COLORADO CLIMATE CHANGE VULNERABILITY STUDY

A report submitted to the Colorado Energy Office

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Colorado Climate Change Vulnerability Study

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Damage from the 2002 Hayman Fire is evident 12 years later in this May 2014 panoramic image of the Lost Creek Wilderness. Photo: Eric Gordon.

EXECUTIVE SUMMARY

Overview of Report

Colorado's climate has warmed in recent decades, and climate models unanimously project this warming trend will continue into the future. Climate change has and will continue to impact the state's resources in a variety of ways, including more rapid snowmelt, longer and more severe droughts, and longer growing seasons. Moreover, Colorado experiences numerous climate-related disasters, such as floods, droughts, and wildfires, which will continue to occur in the future and pose serious hazards to public safety and the economy, regardless of the rate at which the climate warms.

During its 2013 session, the Colorado Legislature passed HB13-1293, which declared that "climate change presents serious, diverse, and ongoing issues for the state's people, economy, and environment." Among other provisions, the bill required the governor to submit an annual report to a number of committees within the legislature "on climate change issues generally, the current climate action plan…and the specific ways in which climate change affects the state." The Colorado Energy Office commissioned the University of Colorado Boulder and Colorado State University to assemble a team of Colorado-based experts to complete this study, as one initial step in a multi-agency response to the requirements of HB 13-1293.

The Colorado Climate Change Vulnerability Study provides an overview of key vulnerabilities that climate variability and change will pose for Colorado's economy and resources. The purpose of the study is to provide state agencies, local governments, and others with background for preparedness planning.

"Key vulnerabilities" are defined as "those aspects of the state's economy, resources, or populations that experience negative effects from climate variability or change, and that lack sufficient capacity to adapt to those effects." Vulnerability is a function of both impacts (the effects of climate variability or climate change on a given system or resource) as well as adaptive capacity (the ability of the economy, resources, or population to effectively adapt to such events and changes). The report analyzes vulnerabilities related to both current climate variability—including extreme weather events—and future climate change.

Colorado's Climate: Past and Future History

Chapter 2 of this report provides a brief summary of *Climate Change in Colorado* (http://wwa.colorado.edu/climate/co2014report), which synthesizes observed climate and projected future climate for the state of Colorado. Historic observations of Colorado's climate include:

- An increase in statewide annual average temperatures of 2 degrees Fahrenheit (°F) over the past 30 years and 2.5°F degrees over the past 50 years, with daily minimum temperatures increasing more than daily maximum temperatures over the past 30 years.
- An increase in temperatures in all seasons, with the largest trend in summer, followed by fall, spring, and winter.
- No long-term trends in average annual precipitation statewide.
- Below-average snowpack since 2000 in all eight major river basins in Colorado, although there are no trends over the past 30 or 50 years.
- Snowmelt and peak runoff have shifted 1-4 weeks earlier across Colorado's river basins over the past 30 years due to the combination of lower snow-water equivalent (SWE) since 2000, warming spring temperatures, and enhanced solar absorption from dust-on-snow.
- A trend toward more frequent soil moisture drought conditions in Colorado over the past 30 years.
- No evidence of increasing trends in heavy precipitation events or flooding statewide.
- Multiple droughts prior to 1900 that were more severe and sustained than any in the observed record, as seen in tree-ring records.

Projections from Global Climate Models (GCMs), under a mid-range emissions scenario, indicate the a number of changes and continued uncertainties for Colorado's climate in the mid-21st century:

- An increase in statewide average annual temperatures of 2.5°F to 5.5°F relative to a 1971–2000 baseline. Summers are projected to warm slightly more than winters. Typical summer temperatures in 2050 are projected to be warmer than in all but the very hottest summers in the observed record.
- Climate projections do not agree on whether average annual precipitation will increase or decrease statewide, though winter precipitation is likely to increase by mid-century.
- Most projections show that April 1 snowpack will decline by mid-century due to the large projected warming.
- Spring runoff is projected to shift 1–3 weeks earlier due to warming, with late summer flows likely to decrease as the peak shifts earlier.
- Most projections of future hydrology show decreases in annual streamflow by 2050 for Colorado's major rivers. In some projections, however, the projected increases in precipitation are large enough to overcome the effect of warming, and so these projections show increased streamflow.
- Heat waves, droughts and wildfires are projected to increase in frequency and severity due to the projected overall warming.
- Winter precipitation events are projected to increase in frequency and magnitude, but projections currently show no changes in summertime convective storms by mid-century.

Demography, Land Use, and Economics

Where Colorado residents live and work, how they make their living, and what capacity they have for mitigating climate impacts are all directly connected to climate vulnerability. Chapter 3 of this report finds that a number of demographic, land use and economic factors could impact the state's vulnerability to climate, including:

- The population of residents 65 and older, who tend to be more vulnerable to extremes like heat and cold, will increase 125% by the year 2030.
- An estimated 12.5% of Colorado residents currently live in poverty, potentially making them less able to adapt to climate variability and climate change.
- Only 20% of Colorado's wildland-urban interface (WUI) is currently developed, with the potential for future development of the remaining 80%. Continued development in the WUI, especially along the Front Range urban corridor, could increase the level of population and property exposed to damaging and dangerous fires.
- As evidenced by the September 2013 flooding along the Front Range, Colorado has significant property exposed to flooding both within and outside of mapped floodplains, with billions of dollars of property at risk.
- Although virtually any aspect of Colorado's economy could be affected by changes in the climate, specific industries that rely on natural resources—agriculture, tourism and recreation, and mining and extraction—are particularly vulnerable.

Key Vulnerabilities by Sector

Ecosystems Sector

Colorado's ecosystems provide critical services to the state's residents and its economy, such as spaces for recreation and tourism, provision of water supplies, and lands for farming and ranching. Climate strongly influences the location and character of ecosystems across the state, and future changes in the climate will likely produce changes across our natural landscapes, including:

<u>Forests</u>

- Due to longer and more severe droughts, more frequent and severe fires, and conditions more suitable to insect outbreaks and spread of non-native plant species, individual trees and forested landscapes will likely become more vulnerable to insect and pathogen invasions.
- If wildfires become more frequent and severe, landscapes will be vulnerable to changes in connectivity, shifts from carbon sinks to carbon sources, and shifts in vegetation distribution and type.

<u>Alpine Ecosystems</u>

- Alpine plants are vulnerable to phenology shifts caused by rising spring temperatures and earlier snowmelt onset, potentially leading to mid-summer declines.

<u>Grasslands</u>

- Grass types that fare better in drought conditions are likely to become more dominant; less drought-tolerant species are therefore vulnerable to increased frequency and severity of drought.

<u>Wildlife</u>

- Aquatic species are vulnerable to decline due to reductions in habitat suitability, especially connected to rising water temperatures as well as more frequent and severe fires, forest fragmentation and other changes in habitats.

Water Sector

Water is connected to virtually every aspect of life in Colorado. Analysis in this report covers the effects of climate variability, extreme events, and climate change on water supply, water demand, water quality, flood mitigation, and nonconsumptive uses. Potential key vulnerabilities in the water sector include:

Water Supply

- Water supply entities with inadequate storage, especially agricultural water supplies and small Municipal and Industrial (M&I) utilities, are vulnerable to earlier snowmelt timing and runoff.
- Entities with junior rights or little storage are potentially vulnerable to future low flows.
- Virtually all water supply entities and their customers are vulnerable to longer and more intense droughts, especially mega-droughts.
- Water supply entities in areas like the San Luis Valley or South Metro that rely heavily on groundwater to supplement surface water supplies, as well as private homes and small community water supplies that rely on groundwater, are vulnerable to potential reductions in groundwater recharge.
- Elements of water supply infrastructure such as older dams, ditches, and canals, as well as reservoirs in areas with high potential for wildfire, are vulnerable to extreme events and increased wildfire risk.

Water Demand

- Agriculture producers needing late summer irrigation and some M&I utilities with junior rights are vulnerable to earlier snowmelt timing and lower late summer flows.
- Those with junior rights facing greater competition among multiple sectors are vulnerable to interaction of heat and lower flows with existing demand trends.

Water Quality

- M&I utilities with older treatment technology or lower treatment capacity, as well as aquatic organisms and ecosystems, are vulnerable to lower flows and higher water temperatures resulting in greater concentrations of pollutants
- Water treatment facilities in fire-prone areas are vulnerable to greater likelihood of wildfire leading to higher chances of erosion.

Flood Mitigation

- Large portions of the state that exist in areas of high flood risk and have engaged in little mitigation are vulnerable to continued high risk of extreme precipitation events.

Nonconsumptive Uses

- Earlier and faster runoff may create vulnerabilities for rafting, fishing, and other recreation activities by reducing appropriate flows.
- Endangered fish recovery programs are vulnerable to potentially reduced average streamflow.

Agriculture Sector

Agriculture is a $24 billion industry in Colorado, comprising a key part of the state's economy and providing food supplies to the state and elsewhere. Higher temperatures and other impacts will result in a combination of negative and positive effects on the state's agricultural industry. Potential key vulnerabilities by sub-sector include:

Field crops

- Crop yields are vulnerable to reductions due to heat stress.
- Farmers and ranchers are potentially vulnerable to more frequent losses of crops,

forage, and soil from increasingly severe future droughts.

- Crops are vulnerable to increased weeds and pests due to longer growing season.
- Farmers are potentially vulnerable to production losses due to irrigation shortages from reduced streamflows.
- Crops could be potentially affected by weeds encouraged by CO_2 fertilization.
- Farmers and ranchers are potentially vulnerable to continued losses of crops, facilities (structures, ditches, equipment) from extreme weather.

Fruits and vegetables

- Fruit crops are vulnerable to frost damage worsened by early budburst.
- Fruit and vegetable crops are vulnerable to increased potential for water shortages occurring simultaneously with higher crop water demand from increased drought.
- Farms are vulnerable to reduced production due to limited irrigation supply, increased water prices from reduced streamflow, especially in late summer.

Livestock

- Cattle are vulnerable to lower weight gain and other health problems due to higher temperatures.
- Ranchers are vulnerable to feed price shocks from increased drought.

Green industry

- The industry is vulnerable to damage to facilities and products from extreme weather.
- Climate warming could produce vulnerabilities from loss of production due to water use restrictions from reduced streamflow.

Energy Sector

Although the physical impacts of climate on electricity supplies are fairly well studied, less is known about impacts to fossil fuel extraction and production. In addition, the energy sector is unique in that energy-related activities are fundamental drivers and responders to both climate mitigation and adaptation measures. Potential key vulnerabilities in this sector include:

- Cascading effects of drought, heat waves, and wildfire, coupled with increased penetration of air conditioning in the Colorado market could lead to water scarcity and grid stress, with attendant price increases and system instabilities.
- The electricity industry faces increased vulnerability to greater competition for water supplies and increased generation costs as temperatures rise.
- The energy sector is potentially vulnerable to large increases in energy use if reductions in overall water supplies lead to the creation of energy-intensive water projects.
- If future greenhouse gas regulations are implemented, the energy sector and consumers would be vulnerable to the uncertainty of future energy price increases as well as costs associated with crop production, water use, and transportation.

Transportation Sector

There are two major types of climate sensitivities in Colorado's transportation sector—the sensitivity of road, rail, and airport infrastructure to the physical impacts of extreme heat and heavy precipitation; and the sensitivity of travel behavior and safety to impaired visibility and traction from wildfires and precipitation events. Particular key vulnerabilities in this sector include:

- The state's road network may be vulnerable to increases in road maintenance needs and road closures from heat-related problems.
- Airports unable to extend runways may

find themselves vulnerable to reduced cargo capacity due to warmer air, which can make passenger flights less cost effective.

- Rail lines may become increasingly vulnerable to heat due to the very high cost of installing more heat-resistant tracks.
- All elements of the transportation system, especially roads, are vulnerable to closures due to increased wildfires.
- The state's road network could be vulnerable to closures and infrastructure damage due to intense precipitation, even under the current climate.
- Communities with limited road access are highly vulnerable to being cut off by floods or winter storms.
- Airports could be vulnerable to damage to runways and drainage systems from flooding events and winter storms that overwhelm their existing capacity to respond.
- Railroads could be vulnerable to damage from flooding and winter storms that overwhelm their capacity to respond.

Outdoor Recreation and Tourism Sector

Colorado residents and visitors to our state enjoy a variety of activities including hiking, camping, wildlife viewing, biking, hunting, four-wheeling, golfing, fishing, rafting, kayaking, sailing, climbing, mountaineering, skiing, snowshoeing, and snowmobiling. Although climate impacts may be both positive and negative in this sector, a number of potential key vulnerabilities stand out:

- The commercial rafting industry is vulnerable to reduced season length due to shorter, faster runoff.
- Wildlife viewing may be vulnerable as coyote, elk, and raccoons become more common while marmot and pika become less common as the climate warms.
- Fly fishing could be vulnerable as rising stream temperatures and declining streamflows reduce habitat for coldwater trout species.
- A number of activities, notably skiing and rafting, are vulnerable to continued large swings in temperature and precipitation from year to year as well as the effect such swings can have on perceptions of tourism and recreation in Colorado.
- Virtually all summertime recreation and tourism opportunities are vulnerable to wildfire, which can close roads, destroy trails and campgrounds, cause air quality problems, and result in potential out-of-town visitors deciding not to travel to Colorado.
- National park visitors may be less likely to see snow-capped mountains and glaciers.

Public Health Sector

This report provides an overview of the possible impacts of climate variability and climate change to the prevalence of disease, injury, and death in society. However, there are few straightforward causal links to climate-related impacts. Continuous demographic changes, existing regulation, ongoing improvements to infrastructure, improvements in air quality, and adaptation strategies like vector control are often just as important or more important than climate to future public health impacts. Specific populations within Colorado may be disproportionately vulnerable to climate-related health problems, including:

- Very young children, elderly, chronically ill persons taking drugs that impair thermoregulation, and outdoor workers are vulnerable to higher daytime temperatures.
- Children and pregnant women, outdoor workers, and individuals with pulmonary diseases, cardiovascular disease, and compromised respiratory and circulatory systems are vulnerable to rising concentrations of ground-level ozone, fine particulates, and aeroallergens due to climate warming.

- Individuals who work outdoors, outdoor recreators, and children are vulnerable to an increase in West Nile virus.
- Rural communities, veterinarians, and hunters are vulnerable to a climate-related increase in the incidence of plague.
- People who are involved in home remodeling or are working in a shed or barn are more vulnerable to an increase in Hantavirus, which may become more common with climate warming.
- Elderly and disabled individuals are vulnerable to floods, wildfires, and other extreme events because they have relatively greater difficulty evacuating.
- Emergency workers are vulnerable to hazards from floods, wildfires, and other extreme events.
- A number of vulnerable populations may face added effects of poor air quality due to smoke from wildfires.

Moving Toward Preparedness

The final chapter of this report describes ways in which the state might prepare for the effects of climate variability and change, commonly referred to as either "adaptation" or "preparedness." Most adaptation approaches focus broadly on understanding vulnerabilities to future climate, developing plans capable of buffering against a variety of future impacts, and monitoring impacts to adjust those activities as needed. While this study does not provide specific steps related to adaptation or preparedness planning in a given sector, we do provide a template that state agencies can use to develop a preparedness plan, which includes the following steps:

1) provide leadership from the highest possible levels
2) assign responsibility for climate preparedness planning
3) catalog long-term planning and short-term operation areas relevant to climate
4) connect with experts
5) engage with stakeholders
6) conduct a vulnerability assessment if needed
7) analyze risks based on probabilities
8) set a vision and goals for a preparedness plan
9) develop and implement a preparedness plan
10) monitor impacts and refine plan as needed

If a vulnerability assessment is needed (#6 above), the report suggests the following series of steps:

1) identify planning area
2) identify climate variable
3) identify projected change
4) describe level of confidence
5) describe potential impacts
6) describe adaptive capacity
7) assess vulnerability

Agencies can use the results of this exercise to set priorities. Assuming limited resources are available for climate preparedness, identifying the most vulnerable resources or populations can help the agency decide where to focus its planning efforts.

Panorama of Loveland Pass, Colorado. Photo: Ben Livneh.

CHAPTER 1
INTRODUCTION AND PURPOSE OF STUDY

I. Introduction

During its 2013 session, the Colorado Legislature passed HB 13-1293, which declared that “climate change presents serious, diverse, and ongoing issues for the state’s people, economy, and environment.” Among other provisions, the bill required a person appointed by the Governor to submit an annual report to a number of committees within the legislature “on climate change issues generally, the current climate action plan…and the specific ways in which climate change affects the state.”

Colorado’s climate has warmed in recent decades, and climate models unanimously project this warming trend will continue into the future. Although the actual pace of warming is dependent on the rate of worldwide greenhouse gas emissions, climate change has and will continue to impact the state’s resources in a variety of ways, including more rapid snowmelt, longer and more severe droughts, and longer growing seasons. (For an overview of the observed and potential future changes to Colorado’s climate, see Chapter 2.) Moreover, Colorado experiences numerous climate-related disasters, such as tornados, hailstorms, and wildfires, which will continue to occur in the future and pose serious hazards to public safety and the economy.

A clear scientific consensus indicates that man-made greenhouse gas emissions have caused the planet—and consequently Colorado—to warm in recent decades. This trend is expected to continue into the future, although the actual pace of warming is dependent on the rate at which greenhouse gas emissions continue and a variety of other factors. Rising temperatures have and will continue to impact the state’s

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resources in a variety of ways, including more rapid snowmelt, longer and more severe droughts, and longer growing seasons. (For an overview of the observed and potential future changes to Colorado's climate, see Chapter 2.) Moreover, Colorado experiences numerous climate-related disasters, such as tornados, hailstorms, and wildfires, that will continue to occur and may be exacerbated by climate change.

Multiple state agencies, including the Colorado Energy Office, the Colorado Department of Public Health and the Environment, and the Colorado Water Conservation Board are leading efforts to respond to this legislation and to meet the challenges of climate change in the state. The Colorado Energy Office's contribution to date includes commissioning the University of Colorado Boulder and Colorado State University to assemble a team of Colorado-based experts to complete this climate vulnerability study.

The purpose of this particular study is to provide an overview of the key vulnerabilities that climate change and climate variability will pose for Colorado's economy and resources in order to provide state agencies, local governments, and others with background for preparedness planning. Readers should recognize that climate-related impacts interact with major other stressors, such as changes in the economy or demographic shifts, to produce net effects that can vary across the state or over time.

We focus on analyzing the effects of both the variability of the current climate—including extreme weather events—and of future climate change. While the climate of the future will see changes in average conditions, variability will still be a key characteristic of the state's climate. For example, a long-term warming trend in average temperatures does not mean that Colorado will no longer experience wintertime deep freezes. Climate preparedness thus depends on being aware of the year-to-year and seasonal variability in our current climate, the potential for extreme weather events, and the longer-term shifts that may happen in the future.

While we attempt to highlight where climate variability and change will negatively affect Colorado's economy and way of life, we cannot provide a forecast of how Colorado's climate and weather will change in the future, nor can we enumerate predicted impacts across sectors. Doing so would be unrealistic given the uncertainties inherent in both the pace of future climate change—which in turn depends on the rate of greenhouse gas emissions worldwide—and on how changes in the global climate system will play out in Colorado. This study is also not intended to provide a quantitative, comparative assessment of specific vulnerabilities in different sectors or regions of the state, as has been done previously in other states (see Chapter 11 for examples) or in Colorado with respect to specific concerns (see, for example, the CWCB Drought Vulnerability Study). Such an assessment may be considered as part of future efforts.

Instead, the aim here is to provide a broad overview of the ways in which climate variability and climate change pose challenges to different sectors and regions, and to highlight areas where the state is lacking in sufficient capacity to adapt to future climate

Figure 1.1. The road-plowing capabilities of governments in Colorado provide the state with adaptive capacity to handle more or less snowy individual winters or an overall trend towards more intense winter storms, which could be possible under climate change (Photo: Michael Rieger, Federal Emergency Management Agency).

impacts. This information is intended to serve as a basis for future preparedness planning throughout the state and elsewhere. It can also provide a baseline for more detailed vulnerability assessments that could be developed as part of focused, sector-specific reports. Thus the remainder of this study focuses on identifying key vulnerabilities in the state, which are defined as:

> Those aspects of the state's economy, resources, or populations that experience negative effects from climate variability or change, and that lack sufficient capacity to adapt to those effects.

A vulnerability is also a function of both the effects of climate variability or climate change on a given system or resource (known as impacts) and of the ability of the economy, resources, or population to effectively adapt to such events and changes (known as adaptive capacity). For example, the road-plowing capabilities of the Colorado Department of Transportation (CDOT) (Figure 1.1) and local authorities mean that Colorado is less vulnerable to large snowstorms than many other regions of the country, especially those where winter weather is not as common. A homeowner in a forested area who has created defensible space around his or her house and installed a metal roof would similarly be less vulnerable to wildfire than a neighbor whose house features a cedar shake roof. Note, however, that vulnerability can be complicated by interactions among sectors with varying levels of adaptive capacity, as would be the case with changes in snowmelt and runoff timing affecting multiple sectors.

Figure 1.2. "Weather" refers to the state of the atmosphere at any given time, such as a sunny day at Pearl Lake near Steamboat Springs. The forecasted state of the atmosphere up to a week into the future is also considered to be part of weather (Photo: Ami Nacu-Schmidt).

In addition to understanding the components of climate vulnerability as they will be used throughout this study, it is important to use clear concepts of climate, weather, and climate change. Doing so can help increase climate literacy and ensure that climate preparedness becomes a routine part of government and business planning. It can also help prevent too strong a focus on long-term trends and not enough on vulnerabilities to our existing climate, especially extreme weather events

To begin, weather is quite distinct from climate. Weather is the state of the atmosphere at a given time (75°F and sunny, for example; Figure 1.2) and the forecasted change in the state of the atmosphere for roughly a week into the future. Climate, on the other hand, is the average of weather conditions over a long period, usually a few decades—for example, the average high temperature on a given day at a given location for the past 100 years.

Climate variability refers to the fluctuation of these climate conditions above and below a given average over a variety of time scales. For example, the average February temperature in Fort Collins from 1971-2000 ranged from 22°F to 39°F. A string of very dry months or even dry years can occur as part of natural climate variability. These changes are sometimes tied to large-scale cycles in the atmosphere and the world's oceans, such as the well-known El Niño phenomenon.

Climate change (also called "global warming") refers to a pronounced trend in average climate conditions over a period of decades or longer, such as mean temperature or average annual precipitation. True climate changes are statistically distinguishable from past changes due to climate variability. Although the global climate has naturally changed over the course of the existence of the planet, man-made greenhouse gas emissions have resulted in dramatic warming since the mid-20th century (see Chapter 2). These emissions are causing temperatures to rise and adding additional energy to the climate system, which is expected to result in a variety of future impacts.[1]

It is also important to emphasize that although climate change is most obviously evident through changes in long-term trends like average temperature, the climate will still feature significant variability. Thus while temperatures across Colorado are expected to progressively warm in the future, we will continue to experience Arctic cold waves that grip the state nearly every winter. Although summers will generally warm in the future, Colorado could still see individual relatively cool summers. Climate change may also amplify some aspects of climate variability and weather–for example, one study using climate projections indicates that winter snowstorms may become more intense in Colorado (see Chapter 2). Understanding the long-term effects of greenhouse gas emissions on climate variability and individual weather events is one of the more challenging areas of climate science. This highlights the need to prepare for an uncertain climate future and recognize multiple kinds of climate vulnerabilities, rather than expecting that projections of future climate will be clear enough to provide specific guidance for decision making. This study is intended to provide a sense of that uncertainty and some ideas of how to prepare for it.

1 These definitions are adapted from the WWA/CWCB "Climate Change in Colorado" report (Lukas et al. 2014).

For additional information regarding the science of climate change, we recommend consulting the 2014 *Climate Change in Colorado* report (http://wwa.colorado.edu/climate/co2014report). Additional relevant information on climate science and climate impacts at broader scales than the state can be found in the *Assessment of Climate Change in the Southwest United States* (Garfin et al. 2013; http://www.swcarr.arizona.edu) and the newly released National Climate Assessment (Melillo et al. 2014; http://nca2014.globalchange.gov).

II. Climate and Colorado's History

In preparing for future climate impacts, Coloradans can draw on a long history of adapting to the varied climate of their state. Some of the state's earliest inhabitants were

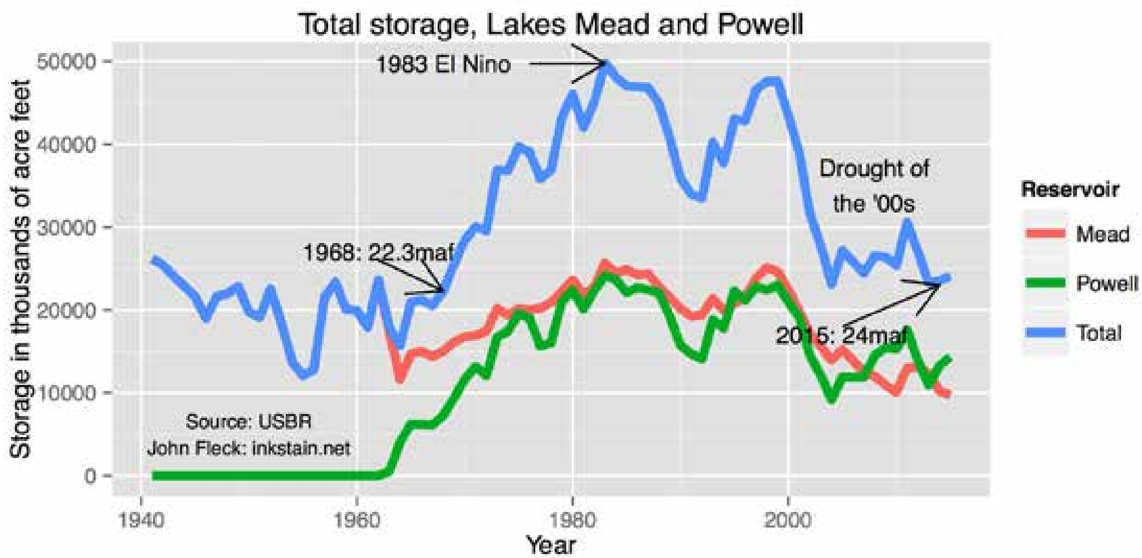

Figure 1.3. The 2000s featured the worst 14-year drought on record for the Colorado River, as demonstrated in the storage levels at Lakes Mead and Powell (John Fleck, inkstain.net).

Figure 1.4. The Black Forest Fire in 2013 claimed two lives and 500 homes. As temperatures warm, wildfires are expected to become more frequent and more intense across the western United States (Photo: Capt. Darin Overstreet, Defenseimagery.mil).

Figure 1.5. Devastating floods across parts of the Front Range in September 2013 claimed 10 lives and caused more than $2 billion in estimated repair and recovery costs. Although there is no evidence yet that climate change will result in worsening floods across Colorado, the state is clearly vulnerable to these types of events (Photo: Raul Valenzuela, Cooperative Institute for Research in Environmental Sciences).

Ancient Pueblo peoples who built cities like Mesa Verde in the dry southwestern corner of what would become Colorado. Closer to modern times, the eastern plains were described by Major Stephen Long in 1823 as part of "The Great American Desert," yet 19th century settlers persisted in planting dryland wheat and irrigating large sections of the plains to make agriculture work. The Rocky Mountains also posed such a difficult snow-bound barrier to travel that the first transcontinental rail route went over South Pass in Wyoming and avoided Colorado altogether, but eventually rail lines and highways provided efficient routes across the Continental Divide, culminating with interstate highway access through those mountains via the Eisenhower and Johnson tunnels.

Despite Colorado's success in adapting to its sometimes harsh and varied weather, the climate of the region can still have significant impacts on the economy of the state and the well being of its residents. Since 2000, a 14-year drought in the Upper Colorado River Basin, unprecedented in more than 100 years of gaged records (K. Nowak, pers. Comm.; Figure 1.3), has stressed water users in Colorado and throughout the southwest. In that time, the state has also seen winter storms drop several feet of snow across the foothills and the urban corridor (2003 and 2006), summer storms dump devastating hail (including the July 1990 Front Range storm event, considered the costliest hailstorm in U.S. history), and steady rains cause major flooding (2013). Slower and less dramatic, drought can also be quite devastating, as seen in 2002. Drought also makes conditions ripe for wildfire—the record for most destructive fire in the state's history has been topped three times in recent years (Fourmile Canyon Fire in 2010, Waldo Canyon Fire in 2012, and Black Forest Fire in 2013). Although an individual weather disaster is not necessarily connected to climate change, these types of extreme events will continue to occur in the future and present some of the most significant vulnerabilities in the state. Throughout this report, we consider vulnerabilities to future trends in our climate together with analyses of vulnerabilities to potential extreme climate-related disasters.

2013, in fact, stood out as a year of notable events in Colorado and a stark reminder of the need to prepare the state for climate-related disasters. In early June, lightning sparked two fires in southern Colorado that eventually merged into the West Fork Fire Complex, one of the largest fires in state history. That same month, the Black Forest Fire (Figure 1.4) erupted near Monument, claiming two lives and burning 500 homes, becoming the most destructive fire in state history (RMIIA undated). In a dramatic counterpoint to the dry conditions that fueled those blazes, September 2013 brought devastating floods (Figure 1.5) as heavy rains set new precipitation records across much of the Front Range (WWA 2013). Ten people died (Colorado OEM 2013), nearly 20,000 buildings were heavily damaged or destroyed, and the costs of repair and recovery were estimated at more than $2 billion (CWCB 2013).

By and large, these types of climate impacts are not out of line with what our state has experienced in its history. The effects of climate change due to man-made greenhouse gas emissions will exacerbate many of these impacts. The *Climate Change in Colorado* report indicates that average temperature will be 4°F warmer by the middle of the 21st century than it was at the end of the 20th century. This projected warming can exacerbate many existing vulnerabilities, making it more challenging for the state and its residents and businesses to cope with future weather events and climate variability. Moreover, rapid economic and demographic changes such as growth in floodplains and in the wildland-urban interface (see Chapter 3) have expanded the number of state residents, homes, and businesses exposed to extreme weather and climate change.

Throughout this study we discuss in more depth how the impacts of climate variability, extreme events, and climate change can affect the state and its economy. To provide a brief idea of the importance of this issue for the state's economy, however, consider that climate can affect:

Figure 1.6. Ranching, a mainstay of Colorado's $24 billion agricultural industry, could be vulnerable to climate change (Photo: United States Department of Agriculture).

- Water supplies needed for virtually every aspect of Colorado's economy and way of life.
- $1.8 billion in annual economic benefit from hunting and fishing, which depends on the wide variety of ecosystems present across the state (BBC Research and Consulting 2008).
- Dryland farming, ranching (Figure 1.6), and other elements of the agriculture industry in Colorado, which produce more than $24 billion in sales each year (Davies et al. 2012).
- Production and consumption of energy in Colorado, including the $4.8 billion spent by Coloradans on electric energy in 2010 (EIA 2013).
- Effective maintenance of Colorado's 88,000 center-line miles of roadway (CDOT 2011) along with rail and air connections that make up Colorado's transportation network.

- Tourism and outdoor recreation, including activities like skiing, rafting, and hiking, which bring in between $8.5 and $15 billion annually (Colorado State Parks 2008).
- The health and well being of all Coloradans, especially those susceptible to climate-sensitive conditions.

III. Structure of Report

The rest of this study is structured as follows:

Colorado's Climate: Past and Future

This section provides a brief overview of the historic (observed) and projected (future) climate of the state.

Other Major Stressors Relevant to Colorado's Future

This section describes demographic, economic, and land use changes that are themselves stressors on Colorado's economy and people, and can potentially exacerbate climate-related vulnerabilities.

Key Vulnerabilities by Sector

This section provides an overview of the major climate-related vulnerabilities across seven sectors important to Colorado's economy and its residents:

- Ecosystems
- Water
- Agriculture
- Energy
- Transportation
- Outdoor Recreation and Tourism
- Public Health

Moving Toward Preparedness

This section provides brief guidelines for state agencies and local governments to begin planning for climate preparedness.

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Kawuneeche Valley located on the west side of Rocky Mountain National Park, Colorado. Photo: Wikimedia Commons, Darekk2.

CHAPTER 2
COLORADO'S CLIMATE: PAST AND FUTURE

Authors

Jeff Lukas, *University of Colorado Boulder*
Eric Gordon, *University of Colorado Boulder*

I. Introduction

Colorado's climate has warmed in recent decades and climate models unanimously project this warming trend will continue into the future. This warming will influence the state's future snowpack, streamflow, drought, and wildfires, although impacts to these will also be affected by future precipitation change, which is less certain than changes in temperature. The pace of manmade greenhouse gas (GHG) emissions worldwide will be a major factor in determining the magnitude of the warming and other future shifts in Colorado's climate.

This chapter provides a brief summary of observed climate and projected future climate across the state. All of the information contained in this chapter comes from *Climate Change in Colorado* (http://wwa.colorado.edu/climate/co2014report), a report co-produced by the Western Water Assessment and the Colorado Water Conservation Board.

Chapter citation: Lukas, J. and E. Gordon (2015). Chapter 2—Colorado's Climate : Past and Future. In *Colorado Climate Change Vulnerability Study*, edited by Eric Gordon and Dennis Ojima. University of Colorado, Boulder, CO and Colorado State University, Fort Collins, CO.

II. Observed Climate in Colorado

Colorado has experienced a long-term warming trend, particularly over the past 30 years, but has seen no trends in precipitation. It is important to recognize that not all global, national, or regional trends are reflected in Colorado. The information provided below is specific to our state.

- In Colorado, statewide annual average temperatures have increased by 2.0°F over the past 30 years and 2.5°F over the past 50 years (Figure 2.1). Warming has been observed over these periods in nearly all regions of the state.

- Daily minimum temperatures in Colorado have warmed more than daily maximum temperatures during the past 30 years. Temperatures have increased in all seasons, with the largest trend in summer, followed by fall, spring, and winter.

- No long-term trends have been detected in average annual precipitation across Colorado, even considering the relatively dry period since 2000 (Figure 2.2).

- Snowpack, as measured by April 1 snow-water equivalent (SWE), has been mainly below-average since 2000 in all eight major Colorado river basins, although there are no trends over the past 30 years or 50 years.

- The timing of snowmelt and peak runoff has shifted earlier in the spring by 1-4 weeks across Colorado's river basins over the past 30 years, due to the combination of lower SWE since 2000, the warming trend in spring temperatures, and enhanced solar absorption from dust-on-snow.

- The Palmer Drought Severity Index (PDSI) shows a trend towards more frequent soil-moisture drought conditions in Colorado over the past 30 years, reflecting the combination of the warming trend and below-average precipitation since 2000.

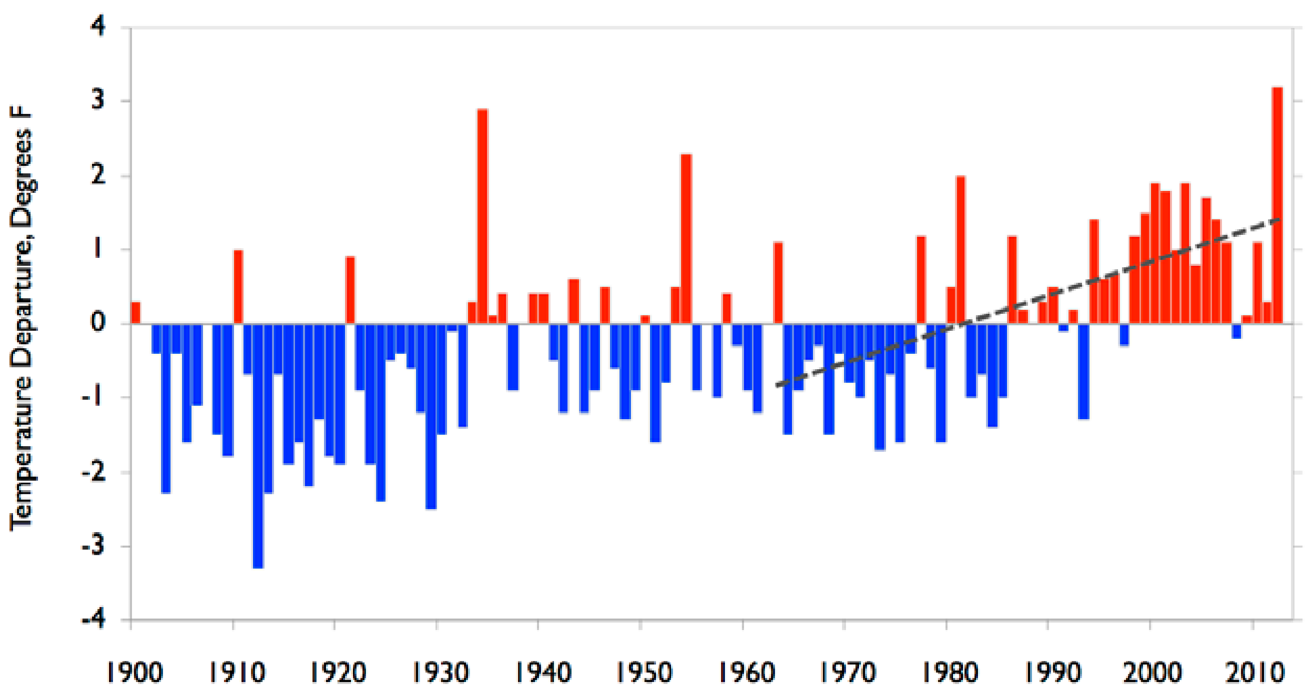

Figure 2.1. Statewide annual average temperatures (°F) across Colorado from 1900–2012. The annual values (red and blue bars) are shown as departures from the 1971-2000 average. The dashed line shows the 50-year trend (+2.5°F), which is statistically significant. 100-year and 30-year increasing trends in this record are also statistically significant. The record shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the late 1960s and 1970s, and consistently warm temperatures since the mid-1990s. (Adapted from Lukas et al. 2014; data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag)

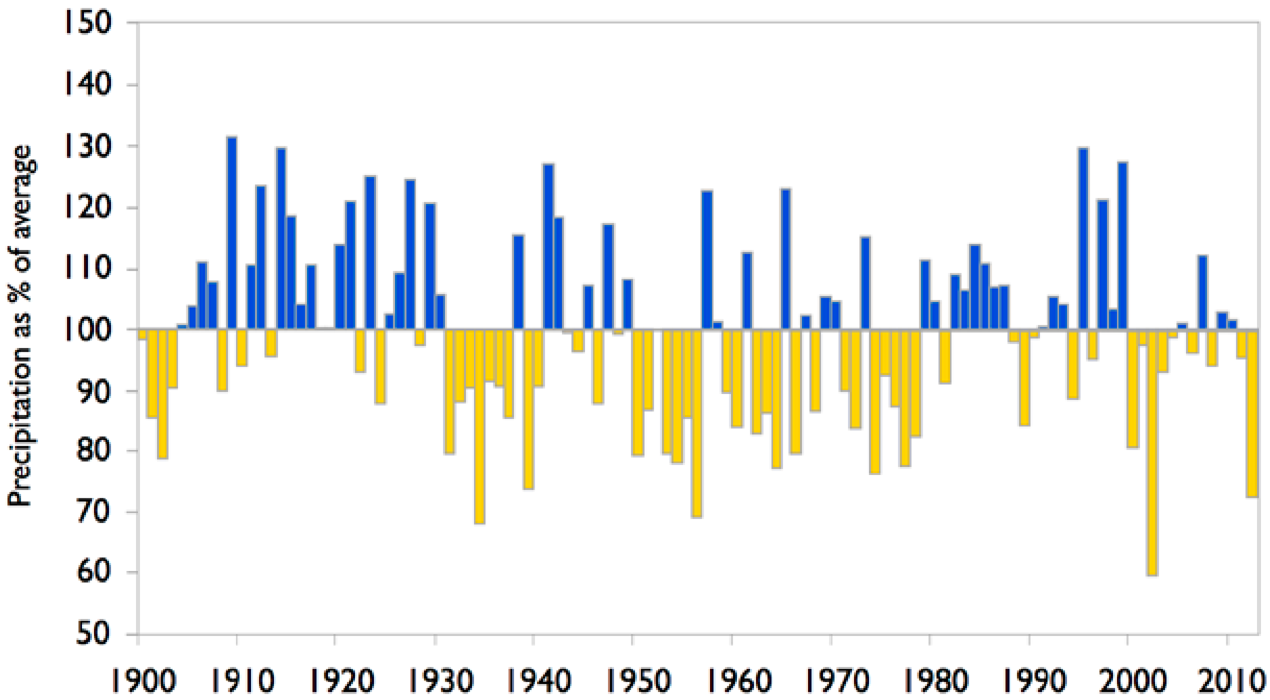

Figure 2.2. Statewide annual precipitation across Colorado from 1900–2012. The annual values (blue and yellow bars) are shown as a percentage of the 1971-2000 average. There are no statistically significant long-term trends in the record. The record shows persistent dry periods in the 1930s, the 1950s, much of the 1960s and 1970s, and the early and mid-2000s. (Adapted from Lukas et al. 2014; data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag)

- There is no evidence for increasing trends in heavy precipitation events or flood events for Colorado.
- Tree-ring records and other paleoclimate indicators of the past 2000 years show that the state experienced multiple droughts prior to 1900 that were more severe and sustained than any seen since then. These prehistoric mega-droughts were driven by natural variability in precipitation and could recur in the future, independent of climate change.

III. An Overview of the Projected Mid-Century Climate in Colorado

Climate projections are produced using Global Climate Models (GCMs), which are highly complex super-computer simulations of the earth's climate system. They represent the globe as a grid of horizontal and vertical boxes and solve fundamental physics equations that describe the transfer of energy, water, and momentum from one box to the next, with mathematical representations of processes that are smaller than the horizontal grids of the models—which are typically 50–150 miles on a side. Over 50 GCMs have been developed and are continuously improved by different research groups around the world.

Climate researchers have much greater confidence in projections of temperature than of precipitation, especially at the regional scale. Changes in precipitation are influenced by more complex processes than changes in temperature.

Note that any single climate projection (i.e., one model run from one GCM) for a given region may differ from other projections because of differences in any or all of the following:

- The scenario of future GHG emissions used to drive the GCM for that projection
- The GCM's representation of key climate processes, which varies between GCMs
- The simulation of natural variability unique to that projection
- The methodology used to downscale the GCM output, if it was downscaled

Given the range of projections—and plausible future climates for our region—it is important to consider multiple climate projections in making summary statements and performing additional impacts assessment. All of the statements below are based on projections from multiple GCMs (typically 30 or more), under a medium-low emissions scenario (RCP 4.5) unless otherwise specified. Note that the middle of the range of the projections (the average or median) is not necessarily the most likely future climate outcome; all projections should be considered to be equally likely.

- All climate model projections indicate substantial future warming in Colorado. The statewide average annual temperatures are projected to warm by +2.5°F to +5°F by 2050 relative to a 1971–2000 baseline under a medium-low emissions scenario (RCP 4.5; Figure 2.3). Under a high emissions scenario (RCP 8.5), the projected warming is larger at mid-century (+3.5°F to +6.5°F), and much larger later in the century as the two scenarios diverge.

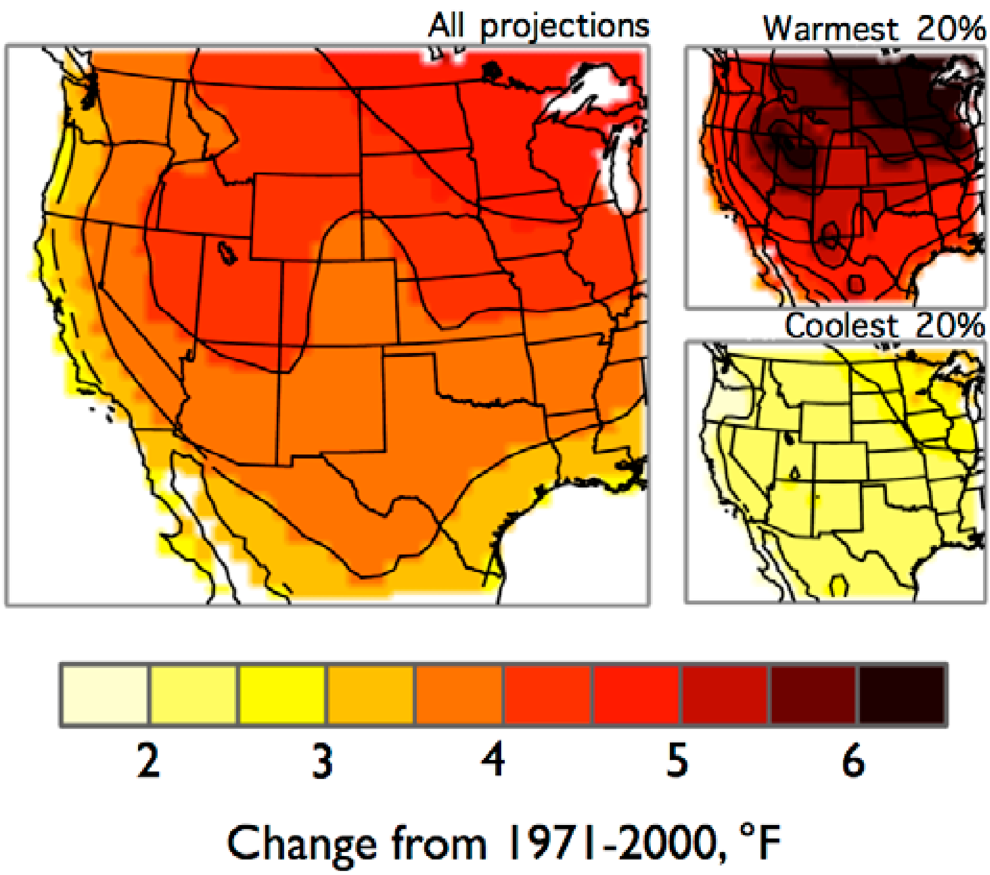

Figure 2.3. Projected annual temperature change by 2035-2064 over the western United States from an average of the outputs from 37 climate models using a scenario of moderate future greenhouse gas emissions (RCP 4.5), compared to a 1971-2000 baseline. The large map shows the average change for all 37 models, and the small maps show the averages of the warmest 20% and coolest 20% of the models, indicating the range of the model projections. All projections show substantial warming for Colorado. (Adapted from Lukas et al. 2014.)

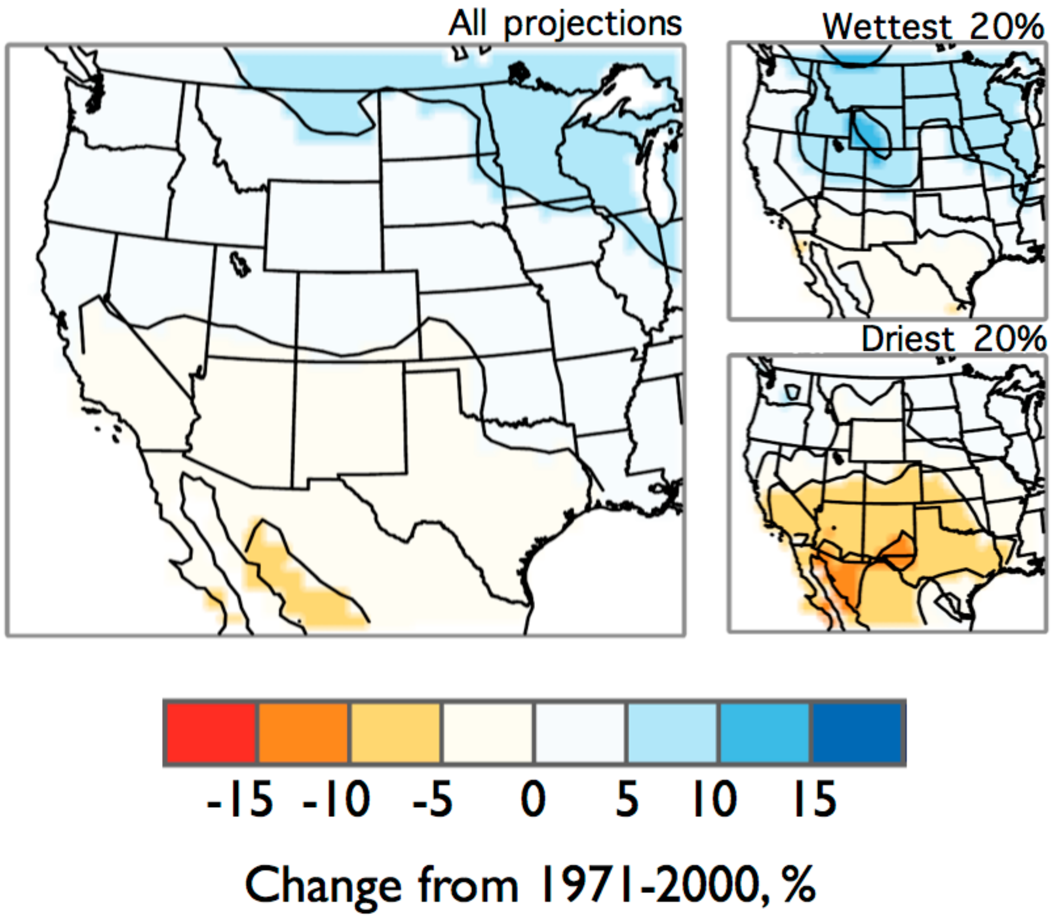

Figure 2.4. Projected annual precipitation change by 2035-2064 over the western United States from an average of the outputs from 37 climate models using a scenario of moderate future greenhouse gas emissions (RCP 4.5), compared to a 1971-2000 baseline. The large map shows the average change for all 37 models, and the small maps show the averages of the wettest 20% and driest 20% of the models, indicating the range of the model projections. The average projected outcome for Colorado (no or little change in annual precipitation) is misleading, as several models project substantial decreases in precipitation, and several other models project substantial increases. (Adapted from Lukas et al. 2014.)

- Summers are projected to warm slightly more than winters. Typical summer temperatures in 2050 are projected under RCP 4.5 to be warmer than in all but the very hottest summers (e.g., 1934, 2000, 2012) that have occurred in the observed record.

- Climate model projections show less agreement regarding the direction of future precipitation change for Colorado (see Figure 2.4). The individual model projections of change by 2050 in statewide annual precipitation under RCP 4.5 range from -5% to +6%. Projections under RCP 8.5 show a similar range of future change (-3% to +8%).

- In nearly all of the projections, winter precipitation increases by the mid-21st century. There is weaker consensus among the projections regarding precipitation in the other seasons.

- Most projections of future hydrology for the mid-21st century show decreased annual streamflow for Colorado's major rivers, due mainly to the large warming

Figure 2.5. Although there is no evidence yet that climate change will affect the frequency or severity of summertime thunderstorms in Colorado (left), one study projected that individual winter storms (right) in the state could become wetter as the climate warms (Left photo: Dr. Mike Coniglio, NOAA NSSL. Right photo: Flickr, Hannu & Hannele).

increasing the loss of moisture from snowpacks, soils, and vegetation. In some of the hydrologic projections, the projected increases in precipitation are large enough to overcome the effect of warming, and so these projections show increased streamflow.

- Changes in the timing of runoff are more certain than changes in the amount of runoff. The peak of spring runoff is projected to shift 1–3 weeks earlier by the mid-21st century due to the projected warming. Late-summer flows are projected to decrease as peak runoff shifts earlier.

- Most projections of Colorado's spring snowpack (April 1 SWE) for the mid-21st century show declines in due to the projected warming. The individual model projections of change in April 1 SWE range from about -30% to +10% in most basins.

- Heat waves, droughts and wildfires are projected to generally increase in frequency and severity in Colorado by the mid-21st century due to the projected warming.

- The frequency and magnitude of extreme precipitation events are generally projected to increase globally as the warmer atmosphere is able to hold more water vapor. For Colorado, detailed studies suggest that winter extreme precipitation events will follow this global increasing trend, but not summer extreme precipitation events (Figure 2.5).

Suburban development in Colorado Springs, Colorado. Photo: Wikimedia Commons, David Shankbone.

CHAPTER 3
DEMOGRAPHY, LAND USE, AND ECONOMICS

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I. Introduction

Colorado has witnessed robust population growth for most of its recent history. Even economic slow-downs, like the mid-1980s energy bust and early-2000s dot-com bust, did not result in net population loss from decade to decade (Limerick et al. undated). But population alone does not tell us much about vulnerability to climate change as defined in this report. What matters is where residents of a place live and work, how they make their living, and what capacity they have for mitigating climate impacts. Some locations and economic activities are more vulnerable to climate fluctuations than others. Further, the types of resources (e.g., water) and services (e.g., transportation infrastructure) demanded by Colorado's resident population and visitors also affect the state's exposure to climate risks (as described in the relevant sectoral chapters).

Some climate elements, like extreme heat or cold, differentially affect certain populations, so changes in Colorado's demographic profile—especially poverty levels, educational attainment, and age—can indicate increasing or decreasing vulnerability. Another important aspect of demography associated with climate vulnerability is where people live, work, and recreate, where they have homes, businesses, and other investments. Some patterns of development are more sensitive to weather and climate extremes than others. Recent events remind us that development in the fire-prone forests and in floodplains is particularly exposed to weather and climate risks. Demographic and land use analysis can help us identify trends that might worsen or lessen the state's climate vulnerability.

Most of Colorado's population engages in economic activities—like manufacturing, information technology, and services of all types—that are relatively insensitive to climate variation. However, as the sector chapters indicate, some sub-sets of the economy, like agriculture and tourism, can be especially vulnerable to climate variability and change, and thus subsets of the population are more at risk.

II. Demography

The U.S. Census estimated that Colorado's total population was 5,268,367 in 2013 (U.S. Census Bureau 2014). The state's population is growing rapidly, as it has for several decades. Colorado's population increased by 1.5% from 2012 to July 2013, with net in-migration responsible for approximately 59% of the new residents. Colorado was the 4th fastest growing state during this period (State Demography Office 2014c). These rates, however, are still well below the more dramatic increases seen in the 1990s and early 2000s (State Demography Office 2013). The Colorado State Demographer's Office projects continued strong population growth over the next few decades, with the state's population expected to reach nearly 6 million in 2020 and 7.8 million in 2040 (Figure 3.1) (State Demography Office 2014a, c).

This growth results from "natural increase" (meaning births over deaths) as well as net in-migration, which has fluctuated a great deal since the 1970s but is projected to contribute roughly half of the increase in population through 2040 (Figure 3.2).

Young adults between the ages of 24 and 37 accounted for most of the net migration in the 2000s (Figure 3.3). A significant portion of the projected population growth will be driven by persons of Hispanic origin (State Demography Office 2014c).

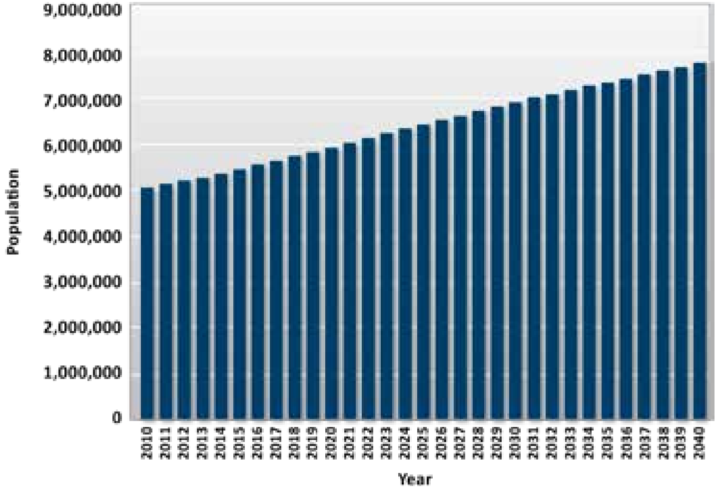

Figure 3.1. Projections of future statewide population (State Demography Office 2014a).

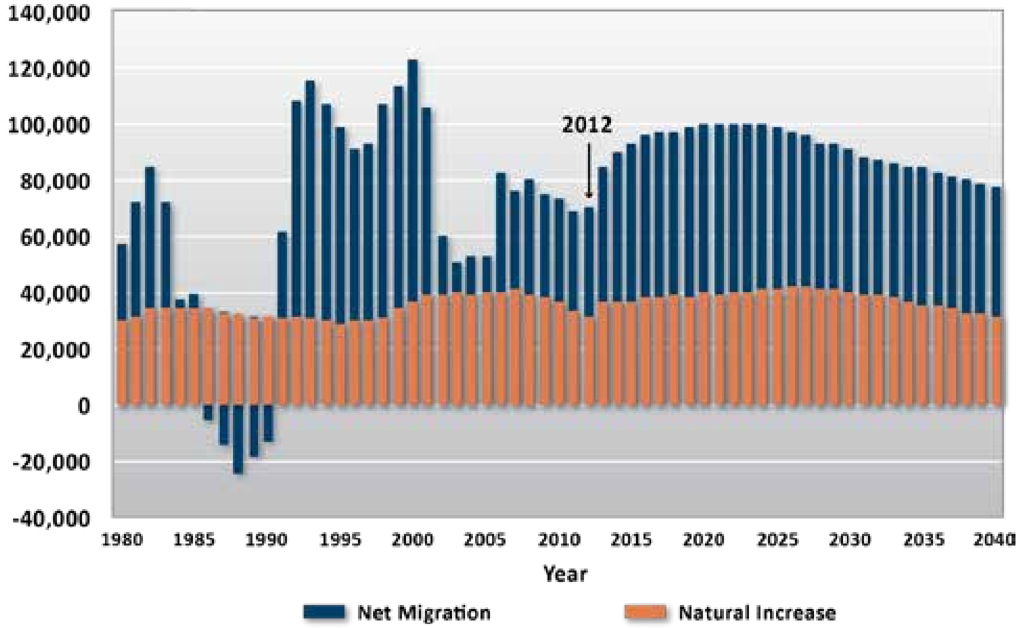

Figure 3.2. Components of population change in Colorado (State Demography Office 2013).

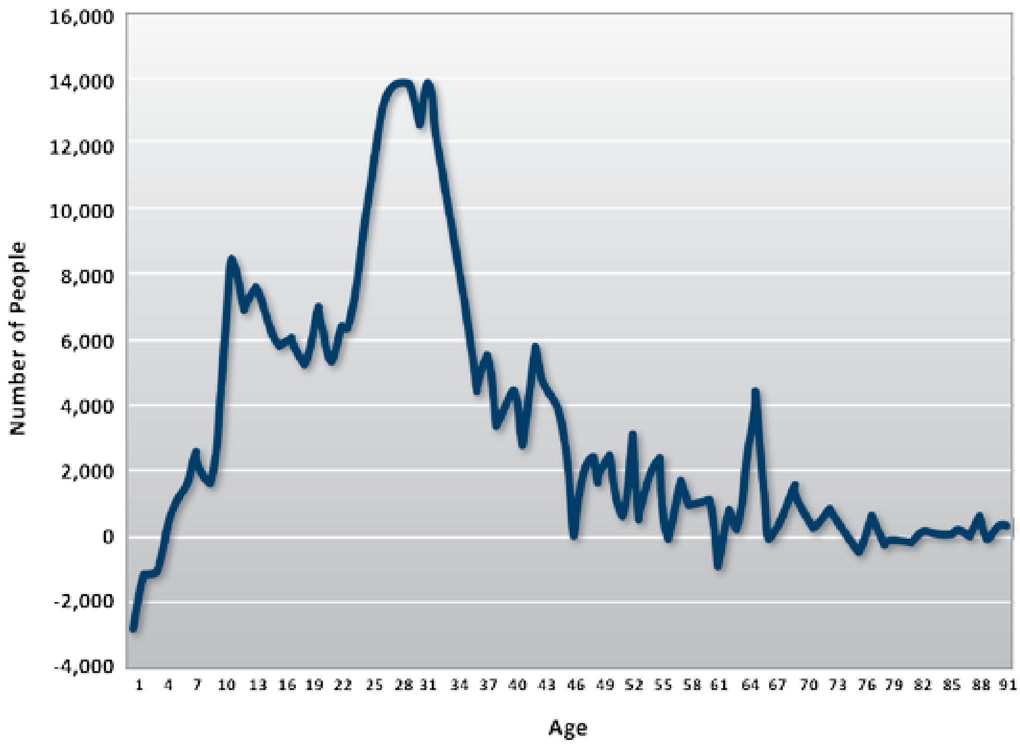

Figure 3.3. Net migration by age 2000-2010 (State Demography Office 2014a).

In the past, fluctuations in migration have generally tracked job creation. Since 2005, however, net migration has continued—albeit at a lower rate—despite slow job growth (Figure 3.4). This trend may be attributable to the aging of the population out of the job market and the fact that Colorado's jobless rate tends to track the national jobless rate, among other reasons.

As is common in a growing population, Colorado is among the youngest states in the U.S., with a median age of 36.1 in 2010 (State Demography Office 2014c). Age data show relatively uniform 5-year age cohorts below the age of 60; however, the state still exhibits a distinct baby boom (born 1946-1964) and baby boom echo (births to baby boomers), as shown in Figure 3.5 (U.S. Census Bureau undated a).

Aging of the baby boom generation will lead to approximately a 125% increase in the population of residents 65 and older by the year 2030 relative to 2010 (State Demography Office 2014c).

Colorado also has a highly educated populace. 47.5 percent of Coloradans between the ages of 25 and 64 hold a two- or four-year degree, well above the national average of 39.4 percent (Lumina Foundation 2014) and one of the highest rates in the nation. Levels of education vary widely by ethnic group (see Figure 3.6) and even more so by geography—Boulder County has the highest proportion of adults with at least an associate's degree (65.7%) while Bent County has the lowest (16.8%) (Lumina Foundation 2014).

Based on data from 2007-2011, an estimated 12.5% of Coloradans are living in poverty (U.S. Census Bureau undated b). Poverty is highest in more rural counties in the southeast and south-central portions of the state (Figure 3.7).

Based on 2007-2011 data, an estimated 16.6% of Colorado's children are living in poverty, with many southern counties as well as Denver showing the highest percentages (U.S. Census Bureau undated c). Income in general also varies widely across the state, with residents of the wealthiest county (Douglas County; median household income

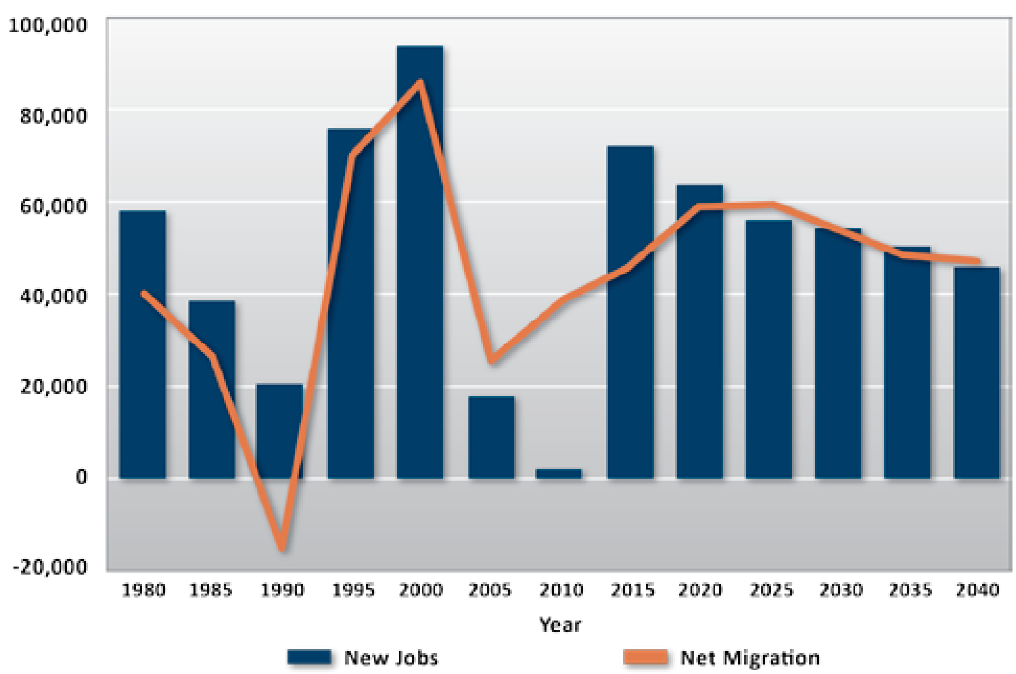

Figure 3.4. New jobs and net migration across Colorado, historic and projected through 2040 (State Demography Office 2013).

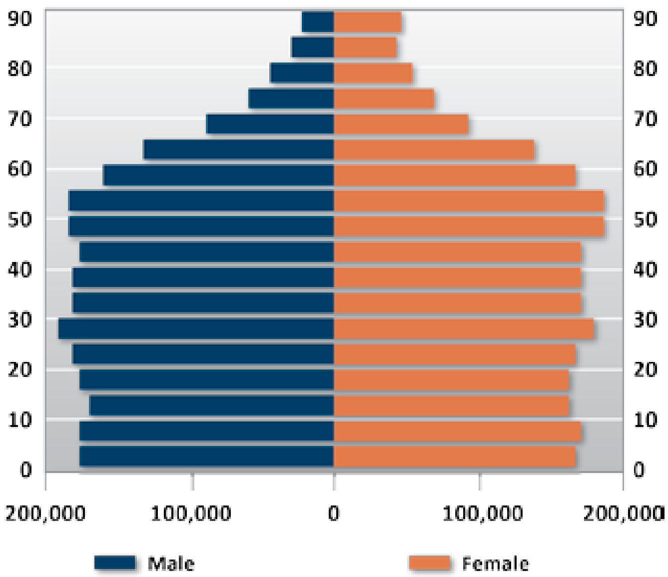

Figure 3.5. Population pyramid for Colorado, showing baby boom and baby boom echo (U.S. Census Bureau undated a).

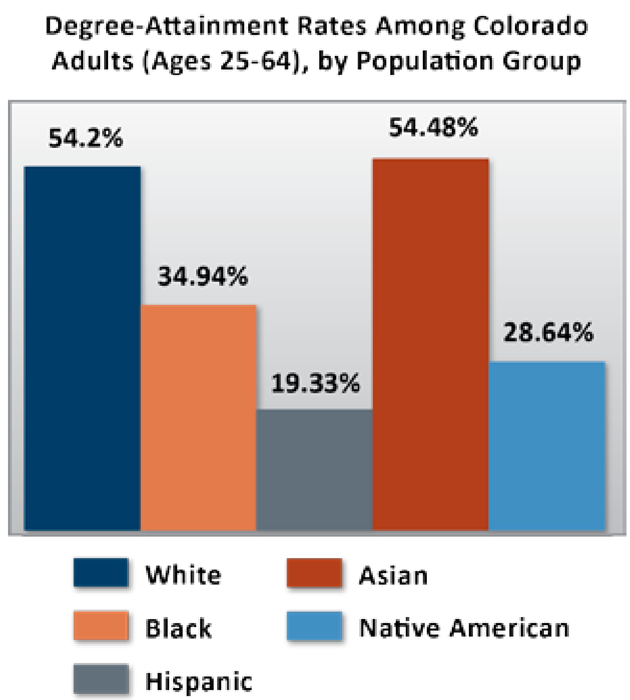

Figure 3.6. Level of educational attainment by ethnicity. From Lumina Foundation (2014), data from U.S. Census Bureau.

of $101,193) earning more than three times that of the poorest county (Huerfano County; median household income of $29,737) (U.S. Census Bureau undated d).

Two key characteristics of Colorado's population bear watching for a potential increase in climate vulnerability: the growing cohort of older persons who are more vulnerable to extremes like heat and cold, and the proportion of residents living in poverty, a factor that likely reduces their ability to adapt to climate variability.

III. Land Use

The other vulnerability factor associated with the state's demographics is where people live and the geography of investments like businesses and infrastructure. Changes in land use patterns will interact with population growth and other demographic shifts, resulting in differential vulnerabilities across specific parts of the state. For example, increased population density in urban areas can increase the sensitivity of water supply systems to future warming. More significantly, however, growing populations in the wildland-urban interface and in floodplains will raise exposure to natural disasters.

The most rapid population growth is expected in Weld and Elbert counties as well as San Miguel and Archuleta counties in southwestern Colorado, along with parts of the Western Slope and Central Mountains (Figure 3.8). Eastern Colorado and the San Luis Valley are expected to experience relatively slower rates of population growth (State Demography Office 2013).

It is important to note that a significant proportion of the land base in Colorado is publicly held, much of it by the federal government. Roughly 40% of Colorado's lands are publicly owned, concentrated in the forested mountainous regions of the state, with some mountain counties having close to 90% public ownership (Klein et al. 2011). This level of public land ownership removes land use control from local communities in many areas. On the other hand, because these lands are not privately controlled or open to development in most cases, they provide large spaces where recreation, grazing, and extraction can shift across the landscape in response to climate-related changes.

More than 80% of the state's population is

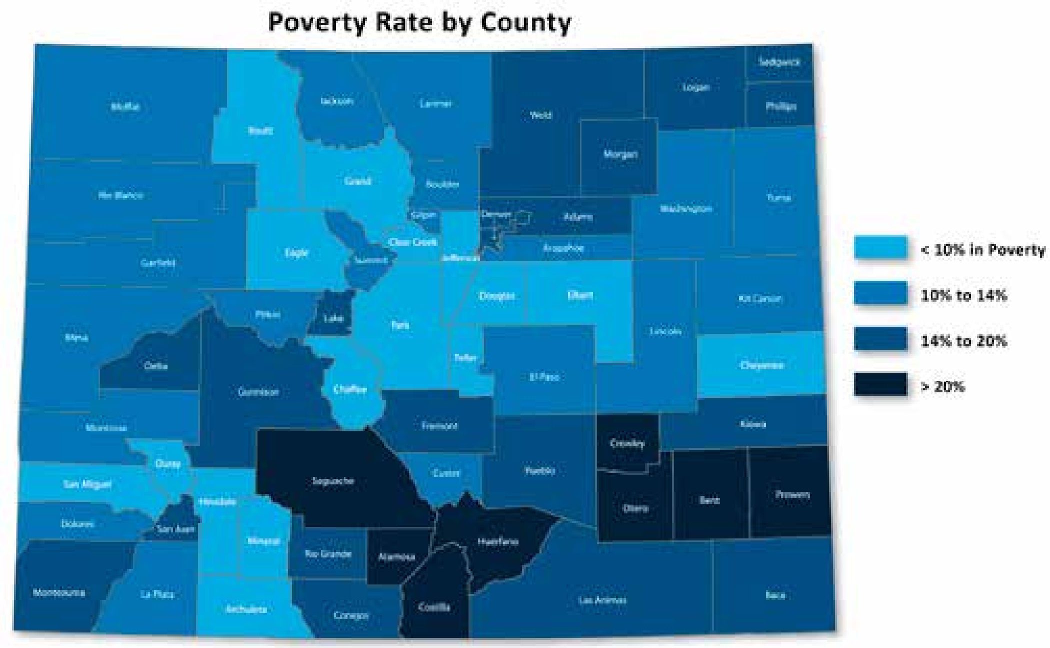

Figure 3.7. Percentage of population living in poverty, by county, in 2012 (State Demography Office 2014b).

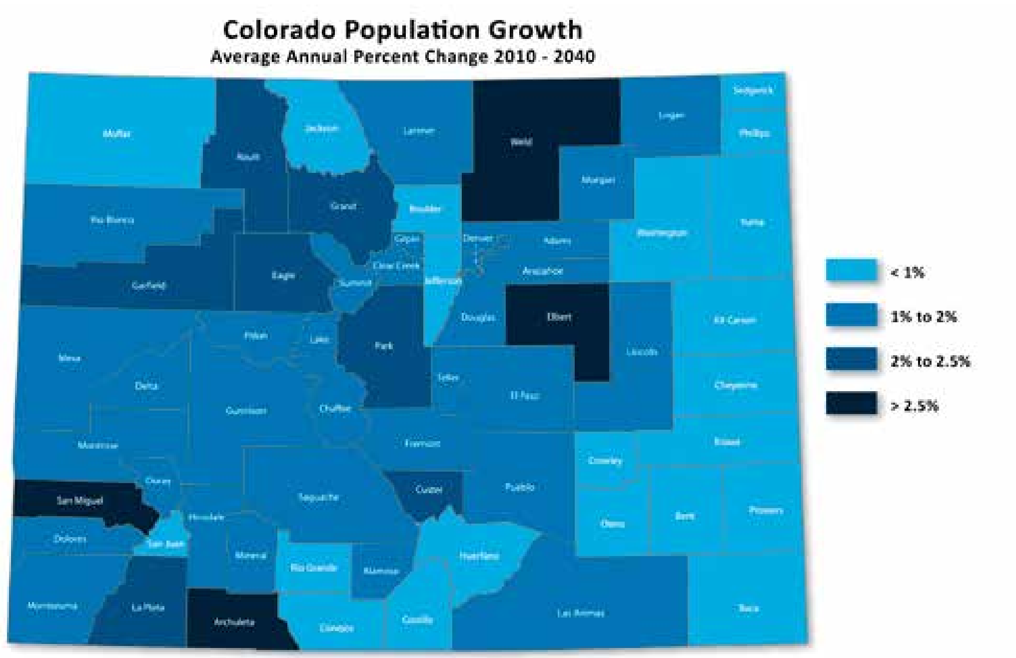

Figure 3.8. Projected population growth by county through the year 2040 (State Demography Office 2013).

concentrated in the urbanized Front Range corridor stretching from Pueblo to Fort Collins (see Figure 3.9). It is along this corridor where we see a prime example of the how development and climate interact to create two main climate vulnerabilities: wildfire and flood.

Wildland-Urban Interface (WUI)

Wildfires result from combinations of weather and climate conditions, vegetation structure and land uses, and ignition sources. Although damaging wildfires can occur on Colorado's eastern plains, as well as in the western sagebrush range, the state's most damaging fires occur in forested landscapes. While much of the forest land in Colorado is public, large tracts of private forested lands, especially along the Front Range, attract development and thus present the risk of damaging and

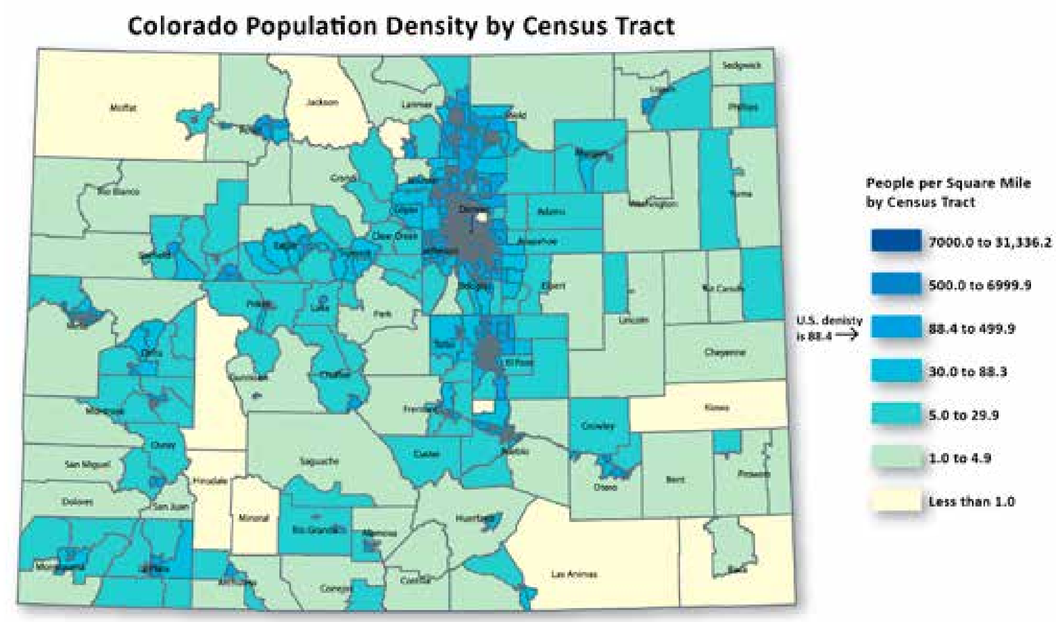

Figure 3.9. Population density across Colorado (U.S. Census Bureau undated a).

dangerous fires when climate and weather conditions conspire to raise fire danger. The risk is concentrated in the so-called "wildland-urban interface" or WUI. Headwaters Economics estimates that, as of 2010, Colorado had 1,778 square miles in the WUI.[1] Only 20% of Colorado's WUI was developed, with the potential for future development of the remaining 80%. Colorado's WUI included 117,472 homes with the largest number (22,866) in Summit County. Over 50% of the WUI in Boulder and Jefferson Counties is already developed (Headwaters Economics 2014).

Using a somewhat different methodology, the CoreLogic Wildfire Hazard Risk Report estimated the number and value of residential properties potentially at risk of wildfire damage in Colorado (Table 3.1).

Researchers at Colorado State University project a 300% increase in Colorado's WUI[2] from 715,500 acres in 2000 to 2,161,400 acres in 2030, as shown in Figure 3.10 (Theobald and Romme 2007). Studies like this suggest that exposure in the WUI is increasing.

In response to the two most destructive wildfires in state history—Waldo Canyon in 2012 and Black Forest in 2013—Governor Hickenlooper created the "Task Force on Wildfire Insurance and Forest Health" and charged it with identifying means of reducing the risk of loss in the WUI. The panel made a number of recommendations, including

	Residential Properties Potentially at Risk of Wildfire Damage 2013	Total Potential Exposure To Wildfire Damage 2013
Total	335,539	$64,891,348,545

Table 3.1. Residential properties at risk of wildfire damage, by number of properties and total value (from Botts et al. 2013).

1 No universally accepted definition of the wildland-urban interface (WUI) exists. Headwaters Economics (2014) defines the WUI as "forested private land within 500 meters of forested public lands."

2 Defined as "the area where homes and urban sprawl press against the wildland, and includes both interface and intermix communities."

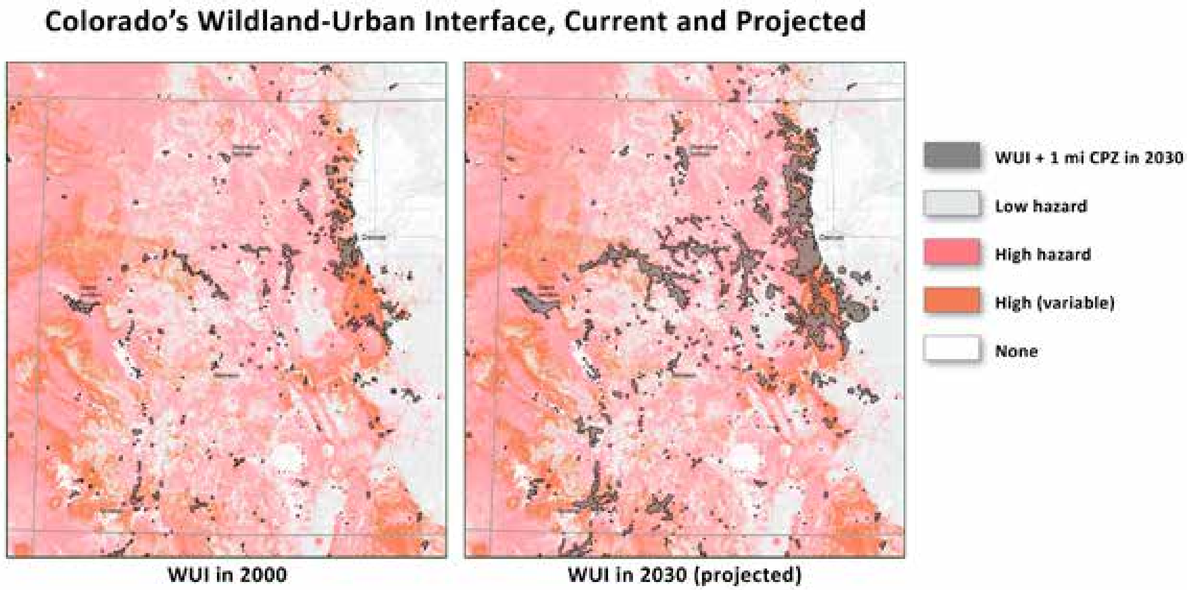

Figure 3.10. Projected increase in size of wildland-urban interface in Colorado, comparing 2000 (left) and 2030 (right; projected) (Theobald and Romme 2007).

continued development of the Colorado Wildfire Risk Assessment Portal (CO-WRAP), wildfire mitigation audits for high-risk homes, and a statewide model ordinance for private properties in the WUI (Wildfire Insurance and Forest Health Task Force 2014). The panel's report also assessed the potential for land use regulations and insurance reform to reduce exposure to wildfire, identifying several barriers that limit the effectiveness of such solutions. For example, the task force concluded that the state could not require insurance of all homeowners, and that premium increases meant to signal the risk and encourage mitigation could also have the unintended consequence of reducing insurance coverage.

Another response is a new center launched by Colorado State University's Department of Forest and Rangeland Stewardship that is dedicated to creating the next generation of wildfire management solutions. The Center for Managing WUI Wildfire Risk will provide "science-based answers to critical questions raised by the most destructive wildfires in Colorado's history" (Colorado State University 2013). One of the Center's first tasks is to create a database that will assess the WUI in Colorado by integrating geographic data, socio-economic characteristics, and wildfire risk potential.

Floodplains

Like wildfires, floods result from a variety of weather and climate conditions, most notably heavy summer thunderstorms, snowmelt, regional rain events, and combinations of these. Flooding may also occur as a result of dam failure. For the most part, flooding occurs along streams and rivers, though heavy precipitation can cause overland floods outside of these floodplains. The definition of floodplain, like the definition of the WUI, varies among sources and agencies. Of particular note is the so-called "100-year floodplain" defined as the area that has a 1% chance of being inundation each year (Figure 3.11).

Geographically larger areas, the 250- and 500-year floodplains, may be mapped for various purposes; extremely hazardous areas, such as zones expected to experience high velocity water flows, may also be mapped within floodplains. The Front Range floods in September 2013 demonstrated the widespread exposure of residential and commercial property, plus infrastructure, to flooding both within and outside of mapped floodplains.

Despite a long history of damaging floods going back to early settlement, billions of dollars of private and public property are at risk from flooding in Colorado. Estimating the

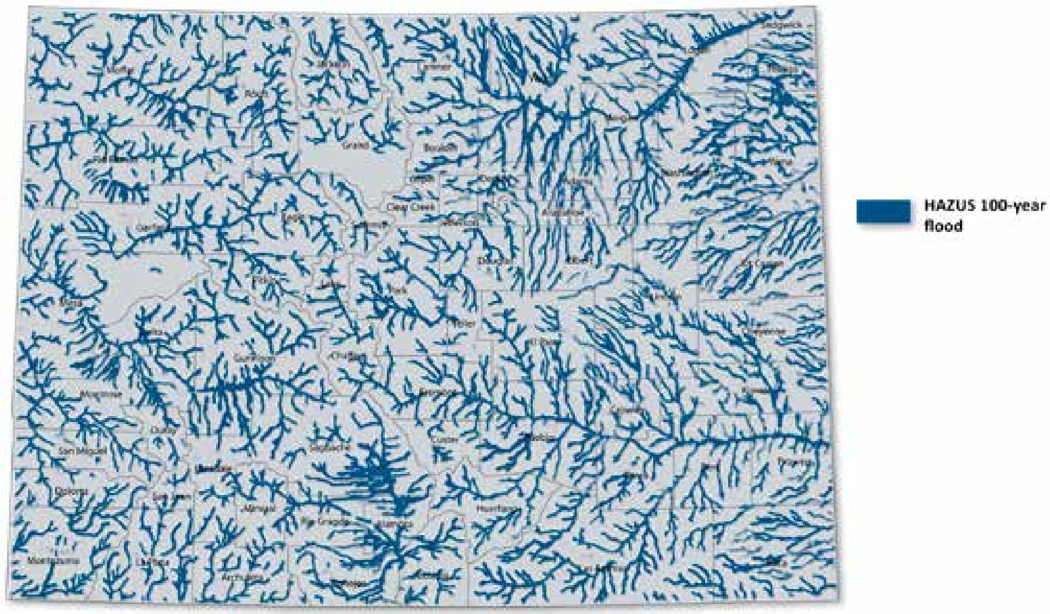

Figure 3.11. Colorado's 100-year floodplains as of 2010 (CWCB 2013).

actual value of total property at risk is very difficult. The Colorado Flood Mitigation Plan (CWCB 2013) applied a modeling analysis to calculate building damage from a 100-year flood for every significant drainage in each county. Some 16,000 buildings are vulnerable to damage, accounting for a total direct economic loss associated with those buildings of some $5.2 billion. An assessment of state assets (buildings, highway bridges, etc.) exposed in 100- and 500-year floodplains in the 2013 update of the flood mitigation plan indicates a risk of about $1.3 billion (excluding local and federal assets). A total of 237 bridges are at risk in the state, with a replacement cost of $237 million. But the 2013 plan update also notes that just one event—the September 2013 floods—while not yet fully accounted for, caused at least $112 million in bridge damage and $475 million in road and bridge repairs (estimated at the end of September).

The flood mitigation plan also recognizes the potential for reducing flood exposure even as communities develop, though it also recognizes the challenge of mitigation within local land use processes, communities that do not participate in the national flood insurance program, and weaknesses in flood plain maps and the map updating process (CWCB 2013). No consistent data are available to reveal whether property exposure to floods is increasing or decreasing over time in the state.

IV. Economy

Climate-related impacts to Colorado's economy will interact with other changes within and outside of the state that affect our major industries. Colorado has a diverse and robust economy compared to many other states in the Interior West. The state has strong retail, manufacturing, agriculture, tourism, and professional services sectors, as well as significant employment in health, construction, and government. This diversity has emerged as the economy has grown robustly over the last several decades, though growth slowed during the mid-1980s energy bust and early-2000s dot-com bust, and the economy contracted, as did the national economy, during the Great Recession in 2009.

Colorado's gross domestic product (GDP) topped $273 billion in 2013, an increase of nearly $22 billion in inflation-adjusted 2009 dollars from 2010. Colorado's 2013 GDP growth ranked 6th among U.S. states (BEA 2014).

Colorado's per capita personal income ($46,897 in 2013) is above that of the U.S. average ($44,765). Personal income growth has been unsteady since the mid-2000s, with strong growth from 2006 through 2008 but a sharp decline in 2009 and 2010, in line with

Year	Colorado GDP	CO % Change from Previous Year	US % Change from Previous Year
2010	$252,035,000,000	1.6	2.2
2011	$255,866,000,000	1.5	1.6
2012	$263,593,000,000	3.0	2.5
2013	$273,721,000,000	3.8	1.8

Table 3.2. Colorado's GDP by year from 2010-2013, including percentage change from previous year and comparative percentage change for the U.S. as a whole (data from BEA 2014).

the overall economic downturn (see Table 3.3) (Leeds School of Business 2014).

In 2013, Colorado's unemployment rate was 6.8%, below the national average of 7.4% (Leeds School of Business 2014). The state's unemployment rate generally moves in the same direction as unemployment across the U.S., demonstrating the strong connection between the state's economic fortunes and the overall state of the national economy. However, prior to and during the recent economic downturn, Colorado's unemployment figures were lower than that of the country as a whole, indicating that the state may be stronger in terms of employment than the nation as a whole and thus resilient to some of the effects of national economic problems. In fact, overall the state "enjoyed a stronger recovery compared to most of the nation" with respect to the recent economic downturn (Leeds School of Business 2013, p. 9). Table 3.4 lists the average annual unemployment rate for Colorado and the U.S. from 2006 through 2013 (Leeds School of Business 2014).

Sources of Employment in Colorado

Since 1970, Colorado has become increasingly a service-based economy and less dependent on manufacturing, farming, and mining for jobs. Table 3.5 shows the percentage of total jobs in service (including transportation, trade, finance, and professional services) compared with the percentage in non-services jobs (such as farming, mining, construction, and manufacturing.) For comparison purposes, national numbers are shown, demonstrating that the increase in services-related jobs since 1970 has been on a similar trend nationwide as in Colorado, although the state has consistently been more service-oriented than the nation as a whole.

The remaining share of jobs in the state is

	2006	2007	2008	2009	2010	2011	2012	2013
Per capita personal income	$40,611	$42,174	$43,377	$41,518	$41,689	$44,183	$46,315	$46,897

Table 3.3. Per capita personal income in Colorado from 2006-2013 (data from Leeds School of Business 2014).

	2006	2007	2008	2009	2010	2011	2012	2013
CO Unemployment Rate	4.3%	3.8%	4.8%	8.1%	9.0%	8.5%	7.8%	6.8%
US Unemployment Rate	4.6%	4.6%	5.8%	9.3%	9.6%	8.9%	8.1%	7.4%

Table 3.4. Colorado's unemployment rate from 2006-2013 (data from Leeds School of Business 2014).

classified as "Government," which declined from a high of 22.6% in 1970 to 13.9% in 2013 (Headwaters Economics undated). Table 3.5 lists specific categories of employment in the state as of the year 2013 in descending order of number of total jobs. As shown in the table, government is by far the largest single category of employer in the state, which is not uncommon across the country. Given the presence of large federal facilities in the Denver region and multiple military facilities, however, specific parts of the state can be disproportionately affected due to government shutdowns or spending reductions.

Table 3.5 also demonstrates the same information for the U.S. as a whole, to provide a comparison. These data demonstrate that Colorado is much more heavily dependent on specific categories of service-related jobs for employment than the nation as a whole. For example, professional and technical services make up 8.8% of jobs in Colorado, whereas in the U.S. as a whole only 6.8% of jobs fall into that category.

The statistics used in Table 3.5 come from Bureau of Labor Statistics and are categorized using the North American Industrial Classification System. Thus these figures may not fully

	# CO Jobs	% CO Jobs	# US Jobs	% US Jobs
Total Employment	3,351,702	--	182,278,200	--
Government	465,782	13.9%	24,045,000	13.2%
Retail trade	315,271	9.4%	18,371,300	10.1%
Health care and social assistance	300,694	9.0%	20,585,600	11.3%
Professional and technical services	295,260	8.8%	12,453,000	6.8%
Accommodation and food services	257,960	7.7%	13,093,400	7.2%
Finance and insurance	207,882	6.2%	9,873,900	5.4%
Construction	200,708	6.0%	9,267,400	5.1%
Administrative and waste services	199,669	6.0%	11,325,100	6.2%
Other services, except public administration	181,119	5.4%	10,617,100	5.8%
Real estate and rental and leasing	178,926	5.3%	7,985,300	4.4%
Manufacturing	148,904	4.4%	12,747,100	7.0%
Wholesale trade	107,965	3.2%	6,343,500	3.5%
Arts, entertainment, and recreation	92,958	2.8%	4,114,500	2.3%
Transportation and warehousing	87,813	2.6%	5,998,600	3.3%
Information	82,421	2.5%	3,254,300	1.8%
Educational services	62,529	1.9%	4,221,300	2.3%
Mining (including fossil fuels)	62,485	1.9%	1,607,000	0.9%
Agriculture	44,369	1.3%	2,629,000	1.4%
Management of companies and enterprises	38,425	1.1%	2,265,400	1.2%
Forestry, fishing, & related activities	12,224	0.4%	902,800	0.5%
Utilities	8,338	0.2%	577,600	0.3%

Table 3.5. Number of jobs and percentage of total jobs by North American Industrial Classification System (NAICS) category, listed in descending order of number of jobs in Colorado for the year 2013 (Headwaters Economics undated - data from U.S. Bureau of Labor Statistics).

capture the sectoral divisions of employment in the state. For example, tourism and travel are not specifically denoted in this list, largely due to the wide variety of companies involved in that industry. Estimates for the number of Coloradans directly employed by the travel and tourism industry in 2013 range from 150,600 (Dean Runyan Associates 2014) to 289,800 (Leeds School of Business 2014).

In addition, these figures do not include indirect economic effects of various industries that can have cascading effects on jobs in other categories. For example, a hospital may directly employ a number of health care professionals, but the location of so many employees in a specific area can boost nearby businesses like food services, increasing employment nearby in a variety of industries. Determining the employment or revenue effects of a given industry requires much more detailed economic impact analyses that are beyond the scope of this report.

Aspects of Colorado's Economy Sensitive to External Shifts and Shocks

In the modern global economy, Colorado's economic well-being is tied to broader economic trends across the country and throughout the world. Here we briefly outline sectors of Colorado's economy that could be particularly sensitive to external economic shifts and shocks in order to provide some picture of where vulnerability to climate could be compounded by vulnerabilities to external economic factors. As climate preparedness efforts proceed, the state is seeking to engage more directly with these industries to collaboratively understand economic vulnerabilities under a changing climate and better prepare the state's economy for a warmer future.

The tourism economy in Colorado is linked directly to the amount of disposable income available to potential non-local visitors and to other factors such as energy prices. Thus, as downturns in the national economy result in reductions in consumer spending, Colorado's tourism economy often suffers. Figure 3.12 shows spending since 2000 by visitors to Colorado. The effects of the post-2001 and 2008-2009 recessions are clearly visible.

In addition, a number of commodity industries that help fuel Colorado's economy are exposed to the vagaries of international commodity markets, where the overall price of the good in question is determined by factors largely out

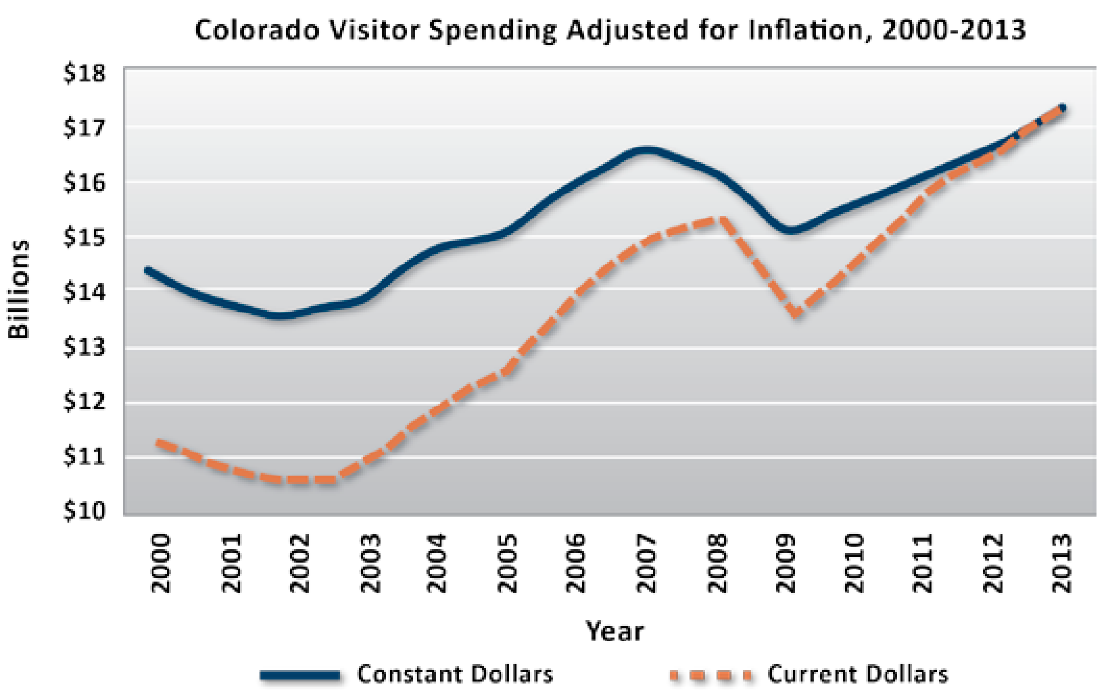

Figure 3.12. Visitor spending in Colorado from 2000-2013 (Dean Runyan Associates 2014).

of the control of producers. Figure 3.13 shows recent volatility in the price of two key crops—wheat and corn (Leeds School of Business 2014).

Thus even as climate can have a significant effect on crop production, external market forces can interact with climate impacts to determine much of a producer's bottom line. Figure 3.14 shows global oil prices and production in Colorado (Leeds School of Business 2014). There we see similar volatility, as oil prices are determined on a global market often moved by such far-flung issues as geopolitical changes in the Middle East.

Aspects of Colorado's Economy Sensitive to Climate

Virtually any aspect of Colorado's economy could be affected by changes in the climate, but specific industries are particularly exposed to climate and extreme weather, especially those

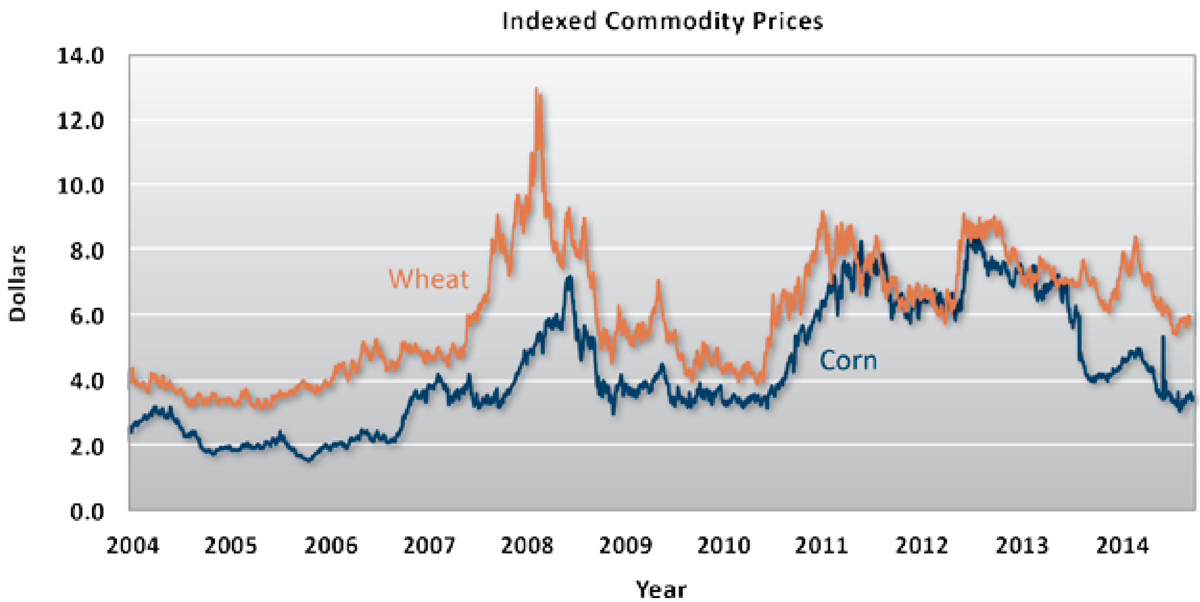

Figure 3.13. Wheat and corn prices from 2004 through 2014 (Leeds School of Business 2014).

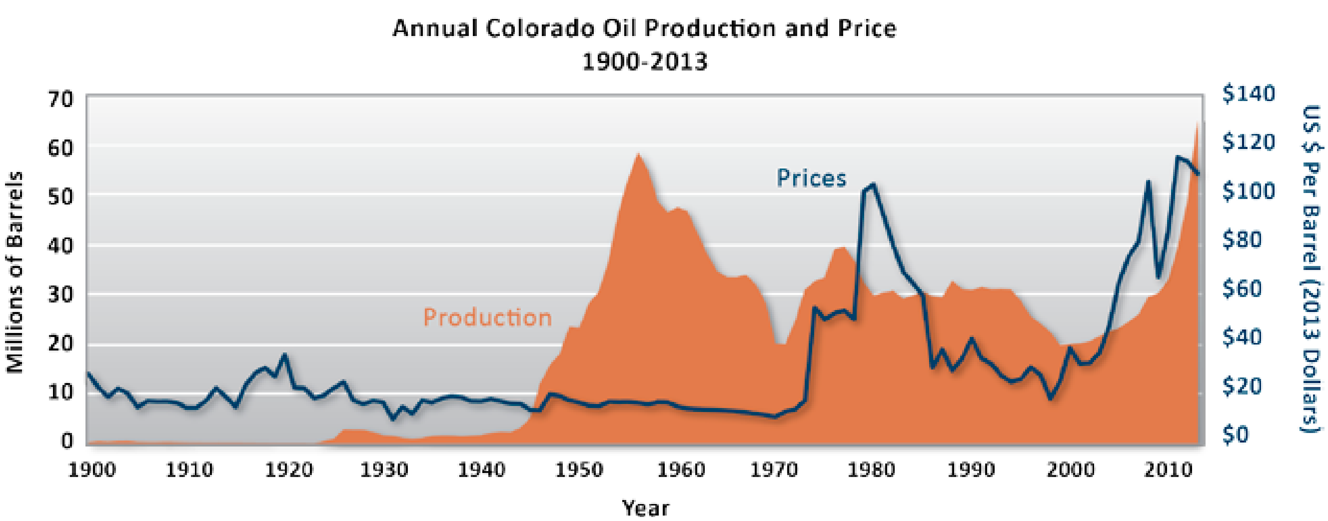

Figure 3.14. Oil production in Colorado and global oil price from 1900-2013 (Leeds School of Business 2014).

that rely on some form of natural resources. These include 1) agriculture, 2) leisure and hospitality (otherwise known as tourism), and 3) mining and extraction.

Agriculture

As discussed further in Chapter 6, climate warming may have uneven effects on different aspects of the agricultural industry in Colorado. Some types of operations may benefit from overall warming, while others may be harmed. The complex interplay between productivity, market prices, and crop insurance has mixed effects on actual farm income and, consequently, employment. In 2013, the most recent year for which there are complete statistics, Colorado net farm income declined from $1.753.3 billion in the previous year to $1.370 billion (Leeds School of Business 2014), which might be an impact from the deep drought of 2012. Net farm income is predicted to be $2.616 billion in 2014 (Leeds School of Business 2014). Individual producers, however, or producers across a specific region could face potential disaster from major hail, drought, or flood events.

Tourism and Recreation

Although defining the tourism economy is complex, as noted above, the sector is a significant generator of revenue in Colorado. In 2013, travel resulted in $4.7 billion in earnings and $976 million in local and state tax revenues (Dean Runyan Associates 2014). Significant travel and tourism revenue comes from hotel and convention visits in Denver that are less exposed to climate impacts, but large portions of Colorado's tourism economy involve outdoor climate-sensitive activities. The ski industry, for example, has seen visitation rise and fall fairly significantly with snowfall and other factors (Leeds School of Business 2014). Other outdoor spaces provide significant opportunities for travel revenues— for example, national parks in Colorado saw 5.4 million visits in 2013 and outdoor recreation resulted in $34.5 billion in economic output in 2014 (Leeds School of Business 2014), but these sorts of areas are vulnerable to climate-related events like wildfire and flooding that can hamper both actual recreation and perception of the state as a desirable place to visit. For example, visits to Rocky Mountain National Park declined by over 50% during the September 2013 floods (Leeds School of Business 2013). Moreover, well-publicized climate events can affect the desire of out-of-state tourists to visit Colorado (see Chapter 9).

Mining and Extraction

Although the mining and fossil fuel extraction industries provide a relatively small fraction of Colorado's job base, their economic impact is significant. In 2013, Colorado's oil, gas, and mining resources were valued at slightly more than $ 15.7 billion (Leeds School of Business 2014). There are some specific climate and weather factors that could hinder mining and extraction, but perhaps the more significant potential climate impact on this industry would be the impact of some type of federal carbon regulation or other price signal changing the cost of fossil fuels.

Note, however, that these climate-sensitive industries are not uniformly spread across the state, so statewide statistics hide the wide variation in potential climate impacts. For example, Kit Carson County has 33.3% of its total jobs in agribusiness, while Summit County has 48.4% of its total jobs in tourism (State Demography Office undated).

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The migratory lark bunting bird was designated the state bird of Colorado in 1931. A female is pictured here. Photo: Wikimedia Commons, Ryan Douglas.

CHAPTER 4
ECOSYSTEMS SECTOR

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I. Brief Description of Sector

The scale, scope and pace of change occurring in ecological systems today—and forecast for the future—are by all accounts unprecedented (Vitousek et al. 1997; NRC 2001; Palmer et al. 2004; IPCC 2007). These changes will have significant impacts on ecosystems in Colorado and their value for the state's residents. In this chapter we describe major ecosystems in Colorado and their management and then discuss key vulnerabilities across the state's landscapes.

Characteristics of Ecosystems in Colorado

Largely due to its varied topography, Colorado is home to many distinct ecosystems. Differences in elevation offer a wide range of precipitation and temperature patterns, from the snowy high mountains of the western and central parts of the state to the drier Great Plains and canyon country (see Figure 4.1). These climatic gradients, in turn, affect the major species that dominate in various areas. The mountains are home to conifer forests that make way to delicate alpine ecosystems above treeline. Headwaters and small streams flow out of these areas, providing habitat for coldwater fish such as the greenback cutthroat trout. In the Great Plains portion of the state, grasslands cover the prairie where the state bird, the lark bunting, can be seen in spring and summer months.

Disturbances such as fires, insect infestations, droughts, and storms are important agents of change and are part of the natural dynamics of ecosystems in Colorado. In Rocky Mountain forests, wildfire (Figure 4.2) is prevalent due to the semi-arid nature of these forests and the convective storms that can bring dry lightning during the summer months. The frequency and severity of fires varies with climate and fuel availability (Schoennagel et al. 2004). Over the past two decades, fires have become

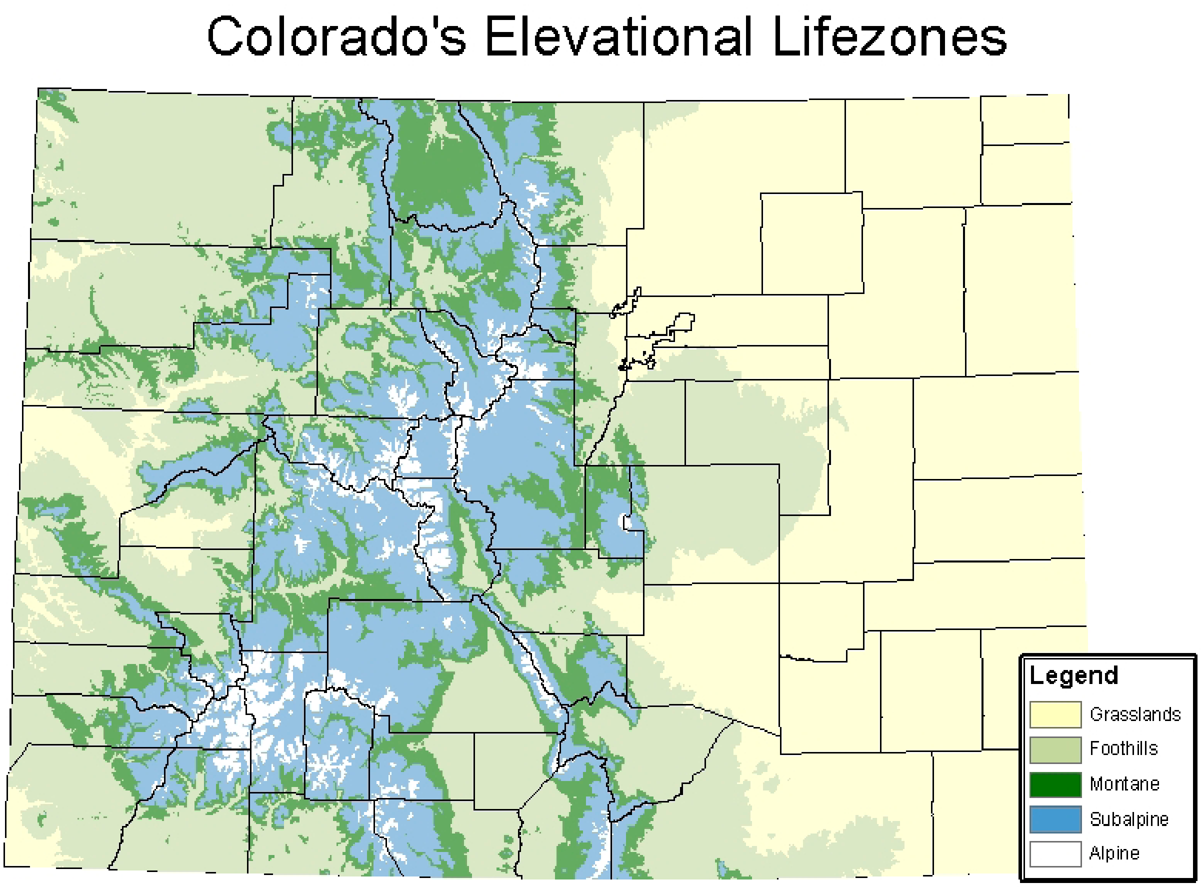

Figure 4.1. The ecosystem types of Colorado generally reflect elevation gradients across the state (Colorado State University Natural Diversity).

Figure 4.2. The 2012 Waldo Canyon Fire outside Colorado Springs was one of Colorado's most destructive fires. Climate research indicates that wildfires in the western United States have become larger and more severe over the past 20 years (Photo: Master Sgt. Jeremy Lock, U.S. Air Force).

larger and have burned with higher severity in some areas compared to the historic record (Kaufmann et al. 2006). In high-severity burn areas, such as the Hayman burn scar, changes in forest structure and composition have occurred as regeneration falters (Massey 2012).

Ecosystem distribution, itself a reflection of climate conditions, impacts disturbance regimes. Shifts in climate patterns across the state of Colorado are likely to alter the frequency, severity, and location of various disturbances such as fire, insect outbreaks, droughts, and major storms, in addition to the potential for shifting overall precipitation patterns and rising temperatures. These changes, in turn, will alter vegetation composition and structure and affect important ecosystem services such as water availability, productivity, biodiversity, and wildlife habitat. Globally, ecological systems are changing in unprecedented ways, a trend that is expected to continue (Vitousek et al. 1997; NRC 2001; Palmer et al. 2004; IPCC 2007) as alterations in multiple climate parameters occur (IPCC 2007; Min et al. 2011). Forecasting how any particular ecosystem will respond to predicted changes in climate requires knowing (1) the magnitude of the change in the climate driver (e.g., change in precipitation or temperature), and (2) the sensitivity, which includes the rate, magnitude and nature of change in the structural and functional attributes of ecosystems to a given change in a climate parameter (Smith et al. 2009).

Value of Ecosystems in Colorado

Ecosystems across Colorado are highly valued for their beauty and grandeur. In addition, they provide key ecosystem services, such as habitat for popular game species, water supplies, and recreation (see Chapter 9). Although calculating the full economic benefit of all ecosystem services in Colorado is difficult, specific areas are illustrative of the value provided by the state's natural landscapes. For example, the economic impact of hunting and fishing in Colorado is significant, contributing $1.84 billion to the state's economy each year (BBC Research and Consulting, 2008). Healthy high elevation forests maintain watershed functioning through soil and snowpack stabilization, ensuring water quality for lower elevations. Demonstrating the value of these watersheds, Denver Water has partnered with the Forest Service to spend $33 million in a five-year period for forest restoration projects, which are seen as vital to watershed protection (Denver Water 2013). Residential water users will pay an additional average of $27 annually for this program (LaRubbio 2012). Other ecosystem services, like aesthetic beauty, pollination, wildlife diversity, or even the timing of snowmelt are more difficult to quantify economically.

Land Management in Colorado

Roughly 40% of Colorado's lands are publicly owned and managed by various federal, state, and local agencies. Federal land ownership in the state is concentrated in the forested mountainous regions, with some mountain counties nearing 90% public ownership (Klein et al. 2011). Table 4.1 describes forest ownership patterns in the state, while Figure 4.3 demonstrates the complex spatial pattern of public land management. This pattern means that ecosystem management across the state often requires cooperation across multiple jurisdictional lines and interaction with private landowners.

The following sections describe potential climate impacts to ecosystems in Colorado and resulting key vulnerabilities. We identify several key impacts relevant for Colorado such as increasing temperatures, drought, timing of snowmelt, and frequency and severity of wildfires. We then examine resulting vulnerabilities across ecotypes—forested ecosystems, grasslands, and alpine ecosystems—as well as the wildlife species that inhabit them.

II. Key Climate Impacts to Sector

Broadly speaking, ecosystem impacts occur when environmental triggers exceed the historical range of variation to which ecosystem processes have previously adapted (Romme et al. 2012). Changes in mean average temperatures and precipitation may have less effect on ecosystems than persistent seasonal shifts in weather patterns or changes in frequency of extreme events. Studies that examine species adaptation and evolutionary shifts, whether they are fast and catastrophic (Dale et al. 2001) or slower and more modulated (Parmesan 2003; Field et al. 2007), provide a basis for incorporating impacts with climate projections. More so than other sectors, ecosystems present the added complexity of spatial or landscape relationships that contribute to the distribution of ecosystems across landscapes. Thus landscape fragmentation due to land use changes may hamper the adaptation of ecosystems to changing climate conditions.

In addition to these climatic and landscape relationships, biotic interactions that contribute to ecosystem functioning, such as pollination, herbivory, and predator-prey relationships, can be affected by climate changes such that one component may be more sensitive to seasonal temperature effects while

Managing Agency or Owner	Percentage of Statewide Forested Land Cover	Number of Acres	Forest Types
U.S. Forest Service	47%	11.3 million	spruce-fir, lodgepole pine, ponderosa pine, and aspen
U.S. Bureau of Land Management	17%	4.2 million	piñon-juniper and oak shrubland
Private landowners	30%	7.1 million	many forest types, notably aspen and mixed conifer
Ute Mountain and Southern Ute Tribes	-	402,303 acres	ponderosa pine and piñon-juniper
U.S. National Park Service	2%	380,925 acres	many major types, including piñon-juniper (Mesa Verde National Park, Great Sand Dunes National Monument, and Dinosaur National Monument), ponderosa pine and aspen (Rocky Mountain National Park)

Table 4.1. Ownership of forested lands in Colorado (Colorado State Forest Service 2009).

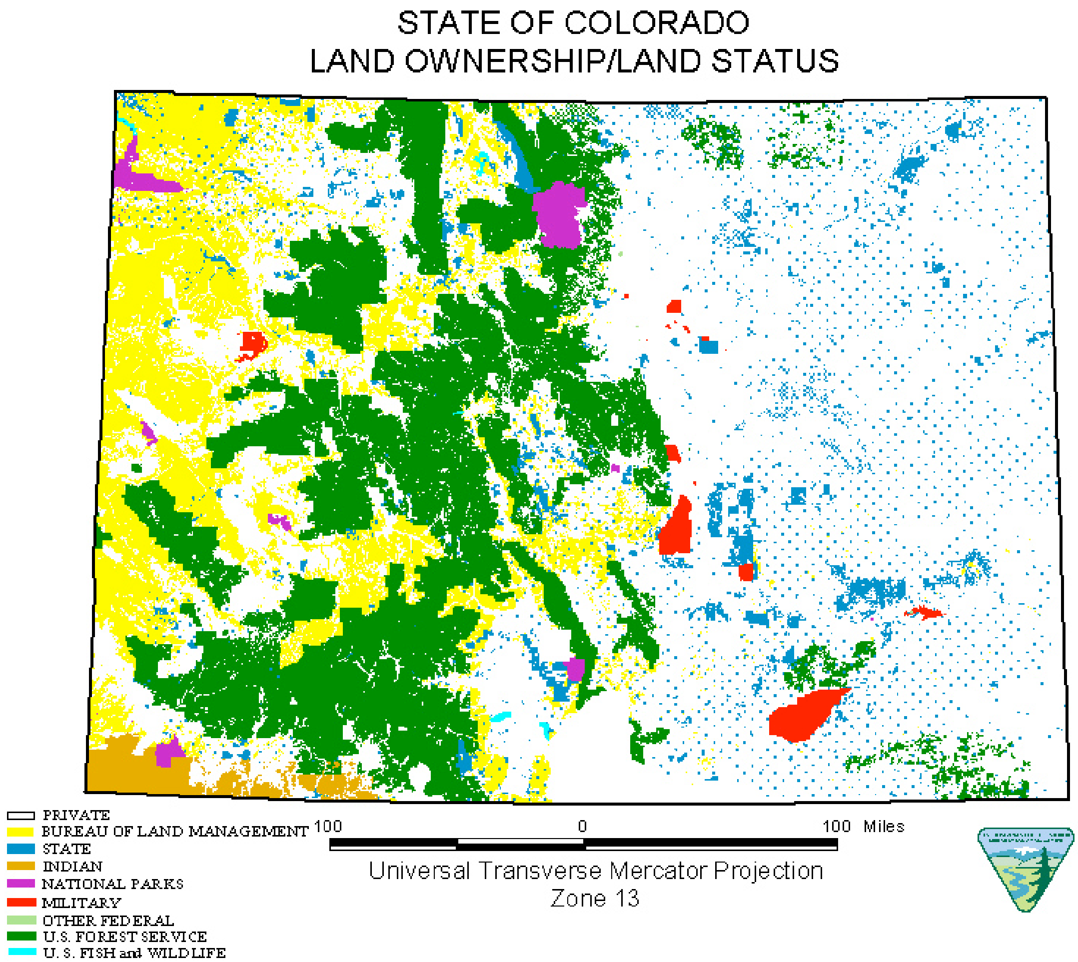

Figure 4.3. Types of land ownership in Colorado, showing the predominance of U.S. Forest Service (green) and Bureau of Land Management (yellow) lands in the western portion of the state (U.S. Department of the Interior, Bureau of Land Management).

another is more sensitive to moisture changes. Differential climate responses between species may disrupt existing ecological relationships. Thus assessing ecosystem impacts can be a complex undertaking when considering the influence of a number of direct and indirect climate shifts.

This complexity adds to the uncertainty of how many ecosystems will respond or change to climate change, but observations of ecosystem responses to recent or past weather events provide some insight into how ecosystems may respond or be affected. Future climate projections indicate that Colorado is likely to see rising average temperatures, longer and hotter heat waves in summer, and earlier snowmelt (see Chapter 2). Land cover change such as forest dieback may have important feedbacks on land-atmospheric exchanges of water and energy and influence local and regional meteorology (Wiedinmyer et al. 2011).

Grasslands

Grassland ecosystems in Colorado (Figure 4.4) dominate the eastern portion of the state and are significant features in some mountain valleys. They are economically important, and provide a wealth of essential ecosystem services, such as soil stabilization, carbon storage and forage production. The past and present-day distribution of grasslands and their ecological attributes are determined primarily by regional precipitation gradients, with temperature a secondary factor (Lauenroth 1979; Axelrod 1985; Sala et al. 1988). In these grasslands, both the mean and extremes of precipitation (e.g., floods and droughts) strongly affect ecosystem processes (Anderson 1990; Hayden 1998). Grasslands are shown to be especially likely to experience biodiversity loss due to their sensitivities. A "maximum impact factor" is assigned for grasslands, rather than other biome types, because of their dependence on precipitation; in other words, plant growth in grasslands is extremely limited by water availability (Sala et al. 2000). Moreover, on a continental scale, variability in precipitation affects productivity more in grasslands than in all other biomes in North America (Knapp and Smith 2001). In addition to climatic gradients, these grassland ecosystems exhibit gradients in C3/C4 dominance (grasses adapted to cooler and warmer temperatures, respectively) (Epstein et al. 1997), soil attributes (Burke et al. 1989, 1991), and gradients in plant species diversity and aboveground productivity, both of which tend to increase with precipitation (Diamond and Smeins 1988; Sala et al. 1988). Across the state, Colorado has significant differences in climate. Therefore, ecosystems differ substantially in species traits, community structure and rates of ecosystem processes.

Although changes in both rainfall and temperature would impact grasslands from the organismic level to the ecosystem level (Epstein et al. 2002; Knapp et al. 2002; Thomey et al. 2011), the major structural and functional aspects of grasslands are governed more strongly by precipitation than temperature at the regional scale. Grasslands show well-documented sensitivity to droughts and changing precipitation regimes (Weaver 1968; Tilman and El Haddi 1992; Heisler-White et al. 2009), reinforcing the importance of changes in precipitation for grassland ecosystem response. Given the uncertainty of projections of precipitation in Colorado (see Chapter 2), it is difficult to determine the full extent of future climate impacts on grasslands.

However, projections do more clearly indicate that droughts in Colorado will become more frequent and intense by mid-century. Drought has played an important role in grasslands worldwide, and moderate drought impacts grasslands in a number of ways. Net ecosystem exchange (the cycling of carbon dioxide (CO_2) into and out of an ecosystem) and above ground net primary production (the amount and rate of vegetation growth) are almost always reduced during droughts (Yahdjian and Sala 2002; Polley et al. 2010; Flanagan and Adkinson 2011), whereas the below ground net primary production may be unchanged or reduced (Shinoda et al. 2010). As droughts become more severe, grass cover typically decreases (Yahdjian and Sala 2002; Evans et al. 2012; Sala et al. 2012). As a result, grasslands become CO_2 sources rather than sinks because plants are not taking up as much CO_2, but CO_2 is still released from soils (Pereira et al. 2007; Parton et al. 2012). Furthermore, a decline in aboveground productivity may result in decreased viability of grazing livestock on grasslands experiencing drought conditions.

Figure 4.4. Grasslands, like this one in Comanche National Grassland, are a major feature of the eastern Colorado plains as well as many valleys in western Colorado (Photo: Wikimedia Commons, cm195902).

Forests

Climate is one of the primary determinants of tree distributions; the range of climate conditions that a species is adapted to influences where it can grow and thrive (Fettig et al 2013). Long-lived tree species with relatively slow rates of migration inevitably become exposed to conditions outside their ecological niches, potentially making them more vulnerable to insect and pathogen disturbance. Moreover, regeneration success following disturbance can be highly influenced by environmental conditions at the time after the disturbance; adverse conditions can influence successional trajectories resulting in species composition or ecosystem shifts (e.g., forest to grassland). Earlier snowmelt could lead to a number of effects such as longer wildfire seasons (Stephens et al. 2013), higher likelihood of extreme fire weather, increased susceptibility of multiple synchronous insect outbreaks, forest die-offs from drought-induced stress, and decreased tree regeneration after disturbance, especially in large areas burned with high severity (Fettig et al. 2013; Vose et al. 2012).

In addition, climate is the primary top-down driver of disturbances in Colorado's forests, especially fire and insect outbreaks. Fire regimes for warm-dry conifer forests dominated by thick-barked ponderosa pine are generally characterized by frequent fires (5-50 year intervals between fires at the scale of an individual stand) burning with low to moderate severity during summer months. By contrast, fire regimes for cool-moist forests, such as lodgepole or spruce-fir forests are characterized as being infrequent (100-500 year intervals) and burning with high severity during extreme drought conditions.

Figure 4.5. Spruce trees killed by the spruce beetle near Wolf Creek Pass. Researchers generally believe that drought conditions in the 2000s led to widespread beetle infestations across Colorado and elsewhere in western North America (Photo: Eric Gordon).

Drought duration and severity can drive outbreaks of insects such as bark beetles (Figure 4.5) as trees lose their resistance to infestations, allowing insect populations to grow to epidemic levels. A combination of warming temperatures in the winter allowing for greater number of mountain pine beetle larvae to overwinter and a longer growing season for the insects to produce have also contributed to the magnitude of the recent mountain pine beetle outbreak. In addition, regrowth following fires in the late 1800s has resulted in large spatial areas of even-aged lodgepole trees that have matured in the absence of extensive logging or burning during the past century. This combination of climate and land use changes has contributed to the extent of bark beetle mortality observed across the Colorado Rocky Mountains.

Changes in disturbance regimes will most likely produce shifts in forest structure and composition at large scales. Tree mortality in some areas could result in forests being replaced by grasslands or shrublands. Some changes in post-disturbance structure and composition have been observed in areas burned with high severity during wildfires, but major, unprecedented changes in forest composition and structure following the mountain pine beetle outbreak have not been documented yet (Collins et al. 2011).

Finally, forest productivity is impacted by drought as well as early snowmelt conditions. Observations from the Niwot Ridge Long Term Ecological Research Station near Nederland reflect multiple occasions where trees have responded to the early snowmelt with an initial burst in productivity (Monson et al. 2005), but as soil moisture declines and seasonal temperatures increase, productivity declines due to lack of soil moisture.

Wildlife and Insect Species

The "intensification or alteration of normal weather patterns" has had documented effects on Colorado's wildlife (Colorado Division of Wildlife 2006). Seasonal or annual changes in weather patterns are tied to habitat alterations and shifts due to specific trends, such as severe late spring storms or the onset of drought due to evapotranspiration in lower river basins (Isaak et al. 2012). In the prairie pothole region in the Northern Great Plains of the U.S., migrating birds have been shown to arrive earlier in the year when spring begins earlier. (Swanson and Palmer 2009). Prolonged rain events and cold weather events have been shown to cause nest failure in Colorado's bird populations (Colorado Division of Wildlife 2006).

Climate projections indicate a strong chance that Colorado will see increases in average and high summertime temperatures, which would likely affect stream temperatures. There is also a moderate chance that streamflows will decrease (see Chapter 2), which would have an even greater effect on stream temperatures. Both streamflow and stream temperature impacts would, in turn, affect aquatic and stream habitat. Flow is not only a major physical determinant of species composition, but species have evolved in response to specific flow regimes, and the maintenance of these patterns is important for "lateral connectivity" of riverine species (Bunn and Arthington 2002). Furthermore, altered flow regimes can aid the invasion and success of exotic and introduced species (Bunn and Arthington 2002).

Independent of changes in precipitation, streams with lower headwaters (<9,000 feet) are expected to experience a larger reduction in streamflow as a result of warming (J. Lukas, pers. comm.). This elevation-related effect is not just a result of lower-elevation basins having generally less snow-water equivalent, but also from differences in the overall water budget. At lower elevations, evapotranspiration due to higher temperatures, lower humidity, and less cloudiness would likely reduce runoff efficiency (streamflow as a fraction of precipitation). Lower elevation forests, for example, have been shown to experience reduced runoff per unit area due to reduced rainfall and snowmelt inputs relative to evapotranspiration (MacDonald and Stednick 2003). Significant warming across Colorado will increase evapotranspiration across all elevations, leaving the lower elevations disproportionately affected in terms of percentage change in stream flow.

Climate warming may also affect water quality in forested watersheds, with resulting impacts on aquatic life. Recent research indicates that sharp increases in sulfates in southern Colorado wilderness lakes likely resulted from increased weathering of pyrite during warmer, drier years. Future climate change could increase acidity and trace metal concentrations in surface waters with negative impacts on aquatic life (Mast et al. 2010). Researchers investigating the Snake River near Dillon have theorized that rising air temperatures most likely melted permafrost and led to a drop in water tables (Ives and Fahey 1971), resulting in increased metal concentrations. These changes in water chemistry could make marginal fish habitats uninhabitable and threaten water supplies (Todd 2012).

Temperature is not only important in terms of streamflow but also affects habitat suitability for species adapted to particular niches. In the Green River Basin in northwestern Colorado, Colorado River cutthroat trout (Figure 4.6) are expected to face significant habitat fragmentation as a result of rising temperatures. Summer flow declines and drought reduce the volume of water available for fish to physically inhabit, while wildfires can result in excessive increases in stream temperatures. Isaak et al. (2012) note that continued temperature increases can "facilitate expansion of nonnative trout into cutthroat trout habitat." On the other hand, Hendrickson et al. (2010) generally found that in Colorado, future climate warming could

Figure 4.6. Native Colorado cutthroat trout face numerous challenges, including rising stream temperatures in a warmer climate (Photo: Jon Ewert, Colorado Division of Parks and Wildlife).

result in habitat suitability expansions for low-elevation fishes such as the sharpnose shiner (*Notropis oxyrhynchus*) and the plains minnow (*Hybognathus placitus*).

III. Key Vulnerabilities

As described in Chapter 1, vulnerability is a function not only of impacts from climate variability and change but also of the ability of a system to adapt to changes, known as "adaptive capacity." Although those concepts apply more readily to human systems, they can provide some greater understanding of which ecosystems and species might be most vulnerable when applied to natural systems, as we do below.

Adaptive Capacity

Mechanisms to adapt to climate change can vary among Colorado's ecosystems, some with greater success than others. Fleishman et al. (2013) note "the probability that a species will occupy and reproduce in a specified geographic area for a selected number of years may increase if the physiology or behavior of individuals of the species is able to change in response to environmental change." Range shift studies show increased adaptability in small, ectothermic, short-lived species (Beever et al. 2011). However, not all species can successfully adjust to a new climate, and may need to migrate to new habitat. Those with little ability to adapt or little new habitat available will have the least adaptive capacity.

Colorado's wide range in elevations generally works to the advantage of species in the state. Mountains provide a ready means for species to find cooler conditions by moving upwards, although changes in slope, soil type, and precipitation may limit the suitability of new habitats at higher elevations. Colorado's elevation does provide a buffer against some of the snow-related impacts of warming temperatures. Most of the reduction in snowpack in the Western United States has occurred below about 8200 feet (Regonda et al. 2005), but much of Colorado's snowpack is above this elevation, where temperatures are more likely to be below freezing for long periods during the winter. Furthermore, alpine organisms are "strongly decoupled from conditions in the free atmosphere" due to minute differences in topography, which mimic temperature differences of large elevational or latitudinal gradients. Thus "for plants unable to, or too slow to adapt to a warmer climate, thermal microhabitat mosaics offer both refuge habitats as well as stepping stones as atmospheric temperatures rise" (Scherrer and Körner 2010).

The relationship between climate change and ecosystems is not a one-way street. Forests and grasslands have important feedbacks on the climate system. Vulnerabilities can be reduced when healthy ecosystems are in place to act as carbon sinks (Bonan 2008). Furthermore, plants are themselves adaptive. In forests, individual tree conditions or overall health can guard against pine beetle infestation (Fettig et al. 2013). In grasslands, changes in vegetation structure can affect moisture uptake; plants can potentially mitigate surrounding drought conditions by altering how much water they use (Cramer et al. 2001).

The adaptive capacity of natural ecosystems can be bolstered by management agency efforts. State and federal agency planning and implementation relevant to climate change in Colorado include the Division of Parks and Wildlife's strategic planning, the Colorado State Forest Service's Statewide Forest Strategy, the U.S. Forest Service's *National Roadmap for Responding to Climate Change*, the U.S. Fish and Wildlife Service's *Climate Adaptation Strategy* and landscape-scale planning, the National Park Service's *Climate Change Response Strategy* (Klein et al. 2011). These efforts involve ecological monitoring, analyses, and scenario planning while also working to establish management guidelines aimed at improving habitat conditions in a warmer future.

The forest products market is also sensitive to shifts in species composition and productivity. However, there are certain adaptive components built into the forest products sector, such as the ability for supply to incentivize mills to change investments, and also for prices to shift with changes in the availability of specific tree species. Additionally, new technologies such as adhesives can be used to make new wood panels and composites, which have replaced older products. Similarly, paper and pallet recycling can reduce harvest pressure on forests, as can using plastics for construction materials like siding and decking products (Irland et al. 2001).

Identifying Key Vulnerabilities

Grasslands

Ecosystem vulnerability across the state will be influenced by changes in soil moisture as driven by increased temperatures during the growing season coupled with changes in precipitation patterns, which would modify growing season water availability. Grassland species may compensate for increased atmospheric CO_2 concentrations with increased water use efficiency. However, these effects are not uniform and other factors, such as increased evapotranspiration or depleted soil moisture, can contribute to lower productivity of these systems (Weaver and Albertson 1943; Clark et al. 2001).

Forests

Forested ecosystems are vulnerable to drought conditions leading to a lack of soil moisture. As indicated above, early snowmelt coupled with a reduction in rainfall during ensuing months may lead to a rapid depletion of soil moisture and declining productivity. Given that climate projections indicate a likely shift to earlier snowmelt timing as the climate warms, forests in Colorado are potentially vulnerable to declining summertime productivity. In addition, as temperatures warm in forested areas, climate-induced physiological stress due to increases in frequency, duration and/or severity of drought and heat can directly increase tree mortality (Allen et al 2010). Independent of precipitation levels, warmer temperatures can lead to water stress; furthermore, increased temperatures can accelerate drought-induced mortality (Allen et al 2010). Warming temperatures and resulting reductions in soil moisture will likely make forested systems more vulnerable to fire events. Decreased snowpacks, earlier snowmelt, and prolonged summer heat waves may expose forested areas to longer fire seasons as plant material dries out earlier in the spring and stays dry later through the fall (Fettig et al., 2013; Fleishman et al. 2013; Vose, Peterson, & Patel-Weynand 2012). Westerling et al. (2011) project increases in the frequency and duration of severe fire weather across the western U.S. by mid-century.

More intense summer droughts would also continue to cause physiological stress and susceptibility of forests to insect outbreaks. Several tree-killing insect species are native to Colorado forests, such as Douglas-fir beetle, Ips beetle, mountain pine beetle, spruce bark beetle, and spruce budworm. Drought-induced stress and warmer winters, combined with large areas of older forests (more than 120+ years old), have created the conditions for beetle populations to grow to epidemic levels. Trees that are drought-stressed have weak resin flow, leaving them less able to "pitch out" invading insects (Allen et al. 2010). Regeneration after the mountain pine beetle in some lodgepole pine forests has been observed to result in similar forest structure and species composition as before the outbreak. In these cases, regeneration is not in the form of new seedlings, but comprised of surviving small trees present before the outbreak—likely not killed due to their small size. Freed of competition from former canopy dominants, surviving saplings can grow at an accelerated rate (W. Romme, pers. comm.). Recent studies, though, indicate that the outbreak may be resulting in more diverse forest structure and composition in some areas (Collins et al. 2010; Diskin et al. 2011; Pelz and Smith 2012). In other areas, the regeneration of even-aged stands may become susceptible to future outbreaks spurred by drought conditions and warmer winters.

Climate shifts can also directly affect tree physiology and result in stress-induced die-offs, such as Sudden Aspen Decline (Anderegg et al. 2013; Hanna and Kulakowski 2012). Long-term effects on tree physiology and resulting die-offs are being observed globally (Allen et al. 2010). The die-off of pinion pines in southern Colorado have been attributed to climate change, setting the stage for a widespread *Ips* ("engraver") beetle outbreak (Breshears et al. 2005).

Figure 4.7. Research indicates that climate warming may produce a two-part season for alpine flowers (Photo: Creative commons License, OakleyOriginals).

Alpine Ecosystems

Warming temperatures may lead to an earlier average onset of spring, pushing alpine plants toward a bi-modal (two-part) flowering season (Figure 4.7). This can affect pollinators that depend on a sustained flower season (Aldridge et al. 2011). Research in the International Tundra Experiment has shown that experimental warming causes an initial response of increased vegetative growth, followed by a secondary surge in reproductive response (Arft et al. 1999). In addition, this earlier leafing can decrease plant nutrient pools, such that over time total nitrogen and phosphorous are depleted (Arft et al. 1999). Baron et al. (2009) found that rock glacier meltwater, above the influence of alpine and subalpine vegetation and soils, contained rising nitrate concentrations. Their findings suggest that warmer summer and fall mean temperatures causing high glacial melt contributed to the crossing of a water quality threshold in the Front Range around the year 2000 (Baron et al. 2009).

Although projections of future precipitation across Colorado are unclear (see Chapter 2), research indicates that any future changes in precipitation could have major impacts on alpine ecosystems. Furthermore, given that the impacts of these changes are uncertain, monitoring trends in alpine ecosystems is especially important.

Aquatic Ecosystems

Aquatic organisms are particularly vulnerable to climate-induced reductions in streamflow. As an example, low Colorado snowpack in 2000 resulted in significantly reduced flows and elevated stream temperatures. This event triggered a rescue mission for a number of endemic cutthroat trout populations in the high elevation reaches of the Rocky Mountains. Similar concerns arise during and after wildfires–even post-fire effects can result in increased summer stream temperatures. Fish habitat was reduced 45-63% following the Hayman Fire in 2002 (Rhoades et al. 2011). However, some species such as the Colorado River cutthroat trout may not be as vulnerable to higher stream temperatures because they are restricted to high-elevation stream fragments where water temperatures will likely remain within a suitable range for this species (Roberts et al. 2013).

A summary of selected key vulnerabilities across Colorado's ecosystems is provided in Table 4.2. As indicated, climate change will heighten the vulnerability of many ecosystem components and affect a number of ecosystem services. The impact of these changes on livelihoods and safety of Colorado residents and visitors can be significant. These cascading effects from ecosystems to ecosystem services will take various pathways in different sectors and regions of the state; however, it appears that every corner of the state will be affected to some extent.

IV. Moving Towards Preparedness

Uncertainties in future precipitation and temperature changes make it difficult to predict climate shifts across Colorado's ecosystems. Thus it is more appropriate to discuss the range of future conditions that Colorado ecosystems could face, rather than a single scenario. The key to preparedness for ecosystems lies in resilient and innovative management strategies that incorporate both public and private actors (Carlsson and Berkes 2005). Options for improving preparedness in this sector include:

	Potential Impacts	Key Vulnerabilities
Forests	• Longer and more severe droughts • More frequent and severe fires • Conditions more suitable to insect outbreaks and spread of non-native plant species	• Individual trees and forested landscapes will likely become more vulnerable to insect and pathogen invasions • Landscapes are vulnerable to changes in connectivity, shifts from carbon sinks to carbon sources, and vegetation cover shifts (forests to grasslands, for example) if wildfires become more frequent and severe
Alpine Ecosystems	• Increased temperatures • Earlier onset of snowmelt	• Alpine plants are vulnerable to phenology shifts caused by rising spring temperatures. As a result, flowering and leaf-out can occur earlier, potentially leading to a mid-summer decline.
Grasslands	• Increased frequency and severity of drought	• Grass types that fare better in drought conditions are likely to become more dominant; less drought-tolerant species are therefore vulnerable to future warming
Wildlife	• More frequent and severe fires • Forest fragmentation and other changes in habitats	• Aquatic species are vulnerable to decline due to reductions in habitat suitability, especially connected to rising water temperatures

Table 4.2. Potential key vulnerabilities sorted by ecotype and impact.

- *Connectivity modeling for wildlife at the landscape scale* (Cushman et al. 2010) is important for informing decisions about ecosystem management (Vitousek et al. 1997). Habitat connectivity—as it relates to natural impacts and human impacts alike—will play a large role in the adaptive capacity of wildlife. Connectivity modeling could help managers make better decisions. Such modeling could draw on the Comprehensive Wildlife Conservation Strategy developed by the Colorado Division of Wildlife in 2006, which provides a baseline for coordinating monitoring and reporting activities. Monitoring continues today as the Colorado Natural Areas Program conducts an inventory of rare species within designated Natural Areas and State Parks. These efforts could be updated and expanded to other public and private lands in the state.

- *Adaptive management for forest goods and services* (Buma and Wessman 2013; Temperli et al. 2012). Tree distributions are likely to change, but appropriate management can facilitate this process in a way that reduces mortality (Fettig et al. 2013) or establishes species adapted to new conditions (Buma and Wessman 2013; Temperli et al. 2012). Knowing how particular species respond to climate changes can facilitate this process. The Colorado State Forest Service and Colorado Forest Restoration Institute are good examples of organizations that facilitate public and private actors in the ongoing efforts to incorporate new science into management.

- *Monitoring for restoration*. The Colorado Parks and Wildlife Species Conservation Trust Fund provides support for ongoing monitoring projects like the Gunnison Basin Selenium Management Program, and native aquatic wildlife conservation in sites like the Gunnison River and Fountain Creek. The programs include monitoring species numbers, the impacts of habitat disruption, and distributions; but Colorado Parks and Wildlife also now increasingly includes habitat management and restoration efforts in its suite of responses to change.

- *Restoration to the historical range of variation (HRV)*. Restoration of ponderosa pine-dominated landscapes to the kind of structure that they had historically may increase natural resilience to fire. Understanding prior ecological states helps managers shift practices toward the forest stand structures, patch sizes, and diversity that existed prior to human intervention (Romme et al. 2012). These kinds of restoration efforts are already underway in the state—for example, in western Colorado with the Uncompahgre Plateau partnership and on the Front Range with the Colorado Forest Restoration Institute.

V. Future Research Needs

Additional research on identifying thresholds, tipping points, and local mechanisms of major change in ecosystems is important for guiding management responses. At present, we cannot predict exactly where such changes are most likely to occur, nor do we know all of the "vital signs" that would warn of impending major changes. Below we provide suggestions of future research efforts that can help bolster our understanding of expected climate impacts on ecosystems and better understand when changes are occurring.

Long-term ecological monitoring

Ecological responses to climate change are complicated by spatial heterogeneity, both in terms of environmental variation and also jurisdictional patterns with divergent management protocols. With regard to forests, this is further complicated by temporal lags; for example, forest decline can confound linkages to increased drought and heat events related to climate change (Allen et al 2010). Climate change will affect forest growth, inventories, and harvest levels slowly, over many decades. These biological changes will affect recreation, wood product markets, and other forest benefits, all with differing lag times (Irland et al. 2001). Therefore, it will be important to study longer-term patterns of forest disturbances to specifically link them to climate drivers.

Long-term ecological data and corresponding climate records will continue to be incredibly important in monitoring Colorado's ecosystems. For example, looking at past records of inter-annual variability in grass growth as it relates to precipitation allows researchers to better understand how grasslands will respond to a range of possible future conditions. The most sensitive grasslands may be those with the lowest mean annual precipitation (Huxman et al. 2004). However, this relationship between plant growth and precipitation is more complicated, as very wet years differ in many ways from very dry years beyond simply precipitation amount (e.g., rainfall patterns, temperature, and cloud cover); moreover, a previous year's climate and production may influence current year's responses in many ecosystems (Oesterheld et al. 2001; Wiegand et al. 2004). Thus, continued *multivariate* monitoring is important for future work examining the vulnerability of Colorado's grasslands.

Ongoing biological monitoring for wildlife

Long-term biological monitoring can provide a continuous record of how species respond to changing conditions. This can provide critical data to assess the predictions of bioclimatic models and help develop traceable accounts of the mechanisms for changes (Isaak et al. 2012). Monitoring is also a key tool for biologists to use in determining the ways in which habitat suitability may expand or decline as well as how species range shifts occur. In Rocky Mountain trout populations, for example, warming stream temperatures can facilitate the expansion of non-native trout into cutthroat trout territory (Isaak et al. 2012); with more information of this type, in addition to examining the impact of streamflow reduction or even wildfires on stream temperatures, better knowledge of fish response can inform management decisions. Ongoing efforts should be consistent with the following principles laid out by Mawdsley and Murphy (2009):

- Identify conservation targets (species, ecosystems, geographic areas, or vegetative communities);
- Develop a conceptual model that relates conservation targets to stressors or threats, as well as conservation activities;
- Use the model to select potential indicators of target status and conservation effectiveness;
- Develop a monitoring program to measure and track indicators;
- Implement conservation activities, measuring indicators to track progress; and
- Use information from the indicator measurements to modify activities and adjust the conceptual models.

Colorado's State Wildlife Action Plan can be used as a guide to monitoring species that are particularly sensitive to climate.[1]

Economic valuation of ecosystems services and the effects of climate change

At the global level, ecosystem services studies have examined the value of ecosystem regulation functions, such as carbon storage in tropical rainforests or carbon sequestration in grasslands (Hawkins 2003). These studies are becoming more common at state and local levels. For example, the city of Chicago documented ecosystem services of urban trees, finding that a 10% increase in tree cover can reduce heating and cooling costs by $50-90 per dwelling each year (Hawkins 2003). The latest generation of ecosystem services studies evaluates the impact of climate change on these services.[2] There is a need to not only document the value of Colorado's ecosystem services, but also to be able to specify the economic impact and direction of changes related to shifting temperatures and precipitation.

1 The Division of Wildlife's Comprehensive Wildlife Conservation Strategy document identifies 205 Species of Greatest Conservation Need, reporting there are no data for 16% of species, while population trends are needed for 81 (40%).

2 See the California Climate Change Center's 2009 report, titled The Impact of Climate Change on California's Ecosystem Services, for example: http://www.energy.ca.gov/2009publications/CEC-500-2009-025/CEC-500-2009-025-F.PDF.

Cross-sectoral impacts

Streamflow, habitat and water quality tie the ecosystems sector to water, energy, and agriculture, and more research is needed to understand how impacts in one sector can exacerbate vulnerabilities in another. For example, although much of the state's water supply comes from watersheds above 8500 feet, there are some important lower-elevation basins that may experience accelerated drought conditions. In these ecosystems, water stress could be aggravated by warming temperatures coupled with evapotranspiration. When coupled with agricultural demand for water, drought stress could become more severe than ever. More research on the effects of drought on lower basins is needed in order to better predict the range of conditions Colorado's grasslands may face.

Understanding the link between drought and grazing

Colorado's grasslands are important for ranching and animal agriculture, and increasing frequency and severity of droughts will have impacts on both grassland ecosystems and ranching. Although there is good evidence that grasslands can withstand single-year and multi-year droughts, excessive grazing would be expected to increase the vulnerability of grasslands to climate shifts. For example, grazing negatively affects leaf area and biomass; thus, overall productivity is expected to decrease further when drought and grazing occur together (Polley et al. 2010; Parton et al. 2012). However, past research reports inconsistent and even conflicting responses to drought, grazing, and drought/grazing interactions in grasslands (Milchunas et al. 1994; Varnamkhasti et al. 1995; Eneboe et al. 2002; Heitschmidt et al. 2005) suggesting that a more rigorous, comparative approach is needed to quantify and understand how ecosystem structure and function will be impacted in the future.

Further consideration of "multiple stressors"

In addition to primary drivers, or climate-related variables, of disturbance, it is also important to consider human impacts/settlements, land use change, and fragmentation. Climate-related disturbance is only one category. Others are grouped in four broad categories: (1) land-use and land-cover change: habitat fragmentation and degradation, urbanization, and infrastructure development; (2) biological disruptions: the introduction of non-native invasive species, diseases, and pests; (3) extractive activities: fishing, forestry, and water withdrawals; and (4) pollution: chemicals, heavy metals, and nutrients. Combined, these processes have already altered 75% of the Earth's ice-free land (Staudt et al. 2013).

Land use patterns will continue to impact species, and a changing climate should be linked into a larger hierarchy of drivers. In other words, a focus on climate cannot exist in the absence of other stressors. Further studies could investigate how these stressors tie in with vulnerabilities. The Front Range could serve as a region of focus (as a mosaic of human modified systems) to exemplify vulnerabilities in a transition zone/interface area that is sensitive to small changes in climate features such as precipitation and drought stress.

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John Martin Dam and Reservoir on the Arkansas River in Bent County, Colorado. Photo: U.S. Army Corps of Engineers Digital Visual Library.

CHAPTER 5
WATER SECTOR

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Water is connected to virtually every part of life in Colorado. Nearly all aspects of the state's economy depend in some way on water supplies, including billions of dollars in agricultural production, popular recreation activities such as skiing and rafting, and numerous industries. Regulation of water in the state is highly complex, involving a diverse set of public and private entities, and water policies intersect with virtually every other sector.

I. Brief Description of Sector

Definition of Sector

In order to constrain the discussion of climate vulnerability in this chapter, we define the water sector as being comprised of five interrelated elements:

- *Water supply* for municipal & industrial (M&I), agricultural, self-supplied industrial, and other uses
- *Water demand* from residents, farmers, and businesses
- *Water quality*, especially in M&I contexts
- *Flood mitigation*
- *Non-consumptive uses* including recreation and environmental flows

These five elements will be used to guide this chapter's discussion of climate impacts, adaptive capacity, and key vulnerabilities in the water sector.

Where Colorado's Water Comes From

The headwaters of four major rivers—the Colorado, the Rio Grande, the Arkansas, and the Platte—begin in the mountains of Colorado and flow into a number of other states throughout the West and Midwest. As shown in Figure 5.1, these and other rivers in the state generate an average of 16 million acre-feet of water per year, two-thirds of which leaves Colorado under obligations from interstate compacts and agreements

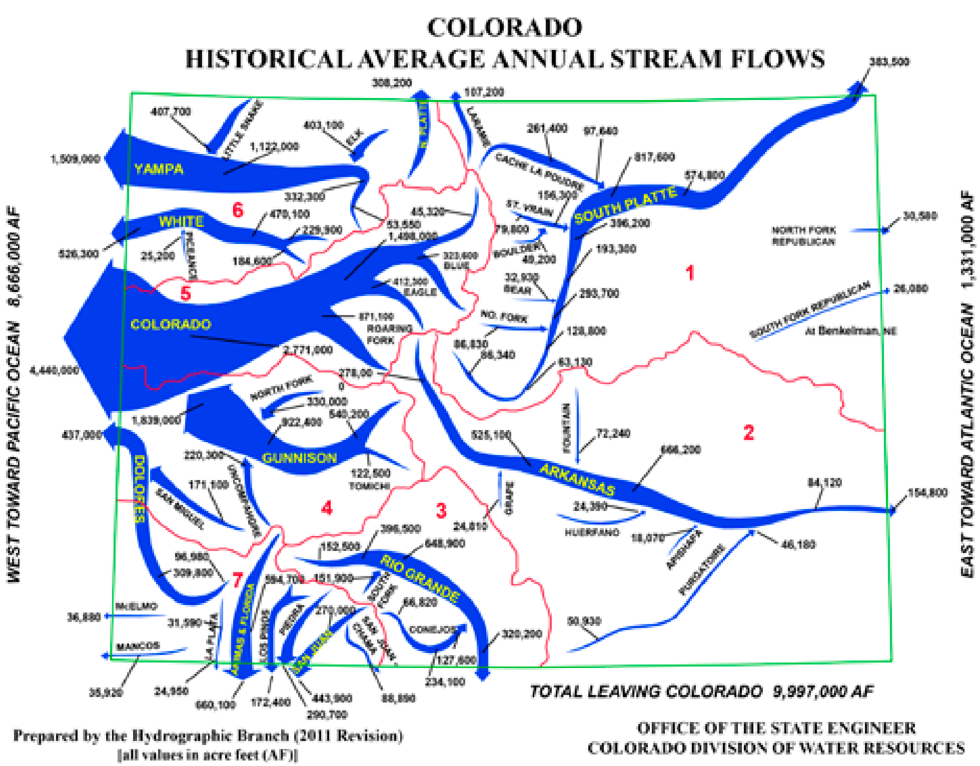

Figure 5.1. Average streamflows for rivers in Colorado. The size of the arrow corresponds to the relative size of average flow. Numbers indicate major river basins (1=South Platte, 2=Arkansas, 3=Rio Grande, 4=Gunnison, 5=Colorado, 6=Yampa/White, 7=San Juan/Dolores.) As shown at the bottom, a total of nearly 10 million acre-feet leaves the state every year (Office of the State Engineer, Colorado Division of Water Resources).

(CWCB undated; CWCB 2011). Because there are no major rivers that flow into Colorado (McKee et al. 1999), virtually all of this water originates from precipitation falling within Colorado, predominantly as snow west of the Continental Divide. Mountain snowpacks in the state provide natural reservoirs that release water throughout the spring and summer.

Surface water supplies and climate are intimately connected through precipitation. Statewide, average annual precipitation is around 16 inches, but precipitation varies enormously over both space and time. Colorado's mountainous terrain leads to dramatic geographic variability, with areas in the San Luis Valley seeing only 7.5 inches of average annual precipitation while some mountainous areas average more than 60 inches (Doesken et al. 2003). Precipitation also varies significantly from season to season and from year to year, ranging from approximately half of average in the driest years to twice the average in the wettest years (Ray et al. 2008).

Multi-year droughts, such as those experienced during-year droughts, such as those experienced during the 1930s, 1950s, and the 2000s, occur at irregular and largely unpredictable intervals. Tree-ring records, however, indicate that pre-historic droughts over the past 2000 years were longer and more severe than even the worst droughts experienced since European settlement of Colorado (Hoerling et al. 2013). This indicates that, even without climate change due to greenhouse gas emissions, natural variability in the climate could result in future droughts worse than any experienced in the modern history of the state. Figure 5.2 shows tree-ring estimates of flow in the Colorado River over the past 1200 years. Particularly notable are the sustained dry periods prior to 1900 that exceed the worst droughts of the 20th century, including a few whose duration was such that they have been characterized as "megadroughts," such as the mid-1100s drought.[1]

Groundwater resources also provide critical water supplies in many parts of Colorado. Most of the nonrenewable groundwater in Colorado comes from three major groundwater basins—the San Luis, Denver, and High Plains Basins—while a number of

1 The term "megadrought" generally refers to any period of 20 or more years of continuous or near-continuous dry conditions (J. Lukas, pers. comm.)

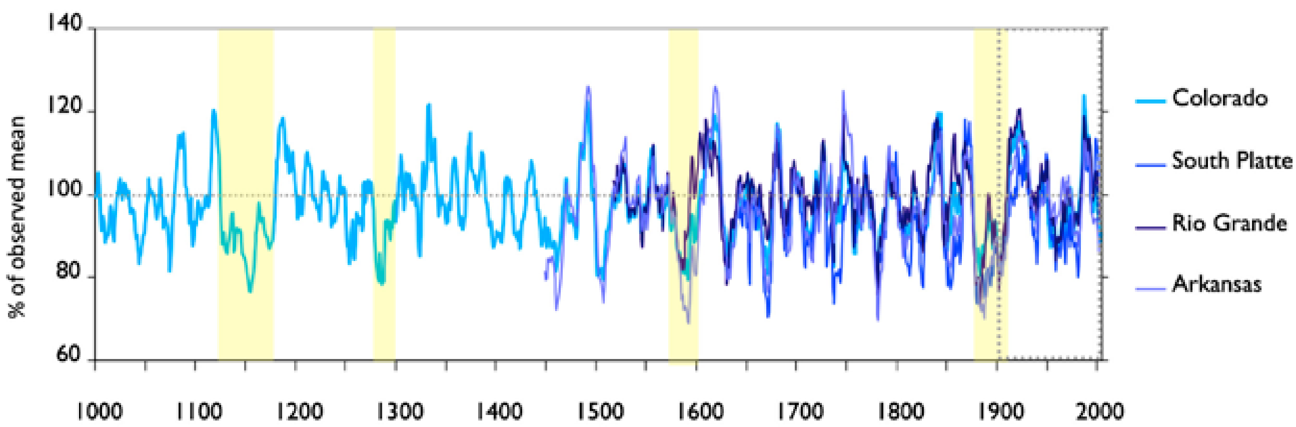

Figure 5.2. Tree ring analyses can provide a picture of Colorado's climate as it existed centuries earlier than the beginning of recorded records. This graph shows streamflow as a percent of the observed average in four of the state's major river basins: the Colorado as measured at Lees Ferry, AZ (1000-2005), the South Platte River as measured at South Platte, CO (1634-2002), the Rio Grande as measured at Del Norte, CO (1508-2002), and the Arkansas River as measured at Salida, CO (1440-2002). All four records show that, prior to 1900, the state experienced droughts that were more severe and sustained than any modern droughts. The yellow shading highlights several notable "megadroughts" (lasting for multiple decades) in the mid-1100s, the late 1200s, the late 1500s and the late 1800s. The 20th century is unusual in having two persistent wet periods and no droughts longer than 10 years. (Source: TreeFlow web resource; http://treeflow.info).

alluvial aquifers are renewable (CWCB 2011). Compared to deep aquifers, the level of these renewable resources is directly connected to recent climate conditions. However, even non-renewable aquifers have a direct connection to climate because many water supply entities use groundwater to supplement surface water supplies, especially during dry years.

How Colorado's Water Supplies Are Used

Although an estimated 80% of the state's surface water originates on the western slope of the Continental Divide, 80% of Colorado's population and most of its irrigated agriculture lies east of the Divide (CWCB 2011). Agriculture accounts for 89% of surface water use in Colorado (SWSI 2011), although some of that water is consumed and some goes back into streams in the form of return flows. The remainder of water use comes from municipal and industrial (M&I) and self-supplied industrial (SSI) entities (CWCB 2011). By 2050, the Statewide Water Supply Initiative (SWSI) projects the share of water going to agricultural use will decline to 82%, with 15% going to M&I use and 3% to SSI (CWCB 2011).

Nonconsumptive water uses—especially those for environmental and recreational purposes—are also important across the state. Many of the state's most popular recreational activities, including fishing (Figure 5.3), waterfowl hunting, and rafting, rely on surface water in streams, lakes, and wetlands. Aquatic ecosystems and fish habitats are highly dependent on sufficient in-stream flows. SWSI identified 33,000 miles of streams and lakes in Colorado as "nonconsumptive focus areas" due to their significant environmental and recreational values (CWCB 2011).

Value of Water in Colorado

Virtually every aspect of Colorado's economy is tied to water. In particular, two critical industries in Colorado—agriculture and outdoor recreation—are highly dependent on water and snow availability and are therefore likely to be particularly vulnerable to climate change (McNeeley 2014). Agricultural products in Colorado, prior to value-added processing,

Figure 5.3. Fly fishing is one of many popular nonconsumptive uses of water in Colorado (Photo: North Platte River, Keary Schmidt).

had a total farm-gate market value of $6.1 billion in 2007 (CWCB 2013a; see also Chapter 6). Total agriculture industry sales were $24 billion of direct output (Davies et al. 2012). Recreation and tourism are estimated to bring in between $8.5 and $15 billion per year (Thomas et al. 2013; CWCB 2013a; see also Chapter 9).

The value of water is also apparent in the economic costs incurred during dry times. Estimates of damages from water shortages during the drought of 2002 range from $1.3 billion (including impacts to agriculture, tourism, and municipal sectors along with wildfire-related costs; Luecke et al. 2003) to $2.8 billion statewide (impacts to agriculture and tourism; Hayes et al. 2004). Preliminary estimates of the 2012-2013 drought indicate that the agricultural sector alone suffered losses of $726 million (Pritchett et al. 2013).

Jurisdiction Over Water in Colorado

The administration and management of water in Colorado is a complex arrangement of government institutions operating at a variety of levels. Actual water deliveries are made by local entities of widely varying sizes, from very small private ditch companies to Denver Water, which serves 1.3 million people in the city of Denver and many of its surrounding suburbs (Denver Water undated a). Most of these entities are regulated by municipal government bodies or elected boards.

State government's primary role in water supply includes long-term statewide water planning, drought and flood planning, water quality, and many other areas. Specific state regulatory agencies include the Division of Water Resources, part of the Department of Natural Resources (DNR), which administers water rights under Colorado's prior appropriation system and monitors streamflow, groundwater, and water use. The Colorado Water Conservation Board, also part of DNR, is responsible for long-term water resources management and planning, including statewide flood mitigation planning (CWCB 2013b). Finally, the Colorado Department of Public Health and Environment ensures compliance with federal and state water quality standards, reviews the design of drinking water and wastewater treatment plants, and manages permitting for sources of pollution.

The federal government also plays a significant role in Colorado's water sector. The U.S. Bureau of Reclamation (USBR) and the U.S. Army Corps of Engineers (USACE) have built and operate a number of water projects and programs in Colorado and in downstream states. The U.S. Environmental Protection Agency (EPA) provides federal oversight over the state's water quality program and jointly with USACE has authority over permitting for any large water project. The U.S. Fish and Wildfire Service (USFWS) is involved in endangered species issues in surface waters and collaborates with other federal agencies and the state of Colorado and others on the Endangered Fish Recovery Program in the Upper Colorado River Basin. The U.S. Department of Agriculture's Natural Resources Conservation Service monitors snowpack and provides the Surface Water Supply Index for Colorado, while the National Weather Service's River Forecast Centers provide additional streamflow monitoring and forecasting capabilities. The Federal Energy Regulatory Commission (FERC) issues permits for hydroelectric power plants. Finally, the National Integrated Drought Information System, based in Boulder, operates the U.S. Drought Portal and coordinates drought information and activities throughout the region.

II. Key Climate Impacts in Sector

In this section, we consider whether and to what extent the five major elements of the water sector (water supply, water demand, water quality, flood mitigation, and nonconsumptive use) will be exposed and sensitive to the effects of climate variability and climate change. As discussed in Chapter 2, future climate changes are expected to result in a 2.5°F to 5°F increase in average annual temperatures by mid-century. Future changes to average annual precipitation, however, are more uncertain. Regardless of the future direction of precipitation, increasing temperatures are expected to cause earlier spring runoff, higher evaporation rates, and more rain instead of snow at lower elevations. Annual streamflow decreases under most of the climate projections, but the uncertainty in future precipitation means that increases in annual streamflow are also possible.

Climate Impacts on Water Supply

One of the most likely impacts of future climate warming on water supplies is a shift in runoff timing. Climate change studies for the region, including the *Colorado River Water Availability Study* (CWCB 2012) and the *Joint Front Range Climate Change Vulnerability Study* (Woodbury et al. 2012) have consistently projected that snowmelt initiation and peak runoff will shift earlier due to warmer temperatures, up to 2-3 weeks by mid-century. In the Upper Colorado River Basin, the effects of temperatures on runoff timing will be exacerbated by the ongoing, and potentially worsening, desert dust deposition on snowpack, which reduces the reflectivity of snow and accelerates snowmelt (Painter et al. 2010). One recent study modeled runoff under projections of climate warming and various scenarios of dust deposition, demonstrating up to six weeks' earlier snowmelt under the most extreme conditions (Deems et al. 2013). Advances in runoff timing will be especially problematic for providers with very little storage or junior water rights, as demonstrated in a 2009 study of climate change vulnerability for Boulder's water supply (Smith et al. 2009).

Projected future increases in average temperature as indicated by climate model results (see Chapter 2) would also tend to reduce streamflows in Colorado, as higher temperatures cause greater evaporation or evaporative losses from lakes, reservoirs, canals, soil moisture and plants including crops. In addition, warmer temperatures would on average produce longer growing seasons which would result in more water use by plants. However, climate projections do not agree on the future trend in annual precipitation, which is the primary driver of streamflow. If there is no trend in future precipitation, a decline, or a slight increase, streamflows will decline due to the effect of warming; a larger increase in precipitation, which is shown in some projections, would offset the effect of warming and lead to higher streamflows (Woodbury et al. 2012). Several recent state-level and regional climate modeling studies have found that annual streamflow decreases across Colorado's river basins in most of the climate projections (see Chapter 2). The *Joint Front Range Climate Change Vulnerability Study* simulated changes in the timing and volume of runoff for 18 gage locations across north-central Colorado under several climate change scenarios for the years 2040 and 2070 and found that the majority of projections resulted in decreasing streamflow at all gages, with the average outcome being a decline from 5-20% (Woodbury et al. 2012). The Bureau of Reclamation's *Colorado River Basin Water Supply and Demand Study* (U.S. Bureau of Reclamation 2012), examining a larger set of projections, found that mean annual streamflows in the Upper Colorado River Basin declined in most projections, with an average outcome of a 9% decline by mid-century. Finally, CWCB's *Colorado River Water Availability Study*, using a similar methodology as the Joint Front Range Study, also found reduced future flows in western Colorado under most of the projections, along with a general increase in winter precipitation and a decrease in summer precipitation and a shift from snow to rain in the early and late winter months (CWCB 2012).[2]

If streamflows do decline in Colorado, as indicated by most climate projections, then hydrological droughts—as indicated by persistent below-normal streamflows—will likely increase in frequency and severity by mid-21st century. Based on those projected changes, combined with what we know of the past from the paleoclimate record (see Figure 5.1), it is also reasonable to conclude that Colorado is likely to experience future droughts that are more intense and of longer duration than any experienced in the 20th century (see Chapter 2). While Colorado's water supply system has withstood the droughts of the 20th century and early 21st century, the recurrence of the droughts seen in the paleo record in a substantially warmed future climate would present significant challenges to that system.

As mentioned earlier, groundwater resources are also critical to water supplies in some portions of the state and can be affected by climate variability and change. We already know that many areas in the state are seeing groundwater levels decline, likely due to overuse. For example, in the Ogallala Aquifer, which is linked to Eastern Colorado's High Plains Aquifer, Steward et al. (2013) estimated that 30% of the aquifer's groundwater has been pumped and another 39% will be depleted over the next 50 years given existing trends. In some locations, reduced precipitation during short or long-term drought can dramatically exacerbate groundwater depletion due to demand. In the San Luis Valley, the drought of 2002 resulted in reduced surface recharge and increased pumping from the San Luis Basin Aquifer, causing a significant decline in groundwater levels (CWCB 2004). While there is much uncertainty about how climate change will affect the magnitude of groundwater recharge, a more immediate impact to groundwater

2 New projections of streamflow for Colorado based on the latest climate model projections became available in spring 2014, too late to include in this report, but they are described in detail in Lukas et al. (2014), Section 5-3. The new projections are generally consistent with the studies summarized above in that the majority of the projections indicate decreased annual streamflow for Colorado's river basins by mid-century. The new projections, like the previous studies, also show the basins with headwaters in the San Juan Mountains having larger decreases in annual streamflow than in other parts of the state.

Figure 5.4. Center-pivot irrigation on wheat growing in Yuma County. As temperatures rise, irrigation water may be used more frequently to cool crops (Photo: Gene Alexander, USDA Natural Resources Conservation Service).

supply will come from increased irrigation demands driven by a warming climate (Taylor et al. 2012), although changing groundwater management strategies could mitigate demand-related impacts.

Beyond the availability of the water itself, water supply infrastructure can also be impacted by climate. Dams, pipelines, ditches, and treatment plants, many of which are already stressed by age and/or by demand levels that exceed what they were designed to deliver (Wilbanks et al. 2012), can all be overwhelmed or damaged by unusually large precipitation events, as evidenced by the September 2013 floods on Colorado's Front Range. (It is difficult to project future changes in extreme weather events, and current climate projections do not agree as to whether there will be an increase in the frequency of summertime convective storms in Colorado, as discussed in Chapter 2). Climate warming is also expected to increase area burned and length of fire season in the Western U.S. (Yue et al. 2013).[3] Post-fire erosion can cause major problems for water supply infrastructure, as evidenced by damage to the Strontia Springs Reservoir from erosion after the Buffalo Creek and Hayman fires (Denver Water undated b).

Widespread forest mortality in Colorado due to bark beetle infestations (nearly two-fifths of forested acres in the state have been affected by some type of bark beetle) also raises concerns about future impacts to waters supplies. Recent research indicates that at the plot scale, tree death from beetle attacks will result in increased snow accumulation and faster melt (Pugh and Gordon 2013). However, the patchy nature of the beetle epidemic over large landscapes, combined with accelerated growth of remaining younger trees in affected stands, is likely helping mitigate larger scale hydrology impacts. To date other land cover changes, such as forest fires and dust deposition on snow, are likely having greater basin-scale impacts in Colorado than beetle infestations.

Climate Impacts on Water Demand

Climate warming is also expected to have complex and interrelated impacts on water demand across multiple sectors. Earlier runoff will lead to lower late summer flows, and if runoff occurs too early, irrigators may not be able to synchronize runoff with their water rights or crop water needs (McNeeley 2014). Higher air temperatures also lead directly to higher rates of evapotranspiration. Warmer spring and fall temperatures will result in longer growing seasons and increased evapotranspiration (ET), particularly for cool season plants. As evapotranspiration rates increase, irrigation requirements are likely to increase for crops and other outdoor plants. Moreover, irrigation (Figure 5.4) is often used to reduce heat stress on crops as air temperatures rise, independent of the crop's irrigation requirement for growth (Vogel et al. 2012). Thermoelectric power generation also uses more water as temperatures rise because of increased evaporation, and the Intermountain West including Colorado has one of the highest water consumption intensity levels (water consumed per kWh produced) due to the number of coal plants using recirculating cooling (Averyt 2012).

3 Widespread tree mortality due to bark beetle infestation may be affecting fire behavior in Colorado, although evidence is mixed as to whether fire ignition and severity are worsened in beetle-kill areas (Hicke et al. 2012).

The likely climate impacts on water demand would exacerbate existing trends in increasing water demand across the state. Unsatisfied water demand for crops is estimated to increase as temperatures rise (Udall 2013; CWCB 2012).[4] Population growth is also expected to increase overall water use; Colorado's population is expected to reach 7.8 million by 2040 (see Chapter 3). CWCB estimates that Colorado's M&I sector will face a shortfall of between 190,000 and 630,000 AFY by 2050, depending on whether new water projects are constructed as well as on actual population growth in the state (CWCB 2011). Overall water demand across the entire Colorado River basin is projected to increase by 1.1 to 3.4 MAF through 2060, with 64-76% of the increase from the M&I sector. The Bureau of Reclamation describes climate impacts on demand from the Colorado River as "substantial" (U.S. Bureau of Reclamation 2012).

Climate change also has implications for multiple water quality issues in Colorado. If warmer temperatures result in lower average flows, water utilities may need to engage in or invest in more water treatment to meet applicable standards, since concentrations of metals, sediments, nutrients or other contaminants increase as flows decrease. As an example, one study found that a 30% reduction in annual flows from climate change would increase drinking water treatment costs by 12% in Aurora (Towler et al. 2012). A warmer future is also likely to result in warmer water temperatures, which can in turn lead to greater levels of organic matter production in surface waters and thus increased disinfection by-products that are costly to remove as required to meet water quality standards (Vogel et al. 2012). Moreover, higher water temperatures can have negative impacts on aquatic species (Caissie 2006).

Climate-driven watershed disturbances can also impact water quality. Wildfire, which is likely to increase in terms of area burned and length of season under projected future climate conditions in the western U.S. (Yue et al. 2013), can increase erosion and sedimentation rates in basins that supply municipal water systems. For example, high-severity burns from the 2002 Hayman Fire in Colorado resulted in elevated streamwater nitrate and turbidity, and these measures remained elevated five years after the fire (Rhoades et al. 2011). The impacts of bark beetle infestations on water quality are less clear–one recent study found a significant increase in dissolved organic carbon and disinfection byproducts[5] in water treatment plants using water from beetle-infested watersheds in Colorado (Mikkelson et al. 2012), while another study found no significant increase in nitrate concentrations in streams running through beetle-infested forests (Rhoades et al. 2013).

Climate Impacts on Flood Mitigation

Recent history clearly demonstrates the destructive impact of floods in Colorado. In July 1997, Fort Collins experienced an extreme flash flood that resulted in five deaths, 54 injuries, the loss of 200 homes, and over $250 million in economic losses (Wilhelmi and Morss 2013). In September 2013, extensive flooding across portions of the Front Range resulted in 10 deaths, thousands of homes damaged or destroyed, and an early estimate of $2 billion in economic losses (CWCB 2013b). Colorado's recently updated Flood Hazard Mitigation Plan estimates that Colorado will experience a major flooding disaster every five years (CWCB 2013b).[6] Again, there is no consensus among projections that the warm-season extreme precipitation events that cause most Colorado floods will increase in frequency or intensity in the future (see Chapter 2). However, future flood impacts could be exacerbated by development of the floodplain and other factors (CWCB 2013b).

Climate Impacts on Environmental and Recreational Uses

Climate change is also expected to impact environmental and recreational uses of water. If

4 At some point, however, soil moisture drops so low that plants stop transpiring altogether.

5 Disinfection byproducts are chemicals created as a result of treating water to remove organic matter. Many of these chemicals are regulated by the Environmental Protection Agency.

6 This estimate is based on the historic incidence of flooding which would not take into account the potential additive effect of climate change.

average streamflow decreases in the future—a likely outcome across the climate projections (see Chapter 2)—resulting competition for diminishing resources could impact rafting, fishing, and other recreation activities (see Chapter 9 for more details) along with aquatic habitats. Of particular note is the Upper Colorado River Endangered Fish Recovery Program, which seeks to achieve natural, self-sustaining populations of the humpback chub, bonytail, Colorado pikeminnow, and razorback sucker so these species no longer require protection under the federal Endangered Species Act. That goal, however, is hampered by the threat of reduced streamflows and higher stream temperatures often associated with droughts or climate change. In 2012, for example, extremely low flows in the Colorado River threatened the operation of fish passages that are essential to the program (Upper Colorado River Endangered Fish Recovery Program undated).

III. Vulnerability in Colorado's Water Sector

As described in Chapter 1, vulnerability is a function of both impact due to climate variability or climate change and the ability of the sector to adapt to such impacts (known as "adaptive capacity"). In this section we first provide a brief qualitative discussion of existing adaptive capacity in Colorado's water sector. We then consider the impacts described in the previous section in light of this capacity and provide a brief qualitative summary of potentially vulnerable entities. Absent a comprehensive, formal vulnerability assessment, it is difficult to ascertain what the effects of the current adaptation activities have been on the state's vulnerabilities to climate change in the water sector.

Figure 5.5. The McPhee Reservoir, along the Dolores River in Montezuma County, is an example of water storage infrastructure that provides some adaptive capacity in the water sector (Photo: Wikimedia Commons, Doc Searls).

Adaptive Capacity in the Water Sector

The *Colorado Climate Preparedness Project* (Klein et al. 2011) cataloged a number of existing efforts that could provide adaptive capacity for climate change. These and other adaptation-related activities can be divided into five categories: 1) physical adaptations to supply and demand changes; 2) climate change-related studies; 3) long-term planning; 4) monitoring and decision support tools; and 5) legal, regulatory, and other institutional efforts. Below we draw on the *Colorado Climate Preparedness Project* and other sources to summarize adaptive capacity available in each of those categories for the five major water sector elements.

WATER SUPPLY

Physical adaptations

- Colorado's complex system of water storage and conveyance (Figure 5.5) has served as the "primary mechanism for reducing sensitivity to fluctuating amounts of water due to climate variability and change" (McNeeley 2014).

- Changes to agricultural water leases, leases of irrigation rights from farmers, reduction of minimum streamflow bypasses, increased use of ditch water for park irrigation, drilling of supplemental wells, and trucking in emergency water supplies are used by the M&I sector as needed (CWCB 2013a).

- Leasing of additional water and changes in crop types are used by the agriculture sector as available.
- Use of recycled water (CWCB 2013a).
- CWCB administers the state weather modification program, which has invested in cloud seeding efforts across the state although evidence of the effectiveness of this technique is mixed (Klein et al. 2011).

Climate change-related studies

- In 2008 CWCB commissioned the Western Water Assessment to produce *Climate Change in Colorado* (Ray et al. 2008), a summary of the physical science of climate change relevant to the state. That report was updated in 2014.
- In 2010 Western Water Assessment released the *Colorado Climate Preparedness Project* (Klein et al. 2011), funded by CWCB, the Governor's Energy Office, and the Department of Agriculture.
- CWCB completed the *Colorado River Water Availability Study* (CWCB 2012), which was aimed at determining how much water would be available for the state to develop from Colorado River supplies under a number of alternative hydrologies, including climate change scenarios. As of early 2014, a second phase of that study was being conducted.
- The state participated in the USBR's *Colorado River Basin Study*, which assessed the future trajectories of water supply and demand on the entire Colorado River system (U.S. Bureau of Reclamation 2012).
- The *Joint Front Range Climate Change Study* (Woodbury et al. 2012) examined impacts to future streamflow in the Colorado, South Platte, and Arkansas basins under multiple scenarios of future climate warming.

Long-term planning

- The Statewide Water Supply Initiative (CWCB 2011) comprehensively assesses Colorado's water supply needs and examines possible approaches to meet those needs. As part of the current SWSI planning process, the CWCB, Interbasin Compact Committee (IBCC) and Basin Roundtables (described below) are engaging in a climate scenario planning analysis to better understand the state's water supply future.[7]
- Development of the Colorado Water Plan, to be completed in December 2015, will build on the work of the Basin Roundtables and the IBCC as well as the Statewide Water Supply Initiative.
- The State Drought Mitigation and Response Plan and accompanying vulnerability assessment identified areas of greatest drought concern and laid out a process for statewide drought response.
- Certain individual water utilities have begun to use scenario planning or integrated resource planning that incorporates climate change.

Monitoring and decision support tools

- A variety of tools are used to monitor water availability and drought status, including the NRCS SNOTEL network, National Weather Service forecasts and reports, precipitation and drought monitoring provided by the Colorado Climate Center at CSU (including the modified Palmer Drought Severity Index and the Standardized Precipitation Index), the Statewide Water Supply Index produced by NRCS, the U.S. Drought Monitor produced by the National Drought Mitigation Center, and the U.S. Drought Portal maintained by NIDIS.
- Colorado is also the only western state that operates its own network of stream gages for water supply monitoring, complementing

7 CWCB, the IBCC, and the basin roundtables have developed five future scenarios to analyze within the SWSI process. This type of scenario planning is intended to provide the opportunity to plan for a wide range of equally plausible futures. The SWSI planning process will examine year-to-year variable weather extremes such as flood and drought and how those may impact future water supplies and the overall gap that may exist between water supplies and water demands in 2050. Both of these analyses will be used to inform the Colorado Water Plan currently in development.

the nationwide USGS stream gage network (Klein et al. 2011).

Legal, regulatory, and other institutional efforts

- The Colorado Water for the 21st Century Act (passed in 2005) created nine Basin Roundtables that are responsible for assessing consumptive and non-consumptive water needs for each basin, assessing available water supplies and developing projects or methods to meet identified water needs. That same law also created an Interbasin Compact Committee (IBCC) to encourage dialogue on water, broaden the range of stakeholders that participate in water decisions, and create a process through which decision-making power rests with those living in the state's river basins.

- Efforts to build social capital through the Basin Roundtable process have helped some communities cooperate during drought (McNeeley 2014).

- Informal adaptive capacity for dealing with drought has been documented among ranchers in the Gunnison Basin (The Nature Conservancy et al. 2011), agricultural producers (Pritchett et al. 2013) and tourism industry operators (Thomas et al. 2013).

WATER DEMAND

Physical adaptations

- Water conservation, especially by agricultural and M&I users, already provides significant adaptive capacity for drought and would provide some adaptive capacity in a warming future.

Climate change-related studies

- The *Climate Change in Colorado Report* (see Chapter 2) considers the effects of climate warming on evapotranspiration.

- The *Colorado River Water Availability Study* (CWCB 2012) assessed possible future water demands along the Colorado River to determine water available for development within Colorado.

- USBR's *Colorado River Basin Study* assessed future demands on the entire Colorado River system (U.S. Bureau of Reclamation 2012).

Long-term planning

- The Statewide Water Supply Initiative (CWCB 2011) provides a comprehensive assessment of Colorado's water supply needs.

- The State Water Plan is also intended to provide guidance on meeting future water needs.

- The State Drought Mitigation Plan lays out a response plan in case of insufficient water to meet demands.

Monitoring and decision support tools

- In addition to the drought monitoring tools described above, the Vegetation Drought Response Index operated by the U.S. Geological Survey provides information about vegetation water stress and crop water needs.

Legal, regulatory, and other institutional efforts

- The Basin Roundtables and the IBCC process provide mechanisms for understanding and coordinating water demand in specific basins and across the state.

- The Water Conservation Act of 1991 (§C.R.S. 37-60-126) requires certain water supply entities to develop water conservation plans.

WATER QUALITY

Physical adaptations

- Streambank restoration efforts can reduce sediment loads and water temperature and increase assimilative capacity.

- Watershed planning and source protection efforts, such as the Forests to Faucets Partnership between Denver Water and the U.S. Forest Service, can help mitigate some of the climate-related impacts of fire and other disturbances.

Legal, regulatory, and other institutional efforts

- Water quality regulations are generally set at the federal level; federal agencies like the EPA will determine how much climate change can be integrated into water quality planning (Klein et al. 2011).

FLOOD MITIGATION

Physical adaptations

- Communities across the state have built a wide variety of flood prevention structures, such as Chatfield Dam south of Denver.
- Flood warning systems exist in some communities.
- Existing land use requirements for floodplains and floodways, especially reductions in structures in floodplains and implementation of freeboard requirements.

Long-term planning

- CWCB is responsible for the Flood Mitigation Plan, most recently updated in 2013 (CWCB 2013b).
- Coordination of federal, state, and local flood-related resources is accomplished through the Colorado Flood Task Force.
- The state also disseminates flood-related information, documents flood damages and flooded areas, maps flood-prone boundaries, and provides technical guidance and financial support to communities as needed.
- Some communities have flood management programs that include measures such as floodplains mapping, regulation of floodplain development, reduction of flood hazards, and helping residents prepare for emergencies.

Legal, regulatory, and other institutional efforts

- The Federal Emergency Management Agency administers the National Flood Insurance Program, aimed at reducing overall losses during flood events.
- CWCB develops and implements floodplain rules and regulations aimed at improved public safety and reduced flood losses.

NONCONSUMPTIVE USE

Legal, regulatory, and other institutional efforts

- A short-term water leasing statute (§C.R.S. 37-83-105) was passed in 2003 to permit the CWCB to lease water on short notice for the instream flow program.
- Additional capacity to adapt to water shortages for aquatic habitat includes the ability to create additional water storage under the Upper Colorado River Endangered Fish Recovery Program, which can to respond to shortages in times of drought (McNeeley 2014).

Considerations of Vulnerability in Existing Reports and Plans

A number of reports and studies have already investigated aspects of vulnerability to climate variability and change in Colorado's water sector. Below we review those briefly and then provide a table summarizing potential vulnerabilities within each of the elements of the water sector.

Colorado Drought Mitigation and Response Plan

CWCB's updated *State Drought Mitigation and Response Plan* (CWCB 2013a) assessed vulnerabilities to drought in Colorado. The analyses conducted for the plan showed that agriculture, certain recreation industries, some M&I providers, and the environment are generally most vulnerable to drought. Key vulnerabilities identified for agriculture include dryland crop loss from lack of precipitation, irrigated crop loss from inadequate irrigation water, limited forage, limited pasture and feed hay production, and an increase in the price of corn feed crop (CWCB 2013a). In some areas, groundwater can provide supplemental irrigation water if surface supplies are insufficient during drought, but lack of precipitation causes aquifer drawdown (CWCB 2013a). However, increasing competition from other sectors experiencing increased demand resulting from Colorado's population growth will place additional stress on the agriculture sector's water resources to meet these demands (CWCB 2013a).

The Drought Plan noted that an individual M&I provider's vulnerability to drought depends on multiple factors including junior water rights, lack of storage, and a water source in a single watershed (CWCB 2013a). The groundwater supplies currently relied upon by south Metro region M&I providers, for example, are less vulnerable to drought than surface water, but their depletion is unsustainable in the long term. As these providers increasingly switch to surface water supplies, they will become more vulnerable to climate impacts (CWCB 2013a).

The Drought Plan also identified a potential vulnerability related to the difficulty of meeting compact obligations in a warmer future. For example, a Colorado River Compact call could result in the curtailment of supply to many water users (CWCB 2013a). This finding is in line with the *Colorado River Water Availability Study*, which recognized significant uncertainties and unanswered legal questions regarding climate change and the Colorado River Compact, concluding that it was "not appropriate to finalize quantification of the effect of Compact constraints on water availability to water rights in Colorado through this study at this time" (CWCB 2012, p. 2-13).

Finally, the Drought Plan developed a set of indicators of drought vulnerability for environmental water availability that included impaired streams and water bodies, extent of beetle-affected forest, amount of wildfire threat acreage, and riparian habitat (CWCB 2013a). Using these indicators, Larimer, Weld, Las Animas, Garfield, Mesa and Moffat counties appeared to be the most vulnerable, indicating the highest potential for loss of ecosystem services during drought (CWCB 2013a).

Colorado Flood Hazard Mitigation Plan

Colorado's recently updated Flood Hazard Mitigation Plan assessed vulnerability to flooding at the county level by looking at previous flood events and impacts, population and area affected by flooding, potential total building loss, potential percent building loss, potential per capita loss, and exposure of state assets (CWCB 2013b). Using these factors, vulnerability to total direct economic building loss was highest in Denver, Arapahoe, Boulder, Larimer, Adams, El Paso, Pueblo, Jefferson, Weld, and Eagle counties. Percent building loss was highest in Prowers, Phillips, Morgan, Crowley, Eagle, Moffat, Clear Creek, Cheyenne, and Mineral counties. Arapahoe, Adams, Boulder, Denver, Weld, Larimer, El Paso, Jefferson, and Prowers counties face the highest risk of displaced population because they contain the major population centers. Highest per capita loss vulnerability was found in Prowers, Phillips, Mineral, Eagle, Hinsdale, Summit, Clear Creek, Pitkin, Morgan, and Moffat counties. Using the number of National Flood Insurance Program (NFIP) claims since 1978 through August 2013 as a metric, the Denver Metro, Fort Collins and Colorado Springs areas are the most vulnerable to flood-related losses, partly due to the value of structures there. Future flood vulnerability could be exacerbated by rapid growth, more development of the floodplain, greater numbers of vulnerable populations, and failure to participate in the NFIP (CWCB 2013b).

City of Boulder Climate Change Vulnerability Analysis

Among M&I providers, vulnerability to climate change-induced alterations in the timing and volume of runoff will be determined by specific characteristics of each utility and its supply sources. Among those that have already assessed their own vulnerability is the City of Boulder, whose 2009 climate change vulnerability analysis pointed to the potential for some M&I providers with reservoir storage (such as Boulder) to benefit from earlier runoff since they could fill their reservoirs before downstream irrigators with senior rights need to use the flows for summer crops (Smith et al. 2009). That study concluded that M&I providers in general might be less vulnerable to changes to hydrology than other users because of their years of experience coping with variability and uncertainty in water supply, well-established conservation plans, a citizenry that is accustomed to reducing water use during drought, and reservoir storage (Smith et al. 2009).

Vulnerabilities identified in other studies

Other potential vulnerabilities identified in more general studies of climate-related vulnerabilities include:

- Vulnerability of water rights due to changes in melt timing. Kenney et al. (2008) found that earlier snowmelt could lead to mismatches between dates of water rights and hydrographs. Although such problems were rare as of the writing of that paper, water rights could face future vulnerabilities to continued advances in snowmelt timing.

- Vulnerability of water supplies due to requirements for environmental flows under the Endangered Species Act (ESA) (Klein et al. 2011). The ESA can directly conflict with interstate water compacts and state prior appropriation water laws (Loomis and Ballweber 2012).

- Vulnerability of tribal populations. Across the American Southwest, tribes have greater vulnerability to climate change than most groups (Redsteer et al. 2013), although specific vulnerabilities may depend on the context of each individual tribe. Tribal cultural ties to specific lands or water resources can lead to greater vulnerabilities.

Key Vulnerabilities

Table 5.1 summarizes the key impacts outlined in Section II and describes key potential vulnerabilities to those impacts.

IV. Moving Toward Preparedness

Existing Preparedness Efforts

More effort has been expended to study and plan for the effects of climate variability and climate change in the water sector than any other sector, commensurate with the far-reaching importance of water to Colorado's economy. Collectively, this work provides a valuable foundation for further efforts.

As mentioned in the previous section, a significant amount of climate-change related analysis has already been conducted for Colorado's water resources. The state and some larger water supply providers have engaged in long-term planning efforts like the Statewide Water Supply Initiative (CWCB 2011). On the other hand, many other entities critical to water supply across the state, such as small municipal utilities and ditch companies, have very little capacity to conduct climate vulnerability analysis or long-term planning. The *Boulder County Climate Change Preparedness Plan* (Vogel et al. 2012) found such a disparity among water providers in that county.

Developing a Formal Climate Change Vulnerability Assessment

A key next step in preparedness planning for the water sector would be to build on the state drought vulnerability assessment with a formal, water-specific climate change vulnerability assessment for surface and groundwater supplies. Such an assessment could provide a concrete picture of what aspects of Colorado's water sector and what portions of the state would most benefit from climate preparedness efforts. There are several examples of vulnerability assessment methodologies that could inform this process, including Colorado's own drought vulnerability assessment (CWCB 2013a), the *Climate Change Handbook for Regional Water Planning* (U.S. EPA and CDWR 2011), and *Preparing for Climate Change: A Guidebook for Local, Regional and State Governments* (CSES 2007).

Recommendations from the Colorado Climate Preparedness Project

Additional preparedness and adaptation activities for the water sector were identified in the *Colorado Climate Preparedness Project* (Klein et al. 2011), many of which are still relevant and appropriate today:

Coordinating and leveraging activities across federal, state, and local government along with private sector entities

Coordinating across all levels of government and the private sector will be useful in enlarging the range of preparedness and adaptation options by gleaning lessons from other programs, enriching planning with local and regional conditions, and providing technical support.

Colorado has already optimized opportunities to use existing federal partnerships and resources to prepare for and mitigate impacts from extreme weather events and climate change. For example, the state developed a

Observed or Projected Physical Impacts of Climate	Key Potential Vulnerabilities
Water Supply	
Earlier snowmelt timing and runoff	Water supply entities with inadequate storage, especially agricultural water supplies and small M&I utilities
Potential reduction in average streamflow	Vulnerability to low flows could be high for those entities with junior rights or little storage
Longer and more intense droughts, especially megadroughts	Virtually all water supply entities and their customers
Potential reduction in groundwater recharge	Water supply entities in areas like the San Luis Valley or South Metro that rely heavily on groundwater to supplement surface water supplies. Private homes and small community water supplies that rely on groundwater, especially those with no backup supply
Impacts of extreme events and increased wildfire risk	Elements of water supply infrastructure such as older dams, ditches, and canals; reservoirs in areas with high potential for wildfire
Water Demand	
Earlier snowmelt timing and lower late summer flows	Agriculture producers needing late summer irrigation and some M&I utilities with junior rights
Interaction of heat and lower flows with existing demand trends	Those with junior rights facing greater competition among multiple sectors
Water Quality	
Lower flows and higher water temperatures resulting in greater concentrations of pollutants	M&I utilities with older treatment technology or lower treatment capacity; aquatic organisms and ecosystems
Greater likelihood of wildfire leading to higher chances of erosion	Water treatment facilities in fire-prone areas
Flood Mitigation	
Continued high risk of extreme precipitation events	Large portions of the state that exist in areas of high flood risk and have engaged in little mitigation
Nonconsumptive Uses	
Earlier snowmelt timing and runoff	Earlier and faster runoff may reduce flows appropriate for rafting, fishing, and other recreation activities
Potentially reduced average streamflow	Endangered fish recovery programs

Table 5.1. Climate impacts and key potential vulnerabilities.

partnership with NOAA's National Integrated Drought Information System (NIDIS) to build a drought early warning system in the Upper Colorado River Basin. More recently, Colorado is participating as a partner in the proposed Western Watershed Enhancement Partnership, which would bring together federal resources to mitigate wildfire risks that could harm major water supply resources. The first pilot for this partnership will take place in the Upper Colorado and Big Thompson headwaters (USDA 2013).

Informing the planning process

Given the importance of monitoring changes in the current climate, continued funding of existing data monitoring stations and installation of stations in areas identified as critical would greatly assist planning and response efforts. Monitoring would support efforts to understand future water demand trends and how those trends might be impacted by climate variability and change. Planning in the water sector would also benefit from funding of process-level hydrology studies that include groundwater-surface water models.

Changes in runoff timing and amounts, along with the possibility of future megadroughts (such as the drought of the 1100s as shown in Figure 5.1), have the potential to complicate Colorado's interstate compact obligations as well as in-state water rights administration. To prepare for these contingencies, Colorado could continue to support analysis, research, and modeling to better understand the effects of climate change impacts on interstate compact compliance.

Finally, while the state has begun to incorporate climate change considerations into SWSI and other planning processes, not all water supply entities have done so or even have the capacity to do so. Giving water providers the ability to understand how to directly integrate climate change questions into planning can help improve preparedness. The *Boulder County Climate Change Preparedness Plan* (Vogel et al. 2012) recommends integrating climate change considerations into all planning processes and setting up a mechanism for information sharing to benefit smaller entities.

Stakeholder and public outreach

The state can continue to use the Interbasin Compact Committee and Basin Roundtables to engage the stakeholder communities and the public in the state's water planning activities. The state has invested many resources in this successful public engagement process and is already using the process to begin the discussion of climate change preparedness. Continued education of policymakers, water managers and the public on the impacts of climate change and the state of preparedness planning science can help make the idea of adaptation to climate change more politically palatable. The current State Water Plan process provides an ideal mechanism for this engagement.

Regulatory and policy options

It would be useful for the state to continue to monitor the interplay between federal laws and state water rights as climate change unfolds and as new or modified legislation is proposed. In particular, future modifications to federal legislation such as the Clean Water Act and U.S. Army Corps of Engineers regulations might be modified to include use of model projections for drought and flood planning.

V. Future Research Needs

Additional research could facilitate the climate change preparedness planning process in order to improve adaptive capacity and reduce vulnerability across the state. Table 5.2 provides a list, organized by water sector element, provides suggested areas where additional research could be helpful.

Water Sector Element	Suggested Research Areas
Water supply	• Impacts of bark beetle infestations on water supply • Impacts of wildfire on water storage and conveyance infrastructure • Impacts of earlier runoff on water rights administration and interstate compacts • Impacts of dust on snow events on timing and supply in a warming climate • Probability of future megadroughts occurring as seen in tree ring records • Impact of low flows on Endangered Species Act requirements and resulting impacts to water supplies
Water demand	• Predictability of evapotranspiration and vegetative water demand at seasonal scales and in climate projections • Influence of socioeconomic factors and climate warming on changes in future water use by various sectors
Water quality	• Impacts of fire on water quality • Impact of 2050 predicted warming on current water and wastewater treatment infrastructure and processes • Predictability of future fire risk; evaluation of fire mitigation activities for protecting water supplies • Connections between bark beetle infestations and water quality
Flood mitigation	• Assessment of performance of flood mitigation structures and plans during the September 2013 Front Range flooding • Identification of vulnerable areas that lack flood mitigation and warning strategies
Nonconsumptive uses	• Effectiveness of measures to improve fish recovery and population sustainability under future climate warming • Adaptability of recreation sector to earlier runoff timing and lower average flows

Table 5.2. Future research needs.

Box 5-1
San Luis Valley Regional Highlight: Growing Concerns about Groundwater Depletion

The San Luis Valley in south-central Colorado receives an annual average of only 7.5 inches of precipitation on the valley floor, making it one of the largest high desert valleys in the world. The northern end of the valley is an enclosed basin where water does not leave, while the southern end of the basin forms the headwaters of the Rio Grande River (Emery undated).

Water is critical here to support agriculture, the primary economic driver in the region (SLVDR undated). Much of the Valley's agriculture depends on groundwater supplies that irrigate over 600,000 acres of agricultural land (CWCB 2011, P. 1-15). Groundwater from the region's unconfined aquifer is being depleted rapidly due to over pumping and drought (see Figure 5.6); since 2002 the aquifer level has dropped nearly 800,000 acre-feet (Heide undated). These supply concerns have led to some dramatic adaptations—at least 60,000 acres are expected to be fallowed under a program to voluntarily reduce pumping (SLVDR undated).

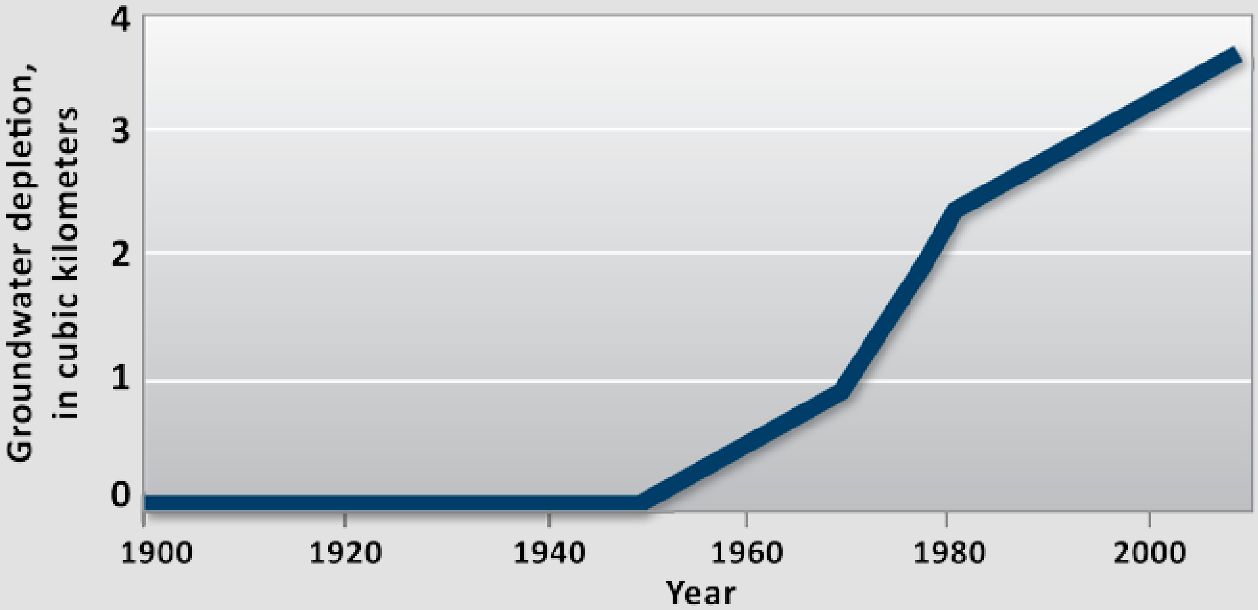

Figure 5.6. Cumulative groundwater depletion, San Luis Valley, 1900-2008 (Konikow 2013).

If climate change results in decreased future streamflows in the Rio Grande headwaters, the Valley region may become even more dependent on groundwater, accelerating groundwater depletion rates. In addition, higher temperatures during the growing season could increase water requirements for irrigation. Some are already predicting that agricultural users will eventually find it more advantageous to sell their water to the Front Range's growing cities than to grow alfalfa. As the climate warms, this regions dependence on groundwater supplies may become an increasing vulnerability (Heide undated).

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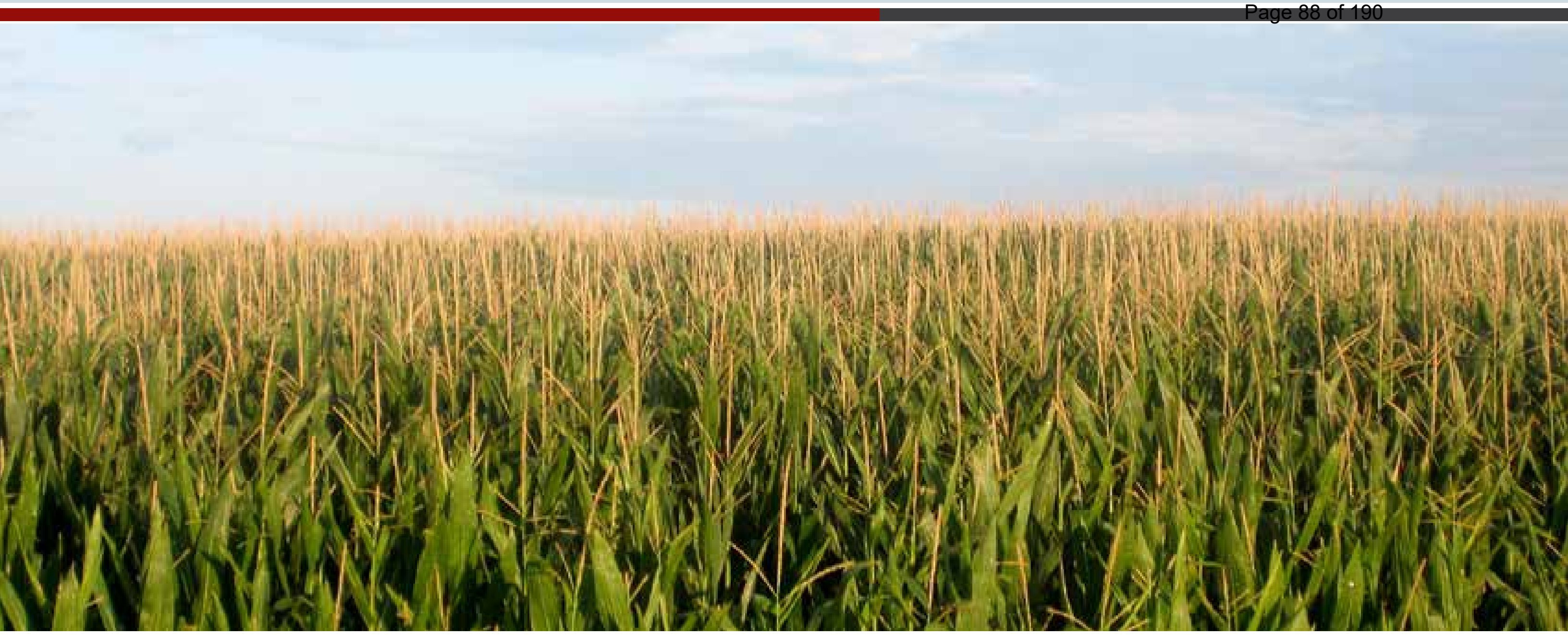

Cornfields in Prowers County, Colorado. Photo: Wikimedia Commons, Billy Hathorn.

CHAPTER 6
AGRICULTURE SECTOR

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I. Background

Agriculture is a key element of Colorado's culture and economy. A $24 billion industry (Davies et al. 2012), Colorado's agricultural sector provides food supplies while contributing to the state's economic vitality. In 2012, Colorado agricultural products totaled $8.2 billion in sales, including $2 billion in international exports, with net farm and ranch income of $1.7 billion distributed over 36,700 operations.

However, agriculture in the state faces a number of climate impacts. In 2013 alone, Colorado Agriculture Commissioner John Salazar noted, "Colorado agriculture faced many weather challenges," including early drought, significant frost damage to West Slope peach crops, a costly hail outbreak in northern Colorado during August, and record rains and flooding along the Front Range in September that caused millions of dollars of damage to crops, fields, livestock facilities, irrigation infrastructure, and farm and ranch buildings (Salazar 2014). Severe weather was a factor in reducing net farm income below expectations, to $1.58 billion in 2013.

Previous climate impact assessments have concluded that modern agriculture, as practiced across Colorado, is sensitive to weather and climate impacts. On the other hand, those same assessments describe the sector as very adaptable, a trait that helps agricultural producers deal not only with weather and climate, but also market swings, technological innovations, and changes in the social and policy context of their industry. Evaluating this sector's vulnerabilities in the context of projected climate change is important not only for maintaining the value of this industry but also for assisting informed decision making regarding the future of Colorado agriculture.

We organize this chapter around four key elements of agriculture in Colorado:

- field crops
- fruit and vegetable production
- livestock
- the green industry (e.g. ornamental horticulture sectors of the agricultural and service industries)

Figure 6.1 demonstrates the relative value of each of these elements in terms of 2012 cash receipts.

Geographically, most farming activities—especially field crops and livestock—occur in the eastern portions of the state, which happen to be the westernmost portions of the Great Plains (USDA National Agricultural Statistics Service 2007; Colorado Water Conservation Board 2013). Much of Colorado's green industry lies along the Front Range corridor, while a diverse patchwork of agricultural activity can be found in the western part of the state. Potatoes, Colorado's largest vegetable crop by value, are grown in the San Luis Valley, while the Grand Valley features numerous fruit orchards. The most extensive agricultural activity on the western slope is range livestock on both private and public lands. Figure 6.2 shows major crops grown in farming regions across the state.

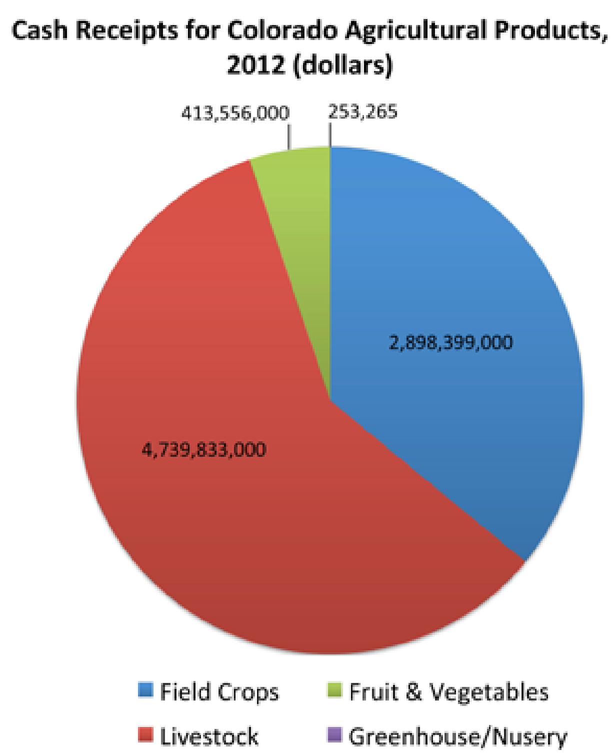

Figure 6.1. Cash receipts for the major elements of Colorado's agriculture sector, demonstrating the relatively high value of livestock and field crops. Data from the Colorado Department of Agriculture and the National Agricultural Statistical Service.

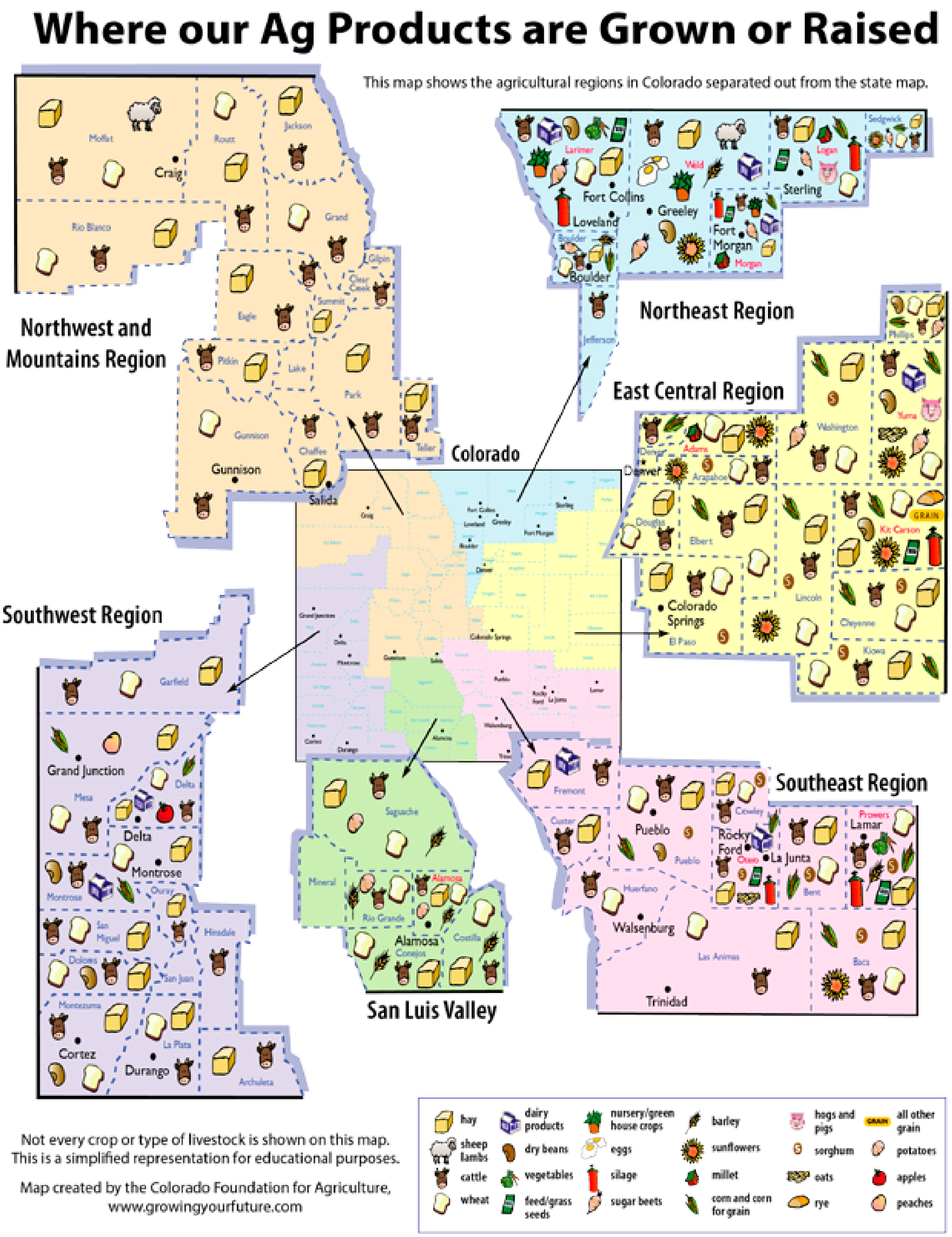

Figure 6.2. Colorado's climatic and topographic diversity provide a variety of agricultural opportunities across the state (Colorado Foundation for Agriculture).

In terms of cash receipts (see Figure 6.1), livestock products are the biggest element of Colorado's agricultural sector, with large feeding operations in the eastern portions of the state and grazing across the high plains, the intermountain valleys, and the West Slope producing some $4.2 billion in sales. Crops brought in another $2.9 billion (USDA National Agricultural Statistics Service 2007; 2013).

Regulations and policies related to agriculture in the state derive primarily from the U.S. Department of Agriculture, including major crop support and insurance programs. The Colorado Department of Agriculture plays a supporting role through marketing, data collection, and programs such as soil conservation. A number of agencies at the state and federal level have authority over other issues relevant to agriculture, such as water supply (Colorado Water Conservation Board, U.S. Bureau of Reclamation, and others), water quality (Colorado Department of Health and the Environment and Environmental Protection Agency), and endangered species (U.S. Fish and Wildlife Service and Colorado Division of Parks and Wildlife).

II. Key Climate Change Impacts

Virtually every aspect of the agriculture sector is highly sensitive to climate conditions, and a changing climate may have both positive and negative effects. For example, some researchers have suggested that increases in temperature and carbon dioxide (CO_2) may be beneficial for crops in certain regions. To realize these benefits, however, critical other elements such as nutrient levels, soil moisture, water availability, and other conditions must also be present. Agriculture in Colorado is vulnerable to some of the predicted impacts of climate change, including less reliable water supplies, increased temperatures, and increased pests (Colorado Water Conservation Board 2013). Changes in the frequency and severity of droughts, precipitation, and floods could also pose new challenges for farmers, ranchers and land managers. Overall, the effects of climate change need to be considered in conjunction with other evolving factors that affect agricultural production, such as changes in farming practices and technology and the evolution of various support systems like research, government policy, extension, insurance, and other factors (Leary et al. 2006; Bryan et al. 2009). For example, volatility in local, national and international agricultural markets and the cost of energy, fertilizers, and other inputs tend to be major sources of concern among producers of agricultural goods (Jackson et al. 2012a, 2012b).

In addition to their sensitivities to the physical impacts of climate variability and change, agricultural activities are a significant source of greenhouse gases (GHGs) that contribute to warming of the planet. The levels of GHGs emitted from a given agricultural operation are closely linked to production systems and management. Thus consideration of climate change in agriculture encompasses both adapting to impacts of climate as well as understanding the effects of greenhouse gas mitigation opportunities could present opportunities or challenges for the sector. To date, agriculture sector options for reducing GHGs include efforts to reduce emissions of nitrous oxide, coordinated regulation of confined feeding operations, and the development of a host of agriculturally related offset protocols (Jackson et al. 2012b).

Impacts on Field Crops

As described in Chapter 2, Colorado has seen steady increases in average temperatures and is projected to continue to warm by mid-century, with more warming in summer than in winter. Climate models currently project no clear trend in precipitation other than continued inter-seasonal and interannual variability. Rising summer temperatures, however, would result in greater frequency and severity of drought, and may lead to reduced streamflow as evaporation rates rise. There is no evidence yet that summertime thunderstorms would change in frequency or severity.

Changes in these variables are likely to have significant impacts on crop yields. Shifts in seasonal patterns, especially in the spring and fall, can impact crop productivity across the state. Increased temperatures may make many crops grow more quickly, but warming could also reduce yields in other crops. For any particular crop, the specific effects of increased temperatures will depend on the crop's optimal temperature for growth, pollination, and seed set. Many crops show threshold effects–if warming exceeds a crop's optimum temperature, yields can decline (Karl et al. 2009; U.S. EPA 2013). Research on some crops important to Colorado indicates reduced overall yields under many climate change scenarios. Dryland crops in particular, especially wheat (Figure 6.3), show declining yields under many climate change scenarios due directly to heat and water stress (Ko et al. 2012). However, irrigated crops such as corn appear to be sensitive to increased heat even when sufficient irrigation water is applied (Islam et al. 2012).

Rising temperatures are expected to increase water needs for many crops (Udall 2013). Regardless of changes in precipitation, warmer temperatures during the growing season will increase evaporative demand, which raises evapotranspiration rates. In addition, water is often used to cool the ambient temperature to reduce the direct effects of heat on crop yields (Karl et al. 2009).

Figure 6.3. Rising temperatures and increased water stress due to climate warming may result in reductions in future wheat yields in Colorado (Photo: iStock, JuliScalzi).

Some studies indicate that higher CO_2 levels can offset some direct climate effects and even increase yields for some crops. Wheat, for example, could see increased yields of 30 percent or more under a doubling of CO_2 concentrations (U.S. Climate Change Science Program 2008; Karl et al. 2009; Hatfield et al. 2011), although those increases could be offset by increased moisture and heat stress. The yields for other crops, such as corn, exhibit a much smaller response (less than 10 percent increases). However, it is most likely that other factors will counteract these potential increases in yield. For example, if growing season temperatures rise, plant water requirements increase and yields may decrease.

Extreme temperatures and severe weather can also prevent crops from achieving optimal growth. Floods and droughts can damage crops, fields, and equipment. For example, the 2012 Colorado drought caused an estimated loss of $726 million in the agriculture sector alone (Pritchett et al. 2013). Dealing with drought will become a greater challenge as rising summer temperatures are expected to increase the frequency and severity of droughts in the future (see Chapter 2).

As of 2011, Colorado is the fourth largest producer of winter wheat in the country. The majority of the state's wheat is produced under dryland conditions (no irrigation) in a semi-arid environment characterized by hot summer days with high sunlight intensity, a summer rainfall pattern, and cold, dry winters (Farahani et al. 1998). Wheat producers in eastern Colorado have adapted cropping practices to limited rainfall and to recurring periods of drought, primarily by using a traditional winter wheat-summer fallow crop rotation. The 10-month wheat growth period (September to July) avoids summer heat and drought and is followed by a 14-month fallow period used to store water for the subsequent crop. Although producing one crop every two years is an adaptation that stabilizes production under the extreme climate conditions of the plains, summer fallowing has major limitations for long-term sustainability. Frequent tillage and low productivity of the wheat-summer fallow system has resulted in soil degradation and loss of organic matter on millions of acres (Westfall et al. 2010).

Impacts on Fruits and Vegetables

The production of fruit and vegetables is highly sensitive to seasonal shifts in temperature and precipitation extremes. Early spring thaws resulting in bud burst followed by subsequent freezes negatively impact fruit and vegetable production. Moreover, fruit and vegetable producers in Colorado are highly dependent on the availability of water resources. Crop damage due to drought conditions resulted in one of the largest record insurance payouts in 2012 and increased overall from 2000 through 2012 (USDA Risk Management Agency 2013). On the other hand, some growers such as fruit orchards on the West Slope might benefit from an expected reduction in frost hazards as the climate warms.

Figure 6.4. Colorado is the nation's fifth-largest potato growing state, with significant crops on the northeast plains and in the San Luis Valley (pictured) (Photo: iStock, chapin31).

Potatoes (Figure 6.4), grown primarily in the San Luis Valley, are Colorado's largest vegetable crop by volume and sales. Colorado's potato industry includes the summer potato harvest and a fall crop, which together make Colorado the fifth largest potato growing state in the nation. Key to Colorado's potato industry is seed potato production in the San Luis Valley. Future changes to streamflow and annual aquifer recharge in the San Luis Valley would likely affect the viability of potato production in Colorado. As discussed in Chapter 2, absent a significant increase in future precipitation, streamflows are likely to decline on average and occur earlier in the year.

Beans, onions, carrots, cabbage, cantaloupes, and sweet corn round out Colorado's vegetable crop production, totaling some $450 million in sales. Little research is available yet on the climate sensitivities of such crops, but concerns include severe weather, heat stress, irrigation water shortages, and pests. Because vegetable production in Colorado is limited by growing season and cold temperatures, especially at higher elevations, there is some opportunity for improved production in a warmer climate.

Impacts on Livestock

The livestock most commonly produced in Colorado is cattle (Figure 6.5) for both beef and dairy, accounting for over $3 billion in sales. Colorado is also the leading U.S. state in production of sheep and lamb, which brought in $112 million in sales in 2010 (the last year with data), plus $3.7 million in wool production. These valuable livestock operations could face a number of negative climate impacts. Heat waves, which are projected to increase under climate change, could directly threaten livestock, reducing weight gain and sometimes causing fatal stress. Heat stress affects animals both directly and indirectly; it can increase an animal's vulnerability to disease, reduce fertility, and reduce milk production in dairy animals. Climate change may also affect

Figure 6.5. Cattle account for over $3 billion in annual sales in Colorado but can suffer from reduced weight gain or fatal heat stress due to extreme high temperatures (Photo: Creative Commons, Jeremiah/Reagan Kemper).

native range forage, pasture productivity, and feed supplies (Joyce et al. 2013; Polley et al. 2013). Drought reduces the amount of quality forage available to grazing livestock, and prolonged drought can permanently degrade rangelands. Some areas could experience longer, more intense droughts resulting from higher summer temperatures and reduced precipitation. For animals that are "finished" on grain (typically in feeding facilities) reductions in crop production due to drought could also raise prices. Grain stocks fed to animals may be somewhat buffered to local climate changes since Colorado imports a high percentage of grain that is used in the feed industry, but experience with drought-inflated hay prices across the U.S. in 2002 and 2012 suggest some vulnerability even to drought occurring in other parts of the country. Intense and/or enduring drought leads to livestock herd reductions, which temporarily reduces prices and negatively affects producers' genetic investment in their herd. It may require many years to rebuild a herd's genetic capabilities after drought conditions subside (Joyce et al. 2013).

Recent research has found that declines in milk production due to climate change will vary across the U.S. due to differences in humidity (Aggarwal and Upadhyay 2013). For example, high humidity and hot nights make the southeastern U.S. the most "unfriendly" place in the country for dairy cows. Scientists and the dairy industry have long known about and studied the impact of heat stress on cows' milk production. Dairy farmers are already clustering their operations in the most comfortable areas for cows. Indeed, many of the same factors that have made Colorado a favorable location for cattle feeding operations have also made it favorable for dairy production. These include an arid and relatively cool climate favorable for maintaining animal health and environmental standards along with proximity to markets and market infrastructure. However, the intensive management of these operations will stress water availability and quality. In addition, climate change may increase the prevalence of parasites and diseases that affect livestock (i.e., the earlier onset of spring and warmer winters could allow some parasites and pathogens to survive more easily).

Impacts on the Green Industry

Often overlooked when considering traditional agriculture, the green industry includes plants raised for residential, recreational, and commercial landscaping, gardening, or for indoor ornamental use. The industry accounted for $253 million in sales during 2012. Common species grown in greenhouses and nurseries include trees, shrubs, flowers, groundcover, and turf for landscaping, as well as indoor and outdoor potted plants for gardening and ornamental uses. Greenhouse and nursery crops are considered high value crops. As such, they do not typically require significant land, but can be fairly intensive in their requirements of water, fertilizer, and pesticides.

The green industry is sensitive to climate in several ways. First, demand for its products varies with climate and can be affect by water supply variation. The industry's production facilities are susceptible to flood, wind, and hail damage. Finally, the green industry's production could be vulnerable to water availability and water restrictions imposed by local governments during periods of drought. However, the high value of these crops relative to field crops and livestock may enable producers to pay a premium for water, and thus buffer against some of the effects of climate change.

III. Key Vulnerabilities and Adaptability in Agriculture

The dangers that climate poses to agriculture—and, correspondingly, the threat our current approach to agriculture poses to potential regional climate patterns—have been recognized and quantified (U.S. Climate Change Science Program 2008). The Intergovernmental Panel on Climate Change (IPCC) concluded in its recently released Fifth Assessment Report (IPCC Working Group II 2014a) that global warming by the middle of this century will have reduced most crop yields by an average of 2 percent per decade below the trend defined by technology and other factors (p. 25). Yields may increase in some areas, and some crops, especially in the mid and high latitudes, may fare better than low-latitude crops. Yet demand for crops will have grown 14 percent per decade by 2050, and thus food security overall may decline. Global agriculture is thus challenged to adapt both to growing global demands for products and to an uncertain future climate. Unfortunately, we do not have a recent, detailed assessment for agriculture in Colorado, although the IPCC assessment for North America indicates that agriculture across the continent will experience mixed impacts from climate change and is capable of adapting to offset those impacts, especially up to about the equivalent of 2 degrees Celsius warming (IPCC Working Group II 2014b). Still, a rough assessment of the state's agricultural vulnerabilities and adaptability can be offered, and the prospects for adaptation here are generally strong, given proper market, technology, and policy conditions.

Adaptive Capacity for Crops (Moderate)

Major efforts have been made to link climate change models with crop models to predict climate change effects on cropping systems and to explore adaptation approaches (Easterling et al. 1996; Brown and Rosenberg 1999; Guerena et al. 2001; Mearns et al. 2001; Izaurralde et al. 2003; Thomson et al. 2005; Lobell et al. 2006; Geogescu et al. 2011). Adaptation can be incremental, including changes in seeding time and rate, fertilizer and pesticide application, and continue breeding of climate tolerant varieties. For example, wheat varieties are more drought-tolerant than they were in the intense droughts of the 1930s and 1950s. Winter wheat has also been made less susceptible to winter kill. Yet drought tolerance does not always appeal to farmers wishing to maximize yields in normal to wet years, so yields do still vary with the climate from year to year. Social adaptations include disaster support, crop insurance, and rural development assistance that help to sustain rural economies even when, as in 2013, weather and climate affects production and income.

Adaptive Capacity for Farming Systems and Livestock (High)

The largest volume and value of crop production in Colorado is comprised of crops intended primarily for consumption by livestock. This includes grains such as corn, sorghum, millet, barley, oats, and rye as well as silage (mostly from varieties of corn and sorghum), along with grass and alfalfa hay. Thus adaptation in the crop sector is also important to livestock production.

Given that average temperatures are projected to increase across Colorado (see Chapter 2), heat stress on livestock could increase and water demand to maintain the livestock may also increase. The animals most at risk may be those associated with confined animal feedlot operations. These systems tend to have higher density of animals and reduced capacity for maintaining cool nighttime temperatures.

Adaptive Capacity for Water Use (High)

Agriculture is the largest user of water in the state (Figure 6.6). If competition for water increases under climate change, then increased vulnerability in various sectors of agriculture may occur. Agricultural water is more subject to "buy and dry" as other sectors lease or purchase water from farms to make up for decreased supplies and increased demands from warmer temperatures, drought, and population growth. New technologies and processes provide opportunities for optimizing agriculture's water footprint, including the monitoring of water use and improved crop varieties that are more drought resistant. Perhaps more importantly, additional efficiency in water use involves tradeoffs–conserving water might mean reducing profits, altering return flows to riparian areas, and changing the recharge rates of alluvial aquifers.

Figure 6.6. Agriculture is the dominant water user in Colorado and faces climate vulnerabilities due to increased water stress in a warming future (Photo: iStock, jonmullen).

Water quality in general is also likely to worsen under warmer and drier conditions. Soil salinity, nitrate concentrations, and increased chemical concentrations in agricultural runoff would be exacerbated by rising temperatures and decreasing streamflow levels. Intensification of rainfall will not alleviate these problems, but may impact facilities holding agricultural waste around animal feedlots.

For more on the effects of climate change on water supplies in Colorado, see Chapter 4.

Potential in Agriculture for Mitigating GHG Emissions

Creating sustainable agricultural systems can help reduce agricultural GHG emissions through energy conservation, lower levels of carbon-based inputs, lower use of fertilizer and other features that minimize GHG emissions. Agricultural land can also serve as a sink for GHG emissions, especially through soil carbon sequestration, which could help moderate climate change. However, agricultural land can serve as an effective GHG sink over the long term only if agricultural systems are adopted to improve overall soil quality and provide for relatively stable GHG reduction or sequestration that can be verified and measured with reasonable accuracy. Agricultural crop and forage production systems intended to sequester carbon also need to be assessed for the effects that changing soil carbon levels and other system features have on the potent GHGs nitrous oxide and methane. These system features include, among others, fertilizer use and efficiency, nitrogen sequestration, and overall GHG emissions of associated livestock production systems. Overall, though, there is reason to expect that sustainable systems not only reduce GHG emissions, but are less susceptible to impacts from weather and climate fluctuations.

Based on the adaptive capacity identified above and our expert analysis of potential climate impacts, we have summarized key

	Climate Impact	Key Vulnerabilities
Field Crops	• Rising temperatures	• Crop yields vulnerable to reductions due to heat stress
	• Increasing frequency and severity of drought	• More frequent losses of crops, forage, and soil
	• Earlier onset of spring; longer growing seasons	• Crops vulnerable to increased weeds and pests due to longer growing season
	• Potentially reduced streamflow	• Production losses due to irrigation shortages
	• Increased CO_2 levels	• Crops potentially affected by weeds encouraged by CO_2 fertilization
	• Extreme weather events	• Continued losses of crops, facilities (structures, ditches, equipment)
Fruits and Vegatables	• Earlier spring thaws	• Fruit crops vulnerable to frost damage worsened by early budburst
	• Increasing frequency and severity of drought	• Increased potential for water shortages occurring simultaneously with higher crop water demand
	• Reduction streamflow, especially in late summer	• Reduced production due to limited irrigation supply, increased water prices
Livestock	• More favorable conditions for pathogens	• Cattle vulnerable to lower weight gain and other health problems due to higher temperatures
	• Increasing temperatures	• Loss of weight and animal health in higher temperature; increased costs of facilities
Green Industry	• Extreme weather events	• Damage to facilities and products
	• Potential reduction in streamflow	• Loss of production due to water use restrictions

Table 6.1. Potential key vulnerabilities in Colorado's agriculture sector.

vulnerabilities in Colorado's agriculture sector in Table 6.1.

IV. Moving Toward Preparedness

The Colorado Climate Preparedness Report concluded that:

> The agricultural sector in Colorado, already accustomed to coping with weather and climate variability, and uncertain future markets, appears to have tremendous capacity to adapt to climate variability and change. However, this sector also faces challenges from changes in a key production input, water resources, and a key risk, extreme events. Moreover, the sector faces large uncertainties in how climate change will affect agricultural production and markets elsewhere. Finally, the sector faces uncertain future policy; for example, potential changes in crop support programs, and in critical conservation provisions of federal law such as the

Conservation Reserve Program (Klein et al. 2011, p. 67).

An important part of supporting adaptation and sustaining a healthy agricultural sector in a changing climate will be information on impacts, changing vulnerability, and adaptation. Current efforts to track the sector are helpful, and studies like the assessment of drought vulnerability by the CWCB (Colorado Water Conservation Board 2013) and agricultural reporting of the Colorado Department of Agriculture and the National Agricultural Statistics Service are vital to helping producers and policymakers respond to change. Efforts might be increased to track vulnerability, impacts, and adaptation as the climate changes. For example, some researchers have proposed that agricultural systems are well-tuned to climate and adaptive to change; however, given projections of climate changes, it would be useful to develop a set of observational and research activities to enhance the resilience of Colorado agriculture. Resilient agriculture systems are those that are more likely to maintain economic, ecological, and social benefits in the face of dramatic external changes such as climate change and price swings. In the face of uncertainty, food production systems should be established which are diverse and relatively flexible, with integration and coordination of livestock and crop production.

V. Future Research Needs

One option for addressing the preparedness concerns described above would be to develop a spatially explicit agricultural vulnerability index for Colorado derived from climate, crop, land use, and socioeconomic variables. The underlying factors contributing to vulnerability differ among these regions within the state, indicating that future studies and responses could benefit from adopting a contextualized "place-based" approach. As an example of this approach, a research team could conduct the following: (1) an econometric analysis of crop acreages under future climate change projections; (2) a hydrologic model of each major watershed that simulates the impact of future climate and crop acreage projections on local water supplies; (3) county-wide inventories of agricultural GHG emissions; (4) a survey of farmers' views on climate change, its impacts and what adaptation and mitigation strategies they might be inclined to adopt; and (5) an urban growth model that evaluates various future development scenarios and the impact on agricultural lands and GHG emissions. Such a study could be used to create on-farm case studies that highlight the possible benefits of innovative agricultural practices (for example, cover cropping, or no-till systems on carbon storage and renewable energy production from crop residues) that link adaptation and mitigation. Some of this research is underway, but better coordination could be marshaled in the face of climate change. Further education is necessary on topics such as deficit irrigation, grazing management, water banking, interruptible supply agreements, and even cryogenic embryo storage during drought.

Other research activities to be considered include:

- Studies on drought and heat resistant crop types
- Evaluation of crop diversity to enhance crop system resilience
- Water use improvement at the crop level, as well as at the agricultural system level
- Design of sustainable agricultural to include crop-livestock systems, particularly under dryland conditions.
- Evaluation of multiple stress impacts on the vulnerability of agricultural systems under different specific climate scenarios
- Long-term analysis of land and water quality under current and future climate projections

Box 6-1
Northwest Colorado Regional Highlight: Vulnerability of Ranching to Drought

Ranching (Figure 6.7) dominates regional agriculture in northwestern Colorado; livestock makes up almost 90% of the agricultural products sold in Moffat, Routt, and Rio Blanco counties (Gangwer 2011). This dependence on ranching creates significant climate exposure. Ranching is particularly sensitive to climate, as the health of grasslands is directly tied to the availability of precipitation (see Chapter 4). For farmers and ranchers in the region, drought can have a twofold impact—reduced forage quality along with decreased availability of grass and hay as feed for livestock (Gangwer 2011).

Although the primary impacts of drought on ranching include lower stream flows and decreased natural forage, secondary impacts can range from poor cattle health to the economic failure of family ranches. To avoid these secondary impacts, farmers and ranchers have developed adaptive capacity to cope with the primary impacts of drought in a number of ways. Some ranchers thin their herds by selling off livestock during times of drought (Gangwer 2011). This reduces the number of animals grazing on the land, which can compensate to some degree for lower productivity of grasslands that may be drought-stressed. Others may choose to purchase additional hay, although the cost of feed has risen considerably since the late 2000s. Still others may choose to haul in irrigation water.

These choices are not easy, however, especially when families must balance them in the context of maintaining the economic viability of continuing to keep working ranches in operation (Gangwer 2011). Climate model projections indicate that there is good reason to expect droughts to continue into the future and that streamflows may decline (see Chapter 2). These changes could increase climate vulnerability for ranching in northwestern Colorado. Although ranchers do have a great deal of adaptive capacity, reductions in irrigation water available to grow feed along with more intense droughts affecting range quality could make it very difficult to continue to operate economically viable ranches.

Figure 6.7. Cows grazing in northwestern Colorado. Ranching dominates regional agriculture in that corner of the state (Photo: Kristin Gangwer).

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President Barack Obama and Vice President Joe Biden speak with the CEO of Namaste Solar Electric, while looking at solar panels at the Denver Museum of Nature and Science in Denver. Photo: Official White House by Pete Souza.

CHAPTER 7
ENERGY SECTOR

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I. Brief Description of Sector

This analysis of climate vulnerabilities within the energy sector in Colorado covers energy *production*, which refers to the extraction or generation of various sources of energy used to power the economy; *conversion*, which refers to the generation of electricity from a variety of other energy sources; and *consumption*, which refers to the use of those and other sources in a variety of applications.

Colorado is a significant producer of fossil and renewable fuels. In 2011, U.S. Energy Information Administration data indicate that Colorado produced 26,890 short tons of coal, 1,637,576 million cubic feet of natural gas, 39,125,000 barrels of oil, and 3,057,000 barrels of ethanol. Colorado produces 3.5% of all energy in the United States, ranking 7th among the states. It is notably the 5th largest producing state for natural gas, the 9th largest in coal production, and the 10th largest in oil (EIA 2013a) while also having the 5th highest level of electricity generation from solar resources and the 9th highest from wind resources (EERE 2013).

Electricity in Colorado is generated from a variety of sources, although coal—the source of 66% of all electric generation in 2012—still dominates. As Figure 7.1 shows, coal's share of the electric generation portfolio has decreased since 2001, with wind power representing a distinctly larger share (EIA 2013b). Colorado gets approximately 3% of its electricity from hydropower sources (mostly small dams). In addition, two pumped hydroelectric plants are considered critical to meeting peak demands (Klein et al. 2011).

In 2012, oil and gas production in Colorado totaled $9.3 billion, and the industry's estimated overall economic output was $29.6 billion (Lewandowski and Wobbekind 2013). The Colorado Mining Association estimated that 2012 coal production in the state generated $2.75 billion in sales and associated economic activities (Leeds School of Business 2014). The solar industry generates $1.4 billion in Colorado (The Solar Foundation 2013).[1]

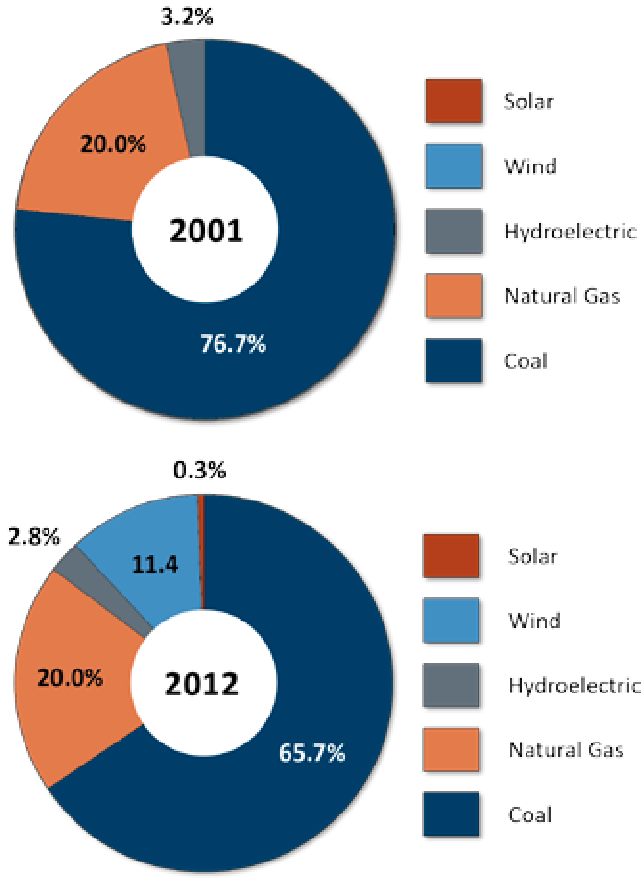

Figure 7.1. Electricity generation in Colorado by type of source, 2001 (top) vs. 2012 (bottom). From U.S. Energy Information Administration (EIA 2013b).

Electricity generation is quite valuable–in 2012, revenues from the sale of electricity in Colorado totaled $4.84 billion (EIA 2013c). The state ranks 18th among U.S. states in terms of fuel ethanol production capacity (125 million gallons per year) but lacks biodiesel production capacity (ERS 2014). Biomass, including energy derived from beetle-killed timber, is a growing industry in Colorado.[2]

Extraction of coal in Colorado is regulated by the state's Division of Reclamation, Mining, and Safety, part of the Department of Natural Resources (DNR). Regulation of oil and gas resources falls under the Colorado Oil and Gas Conservation Commission, another division of DNR. Extraction of fossil fuel resources and generation of wind and solar resources on federal lands is primarily regulated by the

1 Similar figures do not exist for the wind industry, but one report estimated construction and operations of the first 1000 megawatts of wind energy provided more than $260 million in economic output (Reategui and Tegen 2008).

2 Additional information about Colorado's energy sector is available in a 2014 Colorado Energy Office report entitled "Colorado's Energy Industry: Strategic Development Through Collaboration."

federal Bureau of Land Management, although additional agencies are involved when the land in question is owned by other agencies (e.g., U.S. Fish and Wildlife Service or USDA Forest Service.) The sale and distribution of natural gas, including pipeline safety, is regulated by the Colorado Public Utilities Commission (PUC).

Regulation of the generation, distribution, and sale of electricity is more complicated due to the nature of the electric utility industry. More than half of Colorado's customers are served by two investor-owned utilities—Xcel Energy and Black Hills Energy. As publicly regulated utilities, jurisdiction over their provision of electricity is controlled by the PUC. Remaining customers in the state are split nearly equally between 26 rural electric associations and 29 municipal utilities. Rural electric associations are governed by locally elected boards regulated by the U.S. Department of Agriculture's (USDA) Rural Utilities Service, while municipal utilities are regulated directly by their respective municipal governments. Permitting of fossil fuel-based power plants falls under the jurisdiction of the Colorado Department of Public Health and the Environment (CDPHE), while licensing of large hydropower facilities is governed by the U.S. Federal Energy Regulatory Commission along with a number of federal and state entities that may be involved depending on the site in question (Klein et al. 2011).

As a home rule state, Colorado municipalities have more authority over decision making within municipal boundaries than their counterparts in other states. This distinction has significant implications in energy regulation, as seen in debates over electric transmission line siting and regulation of hydraulic fracturing (A. Reed, pers. comm.)

In Colorado, consumption of energy is roughly equally divided among four sectors: residential (23.8%), commercial (19.4%), industrial (28.6%), and transportation (28.2%). By source, Colorado's consumption largely consists of traditional fossil fuels, although renewables constitute a growing share of electricity generation (Table 7.1; EIA 2013a).

Because Colorado has historically had lower prices for natural gas, and because the state has historically very low rates of air conditioning installation and use, household energy costs average $1551 per year, 23% lower than the national average (EIA 2013a).

Fuel Type	Trillion Btu Consumed
Coal	368.9
Natural Gas	476.5
Gasoline	250.8
Fuel Oil	112.2
Biomass	29.7
Non-Hydropower Renewables	53

Table 7.1. Consumption of energy by source in 2010, in trillions of British Thermal Units (Btu). Data from U.S. Energy Information Administration.

II. Key Climate Impacts to Sector

The energy sector is unique in that energy-related activities are fundamental drivers and responders to both climate mitigation and adaptation measures. The burning of fossil fuels to produce energy is the primary driver of global climate change (IPCC 2013); consequently, the energy sector will need to contend with the possibility of future regulations aimed at mitigating climate change through reductions in greenhouse gas emissions (Klein et al. 2011; Tidwell et al. 2013). The sector will also have to address energy-intensive adaptation measures taken by other sectors (e.g. water, agriculture) to minimize their own risks (Skaggs et al. 2012).

Physical Climate Impacts on Energy Supply and Demand

Table 7.2 lists potential physical impacts of climate change on both energy supplies and energy demands in Colorado. As described in Chapter 2, increased average temperatures are expected by mid-century, resulting in earlier surface water runoff timing. Changes

Thermoelectric power generation (natural gas and coal)
Increased water and air temperature • Reduced quantity and quality of cooling water • Reduced efficiency of cooling and turbine operations
Declines in water supply and enhanced drought • Decreased reliability of thermoelectric power plants when water supplies are low [Note: Closed-loop cooling, which is most commonly found in Colorado, is less susceptible to short-term declines in water supply than once-through systems since once-through water demand can increase up to 30% in the summer.]
Oil and Gas
Extreme precipitation and flood events • Disruptions to extraction, transfer and transport of oil and gas resources • Shifts in timing of water availability; reduction in overall water availability resulting in impacts to oil and gas extraction processes that require significant water resources, such as hydraulic fracturing
Hydropower
Extreme events (flood, drought) • Altered hydropower system operation
Shift in timing of water availability • Altered hydropower system operation
Increased air and water temperatures • Enhanced evaporation from reservoirs, affecting hydropower generation
Wind Power
Uncertainty regarding shifts in the spatial distribution and variability of wind speed • Changes to large-scale wind fronts can impact turbine and transmission siting • Changes to drivers of wind can affect short term projections of wind speeds at the height of wind turbines, impacting wind turbine performance and grid management
Solar Power
Increased atmospheric water vapor • Shifts in cloudiness and cloud characteristics can affect siting of commercial scale solar and efficacy of current solar fields and household solar installations
Energy Demand
Increased air temperatures, heat waves • Increased cooling degree days, decreased heating degree days
Decreased local water supplies • Increased energy demands for pumping and conveyance by municipalities and by irrigated agriculture
Declines in water quality • Increased energy demands for water treatment

Table 7.2. Potential physical climate change impacts on the energy supplies relevant to Colorado. Adapted from Schaeffer et al. (2012) and Wilbanks et al. (2012).

to overall precipitation are unclear, but increased temperatures can drive declines in average surface water runoff. More frequent and intense drought events are also expected. Although there is no evidence that climate change will result in changes in the frequency or intensity of future summertime convective storms (see Chapter 2), the nature of Colorado's climate and weather systems in the region means that major storms like the one that produced the September 2013 Front Range flooding—or worse—are likely to occur in the future.

Additional detail on potential climate impacts to energy is provided below.

Physical impacts to fossil fuel and biofuel production

Physical climate impacts could potentially affect the ability of companies to get fossil fuel resources to markets. Extreme weather events such as flooding, heavy snowfall, or thunderstorms can disrupt the production and transportation of fossil fuels (Schaeffer et al. 2012). The 2013 floods along the Front Range provided a clear illustration of that sort of disruption (see Figure 7.2), with 50 reported spills totaling 48,250 gallons of oil. The same incident also led to the spilling of 43,479 gallons of produced water (COGCC 2013).

Figure 7.2. The September 2013 floods along the Front Range resulted in numerous spills of oil and produced water (Photo: Tim Rasmussen/The Denver Post via Getty Images).

In addition, as climate warming affects the availability of surface water and groundwater supplies (see Chapter 4), competition for those supplies is expected to increase, affecting availability and cost of water needed for energy production. Certain oil and gas extraction methods, notably hydraulic fracturing, require water (approximately 50,000 to 350,000 gallons per well in coalbed formations and 2 to 5 million gallons per well in shale formations) (EPA 2010). The Colorado Statewide Water Supply Initiative projects up to 122,000 acre-feet[3] per year of water use for an oil shale industry producing 1.55 million barrels per day (CWCB 2011).

Crops grown as biofuels (primarily for use in the transportation sector) have widely varying water requirements (Kenney and Wilkinson 2012). Extended future droughts may thus affect the viability of biofuels grown in Colorado and the price of biofuels used in the state. Biofuels themselves can also create their own impacts on local climate or water use (Georgescu et al. 2009).

Impacts to thermoelectric power plants

Thermoelectric power generation facilities, which work by turning water into steam to drive turbines and require large quantities of water for cooling (Figure 7.3), lose efficiency as both water and air temperatures rise. Combined-cycle power plants, which are more efficient than traditional plants, are particularly vulnerable as rising air temperatures reduce the density of exhaust gases that need to be pressurized to turn the secondary turbine (Kehlhofer et al. 2009). Traditional single-cycle power plants are affected as warmer temperatures make it more difficult to cool

3 1 acre-foot = 325,851 gallons.

the plant, either through use of surface water or air for cooling. Dry-cooled plants, which do not require water, can lose up to 0.5% of their capacity for every 1°F increase in peak air temperature, more than twice the rate of capacity loss at water-cooled plants (Sathaye et al. 2012).

The relative reduction in capacity of dry versus water-cooled plants is critical in Colorado, where scarcity of water resources and an arid climate make dry cooling an attractive option. Currently, power plants totaling 4150 MW of generation capacity in the Intermountain West use this option (Cooley et al. 2011). Competition for surface water is expected to increase in the future across Colorado, potentially limiting water availability for use in electricity generation (Klein et al. 2011). The prior appropriation system also raises the possibility that generation can be hampered by the status of a given power plant's water rights (Stillwell et al. 2011); conversely, existing water rights holders can be affected if a power plan purchases senior rights.

Recent research shows that only a few basins in Colorado currently experience surface water supply stress due to thermoelectric power generation, but such stresses may become more common in the future, especially during periods of extended drought (Averyt et al. 2013). Total water needs for electricity production will vary widely depending on choices made in types of future generation portfolios including specific choices about cooling technologies (Meldrum et al. 2013).

Physical impacts to renewable electricity generation

Extended droughts often result in lowered reservoir inflows and greater evaporation, driving changes to reservoir operations and impacting hydropower production (Schaeffer et al. 2012). Although hydropower makes up a relatively small proportion of electricity resources in Colorado, some are critical to generation portfolios, such as the Cabin Creek pumped hydro plant in Georgetown owned by Xcel Energy (Klein et al. 2011).

The effectiveness of solar photovoltaic systems, which convert sunlight directly into energy, is directly related to the amount of incoming solar radiation. That, in turn, is affected by a number of atmospheric variables, notably atmospheric water vapor levels and resulting cloudiness (Schaeffer et al. 2012). Although not all studies on this topic are in agreement, there is some indication that solar potential may decrease across the western U.S. in the fall, winter, and spring (DOE 2013). Also, the efficiency and power output of specific types of photovoltaic systems, such as crystalline silicon modules, drop during hot temperatures (Crook et al. 2011; Kawajiri et al. 2011).

Figure 7.3. Xcel Energy's Valmont Power Plant in Boulder uses water stored in three surrounding reservoirs for cooling (Photo: Creative Commons, Let Ideas Compete).

Concentrating solar power (CSP), in which mirrors concentrate solar radiation to heat up water or other liquids, may see negative effects due to reduced water availability, depending on the specific design of a given power plant (DOE 2013). Colorado currently has no operating CSP plants, although a proposal for

Figure 7.4. Snow and other winter weather conditions can negatively affect wind turbine operations (NorthWind 100 turbine in Toksook Bay, Alaska. Photo: National Renewable Energy Laboratory).

one in the San Luis Valley was put forth before being scrapped in 2013.[4]

Changes to wind generation capacity are uncertain. Data from the National Wind Technology Center south of Boulder indicates that El Niño conditions can significantly hamper the development of strong westerly winds (Clifton and Lundquist 2012). To date, however, although overall wind speeds across the U.S. may be declining, no significant changes have been detected in the Southwest (Pryor and Ledolter 2010). Projections of future wind energy density across the U.S. have not shown changes outside the range of natural variability over the next 50 years (Pryor and Barthelmie 2011). Research from California suggests that a lack of sufficient topographic resolution may impede attempts at further projections of changes in location-specific wind speeds (Rasmussen et al. 2011). Winter weather does pose significant concerns for wind turbine operations (Lacroix and Manwell 2000; Figure 7.4), a particular concern given that climate projections indicate the possibility of increasingly intense winter storms in Colorado (see Chapter 2).

Impacts to energy demand

Although climate-related impacts are important to consider in assessing the future of energy demand in Colorado, factors including population growth, policies, and regulations have largely determined future electricity demands in Colorado and will continue to do so. Colorado's population is expected to grow to nearly 6 million by 2020 and 7.8 million by 2040 (see Chapter 3), which would likely increase overall energy consumption. On the other hand, state law and PUC regulations require investor-owned utilities to meet various goals for reducing peak demand and total electricity sales (DSIRE 2012), and the state and some local governments have implemented financial incentives to encourage adoption of cost-effective energy efficiency practices.

However, long-term shifts and short-term perturbations in the climate have the potential to alter future demands. Average temperatures in the state have increased by 2°F over the past 30 years and are expected to increase an additional 4°F by mid-century relative to the end of the 20th century (see Chapter 2). This has the potential to increase cooling degree days and decrease heating degree days in Colorado. All other factors being equal, a decrease in heating degree days would imply a reduction in the need for natural gas and other heating fuels. An increase in cooling degree days would imply an increase in electricity demand due to greater levels of installation and use of air conditioning and other cooling systems, although trends in building construction and personal income may have equal or greater effects on future A/C use. However, despite shifts in long-term trends, the state will still

4 A concentrating photovoltaic plant recently came online in Alamosa; however, this technology is distinctly different from CSP in its use of photovoltaic cells to generate electricity, rather than heating up water or other fluids, as done in standard CSP plant designs.

experience significant climate variability, including cold air outbreaks, heat waves, and extreme precipitation events (see Chapter 2).

Electricity demands could also be affected by future changes in the water sector. The energy intensity of water supplies, including energy needed for pumping, distribution, and treatment, varies widely depending on water source location, type of treatment, and other factors (Cooley and Wilkinson 2012). A 2009 analysis found a range of energy intensities for selected water utilities in Colorado–821 kilowatt-hours per acre-foot (kWh/AF) for Denver Water, 883 kWh/AF for Fort Collins Utilities, 4494 kWh/AF for Parker Water and Sanitation,[5] and 4631 kWh/AF for Colorado Springs' Southern Delivery System[6] (Tellinghuisen 2009). With projected declines in water availability in Colorado, the water sector may need to import water from other regions or increase reliance on recycled water to meet future demand. Depending on choices made about conveyance paths (pumping over mountains compared with gravity fed systems) and energy sources used for water treatment and heating, electricity demands by the water sector could grow significantly in the future.

Impacts to energy distribution systems

Changes in demand will interact with impacts of climate variability and climate change on the electricity grid itself. Among these impacts are reductions in the efficiency of grid infrastructure. As temperatures rise, capacity in transmission lines (Figure 7.5), power substations, and transformers decreases (Tidwell et al. 2013). Some elements of electricity infrastructure, especially above-ground power lines, are particularly vulnerable to damage by extreme weather events (DOE 2013). Moreover, wildfires can severely damage transmission lines (Klein et al. 2011; Tidwell et al. 2013; DOE 2013), a particular concern in rural areas throughout Colorado that are served by a single transmission line. In addition to damaging or destroying transmission equipment directly, high temperatures and smoke from fires can cause circuit outages or damage transformers. Grid operators may even shut down transmission lines in the vicinity of fires to avoid damage (Aspen Environmental Group 2008).

Further, warming temperatures are expected to lead to warmer summers, which, combined with trends in the housing market, are expected to lead to increased installation and use of air conditioning in Colorado. Increased use of air conditioning during summertime heat conditions can strain grid resources and may force utilities to build additional peak generation capacity as peak demands rise (Lu et al. 2008). Compounding these effects are simultaneous increases in plug loads (Klein et al. 2011).

Figure 7.5. As temperatures rise, capacity in transmission lines decreases (Photo: iStock, moonmeister).

5 Parker Water and Sanitation District, like many entities in the South Metro region, relies almost exclusively on groundwater, which requires significant energy for pumping. The actual energy intensity of specific supplies in Parker varies widely based on the source used (Tellinghuisen 2009).

6 The Southern Delivery System is currently under construction, which was not the case when the analysis cited was completed.

On the other hand, warmer winters may lead to a reduced need for home and commercial heating, which is dominated by natural gas fuels in Colorado. One study of energy consumption for Peterson Air Force Base and Fort Carson estimated small increases in electricity use due to cooling needs but small decreases in natural gas consumption due to changes in heating needs by the year 2030 (Darmenova et al. 2013).

Rising temperatures would result in an overall increase in transportation fuel consumption due to greater air conditioning use on hot days (Niermeyer et al. 2013). However, to date there are no comprehensive analysis of changes in driving patterns by Coloradans under warmer temperatures. Future fuel consumption may be strongly influenced by both future fuel prices and the continued increase in overall automobile fuel efficiency due to federal regulations.

Impacts of Potential Carbon Regulations on the Energy Sector

The majority of carbon emissions in Colorado come from the electricity sector (41%; 39.9 gigatons of CO_2) and the transportation sector (31%; 29.7 gigatons of CO_2) (EIA 2013d). Between 2000 and 2010, Colorado's carbon emissions represented the largest absolute increase of any U.S. state, increasing by 11.8 gigatons of CO_2 (EIA 2013d). This was driven in large part by a 38% increase in emissions from the burning of natural gas, primarily for electricity generation in order to meet the demands of a growing population. During this same period, carbon emissions from coal declined by 1%. Even though burning natural gas produces fewer GHG emissions per kWh than coal does, an increase in total electricity generation was large enough to offset the reduced use of coal. This is consistent with national projections that show GHG emissions would remain constant–and global GHG concentrations would continue to increase–even under a projected natural gas intensive future (Clemmer et al. 2012).

Moreover, Colorado is a significant producer of oil, natural gas, and coal, and there is potential for further development of these and other fossil resources. The Piceance Basin in northwest Colorado is part of the Green River Formation, considered potentially to be the world's largest oil resource, and the Niobrara Shale could hold up to 2 billion barrels of oil (EIA 2013a). The degree to which the state will see economic output from these resources would be strongly affected if carbon regulations were to be enacted.

On the other hand, Colorado has potential for development of renewable resources that would presumably not be impacted by potential future carbon regulations (Lopez et al. 2012). The potential for high-quality wind in Colorado is significant (53.5 TWh annually; Hurlbut et al. 2013), and the state's concentrated solar power potential is 3rd in the U.S. There are also significant opportunities for PV and enhanced geothermal (Colorado Geological Survey undated). By 2025, Colorado is expected to have a surplus of prime-quality wind generation (Hurlbut et al 2013). Relative to other states, biopower potential is low.

As would be expected, a reduction in use of fossil fuels for transportation (see Chapter 8 for further discussion), heating, and electricity generation would likely reduce demand for coal, oil, and natural gas extracted in Colorado. Shifts toward electric or plug-in hybrid vehicles would also impact energy resources in Colorado, increasing grid demands during the nighttime hours. A dampening of the daily demand distribution would increase baseline power plant operations, often provided by coal-fired power plants, but also offers opportunities for utilization of wind power, which is often most available at night.

III. Key Vulnerabilities

As described in Chapter 1, vulnerability is a function of both impact due to climate variability or climate change and the ability of the sector to adapt to such impacts (known as "adaptive capacity"). In this section we first provide a brief qualitative discussion of existing adaptive capacity in Colorado's energy sector. We then consider the impacts described in the previous section in light of this capacity and provide a brief qualitative summary of potentially vulnerable entities. This results in a snapshot of key vulnerabilities likely to affect Colorado's energy sector, although the reader should note that a comprehensive, formal vulnerability assessment would be needed in order to ascertain what the effects of the current adaptation activities have been on the state's vulnerabilities to climate change in the energy sector.[7]

Adaptive Capacity

Adaptive capacity is the ability of elements of a given sector to effectively adapt to future climate-related changes (see Chapter 1). Existing climate variability has driven energy systems in Colorado to develop some level of adaptive capacity that may be useful as climate change continues to occur.

Ebinger and Vergara (2011) identified a number of generic practices that have contributed to the development of adaptive capacity in the energy sector, such as the incorporation of climate and weather extremes into long-term planning, improving the flow of climate information into decision making, and integrating climate risk information into operational and management decisions.

Little information exists on the adaptive capacity of extractive industries in Colorado. For electricity, however, more information exists. Klein et al. (2011) identified significant existing adaptive capacity in the electric power industry, which has long contended with seasonal and daily shifts in demand and available generation resources, along with long-term changes like population growth. Elements of this adaptive capacity include:

- Every four years investor-owned utilities in the state submit *electric resource plans* with multiple scenarios of demand forecasts, which can incorporate population growth, increased penetration of air conditioning, and other factors, allowing for consideration of climate change-related shifts in energy use. [Note: adaptive capacity created through this process must be balanced against the long-term consequences of decisions made in resource plans, such as investments in new generation capacity that could be in place for decades.]
- In 2007, Xcel Energy first incorporated the effects of a *potential carbon price in its electric resource plan*.
- All utilities use a variety of strategies to meet summertime *peak demands* for electricity, like building extra peak power or implementing variable-rate pricing schemes.
- The PUC requires investor-owned utilities to include a *planning reserve margin* of additional generation resources available to ensure system stability and prevent power outages. A portion of this reserve is held as *spinning reserve* capable of coming online within 10 minutes.
- *Dynamic metering initiatives* like Xcel's SmartGridCity can improve a utility's ability to match supply and demand.
- The *Clean Air-Clean Jobs Act* will result in reduced carbon intensity and reduced water consumption by power plants along the Front Range.

In addition to that list, Colorado's renewable portfolio generation requirements—among the highest in the country—and demand reduction regulations also provide capacity for the electricity sector to adapt to a less carbon-intensive future. In summary, the electricity sector appears to have significant adaptive capacity but may have less ability to adapt to the uncertainty of future carbon regulations and cascading impacts on and from other sectors. Assessing adaptive capacity across the entire energy sector is difficult without additional data.

Cascading Vulnerabilities

The energy sector in Colorado will be directly impacted by both the physical changes brought

7 The Drought Vulnerability Assessment produced by the Colorado Water Conservation Board provides an example of what such an assessment would look like: http://cwcb.state.co.us/water-management/drought/Documents/StateDroughtMitPlan2013/AnnexBDroughtVulnerabilityAssessmentTechnicalInformation.pdf.

Figure 7.6. Arvada-based SkyFuel designs and builds concentrating solar power (CSP) plants like the parabolic trough plant pictured here in Nevada. Although no utility-scale CSP plants have been built yet in Colorado, they have been proposed and are appealing due to their lack of significant greenhouse gas emissions. The decision of whether to use water versus other substances (like molten salt, as used in this facility) as a heat transfer fluid will determine the level of impact that any new proposed CSP facility would have on water and other sectors (Photo: SkyFuel, http://www.SkyFuel.com).

by climate change, as well as by international, federal, and state mitigation policies aimed at reducing the long-term risks posed by climate change. The sector will also be affected by adaptation efforts taken by other sectors, such as water and land use. Consequently, the sensitivities and vulnerabilities related to climate change are complex, involving tradeoffs and cascading effects across sectors. Whether Colorado moves toward a more fossil fuel intensive future (e.g. natural gas), continues on the same trajectory, or transitions towards renewable sources as part of voluntary or legally-mandated efforts to reduce greenhouse gas emissions, there will be significant impacts on the energy sector itself, ecosystems, land and water use, and the economy (Tidwell et al. 2013).

For example, as a consequence of Colorado's dependence on fossil fuel resources, the energy portfolio of the state is sensitive to climate mitigation and air quality policies. Recent policy changes, however, appear to already be reducing these sensitivities. Current state law requires 30% renewable electricity by investor-owned utilities, 10% by municipal utilities serving more than 40,000 customers, and 20% by rural electric cooperatives serving more than 100,000 customers by the year 2020 (DSIRE 2013). This standard is projected to result in a 7% reduction in total CO_2 emissions for the state (Obeiter et al. 2013).

Mitigation Action	Water	Land	Air/Health
Switch from coal to natural gas fueled power plants	+, –	+, –	+, –
Expansion of wind	+	–	+, –
Private landowners	–	–	+
Expansion of solar thermal technologies (wet cooled)	+	–	+
Expansion of commercial scale PV	+	+	+
Expansion of geothermal	–		+
Expansion of electric vehicle fleet	+, –		+
Expansion of biofuels	–	–	+

Table 7.3. Cascading sensitivities and vulnerabilities across multiple sectors for selected mitigation actions. The table above illustrates decision options that would enhance adaptive capacity and reduce vulnerabilities to climate change for energy, and how that option would potentially affect other sectors impacted by climate change. "+" = positive effect (reduced stress) on sector, "-" = negative effect (increased stress) on sector. Blank = effect not noted. Details about the specific tradeoffs can be found in Skaggs et al. (2012). (Adapted from Table 5.2 in Skaggs et al. 2012).

Adaptation Action	Water	Land	Energy
Switch from recirculating cooling to hybrid or dry cooled power plants	+		
New storage and conveyance of water	+, –	–	–
Switch to drought tolerant crops	+	–	+
Increase transmission capacity to urban areas to reduce power outages during high demand periods		–	+

Table 7.4. Cascading sensitivities and vulnerabilities across multiple sectors for selected adaptation actions. The table above illustrates adaptation decision options that may be taken by different sectors that would affect the capacity of others to mitigate and adapt to climate change. "+" = positive effect (reduced stress) on sector, "-" = negative effect (increased stress) on sector. Blank = effect not noted. Details about the specific tradeoffs can be found in Skaggs et al. (2012). (Adapted from Table 5.2 in Skaggs et al. 2012).

However, depending on the choice of investments in renewable resources, a shift in generation resources could have negative impacts on other sectors in Colorado, resulting in what can be termed "cascading vulnerabilities." For example, utility-scale concentrated solar power (Figure 7.6), although a low carbon energy source, requires large swaths of land for panel installation and additional transmission—both of which have implications for sensitive wildlife habitat and land use practices. Further, CSP technologies are also generally wet-cooled, and because CSP can use as much water as a conventional coal-fired power plant (Macknick et al. 2012), water rights would need to be secured, making siting of CSP in Colorado complicated (as seen in the recent failed attempt to build a large CSP plant in the San Luis Valley.) The Colorado Public Utilities Commission is one of only two utility commissions in the West that requires utilities to report water consumption for existing and proposed generation facilities (Tellinghusen 2011), but it does not directly require a utility to provide evidence of sufficient long-term water availability for thermoelectric generation in its approval process. Thus, although renewable policies will reduce GHG emissions, resulting shifts in generation portfolios can result in cascading vulnerabilities in other sectors. Tables 7.3 and 7.4 describe these vulnerabilities, and additional details can be found in Skaggs et al. (2012). More specific information would require a separate and more detailed analysis.

Key Vulnerabilities

Among the suite of impacts the energy sector faces as a consequence of climate change, four lead to key vulnerabilities: drought, heat waves, and wildfire; rising air temperatures; changes in water availability; and carbon regulations. The vulnerabilities described below could lead to system instability, higher consumer prices, negative economic consequences, and negative effects on other sectors.

Climate Driven Observed and Projected Impacts	Examples of Potential Vulnerabilities
More frequent and intense drought, potentially reduced streamflow, increased wildfire and heat wave risk (see Box 7-1)	
• Increased short-term competition among sectors for limited water supplies would include parties requiring water for energy extraction and water for thermoelectric cooling. • Potentially reduced streamflow would affect availability of water for cooling at thermoelectric plants and for energy extraction. • Elevated air and water temperatures would decrease generation and transmission efficiency. • Wildfire could threaten transmission lines, as well as other energy infrastructure including extraction facilities and power plants. • Heat waves would increase peak air conditioning demands.	The energy sector is potentially vulnerable to cascading effects of drought, heat waves, and wildfire, coupled with increased penetration of air conditioning in the Colorado market, which could lead to water scarcity and grid stress and resulting price increases and system instabilities.
Increasing average air temperatures	
• Increased cooling degree days. • Increased penetration of air conditioning. • Increased evapotranspiration will drive an increase in water use by other sectors. • Higher air temperatures reduce efficiency of cooling at power plants, and the efficiency of transmission lines.	Higher average air temperatures will increase vulnerability within the electricity industry to greater competition for water supplies and increased generation costs.
Long-term decline in average surface water quantities	
• As surface water supplies decline, groundwater use may increase. On average, groundwater pumping requires three times more energy than surface water conveyance. • Water demands may be met by conveying and pumping water to high demand areas, requiring more energy.	Given the unknown possibility of energy needs for future water-related projects, the energy sector is potentially vulnerable to large increases in energy use if reduced water supplies lead to the creation of energy-intensive water projects.
Increasing greenhouse gas emissions and future regulations	
• Potential future GHG regulations would directly impact current investments in the energy sector and could affect the direction of future investments. treatment	The degree to which any future GHG regulations would impact prices is unknown, making the energy sector and consumers vulnerable to the uncertainty of future energy price increases as well as costs associated with crop production, water use, and transportation.

Table 7.5. Key vulnerabilities identified in Colorado's energy sector, corresponding to specific climate-related impacts.

Box 7-1
Compounding Impacts of Drought

Delivery of electricity may become more vulnerable to disruption due to climate-induced extreme heat and drought events as a result of:

- increased demand for home and commercial cooling,
- reduced power-plant efficiencies due to high temperatures,
- reduced transmission-line, substation, and transformer capacities due to elevated temperatures,
- potential loss of hydropower production,
- threatened thermoelectric generation due to limited water supply, and
- threat of wildfire to transmission infrastructure.

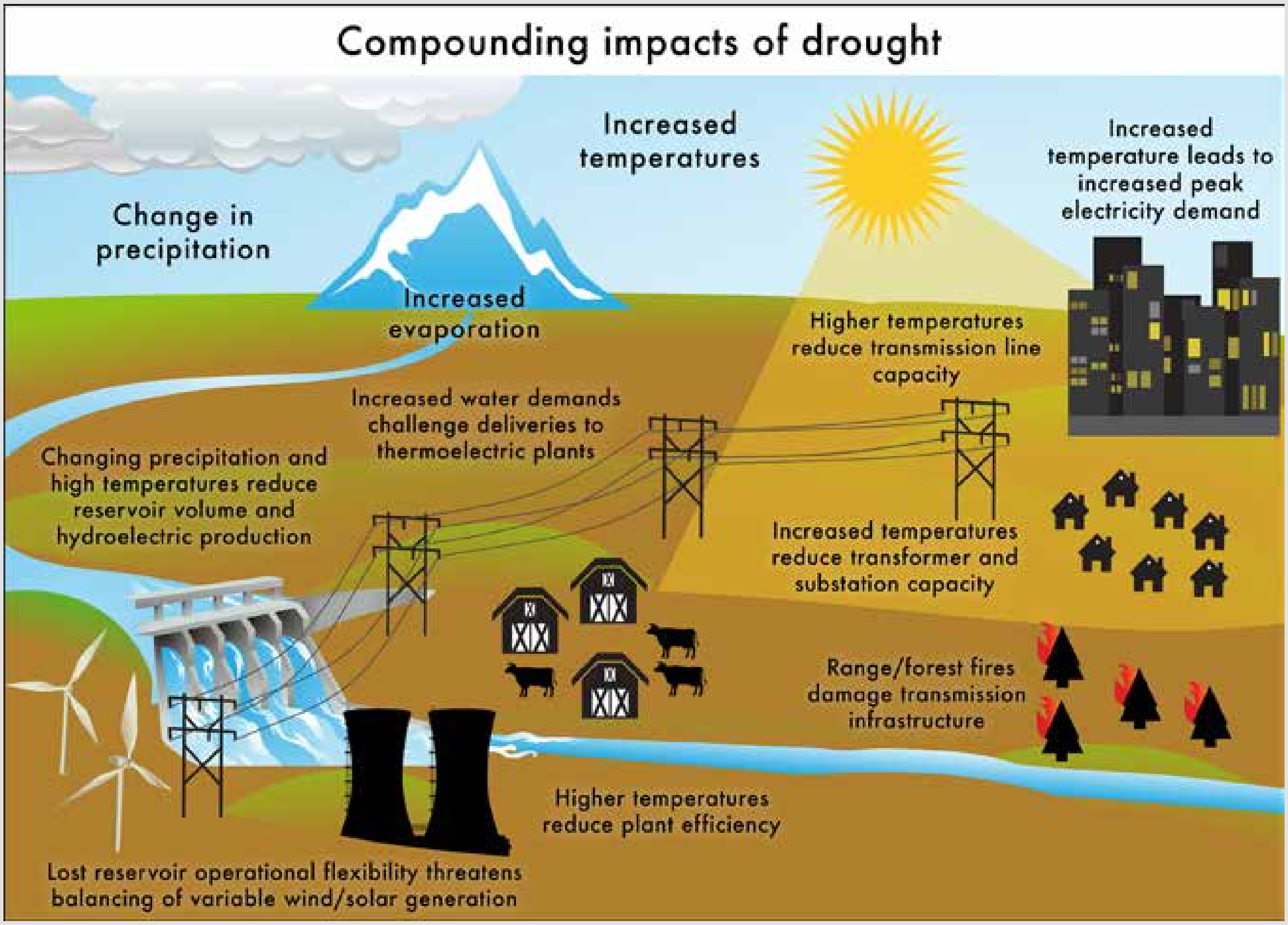

Figure 7.7. Impacts of drought on energy systems. From Tidwell et al. (2013) (reproduced by permission of Island Press, Washington, D.C.).

IV. Moving Towards Preparedness

The energy sector is at the heart of the Colorado, and, increasingly, the U.S economy. In order to adequately prepare the energy sector in the state of Colorado for the short and long term impacts of climate change, the state could engage in a comprehensive vulnerability assessment that builds directly off of this study, brings stakeholders together, and uses a formal methodology to prioritize risks and identify management, planning, and policy mechanisms to enhance adaptive capacity. Additional avenues for elements of such an assessment include existing mechanisms such as the PUC-required electric resource planning process for investor-owned utilities or industry-specific planning processes.

Decision makers in the energy sector may benefit from recognizing that reducing vulnerabilities and minimizing risks around energy and climate change will require interaction with multiple other sectors. Further, since there is no single overarching authority over energy, planning must consider multiple scales, including federal, regional, state and local entities. Given the multi-scale, multi-sector coordination necessary for comprehensive energy planning, it is important to recognize that there are tradeoffs associated with choices that may reduce vulnerabilities for the energy sector alone.

A critical step toward preparedness would be to consider the cascading vulnerabilities related to energy, and how they interplay with other sectors including agriculture, water, and public health. Documenting the authority and roles of key institutions (regulatory, political, industrial) will help reduce redundancies and identify mechanisms for implementing win-win strategies that are of benefit to different sectors. For example, the Western Governors' Association has identified collaboration between planning in the energy and water sectors as a key mechanism for reducing drought vulnerability in the West (WGA 2010, 2011). Considering how different departments and institutions in the state could integrate preparedness planning would improve resilience for the energy sector.

Moreover, understanding societal reactions to various aspects of the energy sector would be critical to effective preparedness planning. For example, societal tolerance of chemical and fossil fuel spills in the environment may create anxiety due to the potential health impacts. Thus planning to prepare for the possibility of infrastructure damage from extreme weather events may warrant additional priority and educational outreach despite the low probability of such events.

More specific options that could improve adaptive capacity and moving toward preparedness, based on the vulnerabilities identified in the previous section, include:

- Statewide planning that includes an accounting of the cascading impacts of drought across the energy sector, an assessment of critical infrastructure and a plan for real-time management across impacted sectors could increase statewide resilience to drought and related climatic events.
- Energy planning that includes the effects of possible future water supply projects can increase preparedness.
- Consideration of potential future demands for energy in planning state water projects and designing conveyance and treatment facilities.
- Consideration of the potential for future GHG regulations and appropriate responses that could help reduce the exposure of the energy sector and Colorado's economy to the negative impacts of such regulations.

Additional guidance on preparedness planning is provided in Chapter 1.

V. Future Research Needs

The intention of this chapter is to provide a broad overview of vulnerabilities in the energy sector and to offer brief guidance on how to begin statewide preparedness planning in the energy sector. Additional research may be beneficial to addressing some gaps in understanding vulnerabilities. Below are some specific suggestions of future research questions that could bolster preparedness planning.

Vulnerability to drought, wildfire, and heat waves

- Development of a methodology for assessing risks posed to health, public safety, and the economy by electricity curtailments and power outages associated with drought, heat waves, and wildfire, including identification of high-risk areas in the state.

Vulnerability to changes in weather systems

- Analysis of likely overall changes in the effectiveness of wind turbine generation at sites in Colorado under future climate change scenarios.

Vulnerability to increasing air temperatures

- Analysis of drivers of trends in air conditioning penetration in Colorado and assessment of mechanisms for reducing impacts on peak load.

Vulnerability to long-term decreases in water availability

- Continued research and development of low-water technologies for energy generation.

- Development of a methodology for identifying of specific areas of water stress related to energy generation in Colorado, building off existing nationwide and regional analyses (Averyt et al. 2013).

Vulnerability to future carbon mitigation policies

- Economic analysis of the relative impact of different carbon mitigation policies and other uncertainties on energy prices and related impacts to crop, transportation, and water prices using scenario analysis.

- Further research into new low-carbon, low-water energy resources, especially those developed in Colorado.

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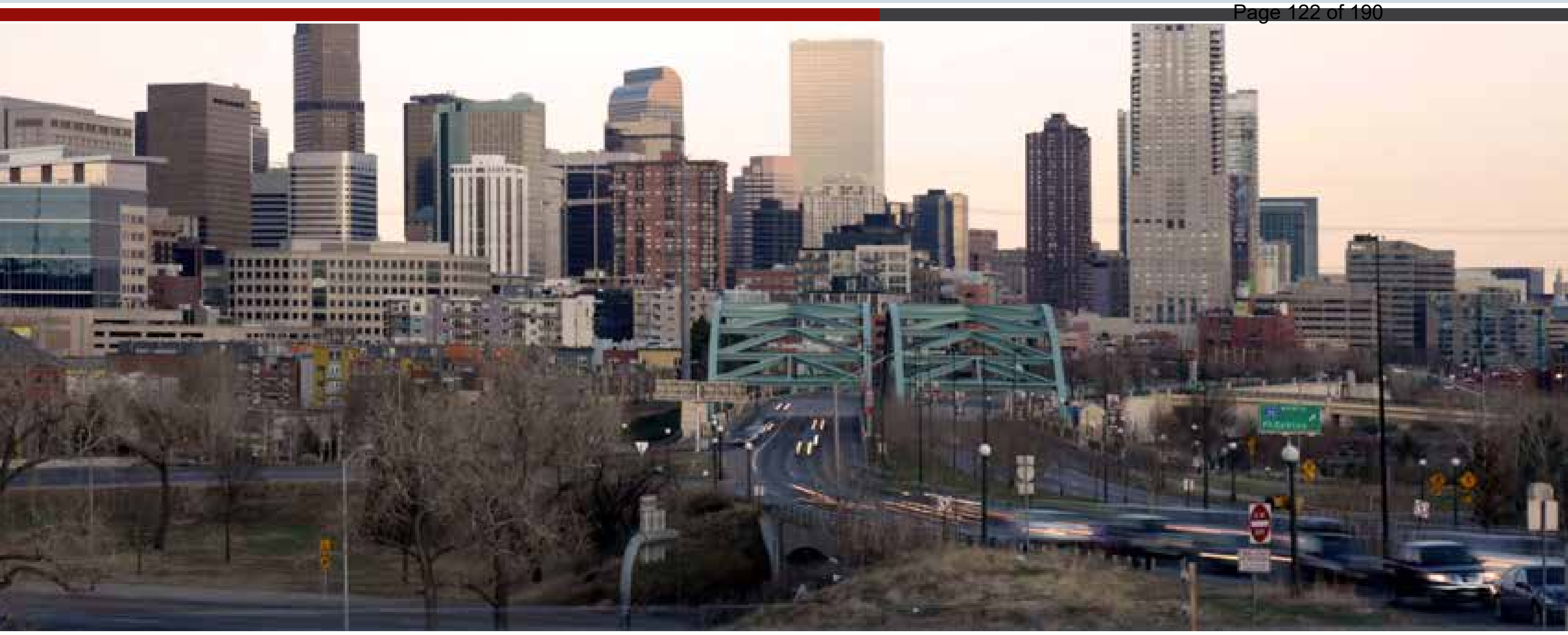

Downtown Denver with traffic. Photo: Shutterstock, EdgeOfReason.

CHAPTER 8
TRANSPORTATION SECTOR

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I. Brief Description of Sector

There are two major types of climate sensitivities in Colorado's transportation sector—the sensitivity of road, rail, and airport infrastructure to the physical impacts of extreme heat and heavy precipitation; and the sensitivity of travel behavior and safety to impaired visibility and traction from wildfires and precipitation events. Unlike many other states, Colorado has no waterways or coasts and thus will not face some of the more serious impacts associated with climate change such as sea level rise, permafrost melting, and intensified coastal storms. Transportation, however, is a critical element of the state's economy, and both the current climate and a warmer future can threaten its viability. This chapter will address the impacts of climate change and climate variability that face Colorado's transportation sector and suggest where its key vulnerabilities lie.

Colorado's Transportation Assets

Colorado has over 88,000 center line miles of roadway (CDOT 2011a). These roadways include a significant number of vehicle bridges, culverts, and tunnels. Interstate highways, including I-70, the major east-west corridor across the state, and I-25, the major north-south corridor along the Front Range, provide a disproportionate amount of the state's road capacity–although the Interstate system accounts for only 10% of Colorado's road miles, it handles approximately 40% of vehicle miles traveled (VMT) (CDOT 2011a). In total, there were 46.2 billion VMT on all Colorado roads and 27.4 billion on state highway roads in 2009; VMT are growing faster than population (CDOT 2011a).

Denver International Airport (DIA; Figure 8.1) is the largest of Colorado's public airports. It served over 53 million passengers in 2012, making it the fifth-busiest airport in North America (Leeds School of Business 2013). In total, Colorado's airport system consists of 74 public-use airports (CDOT 2013c), as well as many private airstrips and other small facilities.

Fourteen freight railroads operating in Colorado own more than 2,800 miles of track in the state and operate on over 2,600 miles of those tracks. Approximately one-fourth of all freight handled in Colorado is moved by rail. Passenger rail in Colorado is served by two Amtrak routes, the California Zephyr route and the Southwest Chief route. Transit in the Denver metro area includes 47 miles of light rail in the Denver metro area with plans for a total of 122 miles, as well as bus service provided by the Regional Transportation District (Parsons Brinckerhoff 2012). In addition to local transit service, CDOT's Division of Transit and Rail is developing an Interregional Express Bus Plan which will provide bus service between Ft. Collins and Denver, Colorado Springs and Denver, and Glenwood Springs and Denver (CDOT undated c).

Economic Impacts of the Transportation Sector

The transportation sector makes significant contributions to Colorado's economy through

Figure 8.1. Denver International Airport is the fifth-busiest airport in North America (Photo: iStock, Lokibaho).

employment and the movement of freight. In 2012, 47,800 people were employed by Colorado's transportation sector, including 18,700 jobs in trucking and 12,700 in air transportation (Leeds School of Business 2013). Colorado's 2010 transportation and warehousing employment annual payroll was valued at $2.4 billion (RITA 2012). An analysis of aviation's total economic impact in the state estimated that 265,700 jobs are created by on-airport activities, off-airport spending by visitors who fly into Colorado, and off-airport activities supported by air cargo shippers, with an annual payroll of $12.6 billion; total annual economic output from the system was estimated at $36.7 billion (CDOT 2013a). The total value of freight shipments in Colorado for all modes of transportation (2007 data) was $125 billion (RITA 2012). Colorado freight is expected to increase by at least a factor of 2.5 by 2035 (CDOT 2008).

Figure 8.2. I-70 west of Denver is critical to the economies of many communities in western Colorado, but often faces severe congestion problems (Photo: iStock, milehightraveler).

Colorado's transportation sector also provides vital infrastructure for other sectors within the state, in particular, the state's tourism and recreation sector. The state's segment of I-70, which is the primary route from the Front Range and DIA to the western portion of the state, was constructed as part of the interstate highway system that connects the eastern and western portions of the U.S. Due to its location, it promoted the development of ski resorts and other mountain recreational activities by allowing access to previously remote locations (Philpott 2013). Colorado's Department of Transportation (CDOT) recognizes the importance of I-70 to its tourist economy: "tourists…expect an effective transportation system when traveling by car, air, bus, or train, to and from airports, ski areas, and Western Slope communities. The I-70 West Corridor is the lifeline to tourism in ski country and the Western Slope" (CDOT 2008; Figure 8.2).

Depending on which economic activities and sub-sectors are included, annual economic revenue from Colorado's recreation and tourism sector has been estimated at anywhere from $8.5 billion to $15 billion (see Chapter 9). Disruption to transportation infrastructure leading to tourist destinations can be costly. One preliminary analysis of the financial impact of the September 2013 floods looked at the possibility that travelers planning next summer's vacations will expect road access to Rocky Mountain National Park to be limited and will choose alternative destinations. Assuming a 30% decline in spending by out-of-state visitors in 2014, 335 jobs would be lost statewide (mostly in Estes Park), statewide activity will decline $27.2 million, real household income will decline $13.9 million and state and local tax revenue will decline $3.1 million (Regional Economics Institute Center for Disaster and Risk Analysis 2013).

Regulation of Transportation Sector

CDOT constructs and maintains the state's highway system, including its bridges, and supports the state's aviation and rail industries

(CDOT 2011c). The department includes several divisions with a variety of responsibilities for the state roadway system including planning, designing and maintaining state highways and assuring that environmental obligations are met. CDOT's extensive planning efforts include a statewide and regional Transportation Improvement Plan (STIP), as well as a 20-year long range plan (CDOT 2011a). CDOT also coordinates planning activities and oversees the planning process between the CDOT engineering regions, Metropolitan Planning Organizations (MPOs), and Transportation Planning Regions (TPRs). A handful of tolled roads exist or are in the planning stages in the Denver metro area. Numerous other roads within the state are built and maintained by local jurisdictions or other entities including the U.S. Forest Service. The discussion in this chapter is primarily focused on CDOT roads but many of the concepts apply equally to other roads within the state.

Federal agencies are also relevant to Colorado's transportation sector. For example, the local field office of the Federal Highway Administration (FHWA) assists CDOT in the planning, construction and maintenance of transportation projects (FHWA undated). FHWA supports research on preparing for the impacts of global climate change on the nation's transportation infrastructure and systems (FHWA 2013). The Federal Emergency Management Agency (FEMA) provides disaster assistance to rebuild local roads and bridges following natural disasters such as flash floods. The U.S. Environmental Protection Agency establishes and enforces standards under the Clean Air Act that impact transportation in Colorado.

II. Key Climate Change Impacts to Sector

As discussed in Chapter 2, Colorado's average temperatures are projected to increase in the future. There are no clear projected trends in the frequency or intensity of warm-season convective extreme precipitation events. However, one study found that extreme winter precipitation increased across future climate projections, indicating that individual winter storms moving across Colorado could become wetter (see Chapter 2). Colorado has a long history of flooding with at least 33 notable flood events since 1864 causing a total of $8.5 billion in damage and 372 deaths; it experiences a major flood disaster roughly once every five years (CWCB 2013). It is reasonable to conclude that Colorado will continue to experience devastating floods regardless of future changes in precipitation; thus, the potential for future flooding is still an important climate-related impact to consider. Droughts are also a future concern—a large majority of model runs indicate that droughts are likely to increase in frequency and severity by mid-21st century, driven by temperature increases (see Chapter 2). Based on those projected changes, combined with what we know of the past from the paleoclimate record (see Figure 5.1 in Chapter 5), it is also reasonable to conclude that Colorado is likely to experience future droughts that could be more intense and of longer duration than any experienced in the 20th century. For more information about current and future droughts, see Chapter 2.

No systematic analyses of the impacts of climate change on Colorado's transportation sector have been done to date. Below we draw from existing analyses of potential climate change impacts to transportation and incorporate what we know of possible climate changes in the state to provide a general overview of potentially relevant impacts.

Road and Bridge Assets

Road materials have a limited range of heat tolerance, and road buckling occurs with sustained temperatures above 90°F. Bridges are particularly vulnerable to extended high temperatures, which stress bridge integrity (Peterson et al. 2008). Extended periods of extreme heat shorten pavement life and cause bridges to expand, with negative economic impacts (Niemeier 2013). These changes will necessitate increased maintenance and construction resulting in higher associated costs,[1] congestion problems, and access

1 Up to half of all road maintenance costs are due to weather (Kwiatowski 2013).

Figure 8.3. Cars plunged into Rock Creek when Dillon Road collapsed near Broomfield during the September 2013 Front Range floods (Photo: Cliff Grassmick,Boulder Daily Camera).

restrictions at times. Significantly hot weather can limit construction crew schedules (Peterson et al. 2008). A reduction in the number of extremely cold days, on the other hand, can increase the number of days crews can work during the colder months and would reduce snow and ice removal costs (FHWA 2010). Freezing and thawing are extremely damaging to roads and can necessitate load restrictions. More frequent freeze/thaw cycles would increase buckling and heaving of pavement and necessitate greater load restrictions (Caldwell et al. 2000; Peterson et al. 2008). More droughts can increase wildfires, which cause road closures, reduced visibility, and a greater risk of mudslides, erosion and flooding (FHWA 2010; Peterson et al. 2008). Increased flooding after fires can cause road closures or safety hazards.

As mentioned above, climate change could increase the severity of extreme winter precipitation events, but regardless of the impact of climate change, the transportation sector needs to be prepared for the impacts of future flooding. Intense precipitation can lead to submerged roads, flooded underpasses, and road scouring and washouts (Peterson et al. 2008). Additional impacts include increased landslides and mudslides that damage roadways; overloading of drainage systems; compromised structural integrity of roads, bridges, and tunnels; adverse impacts on road bases; and the need for larger bridges and culverts (FHWA 2010). These impacts were illustrated in Vermont where flooding from Hurricane Irene closed 335 culverts and damaged 963 culverts (VTrans undated).[2] In Colorado, heavy flooding in September 2013 caused damage to or destroyed 200 lane miles of state roads, 102 bridges and multiple culverts (CDOT 2013d). As one dramatic example, flooding washed out a culvert on Dillon Road near Broomfield, causing the road to collapse and three vehicles to fall into a creek (Paulson 2013), as shown in Figure 8.3.

The need to repair or replace many of these bridges and culverts will limit access and cause congestion in the short term.

Bridges are particularly vulnerable to scour, which results when enough water moves sand or gravel away from a bridge's foundation.[3] Scour separates the riverbed from the bridge substructure, which can make the bridge's foundation unstable (Wright et al. 2012). Given soil type, current status of exposure to scour, and projections of changes in peak 100-year streamflows, Wright et al. (2012) found more than 128,000 U.S. bridges could be vulnerable to greater likelihood of scour as the climate changes, though results depended on time period and emissions scenario examined. The Upper Colorado River Basin stood out as particularly vulnerable when compared to other basins across the country (Wright et al. 2012).[4]

2 Vermont has approximately 60,000 culverts (VTrans 2011).

3 CDOT has been engaged in a study of bridge scour. See http://co.water.usgs.gov/projects/CO251/.

4 The study divided the country up by major

Aviation Assets

Hot air is less dense, which reduces mass flowing over the wing to create lift. Thus planes have more difficulty taking off when air temperatures are high, a problem that more acute at high altitude airports like DIA, where runways must be long enough for large aircraft to build up enough speed to generate sufficient lift. Runways may need to be lengthened or flights delayed or cancelled due to extreme heat, or weight restrictions put in place (TRB 2008; Peterson et al. 2008).[5] DIA could have summer cargo losses as high as 19% by 2030 due to increased temperatures and water vapor in the atmosphere (TRB 2008). In addition, increased precipitation intensity can cause flooding of airports as well as damage to runways and drainage systems, although projections for Colorado do not indicate an increase in summertime storm precipitation intensity (see Chapter 2). Increased drought makes airports more susceptible to wildfires, which threatens airport facilities directly and impairs visibility (Niemeier 2013). Increased heat can cause buckling of runways (TRB 2008).

Rail Assets

Air temperatures over 110°F can cause rail equipment to fail. Heating rail more than 60°F above its neutral temperature (the temperature at which rail is neither expanding nor contracting) can result in deformation of rail lines (see Figure 8.4) as well as derailments (Peterson et al. 2008). An increase in the frequency of temperatures above 77°F will increase track buckling if track is maintained at the current standard; speed restrictions are usually introduced to overcome buckling (Oslakovic et al. 2013). As an illustration, Oslakovic et al. (2013) found that higher summertime temperatures in the Netherlands may cause the number of rail failures to double.

watershed but did not provide enough detail to discern how much of the bridges found to be at risk were in the Colorado portion of the basin vs. other states' portions. The exact percentage of bridges found to be vulnerable varies by future emissions scenario and timeframe. See Wright et al. (2012) for full results.

5 DIA has five runways that are 12,000 feet (3,640 meters) long and the sixth is 16,000 feet (4,853 meters) long (DIA undated).

Figure 8.4. High temperatures can lead to rail deformations such as the "sun kinks" seen here on rail lines in Iowa (Photo: Iowa Department of Transportation).

Additional potential impacts to rail from extreme heat include drying of rail beds and an increased need for air conditioning. Warm and wet winters would cause increased strain on drainage systems, damage to earthworks, failure of saturated embankments, and track circuit problems, while decreasing snow and ice-related and low-temperature incidents. Increased frequency of extreme storms, particularly intense rainfall and extreme wind, are expected to cause an increased possibility of train overturning and derailment, and accidents or network disruption from trees and building debris being deposited on tracks (Baker et al. 2010).

Impacts on Travel Behavior and Safety

Climate has significant impacts on travel behavior and safety. Regional and national studies indicate that intense precipitation reduces traffic safety and efficiency and increases traffic accidents (Niemeier 2013). An increase in future precipitation could have serious ramifications—one study found that an increase in the frequency of moderate to heavy rainfall could increase the number of crashes 17-28%, although safety interventions or other changes could offset some of this increase (Hambly et al. 2013). More frequent flooding would, at a minimum, cause more frequent interruptions of road traffic, and could increase the need for emergency evacuations (TRB 2008). As noted earlier, however, projections of future precipitation in Colorado are unclear, although there is some evidence that winter storms could become more severe.

As temperatures rise, wildfires are expected to increase in frequency and severity, exacerbating traffic hazards such as reduced visibility. CDOT has responded to several major wildfires in recent years, providing emergency response, implementing road closures, handling mud and rock flows, and providing signage (CDOT undated a). Another potential impact to Colorado's roads could result from shifts in transportation patterns in response to changes in "ecologically or recreationally interesting destinations" (TRB 2008, p. 85). For example, Colorado could experience an increase in outdoor recreation/tourism visits to its mountains as tourist destinations in other states become too hot in the summer or snow conditions deteriorate at ski areas in other states, which could have implications for its transportation system (see Klein et al. 2011).

Economic Impacts

Disruption of transportation systems from weather events can have major economic impacts. Freight deliveries can be delayed and supply chains disrupted by inundated roadways (Niemeier 2013). Productivity and wages are lost if individuals are unable to get to work because of road closures (see Regional Economics Institute Center for Disaster and Risk Analysis 2013). Disrupting access to tourist destinations can cause significant declines in economic activity and loss of tax revenue (Regional Economics Institute Center for Disaster and Risk Analysis 2013). More difficult to quantify are "breaks in social networks and families, anxiety, and stress" (Niemeier 2013, p. 307). I-70 is already plagued by congestion that is expected to worsen in the future–estimates indicate that if congestion along I-70 continues at its current rate, tourism spending could be suppressed by as much as 38% by 2025 (FHWA and CDOT 2011). All of these impacts could be exacerbated by Increasingly intense winter storms, which are likely under many future climate projections (see Chapter 2).

Impact of GHG Emission Reduction Policies

Although the direction and impact of future policies is uncertain, it is likely that efforts to reduce greenhouse gas (GHG) emissions will affect Colorado's transportation sector. Figure 8.5 shows Colorado's transportation and total CO_2 emissions from fossil fuel consumption between 1980 and 2011. Transportation CO_2 emissions increased 55% during that time period, while total CO_2 emissions increased 58%. Over the same time period, transportation emissions have fluctuated between 29-32% of total CO_2 emissions.[6]

Colorado has instituted a number of measures aimed at reducing GHG emissions from the transportation sector, including:

- The 2007 Climate Action Plan which recommended the adoption of clean car standards in the absence of federal action (Ritter 2007);[7]
- CDOT's 2035 Statewide Transportation Plan which pledged to "begin identifying strategies and actions to achieve Colorado's transportation goals to address global warming" (CDOT 2008, p. 24). The plan is currently being updated and will continue to address this issue (M. King, pers. comm.);

6 Although the transportation emissions statistics cited here and used in Figure 8.5 are from the U.S. Energy Information Administration, further detail on GHG emissions in Colorado is available through the Colorado Greenhouse Gas Inventory--2014 Update conducted by the Colorado Department of Public Health and the Environment. Their report indicates that 2010 emissions from the transportation sector accounted for approximately 31% of total Colorado CO2 emissions from fossil fuel combustion and 24% of Colorado's total GHG emissions (Arnold et al. 2014).

7 Federal action later superseded the need for Colorado to implement clean car standards as recommended in the Climate Action Plan (RMCO 2013).

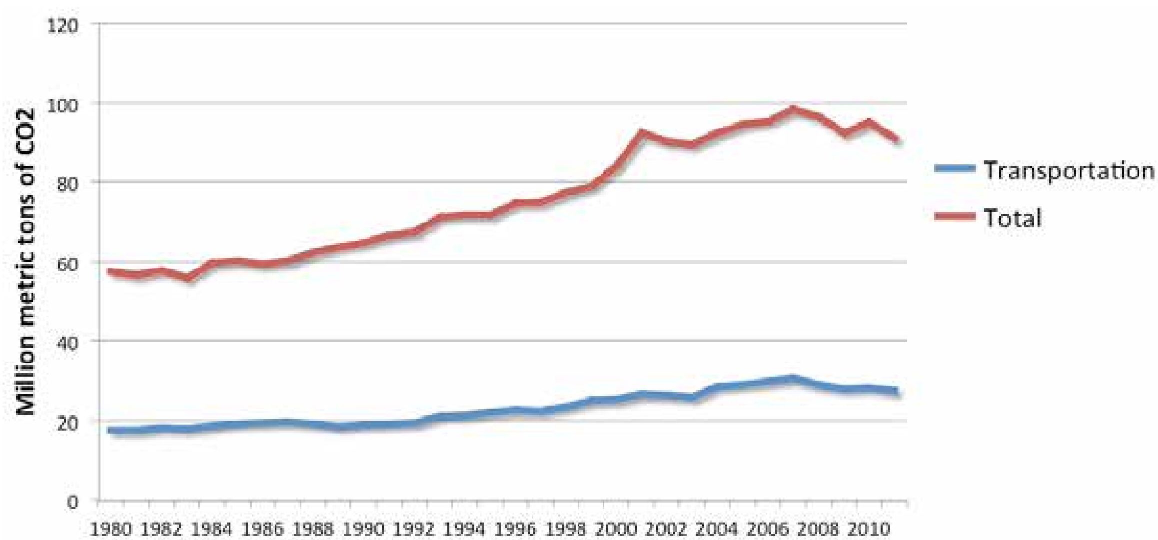

Figure 8.5. Carbon dioxide emissions in Colorado showing total and those solely from transportation sources. Data from U.S. Energy Information Administration (EIA 2014).

- CDOT's 2035 Statewide Transportation Plan Amendment which noted that CDOT is engaged in the development of a "framework" for incorporating GHG emissions reductions into planning before the next Statewide Transportation Plan update (CDOT 2011b, p. 17);
- CDOT Air Quality Policy Directive 1901 approved through the Air Quality Control Commission, effective May 21, 2009 (CDOT undated b);
- CDOT's Air Quality Action Plan, which is a first step in implementing Air Quality Policy Directive 1901 and recommends various strategies to reduce transportation emissions, including use of alternative vehicles and alternative fuels (CDOT 2012a);
- CDOT's participation in the Energy Smart Transportation Initiative that is addressing transportation energy use (CDOT et al. 2012b);
- A partnership among the Colorado Energy Office (CEO), CDOT, and the Regional Air Quality Council (RAQC) on a $30 million, 4-year program designed to encourage the use of compressed natural gas (CNG) vehicles throughout the state;
- An Ecodriving campaign that Governor Ritter joined in 2008. The campaign encouraged drivers to employ measures such as avoiding rapid starts and stops, using cruise control, reducing idling, and knowing the optimal conditions for using air conditioning (Ritter 2008);[8]
- A partnership with the Fostering Electric Vehicle Expansion in the Rockies program which is intended to create a plan to increase the adoption electric vehicles across the state (American Lung Association 2013); and
- A suite of measures aimed at reducing emissions from CDOT operations including Eco Passes for CDOT employees and an anti-idling policy.

Other regulations and initiatives will affect GHG emissions from the transportation sector. Federal regulations to increase the average fuel economy of cars sold in the United States were finalized in 2012, and in 2014 President Obama announced an effort to increase the fuel economy of large trucks. The Renewable Fuel Standard requires that transportation fuel sold in the United States contain a minimum volume of renewable fuel, although EPA recently proposed reducing the advanced biofuel and total renewable fuel standards for 2014 in response various limitations on use of these fuels. Electric vehicles are also becoming more popular, and concern exists that their widespread adoption of electric vehicles will strain the electrical grid if enough customers

8 The current status of this program is unknown.

charge their vehicles during peak hours (Klein et al. 2011). It is not clear how these policies might impact the driving behavior of Colorado residents and, ultimately, GHG emissions in the state.

III. Key Vulnerabilities in Sector

Colorado's transportation sector has demonstrated significant ability to respond to weather extremes under current climate conditions, evidence of what is referred to as "adaptive capacity." For example, following the September 2013 floods along the Front Range, CDOT was able to temporarily repair and reopen all of the damaged roads ahead of the December 1 deadline set by Governor Hickenlooper. However, concern exists that rebuilding and repairing roadways too quickly may create long term vulnerabilities; thus CDOT is reevaluating bridge and culvert design based on the flood experience (K. Sheaffer, pers. comm.). Even with relatively quickly reopened roads, several communities were inaccessible during the weeks that these roads were washed out, causing significant impacts to area residents and businesses. These areas and portions of the road network that are in mountainous terrain, as well as other areas that have few transportation connections, have significantly less adaptive capacity due to a lack of what the FHWA calls "redundant routes or modes" (FHWA 2012a, p. 32). Improving this adaptive capacity in mountain towns, however, may be extremely impractical, given the lack of alternative routes or other transportation mode options for many of these communities.

Further, CDOT's Applied Research and Innovation Branch and Materials and Geotechnical Branch research and evaluate roadway materials that will be more resilient to increased extreme heat events and heavier or more frequent precipitation events for future repaving efforts and other anticipated impacts (see CDOT 2013b). However, the relatively long lifespan of some transportation infrastructure (major bridges have 50-100 year lifespans, TRB 2008) could make it difficult to integrate new materials into roads or bridges unless they are near the end of their lifespans.

The state has engaged in planning efforts to reduce greenhouse gas emissions in the transportation sector, as discussed above, including the Colorado Climate Action Plan, CDOT Air Quality Action Plan, and CDOT 2035 Statewide Transportation Plan and amendment. These efforts could help create capacity to plan for climate change adaptation. However, it is apparent that more focus has been put into reducing greenhouse gas emissions than into adaptation.

Federal agency action also can help increase Colorado's adaptive capacity in the transportation sector. FHWA's Federal-aid and Federal Lands highway funding may be available for climate change adaptation activities (FHWA 2012b). While FEMA's traditional policy has been to fund the replacement of damaged culverts and bridges only to original capacity, it recently agreed to fund the cost of rebuilding culverts in Vermont that were destroyed by flooding from Hurricane Irene to greater capacity so they can withstand future extreme flooding (see Shumlin 2013). As of the writing of this report, CDOT is in discussions with the federal government about reimbursement for rebuilding bridges and culverts damaged in the September 2013 floods to provide greater capacity than in their pre-flood designs.

Adaptive capacity for air travel in Colorado airports likely varies by airport. DIA already has the longest public runway in the country to allow jumbo jets to take off during the summer. Whether this or other Colorado runways will need to be expanded further due to increased heat is a subject for future research.

Colorado is relatively fortunate compared to other states in that its transportation system will not have to prepare for some of the most devastating climate change impacts including sea level rise, melting permafrost, or a potential increase in hurricane frequency and/or intensity. Based on the projected changes to the state's climate, our judgment and our review of the literature, we conclude that the primary key climate change vulnerability in the state's transportation system will result from intense precipitation events—usually snow—limiting access to destinations that do not have alternative routes or modes of transportation. Figure 8.6 shows historic annual average precipitation throughout the state overlaid with a state road map showing major roads and towns. This figure illustrates portions of the state that get significant precipitation, especially in winter, and are served by few transportation links. The combination of potentially increasing winter precipitation events for specific areas within Colorado that have limited transportation options could create significant vulnerabilities in the transportation sector (see Box 8-1).

Even though projections of future climate do not indicate an increase in intense precipitation events, flooding is expected to continue to occur due to climate variability. Floods larger than experienced in our history are still possible due to the rarity of such events. These types of floods can cause significant damage to infrastructure such as bridges and culverts.

Other potential key vulnerabilities include increased roadway deterioration and the need for more maintenance due to extreme heat if Colorado were to experience increased heat waves. In addition, wildfire can cause damage to roads. For example, the Waldo Canyon fire caused increased flooding due to soil and vegetation changes, damaged roads, and increased debris flows that plugged culverts (CDOT 2013e). Further, Colorado is dependent on freight rail for, among other things, the movement of coal for energy. Increasingly hot temperatures can necessitate rail slowdowns and shorter trains (Peterson et al. 2008). Design changes can reduce rail line stress from heat (TRB 2011), yet replacing tracks could be prohibitively expensive (see Oslakovic et al. 2013; DRPT 2008; Vickers 1992). Finally, DIA is an increasingly important transfer point, especially for passengers. If higher temperatures limit the amount of weight that planes can carry, DIA could see flight cancellations and service disruptions (TRB 2008), potentially leading to either higher costs or fewer flights coming to Denver.

CDOT and other road maintenance agencies have some adaptive capacity to cope with climate related impacts, although that

Historic Annual Precipitation and Major Roads and Towns in Colorado

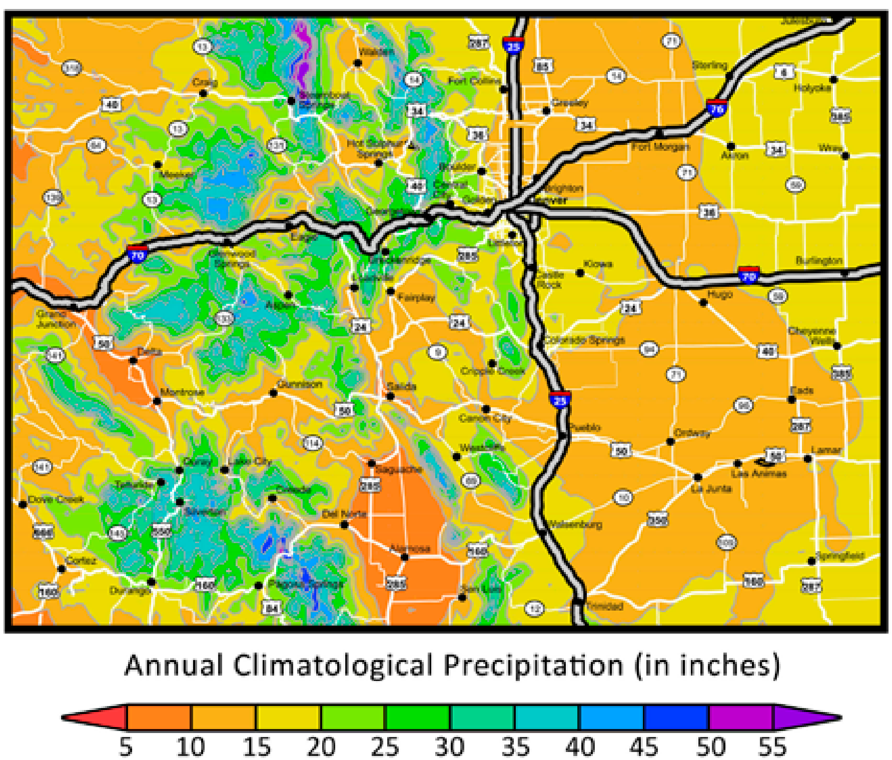

Figure 8.6. The combination of significant precipitation and a lack of multiple road links is a key vulnerability for Colorado. This image shows average annual precipitation for the period 1950-1999 combined with a map of major roads and towns, demonstrating which parts of the state are most likely to be affected by heavy winter precipitation. (Precipitation data: PRISM Climate Group, Oregon State University; road map: iStockphoto, jamirae).

capacity could be overwhelmed if these impacts are severe enough and the state is not adequately proactive in planning for them. Further, budgetary issues may limit the ability of transportation agencies to expand their current capacity to address increased impacts from climate change. There is insufficient information about the adaptive capacity of Colorado's air and rail industries to cope with extreme heat impact on high altitude airports and extreme heat and precipitation impacts on rail, but these could be additional key vulnerabilities if insufficient adaptive capacity exists. The adaptive capacity of rail and air in Colorado is a topic for future research.

Impacts of Current Climate Variability and Future Climate Change	Examples of Potential Vulnerabilities
Sustained extreme heat	
• Causes road and runway buckling • Stresses bridge integrity • Limits construction crew schedules • Results in loss of lift for airplanes • Causes rail deformation as well as derailments	• The possibility of increased future need for road maintenance and road closures for heat-related problems makes the **road** system vulnerable given current adaptive capacity • **Airports** unable to extend runways may find themselves vulnerable to reduced cargo capacity due to warmer air, which can make passenger flights less cost effective. DIA may experience summer cargo losses as high as 19% by 2030. • **Rail lines** are particularly vulnerable to increased heat due to the very high cost of installing more heat-resistant tracks
More frequent and intense drought which increases wildfire risk	
• Causes road closures, reduced visibility, and a greater risk of mudslides; decreases safety • Threatens airport facilities directly and impairs visibility	• All elements of the transportation system, especially **roads**, are vulnerable to closures due to increased wildfires. Communities and travelers are vulnerable to safety hazards from wildfire
Continued flooding events and increased intensity of winter storms	
• Can lead to submerged roads; flooded underpasses; road and bridge scouring; increased landslides and mudslides, overloading of drainage systems, compromised structural integrity of roads, bridges, and tunnels; adverse impacts on road bases; the need for larger bridges and culverts ; road closures; increased maintenance costs • Can cause flooding of airports as well as damage to runways and drainage systems • Can cause flooding of rail lines and damage to rail bed support structures ; winter snows can damage rail track and cables and block tracks	• The state's **road** network could be vulnerable to closures and infrastructure damage due to intense precipitation, even under the current climate, and traffic accidents are linked to extreme weather • Communities with limited **road** access are highly vulnerable to being cut off by floods or winter storms. • **Airports** could be vulnerable to damage to runways and drainage systems from flooding events and winter storms that overwhelm their existing capacity to respond • **Railroads** could be vulnerable to damage from flooding and winter storms that overwhelm their capacity to respond

Table 8.1. Climate impacts and potential vulnerabilities.

Table 8.1 summarizes observed and/ or projected physical climate changes and impacts, and examples of potential vulnerabilities.

III. Moving Toward Preparedness

The state of Colorado will assess whether it wants to adopt proactive adaptation policies for the transportation sector or rely on a reactive approach. A proactive policy approach would entail measures to upgrade roads as they are re-built and maintained, with the goal of adjusting road design to improve resilience to climate impacts. It would encourage local governments and state agencies to proactively analyze their flood vulnerabilities and not wait for damage to occur. This policy may be preferred because it is feasible to assume that the large existing stock of road infrastructure will remain in place in the coming decades and will therefore incur damages that require repair. While many adaptation options are suggested for roads lying in floodplains and other vulnerable areas, these options require very specific, localized data and decision making that encourages local climate impact analysis. Proactive adaptation would entail significant near-term costs to adapt an existing road to future damages that may occur if precipitation or freeze-thaw cycles were to increase in the future.

A reactive strategy, on the other hand, assumes no adaptation changes are put in place—for example, roads would be rebuilt according to existing baseline standards. The costs incurred would thus be from increased maintenance necessary to retain the design life of the original road as degradation of the road infrastructure occurs from climate stressors. This approach requires less up-front costs and eliminates the possibility of spending on upgrades that later prove unnecessary, but leaves the state vulnerable to impacts that may require rebuilding of roads ahead of schedule and increased maintenance costs, especially in the wake of extreme weather events.

The cost of taking action now may avoid more costly retrofits later (Schwartz 2010). A proactive adaptation strategy where roads are designed initially to be more climate resilient was estimated to save up to €90 million annually in the Netherlands compared to a strategy that uses increased maintenance to maintain the life of the road, but makes no changes to the road's initial design (Kwiatkowski et al. 2013).

Should the state choose to take the more proactive approach, a reasonable first step would be to conduct an inventory of transportation assets to determine their potential vulnerability to projected climate changes (TRB 2008). The FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012a) provides a framework for transportation agencies interested in assessing their vulnerability to climate change and extreme weather events. This framework incorporates lessons learned from five climate change vulnerability and risk assessment pilot projects conducted by state DOTs and MPOs in New Jersey, the island of Oahu, San Francisco, Virginia, and the state of Washington using an earlier version of the framework (FHWA 2012a).

Transportation vulnerability could be incorporated into decision making in many ways. Colorado might consider the following options that have been implemented in other states:

- Updating the state transportation plan to include climate change adaptation considerations;
- Integrating climate change considerations into long-term risk management plans for transportation corridors;
- Developing transportation design and engineering standards to minimize climate change risks to vulnerable transportation infrastructure;
- Incorporating climate change considerations into the designs of rebuilt bridges and culverts;
- Regularly cleaning out culverts to prevent wash outs during major storms and floods;
- Improving road weather information

systems and analysis to providing information on climate change impacts to the transportation system;

- Using pervious pavement to manage storm water through reduced runoff and on-site flow control;[9] and
- Developing new strategies to effectively respond to increasingly intense storms, including providing alternative transportation access.

(Meyer et al. 2012)

Specific adaptive measures that can be taken by the transportation sector for the climate impacts Colorado may face include:

- Research and development of new, heat-resistant or resilient materials as needed;
- Replacement of bridge and highway expansion joints;
- Longer runways to account for lower lift-off capacities;
- Design changes to reduce stresses in rail lines;
- More nighttime construction to avoid undue heat stress for construction workers with the added benefit of less traffic disruption;
- Revise outdated Federal Emergency Management Agency floodplain maps;
- Update hydrological storm frequency curves;
- Better land use planning in floodplains;
- Construction of storm retention basins for short, high intensity storms that can cause flash flooding;
- Evacuation plans in case of wildfire, flooding, or other threats to community safety that include alternative evacuation routes and backup power supplies if utilities go down; and
- Rethinking equipment purchases and training of personnel to respond to an increase in winter storms.

(See TRB 2011)

V. Future Research Needs

Future research needs in the transportation sector include a comparison of the cost of proactive versus reactive adaptation approaches. This analysis could include consideration of the long-term economic and social impact of climate-related travel disruptions, a topic that has received little attention (Nieimeier et al. 2013). Other future research needs include:

- An analysis of climate related road closures and repair costs over time;
- Determination of whether climate change will increase the frequency of freeze/thaw cycles in Colorado;
- The availability of new roadway and rail materials that can withstand higher temperatures;
- New design criteria for culverts;
- The impact of increased population and traffic loads on climate-sensitive roads;
- The need to extend runways at airports because of higher heat;
- The adaptive capacity of the rail industry;
- The impact of GHG emission reduction policies–specifically an increase in electric or plug-in hybrid vehicles and an increase in biofuels–on the transportation, energy and agriculture sectors;
- Testing the FHWA climate change/extreme weather vulnerability assessment framework, using risk management approaches; and
- Developing a Colorado-specific vulnerability/risk management model that can be used statewide to identify high-risk areas.

9 CDOT's Drainage Design Manual advises that porous pavement is best used in areas of low traffic volume (CDOT 2004).

Box 8-1
Southwestern Colorado Regional Highlight: Highways and Winter Storms

The southwestern portion of Colorado includes the canyon country of the Colorado Plateau, the ragged San Juan Mountains, and the Gunnison River valley. Some parts of the region are as low as 6,000 feet and provide prime farming and ranching country, but other areas rise to over 14,000 feet and feature some of the state's most spectacular mountain peaks. In fact, San Juan County has the highest mean elevation of any county in the United States at 11,240 feet (Mills undated).

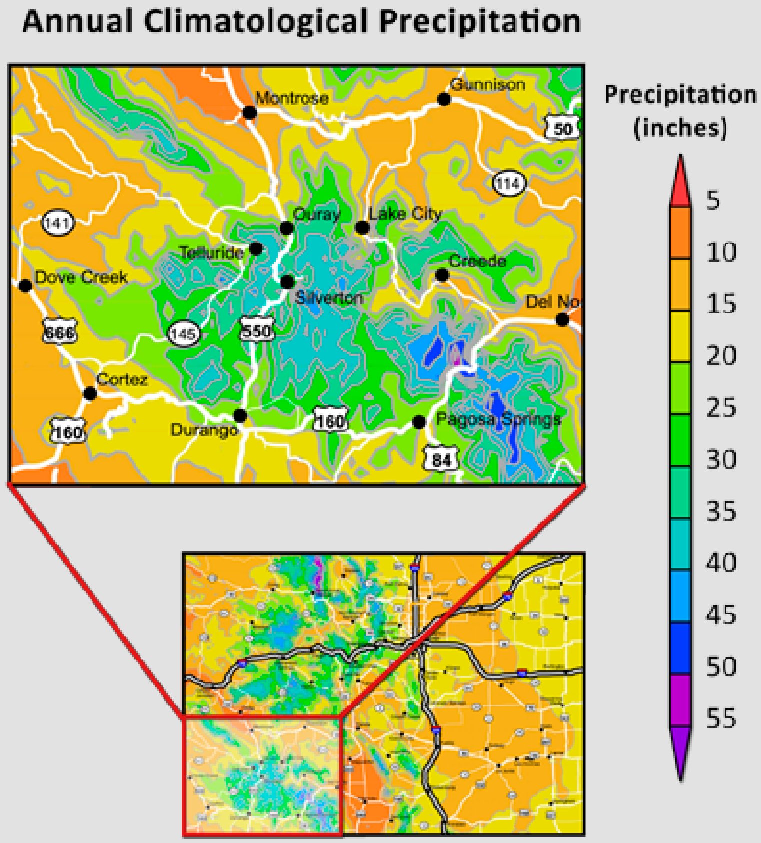

Figure 8.7. Southwestern Colorado has both high levels of precipitation and a concentration of towns without multiple major road connections (Precipitation data: PRISM Climate Group, Oregon State University; road map: iStockphoto, jamirae).

With its rural character, isolated towns, and high mountains, southwestern Colorado sees tremendous impacts from winter weather. Portions of southwestern Colorado receive an average of 40 or more inches of precipitation per year (see Figure 8.7 below), most of which comes in the form of snow. In fact, Red Mountain Pass receives an estimated average of 518 inches of snow per year (Keen undated). Winter storms could become wetter as global temperatures warm (see Chapter 2), resulting in even higher amounts of precipitation falling in these mountainous areas.

With few redundant transportation routes, this area is vulnerable to continued—and possibly worsening—impacts from winter weather. Routes like Highway 550 between Montrose and Durango or Highway 160 between Del Norte and Pagosa Springs can be closed for traffic accidents, deterioration of the road surface, and avalanches or snow and ice conditions. Under these conditions, few feasible alternate transportation routes or other transportation options are available in the winter, meaning commuters unable to get to work and tourists unable to access high elevation towns like Ouray, Silverton, or Pagosa Springs. Figure 8.7 shows the region's highway network and average annual precipitation, providing some idea of the towns most vulnerable to climate impacts on transportation.

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Hikers walking along the North Inlet Trail in the Larimer County portion of Rocky Mountain National Park. Photo: Wikimedia Commons, Brian & Jaclyn Drum.

CHAPTER 9
OUTDOOR RECREATION AND TOURISM SECTOR

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I. Brief Description of Sector

Tourism and recreation are important for Colorado's economy and for the well-being of the people who live and play in the state (Thomas et al. 2013). Visitors and residents alike enjoy a variety of activities including hiking, camping, wildlife viewing, biking, hunting, four-wheeling, golfing, fishing, rafting, kayaking, sailing, climbing, mountaineering, skiing, snowshoeing, and snowmobiling (Klein et al. 2011).

The World Tourism Organization delineates tourism based on how far individuals and groups travel to their destination. Tourism differs from recreation and leisure in that tourists are temporary visitors seeking leisure and recreation geographically apart from where they usually live and work (Scott et al. 2008), often seeking out national and state parks as well as landmarks and historic sites (Longwoods International 2013). Those who self-identify as recreators, on the other hand, are more interested in activities closer to home. In this chapter we delineate the two subsectors by defining tourism as activities involving visits from out of state while recreation involves activities undertaken by state residents.

Most of these activities are directly connected to Colorado's natural beauty and the wealth of parks and other public lands offering recreation and tourism opportunities. The state is home to 13 national parks including well-known Rocky Mountain and Mesa Verde as well as newer additions including Black Canyon of the Gunnison and Great Sand Dunes. 42 state parks also offer abundant opportunities for hiking, camping, fishing, and other activities. Roughly 40% of Colorado's lands are publicly owned, concentrated in the forested mountainous regions of the state, with some mountain counties near 90% public ownership (Klein et al. 2011). The map below depicts the ownership patterns in the state.

As the map in Figure 9.1 conveys, much of the western portion of the state is owned and managed by federal agencies. These federal public lands are vital for recreation, as they literally provide the spaces to be active. Table 9.1 lists some common recreational activities and the number of federal lands opportunities for each activity in the state, as well as a few sample destinations.

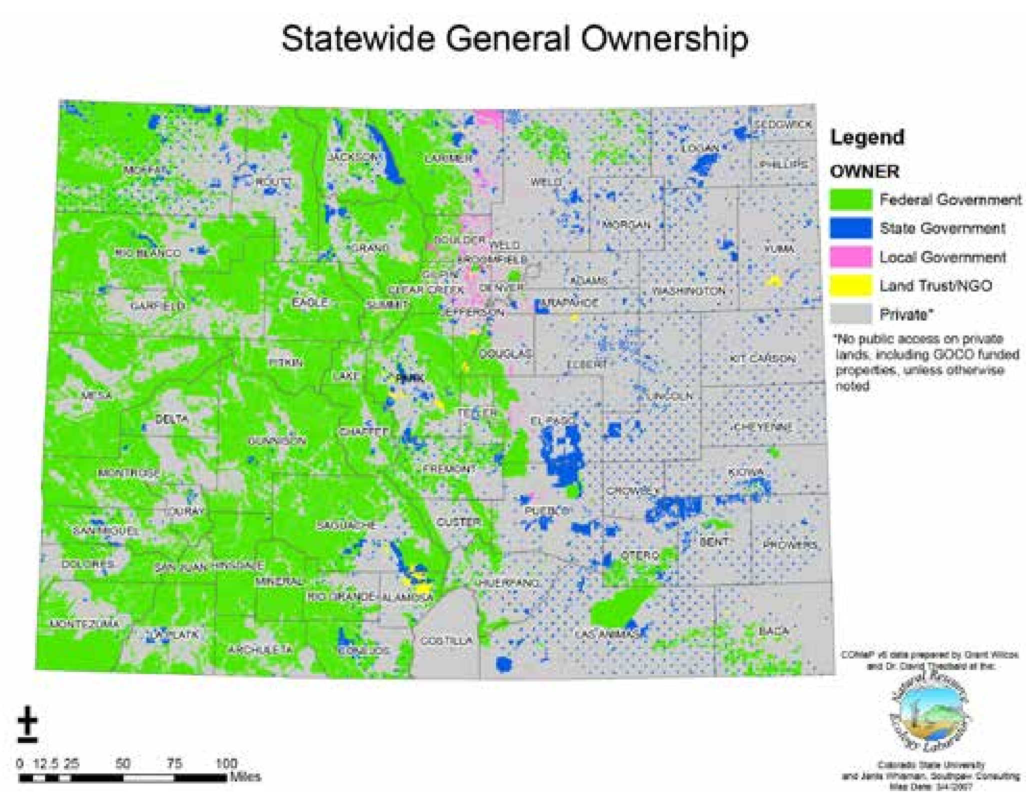

Figure 9.1. Land ownership patterns in Colorado (Wilcox and Theobald 2007).

Activity	Sample Destinations	Number of Locations in the State
Climbing	Boulder Canyon (USFS), Penitente Canyon (BLM), Black Canyon of the Gunnison (NPS)	33
Winter sports: Downhill skiing, cross-country skiing and snowshoeing, or ice fishing	Arapahoe Basin Ski Resort (USFS), Leadville National Fish Hatchery (FWS), Crawford Reservoir (BLM), Mesa Verde National Park (NPS)	65
Boating	Arkansas River (BLM), Rio Grande National Forest (USFS), Chatfield Lake (Army Corps of Engineers)	125
Off Highway Vehicles	Alpine Triangle (BLM), Canyons of the Ancients National Monument (BLM), Cimarron National Grassland (USFS), Rampart Range Motorized Recreation Area (USFS), Silverthorne area (USFS)	161
Wildlife Viewing	Alpine Triangle (BLM), Browns Park National Wildlife Refuge (FWS), The Energy Loop Huntington and Eccles Canyons National Scenic Byway (USFS)	199
Biking	Mesa Top Trailhead (USFS), Gold Belt Recreation Management Area (BLM), Colorado National Monument (NPS)	293
Hiking	Rocky Mountain National Park (NPS), Crested Butte (USFS), Lake Granby (BLM)	647

Table 9.1. A survey of activities on federal public lands in Colorado (Recreation.gov undated).

Access to public lands is critical to this sector. Thus roads have played a key role in the development of some of Colorado's major mountain recreation areas—in fact, many of Colorado's highways were built with tourism in mind. The construction of I-70 provided a direct connection between Denver and many mountain destinations, making Summit and Eagle counties into major tourism destinations. In terms of spending, transportation is the fastest growing component of overnight visitation to the state (Longwoods International 2013). Indeed, I-70 is now its own corridor, hosting rest stops, gas stations, restaurants, and numerous other attractions. Recreation and tourism opportunities dot this highway, in addition to the major ski resorts whose current popularity was at least partly tied to the interstate's construction.

Skiing deserves a special category in its own right given its unique qualities that make it a blend of recreation and tourism. Since the early 20th century, skiing has become an incredibly popular form of recreation in Colorado, made possible due to the U.S. Forest Service's acceptance of recreation as an important use of public forestlands and its policy of granting use concessions to private ski companies. Between 1916 and 1922, visitation to national forests grew from 2.4 million to 6.2 million people, the sheer volume prompting the USFS to reconsider its view that recreation lacked a commercial value in line with timber extraction and grazing (Childers 2012).

Finally, fishing is another iconic element of Colorado's recreation and tourism sector that intersects with land and water resources management. Good fishing opportunities require sufficient flows in streams inhabited by trout and other fish or adequate levels in stocked reservoirs. The conditions of watersheds surrounding popular streams or reservoirs can also affect the viability of fish populations in those waters.

Economic Value

Depending on the economic activities (e.g., fuel costs, meals while traveling to a destination, etc.) or the sub-sectors included (e.g., hiking, skiing, wildlife viewing, among others), recreation and tourism is estimated to bring between $8.5 billion and $15 billion per year (Colorado State Parks 2008). Rocky Mountain National Park (Figure 9.2) alone receives, on average, more than 3.1 million visitors each year, most coming from outside Colorado (Cutler et al. 2013). Methodologies that focus on compiling the total economic impact based on *recreational* activities produce the lower end figures while those that have a more expansive approach and incorporate *tourist-based* activities like transportation, lodging, meals, and retail incidentals produce the higher-end figures.[1] We consider the economic value of the sector both in terms of out-of-state tourist spenders as well as resident recreators.

A more comprehensive assessment by Longwoods International estimated that tourists spent $11.2 billion in the state, when considering both day and overnight visitation (Longwoods International 2013). Day visitors tend to spend money on food, drink, and retail purchases while overnight visitors spend the most on transportation and accommodations. Overnight visitors spent roughly $9.6 billion while day visitors spent $1.6 billion (Longwoods International 2013). Even though 2012 was a drought year, Colorado saw a record 60.2 million trips to the state, the highest total number ever reported (Longwoods International 2013), demonstrating resilience in Colorado's tourism sector (Tourism Industry Assoication of Colorado undated).

Figure 9.2. Rocky Mountain National Park in north-central Colorado receives an average of 3.1 million visitors annually (Photo: iStock, sherwoodimagery).

Much of this revenue goes to privately owned tourism operators, although state, local, and federal landowners also benefit. The private sector derives income from tourism and recreation by selling lift tickets, providing lodging or guide services, and many other activities, while the public sector receives direct income through the sale of items like park passes, camping and fishing permits. In addition to direct contributions to both the public and private sector, the sector brings in significant tax revenues. In 2010, recreation activities contributed $750 million in local and state tax revenue, which represents about 19% of Colorado's economy (Thomas et al. 2013).

1 It is important to note the figures vary depending on which measures are included. Revenues, for example, are based on market prices multiplied by the number of units (i.e. visitor days) while economic impact typically includes multiplier effects. Economic activity is defined as "Dollars spent within region that are attributable to a given industry, event, or policy" while economic benefit is defined as "A net increase in total social welfare. Economic benefits include both market and nonmarket values" (Watson et al. 2007).

There are existing estimates of the economic value of public lands in the state, however. Colorado has 13 National Parks, drawing more than 5.8 million visitors per year and providing $319 million in annual economic benefit (National Park Service 2012). In terms of drawing out-of-state visitors, Colorado is high on the list for vacationers. In 2012, there were nearly 161 million visits to National Forests, with an additional 300 million visits via scenic byways (U.S. Forest Service 2013). The Rocky Mountain region received the highest visitation of all the regions coming in at nearly 31 million visitors, with 1.4 million of these visitors going to wilderness areas (U.S .Forest Service 2013). By and large, those who visit national forests tend to visit sites near their homes, with about 65% of visitors travelling on average less than 100 miles (U.S. Forest Service 2013). The U.S. Forest Service estimates that at the national level, forest visits contribute over $13 billion to the GDP, sustaining about 190,000 full and part-time jobs (U.S. Forest Service 2013).

Activity	Number of Participants Per Year	Yearly Statewide Revenue
Skiing	11.4 million	$2.6 billion
Visiting Rocky Mountain National Park	3.1 million	$200 million
Rafting	411,100	$128 million
Hunting & Fishing	12.7 million	$1.84 billion
Wildlife Viewing	9.4 million	$1.2 billion

Table 9.2. Popular activities, levels of participation, and yearly statewide revenue (Colorado Ski Country USA undated; Longwoods International 2013; Aspen Global Change Institute 2006; Cutler et al. 2013; Bennet 2013; Colorado River Outfitters Association 2013; BBC Research and Consulting 2008; Colorado State Parks 2008).

Table 9.2 provides estimates of annual participants and statewide revenue for selected activities common in Colorado.

Regulation of Tourism and Recreation

There is no single agency in Colorado responsible for the regulation of the state's diverse tourism and recreation sector (Klein et al. 2011). Federal public land regulations and management are critical, as the agencies own over about 40% of the state's total land area, including much of the most desirable recreation lands. Chief among those agencies are the U.S. Forest Service, the Bureau of Land Management, and the National Park Service. The state's Division of Parks and Wildlife, meanwhile, regulates state parks. Given the importance of transportation infrastructure for recreation, it is worth mentioning the role of the Colorado Department of Transportation, the federal highway administration, and local transportation agencies. For more on the transportation sector's vulnerabilities in the state, see Chapter 8.

II. Key Climate Impacts to Sector

As described in Chapter 2, Colorado's climate is expected to warm between 2.5°F and 5.5°F by mid-century, with summer months likely warming slightly more than winter months. Projections of precipitation show no clear trend, although rising temperatures will likely result in earlier snowmelt and reduced runoff.

In this section we discuss the impacts that these and other potential future changes to Colorado's climate could have on the tourism and recreation sector. Determining the exact direction of overall impacts to this sector is complex given that temperature increases can reduce interest in some recreation activities while increasing interest in many others. For example, Colorado's topography allows individuals to substantially adjust the temperature they are experiencing by adjusting their altitude, giving the state continuing opportunities in a warming climate. Reductions in snowpack and streamflow would likely negatively impact specific industries, but uncertainty in future precipitation makes anticipating such impacts quite difficult.

It is also worth noting that the effects of climate warming in other parts of the country and the world may have ramifications for tourism and recreation in Colorado. Increases in local as well as global human populations and household income could boost demand for activities available in Colorado. If the state's high elevation helps maintain the availability of certain activities—such as skiing—relative to other areas, then Colorado's tourism industry could benefit.

Below we discuss in more detail how potential climate impacts can affect specific recreation and tourism opportunities.

Snowpack

Climate projections indicate a reduction in April 1 snowpack due to warming temperatures. Actual impacts of climate change on the skiing industry, however, will be affected by a number of different factors besides total snowpack. Our state's high elevation and cold temperatures provide a buffer against many of those effects, at least in the short term. Moreover, negative impacts on the viability of other popular skiing regions across the U.S. could provide a competitive advantage for Colorado's ski industry. For example, one study of future changes in the Arizona ski season showed that by 2050 temperatures will likely exceed the technical snow-making thresholds in the shoulder season, meaning the ski season will be limited to only the times when natural snowfall is sufficient (Bark et al. 2009). In the Northeast, ski tourism has been shown to be vulnerable to climate shifts (Scott et al. 2007)—even the most "sophisticated adaptation strategies" cannot prevent current and expected impacts (Dawson and Scott 2013).

However, Colorado ski resorts could still see negative impacts, especially from warmer autumn temperatures. In Colorado most resorts make snow in October, November, and December to boost early season conditions; therefore, warmer fall temperatures are significant (Wilhelmi et al. 2004). If ski areas do not experience long enough stretches of sub-freezing temperatures, it is conceivable they will not be able to maintain snowy slopes, regardless of whether they have snowmaking equipment or the water supply, shortening the length of the available ski season.

Figure 9.3. Although warmer temperatures could shorten snowmaking season length at Colorado ski resorts, one study found only small changes in March snow-covered area at Steamboat Mountain (pictured) and Crested Butte. The state's ski areas could also benefit in the short term from reduced skiing opportunities elsewhere across the United States (Photo: Eric Gordon).

To date, studies of specific ski areas in Colorado show relatively small changes in snowpack by mid-century. One study of Aspen's ski area noted that resort managers need at least 12 hours per day at or below the 28 to 32 degree Fahrenheit mark in order to engage in effective snowmaking operations. A reduction in that available time could have some impacts—early season ski conditions could be "thinner" by 2030, but the targeted Thanksgiving opening date was unlikely to be affected (Aspen Global Change Institute 2006). Battaglin et al. (2011)

similarly found only small changes in March snow-covered area at Steamboat (Figure 9.3) and Crested Butte resorts by 2050. Thus there is some reason to believe that snow available for skiing in Colorado would be negatively impacted, but the state may fare much better than competing winter destinations across the country, at least by mid-century.[2]

Reduced snowpack is an obvious sensitivity in the ski sector, but also important are earlier melt as well as seasonal shifts in temperature, which affect tourists and recreators' perceived enjoyment and comfort. As one report by the environmental advocacy group Clear the Air notes, "If the West gets less snow, one obvious effect would be less skiing and other snow sports. The season for skiing, snowboarding, and other snow-dependent sports could be shorter and the snow slushier—reducing enjoyment for skiers, profits for skiing-dependent businesses, and tax revenues for state and local governments" (Saunders and Maxwell 2005).

Wildfire

Climate warming is likely to result in more frequent and intense forest fires as a result of arid weather conditions and a longer growing season (The Center for Integrative Environmental Research 2008). Wildfires can result in a host of negative impacts to recreation and tourism, including hiking trails and campgrounds becoming inaccessible due to danger to people and infrastructure during or immediately following an event. Even if parks and trails are re-opened in a timely manner after an event, recreators may not be attracted to fire burned areas (Englin et al. 2001). Visitors may experience more fire bans enacted in order to prevent human-caused wildfires, resulting in fewer campers enjoying the quintessential campfire experience. For example, the wildfires that occurred in 2002 in Colorado were identified as a major factor in the overall summer tourism decline (Wilhelmi et al. 2004).

Fire is not only a risk to the enjoyment factor, but also to safety: increased wildfire frequency and size puts much of the recreation infrastructure at risk, including roads, trailheads, lodging, and the people who use them. Smoke can lead to highway closures, cutting off tourism opportunities in specific parts of the state, along with air quality problems. Even if a particular place is not experiencing a fire, if other parts of the state are, the effects can be contagious—wildfires can reduce the desire of out-of-state tourists to plan trips to Colorado (Thompson 2013). In a Florida study, about half of the tourists surveyed reported they would cancel vacation plans in case of high fire danger conditions, reported health problems from smoke and ash, or the spread of fire to a nearby vacation area (Thapa et al. 2010). Additional research is needed to better understand and quantify the effect of wildfires on recreation behaviors.

Plants and Wildlife

A number of plant and animal species are desirable for recreation and tourism activities like hunting, fishing, and hiking. For example, flower, leaf and wildlife viewing are all popular activities in Colorado, with 1.8 million participating per year in wildlife viewing alone (U.S. Fish and Wildlife Service 2011). Climate may positively or negatively affect the viability of many of these species. For example, a study in the Elk Mountain Range of Colorado has demonstrated a reduction in mid-season flowers in montane meadows, likely due to drought, hotter summer temperatures, and earlier snow melt (Aldridge et al. 2011). This reduced flowering effect is expected to create two separate peak times to view wildflowers, rather than one continuous season. It is important to note, however, that it is unknown how pollinator changes as a result of discontinuous flowering will ultimately affect the wildflower season in the longer term.

Fishing is also a popular activity in Colorado, with about half of those purchasing fishing licenses coming from out of state. Coldwater species, in particular rainbow trout, brown

2 There is also reason to believe that, especially under a future with high emissions of greenhouse gases, skiing in Colorado would become much more difficult by the end of the 21st century. However, few studies have considered that possibility, and it is outside the scope of this study, which focuses on mid-century impacts.

trout, and cutthroat trout, are favored for fishing, although in 2012 there was a slight increase in demand for warm-water game fish such as walleye (Colorado Division of Wildlife 2013). Potential climate impacts on fishing include decreased habitat suitability for coldwater species at lower elevations if temperatures rise and streamflows decline. Other areas of the West have seen more dramatic impacts–for example, bull trout are already so endangered that their capture is prohibited in Glacier National Park and it is possible that "if populations of other trout species decline as precipitously as scientists project, anglers might face more restrictions" in places such as Black Canyon of the Gunnison National Park (Saunders et al. 2009).

Warmer temperatures could also increase the severity of drought conditions, which affect game hunting. The Colorado Division of Parks and Wildlife reports that pheasant hunting (Figure 9.4) in 2013 was negatively impacted by a lack of nesting cover and brood habitat (Colorado Parks and Wildlife 2013a). These effects were particularly felt in northeastern Colorado, with reported "extreme impacts" in terms of pheasant numbers and cover availability, and densities significantly lower than in 2010 or 2011 (Colorado Parks and Wildlife 2013a). Similarly, deer hunting has suffered as a result of drought. The Division of Wildlife reports that two herds, located in the Groundhog area and near Mesa Verde, have experienced significant decline in the past fifteen years. Reasons for the decline include "drought, harsh winters, disease, predators and changing land development patterns that have changed the amount and quality of critical winter range" (Colorado Parks and Wildlife 2013b).

In terms of wildlife viewing, habitat generalists such as coyote, elk, and raccoons are likely to fare better than specialists like moose, pika and snowshoe rabbits (National Park Service and Center for the American West 2007), which may disappoint park visitors interested in viewing unique wildlife that they cannot see at home. Overall, however, projecting future changes in numbers of wildlife species in iconic locations such as Rocky Mountain National Park is quite difficult (National Park Service and Center for the American West 2007).

Freshwater in Streams and Lakes

Warmer temperatures generally increase the demand for reservoir- and lake-based recreation (J. Loomis, pers. comm.). Warmer temperatures are favorable for water-based sports like whitewater rafting (Figure 9.5), boating, fishing, water-skiing, beach vacations, and even newer activities like stand-up paddle boarding. As people seek relief from the heat, Colorado's reservoirs can provide enjoyable spots for recreation. There are 20 state parks with boat ramps, while 30 state parks offer swimming (Colorado Parks and Wildlife 2014). However, decreased reservoir supplies could affect the demand for reservoir-based activities. Reservoir levels may suffer due to higher temperatures as downstream water demands and evaporation rates rise with temperatures.

Figure 9.4. Pheasant hunting in Colorado suffered during the 2000s drought, as dry conditions negatively affected nesting cover and brood habitat (Photo: Jerry Neal, Colorado Parks and Wildlife).

Figure 9.5. Whitewater rafting remains a popular activity along many of Colorado's river corridors, but low runoff years have seen declines in rafting customers (Photo: iStock, SWKrullImaging).

The whitewater rafting industry is sensitive to changes in runoff, although other factors such as the economy and adverse publicity can also play a role as seen in 2002 (Shrestha and Schoengold 2008). 2012, another drought year, saw the rafting industry report a 17.1% decline in visitation; with 412,394 visitor days it was the lowest since 2002 (Blevins 2013; see also Box 9-1).

Length of Recreation Season

A shortening of the winter season or lengthening of the duration of the season deemed suitable for summer activities may alter the timing of recreators' activities and tourist visits. More summer-like conditions during "shoulder seasons" (fall and spring) may make these previously low-volume times more desirable for travel, increasing the demand for tourism services. This is consistent with what is known about visitation patterns in parks around the world during these months (Scott et al. 2008). Tourism matches recreation patterns in Colorado: July, June, and March are the most popular months for leisure tourism or non-business visits (Longwoods International 2013). Previous research on recreation and climate change in the U.S., recognizing an increase in length of the summer recreational season and a shortening of the season for winter recreation, suggests that comfort and enjoyment of particular activities becomes more important for the recreational experiences (Mendelsohn and Markowski 2004). Park visitation, for example, may become more popular in the shoulder season; analysis of both survey data and actual visitation records has shown this trend to be true for Rocky Mountain National Park (Loomis and Richardson 2006). Increased visitation is very likely with warming temperatures in spring and fall, and summer as well (J. Loomis, pers. comm.). Golfing is another activity that benefits from an extended season; research on warming temperatures in the Western U.S. supports this claim (see Loomis and Crespi 1999).

Moreover, seasonality affects the type of recreation activity. Individuals who live in a place that does not have the attributes they desire will justify travelling, sometimes long distances, to enjoy activities. Ski resorts are classic examples of this phenomenon (Irland et al. 2001). This tendency to seek out recreation opportunities not available at home, such as skiing, generally works to Colorado's favor. Colorado's skiing is world-renowned; Aspen, for example, draws visitors from places as far as China in larger numbers (Garrison 2013).

Transportation and Infrastructure Strain

Climate-related impacts to the transportation sector are likely to have significant ramifications for recreation and tourism. Flooding in 2013 resulted in temporary loss of access to Rocky Mountain National Park, leading to decreased visitation not only to Estes Park but likely to other Colorado vacation destinations along the Front Range and beyond (Cutler et al. 2013). Furthermore, heavy rains have been known to cause sink holes in asphalt, resulting in road closures around the state; one such instance near Leadville resulted in a closure to Highway 24, a popular route for tourists and cyclists alike (Hanlon 2012).

Disease vector exposure

Finally, climate warming may result in changes to recreation and tourism behaviors that affect public health. The need for cooling activities during summer may increase public exposure to vectors as people are drawn to recreational waters. This may result in more illnesses due to increased exposure. For more on the effects of climate change on the spread of infectious and vector-borne diseases, see Chapter 10.

III. Key Vulnerabilities

Adaptive Capacity

Recreation and leisure tourism is adaptive by nature—individuals exercise choice in their decisions about how to spend free time. "Spatial, temporal and activity substitution" factor heavily into the adaptive nature of the recreation sector (Scott et al. 2009). Thus the recreation and tourism sector may have significant adaptive capacity when considered as a whole, although specific industries may have relatively lower levels of such capacity, as described in the previous section.

Colorado's unique characteristics may provide additional adaptive capacity for recreation and tourism. The state's broad range of elevation and diversity of activities provide opportunities under a variety of circumstances. For example, even if skiing faces an uncertain long-term future due to impacts on snow, most ski resorts have the added benefit of mountain settings and climate characteristics that provide a host of warm-season recreational opportunities (Klein and Travis 2012). Thus, Telluride ski area now refers to itself as Telluride Ski & Golf, emphasizing its summertime activities as much as skiing.

In the short run, there is some reason to believe that climate warming could be beneficial to some parts of Colorado's recreation and tourism industries, especially when considering other states' vulnerabilities. As described earlier, worsening Northeast ski conditions may lead to an increase in ski visitation in Colorado (Hamilton et al. 2007; Hamilton et al. 2003). Moreover, much of tourism in Colorado comes from residents of hot regions of the country—in 2012, California, Texas, Arizona, and Florida made up the top four states of origin (Longwoods International 2013). As these states become hotter, it is conceivable that travelers may be even more interested in visiting Colorado for vacations.

Perhaps more than in any other sector, perception is closely tied to adaptive capacity in the recreation and tourism sector (Wilhelmi et al. 2004). Historically, a cool climate was one of the selling points of Colorado recreation and tourism. Old advertising slogans reflect this, with a 1950s poster of Pikes Peak showing the beauty of what is described as "Cool, Colorful Colorado" (Philpott and Cronon 2013), and the state's summer temperatures remain a major draw. On the other hand, negative perceptions can be devastating—although low river flows in 2002 corresponded with lower rafting outfitter revenues, further investigation revealed a more marked decline after Gov. Bill Owen commented on national media that

Figure 9.6. Snowmaking is expected to continue to be a key adaptive measure for Colorado's ski industry as the state's climate warms (Photo: iStock, srodgers).

"all of Colorado is burning" (Shrestha and Schoengold 2008).

The ski industry is believed to possess a significant degree of adaptive capacity, beginning with artificial snowmaking (Figure 9.6), which is used at most ski areas in the state. In addition, ski areas are capable of developing new terrain and new methods of skier access, along with a variety of additional techniques aimed at buffering against the effects of low snow seasons.

Finally, a number of innovative drought response strategies may provide adaptive capacity for dealing with future climate variability and change:

- Resort communities can look for opportunities to work with surrounding agricultural areas to reduce vulnerability in times of drought as low levels in rivers and reservoirs affect both sectors (Wilhelmi et al. 2004).
- Sprinkler irrigation can reduce drought impacts on small game birds by providing grass cover for nesting habitat (Colorado Parks and Wildlife 2013a).
- When reservoir levels are high enough, lake-based recreation can benefit while rafting suffers due to low flows (J. Loomis, pers. comm.; Loomis and Crespi 1999).

Potential Vulnerabilities

Nationally, outdoor recreation has seen an increase of 25% over the last decade; while Colorado follows the larger decadal trend, there is more variation between years

Observed and/or projected physical changes	Potential vulnerabilities in Colorado
Earlier snowmelt and runoff timing	• The commercial rafting industry is vulnerable to reduced season length due to shorter, faster runoff.
Climate conditions more favorable to "generalist" wildlife species than "specialists"	• Wildlife viewing as a draw for Colorado tourism may be vulnerable as coyote, elk, and raccoons become more common while marmot and pika become less common (National Park Service and Center for the American West 2007).
Rising stream temperatures and declining stream levels	• Fly fishing, a popular activity across Colorado, could be vulnerable as rising stream temperatures and declining streamflows reduce habitat for coldwater trout species.
Continued interannual variability in precipitation and temperature	• A number of activities, notably skiing and rafting, are vulnerable to continued large swings in temperature and precipitation from year to year as well as the effect such swings can have on perceptions of tourism and recreation in Colorado.
Increased frequency and severity of wildfire	• Virtually all summertime recreation and tourism opportunities are vulnerable to wildfire, which can close roads, destroy trails and campgrounds, cause air quality problems, and result in potential out-of-town visitors deciding not to travel to Colorado.
Shifting away from a snow-capped mountain aesthetic	• Visitors to Mesa Verde National Park and Rocky Mountain National Park may be less likely to see snow-capped mountains in the future (Saunders et al. 2009). • Glaciers in Rocky Mountain National Park may recede, changing the viewscape.

Table 9.3. Observed physical changes and potential vulnerabilities.

(Longwoods International 2013). A number of broad economic and demographic factors affect the ability of the state to attract out-of-town visitors and their spending. Thus although we can identify potential positive and negative impacts of climate change on recreation and tourism, understanding how these impacts will interact with other factors in the future remains a major challenge.

Table 9.3 summarizes key potential vulnerabilities of recreation and tourism in Colorado that stem from impacts identified in Section II. As discussed earlier, a warming climate may have a mix of positive and negative effects on the sector. Table 9.3 focuses only on those deleterious impacts for which, in our judgment, the industry lacks adequate adaptive capacity.

IV. Moving Toward Preparedness

Although preparedness efforts can be difficult in a sector comprised of numerous private companies and little clear regulatory authority, Colorado can draw some lessons from actions taken at the federal level. The Department of Interior's "America's Great Outdoors Initiative" was designed to develop a "21st-century conservation and recreation agenda" by addressing conservation challenges across the public and private sectors (recreation.gov undated). Launched in 2012, the website http://www.recreation.gov allows users to search for activities in Colorado; revealing recreational opportunities in the state ranging from campsites and picnic venues to hiking and tours.

This flexibility to choose between activities as diverse as paddling and diving to climbing and biking will enable recreators to be informed of their choices, based on seasonal variation and also in the face of ecological or resource constraints. Many entities in the private sector have taken on similar diversification efforts. For example, a promotional poster for Durango Mountain Resort lists a wide variety of activities that may not have traditionally been associated with a ski resort; these activities include: music, sleigh rides, fireworks, snowbiking, bungee trampolining, torchlight parades, tubing and ziplining.

The National Park Service has taken a strong approach to preparedness, stating that "responding to climate change is the greatest challenge facing the National Park Service today" and adopting a multi-faceted approach ranging from ongoing scientific monitoring, evaluating adaptation techniques, reducing the agency's carbon footprint, and educating visitors (National Park Service 2014).

In addition to these strategies, managing perceptions about recreation opportunities available in the state may be critical to the sector's future success. For example, Gössling et al. (2012) suggest that environmental changes in the alpine environment do not have to negatively affect tourism, especially if frames of reference are shifted as a landscape evolves. Closing recreational trails following a fire precludes the opportunity to educate the public about post-fire ecology (Englin et al. 2001) or the benefits of proactive response to climate change.

V. Future research needs

Refined Climate Metrics and Downscaled Climate Information

In general, global climate models are too coarse to provide meaningful information for the tourism industry. Although downscaling techniques exist to increase the resolution of climate models, outputs may still not be relevant to tourism and recreation. Thus future research could explore the development of model outputs with alternative metrics—for example, "thermal comfort" of tourists instead of average temperatures or frequency and length of precipitation events relevant to the quality of a tourist experience instead of overall changes to precipitation (Scott et al. 2008).

Understanding the Economic Impact of Activity Shifts

The tourism and recreation sector is built upon leisure preferences and choices about how to spend free time. As recreational opportunities shift, whether due to changes in season length or perceived enjoyment, it would be useful to conduct research on implications for spending and revenue. Having baseline data on the economic contribution of specific recreational activities will help us paint a clearer picture of how changes in temperatures and precipitation will affect the sector overall. Concessions should be made in estimating how benefits to one activity could negatively affect others. For example, researchers point out if anglers go salmon fishing more often, they will likely do other activities, such as trout fishing, less frequently (Watson et al. 2007).

Snow Research

The ski industry's ability to adapt depends to a large degree on the ability to make snow during times where precipitation is lacking. Since a daily continuous period of subfreezing temperatures is needed, it will be important to know when and under what future greenhouse gas emissions scenarios nighttime temperatures will still provide viable conditions for snowmaking.

Fire Studies

As wildfires become more frequent and intense, as expected, both recreation and tourism will continue to be affected. Colorado-specific studies show that hiking declines in a burn area as the aesthetic quality of a trail declines (Hesseln et al. 2004). We do not know, however, the full extent of the impact on tourism. Tourism behavior in response has been studied in other locations, but more Colorado-specific work is needed to show exactly how fire will affect not only the preferences but also the safety of both recreators and tourists.

Drought

In Colorado, it is especially important to have an early warning system in place for drought as users make tough decisions on water allotments, many of which can affect recreation (Alvord et al. 2008). In addition to ongoing research on the effects of climate warming on drought and streamflow, the sector would also benefit from an improved understanding of the nexus between tourism/recreation and drought (Thomas et al. 2013).

Table 9.4 breaks out areas where new scientific analysis would be helpful, both in terms of knowing the impacts of a changing climate and also assessing vulnerability.

Area for New Scientific Analysis	Specific Research Questions
Park visitation patterns and trends	• How do changing conditions like fire, drought, beetle kill, or species migration, affect tourists and recreators' willingness to visit? • Do warmer temperatures result in increased demand for reservoir-based recreation? What is the net effect when considering lower reservoir levels?
Hunting- and angling- specific studies of wildlife response to climate shifts	• Will elk herds stay at higher elevations for longer periods into the hunting season? This has implications for both hunters, who may have to access higher terrain, and the hunting season, the timing of which may need to be altered based on migration patterns. • Historically, state and federal natural resource managers stocked fishing ponds—often with non-native species or by placing fish in waters that had never been host to fish before, e.g. in high alpine lakes (Philpott and Cronon 2013). How will these assemblages fare? • How will migratory bird populations be affected in terms of habitat and population size? More knowledge is also needed on disease vector impacts in game animals and fish populations.
A tourism-climatic index	• A tourism-climatic index allows for measuring "human comfort," incorporating humidity, sunshine, and wind (Alvord et al. 2008). • Application of existing information or methodologies to the Colorado context would help improve understanding of vulnerabilities.
Cross-state comparative case studies	• Application of existing information or methodologies to the Colorado context would help improve understanding of vulnerabilities. • How might Colorado fare when considering this broader complement of factors, and when compared to other states?
Drought-specific impacts	• In Colorado, it is especially important to have an early warning system in place for drought as businesses make tough decisions (Alvord et al. 2008). The Colorado Water Conservation Board reporting process is particularly important here. • There is a need for better understanding of the tourism-recreation-drought nexus (Thomas et al. 2013) and incorporating drought planning in business decisions.
Comparative vulnerability in the ski industry	• While we know that the industry will be affected by changed precipitation patterns and warmer temperatures, it is not clear how these impacts will vary by specific location. Some resorts may be comparatively better positioned. More fine-grained climate models would help parse out this inter-regional variability.

Table 9.4. Future research needs for the tourism and outdoor recreation sectors.

Box 9-1
Central Mountains Regional Highlight: Tourism Vulnerabilities to Warmer Temperatures

The north-central portion of Colorado, west of the Front Range and extending roughly from the Gunnison River basin north to the Wyoming border, is heavily dependent on tourism to support the regional economy in the central mountains (State Demography Office undated). Twelve major ski areas call this region home, and tourists flock to the mountains to pursue summer activities such as rafting, fishing, hiking, hunting, and camping.

As a tourism-dominated region, the central mountains are particularly vulnerable to climate-related changes in water availability. Warmer fall temperatures could delay snow accumulation and snowmaking capacity, as projected in one study of impacts on the Aspen ski resort (Aspen Global Change Institute 2006), although there is currently no indication that midwinter snowpack would be affected at selected Colorado mountains (Aspen Global Change Institute 2006; Battaglin et al. 2011). At the same time, because snow conditions in Colorado could be better than more climate-sensitive resort regions in other parts of the country, winter tourism could increase, bringing additional revenues but also exacerbating transportation problems on I-70 and elsewhere (see Klein et al. 2011).

The rafting industry, a key summertime draw for central mountain communities, is also vulnerable to reduced average streamflow (somewhat likely by mid-century) and earlier snowmelt timing (very likely by mid-century) that could cause flow availability mismatches with prime tourism season. The effects of climate on rafting are already evident from the droughts of 2002 and 2012; Figure 9.7 shows the drop in rafting user days in those years.

Finally, high temperatures and low humidity associated with drought can increase wildfire risk. Wildfires can devastate local tourism economies by leading to trail and campground closures, road closures, and risks to human health (see Wilhelmi et al. 2004). Even without active wildfires, which are less frequent in the high mountains, precautionary fire bans can reduce visitation to state parks (Klein et al. 2011) and other areas.

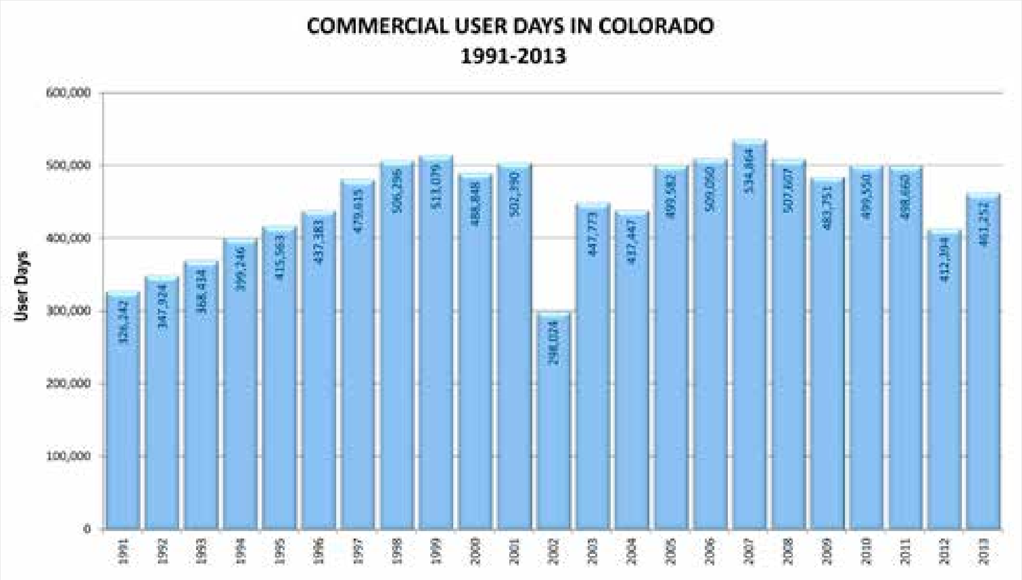

Figure 9.7. Commercial rafting user days in Colorado (CROA 2014).

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Wildfires result in higher concentrations of fine particulates from smoke, which pose public health concerns, especially for those with compromised lung function. Photo: Carol Lawrence, U.S. Air Force.

CHAPTER 10
PUBLIC HEALTH SECTOR

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I. Background

Overview of Public Health in Colorado

Climate influences all aspects of human health and welfare. Our most basic needs for clean water, clean air, food, and shelter are affected by precipitation levels, air quality, and temperature. For example, the cost of heating and cooling homes, schools, and office buildings is directly connected to outdoor temperatures. Extreme events like floods and wildfires are driven by climate and, along with causing immediate loss of life and property, have long-term impacts, altering the availability of and accessibility to goods and services. Due to global connections through modern commerce, the climate experienced by other states and countries can affect the well-being of Coloradans almost as much as local conditions do. Large-scale crop failure due to drought impacts the price and availability of food. Climate can also directly affect our exposure to infectious disease. Changes to long-term weather patterns can change the prevalence and range of many diseases and global transportation of goods and people can amplify the spread.

Although the economic impacts of climate-related public health problems can be difficult to assess, evidence indicates that these types of impacts often entail significant costs. For example, Knowlton et al. (2011) examined six different climate-related public health events across the U.S., five of which are illustrative for Colorado. Their analysis showed costs per 1,000 people of $22,705 for nationwide smog exposure in 2002, $148,792 for a two-week heat wave in California in 2006, $46,449 for a 2002 West Nile virus outbreak in Louisiana, $145,495 for flooding along the Red River in North Dakota in 2009, and $28,819 for wildfires in southern California in 2003. As described below and in other sections of this report, all of these types of events could occur in Colorado, and climate projections indicate rising future temperatures that would exacerbate heat waves, air pollution, wildfires, and West Nile outbreaks in our state.

Agencies Responsible for Public Health

A number of public agencies have authority over monitoring, regulation, and intervention for public health. Monitoring the outcomes discussed previously (diseases, mortality, morbidity) is under the jurisdiction of local, state, federal and international health agencies. For communicable diseases of international concern including vector-borne diseases, the World Health Organization provides lists of diseases that must be reported when they are diagnosed. The state of Colorado maintains a list of reportable diseases, which can include chronic or communicable diseases. Local health departments and state laboratories will report those diseases as required by law. Death certificates are completed by medical examiners or coroners and reported from the county officials to the state and ultimately to the federal reporting system managed by the National Center for Health Statistics, which is part of the Centers for Disease Control and Prevention (CDC). If there is an outbreak of disease that is of concern to a local health department or the state health department, they can invite the CDC in to conduct or assist in the conduct of an outbreak investigation. This could apply to communicable diseases, diseases of unknown origin, or those associated with environmental hazards including, potentially, climate change. Public safety, particularly in an emergency involving disease outbreaks, is a shared responsibility among emergency responders (e.g., police, fire department, paramedics) local hospitals, physicians, other health care providers, and the public health department.

Monitoring and regulation of hazardous exposures to air, water, and food rests with environmental sections within health departments at local and state levels and with different federal agencies including the Environmental Protection Agency, USDA, CDC, and FDA. The Federal Emergency Management Agency (FEMA), the Colorado Office of Emergency Management, and local emergency management agencies are responsible for coordinating response to climate-related events.

Potential Climate Connections to Public Health

This chapter provides an overview of the possible impacts of climate change to the prevalence of disease, injury, and death in society. However, there are few straightforward causal links between public health episodes and changes in the climate. Continuous demographic shifts, existing regulation, ongoing improvements to infrastructure, improvements in air quality, and adaptation strategies like vector control are often just as important or more important than climate to future public health impacts. The Colorado Department of Public Health and the Environment (CDPHE) and county and regional health and public safety offices throughout the state are already addressing many of the impacts presented in this sector in some way, but climate change may pose unanticipated challenges.

While it is difficult to attribute any particular weather event to climate change, public health officials must be prepared to address both known and emerging threats associated with weather regimes that fall within the range of projections. Current weather is the primary influence for some of these emerging threats, while others are driven by multi-year climate trends. In this chapter we identify key areas of concern and provide more information about the topics with direct climate-public health connections. The remainder of this chapter is organized into climate impacts, vulnerable populations, and adaptation.

Major public health areas of concern related to the effects of current climate (including weather extremes) and future climte change include:

- Increases in heat-related illness and mortality through increased frequency in the number and severity of extreme heat days.
- Negative air quality effects through increased pollen production due to spring starting earlier and lasting longer, increased ozone concentration due to higher temperatures, and increased particulates from more frequent wildfires.
- Potential changes in the occurrence of infectious diseases through extended seasons and expanded range for disease vectors as well as possible changes in patterns of interaction of wildlife hosts, vectors, and people.
- Traumatic death and injury due to continued severe storms and more frequent wildfires.
- Continued potential for intense rain events leading to flooding that could result in loss of life and property and contamination of water supplies.[1]
- Increased competition for water and reduced water quality due to increasingly severe droughts. Such competition would affect not only supplies of water for drinking and irrigation, but also recreational waters, negatively affecting the tourism industry and potentially exposing people to higher concentrations of contaminants and pathogens that thrive in warm water.
- Impacts of changing temperature and precipitation patterns within and outside Colorado can lead to higher food prices, increasing food insecurity for low-income families.
- Rising temperatures or other changes in climate trends may affect the incidence of vector-borne disease as a result of expanding or shifting geographic ranges.

While frequently neglected, there are also adverse mental health outcomes related to all of the aforementioned items. This is particularly true for natural disasters where the immediate fear and trauma is followed by long-term displacement for many. Lack of an integrated system of mental health care services may impede ability to respond to an increase in problems (White et al. 2013).

1 Although climate projections do not indicate changes in the frequency or severity of summertime convective storms in the future (see Chapter 2), such events will continue to occur in the future.

Demographic Trends and Social Vulnerability Concerns

Any study of risks to public health must incorporate information about existing demographics as well as trends for the population in question. A healthy population is more resilient, so it is important to assess changes among groups who have known vulnerabilities (older individuals, young children, families in poverty, and the chronically ill/disabled). According to Colorado's State Demography Office, Colorado's annual growth rate from 2000-2010 was approximately 1.7% (Garner 2011; see also Chapter 3). The age cohort consisting of residents aged 55-64 grew by 6.1% annually. Due to this increase, in 2030 the number of Coloradans over age 65 (Figure 10.1) is expected to be 125% larger than it was in 2010 simply due to aging (see Chapter 3). This increase in the population over 65 in 2030 will most likely be accompanied by an increase in the number of disabled and chronically ill individuals in the state. Moreover, other disabilities and illnesses lead to health vulnerabilities among Coloradans—for the years 2011-2012, 12.8% of adults in the state reported having asthma, 7.1% reported having diabetes, 25% reported having hypertension, and 55.8% were overweight or obese (Colorado BRFSS undated).

Socioeconomic status can also exacerbate vulnerability, particularly among children. In 2011, 16.6% of Colorado's children were living in poverty (see Chapter 3). Children under the age of 6 were more likely to live in poverty than older children. Between 2000 and 2011, the number of young Colorado children living in poverty increased by 136%. Young children need safe, healthy environments since early childhood exposures can affect the way a child's brain develops (Colorado Children's Campaign 2013). For more information on demographic trends in Colorado, see Chapter 3.

II. Key Climate Change Impacts

Heat-Related Illnesses and Mortality

Although rarely discussed in Colorado, heat is perhaps the most devastating climate-related public health impact in the country. As Chagnon et al. (1996) note, "the loss of human life by hot spells in summer exceeds that caused by all other weather events in the United States combined including lightning, rainstorms/floods, hurricanes, and tornados."

Figure 10.1. Elderly Coloradans may be particularly vulnerable to public health impacts from climate (Photo: iStock, lawcain).

Heat-related illnesses include:

- Heat *cramps* which result from the loss of body salts and fluid due to sweating.
- Heat *rash* from sweat not evaporating from skin
- Heat *exhaustion* (headache, nausea, dizziness, weakness) due to loss of body salts and fluid.
- Heat *stroke* (confusion, seizures, loss of consciousness), which occurs when the body cannot regulate its core temperature.

Short-term compromised thermoregulation

Figure 10.2. Those involved in working outdoors are particularly vulnerable to the effects of heat-related illnesses, which may become more common in Colorado as climate change results in higher average temperatures and greater extreme heat events (Photo: iStock, kozmoat98).

is thought to occur due to elevated plasma cholesterol along with increased platelets and red blood cell count. The blood then becomes more viscous, leading to decreased blood circulation to vital organs.

Heat related deaths are assumed to be under-reported because they are difficult to identify. Moreover, heat-related illnesses can be exacerbated by existing medical conditions. This is particularly true for individuals with preexisting diabetes, respiratory disease, or cardiovascular disease. Common medications including antidepressants, antihistamines, diuretics, and beta-blockers can all impair thermoregulation (NYC Health undated; Basu and Malig 2011).

Climate change is anticipated to exacerbate heat wave activity (Gershunov et al. 2013). As Colorado continues to warm (see Chapter 2), incidents of high heat days would likely increase. In fact, both the last 30 years and the last 50 years show increasing trends in heat waves in Colorado (Lukas et al. 2014). A recent analysis of high temperatures in Fort Collins showed an average of 8.8 days exceeding 95°F since 2000 (RMCO 2013). Historically, Colorado is not considered high risk for heat-related illnesses and death. This is due in large part to the semi-arid climate with its low humidity, cool nights, and higher elevation. However, with annual temperatures expected to warm by approximately 4°F by mid-century (see Chapter 2) leading to more hot days and warmer nights, heat may pose more of a risk than it has in the past. Moreover, the effect of higher temperatures is compounded in large, densely populated cities where open land and vegetation have been replaced by pavement and buildings that can cause a strong heat island effect. The air in a city can be 2°F to 22°F warmer compared to less developed surrounding areas (Akbari 2005).

Studies indicate that there is no simple relationship between increased heat wave duration and intensity and higher mortality in the United States. This lack of correlation is primarily attributable to the increased availability of air-conditioning in much of the country (Davis et al. 2003). While this may seem comforting, there are work environments that are not in climate-controlled buildings. Workers who have to be outside, such as agriculture workers, construction workers, or road crews are at high risk of heat exposure (Figure 10.2). Children, who have a greater skin surface-to-weight ratio than adults and therefore absorb more heat from their environment, may play outside, or live or attend school in non-air-conditioned buildings making them more vulnerable. The elderly are also at increased risk since they tend to have more chronic conditions that affect thermoregulation.

The fact that historically Colorado is not considered high risk for heat-related illness and death may in fact make it more susceptible. The European heat wave of 2003 was particularly devastating, in part, because it occurred in areas that do not normally experience extreme temperatures. Both the residents and public health officials in these regions were less prepared to respond to this kind of climate event. Like the most afflicted areas in Europe in 2003, air-conditioning is not ubiquitous in Colorado thus reducing the state's adaptive capacity (D'lppoliti et al. 2010).

Air Quality

Climate and weather are critical elements in controlling air quality, which is a significant public health concern in Colorado. As Kinney (2008) described,

> Weather and climate play important roles in determining patterns of air quality over multiple scales in time and space, owing to the fact that emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height. There is growing recognition that development of optimal control strategies for key pollutants like ozone and fine particles now requires assessment of potential future climate conditions and their influence on the attainment of air quality objectives.

Air quality is directly and indirectly dependent on climate and weather. Increasing temperatures and changing weather patterns could result in degradation of ambient air quality due to increases in concentration of ground-level ozone, fine particulates (i.e., PM10 particles, which are less than 10 micrometers in diameter) and aeroallergens. Emissions leading to higher levels of fine particulates and ozone can be influenced by the demand for heating and cooling derived from fossil fuels. Chemical reactions, like those between nitrogen oxides (NOx) and volatile organic compounds (VOCs) that result in ground level ozone (see Figure 10.3), are more rapid with heat. Rising CO_2 has been shown to increase allergenic ragweed pollen production (Wayne et al. 2002). The concentration of fine particulates from smoke increases with wildfire events. Wind speed, and direction combine with temperature gradients and humidity to determine local concentrations and final deposition of pollutants, smoke from wildfires, and pollen. There is also potential for increased exposure to higher concentrations of indoor air pollution from particulates, volatilizing chemicals in furnishing, and moisture-related contaminants due to reduced ventilation from improvements made to improve the insulation in buildings.

Climate change may exacerbate a number of air pollution-related public health risks. For example, exposure to ground-level ozone, which is worst on hot, sunny days, can cause congestion, irritation of the eyes, nose

Figure 10.3. Air pollution results in Denver's "brown cloud." Rising summertime temperatures are expected to increase ground-level ozone and other air pollution problems that impact public health (Photo: iStock, SWKrullImaging).

and throat, and coughing in healthy adults. Inhaling ozone can cause inflammation deep in the lungs and a temporary decrease in lung function. Repeated exposure may result in permanent scarring in the lungs. It can aggravate pulmonary diseases such as chronic obstructive pulmonary disease (COPD) and asthma and increase the occurrence of upper respiratory infections.

Similarly, fine particulates can get deep into lungs and even into the bloodstream. Like ozone, fine particles can irritate the eyes, nose, and throat cause chest congestion. Short-term exposure can exacerbate lung disease and has even been linked to heart attacks and arrhythmias in people with heart disease. Long-term exposure can cause reduced lung function, chronic bronchitis, and premature death (EPA 2009; Peel et al. 2005).

Figure 10.4. Mosquitos transmit West Nile Virus to humans. Although predicting future changes in West Nile Virus incidence is complex and difficult, mild winters and dry springs tend to increase prevalence of the disease (Photo: Centers for Disease Control and Prevention, Public Health Image Library).

The term "aeroallergens" refers to any substance in the air that causes an allergic reaction when inhaled. Common airborne allergens are molds and pollens. Molds are affected by increased humidity. Flooding also usually brings an increase in molds and associated respiratory problems. Assessment and removal of mold must be a high priority in affected buildings.

The onset of pollen production is also tightly linked to weather. As average temperatures rise, pollen production is beginning earlier in the year on average. There is weaker evidence that pollen seasons are getting longer, but studies indicate that the incidence of allergic diseases has increased rapidly in recent decades (Kinney 2008). It is probable that there are multiple factors influencing this rise. However, if pollen production rises with increased CO_2 for ragweed and similar plants, this increase is expected to continue.

Infectious Diseases

Climate plays a role in outbreaks of vector-borne and zoonotic infectious diseases and in the transmission of these diseases to humans. As noted by Gubler et al. (2001), "Most vector-borne diseases exhibit a distinct seasonal pattern, which clearly suggests that they are weather sensitive. Rainfall, temperature, and other weather variables affect in many ways both the vectors and the pathogens they transmit." Unfortunately, such connections are not simple. High temperatures, for example, "can increase or reduce survival rate depending on the vector, its behavior, ecology, and many other factors. Thus, the probability of transmission may or may not be increased by higher temperatures." (Gubler et al. 2001)

Mosquitoes (Figure 10.4), fleas, and ticks, are vectors for a number of diseases in Colorado that are known to cause extreme illness and even death in people. These include West Nile virus, hantavirus, plague, rabies, tularemia, and tick-borne diseases. Predicting climate-related changes to their distribution is extremely difficult due to the complexity of their transmission cycles as well as the effects of human behavior, which can facilitate or hinder the spread of these diseases. The state of the science is far from complete, but does provide insight into the role climate plays in disease emergence and distribution.

Disease monitoring in the state has provided some insight into the complexity of the link between climate and infectious diseases. The Colorado Department of Public Health and Environment has documented 49 human plague cases in Colorado since 1975 and 50 cases of hantavirus since 2003. However, there has been a steep decline in tick-borne disease since 1975, and since 2003 there have only been a handful of cases in any given year. By contrast, since its first appearance in Colorado in 2002, West Nile virus has emerged as the greatest threat with 131 confirmed cases in Colorado in 2012 (Colorado Department of Public Health and Environment, Division of Disease Control and Environmental Epidemiology 2013) and 316 cases and 6 deaths in Colorado in 2013 (CDC 2013a).

All of these diseases pose a significant threat to human health, and each has some connection to climate. However, although climate may strongly influence the spread of disease, temperature and precipitation patterns are not always sufficient to predict increases or decreases in the prevalence of vector-borne diseases or of populations of arthropods such as mosquitoes, ticks, or fleas or of animals that may carry and transmit disease. Weak climate correlations may still be useful in guiding monitoring and planning for response. For example, even though there is significant regional variation, studies have shown that springtime abundance of *Culex tarsalis* mosquito populations, which can transmit West Nile Virus, is inversely associated with the number of cold days in winter and positively correlated with snowpack (Reisen et al. 2008). Additionally, Chung et al. (2013) found that West Nile virus outbreaks in Dallas County, TX have been associated with unusually warm winters. Similarly, hantavirus appears to flourish during El Niño years when Colorado tends to receive above normal precipitation. Higher precipitation enhances the growth of forage for rodents, leading to larger populations, which in turn increases the possibility of human/rodent interaction and disease transmission (Hjelle and Glass 2000) The incidence of plague has been shown to cycle with the Pacific Decadal Oscillation (Ben Ari et al. 2008).

West Nile virus in particular provides a compelling example of how climate influences variability of disease occurrence. It is a mosquito-borne virus that first appeared in the United States in 1999 when a mild winter followed by a drier-than-normal spring may have allowed the virus to establish itself in New York. Approximately 20% of people infected by West Nile virus develop symptoms such as fever, headache, body and joint pains, vomiting, diarrhea, rash, and in extreme cases neurologic illness (e.g. encephalitis or meningitis). Even with mild infections, fatigues can last for many weeks. Cases resulting in neurologic illness have a 10% mortality rate (CDC 2013b).

The virus is maintained in a bird-mosquito-bird cycle and can be amplified by a particular sequence of weather related events. Mild winters and undisturbed pools of water allow more mosquitoes to survive and then rapidly propagate in spring. Dry springs and summers result in lower populations of mosquito predators and also force birds to congregate around fewer pools of water, which enhances interaction among mosquitoes and birds. The organic matter in water where mosquitoes breed becomes more concentrated in mild drought conditions which is optimal for nourishing mosquito larvae. Higher temperatures accelerate the replication of the virus in the mosquito, so it takes less time for the mosquito to become infectious. The sooner a mosquito becomes infectious, the greater the possibility that it will infect a human during its lifespan (Epstein 2000; Epstein 2001).

Changes in temperature and precipitation patterns could change the prevalence and range of West Nile virus, exposing new populations of both birds and people. This is a typical climate-vector-host set of interactions. Plague and Hantavirus outbreaks are similar and cycle with the climate-influenced availability of food and number of predators. Identifying optimal climate conditions for increased host

Figure 10.5. Post-flood clean up in a Boulder neighborhood (Photo: Bruce Raup, CIRES).

infection and numbers of vectors allows public health departments to implement strategies to break the cycle early.

In addition to diseases known to occur locally, changing climate and weather patterns, and migration of people and animals across the country requires ongoing monitoring for emerging threats. The number of terrestrial rabies cases has been growing. The first case of skunk rabies ever documented in Fort Collins occurred 2012. Just over a year later, live rabid skunks have been found in the region in all seasons and the number of cases has been rising steadily (Larimer County Environmental Health Services 2013).

Other diseases spreading in certain areas of the United States are not currently expected to affect Colorado but may become relevant under extreme climate change scenarios. Locally acquired cases of dengue fever have been documented in the continental U.S. in the past few decades, mainly in Texas-Mexico border region; however, in 2009-2010 an outbreak occurred in Key West, FL, (Radke et al. 2012) and in 2013 there were outbreaks in south and central Florida (Florida Department of Health 2013) and southern Texas (Texas Department of State Health Services 2014). The range of the *Aedes* mosquito which is able to transmit dengue, yellow fever and chikungunya viruses has been growing and there is some possibility that it could extend into southeastern Colorado, increasing the risk of locally acquired cases of dengue (NRDC 2013).

Fires and Floods

The 2013 floods along the Front Range (Figure 10.5) and multiple devastating wildfires in 2012 and 2013 have heightened awareness of the potential for natural disasters to result in public health problems in the state. As mentioned earlier, climate projections do not indicate a change in the frequency of extreme rain events but do indicate that conditions ripe for wildfire are likely to worsen as the climate warms. Climate, however, is only one factor in determining the magnitude of such disasters in terms of human health. As discussed in Chapter 3, population growth in the wildland-urban interface (WUI) and in floodplains exposes more people to the risk of traumatic death and injury due to extreme events (NASA Earth Observatory 2013).

The wildfires and the September 2013 flooding provide good case studies for public health impacts due to extreme weather events. In June and July 2013, high temperatures and dry conditions led to 12 wildfires, including the Black Forest Fire, which has the distinction of being the most destructive fire on record in Colorado. Over the two-month period, 570 structures burned and two people died. Since the 1960s, the average annual number of wildfires in Colorado has increased by over 400% and the annual average acreage burned has increased by 1100% (Colorado State Forest Service undated). Prior to 2000, the six most destructive fires in Colorado history destroyed an average of 15 homes. By comparison, the High Park and Waldo Canyon fires of 2012 destroyed 259 and 346 homes respectively, and the Black Forest fire of 2013 destroyed over 500 homes.

People who live in wildfire-prone areas are at risk not only for traumatic injury, but also rapidly declining air quality. Nearby urban and suburban areas are also vulnerable to dense smoke. Wildfires that destroy buildings also have a different chemical composition than those that do not. A study funded by the U.S. Department of Homeland Security, determined that synthetic materials produce more smoke than natural materials. Combustion of styrene-based material forms benzene, phenols and styrene, while vinyl compounds formed acid gases along with benzene and roofing materials form sulfur gas compounds (Fabian et al. 2010).

In terms of loss of life and property, the 2013 Front Range flooding was more destructive than all the 2013 fires combined, with 8 people killed and 1500 homes destroyed. Sewage treatment plants were inundated in several areas, forcing the release of several million gallons of raw and partially treated sewage. Raw sewage is known to contain a variety of bacteria, viruses, and parasites. Accidental ingestion is the most common cause of illness from exposure. Sampling by the Colorado Department of Public Health and the Environment showed high levels of *E. coli* in some areas of the South Platte Basin, with the highest concentration in Boulder Creek and Big Thompson watersheds (Colorado Department of Public Health and Environment 2013). Industrial pollutants also affected water quality—the Colorado Oil and Gas Conservation Commission reported that 48,250 gallons of oil leaked from failed oil lines and containment facilities and releases of 43,479 gallons of produced water (Colorado Oil and Gas Conservation Commission 2013).

Observed and/or projected physical changes	Key Vulnerable Populations
Rising daytime temperatures with less cooling at night	• Very young children, elderly, chronically ill, (particularly those with cardiovascular disease), persons taking drugs that impair thermoregulation; outdoor workers
Increased concentration of ground-level ozone, fine particulates, and aeroallergens	• Children and pregnant women (they breathe in more air per pound of body weight) • Individuals who work outdoors • Individuals with COPD or asthma, individuals with cardiovascular disease, and those with compromised respiratory and circulatory systems
Possible increase in vector-borne diseases	• West Nile – Individuals who work outdoors, outdoor recreation participants, and children all tend to have greater exposure • Plague – Rural communities, veterinarians, hunters/trappers • Hantavirus – Exposure usually occurs indoors in a place that has been contaminated by mice, so people who are involved in home remodeling or are working in a shed or barn are more likely to be exposed
Floods, wildfires, and other extreme events	• Elderly and disabled - Individuals may have difficulty evacuating • Emergency workers • For wildfires: all the vulnerable groups listed as susceptible to poor air quality due to smoke

Table 10.1. Key vulnerable populations exposed to specific public health-related concerns in Colorado, based on analysis for this study.

Finally, the mental health implication of disasters is not inconsequential. The stress of displacement, the loss of one's home, job, and community can lead to depression. Little research exists on this topic, however.

III. Key Vulnerabilities

As described in Chapter 1, vulnerability is a function both of expected climate impacts and the adaptive capacity available to help reduce the effects of those impacts. Public health departments already have significant adaptive capacity given their experience in planning for and responding to various climate-driven health incidents. However, that capacity can be strained by extreme or unexpected events, like long-duration heat waves, large wildfires, or floods. Actual vulnerability depends not only on the level of capacity available in a given area but also on the characteristics of various populations affected by a given event along with interactions of the natural environment, the built environment, social and economic circumstances, and individual and group characteristics.

Figure 10.6. The use of transportation alternatives like bicycling can reduce greenhouse gas emissions and improve the health of Colorado residents (Photo: iStock, RDaniel12).

Table 10.1 provides an overview of key vulnerable populations in Colorado based on our analysis of expected climate-related impacts and existing adaptive capacity.

IV. Moving Toward Preparedness

The CDC has developed a five-step process for public health agencies called Building Resilience Against Climate Change Effects (BRACE) (http://www.cdc.gov/climateandhealth/BRACE.htm) which could be adopted by the state and local public health agencies to increase preparedness in order to reduce costs and improve health outcomes. The steps are:

1. *forecast* climate impacts and vulnerabilities to identify the scope of the most likely climate impacts, the potential health outcomes associated with those impacts, and the populations and locations vulnerable to these health impacts within a jurisdiction;

2. *project* the disease burden to estimate the additional burden of health outcomes due to climate change in order to support prioritization and decision making;

3. *assess* public health interventions to identify the most suitable interventions for the health impacts of greatest concern based on the health risk assessment;

4. *develop and implement* a Climate and Health Adaptation Plan that addresses the health impacts, gaps in the critical public health functions/services, and a plan for enhancing adaptive capacity in the jurisdiction; and

5. *evaluate* the processes used, determine the value of the framework and the value of climate and health activities undertaken to improve quality and incorporate refined input based on updated and new information.

In addition, public health-related climate change impacts cross other sectors such as transportation, urban planning, land use, agriculture, and economic development. For example, fossil fuel-based transportation contributes to greenhouse gas emissions and other air pollutants that reduce local air quality and affect human health; thus, reducing the use of vehicle travel or increasing the use of lower-emissions vehicles could help reduce these pollutants. Promoting active transportation (walking, biking and use of public transportation; Figure 10.6) is another strategy that could improve physical and mental health. Addressing these issues, however, would require interaction with transportation and other sectors.

Exploring the use of urban forestry plans to increase existing tree canopy cover may reduce urban heat islands and therefore reduce heat-related illnesses associated with climate change temperatures. Focusing on areas in communities where vulnerable populations live (e.g. low-income housing, predominately elderly residential areas) may reduce some of the adverse outcomes associated with increasing temperatures. Healthy housing initiatives are also important in relation to reducing asthma and other respiratory diseases and can reduce greenhouse gasses by focusing on energy efficiency efforts on older and substandard properties.

Finally, public health departments could strengthen links with emergency management and disaster preparedness agencies. Colorado's Division of Homeland Security and Emergency Management is responsible for the state's comprehensive emergency management program, which supports local and state agencies. The Division works with local governments to coordinate all aspects of emergency management. Much work has been done on development of emergency preparedness in the state of Colorado. The READYColorado website has information related to preparedness of all kinds, from individuals and families to schools, businesses, and people with disabilities (READYColorado and the State of Colorado 2013). However, greater preparedness comes with recognition of the barriers to making those plans and following steps that have been widely recommended. There are a number of barriers to adopting suggested plans for preparedness including cost of preparation for individuals and organizations/communities, low probability of events reducing the will of people to take action, competing priorities for supporting ongoing activities coupled with decreased funding to support activities related to preparedness, confusing and or contradictory recommendations (especially in the midst of an event), and lack of accountability coupled with ambiguous goals. The wide range of organizations that are involved in emergency preparedness creates the need for ongoing communication and clearly defined roles for each organization.

In addition, public health organizations should offer education and services to enable vulnerable groups prepare themselves for possible adverse climate-related events.

V. Future Research Needs

Monitoring of diseases (e.g. vector-borne diseases, respiratory disease, heat stress, traumatic injuries, mental disorders associated with disasters) and surveillance of disease vectors combined with information about environmental changes will improve understanding of on-the-ground health impacts due to climate change. Most important for understanding the impact of the climate change-related health impacts is to monitor Colorado specific data on:

- community demographics (e.g. age, sex, race/ethnicity, poverty)
- deaths from chronic diseases (cardiovascular disease, asthma, diabetes, stroke)
- traffic-related mortality and injuries
- illnesses caused by infectious diseases (e.g. vectors, food and waterborne outbreaks)
- physical activity, nutrition, and obesity

Analysis of this data, in conjunction with climate observations and projections, could improve our understanding of direct and indirect climate-related health impacts and our ability to prepare for future changes.

Further, data on adverse health impacts could be compiled on communities recently affected by flooding, wildfires, and West Nile virus to provide an estimate of public health costs using the methodology developed by Knowlton et al. (2011) to provide policy makers with economic information needed to help prioritize preparedness efforts.

It is difficult to generalize the climate-related effects on mosquitos, ticks, and other insects and wildlife that can act as disease vectors across Colorado. Therefore, it is important to closely monitor vector populations while continuing to monitor illnesses in humans. Doing so would require the development of cost-effective sampling and analysis for successful and sustainable programs. Ongoing research into methods to control the spread of disease in vectors as well as controls for the vectors themselves may help reduce human exposure.

Finally, research on environment and infrastructure, particularly as it relates to identifying and altering infrastructure to reduce heat islands is critical for determining and assisting populations most vulnerable to extended heat waves.

Box 10-1
Front Range Regional Highlight: Summer Heat Makes Sweltering Schools

In 2013, late August and early September temperatures along the Front Range consistently rose above 90°F. Although that type of heat is not necessarily unusual for the state's biggest cities, it posed serious problems for schools without air conditioning. This lack of adaptive capacity forced drastic actions in some cases—at one point, the Poudre School District in Fort Collins closed all of its schools for the day (Novey 2013).

The heat in 2013 was far from an isolated incident—in 2007 and 2011, temperatures inside classrooms without air conditioning rose above 90°F for at least several consecutive days (Moore 2011). Many schools in Colorado do not have air conditioning systems or other sufficient means of cooling; for example, 24 Boulder Valley schools do not have air conditioning in any of their classrooms, with a disproportionate number of these being elementary schools (Bounds 2013; Moore 2011). Parents, especially of elementary and middle school children have expressed concern for their children's wellbeing and their ability to learn in an environment of extreme heat (Moore 2011).

With few options to change start dates, schools are weighing whether to increase their adaptive capacity by installing cooling equipment. BVSD school board meeting minutes reveals that air conditioning upgrades have been on the agenda for several years. These upgrades would likely not come cheap—in 2010 bond dollars, adding air conditioning was estimated to cost the Poudre School District $45-$50 million (Novey 2013).

Although historically most Colorado schools not have needed air conditioning or other cooling systems, they may become more necessary as the Front Range sees to longer stretches of time with hotter temperatures. 2000–2013 saw an average of 8.8 days per year of 95°F or higher in Fort Collins, and temperatures like those are expected to become more common as the climate changes (RMCO 2013). These rising temperatures have exposed a major vulnerability that could potentially be very expensive to address.

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1898 Panorama photo of Denver, capital of Colorado and the Eastern gateway to the Rocky Mountains. Photo: United States Library of Congress's Prints and Photographs division, digital ID ppmsca.09570.

CHAPTER 11
MOVING TOWARD PREPAREDNESS

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I. What Are Adaptation and Preparedness?

Much of the policy debate around climate change deals with mitigation, or the reduction in greenhouse gas (GHG) emissions. This report, however, emphasizes Colorado's vulnerabilities to climate change and extreme climate events, demonstrating the need for adaptation to future climate impacts across the state. Adaptation can simply be thought of as efforts undertaken to prepare for the effects of climate variability and change. As shown in Figure 11.1, mitigation and adaptation can be considered two complementary aspects to an effective response to climate change that can enhance our society's ability to respond to changes.

Preparedness is a similar, more colloquial term that also refers to the state of being prepared for future climate impacts. This term has been used in multiple climate-related studies and plans in the state, including the *Colorado Climate Preparedness Plan* (Klein et al. 2011) and the *Boulder County Climate Change Preparedness Plan* (Vogel et al. 2012). Note that preparedness and adaptation are used interchangeably in many contexts.

II. What Are the Key Elements of Adaptation/ Preparedness?

A number of approaches to adaptation have been developed in recent years. In general, however, most of these approaches focus on understanding vulnerabilities to future climate, developing plans capable of buffering against a variety of future impacts, and monitoring impacts to adjust those activities as needed. Figure 11.2 shows a generalized adaptation process similar to many in use today. The bi-directional arrows symbolize the iterative nature of adaptation (implying continuous refinement in response to changing conditions and new information), while the inner circle labeled "stakeholder engagement" represents the need to work with interested parties throughout the process.

Figure 11.3 provides a more detailed step-

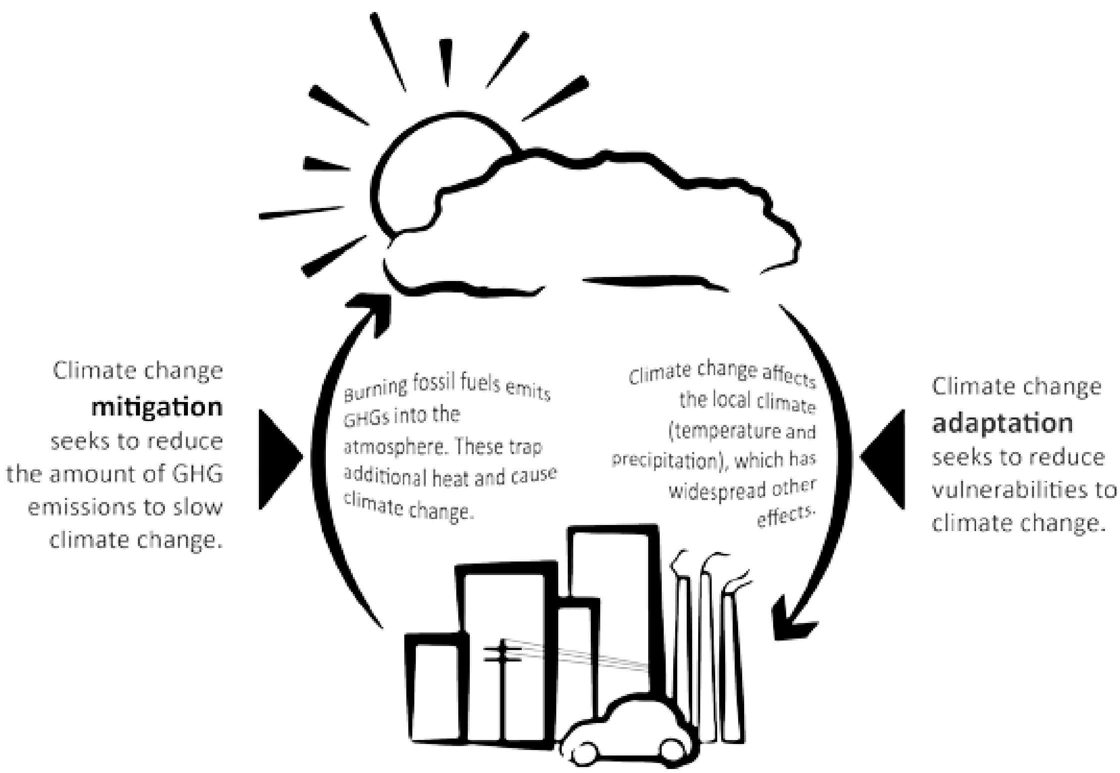

Figure 11.1. Simplified diagram demonstrating the differences between mitigation and adaptation and the connection between the two. Adapted from the California Adaptation Planning Guide (CalEMA and California Natural Resources Agency 2012).

Figure 11.2. Basic elements of a climate adaptation process. Reproduced with permission from Bierbaum et al. (2013).

by-step process for adaptation planning, as described in the California Adaptation Planning Guide written for communities in California. The first four steps in their process (determining exposure, assessing sensitivity, understanding potential impacts, and identifying adaptive capacity) are elements of a formal vulnerability assessment. Our study uses a framework similar to those four steps to identify key climate vulnerabilities in the state, which is intended to give a broad overview of the most significant areas of concern for the state and provide a baseline of information. However, our study does not rigorously analyze the likelihood of future impacts, as would be done in a more formal assessment.

The *Boulder County Climate Change Preparedness Plan* (Vogel et al. 2012) suggests that the following overarching principles be integrated into all forms of planning in order to increase resilience to future climate impacts:

- **Ask the climate question:** Consider if and how current or future weather and climate could affect decision making.
- **Promote adaptive management:** Review policies and plans during implementation and adjust as needed in response to climate or other changes, a process known as adaptive management.
- **Ensure flexibility:** Build flexibility into policies and planning in order to account for the uncertainties of future climate and other factors.
- **"Mainstream" adaptation:** Attempt to incorporate climate adaptation into existing decision processes, rather than making adaptation a separate process.
- **Learn from best practices:** Use lessons learned from elsewhere within a jurisdiction or from other jurisdictions in designing and implementing adaptation plans.
- **Remove barriers to adaptation:** Examine existing laws, policies, and regulations to identify things that could stand in the way of effective adaptation.
- **Recognize the scales at which decisions are made:** Adaptation decisions are made at a variety of scales—from local to federal—and among a variety of organizations both public and private.
- **Recognize the need for leadership and**

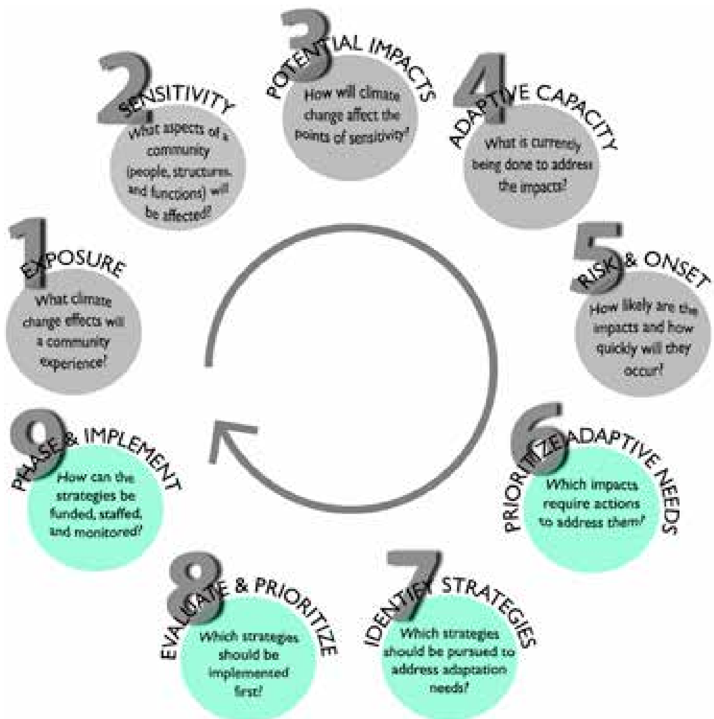

Figure 11.3. Suggested steps in adaptation planning development. Reproduced from the California Adaptation Planning Guide (CalEMA and California Natural Resources Agency 2012).

collaboration: Making adaptation a clear priority of leaders and promoting work across agencies can help spur adaptive activities.

- **Establish clear lines of authority:** Transparency and responsibility will prevent agencies from avoiding or duplicating efforts.
- **Create mechanisms to address impacts that cross jurisdictions:** In the case of the Boulder County plan, a commission including county and city representatives from multiple jurisdictions and agencies served this role.
- **Involve stakeholders:** Departments working to prepare for impacts should work with those most likely to be impacted.
- **Engage in no-regrets decision making:** Long-term decisions that will produce benefits under a wide variety of future climates are ideal.
- **Prepare for multiple possible climate futures:** Projections of future climate still contain significant uncertainty, so it is best not to try to plan for a single climate future.
- **Use available scientific resources:** Colorado is home to significant scientific and technical capacity at universities, government agencies, private companies, and elsewhere that can be brought to bear on climate preparedness.

III. How Can State Agencies and Other Entities Begin Preparedness Planning?

Preparedness planning is best done by the entity needing the plan. Understanding how to prepare for climate impacts requires an in-depth understanding of the resources at risk, short and long-term decisions being made, and policy or regulatory options available. Thus this study does not provide specific steps related to planning in a given sector, but rather provides general guidance.

State agencies can use the following template to develop a preparedness plan. Other entities could also use a modified version of the template.

Box 11-1
Climate Preparedness Template

1. PROVIDE LEADERSHIP FROM THE HIGHEST POSSIBLE LEVELS
   The Colorado Climate Preparedness Plan (Klein et al. 2011), based on a review of other state adaptation plans, identified leadership from the governor and department heads as a critical element necessary to engaging agency staffs in climate preparedness planning.

2. ASSIGN RESPONSIBILITY FOR CLIMATE PREPAREDNESS PLANNING
   Setting clear lines of responsibility can help ensure progress and accountability in dealing with an issue that cuts across many portfolios and often takes staff members out of their standard areas of work. Assigning responsibility could entail designating a staff member as a climate preparedness coordinator or selecting staff from multiple divisions or offices to form a preparedness team.

3. CATALOG LONG-TERM PLANNING AND SHORT-TERM OPERATION AREAS RELEVANT TO CLIMATE
   Climate preparedness entails preparation for both short-term climate extremes (including fires, floods, storms, and drought) and long-term changes in averages. Determining which planning and operational decisions are sensitive to short and long-term climate allows agencies to identify where climate-related planning should be directed. For short-term operations, agencies should identify contingency and emergency plans that may need to be updated with additional climate information based on the best available science. For long-term planning, agencies should identify what planning decisions have the longest time horizons, the least reversibility, and the greatest impact from climate (including extreme weather events). Note that short-term decisions can have long-term implications for preparedness.

4. CONNECT WITH EXPERTS
   Colorado is home to many experts in climate analysis, climate projections, vulnerability assessment, and adaptation planning. The Western Water Assessment at the University of Colorado Boulder and the North Central Climate Science Center at Colorado State University (the entities that organized this study) are home to many of those experts, as are many other institutions such as NCAR and some private companies. Engaging with these experts early on in the preparedness planning process could connect agency personnel with individuals who could help interpret climate information, assess impacts, and think through preparedness efforts.

5. ENGAGE WITH STAKEHOLDERS
   Climate affects a wide variety of constituencies, all of whom can contribute to preparedness planning. Agencies should look to engage with stakeholders to build support for adaptation and develop collaborative efforts that can enhance adaptive capacity.

6. CONDUCT A VULNERABILITY ASSESSMENT IF NEEDED
   For the resources at issue in the long-term decisions identified in Step 3, agencies should consider whether to conduct a formal vulnerability assessment. The first four elements of Figure 3 (exposure, sensitivity, impacts, and adaptive capacity) comprise

Box 11-1
Climate Preparedness Template

a vulnerability assessment. This type of effort is most often warranted when little is known about future climate sensitivities and ramifications of insufficient planning could be quite serious—for example, the building of large infrastructure like dams that could last decades. In many instances, however, a careful consideration of the resources at risk combined with a review of climate projections and/or engagement with climate experts could provide a much less costly means of achieving the same objective. More information on conducting a formal vulnerability assessment is provided in the next section.

7. ANALYZE RISKS BASED ON PROBABILITIES
   Risk has a number of meanings but in this context can be defined as consequence times probability. Thus the risk posed by a high-consequence, low-probability event could be similar to the risk posed by a medium-consequence, medium-probability event. Consequences are determined from a variety of analyses and previous experience with climate events, whereas probabilities can be determined using climate projections and other techniques. Risk analysis facilitates priority-setting exercises so that an agency can focus on areas of greatest risk first.

8. SET A VISION AND GOALS FOR A PREPAREDNESS PLAN
   In general, the goal of any climate preparedness plan is for the planning entity to improve its capacity to handle the consequences of future climate, whatever they may be. However, experience shows that such a broad goal is often too vague to be actionable, especially by agency staff not accustomed to climate preparedness. Thus it is generally beneficial to write a vision statement and set goals particular to the agency and involve staff and stakeholders in the process.

9. DEVELOP AND IMPLEMENT A PREPAREDNESS PLAN
   Based on the information gathered in the preceding steps, the next step would be to develop the preparedness plan itself. Ideally, the plan would not be an additional layer of requirements but rather a guide on how to integrate climate preparedness into existing planning and decision making, a process known as “mainstreaming.” Implementation then becomes a critical exercise in determining to what degree “mainstreaming” is occurring.

10. MONITOR IMPACTS AND REFINE PLAN AS NEEDED
    It is critical that climate preparedness efforts not be seen as one-time planning exercises. Given the unique cross-cutting nature of climate change, preparedness planning may be novel and possibly uncomfortable for many agencies. Thus the process of implementation should be monitored and refined as needed, as should the vision and goals of the plan itself. Further, given that many climate changes are uncertain and will only become apparent over time, monitoring of key climate variables is critical and may also necessitate adjustment of the preparedness plan.

IV. How Should State Agencies Begin Preparedness Planning?

To provide more guidance on the critical Step 6 listed above, we have provided an additional template (Table 11.1) describing how to conduct a preliminary analysis of vulnerabilities to specific climate changes. An in-depth vulnerability assessment as laid out below requires a formal examination of adaptive capacity and potentially quantitative investigation of potential climate impacts.

Once an agency has completed an exercise like the one provided in the template below, the results can be used for priority-setting purposes. Assuming limited resources are available for climate preparedness, identifying the most vulnerable resources or populations can help the agency decide where to focus its planning efforts.

Planning Area refers to the agency's long-term climate-sensitive decisions. These could also be considered "sectors" or "resources" of interest.

Climate Variable refers to a specific climate factor that may or may not change in the future, such as annual average temperature, seasonal precipitation, or number of days below freezing. These variables can be drawn directly from Chapter 2.

Projected Change describes the expected change in the variable at a certain point in the future compared with an existing baseline–for example, projected change by mid-century as compared to a 1971-2000 average. For some variables, projections are not clear enough at this point and would be referred to as "uncertain." Note that the choice of projected time frame should align with decision making time scales—for example, if an agency's planning horizon is 50 years, the vulnerability assessment should use 50-year climate projections.

Level of Confidence refers to the degree to which climate scientists are comfortable with climate projections. Certain variables, like annual average temperature, will entail high confidence, while others where projected change is more difficult to characterize, may entail low confidence. These confidence levels can be drawn from Chapter 2.

Potential Impacts are the effects of these climate changes (including extreme events possible under the current climate) on the planning area in question. Impacts are described generally in Chapters 4-10, but agencies should seek further detail when engaging in formal vulnerability assessment efforts.

Adaptive Capacity is a measure of the ability of the agency and any others involved in the planning area to adapt to climate variability or future climate change. Adaptive capacity can be described qualitatively (e.g., as high, medium, or low) or quantitatively (i.e., using an index).

Vulnerability is the intended output of this template. By assessing potential impacts and existing adaptive capacity, a vulnerability assessment results in a measure of vulnerability for each planning area in question and to each climate variable.

Table 11.2 provides an example of how this assessment template could be used in a planning area (long-term water supply). Note that this example is *for illustrative purposes only* and does not necessarily reflect actual vulnerabilities.

Planning Area	Climate Variable	Projected Change	Level of Confidence	Adaptive Capacity	Vulnerability

Table 11.1. Preliminary template for climate vulnerability assessment.

Planning Area	Climate Variable	Projected Change by Mid-Century	Level of Confidence	Potential Impacts	Adaptive Capacity	Vulnerability
Water Supply	Average annual temperature	+2.5°F to +6.5°F	High	Higher evapotranspiration rates; greater water demand for irrigation and M&I use	Medium: M&I conservation and water transfer mechanisms can help	Moderate vulnerability for overall state water supply
	Average monthly summer temperatures	Typical summer as warm as hottest 10% of summers 1950-1999	High	Higher evapotranspiration rates; greater water demand for irrigation and M&I use, especially in mid to late summer	Medium: M&I conservation and water transfer mechanisms can help	Moderate vulnerability for overall state water supply
	Intense convective precipitation events in summer	No projected change	Low	Intense precipitation events will continue to have significant impacts on water supply infrastructure, water treatment and sewage, etc.	Medium	High vulnerability for specific parts of water supply infrastructure
	Average annual precipitation	+3% with wide range	Low	Annual and decadal variability in precipitation is expected to remain, greatly impacting overall water supply availability	Medium: Colorado has significant capacity to adapt to seasonal and interannual variability but less capacity to adapt to decadal variability	Moderate vulnerability for state as a whole; high vulnerability for some water providers
	Average April Snowpack	-10%	Medium	Reduced spring snowpack can lead to reduced overall water availability	Medium: Reduced water availability will increase competition but some sharing/transfer mechanisms exist	Moderate vulnerability for state as a whole; high vulnerability for some water providers
	Timing of runoff	1-3 weeks earlier	High	Earlier snowmelt can complicate water rights administration, compact compliance, and water availability in late summer	Low: building new storage is difficult	High vulnerability for many water providers
	Average annual runoff	-5% to -15%	Medium	Reduced average runoff can lead to reduced overall water availability	Medium: Reduced water availability will increase competition but some sharing/transfer mechanisms exist	High vulnerability for overall state water supply and some water providers

Table 11.2. Example of use of the proposed vulnerability assessment template. Note that text is for illustrative purposes and does not necessarily reflect actual vulnerabilities.

Both of the templates described above are adapted from *Preparing for Climate Change: A Guidebook Local, Regional, and State Governments* (http://www.cses.washington.edu/db/pdf/snoveretalgb574.pdf) developed by the University of Washington's Climate Impacts Group (Snover et al. 2007). We recommend consulting that document along with the *California Adaptation Planning Guide* (http://resources.ca.gov/climate/safeguarding/adaptation_policy_guide/); CalEMA and California Natural Resources Agency 2012) to find further detail on the concepts behind vulnerability assessment and adaptation planning.

V. How Have Other States Approached Adaptation Planning?

Below we provide brief summaries of state-level climate change plans from other states. Note that in addition to these statewide adaptation plans, several states have climate plans that focus only on one specific sector. For a broader summary of adaptation plans across the country, we recommend consulting the Georgetown Climate Center's webpage on state and local adaptation planning (http://www.georgetownclimate.org/adaptation/state-and-local-plans).

The summaries below show sectors covered, impacts identified, and top-level recommendations provided in each of the plans. Those working on preparedness planning in Colorado might find it useful to read these and other plans in depth and contact officials in those states to learn lessons about the process of developing a preparedness plan. Note that most of the existing state-level adaptation plans are for coastal states and thus focus heavily on impacts from sea level rise. We included a few non-coastal state examples below, but also encourage those in Colorado to engage with the Western Adaptation Alliance (http://www.iscvt.org/program/western-adaptation-alliance-waa/), a network of municipalities in the Interior West that developed for the explicit purpose of working together on adaptation in areas where sea level rise is not an issue. Denver, Boulder, Fort Collins, and Aspen are all members of this alliance.

California

2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008
http://resources.ca.gov/docs/climate/Statewide_Adaptation_Strategy.pdf

Updated by *Safeguarding California: Reducing Climate Risk. An update to the 2009 California Climate Adaptation Strategy* (Public Draft), December 2013
http://resources.ca.gov/climate/safeguarding/

Sectors covered by 2009 report:

1. public health
2. biodiversity and habitat
3. oceans and coastal resources
4. water supply
5. agriculture
6. forestry
7. transportation and energy infrastructure

The 2013 update covers the same areas but discusses the energy and transportation sectors in two separate chapters instead of one and adds a chapter on emergency management.

Impacts identified by 2009 report (not inclusive):

1. increase in extreme heat events
2. decline in air quality
3. increase in floods, drought, wildfire
4. sea level rise
5. changes in streamflow
6. coastal issues – flooding, inundation, wetland loss, erosion, saltwater intrusion, acidification
7. earlier snowmelt
8. increase in insect infestations and invasive species

While many impacts are discussed throughout the 2013 update, the following are highlighted in the Introduction:

1. sea level rise threats to hazardous waste sites in the San Francisco Bay area alone
2. reduction of over 80 percent of suitable climate range for 2/3rds of native flora within a century
3. loss of at least 1/4th of the Sierra snowpack by 2050
4. serious health risks with greater impact on most vulnerable populations
5. significantly declining yields of cherries due to warming
6. new risks and uncertainties for emergency management from more extreme weather events, sea level rise, changing temperature and precipitation patterns, and more severe and frequent wildfires
7. transportation system faces risk of road washouts, route closures, rail buckling, and sea level rise and coastal erosion impacts on ports and low lying airports, coastal roads and highways, bridge supports, transit systems, and energy and fueling infrastructure
8. energy infrastructure vulnerable to rising temperatures and increased risk of flooding and wildfire
9. annual area burned by wildfire predicted to increase substantially

Strategies included in 2009 report:

1. promote comprehensive state agency adaptation planning
2. integrate land use planning and climate adaptation planning
3. improve emergency preparedness and response capacity for climate change impacts
4. expand California's climate change research and science programs and expand public outreach of research to policy-makers and general public

General recommendations in the 2013 update:

- Develop an urban water use plan that reduces reliance on distant, unpredictable sources.
- Promote development of smart grids that are connected, but localized.
- Promote strategies to keep Californians cool and guard against longer, more frequent heat weaves, which are already responsible for a growing number of hospitalizations and deaths.
- Reduce carbon output today to lessen the extent of impacts in the future.
- Provide habitat connectivity and chances for adaptation to help allow species and habitats to survive.
- Improve forest and other habitat resilience.
- Sound science will highlight risks and help provide a path to solutions.
- Assess adequacy of emergency responders.
- Collaborate with federal and local government.

Preparing for the Effects of Climate Change: A Strategy for California. A Report by the California Adaptation Advisory Panel to the State of California on Critical Steps Needed to Adapt to the Effects of Climate Change http://www.pacificcouncil.org/admin/document.doc?id=183

This was a report by the California Adaptation Advisory Panel, established by the 2009 California Climate Adaptation Strategy, to identify the most important next steps for California in preparing for climate change as seen from the perspective of a diverse set of stakeholders in the future of this state.

This report was not organized by sectors but rather by the following specific threats:

1. sea level rise
2. increased risks of reduced water supplies due to expected reduction in the Sierra snowpack, increase in amount of precipitation that falls as rain as opposed to snow, and the potential for increased demand as a result of warmer average temperatures and population growth
3. areas of California where climate change related increased temperatures are projected to lead to increased wildfire risks (primarily in forested areas in the northern half of the

state), and particularly in such areas of the state where there is currently, or could be in the future, homes and infrastructure at risk from increased wild and rangeland fires.

Overall recommendations:

- As a basis for adaptation planning, the state needs to maintain, enhance, and expand the data gathering and monitoring responsibilities of the relevant government and research entities on the actual uses of, and changes to, the natural and physical resources most likely to be affected by climate change.

- Based on the information gathered, to develop the risk assessments that communities need as a starting point in considering alternative actions and in making informed choices. These choices will help communities along the coast gradually adjust to the rising level of the sea, help resource managers and people living at the wildland-urban interface better manage the forests to reduce the threat of fire, and help California to better manage one of the state's most precious natural resources, our water.

- Adaptation planning requires reaching across and beyond traditional agency and jurisdictional boundaries. The State must connect sectors and levels of government in order to proceed. These new relationships must be built on a foundation of information sharing, communications, and more comprehensive thinking and adaptive planning.

- The State needs to develop viable plans for funding the actions that will need to be taken to proactively manage the effects of climate change. Climate change insurance options and the creation of climate adaptation funds should be priority topics for further study.

- Multi-stakeholder assessments must be undertaken for the important threats not covered by this report, namely, natural resources management and public health.

Minnesota

Adapting to Climate Change in Minnesota: 2013 Report of the Interagency Climate Adaptation Team
http://www.pca.state.mn.us/index.php/view-document.html?gid=15414

This report highlights how Minnesota state government is working to adapt to a changing climate, reduce risks and impacts, and increase the resilience of communities. It is not organized by sector but rather describes adaptation actions that have been taken by the following state agencies:

1. Minnesota Department of Agriculture
2. Minnesota Department of Commerce
3. Minnesota Department of Health
4. Minnesota Department of Natural Resources
5. Minnesota Pollution Control Agency
6. Minnesota Department of Public Safety, Division of Homeland Security and Emergency Management
7. Minnesota Department of Transportation
8. Board of Water and Soil Resources
9. Metropolitan Council

Impacts identified:

1. Increasing temperature and extreme heat
2. degradation of air quality
3. drought
4. extreme weather (flooding, storms)
5. changing seasonality and longer term ecological changes

Recommendations: 7 priority areas for further adaptation efforts were identified:

1. building resilience to extreme precipitation
2. implementing best practices that achieve multiple benefits
3. protecting human health
4. strengthening existing ecosystems by addressing ongoing challenges and risks
5. building partnerships with local governments
6. quantifying climate impacts
7. conducting public and community outreach, education, and training

Oregon

The Oregon Climate Change Adaptation Framework December 2010
http://www.oregon.gov/ENERGY/GBLWRM/docs/Framework_Final_DLCD.pdf

The report is organized by risk rather than sector, but sectors that were discussed in the context of risks include:

1. ecosystems
2. built and developed systems
3. public health and safety
4. economy

Impacts identified: the report identified the following risks and assessed their likelihood of occurrence:

Very likely to occur

Risk 1. Increase in average annual air temperatures and likelihood of extreme heat events

Risk 2. Changes in hydrology and water supply; reduced snowpack and water availability in some basins; changes in water quality and timing of water availability

Likely to occur

Risk 3. Increase in wildfire frequency and intensity

Risk 4. Increase in ocean temperatures, with potential for changes in ocean chemistry and increased ocean acidification

Risk 5. Increased incidence of drought

Risk 6. Increased coastal erosion and risk of inundation from increasing sea levels and increasing wave heights and storm surges

Risk 7. Changes in abundance and geographical distributions of plant species and habitats for aquatic and terrestrial wildlife

Risk 8. Increase in diseases, invasive species and insect, animal and plant pests

Risk 9. Loss of wetland ecosystems and services

More likely than not to occur

Risk 10. Increased frequency of extreme precipitation events and incidence and magnitude of damaging floods

Risk 11. Increased incidence of landslides

Recommendations:

- Enhance and sustain public health system capacity to prepare for and respond to heat waves and smoke emergencies, and improve delivery of information on heat events and cooling centers, especially for isolated and vulnerable populations.
- Maintain the capacity to provide assistance to landowners to restore wetlands, uplands and riparian zones to increase the capacity for natural water storage.
- Improve real-time forecasting of water delivery and basin yields to improve management of stored water.
- Improve capacity to provide technical assistance and incentives to increase storage capacity and to improve conservation, reuse, and water use efficiency among all consumptive water uses.
- Include wildfires in planning to reduce vulnerability to natural hazards.
- Restore fire-adapted ecosystems to withstand natural recurring wildfires.
- Develop short- and medium-term climate change adaptation strategies for forests and other fire-prone habitats, and improve development standards to reduce exposure to fire risk at the urban-wildland interface.
- Improve the capabilities of public health agencies to plan for and respond to the public health and safety risks of wildfire emergencies.
- Increase research on the impacts of changes in ocean temperature and chemistry on estuarine and near-shore marine habitats and resources, including commercial and recreational fisheries.

- Improve capacity to provide technical assistance and incentives to increase storage capacity and to improve conservation, reuse, and water use efficiency among all consumptive water uses.
- Inventory and map coastal shorelands that are at risk of erosion or inundation, or are barriers to shoreline migration, and develop long-term state and local adaptation strategies for shorelands.
- Identify ways to manage ecosystems that will improve their resilience to changes in climate conditions.
- Increase monitoring, detection and control measures for pest insects and plant and wildlife diseases.
- Increase surveillance and monitoring for climate-sensitive infectious diseases to humans.
- Increase outreach and community education about disease and invasive species prevention measures.
- Seek new means of securing resources to detect and combat diseases and invasive species.
- Inventory past flood conditions and define and map future flood conditions.
- Improve capability to rapidly assess and repair damaged transportation infrastructure, in order to ensure rapid reopening of transportation corridors.
- Develop public education and outreach on landslide risks and how to adapt to landslide risks.

Washington

Preparing for a Changing Climate Washington State's Integrated Climate Response Strategy
April 2012
https://fortress.wa.gov/ecy/publications/publications/1201004.pdf

Sectors covered:

1. human health
2. ecosystems, species, and habitats
3. ocean and coastlines
4. water resources
5. agriculture
6. forests
7. infrastructure and the built environment

Impacts identified: projections of climate changes include

1. warmer air temperatures
2. drier summers and reduced snowfall
3. more frequent and severe extreme weather events
4. rising sea levels
5. more acidic marine waters
6. warmer water temperatures
7. increasing frequency and severity of wildfire
8. increasing frequency and severity of flooding

Key climate risks are:

1. Increased injuries and disease
2. Increased damage costs and disruptions to communities, transportation systems, and other infrastructure
3. reduced water supply
4. loss of fish, wildlife, and natural systems
5. losses to agriculture and forest industries

Recommendations: seven overarching high-priority climate change response strategies were identified:

1. protect people and communities
2. reduce risk of damage to buildings, transportation systems, and other infrastructure
3. reduce forest and agriculture vulnerability
4. improve water management
5. safeguard fish, wildlife, habitat, and ecosystems
6. reduce risks to ocean and coastlines
7. support the efforts of local communities and strengthen capacity to respond and engage the public

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APPENDIX A "WEATHERING CHANGE" WORKSHOP

Organized by Environmental Defense Fund and Climate Central

October 28, 2013 Denver, CO

In the original Scope of Work for the Colorado Climate Change Vulnerability Study, the project team was responsible for developing a meeting of business leaders to discuss climate change vulnerability issues. Shortly after the project began, however, the project team discovered that the Environmental Defense Fund (EDF) and Climate Central were organizing a meeting on the same time frame with roughly the same goal. Thus, to avoid redundancy, CEO Director Jeff Ackermann contacted EDF to coordinate efforts. Attendance at the "Weather Change" workshop then became the requisite deliverable (including this report), with project lead Eric Gordon giving a brief overview of the Vulnerability Study to the attendees.

"Weathering Change" brought together over 100 people representing Colorado's business community, research entities, and state agencies to discuss changing weather patterns, impacts on key industries, and how to increase resilience and manage risk in a changing climate. Attendees included members of the outdoor recreation, energy, and agriculture industries as well as state and local agencies in the water and energy sectors, NGOs, and others. The state envisions the Weathering Change meeting as a first step in engaging the business community and other partners in strategies to address climate-related vulnerabilities.

To view a summary of "Weathering Change," visit http://www.coloradoweatheringchange.com.

Representatives of a variety of industries, NGOs, universities, and other entities discussed climate change issues at the "Weathering Change" meeting in October 2013.

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