern Pennsylvania and New York also showed high increases in precipitation, but generally low social vulnerability. The central-eastern portion of the region (i.e., Ohio, West Virginia, Virginia, and North Carolina) had high socioeconomic vulnerability and negative trends, indicating that this area is most susceptible to increases in drought or drought-precipitation variability.

## 5. Discussion

### 5.1 Physical Vulnerability

This aim of this study was to identify areas in the Appalachian region that had both high social vulnerability and high physical vulnerability to either precipitation or drought. Long-term trends (1895-2016) revealed high physical vulnerability to increased precipitation in the southwest and in the north. Trends gradually grew drier moving east, with negative values peaking in the Carolinas. However, both positive and negative trends were rather weak, where *tau* values on either spectrum did not exceed  $\pm 0.2$ . This indicates that trends in either direction are slow-moving, and that a fair amount of climate variability still persists in these areas. These findings support current climate projections which show the region exhibiting increases in more severe precipitation events as well as increased variability in both drought and precipitation (e.g., Carter et al. 2018; Dupigny-Giroux et al. 2018).

Trends at 30-year intervals revealed an interesting pattern of alternating wet (*Periods A and C*) and dry periods (*Periods B and D*). However, the strength of these trends were still rather weak, with a maximum *tau* value 0.303 in *Period A*. Again, this suggests that the region still exhibits relatively high variability, even at shorter temporal scales. Drought trends in all four periods also reported much lower rates of statistical significance when compared with precipitation trends. Counties showing drying trends reported less than 10% of statistical significance in each segment, while the rates of significant precipitation trends were consistently much higher, with a minimum rate of 22.5% in *Period B* and a maximum of 85.2% in *Period C*. This may be an indication of how drought functions across this region: dry periods are short-lived and inconsistent, whereas precipitation still occurs regularly despite the presence of drought. It may be more accurate to interpret insignificant *tau* values

as increased variability for both precipitation and drought; hence, why trends were more difficult to detect in these areas.

El Niño patterns may also be responsible for these wet/dry cycles. El Niño oscillations dictate precipitation patterns in the U.S. and are largely responsible for extreme weather events (Meehl et al. 2007). For instance, the 1982-1983 El Niño was the strongest of the century, and produced extremely heavy rain and flooding across the eastern U.S. (Quiroz 1983; Williams 2015). It is likely that this played a key role in explaining why we see such strong positive trends during *Period C*.

It is important to note that, while this 121-year period is the longest available record, only four 30-year periods can be accumulated which is not long enough to accurately confirm whether or not these dry/wet patterns truly exist. Nevertheless, these results show that Appalachia experiences precipitation at a more consistent level than it does drought. These trends may point to a future of increased precipitation and extreme events in the southwest portion of the study area, while areas with weaker trends may indicate higher drought-precipitation variability.

## *5.2 Social Vulnerability*

The southern, south-central, and central subregions exceeded 30% in the three highest vulnerability classifications, indicating that these regions are the most vulnerable. The most obvious cluster in the study area is in Mississippi and western Alabama. Mississippi had the highest ratio of counties with high vulnerability at 70.9%. Components 1-3 contributed to this cluster's high vulnerability, indicating that this area has high populations of rural, impoverished, and nonwhite communities, and residents are least likely to have health

insurance. The area also has high rates of single-parent households and disability rates. There were also some small clusters across the central and south-central subregions (i.e., northern Georgia/southwest North Carolina, northeast Tennessee, and northwest North Carolina/southwest Virginia), although these are not well-defined. It is interesting to note that these counties were consistently classified as rural based on Urban Influence Codes (ERS 2013). This pattern corresponds with past literature that has shown rural areas are typically more vulnerable than their urban counterparts (e.g., Cutter et al. 2003).

Generally speaking, vulnerability ranges from predominantly moderate with some patches of high vulnerability, and gradually decreases towards the northern subregion, with one exception of extreme vulnerability in Holmes County, Ohio. Holmes County was by far the most vulnerable in the entire study area, with a total value nearly twice that of the next highest county. Holmes exhibits high percentages of lacking Internet phone services, vehicle access, health insurance, English proficiency, and has low educational attainment.

### *5.3 Vulnerability to Hydroclimate Extremes*

The bivariate map revealed pronounced spatial patterns of vulnerability to hydroclimate extremes. The southwestern portion of the study area (i.e., Mississippi, Alabama, Tennessee, and western Kentucky) were most vulnerable to increased precipitation, while the north-central and eastern portions (i.e., Ohio, West Virginia, Virginia, and North Carolina) were most vulnerable to increased drought. However, it is important to recall that most of the areas with neutral or weak negative *tau* values were statistically insignificant. The lack of significant trends in these areas may indicate increased variability of both

hydroclimate extremes. With the exception of a few counties, the northern subregion is least socially vulnerable but exhibits trends of increased precipitation.

Results from this study support the findings from climate projections across the region. In the southeast, precipitation is projected to increase, as is the frequency of extreme events receiving at least 3 inches (Carter et al. 2018). The same is true in the northeast, which is expected to receive increased rainfall during the winter months (Hayhoe et al. 2007; Dupigny-Giroux et al. 2018). Projections also indicate increased snowfall for counties surrounding the Great Lakes as a result of the lake effect (Niziol et al. 1995). Drought is expected to increase, and severity may be exacerbated by higher temperatures and evapotranspiration rates (Carter et al. 2018; Gaertner et al. 2019). Overall, the most consistent theme throughout seminal research shows increased variability for both hydroclimate extremes (e.g., Carter et al. 2018; Dupigny-Giroux et al. 2018). Areas showing insignificant trends could be pointing to this increased variability.

#### *5.4 Limitations & Implications*

There were some limitations with this study that bear mentioning. Precipitation data from weather stations was omitted due to its complexity and inconsistent records across the region. Future studies would benefit by incorporating precipitation records across Appalachia. Additionally, examining social vulnerability at the county level is limiting as it over-simplifies the complex distribution of vulnerable communities. For example, a county with overall low vulnerability may have vulnerable populations that are clustered within specific census-tracts. A more effective study should examine these at a finer scale. Finally, this study examines current trends and should not be used to make predictions about the

future. A major takeaway from this study should be that this region experiences high levels of variability of hydroclimate extremes.

Despite these limitations, this study also provides several valuable contributions. The study is among the first to consider the Appalachian region as defined by the Appalachian Regional Commission from a climatological perspective. The Commission is a federal economic partnership whose mission is to tailor policies that address Appalachian-specific issues and work towards building stronger and more resilient communities. By utilizing these boundaries, the study has the potential to reach audiences outside of the scientific community and bring more effective mitigation strategies across the entire region.

The study adds to the literature focusing on drought in wet ecosystems. Drought is highly complex and difficult to assess, but it is crucial to understand how it functions in such climates. Acknowledging how drought uniquely impacts Appalachia will help water managers better prepare for future challenges surrounding water quality and distribution. Finally, this study also provides an in-depth examination on how hydroclimate extremes impact vulnerable communities in Appalachia. The authors identified the central, south-central, and southern subregions as most vulnerable, especially in rural areas. Legislators can tailor mitigation efforts to better address rural needs by developing stronger outreach and education programs that will assist residents in isolated areas to prepare for the effects of hydroclimate extremes.

## 6. Conclusion

Water is an essential part of the Appalachian ecosystem. Though precipitation occurs consistently throughout the year, climate projections suggest that precipitation and drought variability will increase in both severity and frequency in future decades. This projection implies that we will see an increase in related natural hazards, and it is therefore becoming evermore important to understand how current hydroclimatic trends intersect with vulnerable communities in Appalachia. The study utilized Mann-Kendall calculations to identify areas moving towards an increase in precipitation or drought, while incorporating a socioeconomic analysis to locate areas that would be most vulnerable to either hydroclimate extreme.

The authors identified the southwestern portion of the region (Mississippi, Alabama, and Tennessee) to be increasing in precipitation frequency, though these trends were weak and slow-moving. The central-eastern areas (Ohio, West Virginia, Virginia, and North Carolina) showed high drought-precipitation variability. Both areas exhibited high socioeconomic vulnerability which will likely exacerbate the impacts from natural hazards related to both hydroclimate extremes. These findings support current climate projections that show more severe precipitation events in the south, as well as increased precipitation variability across the region.

The study also highlights where vulnerability is highest in Appalachia. The socioeconomic analysis revealed the central, south-central, and southern subregions as most vulnerable, especially in rural areas. This indicates a need to strengthen outreach efforts directed to rural communities. Developing education programs that emphasize preparation and mitigation designed to reach even the most isolated populations would greatly increase resiliency in these areas.

This study provides a unique perspective examining the intersection of physical and social vulnerabilities to hydroclimate extremes. By using the boundaries defined by the Appalachian Regional Commission, findings may reach audiences outside of the scientific community and impact legislation that spans from the local to federal levels. In highlighting specific factors that make a population especially susceptible to environmental hazards, this study emphasizes the need for policies that are designed to build resiliency in underrepresented communities.

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**Table 1.** PDSI trends by subregion for 1895-2016

	<b>1895-2016</b>		
<b>Subregion</b>	<b>Increasing</b>	<b>Decreasing</b>	<b>Insignificant Trend</b>
<b>Southern</b>	69.3%	13.4%	17.3%
<b>South-Central</b>	44.8%	14.1%	41.1%
<b>Central</b>	89.1%	0.0%	10.9%
<b>North-Central</b>	39.7%	0.0%	60.3%
<b>Northern</b>	64.0%	0.0%	36.0%
<b>Total</b>	62.6%	6.2%	31.2%

**Table 2.** PDSI trends at 30-year intervals by subregion

	Period A: 1895-1924			Period B: 1925-1954		
Subregion	Increasing	Decreasing	Insignificant Trend	Increasing	Decreasing	Insignificant Trend
<b>Southern</b>	96.2%	0.0%	3.8%	55.2%	0.0%	44.2%
<b>South-Central</b>	56.5%	0.0%	43.5%	29.4%	0.0%	71.6%
<b>Central</b>	100.0%	0.0%	0.0%	0.0%	6.0%	94.0%
<b>North-Central</b>	87.3%	0.0%	12.7%	9.5%	44.5%	46.0%
<b>Northern</b>	15.1%	16.3%	68.6%	8.1%	9.3%	82.6%
<b>Total</b>	70.5%	3.3%	26.2%	22.5%	9.7%	67.8%
	Period C: 1955-1984			Period D: 1985-2016		
	Increasing	Decreasing	Insignificant Trend	Increasing	Decreasing	Insignificant Trend
<b>Southern</b>	96.2%	0.0%	3.8%	0.0%	4.8%	95.2%
<b>South-Central</b>	86.5%	0.0%	13.5%	31.8%	0.0%	68.2%
<b>Central</b>	48.8%	0.0%	51.2%	82.9%	0.0%	17.1%
<b>North-Central</b>	100.0%	0.0%	0.0%	47.6%	0.0%	52.4%
<b>Northern</b>	100.0%	0.0%	0.0%	55.8%	0.0%	44.2%
<b>Total</b>	85.2%	0.0%	14.8%	40.9%	1.2%	57.9%

**Table 3.** Social vulnerability components preserved by Principal Component Analysis

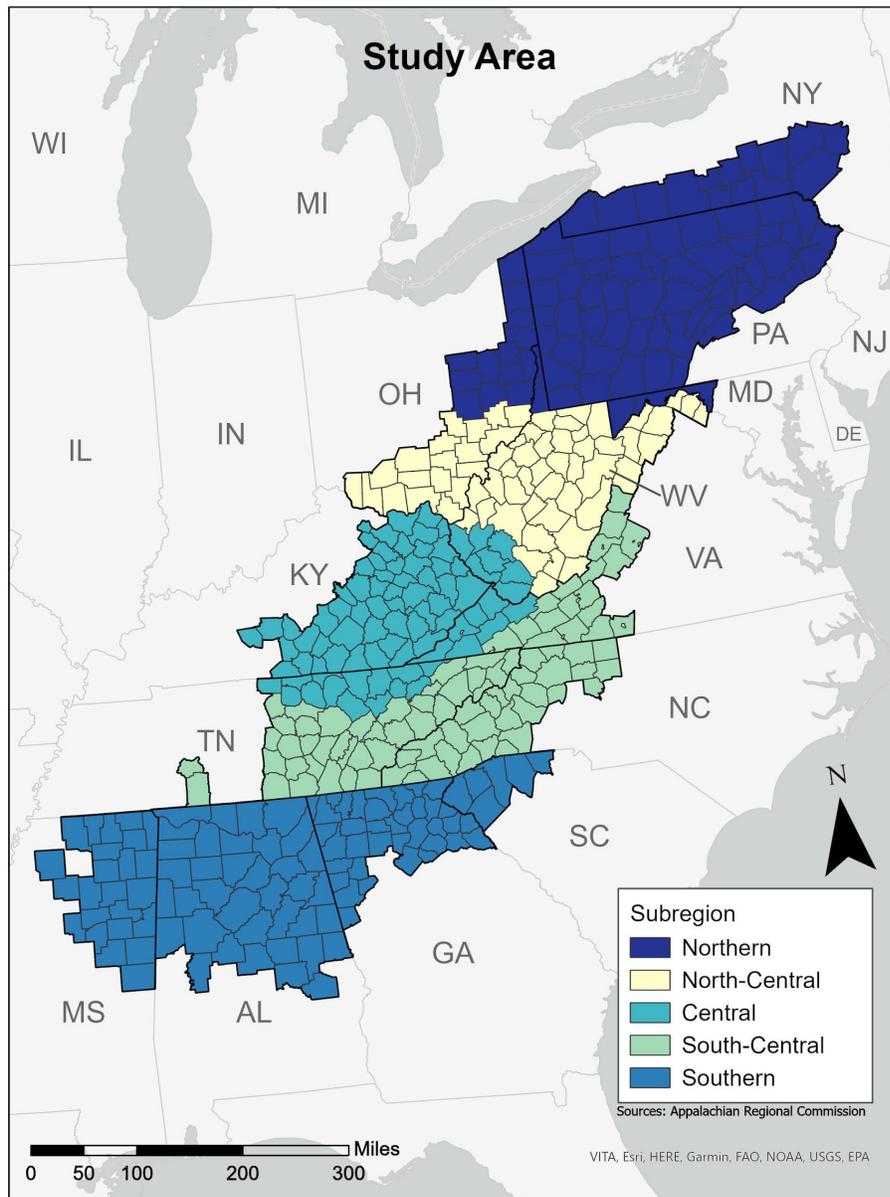
Variable	Component				
	1	2	3	4	5
% Female	-0.23	0.078	<b>0.73</b>	0.223	0.228
% Nonwhite Minorities	-0.05	0.309	<b>0.583</b>	-0.496	-0.303
% Disability	<b>0.777</b>	-0.278	-0.126	0.239	0.048
% Aging (65+)	0.011	-0.048	0.01	<b>0.869</b>	-0.112
Educational Attainment (High School or less)	<b>0.746</b>	0.063	-0.328	0.203	0.158
Unemployment Rate	<b>0.608</b>	-0.384	0.193	-0.185	0.111
Poverty Status (<18 years)	<b>0.832</b>	-0.034	0.224	-0.057	0.125
Poverty Status (18-64 years)	<b>0.773</b>	-0.245	0.082	-0.196	0.19
Poverty Status (65+ years)	<b>0.762</b>	0.033	0.034	-0.098	0.112
Single-Parent Households	0.365	-0.127	<b>0.713</b>	-0.133	-0.069
Low English Proficiency	-0.326	<b>0.623</b>	-0.053	-0.428	0.191
No Health Insurance	0.026	<b>0.907</b>	0.079	-0.017	-0.016
No Vehicle Access	0.308	-0.255	0.119	-0.153	<b>0.729</b>
No Internet	<b>0.776</b>	0.277	0.044	0.265	0.164
No Phone Services	0.246	0.315	-0.063	0.006	<b>0.738</b>
<b>Total Variance Explained:</b>	29.694%	12.417%	10.854%	10.2%	9.373%

**Table 4.** Social vulnerability classifications by subregion

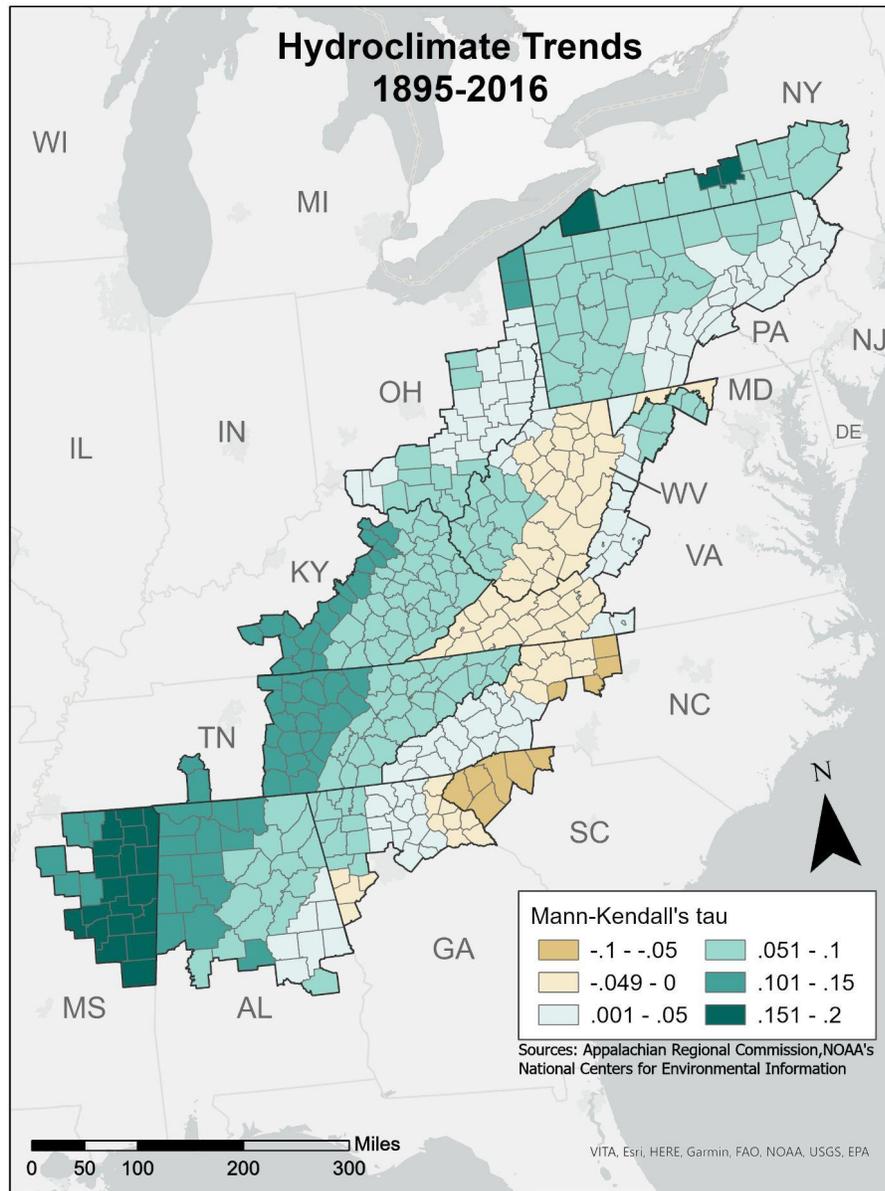
Subregion	Classification						
	Extreme-Low	Low	Moderate-Low	Moderate	Moderate-High	High	Extreme-High
<b>Southern</b>	1.0%	3.8%	20.2%	36.5%	28.8%	8.7%	1.0%
<b>South-Central</b>	1.2%	1.2%	16.5%	47.0%	30.6%	2.3%	1.2%
<b>Central</b>	0.0%	2.4%	15.9%	46.3%	29.3%	4.9%	1.2%
<b>North-Central</b>	3.2%	11.1%	15.9%	47.6%	20.6%	1.6%	0.0%
<b>Northern</b>	2.3%	7.0%	33.7%	51.2%	4.6%	0.0%	1.2%
<b>Total %</b>	1.4%	4.8%	20.7%	45.2%	23.1%	3.8%	1.0%

**Table 5.** Combined physical and social vulnerability classifications by subregion

Classification	Total %	Subregion				
		Southern	South-Cental	Central	North-Central	Northern
Low Social-Low Physical	10.5%	5.8%	11.8%	1.2%	19.0%	17.4%
Moderate Social-Low Physical	11.4%	3.8%	18.8%	2.4%	22.2%	14.0%
High Social-Low Physical	11.9%	7.7%	24.7%	7.3%	17.5%	4.6%
Low Social-Moderate Physical	12.6%	14.4%	5.9%	12.2%	7.9%	20.9%
Moderate Social-Moderate Physical	12.6%	12.5%	12.9%	19.5%	15.9%	3.5%
High Social-Moderate Physical	11.0%	10.6%	7.1%	24.4%	9.5%	3.5%
Low Social-High Physical	10.2%	6.7%	3.5%	12.2%	6.3%	22.1%
Moderate Social-High Physical	9.3%	11.5%	9.4%	9.8%	0.0%	12.8%
High Social-High Physical	10.5%	26.9%	5.9%	11.0%	1.6%	1.2%

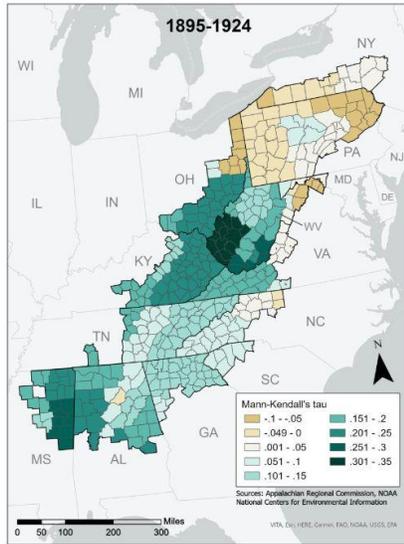


**Fig. 1.** Study area as defined by the Appalachian Regional Commission and subregions

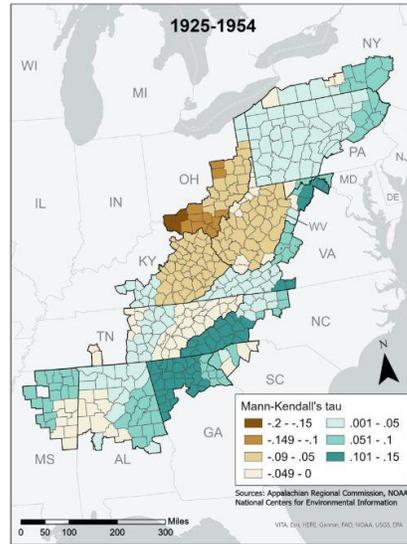


**Fig. 2.** Physical vulnerability represented through PDSI trends for 1895-2016

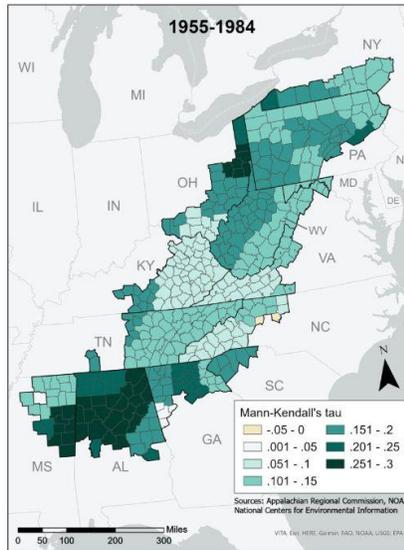
## Hydroclimate Trends Thirty-Year Intervals



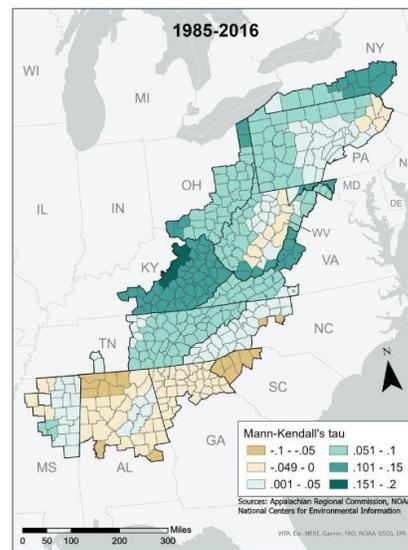
*Period a:* Trends are predominately positive with 74% (312 counties) statistically significant. The strongest tau values ranged from -0.081 in Carbon and Schuylkill counties in Pennsylvania to 0.303 in southwest West Virginia.



*Period b:* Trends are much drier, but only 32.6% (137 counties) are statistically significant. Tau values range from -0.187 in Brown, Clermont, and Highland counties in Ohio to 0.138 in Carroll, Douglas, Haralson, and Heard counties in Georgia.

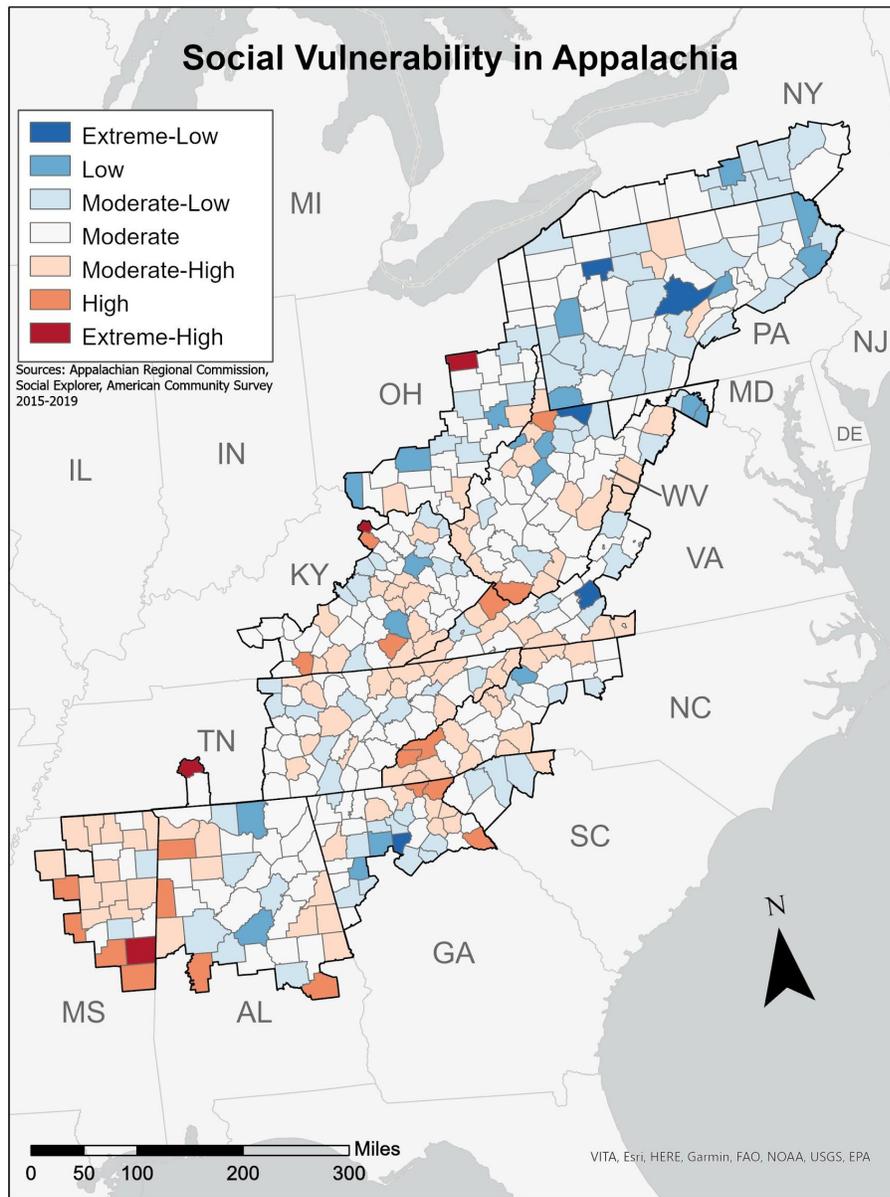


*Period c:* Trends are almost exclusively positive with 85.7% (360 counties) statistically significant. Tau values ranged from -0.005 in Alexander and Davie counties, North Carolina (insignificant) to 0.295 in Calhoun, Cherokee, Etowah, Saint Clair, Shelby, and Talladega counties in Alabama.



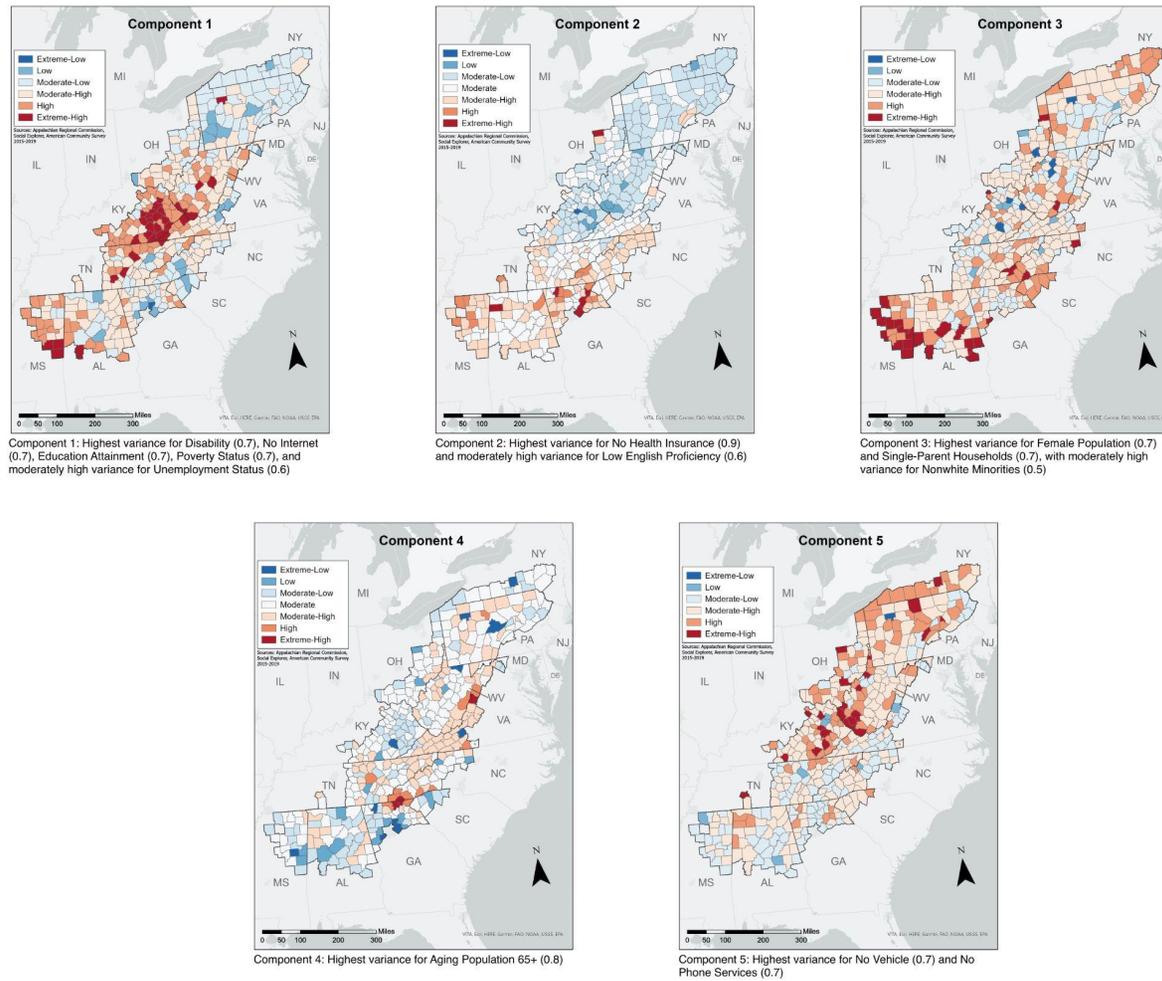
*Period d:* Drying trends are stronger and positive trends grow weaker. 42.3% (178 counties) are statistically significant. The strongest taus ranged from -0.09 in Anderson, Cherokee, and Spartanburg counties in South Carolina to 0.169 along the western edge of Kentucky.

**Fig. 3.** PDSI trends at 30-year intervals

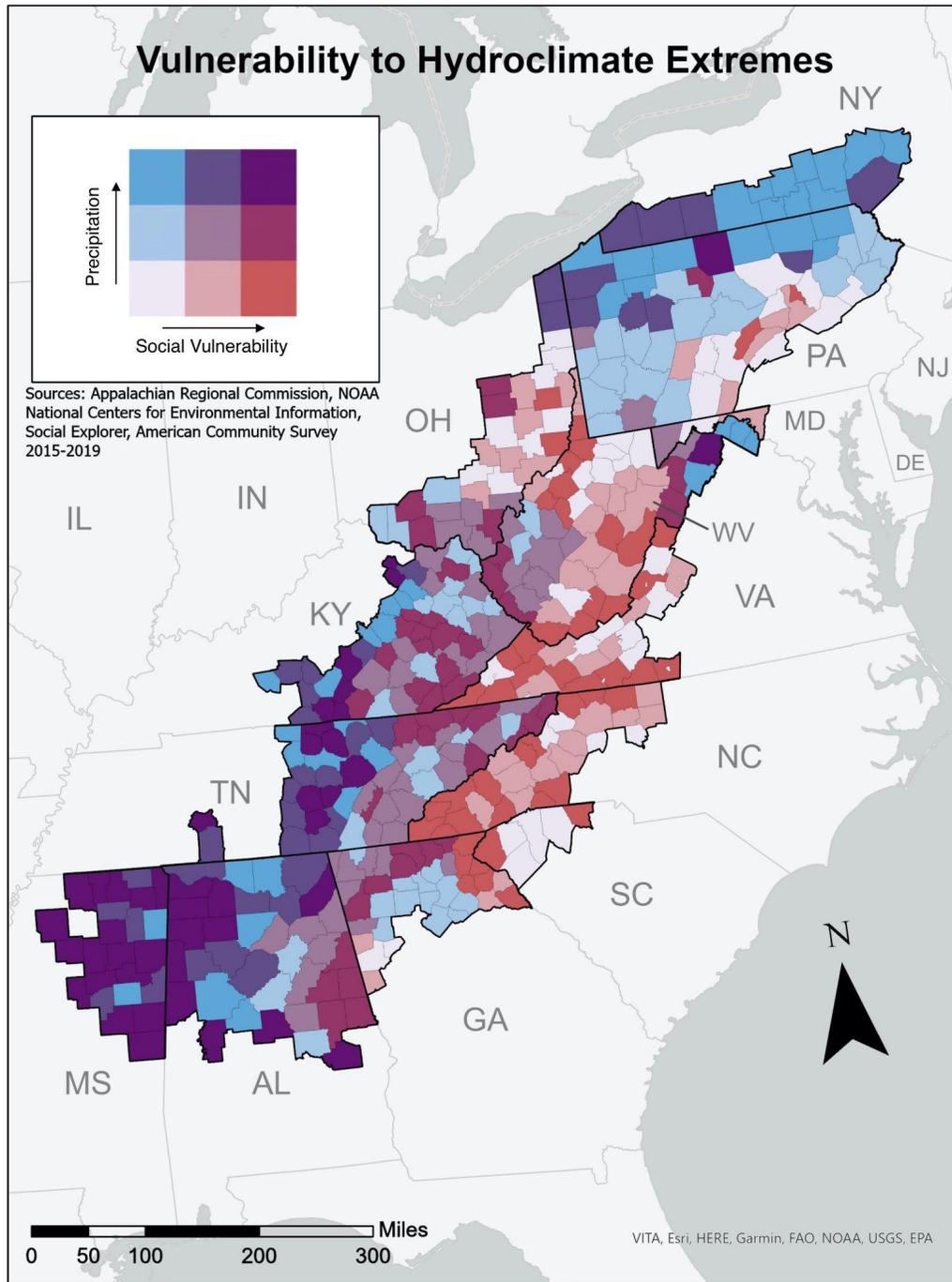


**Fig. 4.** Social vulnerability determined by combined principal components

## Principal Components



**Fig. 5.** Social vulnerability represented by each principal component



**Fig. 6.** Bivariate map combining physical and social vulnerability to hydroclimate extremes. High *tau* values represent increased precipitation and low *tau* values indicate increased drought.

## **Vita**

Leah Rachel Hart Handwerger was born and raised in Baltimore, Maryland. As a child, she spent many summers camping and swimming in the lakes of Maine nestled in the Appalachian Mountains. These experiences instilled a fascination with mountain ecosystems, and particularly, the Appalachians. Although spending most of her youth involved in the arts studying violin, her interests shifted after taking a gap semester in Australia and New Zealand. This incredible opportunity offered a wide array of new experiences that included contributing to numerous conservation projects. This trip inspired Leah to begin a career in the environmental sciences, and Leah moved to the mountains of North Carolina to earn her undergraduate degree in Sustainable Development at Appalachian State University. Upon moving to Boone, Leah marveled at the beauty of the southern Appalachians and fell in love with its unique ecosystem.

Since graduating from Appalachian State, Leah has held a wide variety of internships and seasonal jobs to build her career in the environmental field. Although briefly leaving the region, Leah constantly felt the call of the Appalachians and returned to Western North Carolina. Leah has worked with multiple nonprofit organizations in the area, including spending a year with RiverLink, an organization that seeks to improve water quality in the Asheville region, and Mountain Trail Outdoor School, where she taught environmental education to middle schoolers. Though these positions were incredibly rewarding, Leah came to realize that she was drawn to tasks involving the geographic sciences. Once again, she

packed her bags and moved back to Boone, North Carolina to complete her M.A in Geography at Appalachian State University. She was fortunate enough to earn a Graduate Research Associate Mentoring (GRAM) assistantship with Dr. Margaret Sugg, Dr. Elizabeth Shay, and Dr. Kara Dempsey. Through this position, Leah has participated in numerous research projects that have enlightened her interests in conducting research. Though the future remains open, Leah plans to pursue a career in GIS with the National Parks Service or a similar organization.