COLORADO 2050:
WHY WE NEED CLIMATE RESILIENCY TO PROTECT OUR COMMUNITIES AND WAY OF LIFE

Colorado Fiscal Institute

INTRODUCTION

Climate change is creating challenges for Colorado in many ways. We are already seeing its effects in the form of increased temperatures, lower snowpack, severe drought, and extreme wildfires. These phenomena impose economic damage on the state, put the physical and mental health of Coloradans at risk, threaten biodiversity, and can destabilize ecosystems.

The goal of this research is to identify Colorado communities most at risk of the negative effects of climate change and guide policymakers on potential climate mitigation investments and effective response strategies to build resilient communities in every part of the state.

The study consists of two sections:

1. Exposure to climate change impacts:
   This report focuses on four impact of climate change in different areas of the state:
   a. Heat
   b. Ozone
   c. Wildfires
   d. Drought

2. The need for resiliency:
   Climate change imposes higher costs to communities with the most barriers to socioeconomic success. Low-wage workers, communities of color, people with lower levels of educational attainment, and linguistically isolated groups usually live in more polluted areas, have fewer resources, and less mobility. People with pre-existing health conditions — like asthma or heart disease — are vulnerable to the health impacts of air pollution and the youngest and oldest Coloradans are more susceptible to the health effects of extreme weather events like heat waves. Workers who do their jobs outdoors are also more exposed to the extreme effects of climate change and might have higher financial vulnerability as these types of effects worsen.

METHODOLOGY

In this study, we first ranked census tracts based on their exposure to four climate change impacts: extreme heat, air pollution, wildfires, and drought. We used climate change projections under two emission scenarios: moderate-emission (RCP 4.5) and high-emission (RCP 8.5) by mid-century (2050). We defined a social vulnerability index, which takes into account demographic, socioeconomic, and health indicators in each tract. This index is a number between 0 and 1, which ranks tracts with respect to one another and provides a measure of relative vulnerability of different geographic areas. 0 is the lowest vulnerability and 1 is the highest vulnerability. We used a modified version of the Centers for Disease Control's social vulnerability index (SVI) to make it more relevant to climate change, combining 16 parameters into one index. Finally, we overlayed the climate and social exposure to find tracts that are at higher risk of climate change impacts.

People in these demographic, socioeconomic, and health-related categories are at the highest risk of being exposed to threats posed by climate change. By studying the data, we can find which communities are at the highest risk of each climate threat. Identifying the communities most affected by climate impacts is essential for policymakers as they make decisions about climate adaptation and mitigation.

CLIMATE EXPOSURE

Greenhouse gas (GHG) emissions from human activities have raised global average temperatures significantly during the past 100 years (IPCC, 2013). As global temperatures continue to rise, Colorado will be increasingly exposed to the impacts of climate change. In this study, we analyze Colorado's projected exposure to extreme heat, drought, wildfires, and air pollution.

Extreme Heat: Regions of Colorado have experienced between 0.5 degrees to more than 3 degrees Fahrenheit of warming between 1986–2016 compared to 1901–1960 (Vose et al., 2017). All climate models project that Colorado's climate will warm substantially by 2050 (Lukas et al., 2014). This warming will drive longer, hotter, and more intense heat waves which increase the risk of heat stroke and other illnesses that can cause premature deaths. Young people, older people, people with existing health conditions, and those who work outdoors are affected most by rising temperatures (Hughes and Fenwick, 2016).

Ozone Pollution: Ground-level ozone is formed primarily from reactions between two major classes of air pollutants: volatile organic compounds (VOCs) and nitrogen oxides (NOx).[1] Sunlight and heat accelerate these reactions, so high concentrations of ozone usually occur during summer months. Ground-level ozone can have adverse health effects such as premature death (Nuvolone and Voller, 2018), respiratory and cardiovascular problems (WHO, 2013), and aggravated asthma (Fann et al., 2016). In Colorado, the Denver Metro Area as well as some parts of Boulder and Weld counties have significantly higher ozone concentrations due to their proximity to highways, traffic, and other sources of pollution such as refineries and factories. Climate change can exacerbate ozone pollution because rising temperatures facilitate formation of ozone molecules.

Wildfire: Climate change has also increased the intensity, extent, and duration of wildfire season, particularly due to prolonged dry conditions and reduced soil moisture (Littell et al., 2016, Chikamoto et al., 2017). Wildfire suppressions in the past century and land management policies have also promoted biomass accumulations which have contributed to frequent large wildfires—events that were rare under natural fire regimes (Allen et al., 2002). Three of the largest fires in Colorado occurred in 2020, with the total area of 541,482 acres burned[2]. An increasingly high number of homes in wildland urban interface[3] areas have also elevated wildland fire to a growing public safety concern, causing catastrophic damage in the last two decades.[4]

DEFINITION

IPCC defines exposure as "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. Exposure is an important precondition for considering a vulnerability as key. If a community is not exposed to a certain climate impact, their vulnerability to that impact will be irrelevant "(Oppenheimer et al., 2015).

Drought: Over the past 30 years, soil moisture drought has become more severe in Colorado (Lukas et al., 2014). Drought affects crop yield, water supply, and the recreation industry in Colorado. Moreover, as demand for water increases with the growth of our state's population, the agriculture industry and Colorado's food security will be threatened. Warm and dry conditions have also prolonged periods of bark beetle survival and reproduction, reducing the resistance of trees to beetle attacks and increasing tree mortality (Raffa et al. 2008). Tree mortality affects snow accumulation, snowmelt, and water uptake by vegetation (Lukas et al., 2014), affects water quality (Gonzalez et al., 2018) and makes the forest more susceptible to surface fires (Stephens et al., 2018).

1. https://www.epa.gov/ozone-pollution-and-your-patients-health/what-ozone
2. Wildfire News & Information | Fire Prevention and Control (https://www.colorado.gov/pacific/dfpc/wildfire-news-information)
3. The wildland-urban interface is any area where man-made improvements are built close to, or within, natural terrain and flammable vegetation.
4. https://cdpsdocs.state.co.us/dfpc/WebsitePhotos/Playbook.pdf

Climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC) has developed possible scenarios to show trajectories of future climates based on different levels of GHG concentrations. These trajectories are called Representative Concentration Pathways (RCPs) and represent possible "radiative forcing values"[5] that would result from greenhouse gases in the atmosphere in 2100. As shown in Figure 1, RCP 8.5 represents the high-emission scenario, which increases the global average temperatures by 4.2°–8.5°F by the end of the century, relative to the 1986–2015 average. The high emission scenario is referred to as a "business-as-usual" scenario, which will have the worst climate consequences and occurs if we continue burning fossil fuels at the current trend, without policies to curb our emissions.

Under RCP 4.5 (moderate emission scenario), global average temperatures are projected to increase by 1.7°–4.4°F. This scenario assumes a range of technologies and strategies for reducing greenhouse gas emissions will be adopted to stabilize global temperatures before the end of the century.

In this study, we compare climate impacts under RCP 4.5 and RCP 8.5 scenarios.

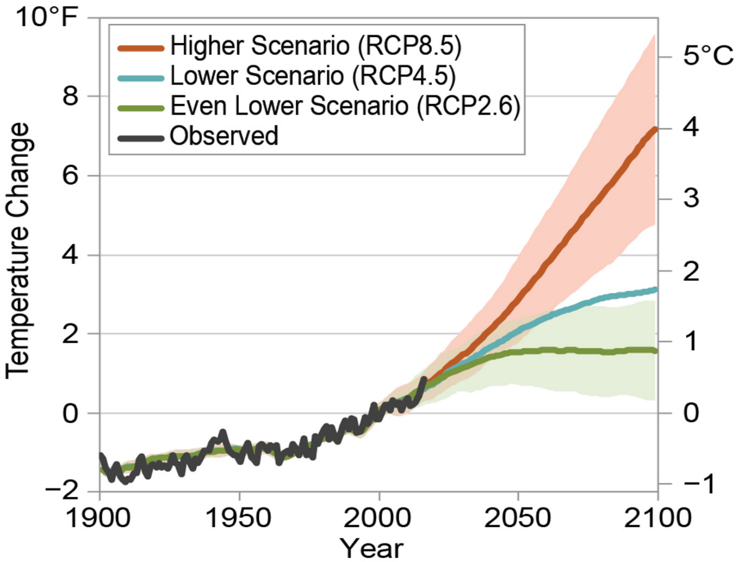


Figure 1: Representative Concentration Pathways

Thick lines represent the average of multiple climate models and the shaded ranges illustrate the 5 percent to 95 percent confidence intervals. Source: Hayhoe et al., 2018

5. "Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in Watts per square meter) at the atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide (CO_2) or the output of the Sun." (Source: IPCC)

EXTREME HEAT

Extreme heat episodes disproportionately threaten the health and well-being of young people, older people, those with certain medical conditions, and outdoor workers (USGCRP, 2016; Hughes and Fenwick, 2016). Since people in different areas of the state have historically adapted to different levels of heat, there is no fixed temperature that can capture the true extreme heat experience at the local level. People in some areas are accustomed to temperatures above 100 degrees in summer, while in other areas temperatures above 90 degrees are difficult to tolerate. Even relatively moderate heat can cause heat-related illness or death for those who are not acclimated to it (Cooley, 2012). For this reason, we define extreme heat as temperatures that are hotter than 95th percentile historic maximum temperatures at each census tract. This is the temperature in each census tract that is historically exceeded on only 5 percent of summer days in the 30-year historic period.

DEFINITION

Extreme heat can be defined in different ways. We use the deviation from an average historical temperature as the definition of extreme heat (Cooley, 2012).

We define days with extreme heat as days when the local daily maximum temperature exceeds the 95th percentile of local historic daily maximum temperature (1980-2010) between May 1 and September 30. This is the daily maximum temperature that is exceeded on 5 percent of summer days in the historic period. By definition, the 95th percentile temperature is exceeded on 7.6 days each summer (5 percent of 153 days of summer).

We compare future temperature projections with historical temperature data to find how many days in each scenario exceed the historic 95th percentile temperature.

Using historic temperature data at 185 temperature monitoring stations, we use ordinary Kriging method to spatially interpolate the temperature everywhere across the state and predict the temperature at each census tract.

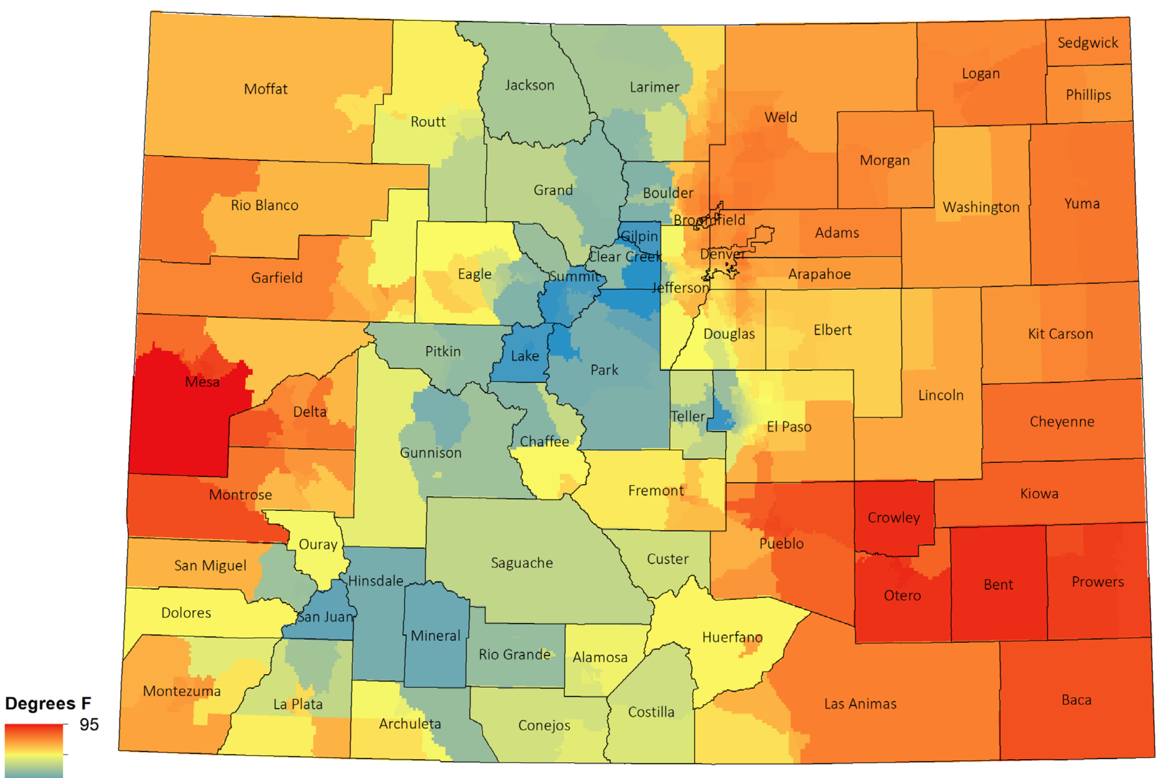


Figure 2: 95th percentile maximum daily temperatures 1980-2010 (degrees Fahrenheit)

TEMPERATURE MODELS

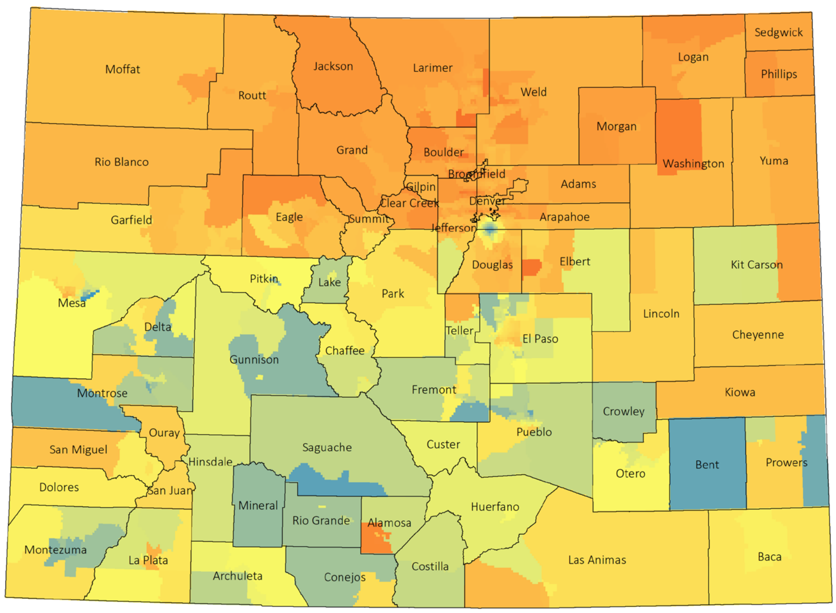
Figure 2 shows the 95th percentile of historic (1980-2010) maximum daily temperatures by census tract. The map shows a wide range of temperatures ranging from 70 degrees in the central and southwest mountains, to 95 degrees in the southeast plains. For example, the temperature that has historically exceeded only 5 percent of days in Bent County is 95 degrees while in Lake County, on average, temperatures have only gone above 70 degrees 5 percent of days in any given year.

For future temperature projections, we use three downscaled CMIP5* models for two emission scenarios, RCP 4.5 (moderate emission scenario) and RCP 8.5 (high emission scenario) by mid-century (2045-2055). Models used for projection of daily maximum temperature are bias-corrected constructed-analogs downscaled data (BCCAv2-CMIP5-Climate-daily), with resolution of 1/8th degrees (about 8.7 miles). For each emission scenario, the average of three models is used (CCSM4 (USA), MRI-CGCM3 (Japan), GDFL-GSM2G (USA)).

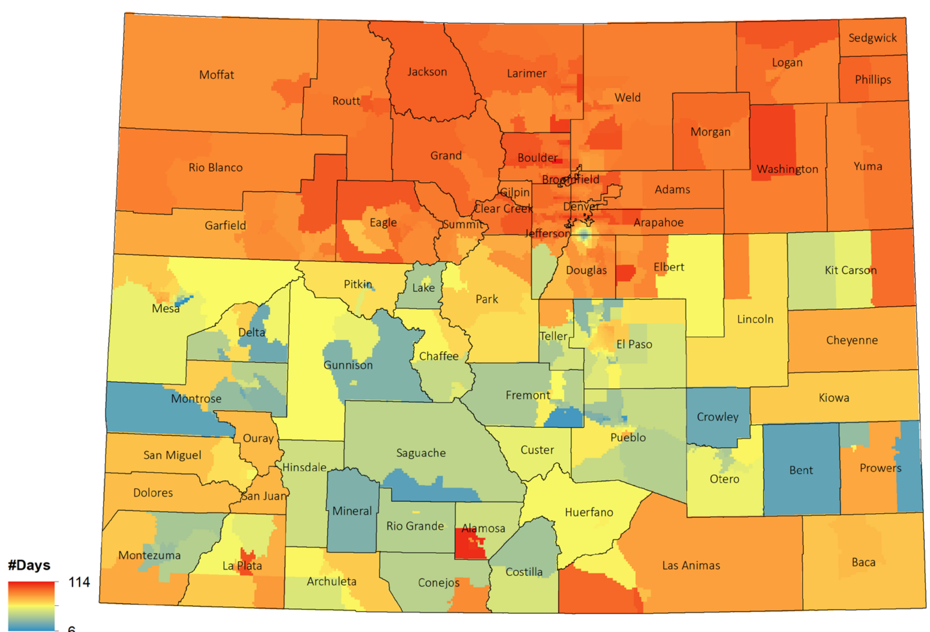
Figure 3 shows the projected number of days those temperatures will exceed the historic 95th percentile by mid-century under two emission scenarios. Under the moderate emission scenario, northern counties as well as the Denver Metro Area are projected to experience 75 days of extreme heat on average, while under high emission scenario, average number of extreme heat days in the same region is projected to be 100 days.

Across the state, in the moderate-emission scenario, the median number of days above the 95th percentile historical is 76.5 days (so half of the census tracts experience at least 76.5 days each summer with temperatures above their local historic extreme). In the high emission scenario, the median is 88.6 days each summer with temperatures exceeding the local extreme. Exposure to extreme temperature significantly increases mortality in all age groups, especially among older people, young children, and people with certain medical conditions (Greene et al., 2011). Between 2011 and 2018, on average about 450 heat-related emergency department visits were made each year across the state. Excess heat also reduces labor hours due to unsuitable working conditions. This is especially true for high-risk industries where workers are doing physical labor and have a direct exposure to outdoor temperatures (e.g.,

Figure 3: Average annual number of summer days exceeding the 95th percentile historic maximum daily temperature, mid-century.



a) Moderate emission scenario



b) High emission scenario

agriculture, construction, utilities, and manufacturing). Increases in temperature will also result in increased energy use for cooling and decreased energy use for heating. Rising temperatures are expected to cause a net increase in electricity consumption since summer cooling needs are expected to grow faster than the decline in winter heating needs.[6]

6. https://nca2014.globalchange.gov/report/sectors/energy

OZONE POLLUTION

Air Pollution (Ozone)
The Environmental Protection Agency (EPA) has implemented national standards for air pollution to protect public health. Any area that does not meet the national primary or secondary ambient air quality standard is classified as a “nonattainment area.” Depending on how high the ozone pollution level is, the ozone nonattainment area can be categorized as marginal, moderate, serious, severe, or extreme.

Since 2016, the Denver Metro Area had been classified by the EPA as a “moderate” nonattainment area for ozone pollution. Under the Clean Air Act, areas that do not attain national ozone standards in a timely manner are reclassified to a higher nonattainment status. In 2019, the EPA reclassified the Denver Metro/North Front Range ozone nonattainment area from “moderate” to “serious” nonattainment. A 2020 study by the American Lung Association ranks Denver in the top 10 of their list of most-polluted cities in the country for ozone pollution.[7] According to a 2017 study[8] by the National Center for Atmospheric Research (NCAR), the major contributors to the North Front Range’s ozone pollution were emissions from oil and gas operations, as well as traffic.

Climate change is expected to increase future levels of ozone concentrations since there is a strong correlation between higher ozone levels and higher temperatures. Moreover, warmer days will increase the demand for air conditioning and electricity consumption, and electric power plants emit NOx,[9] which is one of the components that generate ground-level ozone.

7. https://www.lung.org/research/sota/key-findings/ozone-pollution
8. https://www2.acom.ucar.edu/frappe
9. https://www.giss.nasa.gov/research/features/200402_tango/

DEFINITION AND METHODS

Average daily 8-hour maximum ozone concentration is the daily maximum surface ozone concentration, in parts per billion (PPB), averaged over 8 hours.

We use results of Climate impacts simulations by Skamarock and Klemp (2008) which uses the CCSM4 GCM under RCP8.5 and RCP4.5 and dynamically downscaled over North America using the Weather Research and Forecasting (WRF) model.

In 2015, the EPA set the ground-level ozone standard to 0.070 ppm, averaged over an 8-hour period. This standard is met at an air quality monitor when the 3-year average of the annual fourth-highest daily maximum 8-hour average ozone concentration is less than or equal to 0.070 ppm. Figure 5 shows projections of average ozone concentration levels by mid-century during summer months.

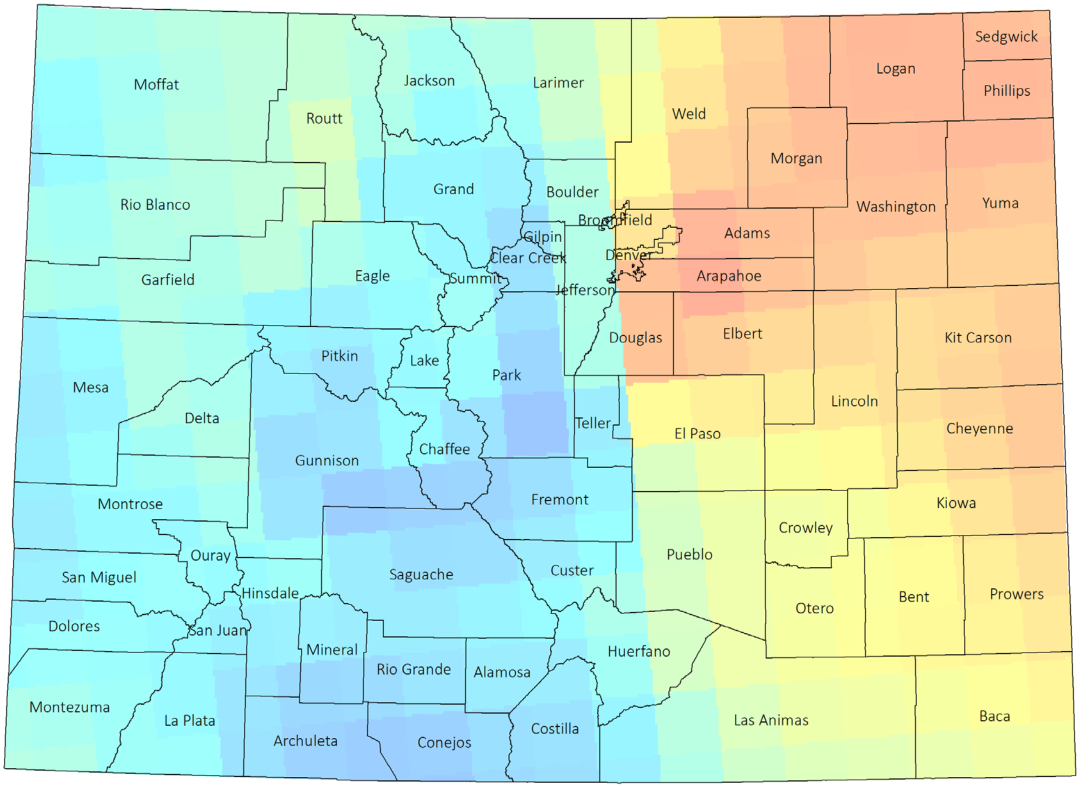
In both scenarios, on average, ozone concentration levels increase by about 3 percent across the state compared to the baseline period (2000).[10] Under both emission scenarios, the highest increase in ozone concentration levels are projected to occur in the Northern Front Range, Northern Plains, and Southern Plains. Some of the counties in these regions (Jefferson, Douglas, Denver, Adams, Arapahoe, Broomfield, Boulder) currently have significantly higher ozone concentrations compared to the rest of the state, which is caused by high proximity to highways and traffic as well as refineries and other factories.

10. Source for 2000 data: EPA daily air quality data (https://www.epa.gov/outdoor-air-quality-data/download-daily-data)

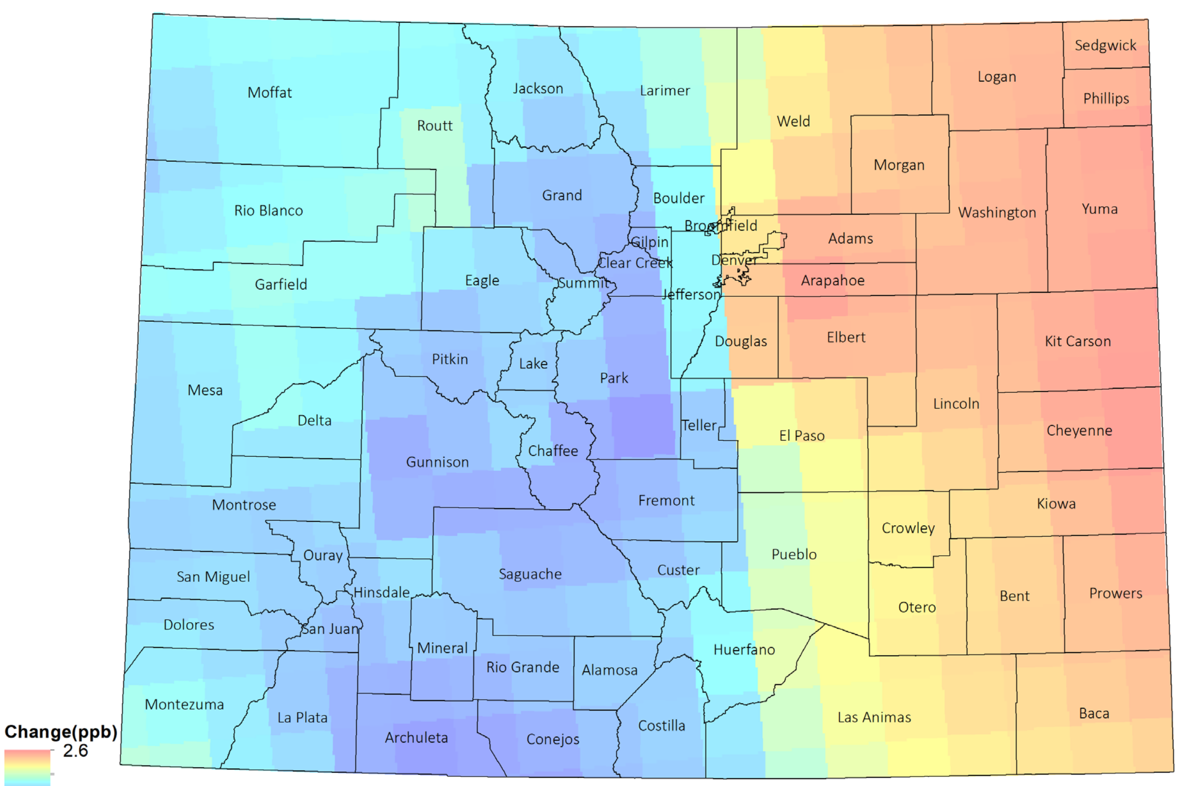
The Impact of Ozone Pollution:
Exposure to ozone pollution can cause serious health complications, including inflammation and damage to the airways, and aggravated lung diseases such as asthma, emphysema, and chronic bronchitis. Exposure to air pollution also increases the risk of death from COVID-19 (Wu et al., 2020). Data from the Colorado Department of Public Health and Environment[11] shows Denver, El Paso, Jefferson, Arapahoe, and Adams counties are top-five counties in deaths from COVID cases. These counties also have high levels of air pollution exposure.

11. https://covid19.colorado.gov/data

Figure 4: Change in summer-average maximum daily 8-hour ozone concentrations (ppb) in 2050 (compared to 2000)



a) Moderate emission scenario



b) High emission scenario

Wildfires:
Forests serve an important role in the ecosystem. Wildlife habitat, erosion control, water filtration, and recreation are all dependent on healthy forests. Climate change increases the probability and intensity of wildfires and increases the wildfire season duration (Abatzoglou & Williams, 2016) through increased heat, long-lasting droughts, reduced soil moisture, and other disturbances, all of which threaten the place of forests in local ecosystems. Wildfires also have severe impacts on air quality and human health. Fire seasons are now 78 days longer than they were 40 years ago, and out of 161 wildfires for which the state was responsible between 1967 and 2018, 138 fires occurred after 2000.[12]

12 https://cdpsdocs.state.co.us/dfpc/WebsitePhotos/Playbook.pdf

DEFINITION AND METHODS

Very high fire danger is defined as the average number of days with 100-Hour Fuel Moisture below 10th percentile of the baseline period (1971-2000).

The 100-Hour Fuel Moisture value represents the modeled moisture content of dead materials on the forest floor. We use a model mean derived from 18 downscaled CMIP5 models to project 100-Hour Fuel Moisture by mid-century.

Figure 5 shows the projections of "very high fire danger" during June, July, and August by mid-century. The darker colors indicate a higher number of days where fire danger is very high. Western counties, especially those in the Grand Valley, Northern Mountains, and western San Juan Mountains regions face the highest risk, especially Mesa, Rio Blanco, and Moffat counties which are projected to face up to 39 days of high summer fire danger by mid-centurymid-century. This is about eight days higher than the historic average (1971-2000) for this area. Prowers, Bent, and Otero counties have fewer projected days with very high fire danger (23 to 25 days), but the change from historic values is higher (they are projected to experience 9-10 extra days with very high fire danger compared to the baseline period).

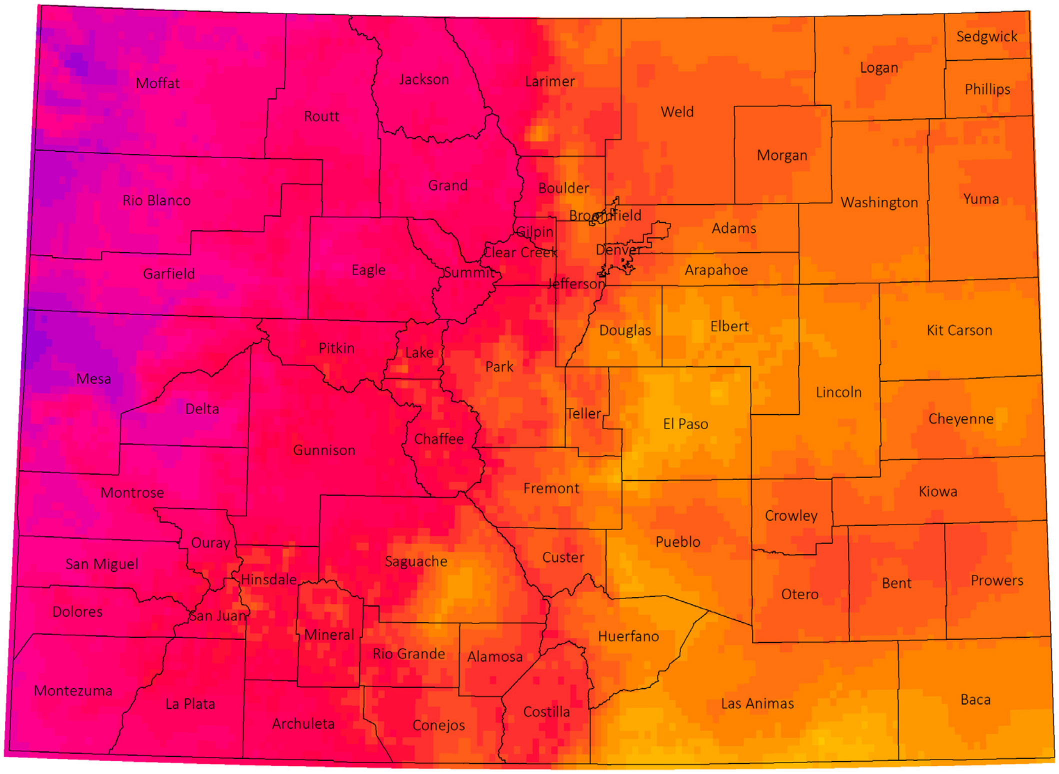
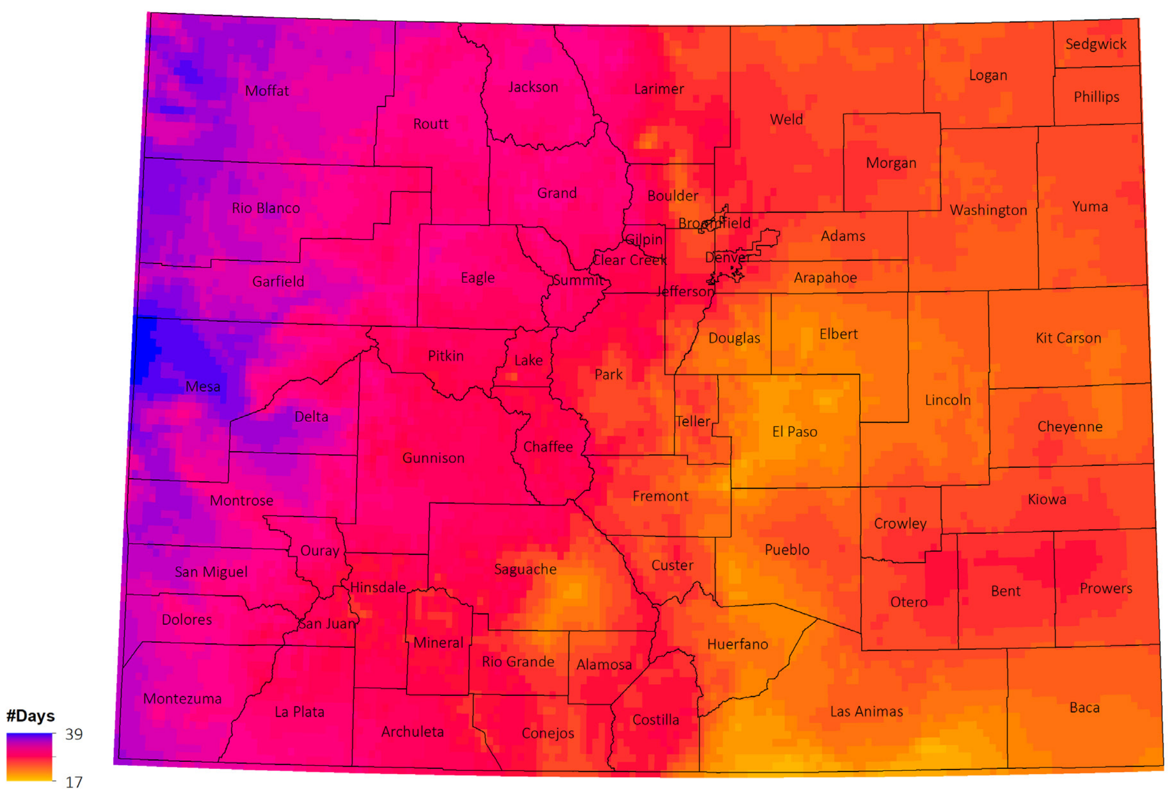


Figure 5: Very high fire danger, mid-century. Source: climatetoolbox.org

a) Moderate emission scenario



b) High emission scenario

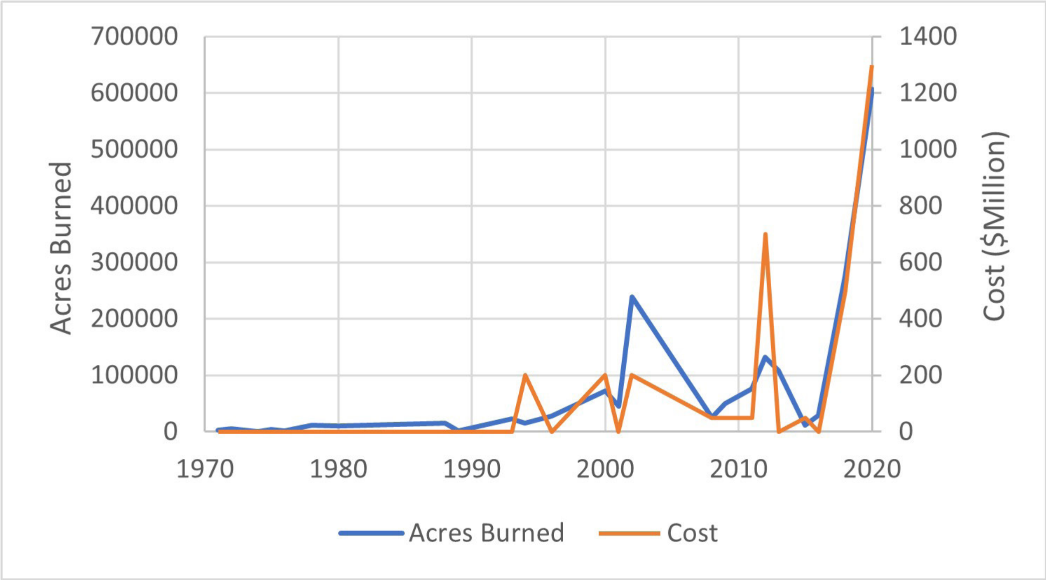


Figure 6: Cost of Wildfires and Acres Burned.

Billion-Dollar Weather and Climate Disasters: Time Series | National Centers for Environmental Information

Between January 2000 and October 2020, Colorado suffered total statewide wildfire-related damages to property and crops of about $1.8 billion, as well as seven deaths and 17 injuries.[13] More than $295 million of these damages and three of the largest wildfires in Colorado happened in 2020 (Cameron peak, 208,663 Acres; East Troublesome, 193,812 Acres; and Pine Gulch, 139,007 Acres).[14] The cost of wildland fire suppression in Colorado has grown significantly with the increased occurrence of large fires. Figure 6 shows the National Oceanic and Atmospheric Administration's estimate of the area burned by wildfires and their estimated cost over the past five decades. The figure shows that costs of wildfires have significantly increased during the past decade. Estimated costs include physical damage to residential, commercial, and government or municipal buildings; material assets within a building; time element losses like business interruption; damage to vehicles and boats; offshore energy platforms; public infrastructure like roads, bridges, and buildings; agricultural assets like crops, livestock, and timber; disaster restoration and wildfire suppression costs. Climate change is projected to increase the number and frequency of such large wildfires.

13. https://www.ncdc.noaa.gov/stormevents/
14. https://www.colorado.gov/pacific/dfpc/wildfire-news-information

DROUGHT

According to the Colorado Climate Center, Colorado endured five significant dry periods prior to 2000: 1893-1905, 1931-1941, 1951-1957, 1963-1965, and 1975-1978. Since the turn of the century, Colorado has experienced several years of severe drought with 2002, 2012, 2018, and 2020 being some of the driest on record.

The 2020 drought ranks as the second-worst drought in the last 20 years across Colorado. It was also the fourth time in two decades – following 2002, 2006 and 2012 – that 100 percent of Colorado was categorized as abnormally dry or in various degrees of drought. By November 2020, 27 percent of the state, mostly in Western Colorado, was in "exceptional" drought condition. Climate change exacerbates drought conditions in many areas of the United States, especially in the Southwest. In Colorado, water and snow-based recreation industries, agriculture, and fish and wildlife population are negatively impacted by drought. Drought can exacerbate fire season since dry vegetation provides fuel and fire can spread easily over dry soil.

Soil moisture

Rising temperatures increase the water evaporation rate from soil and plants and can make the soil drier. During the last few decades, soil became drier in most of the state, especially in the summer (EPA, 2016). In future decades, summer precipitation and runoff are likely to decrease in Colorado and droughts are likely to become more frequent and more severe (Averyt et al., 2011). Dryland crops are entirely dependent on precipitation and are more susceptible to damage from drought. Dryland crops are particularly vulnerable to severe "single-season" droughts that deplete soil moisture (CWC, 2013). Wheat, corn, sorghum, hay, proso millet, and sunflowers are the most extensively grown dryland crops in Colorado.

DEFINITION AND METHODS

Drought is defined as shortage of water that occurs due to lack of precipitation such as rain, snow, or sleet for a prolonged period of time. Even though droughts occur naturally, human activity, such as water use and management can exacerbate dry conditions.

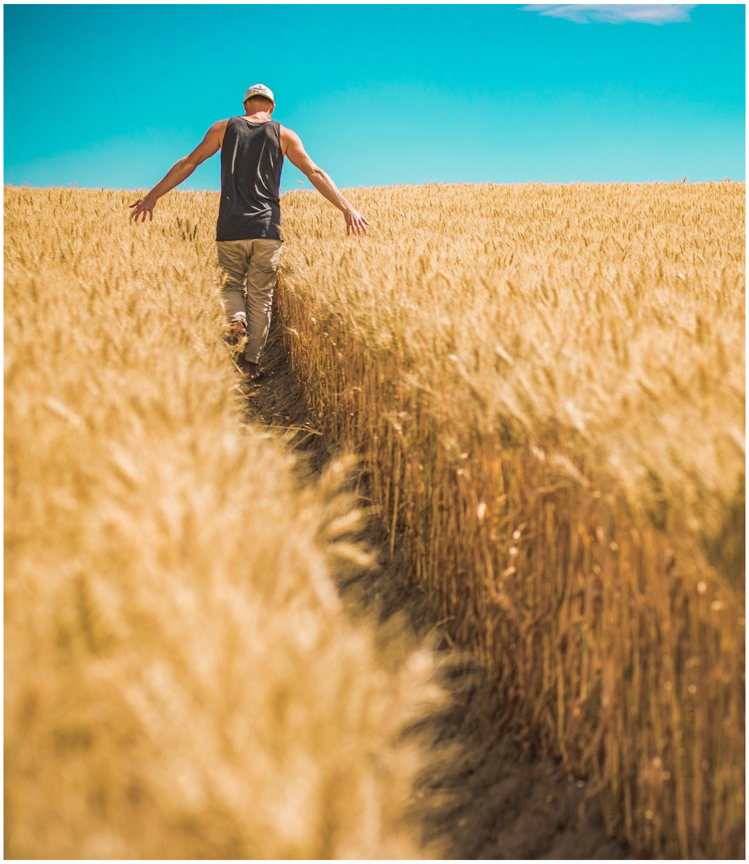


Figure 7 shows the area of farmland as a percentage of the total area of each county. Dark red areas indicate counties with more than 90 percent farmland. The figure shows that eastern counties are more heavily dependent on agriculture and farming compared to the rest of the state. Logan, Sedgwick, Phillips, Kit Carson, and Prowers counties are over 95 percent farmland, meaning drought has significant impacts on the economy in these counties.

Figure 8 shows the percentage of agriculture jobs by county. In Kiowa, Cheyenne, Sedgwick, Washington, and Baca counties, more than 40 percent of all jobs are in the agriculture sector, with Kiowa having the highest agricultural employment (76 percent). These counties are at higher risk of economic loss in times of drought.

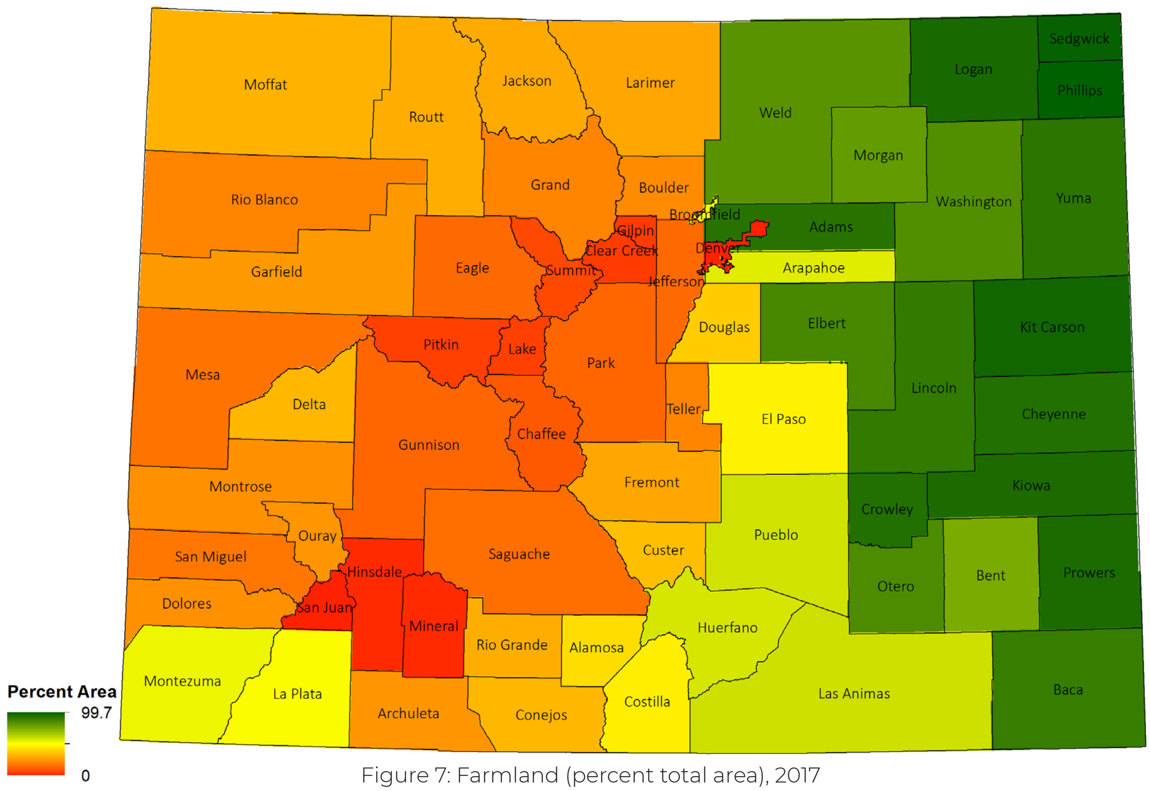


Figure 7: Farmland (percent total area), 2017

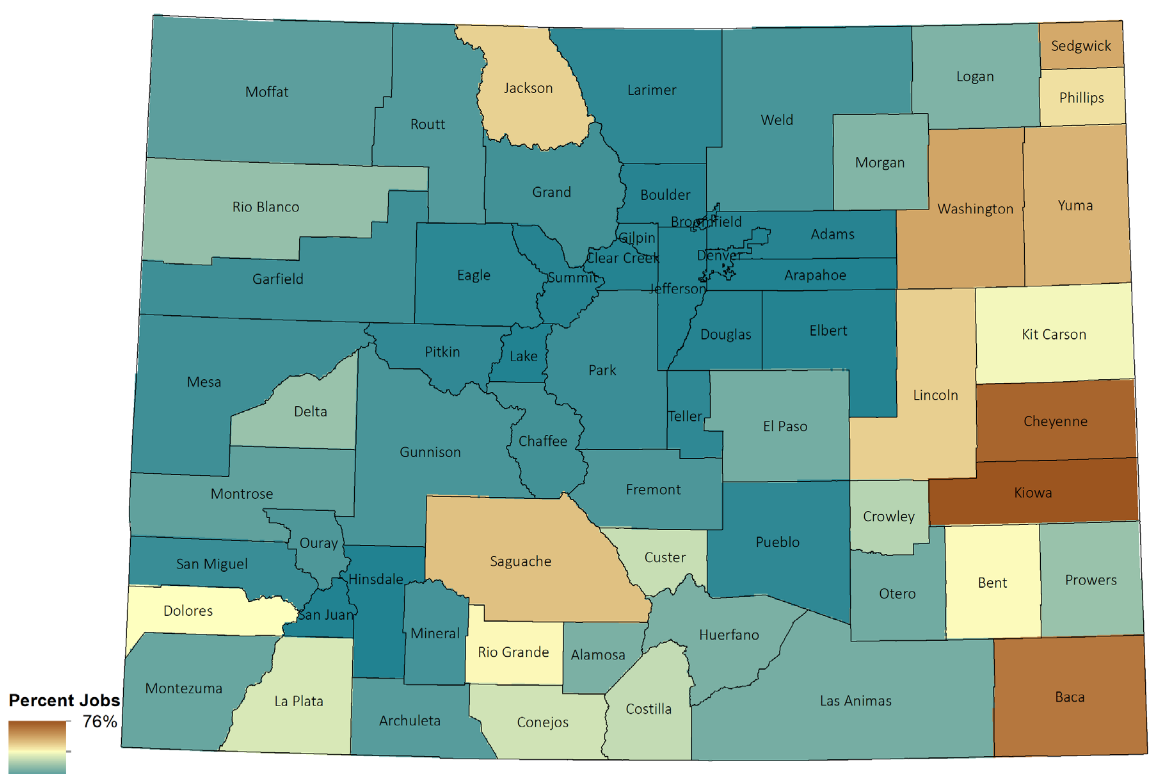


Figure 8: Jobs in Agriculture sector (% employed population over 16 yo), 2019

State Demography Office

We use projections of precipitation anomaly as a proxy for soil moisture that impacts agriculture in Colorado. To find the anomaly, we compared future projections of precipitation with historic average precipitation. Figure 9 shows normal precipitation as an annual average over 30 years (1980-2010) and Figure 10 shows the change in precipitation by mid-century under the high emission scenario.

METHODS

We used average of precipitation projections from three climate models: CCSM4 (USA), MRI-CGCM3 (Japan), and GDFL-GSM2G (USA), and interpolated the projections across the state using ordinary Kriging method to find precipitation change at each census tract.

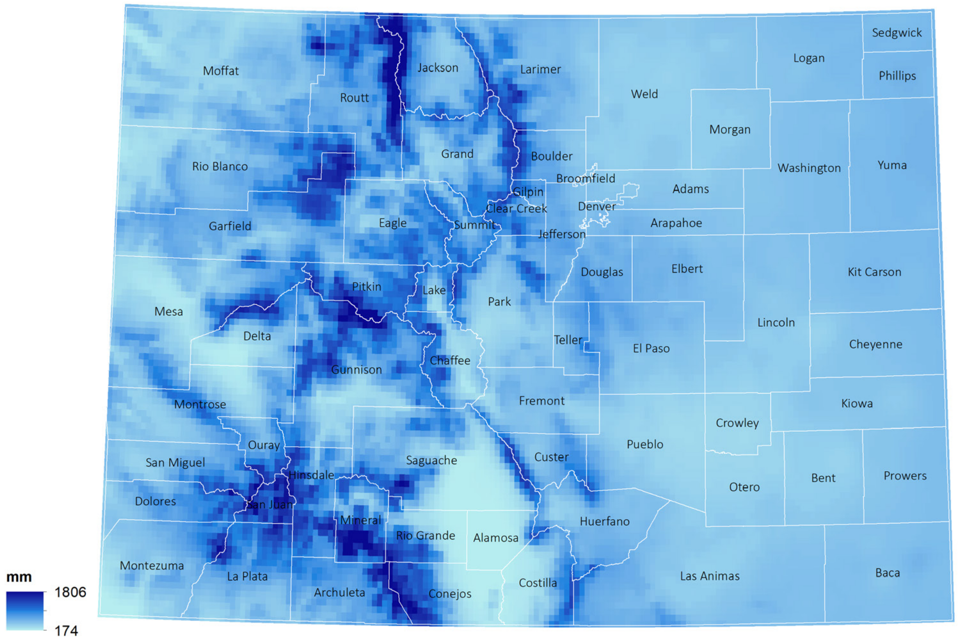


Figure 9: Average annual 30-year (1980-2010) Precipitation (mm)

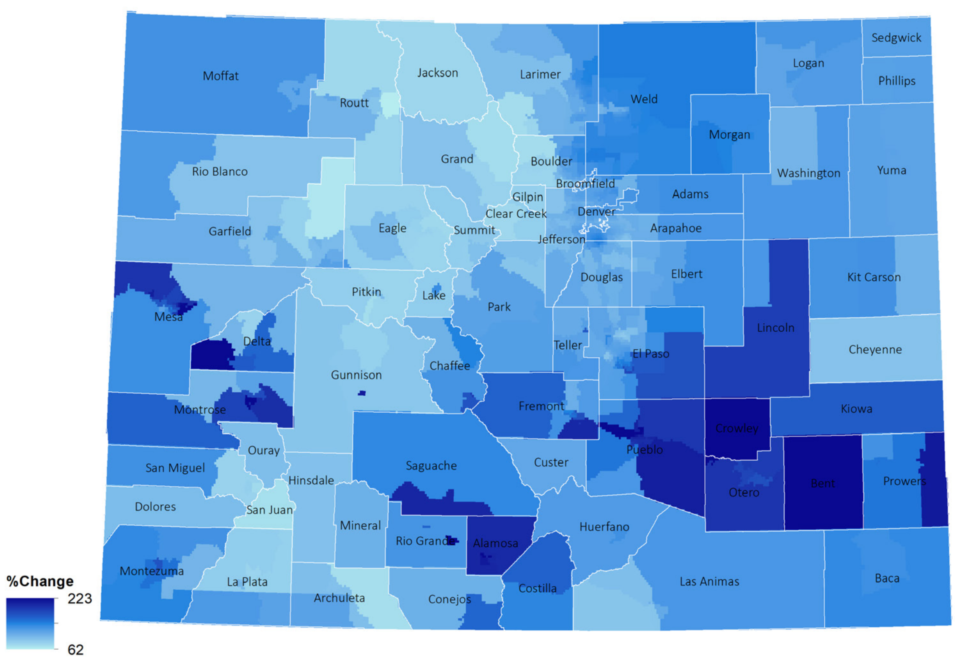


Figure 10: Percent Change from average annual 30-year (1980-2010), mid-century, high emission scenario

Figure 10 shows that the highest decrease in precipitation is projected to occur in the Central Mountains and Western San Juan Mountains regions, where rain and snowfall will decrease by as much as 62 percent. While some counties in the Southern Plains region, especially Bent, Crowley, Otero, Kiowa, and Lincoln, as well as some areas in the Southern Front Range region (Pueblo, El Paso, Fremont) are in fact projected to experience significant increases in precipitation, the model does not distinguish between snow and rainfall. Climate change can shift precipitation from snow to rain and increase the frequency of heavy rainfall. It is estimated that heavy rain has increased in Colorado by 5 percent between 1958 and 2012.[15] An increase in heavy rainfall will increase the risk of flooding, which can destroy homes, roads, and crops. A recent example is the 2013 flood in Northern Colorado, where we received almost a year's worth of rainfall (17 inches) in four days.

15. https://nca2014.globalchange.gov/report/our-changing-climate/heavy-downpours-increasing#graphic-16693

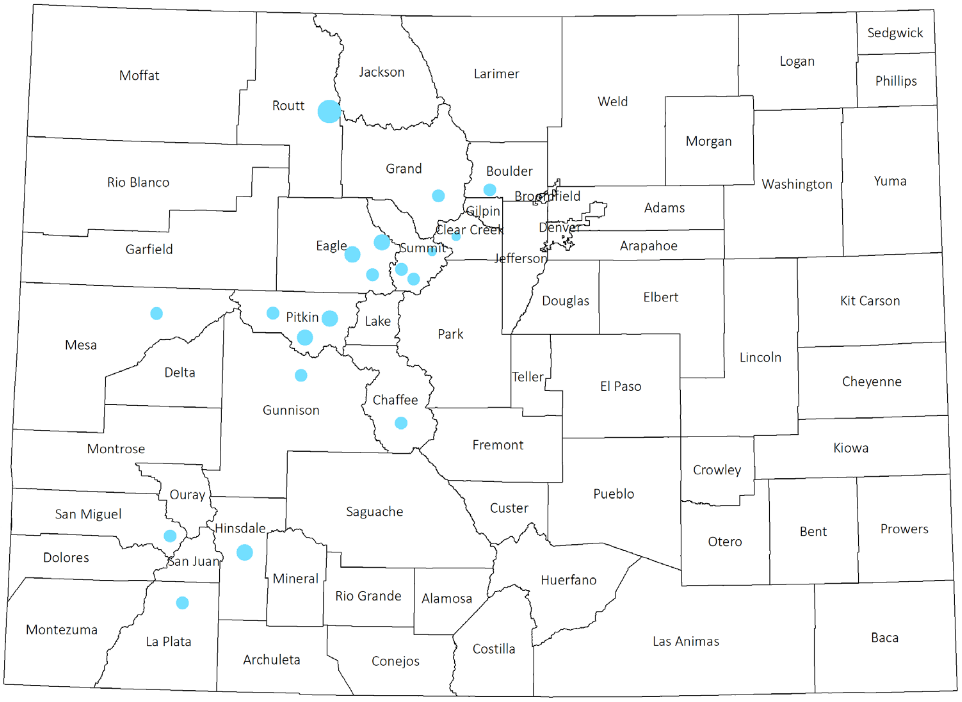
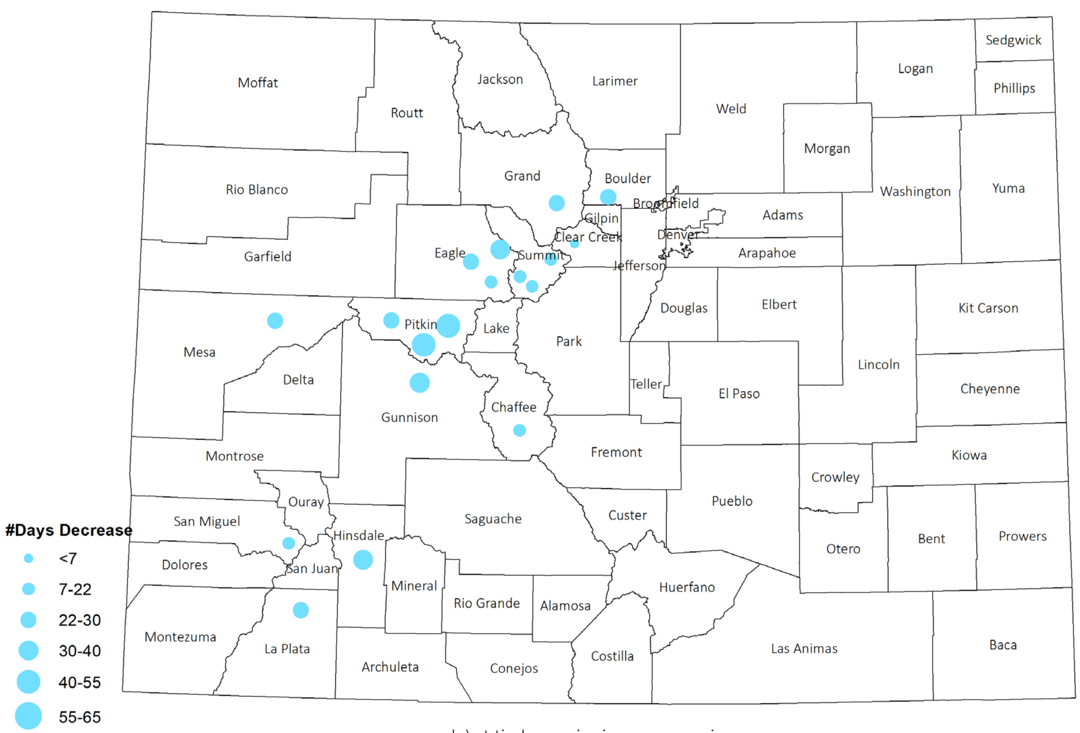


Figure 11: Change in ski season length (#days) compared to baseline (1986-2005)
a) Moderate emission scenario



b) High emission scenario

METHODS

"The analysis uses the Utah Energy Balance (UEB) model, a water and energy balance model which tracks snow-water equivalent (SWE), internal energy of the snowpack, and snow surface age in its simulation of snow accumulation and melt. The model simulates natural snow accumulation and snowmelt at the winter recreation sites using site-specific climatic and topographic characteristics of each site. At each of the modeled locations, results include a simulation of natural snowpack for the 20-year reference period (1986-2005), and future simulations for the 20-year periods centered on the reporting years of 2050 and 2090 for each of five GCMs under RCP8.5 and RCP4.5." (EPA, 2017)

Tourism is a major economic driver for Colorado, contributing greatly to the state's revenue and employment. In 2016, the hospitality industry was Colorado's second-largest employer, employing 165,000 workers and about generating about $5 billion in economic activity. Climate change threatens Colorado's winter tourism as rising temperatures will lead to less snow. The IPCC predicts that a 1.8° F increase in annual global temperatures will decrease snowpack by 20 percent in the Northern Hemisphere (IPCC 2007). Diminishing snowpack will shorten the ski season and skiing in Colorado will become less reliable, leading to climate-related economic losses (Williamson et al., 2008). Figure 12 shows the average change in ski season length (average of change in cross country skiing season length and Nordic skiing season length). Blue circles show the decrease in season length in days at the 19 locations compared to a 1986-2005 baseline. Bigger circles indicate a larger decrease in the season length. Figures show that under the high emission scenario, climate change will shorten ski season at some resorts by as many as 65 days. Even in the moderate emission scenario, the season length could decrease by as many as 53 days (Routt County).

BARRIERS TO RESILIENCY

Individuals and communities are different in their access to resources to prepare for, cope with, and recover from hazardous events such as natural disasters, disease outbreak, or anthropogenic pollution. Socioeconomic status, health, and demographic factors can impact the preparedness and resilience of communities in the face of natural disasters and climate change impacts (Adger, 1999; Otto et al., 2017).

For most of the 20th century, disaster management focused on physical infrastructure. In the 1970s, researchers realized the importance of socioeconomic factors that affected community resilience (Juntunen, 2004). In mitigating and planning for emergencies, state, local, and tribal officials must identify the communities with barriers created by structural inequality and disinvestment in order to serve those residents over the course of a disaster.

As we saw in the previous section, climate change will exacerbate exposure to environmental hazards. Climate change is also expected to exacerbate existing barriers and inequalities, which in turn will deepen intergenerational inequity by creating even more barriers for communities to overcome in order to access natural and financial resources (Otto et al., 2017).

To determine the ability for Colorado communities to be resilient to climate change, we used a modified version of the Centers for Disease Control and Prevention's "social vulnerability" index (SVI) that takes into account a combination of demographic, socioeconomic, and health variables. The SVI indicates the relative threat to every U.S. Census tract. "The SVI is intended to spatially identify [these] populations, to help more completely understand the risk of hazards to these populations, and to aid in mitigating, preparing for, responding to, and recovering from that risk" (Flanagan et al., 2011).

DEFINITION

IPCC defines vulnerability as "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." (Oppenheimer et al., 2015).

To calculate the social vulnerability index, we use the methodology used by CDC to calculate the SVI: For each census tract, we generated its percentile rank among all tracts for each individual variable, as well as its overall position. For overall tract rankings we summed the percentiles, and then calculated overall percentile rankings.

Before ranking, we adjusted the cardinality to ensure that the sign of the factor reflects its contribution to vulnerability. For example, a high percentage of linguistically isolated residents indicate higher vulnerability, giving this variable a cardinality of +1, while higher income indicates lower vulnerability, and receives cardinality of -1.

We should keep in mind that the SVI has certain limitations. First, it compares census tracts based on where people live, not necessarily where they work or play. Second, the composition of some smaller census tracts might change rapidly, and the geographic boundaries of census tracts can change based on changes in population. Finally, SVI does not take into account the vulnerability of the physical infrastructure and community assets or other resources that may help to reduce the effects of the hazard.

The parameters used in our analysis are:

Economic:
- Poverty (percentage of people below federal poverty line (2014-18 ACS))
- Unemployment (percentage, civilian noninstitutionalized (2014-18 ACS))
- PCI (Per capita income (2014-18 ACS))
- Home ownership (% Renter-occupied, Occupied housing units (2014-18 ACS))
- Vehicle ownership (% population with no vehicles (2014-18 ACS))

Health:
- Heart disease mortality (Age adjusted heart disease mortality rate per 100,000 population (CDPHE, 2017))
- Asthma hospitalization (Age adjusted asthma hospitalization rate per 100,000 population (CDPHE,2017))
- Uninsured population (% population (2014-18 ACS))

Social/Demographic:
- Education (% population 25 and over with no high school diploma (2014-18 ACS))
- Youth population (% population 17 years old and under (2014-18 ACS))
- Older population (% population 65 years old and over (2014-18 ACS))
- Disability (% population older than age 5 with a disability (2014-18 ACS))
- Non-white (percentage, all persons except white, non-Hispanic (2014-18 ACS))
- Linguistic isolation (Percentage of persons (age 5+) who speak English “less than well” (2014-18 ACS))
- Outdoor workers (% civilian employed population 16 years and over that work in natural resources, construction, and maintenance occupations (2014-18 ACS))
- Group quarters (% population, Persons in institutionalized group quarters (2014-18 ACS))

We added health variables to the CDC’s SVI parameters since people with health conditions, especially those with heart and respiratory diseases, face the greatest climate-related threats, such as being exposed to air pollution from wildfires and ozone pollution. Lack of access to health insurance, leading to higher costs of emergency department visits or hospitalization, is another barrier that will become increasingly important to overcome. We also added the percentage of outdoor workers to the demographic variables of the CDC’s SVI since those who work outdoors are more exposed to extreme heat and different air pollutants.

Figure 12 shows percentile rankings of census tracts by the overall social vulnerability index.

Figure 13 presents the same index for the Denver area. As mentioned earlier, the index is a number between 0 and 1, with 1 indicating a greater threat faced by climate impacts in comparison to the rest of the state. The light yellow color indicates lower levels while dark blue areas face the greatest threats. Yuma County, areas around Greeley and southwest areas of Weld County, Colorado Springs, Commerce City, Aurora, and parts of Denver are among the areas with populations facing the greatest threats posed by climate change, with the SVI of over 0.99. Bent, Costilla, Conejos, Saguache, Lake, Delta, and Pueblo Counties are also among counties facing the most threats.

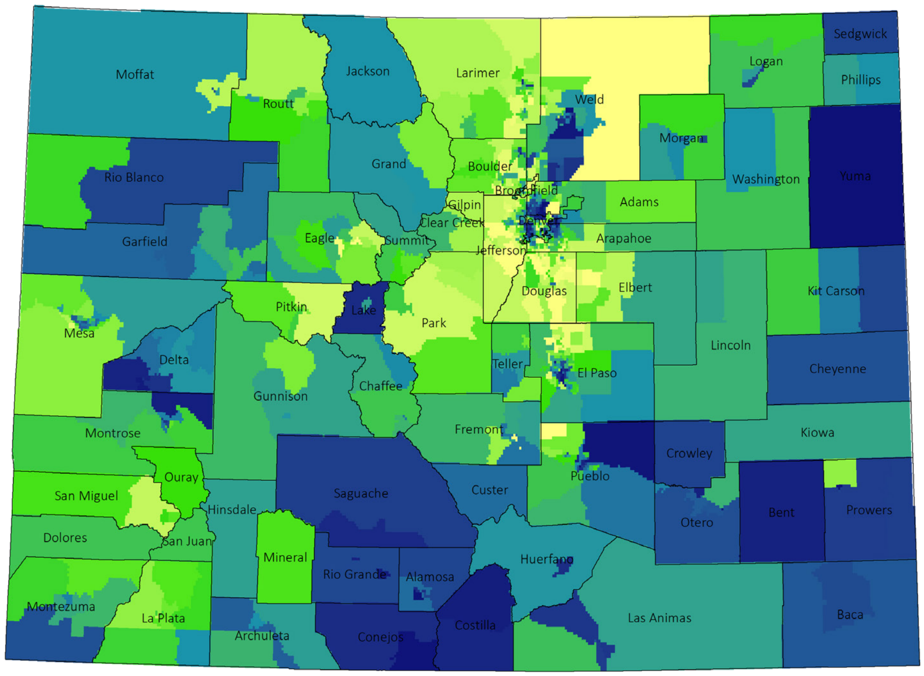


Figure 12: Percentile Ranking of Social Vulnerability Index

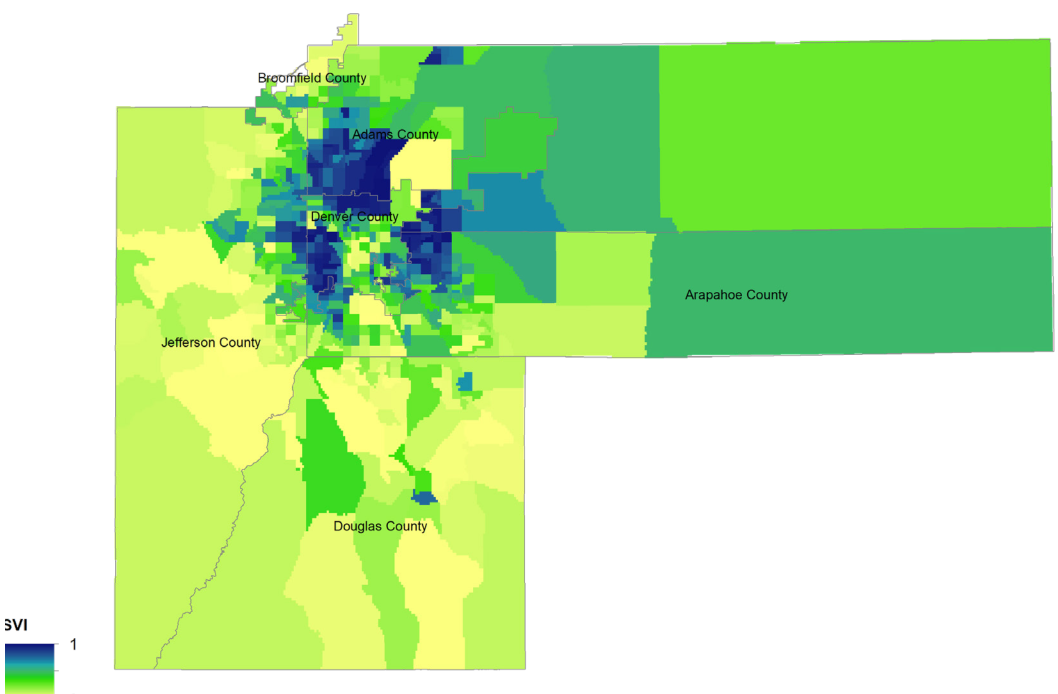
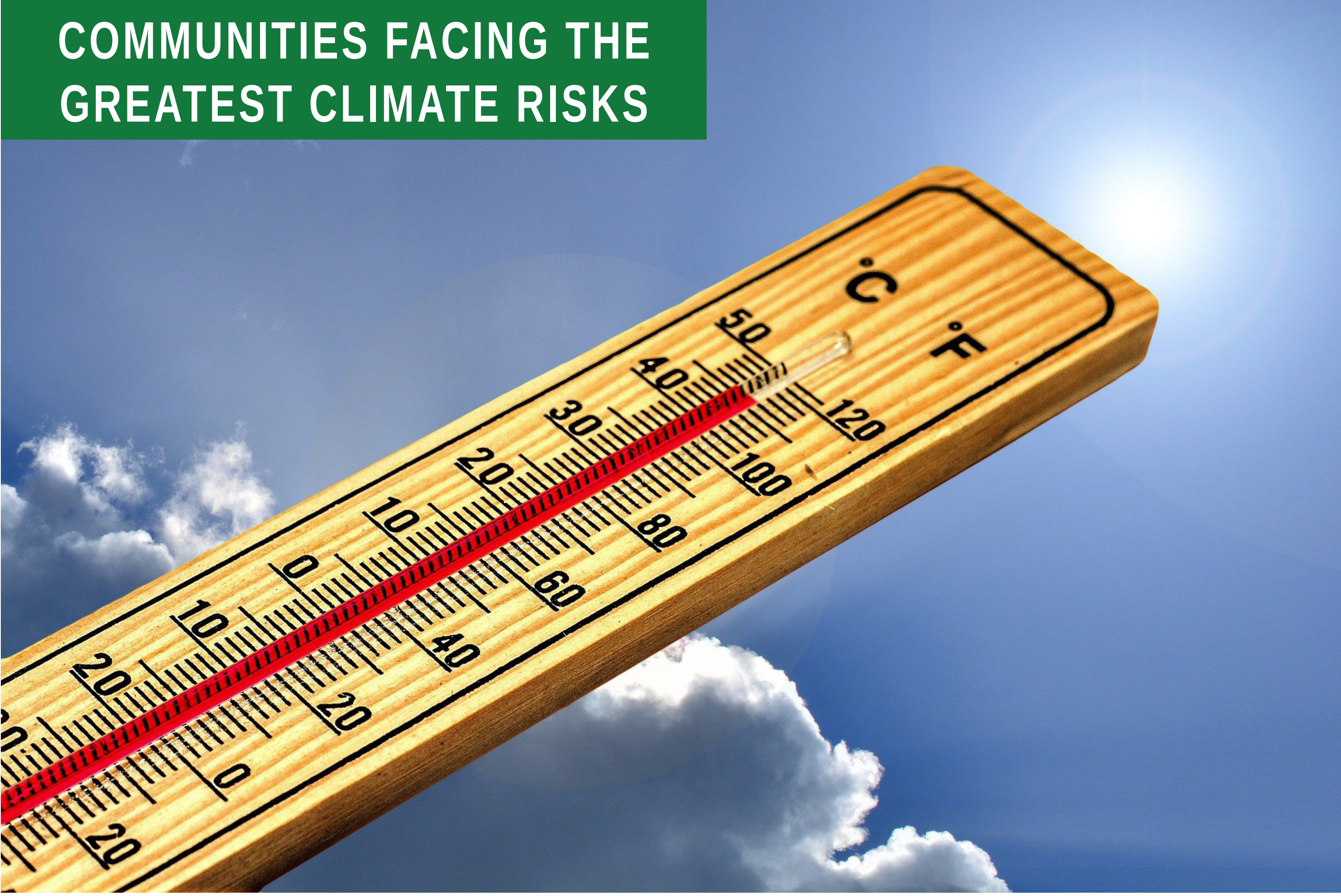


Figure 13: Percentile Ranking of Social Vulnerability Index, Denver Area

COMMUNITIES FACING THE GREATEST CLIMATE RISKS



DEFINITION

IPCC defines risk as the intersection of exposure and vulnerability: “The severity of the impacts climate events depends strongly on the level of vulnerability and exposure to these events.” Vulnerability reduction is a core element of adaptation and disaster risk management (Cardona et al., 2012).

METHODS

We find the percentile ranking of census tracts for exposure to each climate impact, so that each tract is given a score between 0 and 1 that indicates its projected relative exposure to that specific climate impact. Then we add the climate exposure score to the social vulnerability score and perform the percentile ranking again (so the climate exposure and social vulnerability components are weighted equally in the final climate impact vulnerability score).

In order to determine which Colorado communities face the greatest threats from extreme heat, drought, ozone pollution, and wildfires, we overlayed the data showing communities with the greatest socioeconomic barriers with the projected exposure to climate change impacts under the high emission scenario.

Since some socioeconomic, demographic, and health factors play a more important role in how resilient a community is to certain climate impacts, we underscored the role of such factors by assigning a higher weight to them.

Risk of extreme heat

Older people face the greatest threats from extreme heat brought on by climate change (Kovats and Kristie, 2006). During the 1995 heat wave in Chicago, 371 deaths out of 552 were people 65 years or older. In August 2003, a French heatwave caused an estimated 14,800 deaths, mainly women older than 75 (Pirard et al., 2005). In addition to older people, infants, young children, people with chronic health problems (especially pre-existing heart disease), as well as people who engage in high levels of outdoor physical activity are threatened by extreme heat (Rozzini et al., 2004; Kovats and Kristie, 2006; Coates et al., 2014). Socioeconomic status can also have an affect on whether someone is more likely to be admitted to emergency room due to extreme temperatures. (Wichmann et al., 2011).

RISK OF EXTREME HEAT

Figure 14 shows the risk of extreme heat across Colorado and Figure 15 shows the same index in the Denver Metro Area. Areas colored with light yellow face lower threats and areas colored as dark blue face the highest threats from extreme heat because they will be exposed to more hot days when temperatures exceed the 95th percentile maximum historic temperatures. The data shows Yuma, Sedgwick, Phillips, Jackson, Adams, Denver, and Arapahoe are the counties that will be most adversely affected by higher temperatures. People in Alamosa (Alamosa), Greeley (Weld), and Akron (Washington) will face the greatest threats to their health and well-being due to extreme heat.

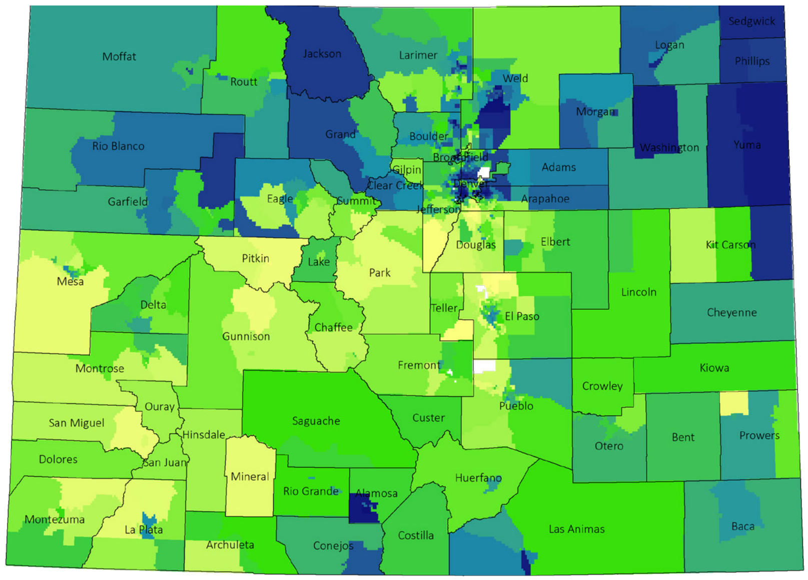


Figure 14: Risk of Extreme Heat

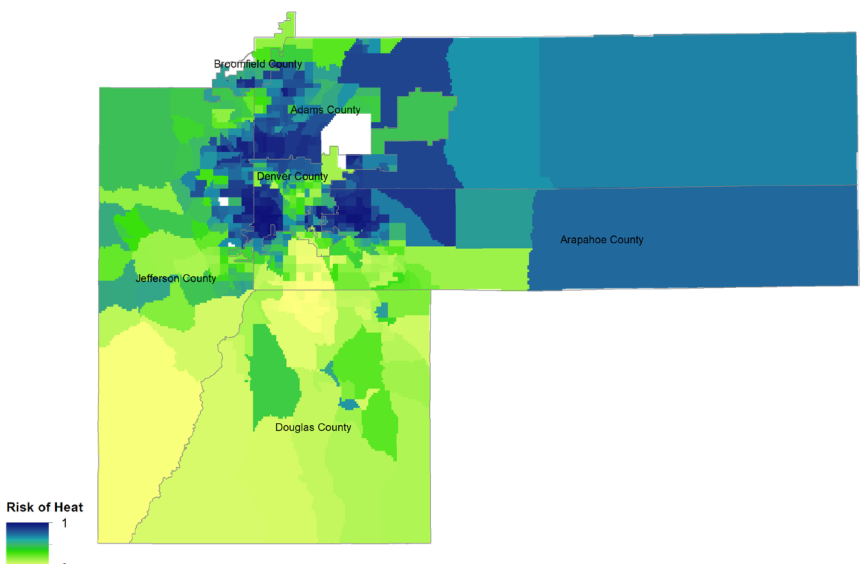


Figure 15: Risk of Extreme Heat, Denver Area

METHODS

The "Risk of extreme heat" index is a combination of social vulnerability parameters and projected exposure to heat by mid-century under the high emission scenario. This index is a number between 0 and 1 which ranks census tracts with respect to one another. In this case, census tracts with higher relative social vulnerability to extreme heat are projected to experience more days in summer when temperatures exceed the 95th percentile of historic maximum temperatures and also have populations that are more vulnerable to heat.

Considering the factors mentioned in the literature and the available data for Colorado census tracts, we want to emphasize the importance of these factors in making a community more vulnerable, so we assign a weight of 2 to these parameters in the vulnerability index:

- **older population**
- **youth population**
- **cardiovascular disease**
- **asthma**
- **people who earn low incomes**
- **outdoor workers**

RISK OF OZONE POLLUTION

Figure 16 shows the risk of ozone pollution across the state. Light yellow indicates lower risk and dark blue color indicates higher risk of ozone pollution relative to rest of the state. The northern plains and southern plains are the areas most likely to experience climate-related threats from ozone pollution because they have higher populations of children, older Coloradans, people with health complications like asthma, and people who work and play outdoors. Like their rural counterparts, urban areas like Adams, Arapahoe, and Denver counties are also among the areas that will see worse ozone pollution by mid-century.

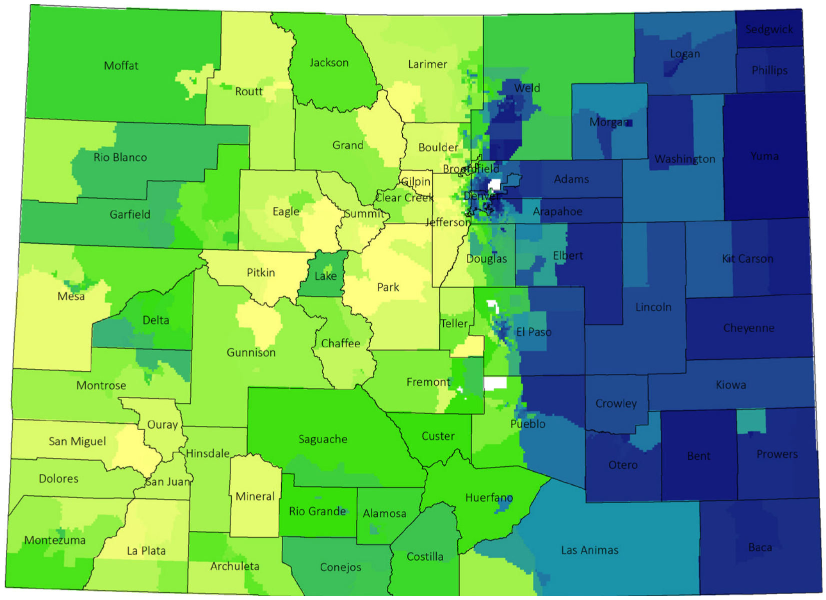


Figure 16: Risk of Ozone pollution

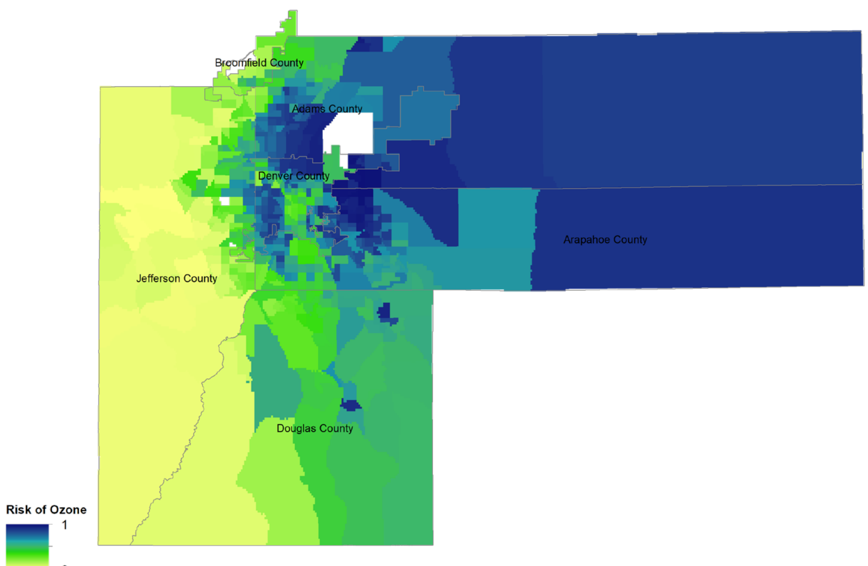


Figure 17: Risk of Ozone pollution, Denver Area

METHODS

The "Risk of ozone pollution" index is a combination of social vulnerability parameters and projected exposure to ozone pollution by mid-century under the high emission scenario. This index is a number between 0 and 1 which ranks census tracts with respect to one another.

The most important predictors are vulnerability to ozone pollution, are age, asthma, heart disease and the number of people who work outdoors. Both children and older people are more likely to be hospitalized or die from short-term ozone exposure. Since these are the most important predictors of vulnerability to ozone pollution, we assign a weight of 2 to them to our social vulnerability to ozone index:

- **older**
- **youth**
- **asthma**
- **heart disease**
- **outdoor workers**

RISK OF WILDFIRES

Particulate matter from wildfire smoke increases respiratory problems and hospital admissions, especially among older people (Liu et al., 2017a). Moreover, increased risk of respiratory admissions from wildfire smoke is significantly higher for some Coloradans than others and can increase based on gender, race, and educational attainment (Liu et al., 2017b). In the event of a wildfire, those with less mobility (access to transit or car ownership) and linguistically isolated people are more at risk (Wong et al., 2020; Méndez et el., 2020). People who earn low incomes are less likely to have the resources and mitigation programs in place to help absorb loss (Poudyal et al., 2012).

Population growth in the past has resulted in more and more people living in areas surrounded by burnable forest and grassland, increasing the likelihood of wildfire ignition caused by people (Poudyal et al., 2012) and has made more people at risk of negative impacts from wildfires. These areas are called Wildland Urban Interface (WUI).

Figure 19 shows the map of WUI, prepared by the Colorado State Forest Service. The map shows areas where housing development has happened in proximity to burnable land and different colors show different levels of housing density. There are seven levels in the WUI based on housing density (houses per acre). Housing density categories vary from “less than 1 house per 40 acres” (gray color) to “greater than 3 houses per acre” (dark purple color).

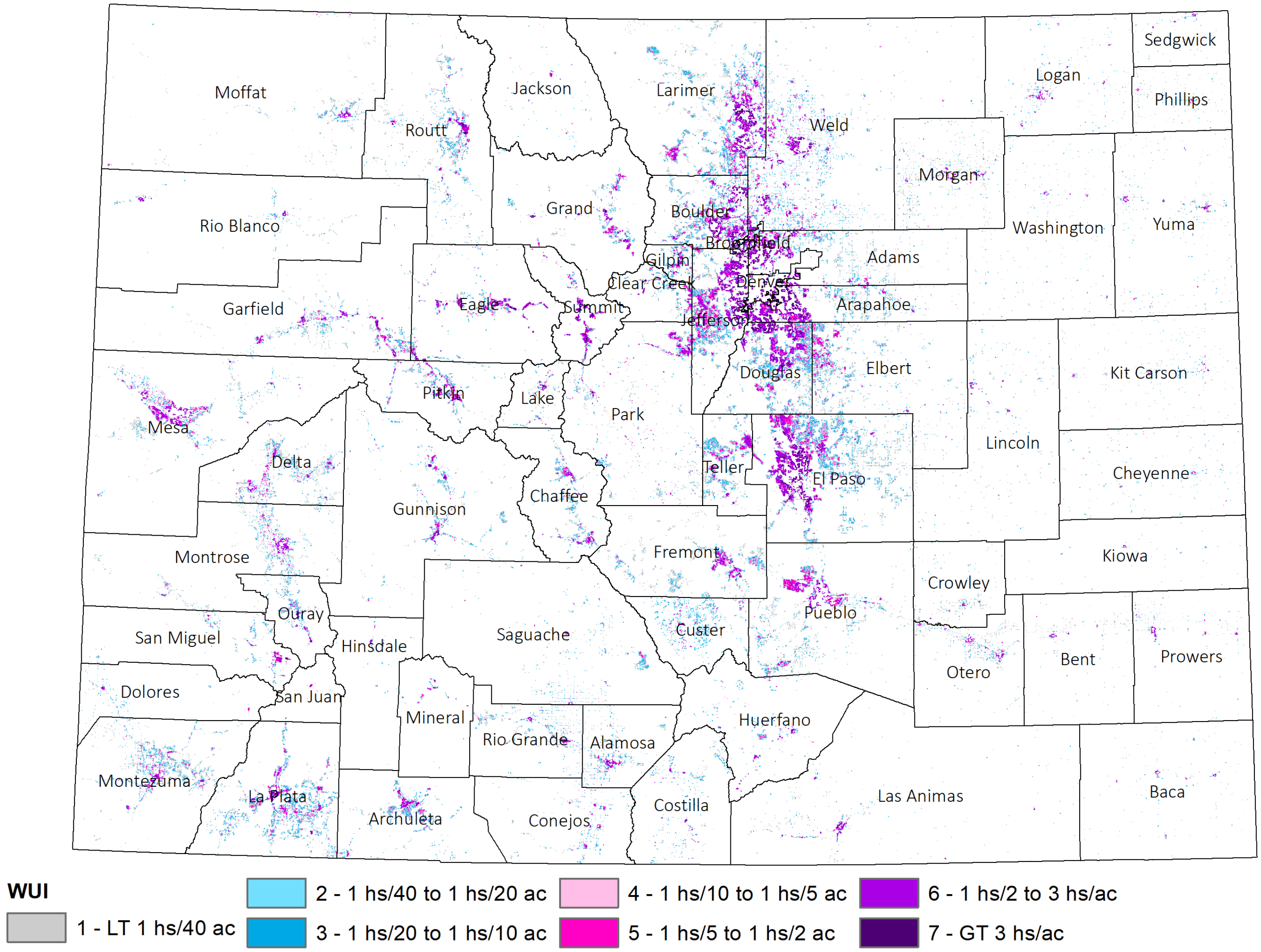


Figure 18: Wildland Urban Interface, 2018

Figure 20 shows risk of wildfires, which is an overlay of the weighted social vulnerability index, WUI, and fire danger by mid-century. Figure 21 shows the same index for the Denver Metro Area. The Northern and Central Mountains areas, the Grand Valley, and the Western San Juan Mountains are at the highest risk of wildfires. Moreover, Jefferson and Denver counties and some areas of Weld and Larimer counties are at high risk of wildfires as well.

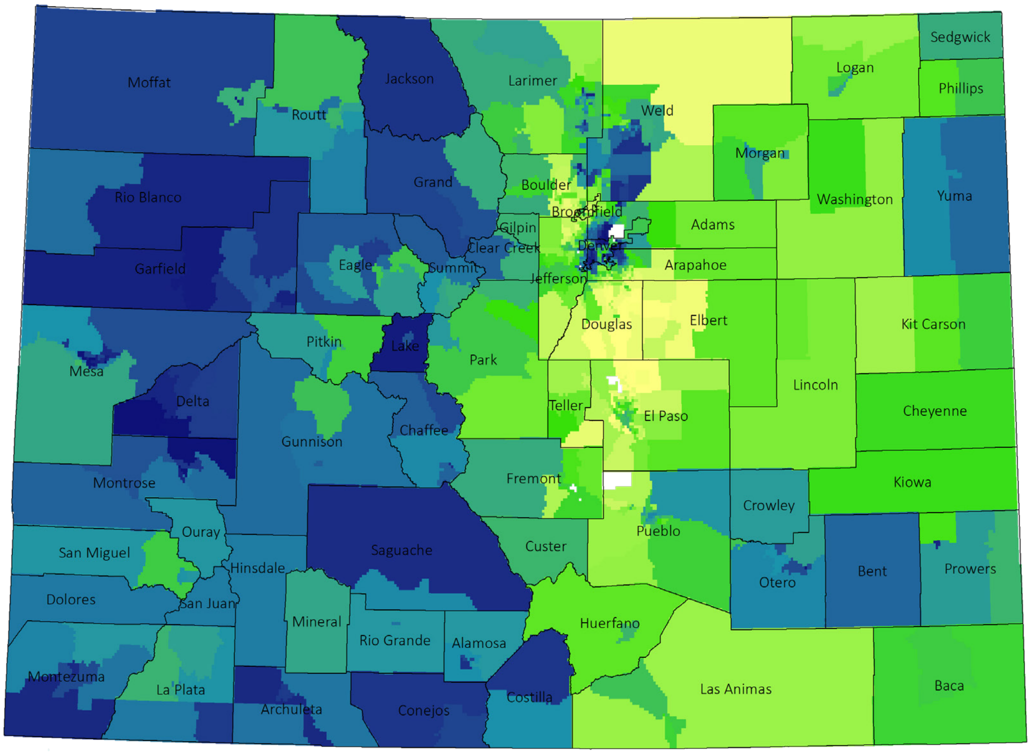


Figure 19: Risk of Wildfires

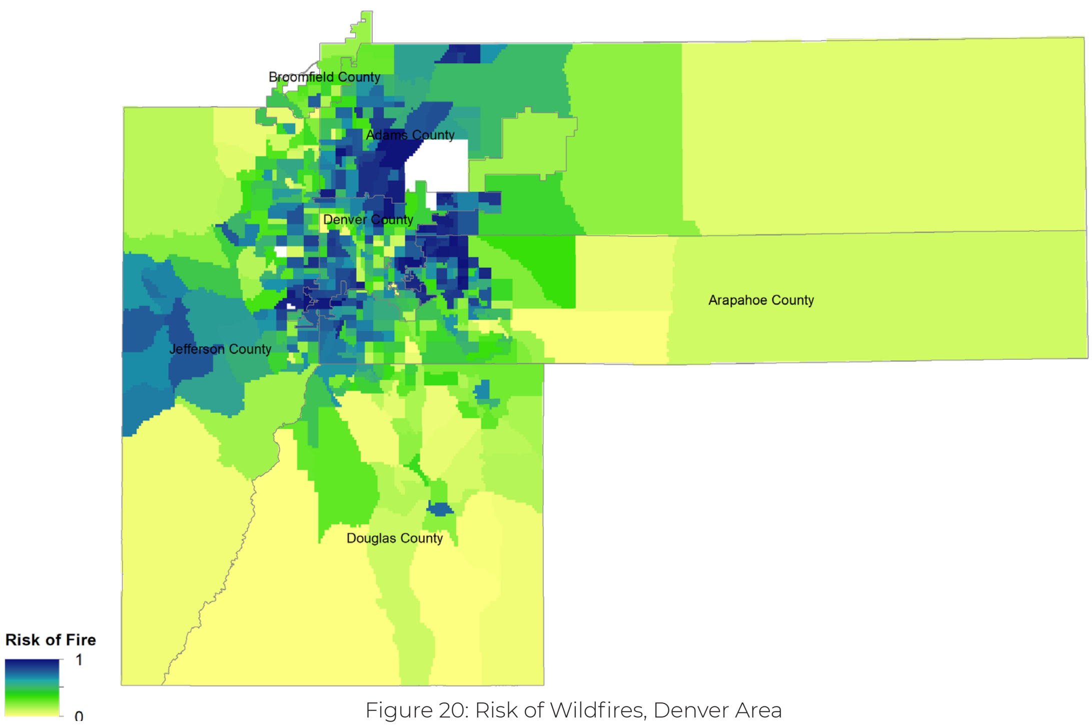


Figure 20: Risk of Wildfires, Denver Area

METHODS

This "Risk of wildfires" index is a combination of social vulnerability parameters (with a weight of 2 assigned to age 65+ population, people of color, asthma, education, income, vehicle ownership, and linguistic isolation,) and projected exposure to wildfire danger by mid-century under the high emission scenario. This index is a number between 0 and 1 which ranks census tracts with respect to one another. In this case, census tracts with higher relative risk of wildfires are projected to experience larger number of days with very high fire danger, have populations that are more vulnerable to wildfires.

We include the WUI in calculating the index using the percentage of the area of a census tract that is in a WUI. A tract which has a larger percentage of WUI area is at higher risk of adverse effects of wildfires.

RISK OF DROUGHT

This "Risk of drought" index is a combination of social vulnerability parameters and projected exposure to drought by mid-century under the high emission scenario. This index is a number between 0 and 1 which ranks census tracts with respect to one another. In this case, census tracts with higher relative social vulnerability to drought are projected to experience a larger decrease in precipitation, have populations that are more vulnerable to drought (agriculture sector workers), and geographies in which the economy is directly impacted by precipitation (farmlands and ski resorts). We then overlay these parameters on the social vulnerability index.

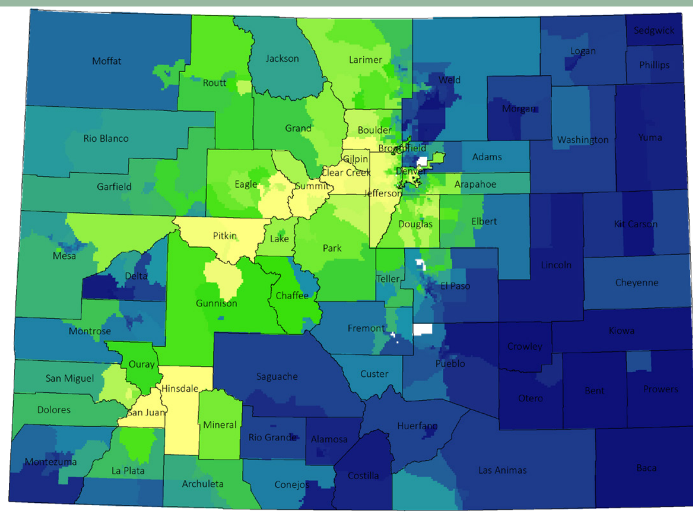


Figure 21: Risk of Drought

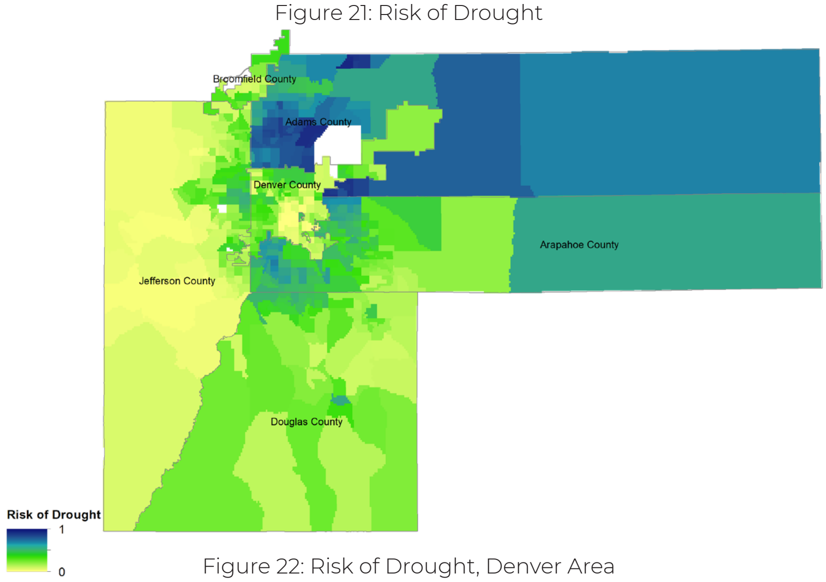


Figure 22: Risk of Drought, Denver Area

Farmers and ranchers, who typically use nearly 90 percent of the state's available water supplies[16], have been significantly impacted by drought in the past decade. 2020 was the third-driest water year on record, followed by 2002 and 2012. In 2020, Severe and Extreme drought conditions originated in the Southwest and Southeast, and then expanded up the Eastern Plains and Western Slope. On the plains, hot dry winds and lack of average moisture levels made it hard for crops to survive.[17] Many Western Slope ranchers also faced irrigation water and cattle feed shortages.[18]

The persistent drought conditions faced by Colorado farmers and ranchers in recent years are part of a long-term trend driven in large part by climate change. Lower snowpack accumulation, discussed above as being a major threat to the state's outdoor recreation and ski industries, carries perhaps an even greater impact on much-needed water supply for agriculture.

Figure 21 shows the risk of drought across the state. We can see the effects of drought have a widespread impact: the Northern and Southern Plains, San Luis Valley area, and parts of the Front Range Region face greater drought threats due to their high percentage of farmland as well as agricultural jobs in these counties. Even the Southwest and Northern Mountains must become resilient to drought since ski resorts will be affected and these areas will experience the highest reductions in precipitation due to climate change.

16. Report: Colorado's farm water use exceeds national average, despite efforts to conserve - Water Education Colorado (https://www.watereducationcolorado.org/fresh-water-news/report-colorados-farm-water-use-exceeds-national-average-despite-efforts-to-conserve/)
17. https://www.youtube.com/watch?v=bIn4eyx8nnk
18. https://www.westernslopenow.com/news/local-news/ranchers-and-cattle-alike-impacted-by-worsening-drought/

DISCUSSION

Resiliency to climate change is important because some populations may have less capacity to prepare for, respond to, and recover from climate-related hazards and effects and therefore will be disproportionately harmed by climate change. Geographic location, type of occupation and economic dependence on climate-sensitive environments, as well as health conditions and demographics mean some groups and communities face greater threats than others from different climate impacts.

Our maps show that climate change will affect different regions of the state differently. While communities in Northern Colorado are more vulnerable to extreme heat, eastern plains communities will face increased ozone pollution and Western Slope communities will be dealing with more wildfires. Drought will have a widespread effect across the state since eastern counties are mainly comprised of farmland and some western Colorado economies rely heavily on winter outdoor recreation. People with different demographic characteristics and socioeconomic status might live in similar geographic areas that expose them to similar climate impacts, but those who face the greatest barriers to climate resiliency will be more adversely affected by the same hazards. By looking at the totality of the threats faced by exposure to climate impacts, it can serve as a reminder that policymaking cannot only focus on places where the climate impacts are expected. Adaptive measures must also be tailored to the people and communities living in the area.

It is important to note that these rankings are relative to the rest of the state. Locations with “low” exposure and vulnerability rankings still face grave threats from climate harm and should not be seen as “safe” from these climate impacts due to their low percentile ranking. Instead, the rankings should tell policymakers where adaptation is most needed and indicate which strategies would be most effective in building resilient communities across the state.

Climate projections show that mild actions to limit increases in greenhouse gas emissions (RCP 4.5) significantly mitigate the impacts compared to business-as-usual practices (RCP 8.5), so it is essential to invest in mitigation now to avoid potentially irreversible damages to ecosystems. Failing to take action on climate change will create significant costs for Colorado: physical and mental health problems, lost days of school, loss of ecosystems, and damage to infrastructure are just a few examples. Indeed, these costs are already here: An analysis[19] conducted by the National Centers for Environmental Information (NCEI) shows that in 2020 alone, Colorado suffered $1.7 billion in costs from wildfires and drought. Estimated costs can also include physical damage to residential, commercial, and government or municipal buildings; material assets within a building; time element losses like business interruption; damage to vehicles and boats; offshore energy platforms; public infrastructure like roads, bridges, and buildings; agricultural assets like crops, livestock, and timber; disaster restoration and wildfire suppression costs. Climate change is projected to increase the frequency of such billion-dollar disasters.

To mitigate these damages in the future, Colorado needs to accelerate our transition away from coal and other fossil fuels, raise funds to invest in mitigation projects and renewable energies, invest in communities that will be disproportionately affected by climate change—whether due to geography or historical and structural inequities—and prepare a just transition to renewable energy for fossil-fuel dependent communities.

19. Did You Know? | Monitoring References | National Centers for Environmental Information (https://www.ncdc.noaa.gov/monitoring-references/dyk/billions-calculations)

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