A VULNERABILITY ASSESSMENT OF EXTREME DROUGHT AND UNPRECEDENTED WILDFIRE IN THE SOUTHERN APPALACHIAN MOUNTAINS

by

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Abstract

In 2016, an extreme drought occurred in the southeastern United States. Dry conditions resulted in unprecedented wildfires throughout the southern Appalachian Mountains, specifically in western North Carolina. Western North Carolina is an important source of water for nearby metropolitan locations. In the future, climate change is expected to increase temperatures, alter precipitation, and stress water resources in the region, which could lead to more frequent drought and wildfire. The recent drought and wildfire events offer an opportunity to assess vulnerability and prepare for resilience. The study explores the spatiotemporal characteristics of the recent wildfires by identifying wildfires that contributed to diminished air quality across the state. The study then explores wildfire vulnerability by identifying communities with the greatest socioeconomic vulnerability to wildfires and locations with the greatest physical vulnerability to wildfires. The result is a future wildfire vulnerability index for western North Carolina. The results indicate that quality of life was significantly impacted by the recent drought and wildfire events and the greatest wildfire vulnerability occurs in the southwestern portion of the state with a gradual decrease heading eastward. The individual socioeconomic and physical characteristics of locations must be considered when determining emergency management practices relating to drought and wildfire. *Key Words: Appalachian Mountains, Drought, Resilience, Wildfire, Vulnerability*

Introduction

In 2016, an extreme drought occurred in the southeastern United States. Dry conditions resulted in unprecedented wildfires throughout the southern Appalachian Mountains, specifically in western North Carolina. Western North Carolina is an important source of water for nearby metropolitan locations, including Charlotte, North Carolina and Atlanta, Georgia. The region's natural beauty has contributed to a thriving tourism industry, rapidly growing population, and dramatic modification of the natural environment, which have placed stress on the region's water resources and contributed to increased wildfire vulnerability. In the future, the region's freshwater availability is predicted to decline due to both climate and human related factors (EPA 2017). When combined with existing stress on water resources, community health could be impacted (USGCRP 2014). Alley et al. (2003) notes, "Given the deep uncertainty about the nature and speed of future climate changes, policymaking thus might focus on reducing vulnerability of systems to impacts by enhancing ecological and societal resiliency and adaptability." The recent drought and wildfires offer an opportunity to assess vulnerability and prepare for resilience.

The following study explores vulnerability in western North Carolina (Figure 1). According to the Western North Carolina Vitality Index (2016), western North Carolina encompasses 27 counties in North Carolina. Western North Carolina is the focus because it is an important source of water for the surrounding region, possesses regional characteristics that increase drought and wildfire vulnerability, and was significantly impacted by the recent drought and wildfire event.

Figure 1. The 27 counties in western North Carolina.

The objective is to explore the impacts and characteristics of the recent event and assess vulnerability to future events in western North Carolina. The study aims to answer the following questions:

- What were the spatiotemporal characteristics of the recent wildfires in North Carolina?
- Where is wildfire vulnerability in western North Carolina?

While many assessments of water-related vulnerability have focused on the developing world (e.g. Sullivan 2011), few studies have explored water vulnerability on the Eastern Coast of the United States. Southern Appalachia is typically not considered water vulnerable with some climate models even projecting the region to experience increased water availability in the future (Manabe et al. 2004). However, the recent event proved that drought and wildfire are very real threats, particularly as increased climate variability results in unpredictable changes in temperature and precipitation patterns. In the United States, drought and wildfire studies have focused primarily on the western and midwestern regions (e.g. McNeeley et al. 2016). Of the drought and wildfire studies in the southeastern portion of the country, most have focused on the impacts on ecosystems and agricultural systems instead of vulnerable human populations (e.g. Mitchell et al. 2014).

Geospatial technologies offer a valuable tool for demonstrating the impacts of drought and wildfire. The following study demonstrates the widespread impacts associated with wildfires through a mixed-method approach using content analysis, trajectory modeling, and geographic information systems (GIS). In addition, vulnerable communities are evaluated to assess their potential wildfire exposure by examining socioeconomic and physical characteristics. Ultimately, results from this analysis will provide transparency to potentially vulnerable populations, as well as inform the public about potential hazards stemming from projected climate variability. In addition to filling literature gaps about water-related vulnerability in the southeast, the study offers one of the first analyses of the recent drought and wildfire event. The study also complements ongoing efforts by surrounding state universities exploring coastal water vulnerability in North Carolina (e.g. Schiavinato and Payne 2015).

Background

Vulnerability, Adaptation, and Resilience

The concepts of vulnerability, adaptation, and resilience are used throughout scientific literature to describe both human and environmental systems. There are a variety of definitions for vulnerability, adaptation, and resilience (Fussel 2007; Gallopin 2006; Lei et al. 2013). The variety of conceptualizations complicate climate change research (Fussel 2007). Therefore, definitions provided by the Intergovernmental Panel on Climate Change (IPCC), a synthesis of climate change research, are used throughout the study.

Vulnerability describes the propensity or predisposition to be adversely affected (IPCC 2012). Public perceptions of vulnerability vary based on demographic, attitudinal, social, and physical contexts (Brody et al. 2008). Many studies have focused on water vulnerability. Kohl and Knox (2016) explored how interactions between science, nature, and society produce varying epistemologies, scientific and political ways of knowing, about water vulnerability. Similarly, McNeeley et al. (2016) found that water vulnerability perception and management vary based on local nuances and issues, including historical events and natural resources.

Adaptation in human systems refers to the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities, while adaptation in natural systems refers to the process of adjustment to actual climate and its effects (IPCC 2012). Technology is one method of adaptation.

Resilience encompasses the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of essential basic structures and functions (IPCC 2012). Resilience can be strengthened through education, communication, and policymaking.

The relationship between vulnerability, adaptation, and resilience is debated amongst members of the scientific community. Despite debate about the relationships between the terminologies, all three terminologies are manifestations of general processes describing the response to changes in the relationship between open, dynamic systems and their external environments (Lei et al. 2013; Gallopin 2006). Previous studies have established that vulnerability, adaptation, and resilience vary across landscapes and scales, which indicates that the concepts are geographical in nature (Emrich and Cutter 2011; Sullivan 2011).

Water and Drought

Water is fundamental to both human and environmental systems. In water-rich locations, water is a convenient utility. In contrast, water represents day-to-day survival and most activities revolve around water supply and usage in water-poor locations (AAG 2011). Water scarcity threatens food security, as well as overall human health (Hanjra and Qureshi 2010). Without water, biological organisms are unable to complete necessary physiological processes that sustain life (AAG 2011). The three primary water resource issues are shortages, surpluses, and resource impairment. Shortages occur due to droughts, surpluses occur due to floods, and resource impairment occurs due to pollution or contamination. All of these issues contribute to the complexity of water systems.

Water security is most threatened by human activities, climate change, and extreme events. Human factors, including demographic, technological, economic, social, and political factors, greatly influence water supply and demand (Frederick and Major 1997). Currently, the largest source of freshwater withdrawals is for agricultural purposes, primarily irrigation

(Taylor et al. 2013). Increasing populations, development, and standards of living further expand water consumption. Throughout the early part of the century, the primary determinants of changing levels of relative water demand and vulnerability to water stress will be the growth and economic development of the human population (Vorosmarty 2000). The increases in water demand will stress resources, as well as an aging water infrastructure. As a result, there will be large economic costs associated with the implementation of response strategies or the consequences of inaction (Vorosmarty 2000).

In the future, climate change will continue to threaten water availability. Increasing temperatures will accelerate the hydrologic cycle, which will alter precipitation, runoff, evapotranspiration, soil moisture and infiltration, and the intensity and frequency of floods and droughts (Frederick and Major 1997). In response to climate change, water demands will likely change. Agricultural water demands are particularly sensitive to changes in precipitation, temperatures, and carbon dioxide concentrations (Frederick and Major 1997). Groundwater availability will also be impacted by climate change. Groundwater is crucial because it enhances the resilience of domestic, agricultural, and industrial uses of freshwater (Taylor et al. 2013). As variability in precipitation increases, groundwater will become more valuable because it is a source of water during emergency conditions (Taylor et al. 2013). The precise characteristics of future climate change are unpredictable, but projected increases in variability will contribute to water vulnerability.

A warming climate increases the prevalence of extreme events involving and impacting water resources. An extreme event is defined as the occurrence of a value of a weather or climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable (IPCC 2012). An extreme impact reflects highlysignificant and typically long-lasting consequences to society, the natural physical environment, or ecosystems (IPCC 2012). According to the National Oceanic and Atmospheric Administration (NOAA) (2017), water-related events, including tropical cyclones, floods, and droughts, topped the list of Billion Dollar Climate and Weather Disasters from 1980 to 2016.

Drought has a slow onset compared to most extreme events, which can make the affects less tangible. A drought is defined as a period of abnormally dry weather long enough to cause a serious hydrological imbalance (IPCC 2012). There are four types of drought (NOAA 2017): meteorological, hydrological, agricultural, and socioeconomic. A meteorological drought occurs when dry weather patterns dominate an area, hydrological drought occurs when low water supply becomes evident, agricultural drought occurs when crops become affected, and socioeconomic drought relates the supply and demand of various commodities to drought. The four types of drought are interrelated and can impact human systems in a variety of ways. As a result of drought, water resources become stressed. As water resources become stressed, the potential for wildfires increases.

Wildfire

A wildfire is an uncontrolled fire burning in an area of vegetative fuels such as grasslands, brush, or woodlands (High Country Mitigation Plan 2012). Wildfires are influenced by regional climatic and topographic characteristics. Climate influences vegetation productivity and fuel accumulation and controls the frequency of weather conducive to wildfire. Topography influences precipitation, runoff, temperature, wind, and solar radiation, which affect flammability through fuel production and moisture (Flatley et al. 2011).

Historical management practices also influence wildfire characteristics. Since the 1980s, the Forest Service has utilized prescribed burns. Prescribed burns are controlled applications of fire to wildland fuels under specified environmental and weather conditions to produce a fire that is confined to a predetermined area (North Carolina Forest Service 2016). In the absence of prescribed burns, fuel loading occurs. Loading is particularly intense on private lands where prescribed burns do not happen. Heavier fuels combined with other ideal characteristics, such as steep slopes, high winds, high temperatures, low humidity, and low precipitation, increase the vulnerability of communities located along the urban-wildland interface (High Country Mitigation Plan 2012). Drought further increases the frequency and intensity of both anthropogenic and natural wildfire outbreaks.

Both human development and wildfire management has dramatically changed throughout the past century, which has influenced wildfire prevalence. Early fires were caused by lightning. Native Americans increased the frequency and seasonality of lightning-caused fires in the ecosystems they inhabited. In early history, fires varied based on land ownership by the Native Americans and the Europeans. Industrialization, which involved the harvesting of cotton, turpentine, and timber throughout the nineteenth century, contributed to greater fire frequency and intensity (Fowler and Konopik 2007). Fire suppression and land use change began in the early twentieth century. In the absence of fire, important temperate tree species declined in abundance and failed to regenerate, while fire-intolerant species took over (Aldrich et al. 2014). The Forest Service's shift from suppression to management with controlled burning forever changed fire regimes throughout the southeast (Fowler and Konopik 2007).

Wildfires are hazardous to human health, primarily due to smoke exposure. The smoke from wildfires contains pollutants that threaten health, including carbon monoxide, nitrogen dioxide, ozone, particulate matter, polycyclic aromatic hydrocarbons, and volatile organic compounds (Reid et al. 2016). The Environmental Protection Agency (EPA)'s Clean Air Act requires National Ambient Air Quality Standards for six criteria pollutants that are considered harmful to public health and the environment: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM 2.5 and PM 10), and sulfur dioxide (SO_2) (EPA 2017). The Forest Service identifies airborne particulate matter as the component of greatest concern for the public (U.S. Forest Service 2017). Finer particulate matter, PM 2.5, is a greater health concern than larger particulate matter, PM 10, because fine matter is easily trapped by the respiratory system and can penetrate more deeply into the lungs (NCDEQ 2017). Particulates contribute to chronic diseases and reduced life expectancy (Liu et al. 2016). Studies on the health impacts of non-occupational exposure to wildfire smoke have been consistently associated with mortality, respiratory morbidities, and general respiratory effects (Liu et al. 2015). Gradually, the wildfire season has increased and will likely continue to increase in the future due to climate change (Liu et al. 2015; Reid et al. 2016). An increase in wildfires means an increase in smoke exposure, which impacts human health.

Vulnerability to smoke exposure varies according to socioeconomic characteristics. Rappold et al. (2012) found that communities with lower socioeconomic status were at an increased risk from pollutants. Of the socioeconomic indicators, income was the best indicator of risk. Therefore, the health impacts of wildfire can be analyzed on the basis of their spatiotemporal characteristics, as well as the socioeconomic characteristics of the populations that are exposed to them.

Drought and Wildfire in Southern Appalachia

Mountains are complex geographies that experience unique climatological events. The varying climate and topography of mountainous regions influence wildfires. Southern Appalachia's climate is similar to other mid-latitude locations with cold winters and warm summers. However, there is variability in temperature and precipitation amounts across the region due to the elevation gradient, which influences the spatiotemporal characteristics of drought and wildfire events. Previous studies have demonstrated the influence that climate and topography, particularly variations in moisture, have on wildfire in Appalachia (Aldrich et al. 2014; Flatley et al. 2011; Lafon et al. 2005). In the mountains, winds caused by steep topography further encourage wildfire growth. Additionally, a history of wildfires suppression has contributed to accumulating fuel loads, which also encourage wildfire growth.

Southern Appalachia is also characterized by aesthetic beauty and rich biodiversity. The scenic landscape attracts large number of tourists to the region for recreational activities, including hiking and winter sports. Southern Appalachia is a hotspot for salamanders and fungi and home to a variety of endemic species that are found nowhere else in the world (Highlands Biological Station 2017). In Appalachia, wildfire promotes the growth of open forests of oak, chestnut, and pine (Lafon et al. 2005). Wildfire is a valuable component of the ecosystem in Appalachia.

While fire-dependent ecosystems rely on fire, fire-sensitive ecosystems rely on fire suppression. The wildland-urban interface refers to locations where human developments and wildland fuels are located in close proximity to each other (Lein and Stump 2009). Throughout Southern Appalachia, homes and businesses surround patches of dense vegetation, which contributes to wildfire vulnerability. An increasing number of drought events could limit necessary prescribed burning and encourage uncontrollable wildfires that threaten human development. The combination of increased shifts in forest composition and potential for wildfire occurrence could reduce both the quality and quantity of water (Mitchell et al. 2014). Overall, Southern Appalachia's climatological and topographical characteristics are components of a delicate system that will be impacted by projected climate variations.

2016 Drought in North Carolina

The U.S. Drought Monitor (2017) classifies drought on a scale from zero to four. Category zero indicates abnormally dry conditions. Impacts include short-term dryness that slows planting and the growth of crops or pastures. Category one indicates moderate drought. Impacts include some damage to crops and pastures, low streams and reservoirs, developing or imminent water shortages, and voluntary water-use restrictions. Category two indicates severe drought. Impacts include likely crop or pasture losses, common water shortages, and imposed water restrictions. Category three indicates extreme drought. Impacts include major crop and pasture losses and widespread water shortages and restrictions. Finally, category four indicates exceptional drought. Impacts include exceptional and widespread crop and pasture losses and shortages of water in reservoirs, streams, and wells creating water emergencies.

North Carolina has experienced three severe droughts since 2000, according to the U.S. Drought Monitor (2017). The 2002 drought was the most severe drought on record for

North Carolina until 2007. During the week of August 20th in 2002, 33.9 percent of the state was in D4 conditions. The 2007-8 drought is the most severe drought on record for North Carolina. During the weeks of December 11th, 18th, and 25th in 2007, 66.2 percent of the state was in D4 conditions. Though the 2016 drought was not as severe as the droughts in 2002 and 2007-8, it was the third most severe drought on record for North Carolina. The drought records reveal that the beginning of the drought occurred on the week of March 29th, 2016. By November 29th in 2016, 4.5 percent of the state was in D4 conditions.

Western North Carolina went 80 days without a significant rainfall event resulting in greater than a quarter of an inch of precipitation (Margulis 2016). By November, 30 counties in the region were in a drought (Henderson 2016). In Asheville, annual precipitation was 11.5 inches below the normal annual value in November (Margulis 2016). The drought was the worst drought in western North Carolina since the spring of 1985 (Margulis 2016). The dry conditions contrasted conditions in 2015, which was the second-wettest year on record due to an El Nino (Margulis 2016).

Agriculturally, the drought lowered winter hay yields and farms experienced grass and hay shortages, so calves were sold earlier to relieve pressures on feed supplies (Henderson 2016; Margulis 2016). There were reductions in hay and livestock profits for farmers throughout western North Carolina (Margulis 2016). In addition, blueberries were smaller due to the dry conditions (Margulis 2016). Other annual crops, such as tomatoes, corn, and cold beans, required additional irrigation, which further stressed water resources in the region (Margulis 2016).

Ecologically, the drought dried forests, grasses, and creek and river beds (Margulis 2016). In addition, the drought caused tulip and yellow poplar trees to lose their leaves

(Margulis 2016). Other tree species held onto the dry leaves for longer (Margulis 2016). In October, water restrictions began in western North Carolina (Margulis 2016). By November, seven water systems were under mandatory water restrictions (Henderson 2016). Mecklenburg County customers were asked to voluntarily reduce their water use because the county's water supply is the Catawba River, which comes from western North Carolina (Henderson 2016). The dry conditions supported the severe outbreak of wildfires.

2016 Wildfire in North Carolina

Based on records from the North Carolina Forest Service (2016), the year with the highest number of wildfires was 1981 and the year with the highest number of acres burned was 1941 (Figure 2). Due to enhanced fire management, the annual number of acres burned has dramatically decreased throughout the past century. However, the number of wildfires has increased.

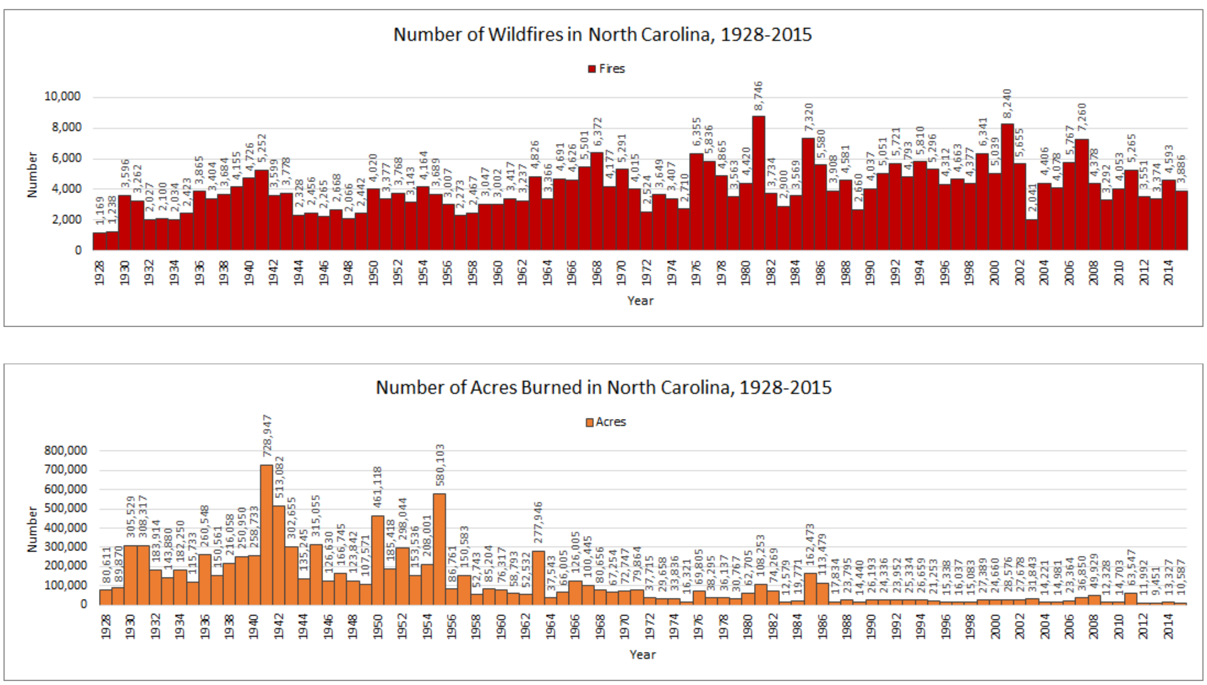

Figure 2. The number of wildfires and acres burned per year since 1928.

North Carolina's fire season generally occurs from late winter through late spring with a shorter season in autumn after the leaves have fallen (Margulis 2016). In the winter and spring, there are drier and windier days due to cold fronts, which encourage wildfire growth (Margulis 2016). Historically, the largest wildfires have occurred in the northeastern portion of North Carolina. The largest fire in state history was the Lake Phelps fire in 1955, in which an estimated 203,000 acres were burned (Davis 2015). Monetary losses, primarily to privately owned timberland, amounted to three to four million dollars (Davis 2015). The second largest fire in state history was the Allen Road fire in 1985, which burned 95,000 acres (Davis 2015). There was an increase in wildfires in the late 1990s through 2011 because of drier air, warmer temperatures, and reduced rainfall attributed to a La Nina (Margulis 2016). The 2008-11 period was a particularly severe fire period for the state’s coastal plains (Margulis 2016). The Evans Road fire was ignited during the worst drought in the state’s history and burned 41,500 acres in 2008, which made it the worst fire since 1985 (Davis 2015). In 2011, the Pains Bay fire burned 45,000 acres and the Juniper Road fire burned 31,140 acres in coastal locations (Margulis 2016). It is unusual for large wildfires to occur in western North Carolina. The recent wildfires resembled the coastal ones because they occurred during a drought and ignited and spread rapidly.

The recent wildfires were supported by a combination of ideal climatic and topographic characteristics, accumulating fuel loads, and extremely dry conditions caused by the drought. La Nina conditions further contributed to wildfires in western North Carolina (Margulis 2016). Arson was suspected as the cause for several wildfires, while others were caused by lightning, unattended campfires, and discarded cigarettes (Washburn 2016). According to the North Carolina Forest Service (2016), the number of fires and acres burned in 2016 was the largest for the past ten-year average for November. As thousands of acres burned, the Forest Service banned open burning in 25 counties in November (Henderson 2016). In addition, the State Parks Division closed Chimney Rock, New River, Gorges, Elk Knob, Mount Mitchell, and Mount Jefferson State Parks (Henderson and Janes 2016). Meteorologists and fire behavior specialists were brought in to predict fire behavior based upon winds, fuels, and terrain (Washburn 2016). Firefighters from all over the country were brought in to work shifts (Washburn 2016).

The recent wildfires resembled fires in California (Washburn 2016). Usually, wildfires burn loads on the ground in western North Carolina. Because the drought kept the leaves on the trees for longer, flames burned higher into canopies (Margulis 2016). Dry conditions allowed fires to penetrate roots, as well as burn riparian areas (Chavez 2016). Ecosystems that are usually moist, such as rich and acidic coves and surfaces covered in moss, were dry and at risk of burning (Chavez 2016). As firefighters created containment lines by cutting trees, removing brush, and clearing leaves, leaves continued to fall on the lines, which caused many wildfires to breach containment repeatedly (Ball 2016; Margulis 2016). Winds combined with steep slopes further contributed to the wildfires by encouraging fires to jump (Henderson and Janes 2016). The warm conditions led to increased evaporation and transpiration, which further exacerbated issues (Chavez 2016).

The winds dispersed smoke across the state, including the Piedmont. In November, air quality warnings were issued throughout North Carolina (Washburn 2016). On November 11th, Chimney Rock ordered mandatory evacuations as nearby wildfires breached containment lines and threatened homes and businesses (Henderson and Janes 2016). Other nearby communities experienced voluntary evacuations (Ball 2016). Hotels in the area were filled with evacuated residents (Washburn 2016). Shelters were moved farther away from the wildfires (Ball 2016).

The brunt of the wildfires occurred around Thanksgiving, which led to disrupted holiday plans. Travelers were advised to use caution when traveling due to smoke on roadways causing limited visibility (Margulis 2016). Many holiday marathons were cancelled due to diminished air quality (Margulis 2016). Hiking trails, including portions of the Appalachian Trail, were closed and hikers were discouraged from hiking due to smoke exposure (Chavez 2016). At nearby campgrounds, campers were encouraged to stay inside and wear a cloth over their faces when outside (Henderson and Janes 2016). The hunting season was interrupted (Chavez 2016). The mountain tourism industry, dependent on the autumn leaf-viewing population, suffered (Washburn 2016). In the end, the blazes totaled more than $30 million in damage (Margulis 2016).

A cold front and significant rainfall moved into western North Carolina on November 28th, which brought many wildfires toward containment (Margulis 2016). On December 9th, the North Carolina Forest Service's Joint Information Network (2016) posted their final post that all fires in western North Carolina were 100 percent contained with the exception of the Rock Mountain Fire, which was 95 percent contained. Finally, precipitation ended the wildfire outbreak by mid-December. Overall, the wildfires negatively influenced quality of life during the final quarter of 2016.

Methods

The availability of socioeconomic and physical data combined with geospatial data collected during last year's unprecedented event offer an opportunity to explore the impacts and characteristics of the recent event and assess vulnerability to future events in western

North Carolina. The two research questions were investigated using targeted data from a variety of sources.

What were the spatiotemporal characteristics of the recent wildfires in North Carolina?

The first objective was to determine when and where large wildfires influenced air quality in North Carolina. The dates with hazardous air quality were determined by looking at ambient measurements of PM 2.5 collected at monitoring stations across the state and available through the North Carolina Department of Environmental Quality (NCDEQ) (2017). The 24-hour primary and secondary regulated standards for PM 2.5 are 35 micrograms per cubic meter of air ($\mu g/m^3$); however, many days had one or more stations that greatly exceeded these standard values (EPA 2017). All stations that recorded a measurement in the highest range ($\geq 56\ \mu g/m^3$) were explored. A total of eight days and thirteen monitoring station measurements revealed hazardous levels of PM 2.5 in November (Table 1).

Table 1. Dates with unhealthy air quality.

Date	**Hazardous PM 2.5 Measurement** ($\mu g/m^3$)
11/9/2016	Bryson City - 56.4
11/12/2016	Bryson City - 57.6
11/13/2016	Board of Education Building - 87.0 Bryson City - 65.2
11/14/2016	Board of Education Building - 69.0 Bryson City - 63.1 Hickory First Street - 59.7 Spruce Pine - 62.5
11/15/2016	Hickory First Street - 59.0
11/16/2016	Garinger High School - 60.7
11/22/2016	Spruce Pine - 82.5
11/23/2016	Board of Education Building - 65.2 Bryson City - 99.4

The next step was to run backward trajectories for the days with hazardous air quality. The NOAA Air Resources Laboratory (ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model and 40-kilometer Eta Data Assimilation System (EDAS) three-hour archive data were to create 72-hour backward air trajectories ending at each station recording an unhealthy measurement of particulate matter. Three atmospheric heights were modeled: the lower atmosphere at 500 meters, the middle at 3,000 meters, and the upper at 5,000 meters. Shapefiles for each trajectory were downloaded. The trajectory shapefiles were available in point form with identification numbers corresponding to the atmospheric level and trajectory hour.

Using ArcMap 10.3.1, each of the trajectory shapefiles were divided into three shapefiles: one for the lower atmosphere, one for the middle atmosphere, and one for the upper atmosphere. The points to line tool was used to create lines connecting the points for each of the three atmospheric heights for each station. The merge tool was used to combine the three trajectory lines for each station into a single shapefile with attributes edited to reflect the atmospheric height. A one-mile buffer was applied to all of the trajectory lines to compensate for trajectory errors (NOAA 2007).

Boundary polygons for wildfires occurring in November in North Carolina (33) and the surrounding states of South Carolina (1), Tennessee (26), Georgia (5), and Virginia (3) were acquired from the National Interagency Fire Center (NIFC)'s File Transfer Protocol (FTP) Server, which is an official site for interagency wildland fire incident data and documents (NIFC 2017). The majority of the polygons were based upon infrared heat perimeters. All polygons were combined into shapefiles by state using the merge tool. The attribute table was edited to include the date of the most recent boundary update, the states affected by the wildfire, and the pathname to the source. The approximate start and containment dates of each wildfire were also added to the attribute table based upon information on InciWeb (2017). When no information about start and containment dates was available on InciWeb, information from imagery collection dates, newspaper articles, and community updates were used to approximate the dates. The state wildfire shapefiles were merged into one shapefile and projected into Albers Conical Equal Area. Acreage was calculated for each of the wildfire boundaries (Table 2).

Table 2. Wildfires in North Carolina and surrounding states in 2016.

Fire Name	Affected State	Start Date	Containment Date	GIS Acres
Bald Knob	TN	11/20/2016	11/27/2016*	1293.2
Beech Grove Road	TN	11/19/2016	11/27/2016*	360.6
Bench Bluff	TN	11/7/2016	11/16/2016*	2024.8
Big Poplar	TN	11/17/2016	11/19/2016*	146.6
Boardtree	NC	10/25/2016*	12/15/2016*	0.4
Boteler	NC	10/25/2016	12/15/2016	9025.3
Buck Creek	NC	10/25/2016*	12/15/2016*	5.5
Bull Pen	NC	10/25/2016*	12/15/2016*	6.4
Burrell	GA	11/10/2016*	11/12/2016*	164.0
Camp Branch	NC	11/23/2016	12/15/2016	3423.9
Cathey Gap	NC	11/17/2016	11/25/2016	122.8
Cave Cove	TN	11/15/2016	11/18/2016*	277.9
Charley Creek	NC	10/25/2016*	12/15/2016*	6.4
Chestnut Knob	NC	11/6/2016	12/4/2016	6436.4
Chimney Rock	TN	11/26/2016*	11/27/2016*	524.7
Chimney Tops 2	TN	11/23/2016	12/20/2016	17896.2
Clear Creek	NC	11/20/2016	12/1/2016	3164.8
Cliffside	NC	11/2/2016	11/10/2016	110.4
Cool Branch Road	TN	11/19/2016*	11/24/2016*	314.1
Dick's Creek	NC	10/23/2016	12/2/2016	728.8
Dobson 3	NC	11/2/2016	11/25/2016	565.6
Eades Hollow	VA	11/22/2016*	11/22/2016*	886.0

East Miller Cove	TN	11/17/2016	12/1/2016*	1502.1
Flipper's Bend	TN	11/5/2016	11/13/2016*	2074.0
Grape Cove	NC	10/26/2016*	12/15/2016*	10.6
Highway 151	NC	11/24/2016	11/27/2016	245.3
Hobbstown	TN	11/14/2016	11/16/2016*	820.8
Horton	NC	11/21/2016	12/2/2016	1420.7
Howard Gap	NC	10/25/2016*	12/15/2016*	0.2
Ivydale Trail 2	TN	11/24/2016*	11/27/2016*	85.2
Jones Creek	NC	10/25/2016*	12/15/2016*	0.9
Jones Gap	NC	10/29/2016*	12/15/2016*	8.2
Knob	NC	11/2/2016	11/20/2016	1129.8
Lee Valley Road	TN	11/20/2016*	11/22/2016*	310.6
Little Brushy Road	TN	11/23/2016	11/27/2016*	435.0
Maple Springs	NC	11/4/2016	12/5/2016	7780.8
May Branch	NC	11/3/2016	11/12/2016	175.4
Mile Marker 156	TN	11/12/2016	11/22/2016*	943.7
Moses Creek	NC	10/28/2016	11/10/2016	29.6
Moss Knob	NC	10/25/2016*	12/15/2016*	6.8
Mount Pleasant	VA	11/19/2016	11/29/2016	11212.0
Mulberry	NC	10/25/2016*	12/15/2016*	1.3
Muskrat Valley	NC	11/11/2016	11/21/2016	103.6
Neddy Mountain Road	TN	11/11/2016	11/17/2016*	926.0
New River Fires	TN	11/17/2016*	11/17/2016*	3949.0
Nick	NC	10/25/2016*	12/15/2016*	0.2
Old Mountain Road	TN	11/17/2016	11/20/2016*	201.0
Old Roughy	NC	11/8/2016	12/5/2016	658.1
Party Rock	NC	11/5/2016	11/29/2016	7143.5
Pinnacle Mountain	NC, SC	11/9/2016	12/5/2016	10178.3
Quarry Creek	TN	11/16/2016*	11/20/2016*	572.9
Rattlesnake Hollow	TN	11/21/2016*	11/21/2016*	190.4
Raven Rock	VA, KT	11/5/2016*	11/25/2016*	2029.4
Ridge Gap	NC	10/25/2016*	12/15/2016*	1.4
Rock Mountain	GA, NC	11/9/2016	12/15/2016	24708.0
Rough Ridge	GA	10/16/2016	11/30/2016	28087.9

Stinking Creek	TN	11/15/2016*	11/16/2016*	10628.4
Stoney Fork Road 3	TN	11/21/2016	11/27/2016*	1444.9
Tatum Gulf	GA, AL	11/13/2016*	11/21/2016*	3519.2
Tellico	NC	11/3/2016	12/15/2016	13877.1
Tiger Creek	TN	11/23/2016*	11/25/2016*	6.4
Timber Ridge	GA	11/12/2016	11/25/2016	1102.4
Tracey Beach Road	TN	11/25/2016*	11/25/2016*	5.3
Washington Creek	NC	11/10/2016	11/10/2016	179.5
White Oak Circle	TN	11/15/2016*	11/20/2016*	3135.3
Whitewater	NC	10/25/2016*	12/15/2016*	22.9
Wine Springs	NC	10/25/2016*	12/15/2016*	92.8
Wolf Creek	TN	11/21/2016*	11/21/2016*	379.2

*Date approximated from imagery collection dates or other supplementary information.

Next, the trajectories and wildfire polygons were intersected to determine whether the hazardous levels of particulate matter measured at monitoring stations could be attributed to wildfires occurring at the same time. The trajectory lines for each station and the combined wildfires shapefile were intersected using the intersect tool. The results of the intersections were compared to the start and containment dates of the wildfires to determine which wildfires contributed to hazardous air quality.

Where is wildfire vulnerability in western North Carolina?

The second objective was to determine where wildfire vulnerability is by creating a socioeconomic vulnerability index based on socioeconomic characteristics, a wildfire hazard index based on physical characteristics, and an overall wildfire vulnerability index based on a combination of the socioeconomic and physical indexes.

The first step was to determine where vulnerable communities are located in the western portion of the state based on selected socioeconomic characteristics that make populations more vulnerable to wildfire exposure. Data were obtained from the U.S. Census

Bureau's American FactFinder (U.S. Census Bureau 2017). American Community Survey (ACS)'s 5-year estimates were selected because the 5-year estimates are the most reliable estimates available (U.S. Census Bureau 2016). One variable was acquired from the 2010 Census instead of ACS.

Socioeconomic characteristics relevant to wildfire vulnerability were selected based on a countrywide comparative study of wildfire potential and social vulnerability by Wigtil et al. (2016). The variables that related specifically to wildfire vulnerability were chosen. Percentages were obtained or calculated to normalize the data across the study area. The total percentage of younger (under 5 years old) and older (65 years or older) individuals in each tract were included because these groups are most vulnerable to wildfire exposure (EPA 2016). The percentage of individuals in poverty were included because these populations may lack the economic resources to avoid wildfire exposure. The percentages of individuals with disabilities and households without vehicles were included because these populations are more likely to lack mobility in emergency situations. Individuals lacking proficiency in English were also included because these populations are less likely to be informed about wildfire events. Finally, the percentage of individuals classified as "rural" during the 2010 Census were included because rural individuals are less likely to have access to telephone and internet communications or to receive announcements about wildfire events. Variables concerning race and gender were omitted because though they influence social vulnerability, they do not directly influence wildfire vulnerability.

Data were downloaded for the state at the census tract level. Tracts enable a higher amount of detail than counties, while also having the selected variables available. The data were joined to 2016 TIGER/Line shapefiles of census tracts obtained from the U.S. Census

Bureau (2017). The tracts falling within the counties in the western portion of the state were exported from the statewide file as a new shapefile of census tracts with joined socioeconomic characteristics. There was no information available for three of the tracts (9801 in Haywood County, 9801 in Henderson County, and 9802 in Swain County), so they were omitted from the study.

The socioeconomic variables for the joined census tracts were converted to raster using the polygon to raster tool. A cell size of 30 meters was selected to allow for subsequent comparison with raster datasets of elevation, aspect, slope, and land cover. The reclassify tool was used to reclassify the six socioeconomic variables. Each variable was classified into ten classes using the equal interval method. The lowest percentages were classified as ones and the highest percentages were classifieds as tens.

The reclassified datasets were combined using raster calculator. Weights were not assigned to the values because each of the variables equally influence vulnerability. Each of the six variables was multiplied by 0.16 and added together using raster calculator. The result was a socioeconomic vulnerability index ranging from 1.8 to 5.8. The raster calculator was used to create a raster displaying all cells with values equal to 5.8 and a raster displaying all cells equal to 1.8. The tracts shapefile was then overlaid onto the output to determine which tracts had the highest and lowest socioeconomic vulnerability.

The second step was to determine vulnerable locations in the western portion of the state based on topographic characteristics that make landscapes more susceptible to wildfire. The 30-meter 2011 National Land Cover Database (NLCD) was obtained from the Multi-Resolution Land Characteristics Consortium (MRLC) (2017). The NLCD was clipped with the shapefile of the 27 counties in western North Carolina using the raster clip tool.

The 20-foot digital elevation models (DEM) for each of the counties in western North Carolina were obtained from North Carolina One Map (2017). The DEMs were mosaicked together using the mosaic to new raster tool. The DEM was then projected into Albers Conical Equal Area. A cubic convolution resampling technique was selected because it is the best method for continuous data (ESRI 2017). The cell size was changed to 30 meters for uniformity. From the DEM, slope and aspect were derived using the slope and aspect tools.

The next step was to reclassify elevation, slope, aspect, and land cover based upon their influence on wildfire. The reclassification values were selected based on a study on the influence of various topographic factors on wildfires in eastern Kentucky by Maingi and Henry (2007). For elevation, the highest elevations were reclassified with the highest values. Elevation influences moisture and vegetation composition. Oaks and other highly-combustible hardwood species are found at higher elevations in the southeastern portion of the country (Maingi and Henry 2007). For aspect, southern and southwest facing slopes were reclassified with the highest values. Slopes facing the south and southwest receive the most solar radiation in the Northern Hemisphere (Auburn University 2017). As a result, southern and southwest facing slopes are the warmest and driest and stay greener for longer. For slope, the steepest grades were reclassified with the highest values. Steep slopes encourage wildfire growth by facilitating precipitation runoff and rapid burning due to greater radiant and convective heat combined with drafts (Auburn University 2017). Steep slopes also make wildfire containment more challenging.

For land cover, water land cover types, including open water and perennial ice and snow, were assigned classification values of zero. Wetland land cover types, including woody wetlands and emergent herbaceous wetlands, were assigned values of one. Barren land consisting of rock, sand, and clay was assigned a value of two. Developed low, medium, and high intensity lands were assigned values of three. Developed open space land was assigned a value of four. The vegetative land cover types were classified the highest, based on findings by Lein and Stump (2009). The planted and cultivated land cover types, including pasture and hay and cultivated crops, were assigned values of six. Shrub land cover was assigned a value of seven. Grassland and herbaceous land cover was assigned a value of eight. Finally, evergreen forest was assigned a value of nine and mixed and deciduous forests were assigned values of ten.

The reclassified datasets were combined using raster calculator. Fuel is the most important variable influencing wildfire, followed by slope (Maingi and Henry 2007). The land cover layer was weighted at 40 percent, the slope layer was weighted at 30 percent, and the elevation and aspect layers were weighted at 15 percent. While elevation and aspect also influence wildfire, their influence is not as strong. The variables were added together using raster calculator. The result was a wildfire hazard index ranging from 0.8 to 9.7. The raster calculator was used to create rasters displaying cells with values less than 5 and cells greater than 5. The zonal statistics as table tool was then used to produce a count of the number of highest and lowest hazard cells falling into each county. A new field was created in the zonal statistics table and the percentages of each county with high hazard and low hazard were calculated.

The final step was to produce an index of wildfire vulnerability. The socioeconomic vulnerability index and wildfire hazard index were each weighed at 50 percent and added together using raster calculator. The result was the combined wildfire vulnerability index ranging from 1.4 to 7.4. The raster calculator was used to create a raster displaying all cells with values greater than 5 and a raster displaying all cells less than 5. The zonal statistics as table tool was then used to count the number of highest vulnerability cells and lowest vulnerability cells falling into each count. A new field was created in the zonal statistics table and the percentage of each county with high vulnerability and the percentage of each county with low vulnerability was calculated.

Results

What were the spatiotemporal characteristics of the recent wildfires in North Carolina?

The acreage calculations revealed that the largest wildfire in the vicinity of North Carolina was the Rough Ridge fire in Georgia, which spanned 28,088 acres. Rough Ridge was followed by the 24,708-acre Rock Mountain fire in Georgia and North Carolina, 17,896-acre Chimney Tops 2 fire in Tennessee, 13,877-acre Tellico fire in North Carolina, and 11,211-acre Mount Pleasant fire in Virginia. In addition to the Rock Mountain and Tellico fires, the 9,025-acre Boteler fire, 7,781-acre Maple Springs fire, and 7,143-acre Party Rock fire were significant events that took place in western North Carolina in 2016. All of the aforementioned fires began in late October or early November and persisted until containment in late November or early December of 2016. In addition, all of the wildfires in North Carolina occurred in the counties comprising the western portion of the state where drought conditions were the most extreme throughout 2016.

Intersections between lower-level atmospheric trajectories and wildfire events were the focus of the study because particulate matter is most likely to travel through the lower atmosphere, but middle and upper level intersections are noted as well. On November 9th, the Bryson City station in Swain County measured 56.4 $\mu g/m^3$ of PM 2.5. Based on the trajectory and wildfire intersections, the measured levels of particulate matter at the station can be attributed to a combination of lower-level smoke from the Rock Mountain fire in Georgia and North Carolina. There were also intersections between the middle-level trajectory and the Flipper's Bend fire in Tennessee and middle and upper-level trajectories and the Maple Springs fire in North Carolina.

On November 12th, the Bryson City station in Swain County measured 57.6 $\mu g/m^3$ of PM 2.5. The levels of particulate matter possibly resulted from lower-level smoke from the Stoney Fork Road Three, Stinking Creek, New River, and Ivydale Trail Two fires in Tennessee, but the exact dates for these fires are uncertain. There was also an intersection between the upper-level trajectory and the Maple Springs fire in North Carolina.

On November 13th, the Board of Education station in Buncombe County and Bryson City station in Swain County recorded unhealthy levels of PM 2.5. The Board of Education station measured 87.0 $\mu g/m^3$. There were intersections between the middle-level trajectory and the Flipper's Bend fire in Tennessee and the upper-level trajectory and the Maple Springs and Dobson Three fires in North Carolina. The Bryson City station measured 65.2 $\mu g/m^3$. The levels of particulate matter possibly resulted from lower-level smoke from the Washington Creek fire in North Carolina, but the exact date for this fire is uncertain. There were also intersections between the upper-level trajectory and the Maple Springs and Old Roughy fires in North Carolina.

On November 14th, the Board of Education station in Buncombe County, Bryson City station in Swain County, Hickory First Street station in Catawba County, and Spruce Pine station in Mitchell County recorded unhealthy levels of PM 2.5. The Board of Education station measured 69.0 $\mu g/m^3$; however, there were no intersections between the wildfire polygons and air trajectories for this station on this day. The Bryson City station measured

63.1 μg/m^3. The levels of particulate matter can be attributed to a combination of lower-level smoke from the Charley Creek, Tellico, and Party Rock fires in North Carolina. There was also an intersection between the middle-level trajectory and the Dobson Three fire in North Carolina and the upper-level trajectory and the Party Rock fire in North Carolina. The Hickory First Street station measured 59.7 μg/m^3; however, there were no intersections between the wildfire polygons and the air trajectories for this station on this day. The Spruce Pine station measured 62.5 μg/m^3. There were intersections between the middle and upper level trajectories and the Chestnut Knob fire in North Carolina.

On November 15th, the Hickory First Street station in Catawba County measured 59.0 μg/m^3 of PM 2.5. The levels of particulate matter can be attributed to a combination of middle-level smoke from the White Oak Circle, Stinking Creek, and Mile Marker 156 fires in Tennessee and the Rock Mountain fire in Georgia and North Carolina and upper-level smoke from the Maple Springs fire in North Carolina. The levels of particulate matter also possibly resulted from upper-level smoke from the Washington Creek fire in North Carolina, but the exact date for this fire is uncertain.

On November 16th, the Garinger High School station in Mecklenburg County measured 60.7 μg/m^3 of PM 2.5. There was an intersection between the upper-level trajectory and the New River fires in Tennessee, but the exact dates for these fires are uncertain.

On November 22nd, the Spruce Pine station in Mitchell County measured 82.5 μg/m^3 of PM 2.5; however, there were no intersections between the wildfire polygons and air trajectories for this station on this day.

On November 23rd, the Bryson City station in Swain County and Board of Education station in Buncombe County recorded unhealthy levels of PM 2.5. The Bryson City station measured 65.2 μg/m^3. The levels of particulate matter can be attributed to a combination of lower-level smoke from the Tellico and Boteler fires in North Carolina. There were also intersections between the middle and upper level trajectories and the Maple Springs fire in North Carolina. The Board of Education station measured 99.4 μg/m^3. The levels of particulate matter can be attributed to a combination of lower-level smoke from the Dick's Creek and Dobson Three fires in North Carolina and the Chimney Tops Two fire in Tennessee. There was also an intersection between the upper-level trajectory and the Chimney Tops Two fire in Tennessee.

In summary, six measurements of unhealthy particulate matter were successfully attributed to wildfires through lower-level trajectories: November 9th, 12th, 13th, 14th, and 23rd at the Bryson City station in Swain County and November 23rd at the Board of Education station in Buncombe County (Table 3). All of the air quality monitoring stations that reflected diminished air quality that could be attributed to specific wildfires were located in western North Carolina. This indicated that western North Carolina's quality of life was particularly impacted by the wildfires in 2016.

Table 3. Measurements attributed to wildfire events through lower-level trajectories.

Date	Station	Wildfire Event(s)
11/9/2016	Bryson City	Rock Mountain
11/12/2016	Bryson City	Stoney Fork Road 3, Stinking Creek, New River, Ivydale Trail 2
11/13/2016	Bryson City	Washington Creek
11/14/2016	Bryson City	Charley Creek, Tellico, Party Rock
11/23/2016	Bryson City Board of Education	Tellico, Boteler Dick's Creek, Dobson Three, Chimney Tops 2

Where is wildfire vulnerability in western North Carolina?

The results of the socioeconomic vulnerability analysis revealed that the tract with the highest vulnerability value, 5.8, was Tract 9010.03 in Surry County and the tracts with the lowest vulnerability, 1.8, was Tract 22.05 in Buncombe County and Tract 9306 and Henderson County (Figure 3).

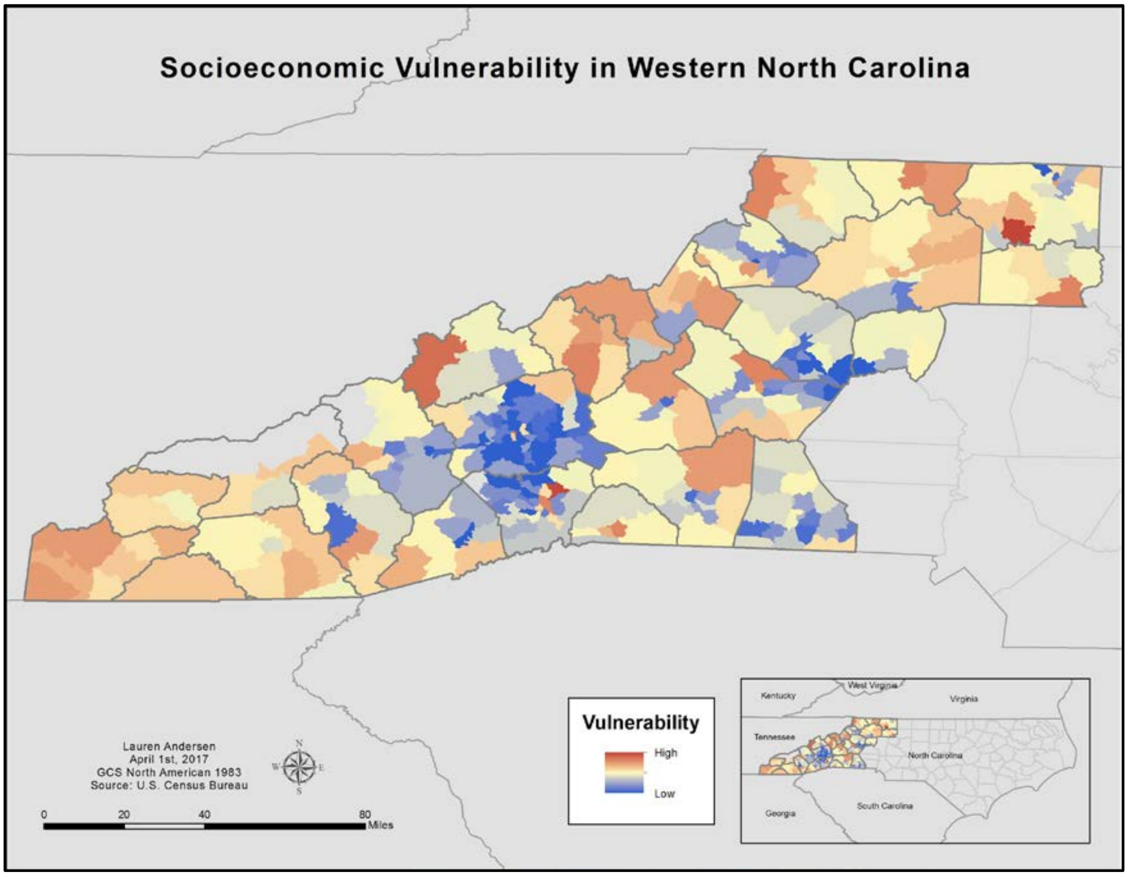

Figure 3. The results of the socioeconomic vulnerability analysis for western North Carolina.

The results of the wildfire hazard analysis based on physical characteristics revealed that Swain County has the highest wildfire hazard, while Cleveland County has the lowest wildfire hazard (Figure 4). Swain County has the highest percentage of high hazard cells with 95 percent of the cells in the county above an index value of 5, followed by Graham (93 percent), Jackson (92 percent), Mitchell (92 percent), and Yancey (92 percent). Cleveland County has the highest percentage of low hazard cells with 59 percent of the cells in the county below an index value of 5, followed by Yadkin (57 percent), Alexander (43 percent), Surry (40 percent), and Rutherford (36 percent).

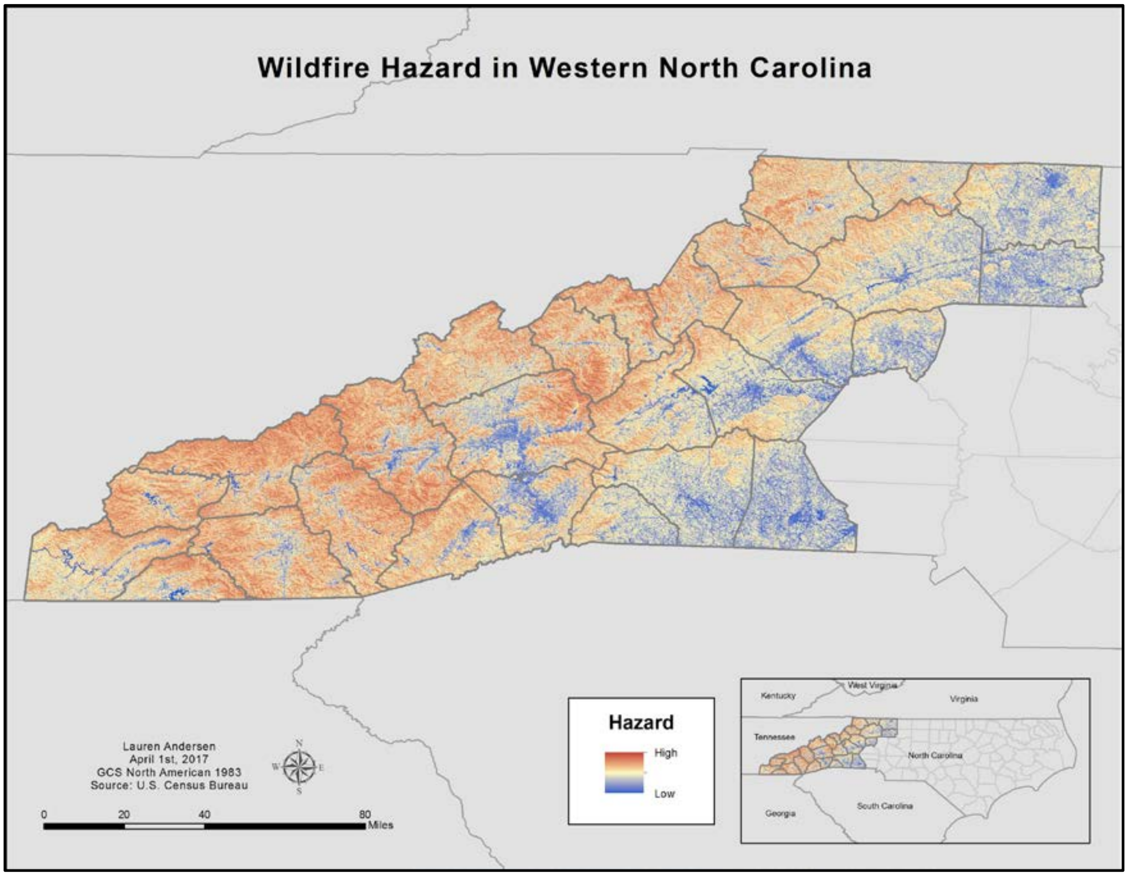

Figure 4. The results of the wildfire hazard analysis for western North Carolina.

The wildfire polygons were overlaid on the wildfire hazard analysis (Figure 5). A comparison between the hazard index and wildfire polygons reveals that the wildfire hazard index is an accurate predictor of wildfire activity. All of the wildfires fall within locations with moderate to high wildfire hazard values, which indicates that the classification values for the physical characteristics were suitable for evaluating vulnerability in western North Carolina.

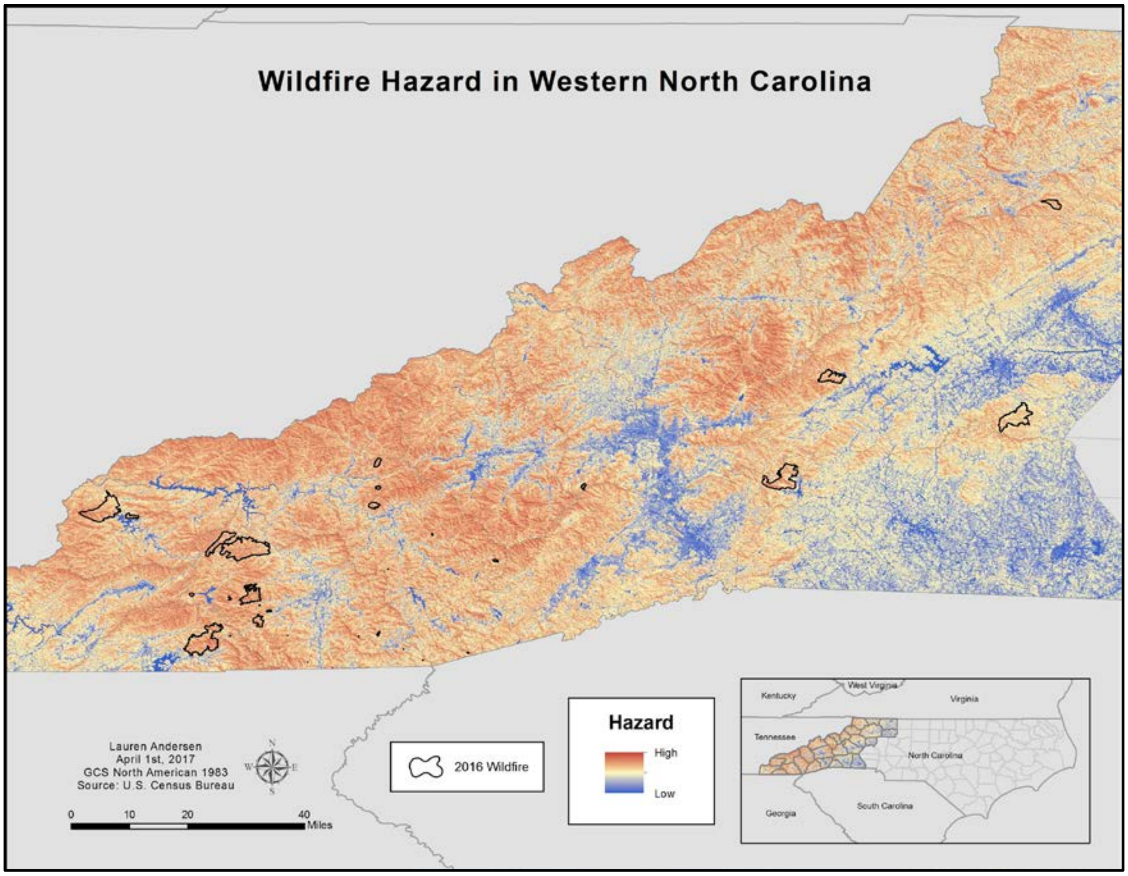

Figure 5. The wildfire hazard analysis with wildfires from 2016.

The socioeconomic vulnerability and wildfire hazard analyses were combined to produce an overall wildfire vulnerability index (Figure 6). The wildfire vulnerability index revealed patterns of vulnerability across western North Carolina. The results of the overall wildfire vulnerability analysis revealed that Graham County has the highest overall vulnerability to wildfires, while Cleveland County has the lowest overall vulnerability to wildfires. Graham County has the highest percentage of high vulnerability cells with 91 percent of the cells in the county above an index value of 5, followed by Yancey (90 percent), Mitchell (89 percent), and Swain, Cherokee, and Macon (86 percent). Cleveland County has the highest percentage of low hazard cells with 87 percent of the cells in the county below an index value of 5, followed by Yadkin (75 percent), Alexander (68 percent), Surry (58 percent), and Henderson (55 percent). Overall, vulnerability increased moving southwestward and decreased moving eastward toward the Piedmont of North Carolina.

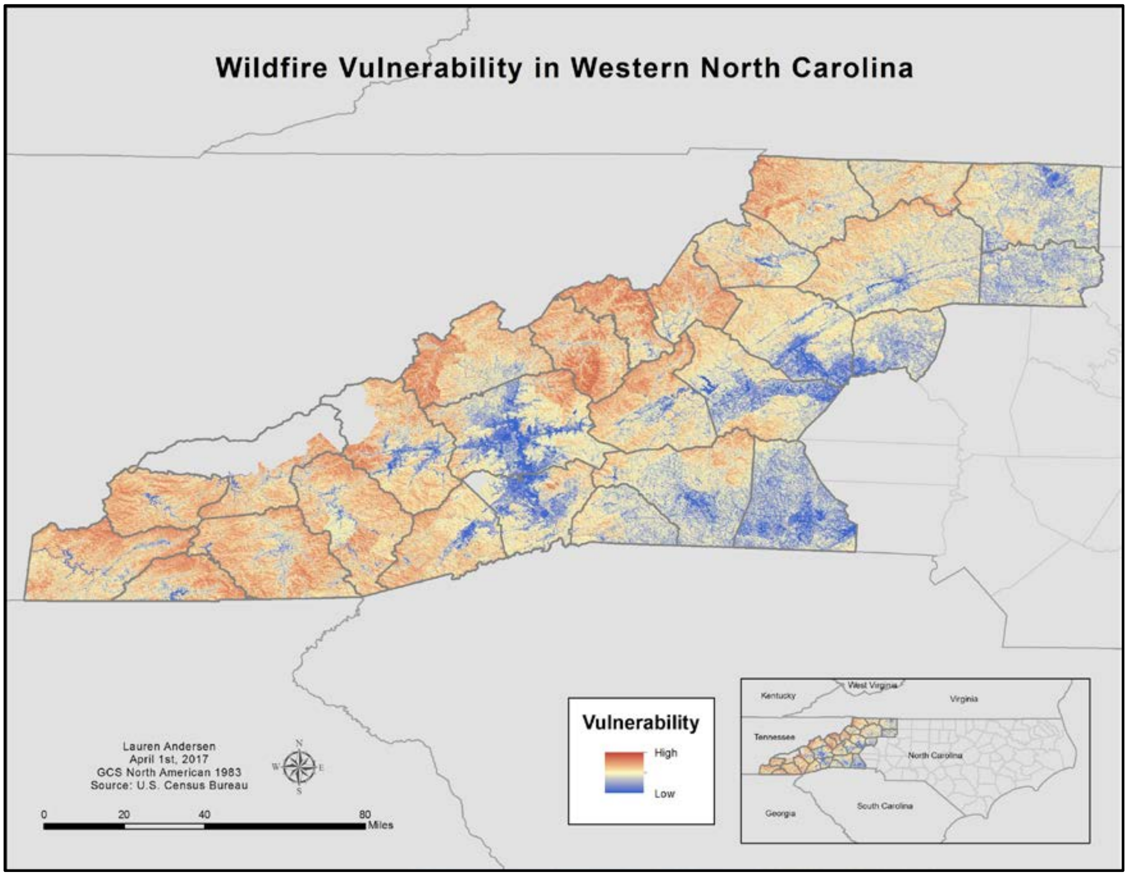

Figure 6. The results of the combined wildfire vulnerability analysis for western North Carolina.

Discussion

The extremely dry conditions beginning in the spring most significantly contributed to the wildfire outbreak in the fall. The wildfire outbreak impacted most of the southeastern United States, especially the Appalachian Mountains. Many of the days with the unhealthiest air quality in the state were attributed to large wildfires, including the Rock Mountain, Tellico, Party Rock, and Boteler fires, using trajectories. The smoke from the wildfires affected air quality throughout North Carolina, even as far east as Charlotte. Western North Carolina was particularly impacted by wildfires with approximately 33 wildfires occurring in

November. The wildfires followed the spatiotemporal pattern of the drought with the worst of both the drought and the wildfires occurring in the counties comprising western North Carolina, particularly the southwestern ones.

Newspaper articles illustrate how the western portion of the state was impacted particularly dramatically by the drought and wildfires. Throughout the western portion of the state, communities were evacuated and individuals were encouraged to remain inside for many days in November. Individuals with respiratory conditions struggled to breath amidst the blanket of smoke covering the state and populations who were normally not impacted by smoke exposure experienced diminished quality of life as the wildfires persisted. There were regulations placed on water usage and open burns and business owners were forced to close during the peak season for tourism because many popular tourist attractions were closed or unsafe to visit. In addition to the economic loses by local business owners, FEMA, North Carolina, and surrounding states expended millions of dollars fighting the wildfires. As revealed by analyses of articles and modeling of impacts, the influence of wildfires, especially wildfires as unprecedented as the recent ones, is complex and far-reaching across spatiotemporal scales.

The socioeconomic vulnerability analysis revealed the highest socioeconomic wildfire vulnerability in a tract in Surry County, which is a rural location bordering Elkin, North Carolina. Vulnerability is greatest here because the population is largely rural and have fewer resources and less mobility compared to surrounding locations in western North Carolina. It is likely that access to emergency services and communications is limited for many individuals. A wildfire event would likely be unexpected for many members of the population and as a result, individuals would struggle to cope with the impacts. In counties where all tracts demonstrate moderate to high vulnerability, such as Cherokee, Clay, and Graham, emergency services would be particularly taxed and communities would be especially vulnerable in the event of a wildfire. In contrast, the lowest socioeconomic wildfire vulnerability was in adjacent tracts in Buncombe and Henderson counties. A cluster of low vulnerability can be seen in central the central portion of western North Carolina surrounding Buncombe County, which is home to Asheville, North Carolina. Asheville is urbanized with a rapidly-growing young population. Wildfires have the potential to be destructive in urban locations, as seen in Gatlinburg, Tennessee in 2016. However, urban communities have the resources and mobility to be adaptive and resilient when confronted with wildfire exposure. The urbanized nature of this location means that communities have greater access to emergency services and communications as well. Overall, the greatest amount of socioeconomic vulnerability related to wildfires occurs in the southwestern portion of the state and decreases moving away from the mountains and toward the piedmont of North Carolina. The stark contrast between Buncombe and Watauga and other western counties highlights a troubling disparity that is prevalent in many scenic regions dependent on tourism and seasonal industries. This disparity further contributes to the challenge of equitably addressing vulnerability in policymaking.

The wildfire hazard analysis revealed the highest percentage of susceptibility to wildfire is in Swain County, followed by the counties of Graham, Jackson, Mitchell, and Yancey. Many of the counties are toward the southwestern portion of western North Carolina, so they have the greatest elevation, slope, and vegetation. The lowest percentage of susceptibility to wildfire is in Cleveland County, followed by the counties of Yadkin, Alexander, Surry, and Rutherford. All of the counties are toward the easternmost portion of western North Carolina, so they have the lowest elevation and slope and least vegetation.

In the case of the outbreak in 2016, a perfect storm of ideal conditions came together to produce unprecedented wildfire throughout Southern Appalachia. Wildfire probability is influenced by meteorological and atmospheric factors, such as La Ninas, and these factors should also be considered when assessing wildfire hazard. Though dry conditions cannot be controlled, other contributors to the wildfires, such as accumulating fuel loads, can be. Currently, the Forest Service uses controlled burns for fire management, but these controlled burns require money and manpower and cannot be conducted unless conditions are perfect for burning. Additionally, controlled burns only occur on public lands, which leaves fuels to accumulate on private lands. In many states, the Department of Natural Resources offers services to assist private landowners with developing prescribed burn plans, which can help cut back on accumulating fuel loads on private lands. The human influence on wildfire also cannot be ignored. In 2016, many wildfires began as a result of irresponsible behavior or arson. Public outreach can help inform citizens about the consequences of irresponsible actions in nature. Patrols and surveillance of popular camping destinations, as well as tougher penalties, can help curb arson.

The combined vulnerability analysis reflects a combination of the results from the socioeconomic vulnerability and wildfire hazard analysis. Graham County has the highest percentage of wildfire vulnerability, followed by Yancey, Mitchell, and Swain, Cherokee, and Macon counties. Cleveland County has the lowest percentage of vulnerability, followed by Yadkin, Alexander, Surry, and Henderson counties. Graham County is located in the southwestern portion of western North Carolina and has high socioeconomic vulnerability.

Cleveland County is located in the eastern portion of the county and has low socioeconomic vulnerability. The results reveal that wildfire vulnerability increases moving farther into Appalachia. The increase in vulnerability moving westward can be attributed to ideal topographic conditions for wildfire growth, larger numbers of rural populations, and a growing urban-wildland interface throughout the southeastern Appalachian Mountains. Because mountain environments are more vulnerable to wildfire hazard, emergency management dealing with wildfire events should focus on communities living in mountain environments.

To increase awareness about the impacts of climate change on wildfire events and improve community resilience, it is imperative that public participation involving education, communication, and discussion takes place. It is also imperative that counties develop emergency management programs that consider small-scale characteristics. Programs that effectively address vulnerability provide special consideration to populations who are young, elderly, impoverished, disabled, or without access to transportation and communication services. In addition, effective programs consider the physical landscape and how various factors influence vulnerability to extreme events, such as drought.

It is also crucial that policymakers look toward the future. NOAA (2017)'s Quarterly Climate Impacts and Outlook for Winter 2017 revealed decreased streamflow, lake levels, and soil moisture persisting throughout the first quarter of 2017 resulting from the drought event in 2016. In addition, the review revealed above average temperatures and below average precipitation across the southeast region. As a result, the drought reintensified across western North Carolina in early 2017. The recent recurring drought events reinforce how important it is for policymakers to begin to plan for increased temperature and precipitation extremes and the subsequent droughts and wildfires that could accompany them.

There were several limitations to this study. Most pollutants have numerous sources, so it is challenging to distinguish pollutants caused strictly by wildfires. It is possible that some levels of pollutants stem from events other than wildfires. In addition, the study did not include all wildfire events occurring in the southeastern United States. There were several smaller wildfires where fire perimeter shapefiles were unable to be produced due to smoky conditions, such as the Roaring fire in Virginia. These wildfires were excluded from the study. Another limitation is the estimated 15 to 30 percent error associated with trajectory travel distance (NOAA 2007). The one-mile buffer was applied to compensate for this error; however, it is possible that the trajectories were not completely representative of atmospheric patterns. In the socioeconomic analysis, three counties had to be omitted due to lack of data, which could have influenced the results. ACS estimates do have high margins of error; therefore, the results are subject to inaccuracies.

In the future, forward trajectories would enhance the depth of this study by determining how each wildfire event impacted air quality. Additional information on air masses and data on other pollutants could also improve the study. The addition of more socioeconomic variables, such as occupation and access to telephone and internet services, could enhance the results of the socioeconomic vulnerability analysis. The integration of remotely-sensed imagery of vegetation and variables such as distance to water and development could strengthen the assessment of wildfire hazard locations. The analyses in this study could also be expanded to incorporate a larger geography to assist policymakers with planning for water vulnerability across regional boundaries.

Conclusion

The extreme drought combined with ideal climatic conditions and topographic characteristics and fuel loads fostered unprecedented wildfire development throughout the southeastern United States in 2016. Wildfires throughout the southeastern portion of the country brought smoke into North Carolina, which diminished quality of life throughout the state. In western North Carolina, wildfires and subsequent smoke exposure dramatically influenced the local economy by disrupting the largest tourism season. The recent events offered an opportunity to explore the impacts and characteristics of wildfires in North Carolina. Following the pattern of the drought event, the wildfires occurred in the final quarter of 2016 and most dramatically impacted air quality in western North Carolina. According to the calculated acreage, the largest wildfire occurring in the state was the Tellico fire, which totaled 13,877 acres. The 9,025-acre Boteler fire, 7,781-acre Maple Springs fire, and 7,143-acre Party Rock fire also significantly impacted communities in western North Carolina.

Socioeconomically, Surry County had the tract with the highest amount of vulnerability, while Buncombe and Henderson County had tracts with the least amount of vulnerability. Based upon physical characteristics of the landscape, the county with the greatest wildfire hazard was Swain County and the county with the least wildfire hazard was Cleveland County.

The wildfire vulnerability index revealed the greatest vulnerability to wildfire events in the southwestern portion of the state with a gradual decrease heading eastward. Graham County contained the largest percentage of high vulnerability and Cleveland County contained the largest percentage of low vulnerability. A notable exception to the west-east pattern was Buncombe County, where the socioeconomic characteristics of the population diminished overall wildfire vulnerability. The wildfire vulnerability analysis reflects the disparity across western North Carolina. The findings indicate that small-scale socioeconomic and physical characteristics must be considered when determining emergency management practices relating to drought and wildfire.

The results of the study provide transparency to vulnerable populations, as well as inform the public about potential hazards stemming from projected climate variability. In addition to filling literature gaps about water-related vulnerability in the southeast, the study provides one of the first analyses of the recent drought and wildfire event.

This study was the first step toward the objective of creating a comprehensive website featuring mapping and visualization outputs, interview and survey results, technical and non-technical summary documents, and links to relevant academic peer-reviewed journals as part of a research cluster focusing on mountain vulnerability involving Dr. Maggie Sugg, Dr. Elizabeth Shay, and Dr. Kara Dempsey and supported by the Research Institute for Environment, Energy, and Economics (RIEEE) at Appalachian State University.

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