Vulnerability of Ecosystem Services Along the Colorado Front Range

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Introduction

Ecosystem services, broadly defined, are the benefits humans get from nature. When first introduced, the phrase "ecosystem services" was meant to capture many of the benefits resource managers (and humans, in general) had largely ignored in economic analyses, such as purification of water and pollination of plants (Daily 1997). Managing for ecosystem services meant improving the condition of the natural system (i.e., natural capital) in a way that made it more likely that those services would be provided (Brown et al. 2007). Ecosystem services were initially held distinct from "ecosystem goods," which include tangible environmental products like timber, fish, and minerals. Ecosystem goods, because they form the basis of many economies, have long been studied and valued. Today, ecosystem services and ecosystem goods are usually lumped together and referred to generically as ecosystem services.

The Multiple-Use Sustained-Yield Act of 1960 directs national forests to be managed for outdoor recreation, range, timber, watershed, wildlife, and fish. The 2012 Forest Service Planning Rule further directed national forests to manage for key ecosystem services beyond the five traditional multiple uses, where key ecosystem services are defined as ecosystem services that are: (1) important to people in the broader landscape or beyond the plan area itself, and (2) likely to be affected by the management plan under revision. In practice, there is little difference between multiple-use and ecosystem services as used by Forest Service staff, and the terms multiple-use and key ecosystem services are often used interchangeably (Jaworski et al. 2018).

One of the primary purposes of an ecosystem services approach to management is to align policy outcomes with benefits to the people and communities that are connected to the forests. In many cases, focusing on the human benefits derived from national forests also expands the geographic scope of management beyond national forest boundaries. As recognized in the Shared Stewardship mission of the Forest Service, national forests are part of a landscape that provides natural capital to local economies, defines regional cultures, and regulates global climate. Social and economic forces, therefore, play an important role in understanding ecosystem services. They help us identify the users and stakeholders of the forest resources, the types of natural resources they value, and the impacts people are likely to have on the natural resources. Understanding how ecosystem services are vulnerable can help with long-term forest planning, adaptation to climate change, and engagement with local communities.

The first part of this chapter describes some of the potential hazards to ecosystem services from climate change and the social forces that are defining the Colorado Front Range (Front Range) that are likely to impact the condition and demand for ecosystem services. Climate impacts include increased frequency of fire, flood, and drought, insects and disease, and decreased snowpack; social forces include population growth and changing demographics. Other sections focus on specific ecosystem services, including water and watershed health, mining, forage for wildlife and livestock, and carbon sequestration (an example of ecosystem services on two national forests is given below in box 1). These ecosystem services are likely to be either affected by climate change, affected by socioeconomic forces in the region (like large changes in the region's population), or play an important role in climate change policy and mitigation. (Note that some ecosystem services (e.g., recreation) are addressed in resource-specific chapters elsewhere in this report and not addressed here.) The chapter concludes with potential uses of this assessment for management.

Box 1—Within U.S. Forest Service Region 2, the Rio Grande and Grand Mesa and Gunnison (GMUG) National Forests have completed or are in the process of completing their forest plan revisions according to the 2012 Planning Rule. Key ecosystem services identified and addressed in those plans are shown below.

Rio Grande	GMUG
Fish and wildlife	Forage for grazing
Forage	Timber
Mineral deposits	Cultural, historic, sacred sites
Nontimber forest products	Outdoor recreation and human enjoyment of fish and wildlife species
Timber	Solitude, spirituality, sense of escape
Cultural, historic, sacred sites	Water resources
Landscapes and features providing recreation and scenery	--
Solitude, spirituality, sense of escape	--
Water quantity, quality, storage, and flood control	--
Pollination	--
Support of habitat, species diversity, abundance, and distribution	--

Drivers of Change

Climate change is already affecting ecosystem services and communities throughout the Front Range, with changes expected to become more severe in the future. Since the late 19th century, temperatures in the Pike-San Isabel and Arapahoe-Roosevelt National Forests (PSI and AR, respectively) have increased by 2 °F, with an expected increase by mid-century of 2.5 to 5.5 degrees. These temperature increases have significant impacts on water-related ecosystem services by increasing the frequency of drought and extreme runoff events, shifting the timing of annual runoff, increasing fire frequency, and increasing water demand for human use.

Social changes currently underway along the Front Range compound impacts due to climate change. The dominant social force likely to affect ecosystem services on the Front Range is population growth, expected to affect both the supply of and demand for ecosystem services. The conversion of open space to urban development, for example, can cause habitat fragmentation and adversely affect water quality while it can also increase demand for recreation opportunities and water for municipalities.

Between 1980 and 2010, Colorado's population grew by 74 percent, with the highest growth rates seen along the Front Range and I-70 corridor. The Front Range Urban Corridor is now home to an estimated 4.5 million people. According to the Colorado State Demography Office, population is expected to increase 61 percent statewide between 2010 and 2050, with the Front Range and I-70 corridor continuing to see higher than average rates of growth. Figure 1 shows population and per capita personal income projections for the Denver metropolitan statistical area[1] from Wear and Prestemon (2019) for five Shared Socioeconomic Pathways (SSPs). The SSPs are trajectories of population, demographics, and income scenarios over the next century. The SSP projections are bounded by SSP5 (high growth) and SSP3 (low growth). They are usually paired with climate change scenarios to examine interactions between social forces, climate change, and other natural resources. Figure 2 shows Colorado-wide population projections by county for the low growth (SSP3) and high growth (SSP5) SSPs. Front Range counties Douglas, El Paso, and Arapaho Counties are projected to have the highest growth rates in the State; projections for personal income per capita show the highest growth in Douglas, Clear Creek, and Gilpin Counties.

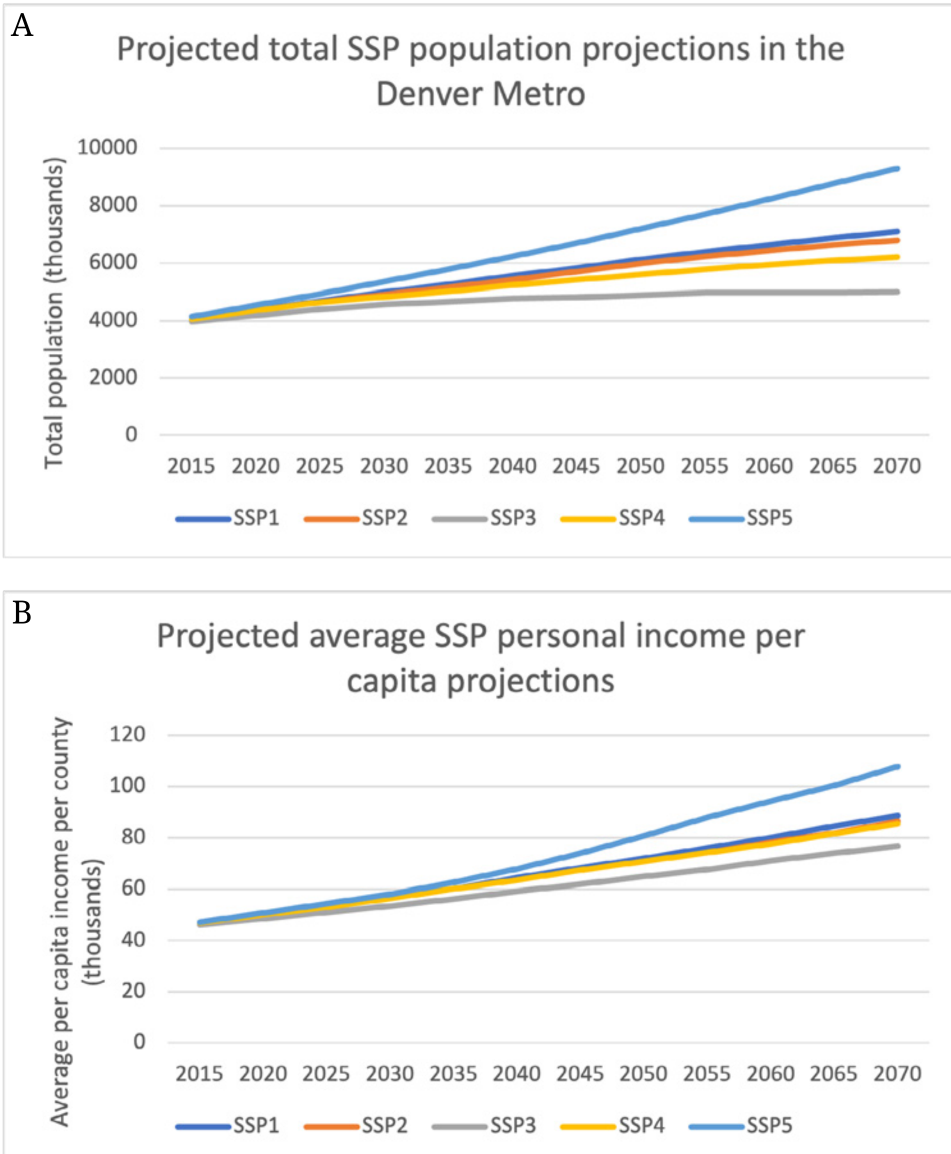


Figure 1a-b—Population and personal income projections for the Denver metro (Wear and Prestemon 2019).

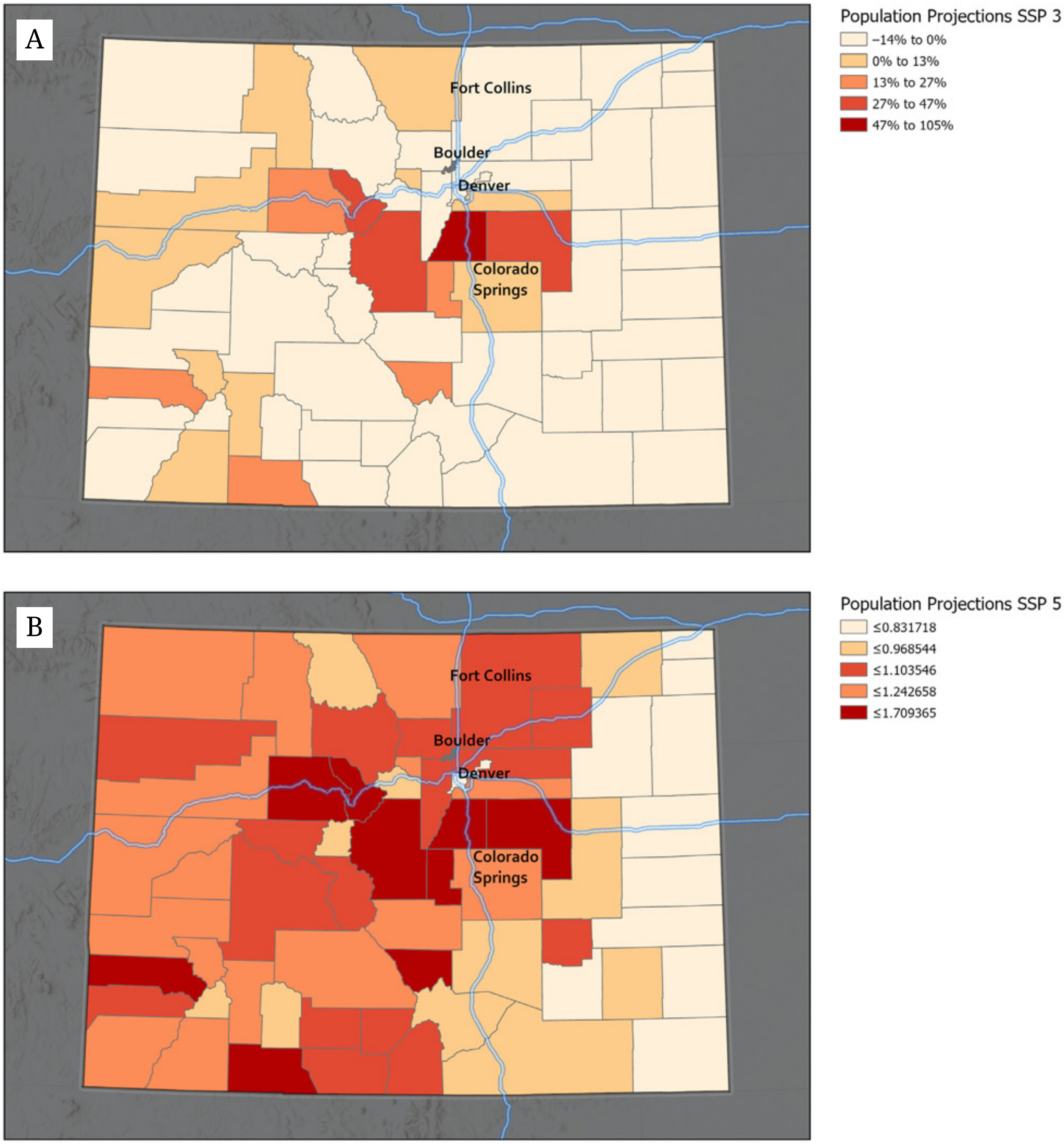


Figure 2a-b—County-level population growth projections for Colorado (Wear and Prestemon 2019).

Much of this growth will spill into the wildland-urban interface (WUI), an area of particular concern for the U.S. Forest Service. Figure 3 shows the projected growth in Colorado's WUI. Knight et al. (1995) find that, because much of the higher-elevation land in the Front Range is federally owned, private developable land in the WUI is often confined to the lower elevations, which are more likely to contain sensitive meadow, grassland, and riparian zones and are more fire prone. Threats to the region, particularly watersheds, due to development can be seen on the interactive Forest Service maps for the Forests to Faucets 2.0 Story Map.[2] Increases in fencing, buildings, and roads that accompany WUI development increase noise, human presence, and habitat fragmentation, and have been linked to reduction of native species and the introduction of exotic species. Domestic cats that range outdoors have the potential to significantly decrease songbird populations and depress prey populations for small and medium-sized predators (Loss et al. 2013). While these impacts are not directly related to climate, they are likely to increase sensitivity to climate change.

Figure 3—Increase in wildland-urban interface (WUI) throughout Colorado (1990–2010). White areas show the expansion of WUI from 1990 to 2010.

Social Vulnerability Index

An oft-cited measure of vulnerability to climate change and other environmental stressors is the "social vulnerability index." Such indices attempt to measure a community's vulnerability and resilience to climate change, particularly to sudden extreme events like fires and floods that are projected to be more common. Herein, we examine variables included in the Center for Disease Control's (CDC) social vulnerability index (SVI), which uses 15 variables from the U.S. Census at the tract level to help officials assess a community's vulnerability to hazards. The CDC's SVI index shows the relative vulnerability of census tracts throughout the United States, in aggregate and disaggregated according to four themes: socioeconomic status, household composition and disability, minority status and language, and housing and transportation (figs. 4 and 5). Low values indicate low vulnerability and high values indicate high vulnerability. The socioeconomic status theme includes a number of income variables; household composition includes variables related to age and disabilities; minority status and language includes ethnic, racial, and language information; and the housing and transportation theme includes variables related to housing density and occupancy rates, number of people in homes, and whether households have vehicles.

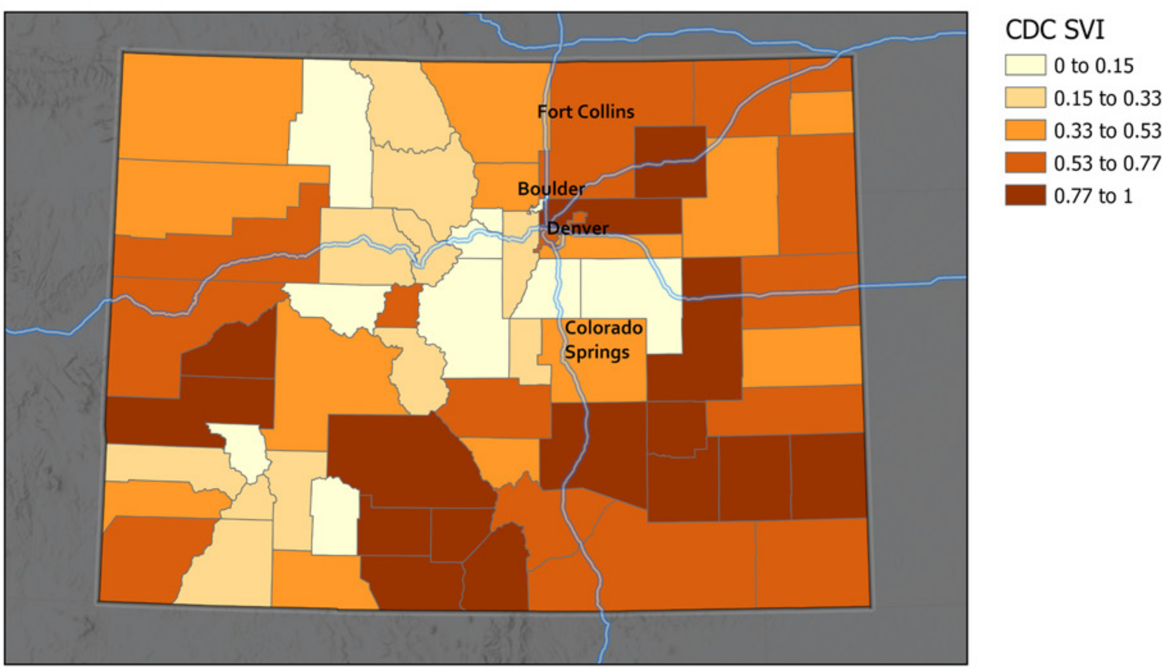


Figure 4—Aggregate Social Vulnerability Index (SoVI) for Colorado (0 = low vulnerability, 1 = high vulnerability)

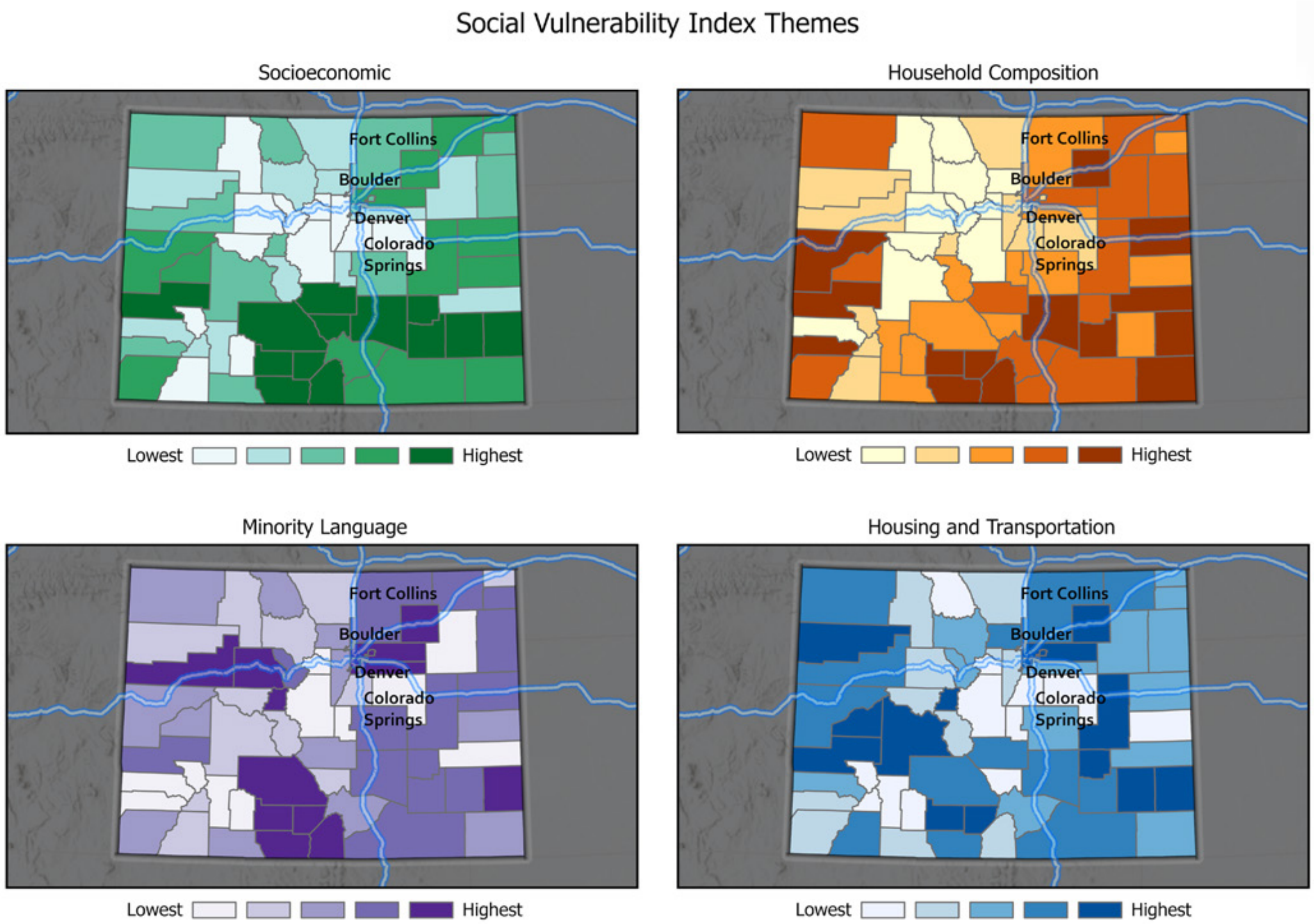


Figure 5—Social Vulnerability Index (SoVI) by theme (0 = low vulnerability, 1 = high vulnerability).

Table 1 compares SVI scores for census tracts in Colorado that overlap with Front Range national forests boundaries and for census tracts that do not. On average, tracts near the national forests are less vulnerable across all categories except Housing and Transportation. Strong economic growth in many Front Range communities have increased regional incomes (Douglas County, Colorado, has the sixth highest median household income among all counties in the United States), and the average unemployment rate for census tracts near Front Range national forests is about 13 percent lower than that for the rest of the State. The high vulnerability score for Housing and Transportation relative to other scores on the Front Range reflects a high percentage of multi-unit housing, which is not surprising given the role of tourism and second homes in many of the mountain communities. At the time of this writing, however, many of the mountain communities are heavily impacted by COVID-19, and the relatively close living quarters and mixing of people in tourist communities has been highlighted as a potential cause for higher-than-average rates of spread and an exceptional challenge for these communities.

Table 1—Relative SVI (social vulnerability index) rankings for Front Range and non-Front Range (OTHER) Census tracts (0 = low vulnerability, 1 = high vulnerability).

Census tract type	Total SVI	Socio-economic	Household composition	Minority status	Housing and transportation
Front Range	0.3816	0.3946	0.3876	0.2566	0.5109
Other	0.5072	0.5062	0.5055	0.5149	0.5004

Notably, even though the region might not be highly vulnerable according to indices like the SVI, individual households and community groups might be highly vulnerable. Regional averages can mask many issues households face, particularly when an area is experiencing rapid growth. Higher property values mean higher rents and the potential to displace poorer residents. Such displacement has been shown to adversely affect social-emotional outcomes for early and middle school children. And while there may be job growth in rural Front Range communities, many of those jobs are low paying jobs in the service and tourism sectors. In 2016, the tourism sector was the second largest provider of jobs in Colorado.[3] During recessionary periods, the demand for tourism-related goods and services generally decreases more than for other goods. Mountain communities in the Front Range experienced this phenomenon following the collapse of the real estate market in 2008. The hospitality and tourism industry suffered as a result of the economic crisis and subsequent recession. During the recovery period from the recession, occupancy rates at ski lodges in the Rocky Mountains dropped by approximately 12.4 percent (Berwyn 2009). Similar impacts seem to currently be playing out due to the COVID-19 pandemic, resulting in declines in the service sector, and closing of company-provided housing for ski resort and other hospitality workers. While a good long-term investment for regional growth, such dependency on an industry with cyclical variability gives the region lower resiliency from economic turmoil. Social changes and the unique features of rural and WUI communities near national forests suggest the need for a new vulnerability index, instead of the one used by the CDC, that captures local employment related to the Forest Service.

Minority Populations and Engagement With Front Range National Forests

By 2044, the United States is projected to be a majority-minority nation (Colby and Ortman 2015). While not directly tied to climate change, national forests that fail to recognize and manage for this trend will fail to meet the Forest Service's goal of delivering benefits to the public (the entire public) and risk becoming irrelevant (Chavez 2000; Dawson et al. 2016; Flores et al. 2018). Adapting to climate change should account for the diversity of stakeholders. Flores et al. (2018) investigated differences between the demographics of communities surrounding national forests and visitors on the forests. They measure what they call an "inequality gap," that measures the disparity in national forest utilization between racial minorities and their white counterparts. The residents of counties around the Arapaho-Roosevelt and Pike-San Isabel National Forests are 39 percent and 42 percent minorities. Comparatively, minorities make up 8 percent and 4 percent of total visitation on the Arapaho-Roosevelt and Pike-San Isabel National Forests. These percentages imply an inequality gap for the Arapaho-Roosevelt of 31, and an inequality gap for the Pike-San Isabel of 38. The national average inequality gap is 23, making the Front Range national forests among the least diverse national forests in the country, which is true, in general, for national forests throughout Region 2. Chavez (2000) suggests the best way to include under-represented groups is to invite, include, and involve minorities in management decisions and programs. “Inviting” could be as simple as making sure outreach materials are multilingual. “Including” means including diverse groups in decision processes and soliciting diverse opinions on planned projects. “Involving” means getting diverse groups involved in implementing, a key part of which is including minorities in the workforce.

Understanding social networks among minorities and people that describe themselves as having the ability to speak English “less than well” is important to a community’s ability to cope with climate change, especially with regard to providing emergency assistance during disasters. During the 2013 Front Range floods, more than 11,000 people were evacuated, requiring community-wide coordination with emergency services, local volunteers, and the National Guard. After being displaced from their residences, non-English speakers and immigrant households often have fewer options to stay with friends and fewer informal short-term housing options. Minority groups are more vulnerable during emergency situations due to (1) conflict between minority communities and local agencies and governments and (2) diminished social and resource capital (Fothergill 1999). Often, local agencies in minority communities have less resources than their Caucasian counterparts. Those who have access to adequate resources may be less inclined to use emergency services due to a lack of trust in government officials, particularly among undocumented immigrants. Less wealthy minority communities also tend to have a higher dependency on alternate or public forms of transportation, which may prevent individuals from having the ability to flee from a dangerous situation (Fothergill 1999).

Water Resources

About 42 percent of Colorado’s water originates on forested land (Brown et al. 2008). Most of this begins in higher elevations as snowfall and becomes available for consumptive use with spring runoff. Tables 2 and 3 show the watersheds that get at least 10 percent of their water from the Arapaho-Roosevelt and Pike-San Isabel National Forests (Luce 2015) with surface water intakes for household consumption. Surface water intakes from these national forests serve over 2.6 million people and 2.3 million people on the Arapaho-Roosevelt and Pike-San Isabel, respectively. Note, some of the watersheds are shared between these national forests and are counted toward both forests’ totals. The Upper South Platte, for example, serves about 1.6 million people and has contributions from both Forests.

While water yield is provided at a fairly fine spatial scale, historical water demand data is much coarser. This section makes use of Brown et al. (2013), who project water use for 4-digit HUCs for several climate change scenarios. The 4-digit Hydrologic Unit Codes (HUCs) used in this section are the North Platte (HUC 1018), South Platte (HUC 1019), Upper Arkansas (HUC 1102), Upper Cimarron (HUC 1104), and Colorado Headwaters (HUC 1401).

Table 2—Contributions to 8-digit HUCs (hydrologic unit codes) from the Arapaho-Roosevelt National Forests.

HUC name	8-digit HUC	Water contribution (%)	Forest land occupied (%)	Population served
Colorado Headwaters	14010001	21	23	26,829
Upper Laramie	10180010	66	12	198
Upper South Platte	10190002	15	3	1,574,518
Clear	10190004	80	46	228,954
St. Vrain	10190005	60	39	373,320
Big Thompson	10190006	13	37	210,577
Cache La Poudre	10190007	75	39	199,252
Crow	10190009	12	24	19,032

Table 3—Contributions to 8-digit HUCs (hydrologic unit codes) from the Pike-San Isabel National Forests.

HUC name	8-digit HUC	Water contribution (%)	Forest land occupied (%)	Population served
South Platte Headwaters	10190001	82	48	420,625
Upper South Platte	10190002	64	50	1,574,518
Arkansas Headwaters	11020001	82	46	16,943
Upper Arkansas	11020002	38	13	210,907
Fountain	11020003	58	23	78,378
Huerfano	11020006	45	13	7,113
Purgatoire	11020010	12	7	10,902

The largest user of water on the Front Range is irrigated agriculture, accounting for 89 percent of total consumptive water use in 2010.[4] Significant advances have been made in irrigation efficiency, leading to an overall decrease in water withdrawals for agriculture in the Front Range. Whether or not that trend will continue in a warmer climate is uncertain. Most projections show water use increasing in the agricultural sector to compensate for rising temperatures, more frequent drought, and increased needs by plants (Warziniack et al. 2022). All else equal, this would imply an increase in water demand for agriculture on the Front Range. However, there is increasing pressure to divert both land and water out of agriculture to support residential growth, and increased frequency of drought and extreme rainfall events could adversely affect the agricultural sector. Figure 6 shows projections by Brown (2013) in consumptive use of water by economic sector. These projections account for trends in regional acreage devoted to agriculture, improvements in irrigation efficiency, and impacts of rising temperatures on crops' needs, but do not account for competition for water among uses, namely between agriculture and household use. Brown's (2013) projections reflect desired water use assuming water is not more constraining than it is today, and therefore, likely overestimate actual withdrawals in the face of increasing scarcity.

The highest value and fastest growing categories of water use on the Front Range are domestic and public water use (water used by households and in public spaces) and commercial and industrial water use (water used by firms and manufacturers). Usage per capita among households has been decreasing due to improvements in appliances and more reliable water metering. These gains in efficiency, however, do not offset large population and economic growth experienced on the Front Range. Even allowing for gains in water use efficiency, consumptive water use for households is expected to double by the end of the century compared to 2010 levels. Water use in the commercial and industrial sector is expected to grow even faster, seeing a projected 280 percent increase over 2010 levels by the end of the century. These increases in demands combined with a decrease in water yield makes the Front Range one of the most vulnerable regions in the country with respect to water shortage (Foti et al. 2012).

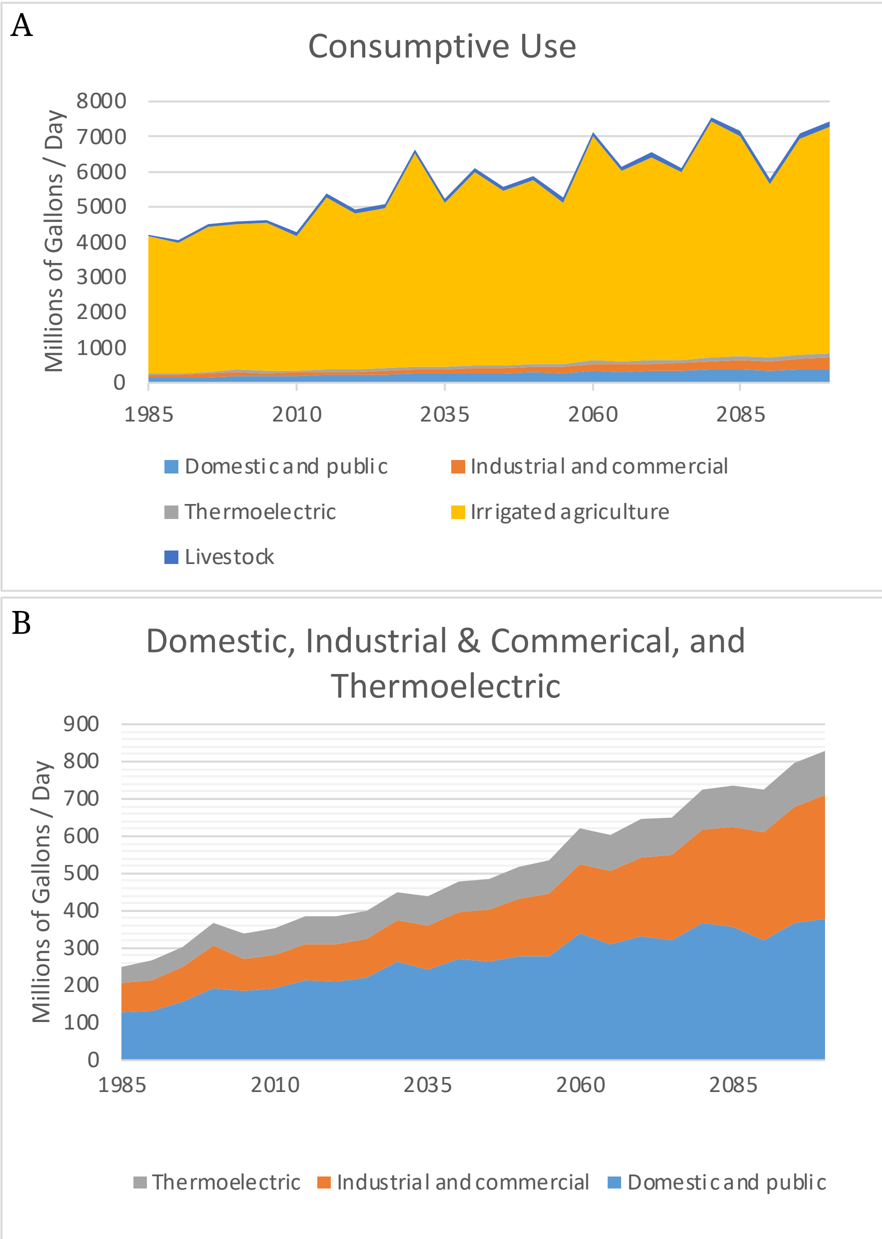


Figure 6a-b—Consumptive water use by economic sector on the Front Range.

Timing of Water Availability, Floods, and Drought

Climate change scenarios predict more frequent droughts, earlier and less reliable runoff from snowpack, and lower summer flows (Ehsani et al. 2017; Fassnacht et al. 2018). Climate models for Front Range forests show increases in spring runoff of 20 to 80 percent and decreases of 10 to 50 percent in Summer and Fall. Such conditions might necessitate greater water storage in reservoirs, particularly as warmer temperatures and drought increase the need for irrigation for crops. With lower water yields and higher demands, many of the area's existing reservoirs could occasionally be drawn down by the end of the century (fig. 7). Warziniack and Brown (2019) find that between 5 and 25 percent of the water currently going to agriculture would be needed to cover future household demands as the region gets both drier and more populous. Several regional storage projects have begun in order to respond to aging water infrastructure and a growing population. The Arapaho-Roosevelt National Forests have three proposals under review to increase storage and diversion capacity for existing projects. These proposals would likely affect the Seaman Reservoir expansion, Windy Gap Firming Project, and Gross Reservoir expansion.

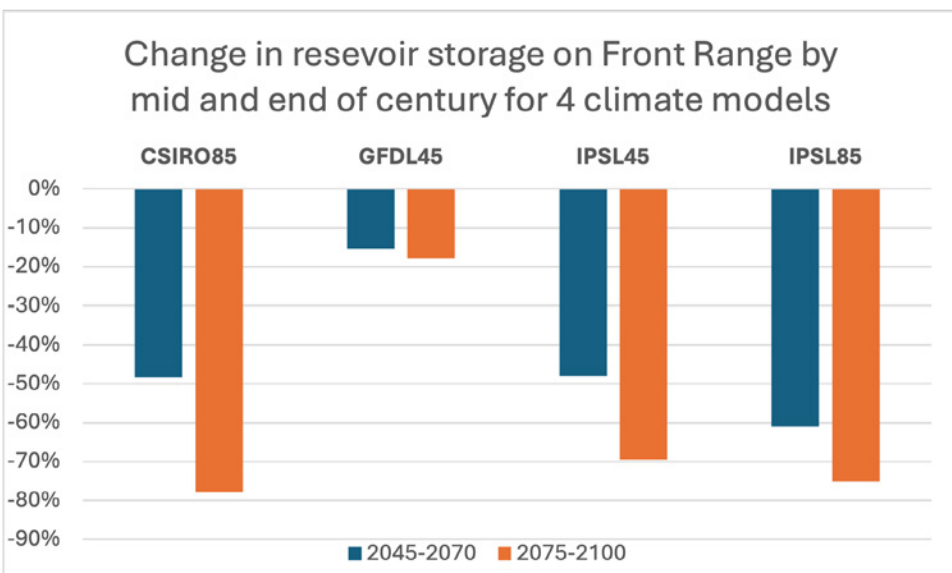


Figure 7—Reservoir storage for CSIRO, GFDL, and IPSL global climate models (GCMs) and Relative Concentration Pathways (RCPs) 4.5 and 8.5. These projections do not account for increased capacity due to infrastructure and storage investments. (Brown et al. 2008).

Climate change is also expected to lead to a higher frequency of floods in some areas of the Front Range (Human 2012). Increased runoff is predicted to be caused by a shift from snow to rain in the shoulder seasons, and from hail to rainfall in summer months. These shifts will cause more flash floods throughout the region. The 2013 flood in the Front Range caused approximately $16 million in damages to roads, bridges, trails, and other facilities. There was additional damage to resources including, but not limited to, archaeological sites, fisheries, and vegetation (ARP 2013).

In addition to damage to roads, homes, businesses, and ecosystems, floods pose a variety of other health-related risks to the community. Following the 2013 flood, tests conducted by the Colorado Health Department showed that the Big Thompson River and Boulder Creek watersheds contained high levels of *E. coli*. Both high temperatures that encourage the growth of *E. coli* bacteria and increased frequency of floods create substantial water quality vulnerabilities along the Front Range.

Water Quality and Watershed Health

Brown and Froemke (2012) calculate risk indices for sediment, nutrient, and toxics for watersheds throughout the country (figure 8). They find less risk and lower variability in conditions for Front Range watersheds compared to an average U.S. watershed. Many of the key watersheds are on protected lands, highlighting the role of national forests in providing much of the region's water supply. Major risks are due to WUI development and wildfire as shown on the Forests to Faucets 2.0 project maps (https://storymaps.arcgis.com/collections/4e450a6c7ed24f0cbae4abc1c07843b7?item=1). In 2020, the two largest wildfires in Colorado's history burned in key Front Range municipal watersheds. Harmful algal blooms are also becoming more prevalent, including in municipal drinking water supply reservoirs and in sources for irrigation water. Nutrients (nitrogen) running off burned forests are contributing to algal blooms in some reservoirs, but as population increases, public water supplies are increasingly at risk. Problems are likely to get worse in the face of growing urban areas and warmer climates.

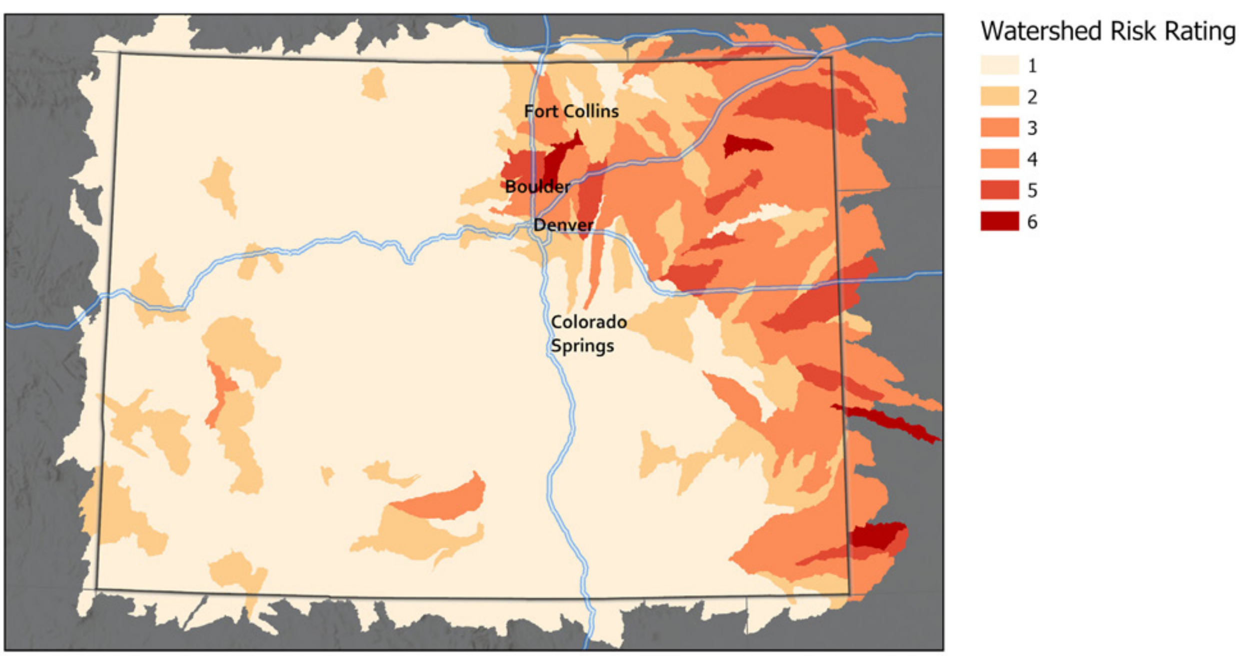


Figure 8—Risk rating for Colorado watersheds (Brown and Froemke 2012).

Risks to Water Quality Related to Mining Operations

There are over 800 abandoned mines or adits (entrances to underground mines) on the Pike-San Isabel, seven of which are considered dangerous or extremely dangerous for safety and human health. Approximately another 70 wells are considered potentially dangerous. In the Arapaho-Roosevelt National Forests, only two abandoned mines are considered dangerous, and 13 are considered potentially dangerous. Figure 9 shows the mines throughout Colorado and their safety classification.

Most of the literature related to mining activity and climate change focuses on acid rock drainage and the increased movement of pollutants such as metal sulfides due to extreme rainfall events and flooding. Watersheds containing active or abandoned mines are affected by complex interactions of surface and subsurface flows that introduce acidity and metals to the receiving stream. These influences may also emanate from natural sources in the underlying bedrock. Some ecosystems on the Front Range have not completely recovered from mining activities that took place in the 19th century, which continue to impact stream channels, sedimentation, and release of toxic chemicals (Schmidt et al. 2012; Wohl 2006, 2011). The Central City/Clear Creek Superfund site, for example, is a product of one of the most active mining areas in the state during the gold and silver rushes of the 1800s. Mining activity left behind tailings, impoundments, and draining mine adits that significantly impact groundwater and heavy metal contamination throughout the watershed. This work is ongoing, and to date, none of the performance measures have been met for remediation.[5]

Risks associated with mine drainage and leaching depend on precipitation and frequency of floods, fires, and other large-scale disturbances (Ossa-Moreno et al. 2018) as well as the level of human and wildlife exposure, all of which are expected to become more common in the future. In wetter years, higher precipitation can introduce more groundwater into the mine works, increasing the amount of exposed rock to water and the amount of water that percolates through tailings and waste rock. Most abandoned mines have exposed metal sulfides, which are harmful when in contact with water supplies and surrounding aquatic ecosystems (Colorado Geological Survey 2016; Parsons 1977; Vasilatos et al. 2015). Effects of acid mine drainage include turning surface waters red, coating creek beds with white aluminum, coating creek beds with metal deposits, and killing aquatic life. When left alone, groundwater that interacts with dangerous mine substances becomes contaminated and enters surface waters.

However, increased flow also dilutes pollutants, and surface waters tend to have lower concentrations of pollutants during wet periods. The low-flow periods, which will become more common with climate change, represent a critical time period in terms of aquatic toxicity; containment sources are undiluted by snowmelt and/or rainfall, and concentrations of mining-related constituents are often at their highest levels (Runkel et al. 2016).

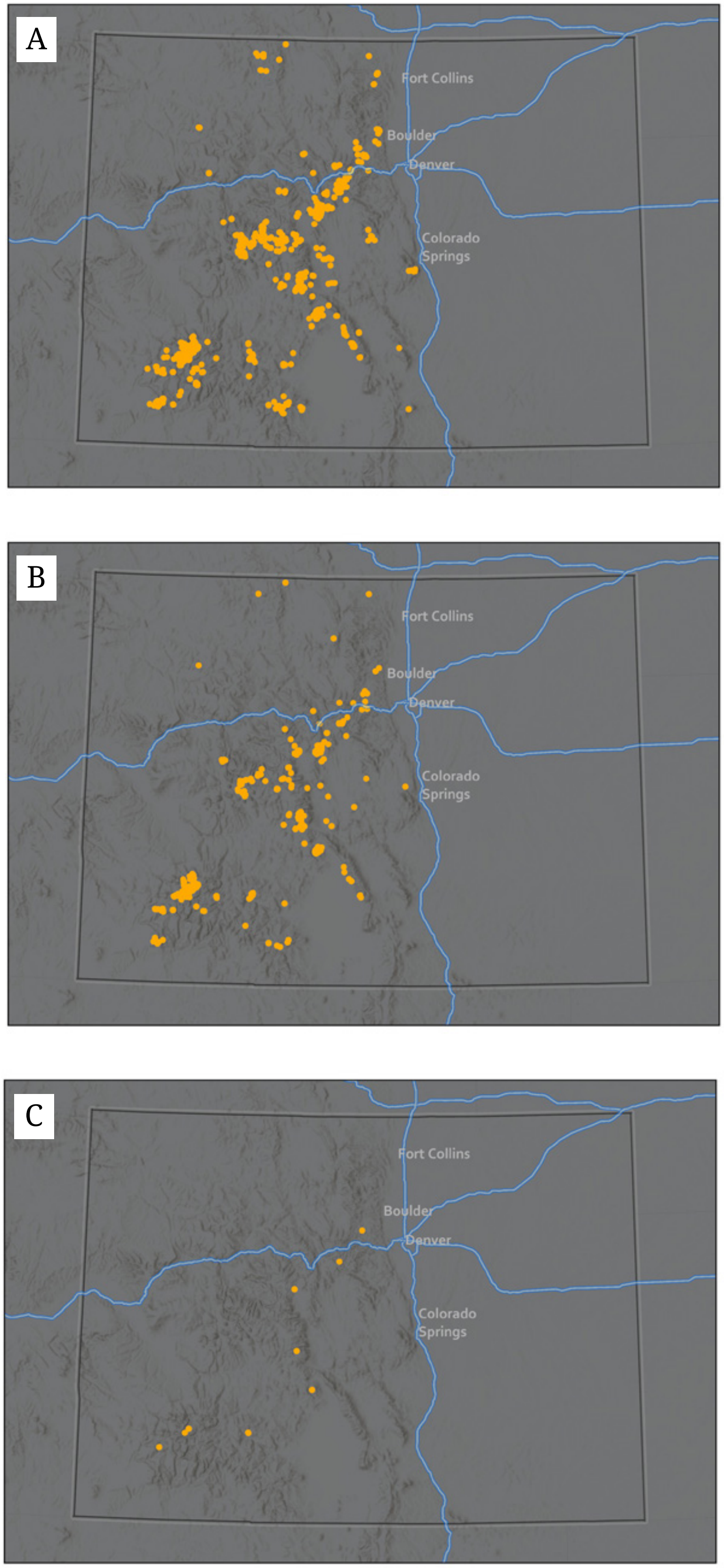


Figure 9a-c—Mines throughout Colorado at (a) slight, (b) significant, and (c) extreme risk to safety and human health.

Flooding and high levels of precipitation can cause collapses in mine roofs, create sinkholes, and cause further contamination (Polak et al. 2016; Whyatt and Varley [n.d.]). Intense rains may also flood mine shafts, damage mine works, and cause other safety concerns. In 2015, an EPA contractor attempting to repair a collapsed section of the adit at the bulkhead of the Gold King mine punctured the bulkhead, causing the release of 3 million gallons of mine water that had built up behind the bulkhead. Following the accident, the river was laced with heavy metals, causing the Animas River to face discoloration throughout Colorado, New Mexico, and Utah.

Rangeland Forage

As fragmentation of the region's rangeland on private lands increases, Federal lands will become more important for species that rely on rangeland forage. According to the Forest Service's Benefits at a Glance reports (https://www.fs.usda.gov/emc/economics/at-a-glance/benefits-to-people.shtml) the Arapaho-Roosevelt National Forests and Pawnee National Grassland support nearly 65,000 animal unit months (AUMs, defined as forage required for one cow-calf pair for one month) of livestock, approximately 3,720 local jobs, and $157,000,000 in local labor income. The Pike-San Isabel National Forests and the Cimarron and Comanche National Grasslands combine to support 152,000 AUMs, 5,260 local jobs, and $212,000,000 in local labor income.

Reeves and Mitchell (2012) find that 29 percent of Colorado's rangeland has been modified by human use. An additional 256,000 acres statewide are at risk from residential development by 2030. Reeves and Mitchell (2012) found that forage demand was below forage supply for most of Colorado, and that in the absence of drought and other disturbances, the ability of the region's rangeland to support livestock is adequate, though conditions vary at more localized levels.

Rangeland health will also be affected by livestock's dependence on reliable water supplies. Currently, the driest month of the year in the Front Range is June, which shifts in some climate scenarios. Seasonal water availability will affect plant competition and possibly cause changes in grass species. High temperatures will also degrade digestibility of forage for livestock and other grazing species (through increases in lignin in plants). Because of the seasonal shift, forage quality will likely increase more among C3 plants than C4 plants and have consequences for nutritional value (Reeves and Mitchell 2012; Trlica 2013). Frequent flash floods may also affect the formation of roots for plants, thus degrading forage health due to seasonal shifts and more extreme precipitation patterns.

Higher temperatures also increase the probability of morbidity and death among livestock and change microbial communities that spread vector-borne diseases, food-borne diseases, and host resistance (Rojas-Downing et al. 2017). In 2012 the agricultural industry across the Front Range was affected by outbreaks of anthrax, equine herpesvirus-1, vesicular stomatitis, and West Nile virus. Anthrax development is typically associated with periods of heavy rainfall, flooding, drought, and other ecological changes, all of which are projected to become more frequent. Wittmann et al. (2001) showed warmer temperatures led to tick infestations (which thrive in high temperatures), causing livestock to lose about 18 percent of their bodyweight.

Carbon Sequestration

The Forest Service Planning Rule requires national forests to develop baseline carbon stocks and consider impacts of management actions on carbon stocks. Much of this work is being done by the agency's Office of Sustainability and Climate (USDA FS 2015) and Forest Service Research and Development (Heath et al. 2011). The following is taken directly or summarized from USDA (2015), "Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System units, Rocky Mountain Region":

Forests sequester carbon in seven primary stocks. They are:

- Live trees—All live woody vegetation at least 1 inch in diameter at breast height (d.b.h.). Some estimates also separate above and below ground stocks in live trees, in which case, below ground includes coarse living roots more than 2 mm in diameter.
- Understory—All live herbaceous and woody vegetation up to 1-inch d.b.h.
- Standing dead trees—Nonliving, but otherwise follow the same definition as live trees and include estimates for below ground roots more than 2 mm in diameter.
- Down dead wood—All nonliving woody biomass with a diameter of at least 7 cm at transect lying on the ground.
- Forest floor—Litter, fumic, and humic layers and all nonliving biomass with a diameter less than 7.5 cm at transect intersection lying on the ground above the mineral soil.
- Soil organic carbon—All organic material in soil to a depth of 1 meter but excluding the coarse roots of the pools mentioned earlier.
- Harvested wood products.

In general, national forests have greater carbon density than private land (28 percent more per forested hectare). Thus, management and impacts of these forests can substantially affect the region's stock of carbon sequestered by forests.

Over the last couple of decades, many of the forests in the Rocky Mountain Region have switched from being a carbon sink to a carbon source, due to both disturbances and aging effects. Stands that were established in the late 1800s and early 1900s reached their maximum rates of productivity around the 1970s. Rates of accumulation declined naturally as these forests matured. This slowing, paired with disturbances over recent decades, has caused the forests to become carbon sources. The latest round of disturbances has led to regrowth in some areas, and these areas are likely to become carbon sinks as rates of growth increase.

The largest pool of carbon in Region 2 is aboveground carbon, followed by soil organic carbon, and carbon stored in matter on the forest floor (fig. 10). These three categories have seen an increase in carbon sequestered between 1990 and 2013. Compared to other national forests in Region 2, the Arapaho-Roosevelt and Pike-San Isabel National Forests fall near the middle among all forests in R2 for sequestered carbon and carbon density (figure 11). Total carbon stored has increased on the Arapaho-Roosevelt but decreased on the Pike-San Isabel, largely in aboveground storage (figure 12).

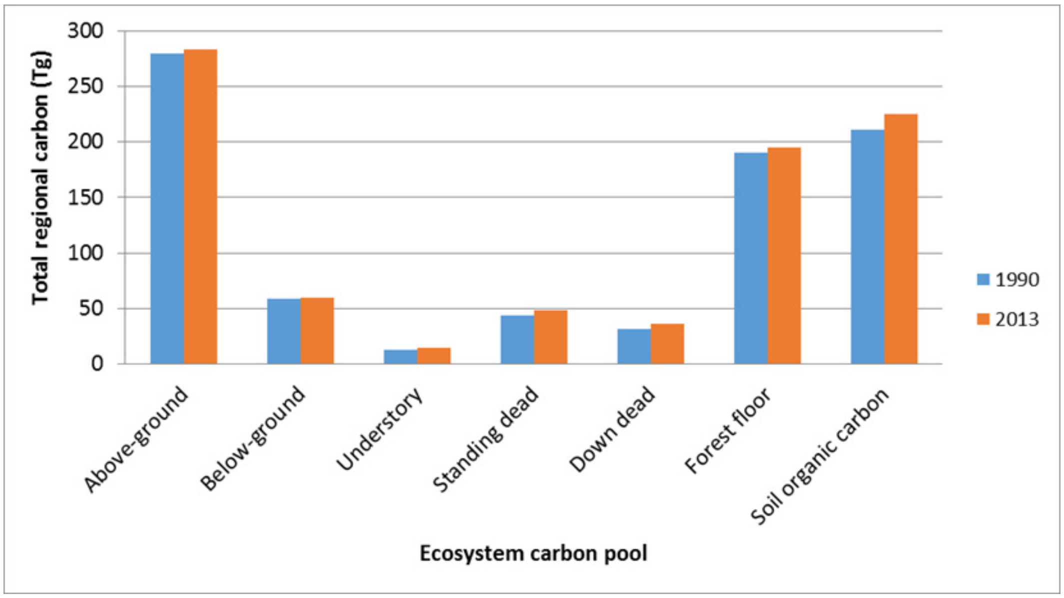


Figure 10—Ecosystem carbon pools for Region 2.

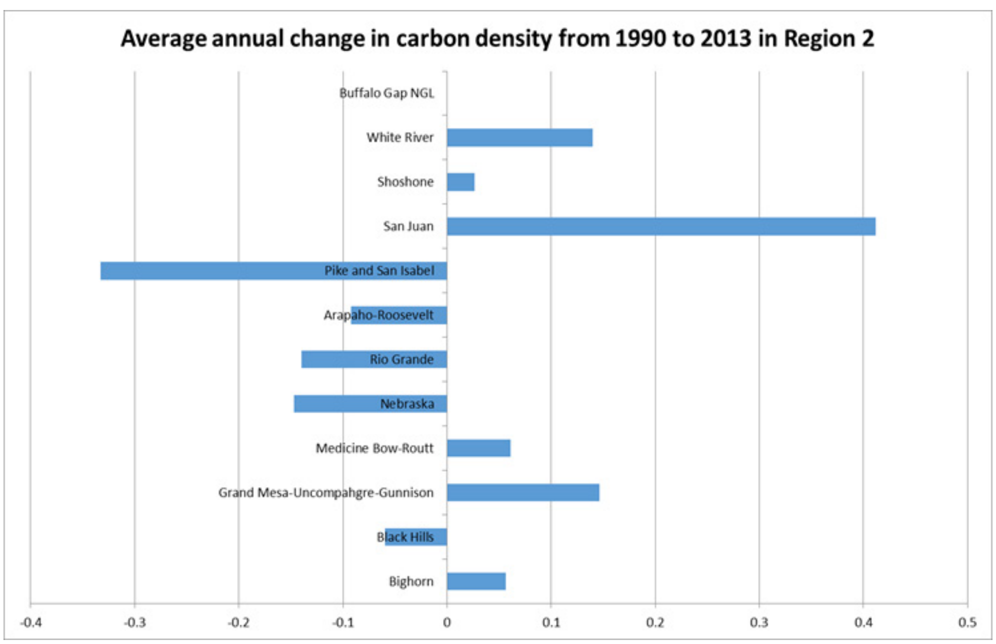
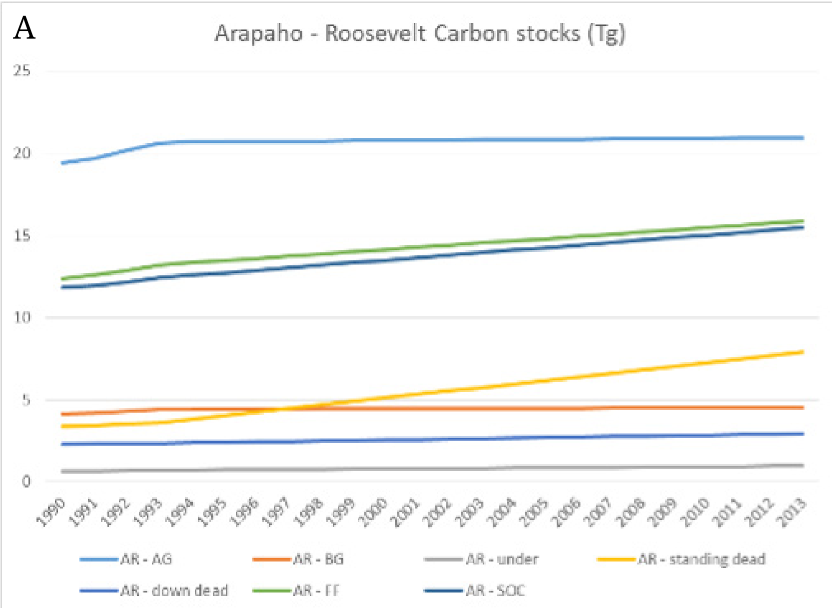


Figure 11—Average annual change in carbon density.



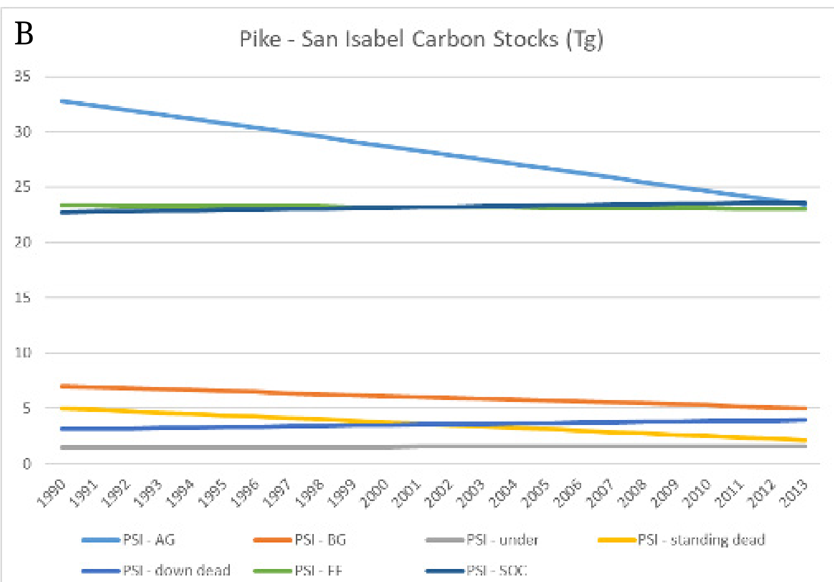


Figure 12a-b—Carbon stocks in the (a) Arapaho-Roosevelt and (b) Pike-San Isabel National Forests.

Key Points and Management Implications

Climate change impacts are likely to be amplified by social forces taking place, especially rapid population growth and shifts in demographic characteristics. Increased population living on the Front Range and in WUI communities means more people will be exposed to fires, floods, and drought, and the resulting impacts on mines and water resources. Increased fragmentation of non-Federal lands will make Front Range national forests even more important for providing ecosystem services.

In general, the Front Range population is wealthier and more educated than the national average, which suggests the region is not particularly vulnerable to climate and environmental change. These regional averages mask small pockets of highly vulnerable populations. Vulnerable people will become more vulnerable as rising home prices and lower wages strain households. Low-income families in the region are more likely to live in close living quarters, which as seen by the combined effects of the COVID-19 pandemic and 2020 wildfires, can amplify the impacts of disease outbreaks and natural disasters. The most vulnerable often lack the resources and support networks to absorb shocks as easily as the more affluent, pushing poor and vulnerable people further to the margins.

A key takeaway from research on social vulnerability is the Forest Service's role in supporting rural economies, in direct employment by the Forest Service and contractors, but also the role of Federal lands in supporting activities like grazing, recreation, and clean water. The Forest Service, with a commitment to serving the American people and increasing diversity of our workforce, is in a unique position to connect with vulnerable populations. Adapting to climate change should account for the diversity of stakeholders by inviting, including, and involving minorities in management decisions and programs. Management should seek to understand the social networks of vulnerable populations to facilitate their climate adaptation and to provide emergency assistance during disasters. Furthermore, given the unique features of WUI and forest-dependent communities, there is a need for more tailored and nuanced vulnerability measures that capture the role the Forest Service plays in local communities.

Notes

[1]Adams, Arapahoe, Broomfield, Clear Creek, City of Denver, Douglas, Elbert, El Paso, Gilpin, Jefferson, Larimer, and Park counties.
[2]https://www.fs.usda.gov/ecosystemservices/FS_Efforts/forests2faucets.shtml
[3]https://choosecolorado.com/key-industries/tourism/ accessed 27 March 2020.
[4]Consumptive-use is water that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from an immediate water environment (water body, surface- or ground-water source, basin) (Shaffer et al.).
[5]https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Healthenv&id=0800257 accessed May 25, 2020.

References

Arapaho and Roosevelt National Forests and Pawnee National Grassland [ARP]. 2013. Flood impact assessment report. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5440234.pdf [Accessed 31 October 2019]

Berwyn, B. 2009. U.S., Colorado tourism hit hard by recession. https://www.summitdaily.com/news/u-s-colorado-tourism-hit-hard-by-recession/

Brown, T.C.; Bergstrom, J.C.; Loomis, J.B. 2007. Defining, valuing and providing ecosystem goods and services. Natural Resources Journal. 47(2): 329–376. https://www.jstor.org/stable/24889176

Brown, T.C.; Foti, R.; Ramirez, J.A. 2013. Projected freshwater withdrawals in the United States under a changing climate. Water Resources Research. 49(3): 1259–1276. https://doi.org/10.1002/wrcr.20076

Brown, T.C.; Froemke, P. 2012. Nationwide assessment of nonpoint source threats to water quality. BioScience. 62(2): 136–146. https://doi.org/10.1525/bio.2012.62.2.7

Brown, T.C.; Hobbins, M.T.; Ramirez, J.A. 2008. Spatial distribution of water supply in the coterminous United States. Journal of the American Water Resources Association. 44(6): 1474–1487. https://doi.org/10.1111/j.1752-1688.2008.00252.x

Chavez, D.J. 2000. Invite, include, and involve! Racial groups, ethnic groups, and leisure. In: Allison, M.T.; Schneider, I.E., eds. Diversity and the recreation profession: Organizational perspectives. State College, PA: Venture Publishing: 179–191.

Colby, S.L.; Ortman, J.M. 2015. Projections of the size and composition of the U.S. population: 2014 to 2060, population estimates and projections. Current Population Reports. P25-1143. U.S. Census Bureau.

Colorado Geological Survey. 2016. Abandoned mine lands. https://coloradogeologicalsurvey.org/hazards/aml/

Daily, G.C. (ed.). 1997. Nature's services. Washington, DC: Island Press. 392 p.

Dawson, C.P.; Cordell, K.; Watson, A.E.; [et al.]. 2016. The U.S. wilderness managers' survey: Charting a path for the future. Journal of Forestry. 114(3): 298–304. https://doi.org/10.5849/jof.15-007

Ehsani, N.; Vörösmarty, C.J.; Fekete, B.M.; [et al.]. 2017. Reservoir operations under climate change: Storage capacity options to mitigate risk. Journal of Hydrology. 555: 435–446. https://doi.org/10.1016/j.jhydrol.2017.09.008

Fassnacht, S.; Venable, N.; McGrath, D.; [et al.]. 2018. Sub-seasonal snowpack trends in the Rocky Mountain National Park Area, Colorado, USA. Water. 10(5): 562. https://doi.org/10.3390/w10050562

Flores, D.; Falco, G.; Roberts, N.S.; [et al.]. 2018. Recreation equity: Is the Forest Service serving its diverse publics? Journal of Forestry. 116(3): 266–272. https://doi.org/10.1093/jofore/fvx016

Fothergill, A.; Maestas, E.G.; Darlington, J.D. 1999. Race, ethnicity, and disasters in the United States: A review of the literature. Disasters. 23(2): 156–173. https://doi.org/10.1111/1467-7717.00111

Foti, R.; Ramirez, J.A.; Brown, T.C. 2012. Vulnerability of U.S. water supply to shortage: A technical document supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. RMRS-GTR-295. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-295

Halofsky, J.E.; Peterson, D.L.; Ho, J.J.; [et al.], eds. 2018. Climate change vulnerability and adaptation in the Intermountain Region [Parts 1 and 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 513 p.
Part 1: https://doi.org/10.2737/RMRS-GTR-375PART1
Part 2: https://doi.org/10.2737/RMRS-GTR-375PART2

Heath, L.S.; Smith, J.E.; Woodall, C.W. [et al.]. 2011. Carbon stocks on forestland of the United States, with emphasis on USDA Forest Service ownership. Ecosphere. 2(1): 1–21. https://doi.org/10.1890/ES10-00126.1

Human, K. 2012. A future without hail? Boulder, CO: NOAA Physical Sciences Laboratory. https://www.esrl.noaa.gov/psd/news/2012/010912.html

Jaworski, Delilah; Kline, Jeffrey D.; Miller, Chris; [et al.]. 2018. Evaluating ecosystem services as management outcomes in national forest and grassland planning assessments. Gen. Tech. Rep. PNW-GTR-968. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 38 p. https://doi.org/10.2737/PNW-GTR-968

Knight, R.L.; Wallace, G.N.; Riebsame, W.E. 1995. Ranching the view: Subdivisions versus agriculture. Conservation Biology. 9(2): 459–461. https://www.jstor.org/stable/2386791

Loss, S.R.; Will, T.; Marr, P.P. 2013. The impact of free-ranging domestic cats on wildlife of the United States. Nature Communications. 4(1): 1–8. https://doi.org/10.1038/ncomms2380

Luce, C. 1970. National forest contributions to streamflow: Rocky Mountain Research Station. https://www.fs.usda.gov/research/rmrs/projects/national-forest-contributions-streamflow

Ossa-Moreno, J.; Mcintyre, N.; Ali, S.; [et al.]. 2018. The hydro-economics of mining. Ecological Economics. 145: 368-379. https://doi.org/10.1016/j.ecolecon.2017.11.010

Parsons, J. 1977. Effects of acid mine wastes on aquatic ecosystems. Water, Air, and Soil Pollution. 7(3). https://doi.org/10.1007/bf00284129

Polak, K.; Różkowski, K.; Czaja, P. 2015. Causes and effects of uncontrolled water inrush into a decommissioned mine shaft. Mine Water and the Environment. 35(2): 128–135. https://doi.org/10.1007/s10230-015-0360-6

Reeves, M.C.; Mitchell, J.E. 2012. A synoptic review of U.S. rangelands: A technical document supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. RMRS-GTR-288. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 128 p. https://doi.org/10.2737/RMRS-GTR-288

Rojas-Downing, M.; Nejadhashemi, P.; Harrigan, T.; [et al.]. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management. 16: 145–163. DOI: https://doi.org/10.1016/j.crm.2017.02.001

Runkel, R.L.; Kimball, B.A.; Nimick, D. A.; [et al.]. 2016. Effects of flow regime on metal concentrations and the attainment of water quality standards in a remediated stream reach, Butte, Montana. Environmental Science & Technology. 50(23): 12641–12649. https://doi.org/10.1021/acs.est.6b03190

Schmidt, T.S.; Clements, W.H.; Wanty, R.B.; [et al.]. 2012. Geologic processes influence the effects of mining on aquatic ecosystems. Ecological Applications. 22: 870–879. https://doi.org/10.1890/11-0806.1

Shaffer, K.; Runkle, D.L. 2007. Consumptive water: Use coefficients for the Great Lakes Basin and climatically similar areas. Reston, VA: U.S. Geological Survey. https://doi.org/10.3133/sir20075197

Trlica, M.J. 2013. Grass growth and response to grazing. Fact Sheet No. 6.108. Fort Collins, CO: Colorado State University Extension. https://extension.colostate.edu/topic-areas/natural-resources/grass-growth-and-response-to%20grazing-6-108/

Turner, S. 2018. Denver water quality warning in effect because of *E. coli* concerns. https://kdvr.com/news/local/denver-water-quality-warning-in-effect-due-to-e-coli/

U.S. Department of Agriculture, Forest Service [USDA FS]. 2015. Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System units; Rocky Mountain Region. 41 p. Whitepaper. https://www.fs.usda.gov/sites/default/files/rocky-mountain-region-carbon-assessment.pdf

Vasilatos, C.; Koukouzas, N.; Alexopoulos, D. 2015. Geochemical control of acid mine drainage in abandoned mines: The case of Ermioni Mine, Greece. Procedia Earth and Planetary Science. 15: 945–950. https://doi.org/10.1016/j.proeps.2015.08.151

Warziniack, T.; Arabi, M.; Brown, T.C.; [et al.]. 2022. Projections of freshwater use in the United States under climate change. Earth's Future. 10(2): e2021EF002222. https://doi.org/10.1029/2021EF002222

Warziniack, T.; Brown, T.C. 2019. The importance of municipal and agricultural demands in future water shortages in the United States. Environmental Research Letters. 14(8): 084036. https://doi.org/10.1088/1748-9326/ab2b76

Wear D.N.; Prestemon, J.P. 2019. Spatiotemporal downscaling of global population and income scenarios for the United States. PLoS One. 14(7): e0219242. https://doi.org/10.1371/journal.pone.0219242

Whyatt, J.; Varley, F. 2008. July. Catastrophic failures of underground evaporite mines. In: Proceedings of the 27th international conference on ground control in mining. Morgantown, WV: College of Engineering and Mineral Resources, West Virginia University. https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/cfoue.pdf

Wittmann, E.J.; Mellor, P.S.; Baylis, M. 2001. Using climate data to map the potential distribution of *Culicoides imicola* (Diptera: Ceratopogonidae) in Europe. Revue Scientifique et Technique. 20: 731–740. http://dx.doi.org/10.20506/rst.20.3.1306

Wohl, E. 2006. Human impacts to mountain streams. In: James, L.A.; Marcus, W.A., eds. The human role in changing fluvial systems. Proceedings of the 37th International Binghamton geomorphology symposium. Geomorphology. 79: 217–248. https://doi.org/10.1016/j.geomorph.2006.06.020