STATE OF NEW MEXICO
BEFORE THE ENVIRONMENTAL IMPROVEMENT BOARD

IN THE MATTER OF PROPOSED AMENDMENTS TO 20.2.91 NMAC
***NEW MOTOR VEHICLE EMISSION STANDARDS*, No. EIB 23-56 (R)**

DIRECT TESTIMONY OF MICHELLE MIANO

I. INTRODUCTION

My name is Michelle Miano, and Honorable Michelle Lujan Grisham appointed me in January 2023 to serve as the Director of the Environmental Protection Division at the New Mexico Environment Department (NMED). As Director, I oversee the Climate Change Bureau, Air Quality Bureau, and Radiation Control Bureau and assist in advancing the goals of each of those programs. My full qualifications are set forth in **NMED Exhibit 15**: Resume of Michelle Miano.

The standards proposed today are an important part of New Mexico's overall effort to address climate change by reducing greenhouse gas emissions in the transportation sector, the second largest source of greenhouse gases in the state, and reducing harmful air pollution, which especially affects residents residing along our big transportation corridors such as I-10, I-40, and I-25. My testimony has several purposes, which are generally to provide a policy basis and an overview of the feasibility of the Proposed Rule. More specifically, I will (1) explain how these standards help fulfill the directive from the Governor as set forth in her Executive Order 2019-03 to address climate change; and (2) place this rulemaking in the context of other current efforts and future initiatives occurring across New Mexico to support clean transportation.

II. POLICY BASIS FOR THE PROPOSED RULE

The Proposed Rule being considered today are the culmination of a policy direction established by the Governor in 2019 for New Mexico. To understand the importance of these standards, it is necessary to describe their place in the Governor's 2019 executive order and her

more recent efforts to reduce greenhouse gas emissions and to protect New Mexico's public health and welfare from the impacts of climate change and air pollution. It is also critical to remember that the citizens of New Mexico re-elected the Governor based on her first-term accomplishments and vision for her second term, and that we have the opportunity to assist in fulfilling that vision today.

A. CLIMATE CRISIS IN NEW MEXICO

The threat of wildfire, drought, workplace heat, and deteriorating public health are a few of the many reasons that Governor Lujan Grisham initiated action to address climate change during her first term. New Mexico is already experiencing the impacts of climate change, and credible forecasts project more significant adverse impacts if we do not act now. The economic costs of inaction are high, while the opportunities associated with a clean energy economy are real and feasible.

We are seeing disruptions in our weather patterns, manifested in hotter and longer summers, more intense storms, and more extreme droughts. For example, recent temperature observations by NASA confirm that 2023 experienced the hottest summer ever recorded in human history,[1] while at the same time, NOAA observed the highest levels of atmospheric greenhouse gases in human history[2].

These observations are no coincidence, and they're having serious impacts on New Mexicans, including less predictable and robust harvests of our agricultural products; an increase

[1] NASA or National Aeronautics and Space Administration, Goddard Space Flight Center. 2023. "Summer 2023 Record High Global Temperatures." *NASA Scientific Visualization Studio.* https://svs.gsfc.nasa.gov/14407#media_group_372024

[2] NOAA or National Oceanic and Atmospheric Administration. 2023. "Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases." https://gml.noaa.gov/ccgg/trends/global.html

in frequency and severity of natural disasters, such as flash floods and wildfires; and health impacts related to hotter weather. For example, the 2022 Calf Canyon/Hermits Peak Fire was the largest and most destructive wildfire in New Mexico's history, burning over 340,000 acres. That same year, the state also suffered from its second-largest wildfire, the Black Fire in the Gila National Forest, which burned over 325,000 acres.

Likewise, warmer year-round temperatures mean additional energy costs to keep residences and businesses cool throughout the year. Our critical infrastructure is vulnerable to our changing climate, including roads, overpasses, bridges, rail, electrical power distribution systems, drinking water and sewer distribution and collection lines, and flood control and drainage systems. Declining air and water quality are disrupting natural habitats and ecosystems. We are seeing warmer and drier winters leading to bark beetle infestations in many forests, fish habitat reduction in warming surface waters, and fewer alpine meadows as ecosystems shift to higher elevations as an adaptation technique. **NMED Exhibit 16**: Confronting Climate Change in New Mexico; https://www.ucsusa.org/resources/confronting-climate-change-new-mexico.

In 2021, the New Mexico Bureau of Geology and Mineral Resources released a report describing the impacts to water resources in New Mexico, see **NMED Exhibit 17**: Climate Change in NM Over the Next 50 Yrs. - Impacts on Water Resources; https://geoinfo.nmt.edu/ClimatePanel/report/.

1. **Principal conclusions of "Climate Change in New Mexico over the Next 50 Years:"**

(A) Global climate models project an average temperature increase across New Mexico of between 5 and 7 degrees Fahrenheit over the next 50 years.

(B) The coupled trends of increasing temperature with no increase in average precipitation leads to a likely projection of increasingly arid conditions, resulting in decreased soil moisture, stressed vegetation, decreased snowpack, and more severe droughts.

(C) All water in New Mexico originates as rain or snow, but most returns to the atmosphere. The small percentage of rain and snow (~3.5%) that supplies groundwater and surface water will decrease as aridity increases, reducing water resources that support wildlife habitat, agriculture, manufacturing, and other economic sectors and are available for human use and consumption.

(D) Climate is a fundamental driver of ongoing and future vegetation changes that will affect the distribution and abundance of water resources.

(E) Delicate soils on New Mexico's landscapes will be damaged by increasing temperature, fire, and erosion, leading to dustier conditions and less hospitable environments for vegetation.

(F) New Mexico has a dynamic landscape; climate change and increasing fire frequency over the next 50 years will amplify recently observed instability, potentially damaging infrastructure and endangering the public.

(G) Surface water supply shortages will drive both agricultural and municipal/industrial water users to rely more heavily on groundwater, a limited resource.

(H) A warming atmosphere could increase the magnitude of future storms, leading to extreme precipitation events and increased flooding.

(I) The quality of surface and groundwater resources will be impacted by a warming climate; the most likely effects may include increased temperature along with higher concentrations of nutrients, dissolved oxygen, and pathogenic organisms.

(J) Statewide impacts will include higher temperatures, greater aridification, lower water quantity and quality, and possibly increased extreme precipitation events. However, the topographic complexity of New Mexico will lead to some prevalent impacts within four distinct regions:

1. **High Mountains**—less snowfall; more evapotranspiration, fires, and erosion; and loss of vegetation.
2. **Northwestern High Desert**—loss of soil, increased dustiness, possible arroyo incision, and change in vegetation patterns.
3. **Rio Grande Valley and Southwest Basins**—lower river flows (25% decrease in Rio Grande flow in 50 years) and greater loss of water from reservoirs.
4. **Eastern Plains**—loss of soil, desertification, increased dustiness, and possibly higher incidence of extreme precipitation events resulting in highly erosive, often localized flooding.

Examples of the impacts listed above have already happened in New Mexico, and as climate disruption accelerates, we should not only be prepared for other climate-induced events to occur, but we should mitigate the obvious sources of the problem.

B. 2019 EXECUTIVE ORDER

In January 2019, during her first month in office, Governor Lujan Grisham signed Executive Order 2019-03 on Addressing Climate Change and Energy Waste Prevention, see **NMED Exhibit 18**: Governor's EO No. 2019-03 – "Executive Order On Addressing Climate Change and Energy Waste Prevention"; https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf. The Executive Order recognizes that human activity is changing the global climate by increasing the concentration of carbon dioxide, methane, and

other greenhouse gases in the atmosphere, which trap heat near the earth's surface, and acknowledges that the planet has as little time remaining to take meaningful climate action in order to limit the increase in global average temperature to 1.5 degrees Celsius – the level necessary to forestall extreme and dramatic climate changes.

The Executive Order directs the state to support the 2015 Paris Agreement Goals by joining the U.S. Climate Alliance (USCA)[3] and establishes an aggressive statewide emissions reduction goal of at least 45% below 2005 levels by 2030. The USCA is a bipartisan coalition of 25 governors working together to advance state-led, high-impact climate actions. Subsequently, Governor Michelle Lujan Grisham publicly announced the added target of reaching net-zero emissions by 2050.

The Executive Order also establishes an interagency Climate Change Task Force ("Task Force") consisting of Secretaries from each state agency with the Secretaries from the New Mexico Environment Department ("NMED") and the Energy Minerals and Natural Resources Department ("EMNRD") as Co-Chairs. The purpose of the Task Force is to provide strategic direction for achieving the 2030 emission reduction goal.

The Executive Order also directed NMED and EMNRD to implement specific emission reduction strategies, including working with "stakeholders on legislation to increase the New Mexico renewable portfolio standard ("RPS") and increase New Mexico's energy efficient standards for electric utilities." The increase in the RPS was accomplished with the passage of the Energy Transition Act by the state legislature in 2019. The increase in energy efficiency was also accomplished in 2019 with amendments to the Efficient Use of Energy Act.

[3] The U.S. Climate Alliance is a bipartisan coalition of 25 governors securing America's net-zero future by advancing state-led, high-impact climate action. https://www.usclimatealliance.org/

The Executive Order directed NMED and EMNRD to "jointly develop a statewide, enforceable regulatory framework to secure reductions in oil and gas sector methane emissions and to prevent waste from new and existing sources and enact such rules as soon as practicable." This directive was fulfilled when the Oil Conservation Commission adopted EMNRD's methane waste rules (19.15.27 NMAC and 19.15.28 NMAC, effective 5/25/2021) and when the EIB adopted NMED's oil and gas sector ozone precursor pollutant rules (20.2.50 NMAC, effective 8/05/2022). Ozone precursors include oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). Because the ozone precursors, VOCs, are emitted along with methane in oil and gas operations, requirements that reduce VOC emissions necessarily have a co-benefit of reducing methane emissions.

The Executive Order also directed the Task Force to evaluate policies and regulatory strategies to meet the emission reduction target, including but not limited to the "adoption of approaches to reduce greenhouse gas and criteria pollutant emissions from light-duty vehicles sold in the state, including Low Emission Vehicle (LEV) emission standards and Zero Emissions Vehicle (ZEV) performance standards." The approval of Clean Cars I (20.2.91 NMAC), or Advanced Clean Cars, by the Environmental Improvement Board and Albuquerque Bernalillo County Air Quality Board ("Boards") in May 2022 accomplished the directive in the Executive Order. However, since California has now updated Advanced Clean Cars to Advanced Clean Cars II, with the first effective model year 2026, New Mexico must follow suit to gain the economic, health, and environmental benefits of reducing emissions from motor vehicles. The inclusion of Advanced Clean Trucks and Heavy-Duty Omnibus rules also help New Mexico achieve the 2030 and 2050 greenhouse gas emission reduction targets.

The Department is before you today to continue its efforts under Executive Order to bring clean vehicle standards to New Mexico. In addition to adopting LEV and ZEV standards for light-duty vehicles, the department is before you today to request the adoption of LEV and ZEV standards for medium and heavy-duty vehicles. These standards will reduce emissions of greenhouse gases while increasing the availability of ZEVs in our state. The Proposed Rule will align New Mexico's regulatory framework with the course set by the Biden administration in Executive Order 14037 and the auto manufacturers. "Collectively, the auto industry has committed to investing more than $330 billion to bring exciting new electric vehicles (EVs) to market, including plug-in hybrid, battery and fuel cell EVs." **NMED Exhibit 19**: Biden EO No. 14037 - Strengthening American Leadership in Clean Cars and Trucks; https://www.govinfo.gov/content/pkg/FR-2021-08-10/pdf/2021-17121.pdf**.**

As mentioned earlier, this is not the first time the Department has been before these Boards with a proposal to adopt clean vehicle standards. In 2007, the Boards held a joint hearing to adopt Advanced Clean Cars for both jurisdictions. The EIB subsequently rescinded the rules in 2013. At that point, the operative LEV standards for the state became the federal standards. In 2022, the Boards again held a joint hearing and adopted the Advanced Clean Cars standards. These vehicle emission standards became effective on July 1, 2022. However, before the implementation of the rule in New Mexico, the California Air Resources Board (CARB) adopted updated standards known as Advanced Clean Cars II. For clean car standards to be implemented in New Mexico, the Boards must adopt the amended Proposed Rule before you in this matter. In addition to the CARB standards for light-duty vehicles, the Department is presenting the CARB regulations for Advanced Clean Trucks and Heavy-duty Omnibus, which require a portion of heavy- and medium-duty vehicles sold in the state to be ZEVs and enact stricter tailpipe

emission limits for new heavy-duty vehicles. Together these three regulations will effectively reduce tailpipe emissions for new vehicles in the state and require the delivery of ZEVs to New Mexico across all vehicle classes.

As described above, the state has put into place powerful policy and regulatory tools to reduce greenhouse gas emissions. The combination of actions that have already been implemented since Governor Lujan Grisham took office, and the policies currently planned for implementation, unlock significant emission reductions by 2030. However, there remains a large gap between that achievement and our 2030 reduction goal. It is for this reason that the Climate Change Task Force spent much of the summer and fall of 2021 analyzing climate policy options that would be sufficiently ambitious and actionable to achieve our reduction targets, see **NMED Exhibit 20**: NM Climate Change Task Force - 2021 Progress and Recommendations. At the request of the state, the Rocky Mountain Institute prepared a New Mexico-specific version of their Energy Policy Simulator tool, a model that looks at the economic and emissions-reduction impacts of various climate policy actions. Using this tool, RMI and the Task Force held a series of planning workshops to evaluate policy goals and internal implementation steps that could become part of our in-progress climate action plans described in Technical Assistance to the State of New Mexico-Energy Policy Simulator. If implemented, the goals and policies identified in the workshops will deliver additional emission reductions that will get New Mexico much closer to the 2030 goal – but not over the finish line, see **NMED Exhibit 21**: Technical Assistance to the State of NM – RMI Energy Policy Simulator.

In 2021, the Climate Change Task Force convened a Climate Equity Working Group of community advocates and environmental justice experts from across New Mexico to draft a set of Climate Equity Guiding Principles to guide the Task Force in developing just and inclusive

climate policies. These principles will underpin the recommended actions for emissions reduction and adaptation and resilience in future proposed climate action plans, as well as serve as a foundational screen for all climate policies developed by the state, see **NMED Exhibit 22**: NM Climate Change Task Force - Climate Equity Guiding Principles. With the adoption of the Proposed Rule, the Boards have an opportunity to advance climate action in New Mexico.

During the spring and summer of 2022, the Task Force convened an ad-hoc Technical Advisory Group (TAG) of industry, environmental nonprofit, government, and policy experts to prioritize our sector-by-sector goals, create feasible, equitable, and rapid implementation plans, and develop more policies to close that final gap between our climate planning efforts and our 2030 emissions reduction target. The TAG's final report, **NMED Exhibit 23**: NM Technical Advisory Group - Input on NM's Climate Goals and Actions, includes the recommendation for the state to adopt the Proposed Rule. The Technical Advisory Group's input, along with the workshops led by RMI, also form the basis of the state's five-year climate action plan, which will rest on the foundation of equity and environmental justice developed in the Climate Equity Principles.

III. FEASIBILITY OF THE PROPOSED RULE

The Proposed Rule is both technically practical and economically reasonable for the following reasons, and the Proposed Rule is both practical and advantageous for consumers.

A. ZEVs Becoming Mainstream, Both Globally & Locally

The ongoing trend toward electrification is being driven by significant forces operating at a global level. Regulations in China and the European Union and carmakers' need to keep pace with their competitors are driving substantial manufacturer investment. This, in turn, brings about cost reduction, technology improvement, and increased model availability.

Given these developments, ZEV sales are soaring. **NMED Exhibit 24**: Zero-Emission Vehicles Factbook, a BloombergNEF special report; https://assets.bbhub.io/professional/sites/24/2022-COP27-ZEV-Transition_Factbook.pdf, prepared for COP27 in November 2022, highlights several trends that support increasing growth in ZEV sales, including:

1. There are roughly 500 zero-emission vehicle models available to buy globally, and the number of available EV models increased the most in the US last year. At the end of 2020, there were just 59 EV models available in the country. This figure had risen 43% to 84 in the first half of 2022;
2. Proposed and confirmed rules in the US, EU, China, and India imply that EVs will be roughly 30% of car sales in those markets by 2025; and
3. Automakers have collectively committed to selling around 43 million EVs per year by 2030, and automakers with planned phase-outs of combustion engines now account for roughly 30% of the global auto market.

Although the COVID-19 outbreak continues to have adverse impacts on global auto manufacturing, long-term commitments to electrification across the globe remain firm, and EV sales have continued to rise in New Mexico.

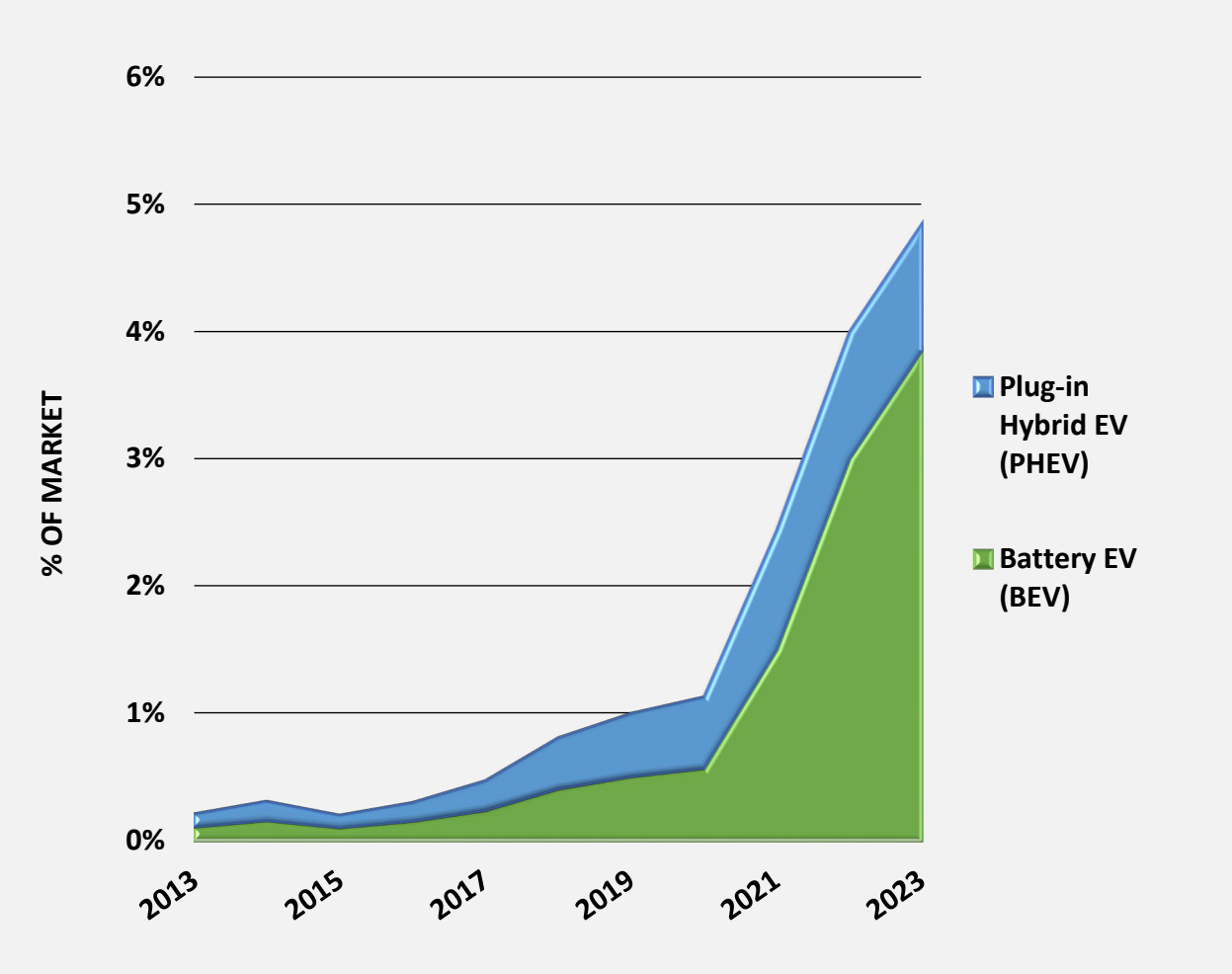
1. New Mexico EV & PHEV Sales

Not only is the uptake occurring globally, but in New Mexico, sales are accelerating rapidly, reaching about 5% of the total market share in the state this year (see Figure 1 and **NMED Exhibit 25**: Advanced Technology Sales Dashboard - New Mexico).[4] Actual BEV plus

[4] Alliance for Automotive Innovation. 2023. "Advanced Technology Sales Dashboard." Data compiled by the Alliance for Automotive Innovation using information provided by S&P Global Mobility (formerly IHS Markit)

PHEV sales in 2022 totaled 2,732 (or about 1.2% of the U.S. market share), and 2023 is projected to see 3,350 zero emission vehicles sold.

Figure 1: New Mexico's BEV + PHEV Market



2. Suitability for New Mexico Conditions

While the Proposed Rule increases the availability of new zero emission vehicles, it does not require all New Mexicans to purchase ZEVs, nor does it ban internal combustion engines in

(2011-2018, November 2019 – Present) and Hedges & Co. (January- October 2019). Date of last update: 8/28/2023. Retrieved 9/13/2023. https://www.autosinnovate.org/EVDashboard

the state of New Mexico. The Department also recognizes that New Mexicans need flexibility in vehicle choice. The Department wants to ensure that New Mexicans desiring to purchase new ZEVs have those vehicles available to them. Manufacturers will not be prioritizing ZEV deliveries to states that do not adopt these rules. Furthermore, by adopting this rule, manufacturers are more likely to deliver affordable ZEVs to everyday New Mexicans, and not just luxury models.

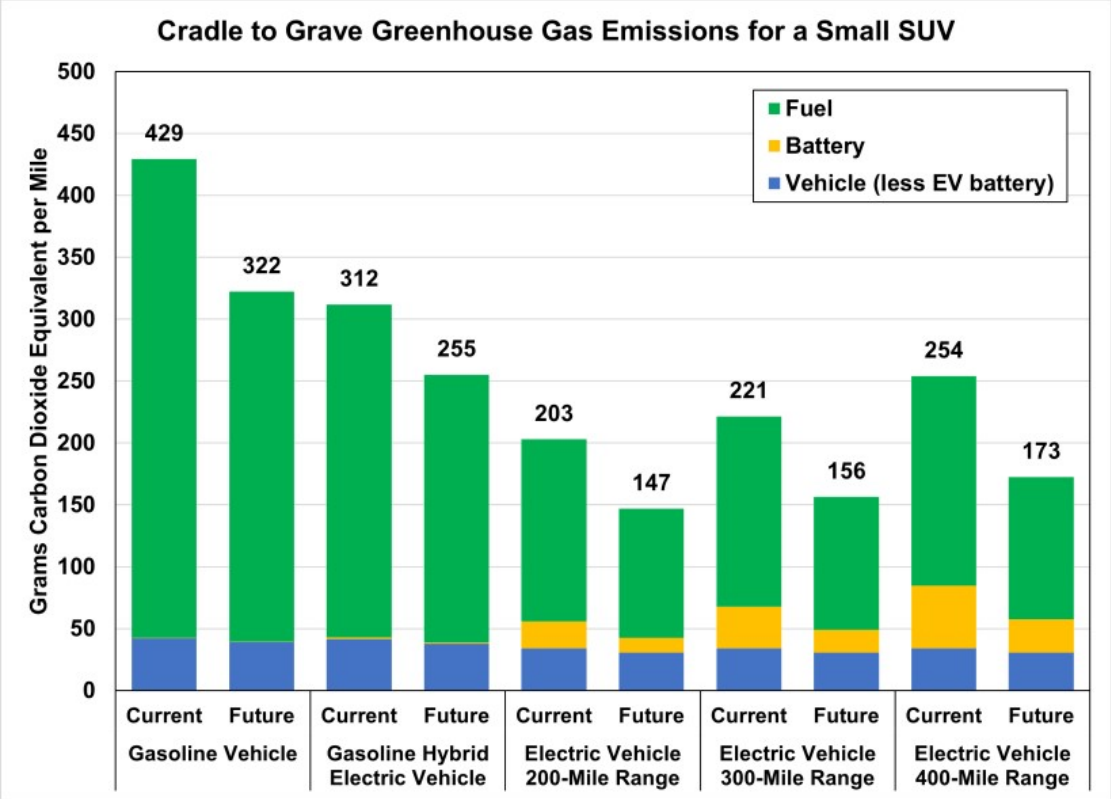
Make no mistake -- manufacturers are investing in zero emission cars and trucks, see **NMED Exhibit 26**: Article - $210 Billion in Announced Investments in EV Manufacturing Headed for the U.S; https://www.atlasevhub.com/data_story/210-billion-of-announced-investments-in-electric-vehicle-manufacturing-headed-for-the-u-s/#:~:text=Vehicle%20manufacturers%20and%20battery%20makers,than%20in%20any%20other%20country. Many are available now, and many more are coming this decade. For example, current EV truck models include the Ford F-150 – the best-selling truck (and vehicle) in the nation, state, and Bernalillo County. Soon-to-be-released (by 2030) EV truck models include the Chevy Silverado EV, GMC Sierra EV, and RAM 1500 REV. Likewise, growing demand for ZEVs in the Class 2b-3 category suggests increased zero-emission pickup truck feasibility. Several manufacturers have made announcements indicating the feasibility of zero-emission pickup trucks. In addition, Rivian recently announced that a portion of the 100,000 vehicles ordered by Amazon will be vans in the Class 2b-3 category. These new announcements show growing demand for ZEVs in this category as they become available. We want New Mexican individuals and businesses to be first in line as these rollouts occur.

B. COMPARING ZEVS TO ICEVS

1. Cradle-to-Grave Greenhouse Gas (GHG) Emissions

According to a recent U.S. Department of Energy, Argonne National Laboratory analysis, electric vehicles have fewer greenhouse gas emissions than conventional vehicles (see Figure 2 and **NMED Exhibit 27**: Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways; https://publications.anl.gov/anlpubs/2016/05/127895.pdf). Their "cradle-to-grave" study accounts for emissions related to raw material extraction, fuel production and transport, vehicle manufacturing, vehicle use, and vehicle end-of-life. However, it does not account for factors like infrastructure systems (e.g., refineries end-of-life or roads and bridges). Future innovation may further enhance efficiency gains for EVs based on adopting advanced technologies in the U.S. in the 2030–2035 timeframe. Precisely, GHG emissions for a small gasoline SUV in 2020 were estimated to be 429 grams of carbon dioxide equivalent (CO2e) per mile, while the same size EV with 300 miles of range had 48% fewer GHG emissions.

Figure 2: Cradle-to-Grave Greenhouse Gas Emissions of EVs & ICEVs

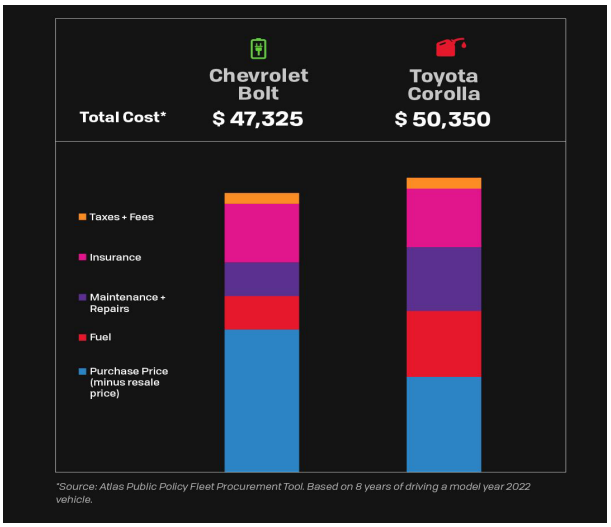


2. Total Cost of Ownership

A recent analysis of four vehicle categories was conducted to understand the total cost of ownership for some of the most popular internal combustion engine (ICE) vehicles and similarly priced electric vehicles (EV) available for purchase in 2022. In all four cases, EVs have a lower Total Cost of Ownership over eight years (see Figure 3, Figure 4, and **NMED Exhibit 28**: Total Cost of Ownership Analysis - Four Popular Models; https://atlaspolicy.com/wp-content/uploads/2022/01/Total-Cost-of-Ownership-Analysis.pdf).

This independent analysis agrees with John Koupal's technical testimony and the Eastern Research Group, Inc. report, both entered in this hearing record. Furthermore, the total cost of EV ownership is expected to continue outpacing gasoline and diesel vehicles, driven by scaling production lines and efficiency gains in manufacturing innovations.

Figure 3: Total Cost of Ownership: 2022 Low-Cost Sedans (left) & Mid-Cost Sedans (right)



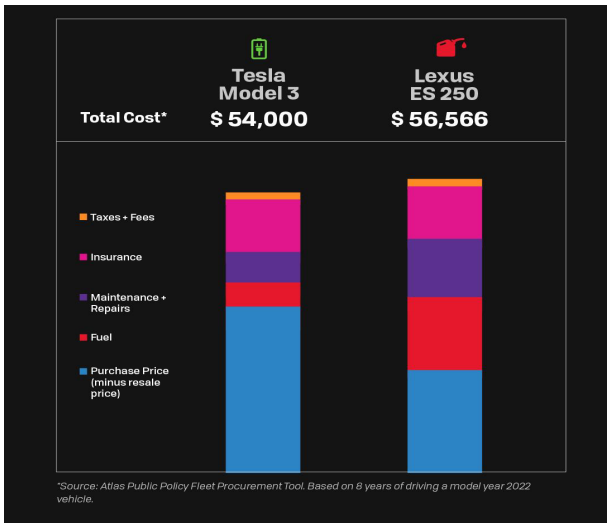
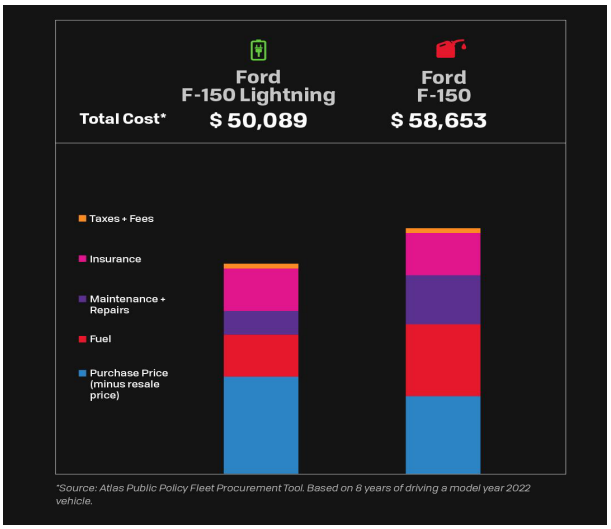
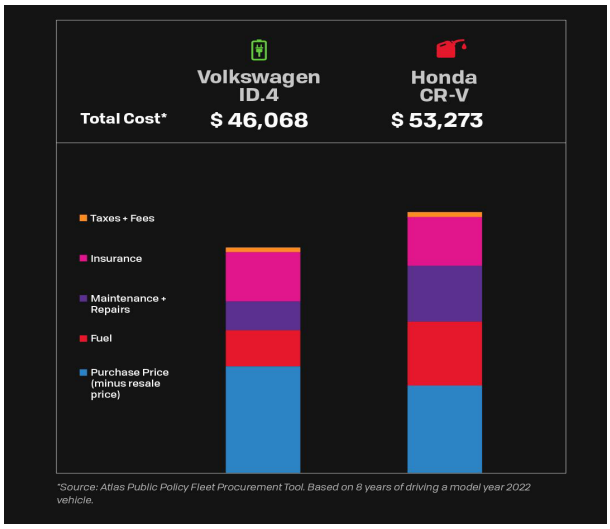


Figure 4: Total Cost of Ownership: 2022 Pickup (left) & SUV (right)





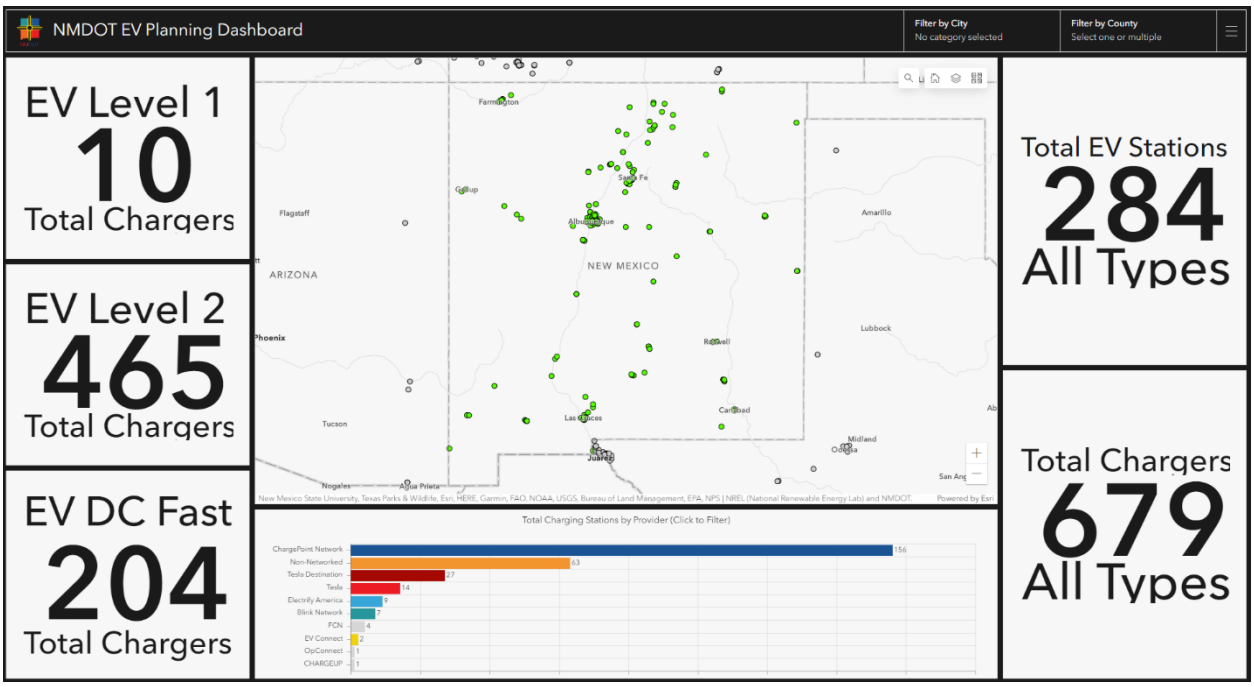
C. ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE) IN NM

1. Current Electric Vehicle Charging Infrastructure in NM

The NM Department of Transportation tracks charging infrastructure across the state in its publicly accessible dashboard (see Figure 6).[5] Their data shows that New Mexico has 679 chargers available today. According to the U.S. Department of Energy's Alternative Fuels Data Center, New Mexico is experiencing more than a 30% increase (year-over-year) in deployment through September 2023, which is nearly a 12% greater growth rate than the average of all other ACC II adopting states (i.e., CAA Section 177 states). Likewise, less than 3% (i.e., 16) of EVSE ports[6] are unavailable (i.e., temporarily out of service or offline) due to maintenance or planned outages.[7]

[5] New Mexico Department of Transportation. 2023. "Electric Vehicle Planning Dashboard." https://nmdot.maps.arcgis.com/apps/dashboards/ac19013bc5b44bc99d3a8f73e3c84019
[6] An EVSE port provides power to charge only one vehicle at a time, even though it may have multiple connectors.
[7] U.S. Department of Energy. 2023. "Electric Vehicle Charging Station Locations." Alternative Fuels Data Center. https://afdc.energy.gov/fuels/electricity_locations.html#/analyze?region=US-NM&fuel=ELEC&status=E&status=T

Figure 5: NM DOT EV Planning Dashboard (screenshot taken 10/19/2023)



2. Electric Vehicle Charging Infrastructure Investments in NM

The New Mexico Departments of Transportation, General Services, Energy Minerals and Natural Resources, and Environment are working to bring additional investments to New Mexico. Specifically, those departments actively request an additional $55M+ to help advance EV Charging Infrastructure Deployment, see **NMED Exhibit 29**: EV Charging Infrastructure – NMDOT at NM Legislature. Some of the investible funds include guaranteed and competitive opportunities (see Table 1):

Table 1: Funding for Charging Infrastructure in New Mexico

Year	Investment Value	Source
2021	$1.2 M	Regular Session Appropriation (transfer)

2021	$10 M	Special Session (ARPA funds)
2022	$0.4 M	Regular Session Appropriation (transfer)
FY2022 – FY2026	$38.4 M	Bipartisan Infrastructure Law: Formulaic funding is apportioned to New Mexico under the new National Electric Vehicle Infrastructure (NEVI) Formula program.
FY2022 – FY2026	Up to $2.5 B	Bipartisan Infrastructure Law: Competitive grant funding is made available over five years to award eligible entities funding for the Charging and Fueling Infrastructure (CFI) Discretionary Grant Program for Community and Corridor Grant Program.
2024	Up to $500 M/project	Inflation Reduction Act: Competitive grant funding is made available to award eligible entities funding for projects, including charging infrastructure, that reduce greenhouse gas emissions through the Climate Pollution Reduction Grant (CPRG).

3. Pending New Mexico Requirements to Install EVSE in New Developments

The NM Regulation and Licensing Department separately proposes to adopt the 2021 International Energy Conservation Code (2021 IECC) energy code change. The 2021 IECC requires new public buildings and residential dwellings to install EV-capable spaces, EV-ready spaces, and EVSE spaces because "decarbonization of transportation is accelerating, driven by economics, regulatory demands, and climate goals." Construction Industries Division (CID) Chief Martin Romero intends to introduce code amendments with a public hearing this year with a vote by the Construction Industries Commission at its November 15, 2023 meeting. Phase-in

of the new energy code would begin January 1, 2024, and the 2021 IECC would be in full effect by July 1, 2024. These requirements will ensure new developments are built to handle the clean vehicle transition.

D. IMPACTS ON THE ELECTRICAL GRID

Power grid resiliency is a focal point for all utilities. Their job is literally to "keep the lights on." Utility companies do this by planning and implementing suitable (1) power generation sources, including renewables, (2) long-range transmission lines, and (3) local power distribution systems, including distributed energy resources. Of course, this transition requires grid modernization, but New Mexico's electric utilities are actively planning for and investing in the electrical grid upgrades necessary to support increasing demand reliably.

For example, in 2020, the New Mexico Legislature passed HB 233 (Energy Grid Modernization Roadmap Act), tasking EMNRD with developing an electric grid modernization plan. In the fall of 2020, EMNRD convened the Grid Modernization Advisory Group (GMAG) to produce a series of action-oriented whitepapers to inform New Mexico's Grid Modernization Roadmap. The Roadmap serves as a guide to electric service providers, regulators, policymakers, and consumers as New Mexico transitions to 100-percent zero-carbon electricity resources by mid-century in accordance with the Energy Transition Act of 2019, see **NMED Exhibit 30**: NM Grid Modernization Roadmap; https://www.emnrd.nm.gov/ecmd/wp-content/uploads/sites/3/GridModernizationRoadmap_FINAL_FOR_PUBLICATION-1.pdf.

1. Opportunities of Grid Modernization Efforts and Utility Rebates

This zero emission vehicle transition also presents several opportunities, including offering technology and incentives to customers to charge vehicles during off-peak hours, which is cheaper for consumers than peak hours and better for the grid at large. Specifically, EVs can

shift load to off-peak periods while increasing overall demand, both of which help create a more efficient, highly utilized grid.

State and federal planning efforts reveal that "New Mexico can … implement demand-side management strategies to minimize the level of additional electricity capacity and generation needed to accommodate (the) transition to EVs. Incorporating smart charging or vehicle-to-grid systems can increase grid flexibility, helping to reduce peak loads and the demand for new electricity generation and capacity, amongst other grid benefits."[8]

For example, New Mexico's largest utility, Public Service Company of New Mexico (PNM), is actively taking advantage of these opportunities by offering incentives through its Transportation Electrification Program (TEP). Specifically, PNM offers residential consumers a $500 rebate for installing a networked Level 2 charger at the point of sale. Similarly, Income-Qualified Rebates include a discounted EV charger purchase price and up to $2,000 in additional installation rebates through their chosen installer. To enhance off-peak charging, PNM's Whole Home Electric Vehicle (WHEV) Rate Pilot provides a low energy cost ($0.03 per kWh) to qualified and enrolled EV drivers from 10:00 PM - 5:00 AM. That general overnight rate is nearly 80% cheaper than peak rates in summer months. For commercial consumers, PNM offers $2,500 for installing Level 2 chargers and $25,000 for installing DC Fast chargers.[9]

[8] U.S. Department of Energy, National Renewables Energy Laboratory. N.D. "State and Local Planning for Energy (SLOPE) Platform Informs Grid Modernization and Transportation Planning in New Mexico." https://maps.nrel.gov/slope/stories/nm

[9] PNM. 2023. "EV Charger Marketplace." https://ev.pnm.com/

As another example, El Paso Electric (EPE) offers charging assistance programs. EPE customers can receive a $500 rebate on qualifying smart Level 2 charging stations; and for eligible low-income customers, an instant rebate of up to $2,300 can be received for the purchase and installation of qualifying smart Level 2 chargers. EPE also offers Commercial Smart Charging Rebates so that business owners, public parking managers, apartment owners, and fleet operators have the opportunity to provide charging services.[10]

E. TAX CREDITS AND CLEAN TRANSPORTATION FUNDING INITIATIVES

1. Federal Clean Vehicle Tax Credit

The Inflation Reduction Act of 2022 (IRA) established a "clean vehicle tax credit" for new electric vehicles purchased by consumers. For some purchases in 2022 and all purchases in 2023, consumers can claim the credit when next filing their taxes. The U.S. Treasury Department very recently announced that starting January 1, 2024, the credit can be applied at point of purchase and transferred from consumer to dealer for immediate financial benefit, instead of waiting until tax season. The consumer will retain the option to claim the credit on their tax return instead of transferring.

If the consumer chooses to make a "transfer election", a registered dealer can provide the allowable credit to the consumer in cash or apply it as a partial payment or down payment towards the sale price. Dealers are required to register and utilize a portal, IRS Energy Credits Online, to apply the credit at time of purchase and process the transfer. The Internal Revenue Service confirmed repayment of the credit to dealers will be processed within 72 hours on the portal and dealers will be able to track progress in live time. The IRS Fact Sheet (linked below) provides detailed guidance to dealers and states that sample forms will be available for dealer use

[10] El Paso Electric. 2023 "EVs for Everyone." https://www.epelectric.com/ev/

at the beginning of next year, see **NMED Exhibit 31**: IRS FAQ on Clean Vehicle Credits; https://www.irs.gov/pub/taxpros/fs-2023-22.pdf.

2. Diesel Emission Reduction Funding

The Department provides U.S. Environmental Protection Agency Diesel Emission Reduction Act (DERA) funding for heavy-duty on-road new diesel or alternative fuel repowers and replacements, as well as off-road all-electric repowers and replacements, with priority to hydrogen fuel cell projects. Any public or private entity or nonprofit organization, based in New Mexico, in existence for at least three consecutive years, and whose vehicles/equipment are registered, (or have an International Registration Plan if applicable) in the State of New Mexico. Eligible projects include, but are not limited to: idle reduction technologies, aerodynamic technologies, and the retrofit or replacement of diesel vehicles and equipment throughout the state. Eligible diesel vehicles, engines and equipment may include: buses (school and Class 5+ transit); Class 5 – Class 8 heavy-duty highway vehicles (e.g. refuse, commercial transportation); marine engines; locomotives; and nonroad engines, equipment, or vehicles such as those used in construction, handling of cargo (including at ports and airports), agriculture, mining, or energy production (including stationary generators and pumps). NMED is actively soliciting proposals for DERA projects that effectively reduce these emissions from heavy-duty diesel-fueled vehicles and equipment.

3. EV Charging Station Make-Ready Building Renovation Tax Credit

The Sustainable Building Tax Credit provides a renovation tax credit for the purchase and installation of EV make-ready infrastructure at existing buildings. Residential properties are eligible for a $500 tax credit, increasing to $1,000 if the infrastructure is for an income-eligible resident. Commercial properties are eligible for a tax credit of 50% of the cost up to $1,500,

increasing to 100% of the cost up to $3,000 if the infrastructure is for affordable housing. This tax credit is available for renovations completed between January 1, 2022 and December 31, 2027, see **NMED Exhibit 32**: Sustainable Building Tax Credit; https://www.emnrd.nm.gov/ecmd/tax-incentives/sustainable-building-tax-credit-sbtc/.

F. CLIMATE INVESTMENT CENTER

On October 13, 2023, the Governor, accompanied by state legislators, announced the establishment of the New Mexico Climate Investment Center to address need for increased funding in equity-focused investments, see **NMED Exhibit 33**: Governor announces NM Climate Investment Center; https://www.governor.state.nm.us/2023/10/13/governor-announces-new-mexico-climate-investment-center/. The Center acknowledges that the effects of our rapidly changing climate "will fall disproportionately on those households and businesses without the economic resources to adapt" and that "[c]urrently there are limited financing options for low-and-moderate income households."[11] As a result, the Center is "creating a portfolio of loan products for residential and commercial customers to increase adoption of mature, commercially viable technologies that reduce greenhouse gas emissions and other pollutants." Specifically, the Center will "focus on closing financial gaps and strengthening existing financial institutions' ability to lend to non-traditional borrowers; and providing direct benefits for low-income, disadvantaged, and Tribal communities" amongst other goals. The establishment of the Center can provide New Mexicans of all income levels an opportunity to access clean transportation options as proposed in this rule if they so choose.

[11] https://nmclimateinvestmentcenter.org/

G. GOVERNOR'S EXECUTIVE ORDER 2023-138 AND FUTURE ACTIONS

On October 16, 2023, Governor Michelle Lujan Grisham held a symposium on the future of transportation in New Mexico. At this symposium, she announced Executive Order 2023-138, see **NMED Exhibit 34**: Governor's EO No. 2023-138 - Transitioning the State of NM's Vehicle Fleet to Net Zero Emissions; https://www.governor.state.nm.us/wp-content/uploads/2023/10/Executive-Order-2023-138.pdf. This executive order directs state agencies to select ZEVs and plug-in hybrid electric vehicles (PHEVs) for all applicable new vehicle purchases, and to create plans for all state vehicles to transition to ZEVs and PHEVs by 2035. By enacting the transition of all state vehicles by 2035, the Governor is leading the state by example, saving taxpayer money over time with lower-total cost of vehicle ownership, and providing added demand for electric vehicles, which will help vehicle manufacturers fulfill the requirements of the Proposed Rule.

At the symposium on the future of transportation, Governor Michelle Lujan Grisham also announced that she plans to ask the legislature in the forthcoming session to enact robust, transferable tax credits for the purchase of both used and new electric vehicles. These tax credits will increase access to ZEVs for moderate- and low-income consumers in New Mexico, and further increase demand. The increased demand for ZEVs from both state purchasing and tax credits will greatly assist dealers in selling the vehicles that manufacturers will deliver in response to the Proposed Rule.

IV. CONCLUSIONS

In conclusion, I would like to remind the Boards of Governor Lujan Grisham's directive to adopt LEV and ZEV emission standards in order to reduce greenhouse gas emissions from transportation, the second largest source of such emissions in the state. The emissions must be

reduced to reach at least a 45% reduction in greenhouse gas emissions by 2030. The standards are one critical measure that will ensure New Mexico can combat climate change, and New Mexico is one of nearly a dozen states that is moving to adopt the Proposed Rule.

We are truly facing a global emergency; this is an opportunity for New Mexico, and these Boards, to continue to be part of the solution. While the Proposed Rule alone is unlikely to reverse the impacts of climate change in New Mexico, it is an important part of the solution and offers a practical and cost-effective method to curb these emissions.

MICHELLE T. MIANO

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WORK EXPERIENCE

Director, Environmental Protection Division

New Mexico Environment Department

January 2023 - current Albuquerque, NM

- Oversee all aspects of the New Mexico Environment Department's Environmental Protection Division, which includes the Air Quality, and Radiation Control, and Climate Change Bureaus.
- Develop and oversee implementation of strategies, including policy and legislative proposals, and manage Division budget.

Senior Attorney

Barnhouse Keegan Solimon & West LLP

Oct 2016 – January 2023 Albuquerque, NM

- Litigated against State of Texas to secure the ability of Tribal client to continue bingo operations.
- Filed amicus brief in U.S. Supreme Court on behalf of *amicus curiae* to support constitutionality of Indian Child Welfare Act.
- Drafted petitions for writ of certiorari against government defendants resulting in grants of the petitions by the New Mexico Court of Appeals.
- Litigated and tried breach of trust case in the U.S. Court of Federal Claims resulting in significant findings of liability in clients' favor.
- Assisted in creating Section 17 holding company for Tribally-owned bank in Southern California to deliver services to Tribal members and the larger community.

Associate Counsel

New Mexico State Land Office

Sep 2015 - Sep 2016 Santa Fe, NM

- Led enforcement action against oil and gas company after discovery of oil spill on New Mexico State Trust Lands.
- Defended Commissioner of Public Lands in legal action challenging denial of permit to use State water resources for oil and gas drilling purposes.
- Drafted memoranda analyzing legal issues presented by the Commissioner of Public Lands and General Counsel.

Staff Attorney

Advocates for Community and Environment

Sep 2014 - Sep 2015 El Prado, NM

- Litigated NEPA issues against Southern Nevada Water Authority's (SNWA) proposal to pump billions of gallons of water per year from rural Nevada and Utah to Las Vegas, which SNWA ultimately abandoned.
- Litigated on behalf of historic rural livestock owners seeking to secure ability to graze livestock on U.S. Forest Service lands.

EDUCATION

Juris Doctor

University of New Mexico School of Law

May 2014

Albuquerque, NM

Awards

- Albert E. Utton Natural Resources Law Award (2014)
- D.C. Semester at U.S. Environmental Protection Agency (2013)
- James E. Sperling Memorial Scholarship Award (2013)
- Association of Public Interest Law Summer Fellowship Award (2012)

Bachelor of Arts
Writing Seminars

Johns Hopkins University

May 2007

Baltimore, MD

Confronting Climate Change in New Mexico

Action needed today to prepare the state for a hotter, drier future

HIGHLIGHTS

New Mexico's climate is getting hotter and drier, driven by regional and global warming trends. This means earlier springs, hotter summers, and less predictable winters. Precipitation patterns are also changing, with more intense droughts and a greater proportion of precipitation falling as rain rather than snow. Shrunken snowpacks and earlier snowmelts contribute to lower stream flows at critical times of the year when the reduced availability of water has greater economic and environmental consequences. To prepare for the expected impacts of these climate trends, New Mexico would benefit from sustained efforts to mitigate the potential consequences of less water, the health impacts of more excessive heat, and increased losses of lives and property from wildfires, while safeguarding the state's natural resources. Other regions of the world can look to New Mexico's growing leadership on planning for water-resource stress periods and increasing drought-resilient renewable energy sources.

Climate change is altering fundamental weather patterns—affecting temperatures, water availability, and weather extremes—that shape the lives of New Mexicans. As a result, the infrastructure and resource-management plans designed for the conditions of the past may not meet future needs of the farmers, ranchers, outdoor enthusiasts, and other residents of New Mexico.

Already, the resources and systems that New Mexicans depend upon are strained, and further changes in the climate may increase the risks to their homes, their businesses, and their lifestyles.

Developments like these are expected to continue, and likely worsen, as average temperatures rise. While the scarcity of water has long defined the Southwest, the National Climate Assessment has advised that "climate changes pose challenges for an already parched region that is expected to get hotter and, in its southern half, significantly drier" (Garfin et al. 2014).[1]

Chili peppers are just one of the crops under threat of climate change in New Mexico, as extreme heat and drought cause water supplies to dwindle.

Federal, state, and local governments can do a great deal to protect New Mexicans from current extreme heat, drought, fire, and flooding and to help them plan and prepare for future impacts. State and federal initiatives are already making financial and information resources more available, especially for assessing needs. The next step is to use such resources to design and implement on-the-ground actions that can reduce the risks and make communities more resilient to climate impacts. Strategic investments in long-term projects are also necessary, as is a refocusing of existing programs on planning and resilience. As the people of New Mexico come to understand what they face, they can prepare a prudent response.

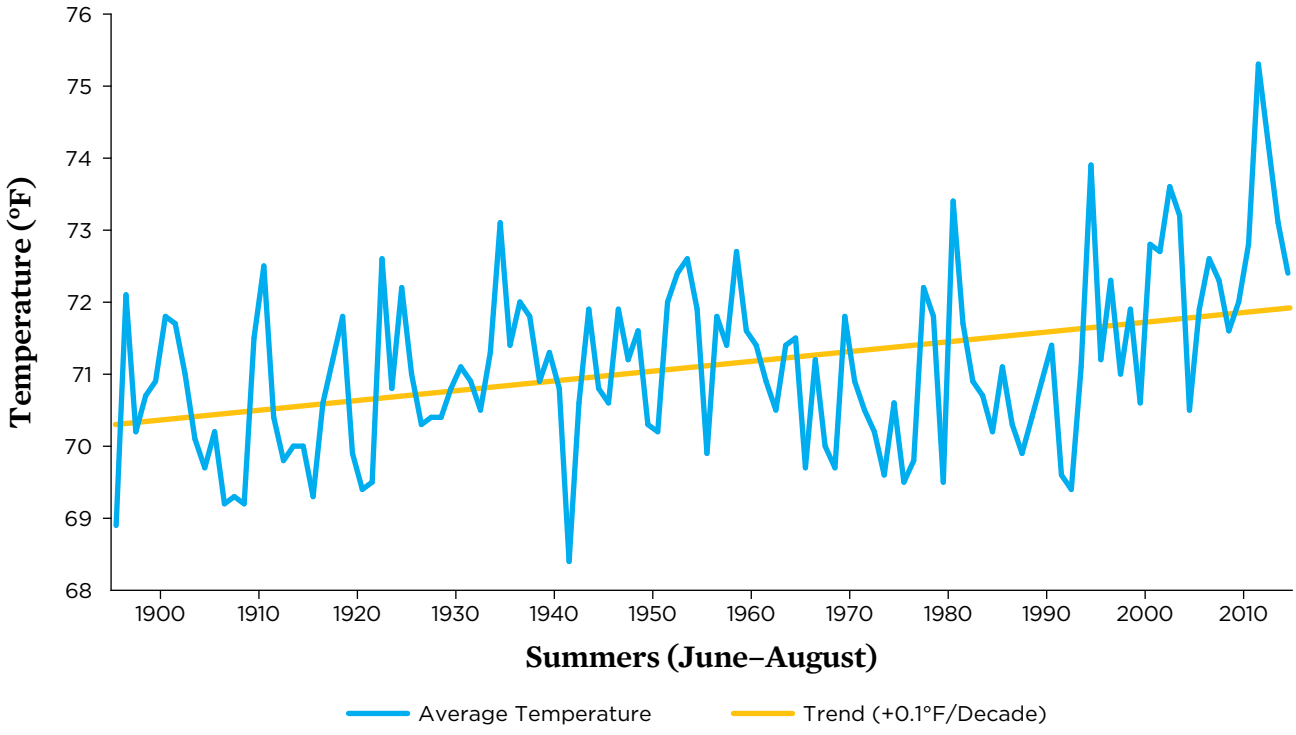
> *"Climate changes pose challenges for an already parched region that is expected to get hotter and, in its southern half, significantly drier."*
>
> — Third National Climate Assessment

Higher Temperatures, More Heat Extremes

In New Mexico, the sixth-fastest-warming state in the nation, the average annual temperature has increased about 0.6°F per decade since 1970 or about 2.7°F over 45 years (Tebaldi et al. 2012). Across the Southwest, the average annual temperature has increased by about 1.5°F, with the decade 2001–2010 being the warmest in over a century (Hoerling et al. 2013).[2] Average annual temperatures in New Mexico are projected to rise another 3.5 to 8.5°F by 2100 (Kunkel et al. 2013).[3]

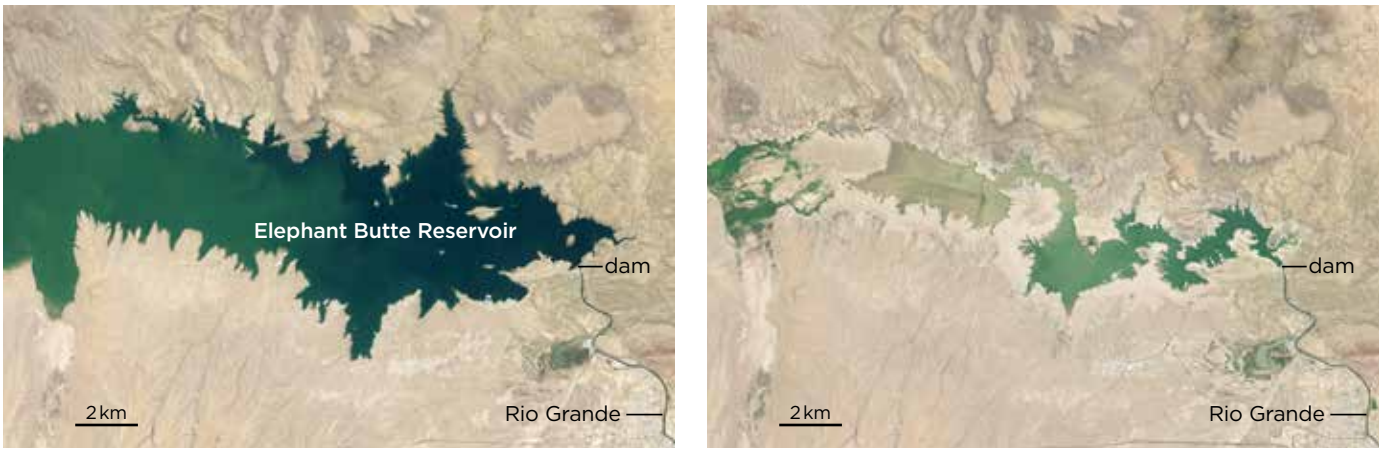
The summer of 2012 was one of the hottest in Albuquerque's history. That year, the city recorded 85 days with temperatures of 90°F or higher (U.S. Climate Data 2012). The following summer, the temperature hit even higher extremes. On June 27,

FIGURE 1. Summer Temperatures in New Mexico are Rising



Summer temperatures in New Mexico vary from year to year, but a careful analysis shows a consistent warming trend—a trend that is projected to continue into the future. Since 1970, the trend has steepened to an increase of about 0.6°F per decade.

SOURCE: NOAA 2016.



In 2013, the Elephant Butte Reservoir reached its lowest level in 40 years (right)—just 3 percent of its storage capacity, compared with a nearly full reservoir in 1994 (left). As a result, farmers received less than 10 percent of their typical irrigation water, forcing them to turn to groundwater and other sources.

2013, the city's main airport, Albuquerque International Sunport, recorded a temperature of 105°F, tied for the second-highest on record (Tassy 2013). Sixty miles away and 1,000 feet higher, the temperature at Santa Fe Municipal Airport reached 102°F, the highest ever recorded there (Oswald 2013).

INCREASING TEMPERATURES, SHRINKING WATER RESOURCES

Between 2001 and 2010, the flow in each of the Southwest's major waterways—the Sacramento-San Joaquin river system, the Colorado River, the Rio Grande, and rivers in the Great Basin—was 5 to 37 percent lower than average for the twentieth century (Hoerling et al. 2013). Late-winter and spring snowpacks are projected to decline, and this and the resulting reductions in runoff and soil moisture are expected to make the water supplies for the Southwest's cities, agriculture, and ecosystems even scarcer (Cayan et al. 2010). Droughts, a persistent risk in New Mexico, have broken historical records in recent years, disrupting the state's most vulnerable economic activities. New Mexico entered a severe six-year drought in 2009, by some measures the worst in more than a century, following closely on the heels of an intense drought in the early 2000s (Fleck 2014a). If heat-trapping gases continue to build up in the atmosphere, future droughts are projected to far outstrip those of the past 800 years (Schwalm et al. 2012).

Flow in the Rio Grande, which relates directly to the amount and timing of snowmelt in the mountains north of Albuquerque, is one of the best indicators of drought in New Mexico. For the decade ending in 2010, its flow was 23 percent lower than the twentieth-century average (Hoerling et al. 2013). Every year from 2009 to 2014 was drier than average on New Mexico's portion of the Rio Grande, and the period from 2011 to 2013 was the hottest and driest since recordkeeping began in 1895 (Cart 2013). The Rio Grande and Elephant Butte reservoirs reached historically low levels, reducing allocations of irrigation water for farmers by more than 90 percent and forcing the city of El Paso to depend entirely on groundwater (Voiland 2013). Ranchers have struggled to maintain their herds, and farmers have become increasingly dependent on groundwater resources, adding costs to save their pecan orchards, chiles, and other crops. Smaller communities worry about the viability of their water supplies, fueled by reports like those from Magdalena, the central New Mexican village that made national news when its wells ran dry and residents turned to bottled water (Walsh et al. 2014). Uncertainty in water supplies—ranging from individual wells to acequias (community-managed irrigation canals) to municipal water supplies—are facing ever-increasing demands.

Across the Southwest, the capacity of snow to store water is crucial to managing water, and climate change risks disrupting this vital source of New Mexico's water supply. In 2015, for the fifth year in a row, New Mexico experienced a drought due to diminished snowfall in the mountains (although spring and summer rains offered some relief) (Fleck 2015). In 2014, for the first time in its 40-year history, the San Juan-Chama Drinking Water Project, designed to supplement water resources for Albuquerque, Santa Fe, and other communities in the Rio Grande watershed, was dry (Fleck 2014b).

In the coming decades, climate change will exacerbate the risk of drought in New Mexico in several ways. The National Climate Assessment projects that many parts of the state will see less precipitation overall and more consecutive dry days (Walsh et al. 2014). Even when areas receive rainfall similar to the typical amount they received historically, higher temperatures will increase the water needs for crops and livestock, while also drying out the soil more rapidly.

Gila Forest/Creative Commons (Flickr)

Drought and wildfire decrease the soil's ability to absorb moisture. When New Mexico's heavy rain falls on this affected soil, it runs off instead of seeping down, causing disruptive and dangerous flash floods.

Most important, higher temperatures will reduce snowpack and promote earlier snowmelt in the headwaters of New Mexico's major rivers, resulting in sharply lower levels of available water at critical times of the year (Garfin et al. 2014).

EXTREME PRECIPITATION AND THE LOSS OF SCARCE WATER

New Mexicans are accustomed to extreme rainfall, with much of the state's precipitation generally falling in July and August, associated with the North American monsoon system. However, climate projections across the United States suggest that even as total annual precipitation decreases in places like the Southwest, the heaviest annual rainfall events may become more intense (Walsh et al. 2014). When heavier precipitation falls on drought-hardened or wildfire-transformed soil, which has a reduced ability to absorb moisture, more of the water runs off into streams instead of percolating into the ground (Chief et al. 2008). This can lead to flash floods, as occurred in 2014, when 90 percent of New Mexico experienced extreme or exceptional drought (Crimmins et al. 2014). The monsoon rains, which arrived late that year, dropped an average of three to six inches of rain across the state over just five days in September, with some areas receiving more than 10 inches (NWS ABQ 2015). Albuquerque received nearly half of its expected annual rainfall in a single deluge (*Albuquerque Journal* 2013). As a result, river floods and crests were exceptional in downstream areas. Such extreme events are projected to become more common, forcing communities to prepare for both extreme droughts and extreme floods.

The Impact on New Mexico's Agriculture and Forests

Higher temperatures year round and more frost-free days during winter—especially in an already hot and moisture-stressed region—are projected to increase the stress on plants, making them more vulnerable to agricultural pests and diseases (Frisvold et al. 2013). At the same time, New Mexico forests will continue to be affected by large and intense fires that occur more frequently, potentially overwhelming current and past efforts to manage forests in ways that reduce such risks (Joyce et al. 2014).

INCREASING COSTS TO AGRICULTURE

New Mexico's multibillion dollar agricultural sector already faces the effects of a warming climate. Farmers and ranchers are facing higher costs for less and lower-quality water, particularly in the southern part of the state. As drought conditions persist, farmers who historically have relied on water allocations from reservoirs and streams to irrigate their crops are

pumping more and more groundwater to make up the deficit. Deeper and deeper wells are needed to accommodate the falling water table, and often the water contains higher levels of salt and other minerals that damage crops and contaminate the soil (Frisvold et al. 2013).

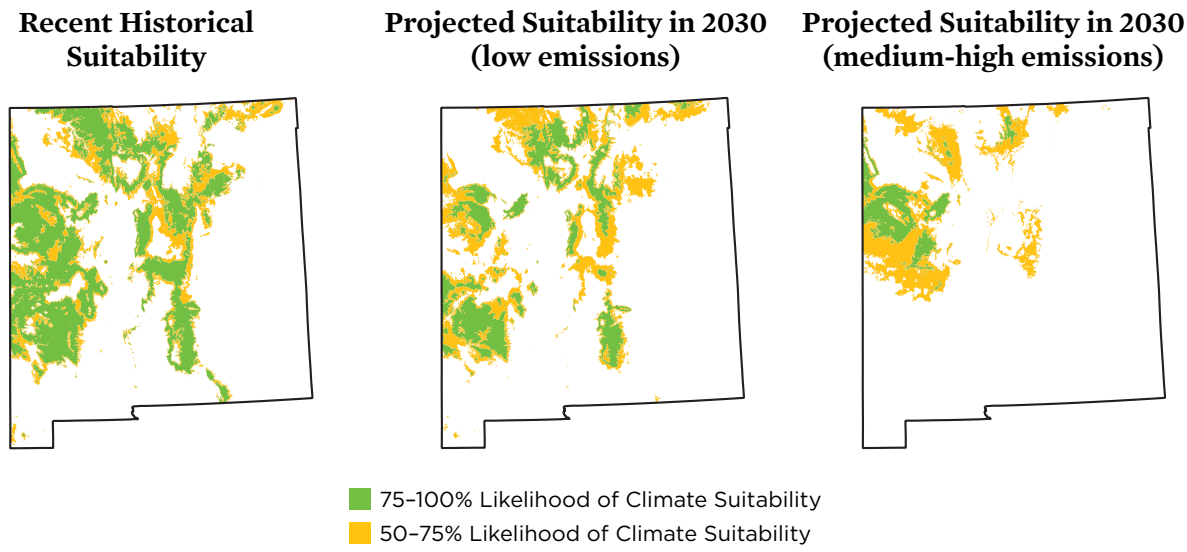
In 2013, Rio Grande farmers received allotments of only 3.5 inches of water per acre, compared with a full allotment of 36 inches in normal years (New Mexico Water Dialogue 2013). This meant they received just a tiny fraction of the 4 to 5 acre-feet needed between planting and harvest (Bosland and Walker 2004). At the same time, ranchers significantly reduced their herd sizes or sold off cattle to give grasslands a chance to recover from extreme drought (Uyttebrouck 2013).

FORESTS

In recent years, drought, insects, and wildfires have ravaged New Mexico forests at a scale not seen in living memory (Funk et al. 2014). The piñon pine, New Mexico's state tree, is important both ecologically and culturally. Few other tree species can survive in the semiarid areas where they are most common, yet the effects of climate change are placing its future persistence in the state at risk (Adams et al. 2009). In the early 2000s, severe heat and drought and bark-beetle infestations caused a massive die-off of piñons. Mortality among mature piñons in the middle Rio Grande Basin exceeded 90 percent (Breshears et al. 2005). As many as 350 million piñons died across the West, with the greatest mortality in the northern New Mexico foothills of the southern Rocky Mountains (Meddens, Hicke, and Ferguson 2012). While mature pine trees live hundreds of years and have experienced severe drought before, this drought was associated with much hotter temperatures than those in the past, in large part due to a changing climate (Adams et al. 2009). The U.S. Forest Service projects that piñons could disappear from much of their current range by 2030—threatening to disrupt the entire forest ecosystem—even if the rise in heat-trapping emissions slows (Rehfeldt et al. 2012).

Hotter, drier conditions lead to more frequent and more destructive wildfires, while earlier snowmelt means that forests are drier for a longer spring season, before monsoon rains moisten the surface. The fire season in New Mexico has lengthened substantially over the past 40 years—from

FIGURE 2. Climate Change is Diminishing the Habitat of Piñon Pines



The degree of climate change will affect the amount of western land suitable for piñon pines in 2030. These maps depict areas modeled to be climatically suitable for the tree species under the recent historical (1961–1990) climate (left), conditions projected for 2030 given lower levels of heat-trapping emissions (center), and conditions projected for 2030 given medium-high levels of emissions (right). Areas in yellow have a 50–75 percent likelihood of being climatically suitable according to the models; areas in green have more than a 75 percent likelihood. These models do not address other factors that affect where species occur, such as soil types.

NOTE: The two future emissions levels are the B1 and A2 scenarios of the Intergovernmental Panel on Climate Change, respectively.

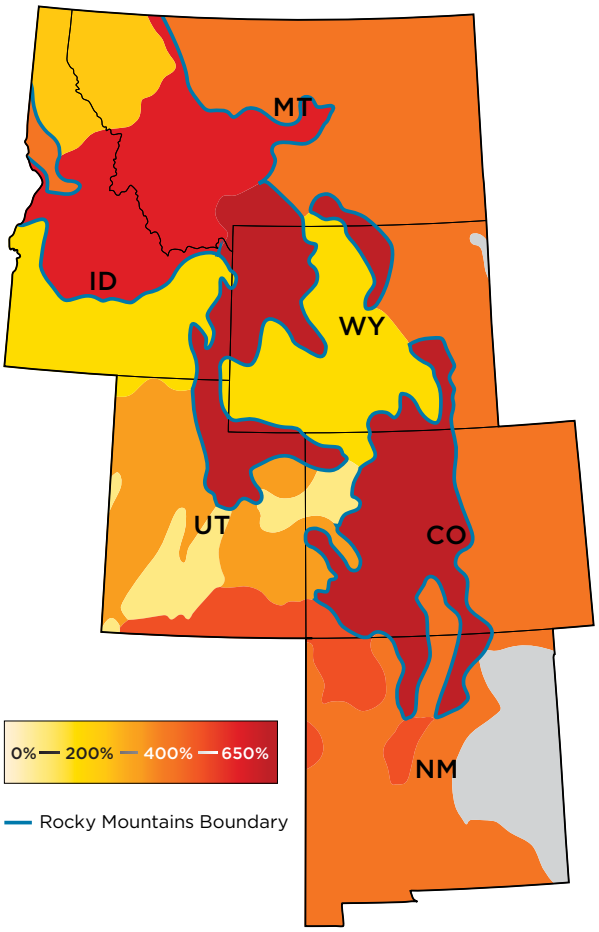
SOURCES: BASED ON USFS MOSCOW LAB 2014.

five months to seven—and fires of more than 1,000 acres occur twice as often (Climate Central 2012; Westerling et al. 2006). Wildfires themselves are a significant source of heat-trapping gases in the atmosphere.

As the Southwest continues to warm, the burn area across the region is projected to rise dramatically. The regions hit hardest are likely see a six-fold increase or more in average area burned each year (see Figure 3).

Two of the largest wildfires in New Mexico's recorded history occurred in 2011 and 2012. In 2011, more than one million acres burned as 1,875 fires raged across the state (NICC 2011). The Las Conchas Fire, then the largest in the history of New Mexico, burned over 156,000 acres (NICC 2011). Damage occurred in parts of Los Alamos National Laboratory, the Santa Clara Pueblo, and affected the water supplies for Santa Fe

FIGURE 3. Rise in Global Temperature Will Lead to Increased Wildfires in New Mexico

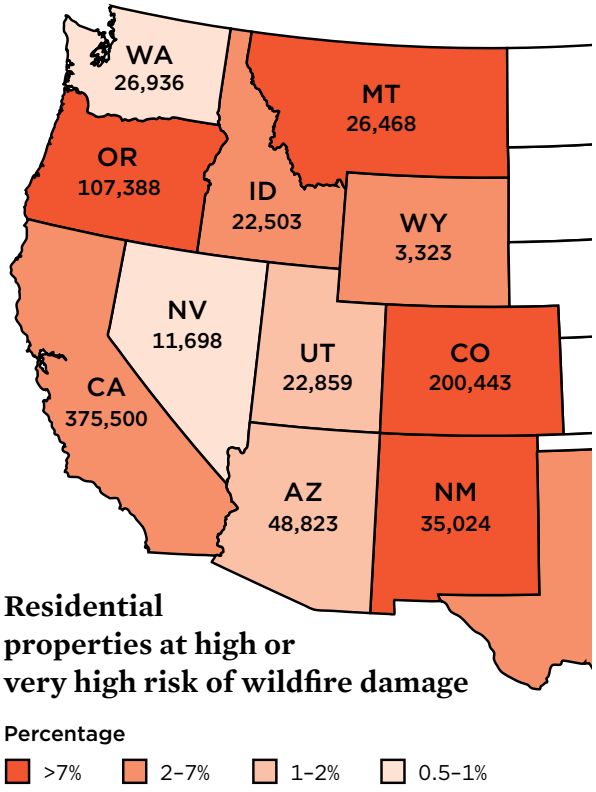


Scientists project that a temperature increase of just 1.8°F will lead to marked increases in acreage burned by wildfires in the western United States, including New Mexico. This figure shows the projected percentage increase in burned area, compared with the 1950–2003 average. Much of New Mexico is expected to see a 400% increase in burned areas, with parts of the Rocky Mountains headed towards a 650% increase.

NOTE: Grey indicates areas with insufficient data for making projections

SOURCES: ADAPTED FROM NRC 2011 AND LITTELL ET AL. 2009.

FIGURE 4. Homes at Risk from Wildfires in the Western United States



Development in or near wildfire-prone areas in the western United States is significantly raising the risks and costs of wildfires. The colors on the map show the percentage of homes in each state that are either in the very high or high wildfire risk categories. The figures in each state show the number of properties that have the highest numeric risk score, factoring in a property's proximity to very high or high wildfire-risk areas. New Mexico is one of the states with the highest percentages of homes in very high and high risk categories, based on terrain, fuel, and vegetation characteristics of the property itself.

SOURCE: BASED ON DATA BY CORELOGIC (BOTTS ET AL. 2013).

BOX 1.

Cultural Heritage: Bandelier National Monument and Los Alamos National Laboratory

Extreme precipitation, flooding, and wildfires have affected sites that are central to New Mexico's heritage. The rock carvings and cliff dwellings of Bandelier National Monument tell the story of some of the earliest inhabitants of the Americas, while their descendants live nearby in modern-day pueblos. Protecting the archaeological, ecological, and cultural features of this landscape has become more difficult as drought, large wildfires, and extreme flooding increase the risks to them and the infrastructure they depend upon. For instance, the Cerro Grande Fire raged through the area in 2000, damaging more than 70 percent of 470 archaeological sites on the adjacent property of Los Alamos National Laboratory, including ancestral pueblo structures and wooden homestead buildings (Nisengard et al. 2002). It also destroyed over 200 buildings in the nearby town of Los Alamos (GAO 2000), including several historic structures from the Manhattan Project era (Nisengard et al. 2002).

In 2011, the Las Conchas Fire, the second-largest wildfire in New Mexico history, burned much of the forest around Bandelier National Monument. Severe flooding from summer thunderstorms in 2011, 2012, and 2013 repeatedly washed out the popular Falls Trail and Frijoles Canyon Trail. Erosion from floods and extreme rainfall is now a major risk to the monument's archaeological heritage.

and Alamogordo during both the fire and related flood events after the fire. Yet the following year, 2012, the Whitewater Baldy Complex Fire surpassed the Las Conchas, burning more than 297,000 acres (Cleetus and Mulik 2014). Wildfires in 2013 to 2015 burned fewer acres annually than in the 2011 and 2012 fire seasons, but the lingering effects of catastrophic wildfires continued to impact the state (NIFC n.d.).

With over 35,000 homes in areas where the wildfire risk is "high" or "very high," New Mexico has the highest percentage of at-risk homes in the West (Figure 4) (Botts et al. 2015). Not surprisingly, the recovery costs from wildfires have soared as more fires, burning in hotter and drier conditions, have increased the risk to the state's residential and commercial properties. Beyond the costs of damage to property and recovery, fire suppression has become more costly as protecting communities and deploying prescribed fires have become more difficult (Cleetus and Mulik 2014).

Reducing Emissions, Building Resilience

New Mexico can take control of its future through a forward-looking, pragmatic response to climate change—a response that builds resilience to changes already underway and lessens emissions of heat-trapping gases.

REDUCE EMISSIONS

Efforts to reduce emissions and transition New Mexico toward low-carbon energy sources are needed in a state that ranks twelfth nationally in energy-related carbon dioxide emissions per capita (EIA 2015b). More than half of the state's nearly 54 million metric tons of CO_2 emissions in 2013 came from the electric power sector, which depended on coal-fired power plants to provide 67 percent of total in-state electricity generation (EIA 2015b; EIA 2015a).

Fortunately, smart and meaningful efforts to transition New Mexico toward a lower-carbon economy are underway. These four steps could pave the way for New Mexico to pivot toward a low-emissions economy—one that recognizes the value of key economic sectors by protecting them from the effects of a changing climate.

1. **Accelerate the pace of investing in renewable energy and strengthen the Renewable Electricity Standard.** New Mexico is blessed with a diverse mix of renewable energy resources, which has helped the state meet interim benchmarks toward its existing renewable electricity standard (RES), a state-established requirement that utilities supply 20 percent of their power from renewable sources by 2020 (Heeter et al. 2014). At the end of 2014, New Mexico already ranked tenth among all states for cumulative installed solar capacity, with more than 150 MW coming online from 2012 to 2014 (SEIA 2014). At that time, New Mexico had developed 812 MW of wind power that provided 7 percent of the state's electricity (AWEA n.d.). Another 330 MW of wind power capacity is under construction (AWEA n.d.).

   Nevertheless, these investments fall far short of the state's tremendous renewable energy resource potential, much of which is economically viable but remains untapped. According to the U.S. Department of Energy,

New Mexico's renewable energy economic potential—led primarily by solar and wind—could produce up to an additional 3,726 terawatt-hours of electricity, which is equivalent to more than 100 times the state's current electricity generation (Brown et al. 2015). Western New Mexico's geologically active regions also hold significant geothermal potential.

State-level RES policies are among most successful and cost-effective means for driving renewable energy development in the United States (Heeter et al. 2014; UCS 2013). By extending and expanding its current RES, which is now set to level off at 20 percent in 2020, New Mexico can encourage low-carbon, efficient energy sources to play a leading role in the state. The examples of states that have committed to targets of at least 40 percent RES by 2030 suggest that New Mexico may be able to double its share of renewable electricity (Barbose 2016).

2. **Manage energy demand through investments in efficiency.** Investing in energy efficiency in homes, businesses, and industry is an effective, affordable strategy for making the transition away from carbon-intensive fossil fuels. In 2014, efficiency investments in the state lowered retail electricity sales by more than half a percent, a significant achievement for a single year (Gilleo et al. 2015). This effort was largely spurred by an important commitment New Mexico made when it adopted an energy efficiency resource standard (EERS) in 2008. Updated in 2013, the EERS requires electricity providers to implement efficiency programs that reduce electricity demand to 10 percent below 2005 levels by 2020 (Gilleo et al. 2015). Going further, a 2012 analysis found that New Mexico could cost-effectively cut electricity use at least 24 percent by 2020 (SWEEP n.d.).

   New Mexico could exercise greater control over its energy demand if its EERS were increased and extended beyond 2020. Leading states with EERS policies are demonstrating that they can reduce electricity use by 1.5 to 2 percent each year, compared with New Mexico's current target of 0.6 percent (Gilleo et al. 2015). New Mexico could ensure adherence to this policy by tightening energy efficiency building codes, helping ensure that new construction uses the most cost-effective and energy-efficient technologies and practices.

3. **Retire high-emissions coal plants.** While New Mexico relies on coal for most of its electricity generation, the economic competitiveness of its aging and inefficient coal power plants is in decline. A lack of modern pollution controls to protect public health—along with increasing competition from cleaner, lower-cost resources such as renewable energy and natural gas—is leading to the retirement of coal plants in the state (Fleischman et al. 2013). For example, three coal generators at a Four Corners facility were closed in 2013; two coal generators at the San Juan generating station are expected to close in 2017. Combined, these retirements will lower carbon emissions from New Mexico's coal power plants by as much as 37 percent (SNL Financial 2015).

4. **Craft a plan to comply with the federal Clean Power Plan.** The U.S. Environmental Protection Agency's Clean Power Plan requires New Mexico to reduce its power plant carbon emissions by 4.9 million tons by 2030, to 28 percent below 2012 levels (EPA 2015). To achieve its emissions-reduction target, New Mexico should develop and implement a strong compliance plan that places a priority on the use of renewable energy and energy efficiency, minimizes the risks of an overreliance on natural gas, and considers closing more of its economically challenged coal plants. New Mexico should also seek to collaborate with other states in its compliance strategy, as multistate efforts have proven successful in achieving cost-effective carbon reductions.

BUILDING RESILIENCE

Even if global efforts to reduce emissions succeed, the current levels of heat-trapping gases will cause the climate to continue to warm for decades, making it essential for New Mexico and its communities to build their resilience to the effects of climate change. Those impacts are costly, and while they heighten risks to the economic security of all communities, they often hit low-income and socially vulnerable communities the hardest (Task Force on Global Climate Change 2015; Melillo, Richmond, and Yohe 2014; IPCC 2014). The agricultural sector is perhaps most at risk, yet it is critical to the state's economy and generates billions of dollars in revenue each year. To survive, New Mexico agriculture depends on water—over 1.3 million acre-feet of water annually, or about 70 percent of the state's total water consumption (Bustillos and Hoel 2014).

New Mexico can prepare its economy by making good use of information resources and investing wisely in planning and response for intensifying wildfires, droughts, floods, and other extreme conditions that accompany climate change. State and community planners need to take future projections of climate change into account—including the way it might add to the effect of other stresses, such as wildfire vulnerability, increased evaporation of agricultural soils and surface reservoirs, and the risk of over-pumping groundwater.

Some New Mexicans are already showing initiative and creativity in the face of these challenges. By taking six steps,

BOX 2.

Generations of Damage: Santa Clara Pueblo

Wildfires often hurt the people least equipped to respond effectively and recover quickly, including rural and tribal communities. In 2011, the Las Conchas Fire burned more than 16,000 acres belonging to the Santa Clara Pueblo community (Dasheno 2012). Wildfires leave the landscape bare and bake the soil, making it less permeable to water, thereby increasing vulnerability to runoff and flooding. Not long after the fire, disaster struck again when heavy rains in the Jemez Mountains surged through the scorched canyons. The pueblo, particularly vulnerable to flooding because of its location at the entrance to Santa Clara Canyon, was under a state of emergency after heavy rains sent tree trunks, boulders, and other debris rushing down the canyon, toppling power lines and washing out roads and bridges. Summer floods in 2012 and 2013 caused further severe damage to the area, forcing the pueblo to declare a state of emergency as fast-flowing water burst through dam structures built to protect the community.

"It will take generations for our community and lands to recover from the devastation of the fire," said Walter Dasheno, governor of Santa Clara Pueblo at the time of the floods. "And because of climate change it is not clear what the future will look like" (Dasheno 2012).

Larry1732/Creative Commons (Wikimedia Commons)

Climate change is increasing the frequency of wildfires, and making it more difficult to recover from their destruction. In 2011, the Santa Clara Pueblo community lost more than 16,000 acres of forested land to wildfire, which cleared the way for heavy flooding the new two summers.

state and federal policies should enable and build on such efforts to safeguard communities.

1. **Support and learn from communities taking systematic steps to reduce risks from wildfire.** In New Mexico, five communities—Elk Ridge, the Greater Eastern Jemez Wildland, Hidden Lake, the Village of Ruidoso, and Taos Pines Ranch—were cited as success stories when they received competitive "FireWise" grants from the National Fire Plan, aimed at reducing wildfire risk and potential home and property losses. Under that program, local fire districts provide communities and their residents with wildfire risk assessments, prescribe mitigation measures, and recommend options for enhancing the long-term health of forests.[4] Such valuable services could be expanded throughout the state, protecting lives and property, while reducing New Mexico's reliance on federal fire suppression efforts.
2. **Learn and share lessons from water innovators within the state who are working through difficult choices.** For example, water users in the Lower Rio Grande Basin in southern New Mexico have faced severe and sustained drought on top of an increasingly arid climate, yet the current priority system by which rights to use water are appropriated has led to more demand for water than can be sustainably supplied. In 2015, Elephant Butte Irrigation District implemented its Depletion Reduction Offset Program (DROP), which gives municipal and industrial water users access to combined groundwater and surface water rights through the leasing and fallowing of irrigated land to reduce depletions from agricultural use.

> *"It will take generations for our community and lands to recover from the devastation of the fire, and because of climate change it is not clear what the future will look like."*
>
> — Walter Dasheno, governor of Santa Clara Pueblo

The reduced demand for agricultural water has offset depletions caused by meeting municipal and industrial demand, allowing the system to remain in balance.

Another, longer-term example is the Rio Grande Water Fund, a public-private partnership that seeks to protect vital watersheds in northern New Mexico through large-scale restoration of forests and watersheds. The fund invests in thinning overgrown forests, restoring streams, and rehabilitating areas that have flooded after wildfires.[5] Although this fund was not designed to address climate resilience, it is well-suited to forward-looking action.

3. **Make better use of monitoring systems to provide early warning of drought, flooding, or other extreme conditions.** For instance, the New Mexico Climate Center housed at New Mexico State University operates a network of weather stations across the state and analyzes the climate data from them.[6] Farmers and ranchers, among others, can use this real-time climate data to help them anticipate and understand climate-driven weather events, inform irrigation schedules, and take proactive steps to protect their investments.

   Another source of information is the New Mexico Office of the State Engineer, which coordinates the Interstate Stream Commission responsible for monitoring the impact of climate change on New Mexico's water supply and the state's ability to manage water resources.[7] The office informs communities about water supply challenges and coordinates their responses. This role should be supported and enhanced.

4. **Ensure that state regulatory regimes recognize the impacts of climate change on resources and take those impacts into account when managing them.** Impacts the state is already experiencing include extreme variability in the supply of surface and groundwater, changes in the quantities and types of water-supply demand, and increases in forest fires and flooding. As the state considers options for planning and managing its water and other resources, it must actively assess current and future climate impacts and incorporate them into regional and state water plans in an iterative and ongoing way. Analyses based on more extreme projections, rather than median projections, provide a "stress-test" approach to considering how future climate extremes may affect water resources and water projects. They could be a helpful approach to managing the state's water resources and designing water infrastructure.

5. **Provide sufficient funding for regional and statewide water planning, administration, and infrastructure designed for the future, not the past.** Additional resources are needed to adequately understand, plan, and address water resource management needs across the state. Given growing demands for water resources to keep the state's economy thriving, investing in water resources pays multiple dividends, and in many ways that are not traditionally measured. For example, better infrastructure would give water managers more precise control over water allocation, helping farmers protect their economic stability, as well as strengthening the communities built upon the acequia irrigation system. In 2013, New Mexico Governor Susana Martinez took a significant step in this regard when she announced the allocation of $112 million from the state's capital investment fund to water infrastructure improvements, saying "Unprecedented drought, wildfires, and floods have put further stress on New Mexico's aging water infrastructure in communities large and small across the state" (Western States Water Council 2013). These funds are a critical step toward addressing unmet needs, which are expected to worsen with climate change.

DOE

One of New Mexico's largest commercial solar PV installations can be found at the Indian Pueblo Cultural Center. This project is a successful example of how New Mexico could increase its renewable energy resources to reduce emissions and build resilience.

6. **Adopt a groundwater measurement and accounting method that is well understood, broadly accepted, and properly integrated across the spectrum of water dealings.** Because groundwater cannot be plainly seen, a variety of metrics are used to assess groundwater levels and storage, including measuring extraction or employing modeling. Metrics and monitoring efforts can be tailored to fit state and local needs. For example, in North Texas, one Groundwater Conservation District measures groundwater extraction by installing a meter or device

to measure water flow that is accurate to within a few percent. In California, the Sacramento Central Groundwater Authority monitors its wells twice a year (SCGA 2012). If needed, scientists have demonstrated that groundwater usage can be effectively modeled in near-real-time with the support of satellite data (Zaitchik, Rodell, and Reichle 2008; Allen, Masahiro, and Trezza 2007). Metering electricity usage by groundwater wells to estimate groundwater pumped from individual wells is key to ensuring groundwater sustainability.

> *"Unprecedented drought, wildfires, and floods have put further stress on New Mexico's aging water infrastructure in communities large and small across the state."*
>
> — Governor Susana Martinez

BOX 3.

Federal Initiatives

- The multiagency National Drought Resilience Partnership, established in 2013, helps states and communities measure and analyze data on water supplies, snowpack, and soil moisture; develop watershed-wide drought plans; and develop resources to help farmers and other water users measure and conserve water and enhance soil health.[8]
- The National Water and Climate Center, a project of the National Resources Conservation Service, conducts the New Mexico Snow Survey Program, providing mountain snowpack data and streamflow forecasts for the state.[9]
- The Southwest Climate Science Center, located in Tucson, Arizona, is a collaboration of scientists and resource managers to better plan for and adapt to climate change in the region.[10]
- The Southwest Climate Regional Hub, located at New Mexico State University in Las Cruces, is one of seven U.S. Department of Agriculture hubs established across the country to help farmers and ranchers adapt their operations to a changing climate.[11]

While many existing federal programs can alleviate some costs, Congress should increase national investments in a number of programs, including the following:

- The New Mexico Drought Preparedness Act of 2015, introduced by U.S. senators Tom Udall and Martin Heinrich, would provide drought relief and address long-term drought challenges by improving the efficiency and effectiveness of water management in the state. If enacted, this act would address drought conditions by targeting critical water-management challenges in the Rio Grande River Basin, which is the state's largest and most economically important watershed. The act would provide for technical assistance to foster a federal acquisition and local water trading program, studies aimed at optimizing basin infrastructure management, maintenance of flow management for ecosystem benefits, and additional funding for drought mitigation and relief.
- The Pre-Disaster Mitigation Grant program is designed to reduce risks to people and property and to diminish reliance on federal funding when disasters occur. The program helps fund hazard-mitigation planning and projects that reduce New Mexico's vulnerability to floods, wildfires, and other extreme weather events.[12]
- The Western Watershed Enhancement Partnership helps reduce wildfire risks to water supplies by partnering with local businesses to clear flammable forest debris and manage forests in ways that strengthen resilience.[13]

Federal investments in climate preparedness and resilience can help protect communities in New Mexico. Larger appropriations and strategic grants for these and similar programs would help New Mexico prepare for droughts, wildfires, and other impacts of climate change, as well as assist communities in times of need and speed recovery when those impacts are felt.

The federal government must make the latest science and data easily accessible to states and communities, delivering them before critical decision moments and leading to better-informed planning decisions. Agencies at all levels of government need to reevaluate existing programs, hold steady or increase disaster-response efforts, and place a high priority on preparedness for climate-change-fueled natural disasters, which are expected to become more harmful and costly. Without smart investments now, the costs will strain the ability of even the most resilient and resourceful communities to cope and recover, draining the budgets of state and local governments.

New Mexico's Path to a Strong, Resilient Future

New Mexico has a long history of facing a challenging climate, and New Mexicans have learned to be resourceful and resilient. The state has invested in meeting the needs of its people, while using approaches and policies aimed at keeping its economy within the limits of its available resources.

The future climate will alter these circumstances, changing the availability of vital resources, making past investments obsolete, and testing the resourcefulness of New Mexico's people. New Mexico can survive and even thrive in this new world, but only if it takes wise steps today. As the future unfolds, New Mexicans deserve the commitment of state and federal policy makers to doing the utmost to limit risks and helping the state become more resilient to the unavoidable challenges.

New resources and investments are only part of the solution. When the state empowers its people to makes better choices for themselves—backed up by forward-looking investments—the people of New Mexico can forge a new path to a resilient future, as they have done many times before. The challenge today is for New Mexico to take the steps necessary to effectively manage and reduce the impacts of climate change and ensure the future security of the state and its residents.

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ENDNOTES

1. *The latest National Climate Assessment, the third, was developed by a team of more than 300 experts, guided by a 60-member Federal Advisory Committee. The report was extensively reviewed by the public, a panel of the National Academy of Sciences, and other experts, including from federal agencies. For more information, see:* http://nca2014.globalchange.gov.
2. *These figures are in comparison with a 1901–1960 reference period.*
3. *These figures are in comparison with a 1971–1999 reference period.*
4. *For more information about the FireWise success stories, see:* www.firewise.org/wildfire-preparedness/be-firewise/success-stories/new-mexico.aspx?sso=0.
5. *For more information about the Rio Grande Water Fund, see:* www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newmexico/new-mexico-rio-grande-water-fund.xml.
6. *For more information about the New Mexico Climate Center, see:* http://weather.nmsu.edu.
7. *For more information about the New Mexico Office of the State Engineer and the Interstate Stream Commission, see:* www.ose.state.nm.us/index.php.
8. *For more information about the National Drought Resilience Partnership, see:* www.drought.gov/drought/content/ndrp.
9. *For more information about the New Mexico Snow Survey Program, see:* www.nrcs.usda.gov/wps/portal/nrcs/main/nm/snow.
10. *For more information about the Southwest Climate Science Center, see:* www.doi.gov//csc/southwest/index.cfm.
11. *For more information about the Southwest Climate Regional Hub, see:* http://swclimatehub.info.
12. *For more information about the Pre-Disaster Mitigation Grant program, see:* https://fema.gov/pre-disaster-mitigation-grant-program.
13. *For more information about the Western Watershed Enhancement Partnership, see:* www.usda.gov/wps/portal/usda/usdahome?contentid=2013/07/0147.xml.

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Climate Change in New Mexico Over the Next 50 Years: Impacts on Water Resources

Editors and Contributing Authors: Nelia W. Dunbar, David S. Gutzler, Kristin S. Pearthree, Fred M. Phillips, Paul W. Bauer

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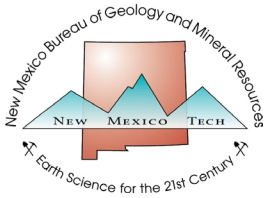
WATER RESOURCES



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Climate Change in New Mexico Over the Next 50 Years: Impacts on Water Resources

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Bulletin 164—Climate Change in New Mexico Over the Next 50 Years: Impacts on Water Resources

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OVERVIEW

CLIMATE CHANGE IN NEW MEXICO

Earth is warming in response to increasing atmospheric carbon dioxide, and this warming will result in greater aridity in many parts of the world, including New Mexico. The primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources. These effects may be accentuated by positive feedback cycles, tipping points, or compounding events. This bulletin compiles, assesses, and integrates existing peer-reviewed published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years and resultant impacts on water resources, and it represents the scientific foundation upon which New Mexico's 50-Year Water Plan will be developed. New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes and related impacts on water resources in different geographic areas of New Mexico over the next 50 years will vary not only by region but also as a function of local elevation and even by hillslope orientation. The currently observed trends of increasing temperature and constant but more variable precipitation will continue over the next 50 years.

OUR CLIMATE FUTURE

Global climate models driven by increasing greenhouse gases project an average temperature increase across the state of New Mexico of between 5° and 7°F over the next 50 years. This regional temperature increase follows the trend observed over the past half century, at a somewhat amplified rate, with the northwest corner of the state projected to experience a slightly higher rise during the same period. Although all models indicate significant increases in temperature, these models do not consistently project a significant change in average annual precipitation across the state, mirroring the absence of a clear trend in recent historical observations. However, some consistent differences in seasonality of precipitation emerge. During the winter, the northern mountains may receive somewhat more precipitation, whereas the southern parts of the state may be drier. Spring precipitation, critical for snowmelt runoff and ecosystems, may decline. Also in the southern part of the state, a trend toward somewhat stronger monsoonal activity may result in more summer precipitation, perhaps shifting toward somewhat later in the year.

The coupled trends of increasing temperature with no clear increasing trend in precipitation lead to a confident projection of increasingly arid conditions, including decreased soil moisture, stressed vegetation, and more severe droughts. Snowpack and associated runoff are projected to decline substantially by 2070, generating diminished headwater streamflow. Warmer temperatures will also cause lower river flows due to increased evaporation as rivers flow downstream. The impacts of climate change on New Mexico's resources are, unfortunately, overwhelmingly negative.

LAND-SURFACE WATER BUDGET

All water that we use in New Mexico originates as rain or snow falling onto the landscape, which either goes to groundwater or surface water or returns to the atmosphere. Of the precipitation that falls on the state, 1.6% runs off into streams and rivers, and 1.8% infiltrates into the ground, recharging subsurface aquifers. Much larger proportions are transpired by plants (78.9%) or evaporated (17.7%). The impact of climate change on all of these pathways will affect our state's water budget. Notably, because of the larger percentages of water lost to evaporation or transpiration, even very small changes in these factors will result in large changes to runoff and recharge. As mentioned in Chapter 2, the climate will continue to warm over the next 50 years, likely without an increase in precipitation, leading to greater statewide aridity. Hydrological modeling indicates declines in both runoff and recharge going forward, amounting to 3% to 5% per decade for both quantities. Historical trends in runoff indicate significant year-to-year variability, as do trends in soil moisture and recharge. But all are generally decreasing, consistent with the results of climate models that project a drying climate. Combining the historical trends with modeling of future changes, significant decreases in runoff and recharge seem very likely.

TERRESTRIAL ECOSYSTEMS

Climate is a fundamental driver of ongoing and future vegetation changes in New Mexico. Future changes in vegetation will affect the distribution and abundance of water resources in New Mexico. Major shifts in climate and vegetation across New Mexico's landscapes have occurred in the past, but the scale and rate of recent and projected climate change is probably unprecedented during the past 11,000 years. Recent warming, along with frequent and persistent droughts, have amplified the severity of vegetation disturbance processes like fire, physiological drought stress, and insect outbreaks, driving substantial changes in New Mexico vegetation since the year 2000. Ongoing and projected vegetation changes include growth declines, reduced canopy and ground cover, massive tree mortality episodes, and species changes in dominant vegetation—foreshadowing more severe changes to come if current warming trends continue as projected. Such major alterations of New Mexico vegetation likely will also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water supply shortages for people, such climate-change-driven water stress could lead to increasing conflict between managing declining water available for human use (e.g., irrigation) and retaining "wild" water for the maintenance of historical ecosystems.

SOILS

Soils play a strong role in determining how New Mexico's diverse landscapes will respond to climate change. Soil cover acts like a sponge, holding in water that falls as rain or snow. The presence of soil supports vegetation and substantially reduces runoff and erosion. Soil enhances other processes such as infiltration of water and aquifer recharge. Soils can be damaged by a warming climate. Loss of vegetation in the Northwestern High Desert and Eastern Plains, where soils are not well developed and are easily damaged, will lead to dustier conditions in much of the state. On mountain hillslopes, the loss of vegetation cover in response to ongoing climate change will increase soil erosion, which then increases hillslope runoff. This, in turn, causes additional increases in soil erosion and bedrock exposure, which can largely prevent widespread recolonization by most plants, including trees. Soils on mountain hillslopes that face south, which are typically hotter and drier, will be damaged sooner by a warming climate than those on generally north-facing hillslopes that are slightly cooler and moister. Soils take many thousands of years to form, so these hillslopes will increasingly support sparse forests or, in some circumstances, be entirely deforested. These changes are already well underway in some mountains in New Mexico.

LANDSCAPE, FIRE, AND EROSION

New Mexico has a dynamic landscape; climate change and increasing fire frequency over the next 50 years will amplify recently observed instability. As the climate changes to warmer conditions, less rainfall will infiltrate into aquifers, leading to increased overland runoff. Landform processes can be complex, but in general the predicted changes in climate and precipitation will lead to increased upland erosion caused by runoff and increased downstream sediment deposition. Canyons, mesas, and small basins or valleys filled with sediment will be particularly affected. Rapid rearrangement of sediments by water is disruptive and potentially hazardous to ecosystems and societies. Dramatic examples of accelerated erosion following the Whitewater–Baldy, Las Conchas, and other wildfires here in New Mexico illustrate the types of hazards created when forested landscapes are severely burned. Post-wildfire erosion is typically initiated by intense rainfall events. Given that both the number of wildfires and rainfall intensities are likely to increase as the climate warms, New Mexico can expect to see increases in widespread erosion and sedimentation across and downstream from upland forested areas in the state. The large volume of sediment predicted to be on the move will be of concern for many reasons, including filling reservoirs, choking channels, and blocking or destroying infrastructure. Positive feedback loops lead to further reductions in slope stability.

SURFACE WATER AND GROUNDWATER

Surface-water supply shortages induced by climate change will drive both agricultural and municipal/industrial water users to rely more heavily on groundwater. Less surface water will lead to lower recharge to some groundwater aquifers. The Lower Rio Grande is an in-progress example of this effect, with prolonged surface-water shortage leading to plunging groundwater levels. All water users in the state will experience decreased water availability as the climate warms and aridification occurs. This decrease in water availability will likely trigger changes in use from lower-value uses to higher-value uses, and this generally means a migration from agricultural water use to municipal/industrial uses. New Mexico has a rich and diverse history of water use that is central to its collective identity. This permanent shift toward a more arid climate will upset the hydrologic balance that has weathered cyclical drought. The declining mean and increasing variability in the surface-water supply is not cyclical, and recovery periods will be fewer and farther between. This will require difficult and divisive policy and management decisions, undoubtedly accompanied by an increase in disputes and litigation. New Mexico is by no means alone in facing these daunting challenges.

RIVERS

New Mexico's major rivers transport both water and sediment through channels, riparian ecosystems, and hydraulic control structures such as dams and reservoirs. As the climate changes, the amount of sediment being delivered to rivers from their watersheds is increasing, impacting the amount of sediment transported by the rivers themselves. This increased sediment load is changing the river channels, and the pace of change will accelerate as the climate continues to warm. Over the next 50 years, flow volume in the major rivers (San Juan, Chama, Rio Grande, Pecos, and Gila) is projected to decline by 16% to 28%, and the frequency of extreme precipitation events, coupled with fire-driven disruption of vegetation in watersheds, is projected to at least double the amount of sediment delivered to and transported by rivers. The beds of undammed rivers will be built up by the extra sediment, which will reduce efficiency of downstream water delivery and make it difficult to divert water into existing acequia systems. In river channels below dams and reservoirs, the impact of reduced flow and increased sediment load can be addressed by flow releases that better balance sediment supply and transport. However, additional channel and vegetation maintenance and management will likely be required, and the capacity of reservoirs will be progressively reduced due to increasing sediment. Finally, the combination of lower water flow and higher sediment input downstream of dams will intensify the narrowing of river channels that has resulted from historical management of river flows.

PRECIPITATION AND STORMWATER

A warming climate could increase the magnitude of future storms, leading to extreme precipitation events and increased flooding in New Mexico. Warmer air can hold more water vapor, approximately 7% more moisture for each 1°C (1.8°F) increase in temperature. Global climate models used to predict future conditions are not detailed enough to simulate individual storms. Three major types of storms occur in New Mexico: short-duration, high-intensity local storms in summer (usually monsoonal); long-duration general storms (caused by winter weather fronts); and occasionally the remnants of tropical storms. The principal risk from extreme precipitation events will be flooding in small watersheds from high-intensity local storms, precisely the storms that are hardest to simulate in climate models. Large-scale regional studies have corroborated the hypothesized increase in extreme precipitation with warming temperature, but few such studies exist on the impact on local storms in the Four Corners states. A study of extreme precipitation events in Colorado and New Mexico was recently completed and has updated estimates of the magnitude of severe storms possible in our state. Data and modeling studies suggest that while the risk of the most severe storms might not increase beyond current estimated values, less severe (but still high-intensity) storms may occur more frequently than at present, which could impact existing stormwater management infrastructure.

WATER QUALITY

A warming climate may affect the quality of both surface and groundwater resources in New Mexico. The most likely effects may include increased temperature along with higher concentrations of nutrients, dissolved oxygen, and pathogenic organisms. Although the quality of groundwater may be affected, it is likely to be limited to locations with shallow groundwater depth and where surface water recharges an aquifer. The New Mexico Environment Department publishes an assessment of the quality of the state's surface waters every 2 years. This recent assessment finds the major causes of impairment of streams and rivers are temperature, nutrients (nitrogen and phosphorous compounds), *E. coli* bacteria, turbidity, and dissolved aluminum. The parameters most likely to be affected by a warming climate are temperature, nutrients, and *E. coli* concentrations. Studies suggest that loss of riparian vegetation is the biggest factor affecting water temperature. Modeling studies of the effects of climate warming on nutrient concentrations are somewhat inconclusive. Recent investigations suggest *E. coli* concentrations may increase as a result of microbial regrowth in warming stream sediments in slow-moving stream reaches. A future threat to water quality is runoff following wildfire events. Postfire runoff can cause depletion of dissolved oxygen far downstream from the burned watershed.

STATEWIDE AND REGIONAL IMPACTS

All regions of New Mexico will be affected by climate change, but the topographic complexity of the state will generate distinct impacts by location. The average temperature will warm across the state, probably between 5° and 7°F, whereas average precipitation is likely to remain constant, even if more variable from year to year, with the possibility of more extreme precipitation events. Snowpack, runoff, and recharge will decline, stressing both surface and groundwater resources. Surface-water quality will decline. Plant communities will be stressed by higher temperatures and greater aridity, leading to more extreme wildfires and increased erosion. Damage to soils related to a number of factors will create greater atmospheric dustiness and lower water infiltration to aquifers.

Although latitude plays a role in the effects of climate change, the bigger impact in New Mexico is related to local topography and elevation. For the purposes of this bulletin, we are dividing New Mexico into four physiographic regions based on projected climate change impacts and associated effects on hydrology. These four regions, which are defined by a combination of latitude and topography, are: the High Mountains (northern mountains, Gila/Mogollon–Datil, and Sacramento Mountains); the Northwestern High Desert (Colorado Plateau, San Juan Basin, and Zuni Mountains region); the Rio Grande Valley and Southwestern Basins; and the Eastern Plains.

RECOMMENDATIONS: DATA GAPS AND CHALLENGES

The process of evaluating and projecting climate change in New Mexico over the next 50 years and examining the impacts on water resources illuminated a number of research topics that should receive attention from the state's science community. A high-priority research target is to better understand a number of facets of precipitation that New Mexico might experience over the next half century. These include seasonality of precipitation, snowpack dynamics, and extreme precipitation. Better understanding of the latter would allow New Mexico planners to consider how to put localized, heavy precipitation to good use and to mitigate damage associated with flooding. Climate, hydrology, and ecology numerical models that allow projection of conditions and behaviors of these natural systems in New Mexico over the next half century are also needed. Finally, a number of observational data gaps have been identified, most notably a thorough and geographically distributed assessment of the water levels in New Mexico aquifers. Other topics include impacts of climate change on soil moisture and groundwater quality, as well as landscape and ecological responses to climate change, in terms of both magnitude and timescales of response. This can be carried out in part by long-term ecological monitoring.

Cerro Pedernal, south of Abiquiu Lake; *photo by Matthew Zimmerer*

I. CLIMATE CHANGE IN NEW MEXICO

Nelia W. Dunbar and David S. Gutzler

Earth is warming in response to increasing atmospheric carbon dioxide, and this warming will result in greater aridity in many parts of the world, including New Mexico. The primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources. These effects may be accentuated by positive feedback cycles, tipping points, or compounding events. This bulletin compiles, assesses, and integrates existing peer-reviewed published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years and resultant impacts on water resources, and it represents the scientific foundation upon which New Mexico's 50-Year Water Plan will be developed. New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes and related impacts on water resources in different geographic areas of New Mexico over the next 50 years will vary not only by region but also as a function of local elevation and even by hillslope orientation. The currently observed trends of increasing temperature and constant but more variable precipitation will continue over the next 50 years.

Abundant scientific research demonstrates that Earth's atmosphere, oceans, and surface are warming and that this warming is largely driven by human-induced activity, principally through a sustained increase in carbon dioxide (CO_2) accumulating in the atmosphere since the beginning of the Industrial Revolution. Carbon dioxide and certain other gases, such as methane, trap heat in the troposphere, causing the planet's surface to warm (as discussed in Intergovernmental Panel on Climate Change [IPCC], 2014b and U.S. Global Change Research Program [USGCRP], 2017). This natural warming process, which is being enhanced by human activity, is called the greenhouse effect. Other extreme weather events, including droughts, prolonged heat waves, and intense precipitation events with associated flooding, are occurring with greater frequency as the troposphere warms. And increasing ocean and atmospheric temperatures are promoting rapid melting of Arctic and Antarctic land-based ice, leading to sea-level rise. Global climate is expected to continue to change in response to ever-increasing levels of atmospheric greenhouse gases, primarily CO_2.

The most significant negative impacts of climate change are distinct in different parts of the world, depending on the sensitivity of local systems to various climate perturbations (USGCRP, 2018). In the southwestern United States, the primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources (Gonzales et al., 2018).

Water quality may also suffer and will affect people worldwide; it will be particularly detrimental to indigenous communities (Jantarasami et al., 2018).

In addition to those reasonably well-understood climate-related hazards, there is a real possibility for three types of less obvious changes in the climate and hydrological systems due to climate disruption (USGCRP, 2017):

1. Positive feedback (or self-reinforcing) cycles—A small change in one or several systems leads to accelerated change. For example, during times of higher temperatures and associated greater demand for surface water, water users will pump additional groundwater. Additionally, as water levels in aquifers drop, the rate of water loss from rivers to underlying aquifers may increase, reducing availability of surface water. The higher temperature will lead to more evaporation and therefore less recharge of aquifers. Associated longer growing seasons and higher temperatures increase stress on the aquifers by further increasing the water demand of vegetation. All of these interrelated factors will lead to lower water availability.
2. Critical threshold (or tipping point) events—A threshold is crossed in a natural system that triggers an irreversible reaction. Reversing the trigger does not restore the natural system to its original condition. For example, when water is pumped from certain aquifers, the pore space in the aquifer will collapse, resulting in a permanently reduced capacity of the aquifer. This change is irreversible.
3. Compounding events—Perturbation in one element of a natural system triggers a change in another system. For example, loss of vegetation and modification of the land surface by intense wildfires can increase the speed at which precipitation flows off the land and in turn lead to increased flood intensity.

Examples of the three effects listed above have already happened in New Mexico, as will be noted in the following chapters of this bulletin. As climate disruption accelerates, we should be prepared for other examples of positive feedback, critical threshold, and compounding events to occur.

In 2006, the New Mexico Office of the State Engineer convened a group of scientists who produced a report entitled *The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources* (Watkins et al., 2006). The report was generated in response to Governor Bill Richardson's recognition that the most significant impact of climate change on New Mexico was going to be the negative impact on the state's water resources. Watkins et al. (2006) focused on the following set of challenges:

- Increasing temperature
- Changes in snowpack elevations and water equivalency
- Changes in available water volumes and timing of water availability
- Increasing precipitation in the form of rain rather than snow due to increasing temperatures
- Smaller spring runoff volumes and/or earlier runoff that will impact water availability for irrigation and for ecological and species needs
- Milder winters and hotter summers, resulting in longer growing seasons and increased plant and human water use
- Increased evaporative losses from reservoirs, streams, and soils due to hotter, drier conditions
- Increased evapotranspiration by agricultural and riparian plants
- An increase in extreme events, including both droughts and floods

New Mexico still faces all of these challenges today, but in the elapsed 15 years, additional research has led to a greater depth of knowledge about both climate change in general and consequences specific to New Mexico. Two IPCC reports (AR4 in 2007–08 and AR5 in 2013–14) have been published since 2006, and AR6 was released in late 2021. Two volumes of the 4th National Climate Assessment for the United States were published in 2017 and 2018, containing a wealth of regionally specific information. And new scientific research on broad impacts of climate change in the desert Southwest region, including New Mexico, has continued to move forward. With the proposed development

of a 50-Year Water Plan for New Mexico by the Interstate Stream Commission, a renewed assessment of climate change and its impact on water resources is timely to providing a foundational assessment for the 50-Year Water Plan.

The primary goal of this bulletin, informally referred to as the Leap Ahead analysis, is to compile, assess, and integrate existing peer-reviewed, published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years and resultant impacts on water resources. The motivation for preparing this bulletin was to have a solid, science-based foundation in support of New Mexico's 50-Year Water Plan published in 2022. The authors of this bulletin are expert New Mexican scientists whose research specialties span a broad and complementary range of research areas. The chapters of the bulletin following this introduction are:

2. Our Climate Future
3. Land-Surface Water Budget
4. Terrestrial Ecosystems
5. Soils
6. Landscape, Fire, and Erosion
7. Surface Water and Groundwater
8. Rivers
9. Precipitation and Stormwater
10. Water Quality
11. Statewide and Regional Impacts
12. Recommendations: Data Gaps and Challenges

In many of the chapters in this bulletin, authors refer to "uncertainty" associated with a given natural process that may occur as a result of climate change. Uncertainty is inherent to scientific investigations, or any field that relies upon experiments and models, and results from the difficulty of obtaining complete information about a natural process or from a lack of agreement about how to interpret results. In many cases, including examples in this bulletin, uncertainty can be expressed in terms of a numerical range in results. In other cases, uncertainty can be expressed as a degree of confidence, as has been done in past IPCC reports, with likelihoods such as "very likely" or "very unlikely" being used. This level of uncertainty analysis is beyond the scope of this bulletin, but readers who want to learn more about how this process was handled by the IPCC may refer to Mastrandrea et al. (2010).

New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes and resultant impacts on water resources in different geographic areas of New Mexico over the next 50 years will vary not only by region but also as a function of local elevation and even by hillslope orientation. Chapter 11 of the bulletin summarizes climate change impacts on water resources that will affect the entire state; it then focuses on particularly important impacts on different regions of the state. For each region, the key climate-related factors that may impact diminishing (or increasing) water resources are highlighted.

Finally, in addition to synthesizing the state of knowledge on climate change and impacts on water resources in New Mexico over the next 50 years, an important aspect of this bulletin has been to identify significant data and modeling gaps and uncertainties and to suggest research directions to strengthen our understanding of these important topics. This is addressed in the final chapter of the bulletin, serving as a blueprint for valuable research directions that will help us better understand and adapt to the impacts of the looming challenges ahead.

The historical climate baseline for New Mexico is key to understanding the changes that are described in this bulletin. A concise, illustrated introduction to the climate of New Mexico and its past and future variability is presented below.

New Mexico has a temperate, semiarid climate, as described by Gutzler (2004). It is located in the subtropical latitude belt where descending air from the Hadley Circulation maintains a generally dry climate (compared to latitudes near the equator or farther north) with a very pronounced seasonal cycle. Its interior position within the North American continent means that moisture evaporating off the ocean must propagate a long distance to reach New Mexico, enhancing the tendency for rain-out before water vapor reaches the state. Its high elevation, with the Continental Divide and Rio Grande rift mountains defining high and complicated topography, keep average annual temperatures cooler than surrounding states to the

west and east (Figure 1.1A). The mountains promote cloud formation and precipitation when moist airflows are forced upslope, so the map of averaged annual precipitation (Figure 1.1B) mimics a map of topography. These moist airflows are associated with frontal systems propagating off the Pacific Ocean in winter and monsoonal moisture from the south in summer. Hydrologic variability from year to year or on longer time scales can arise when these moist air flows follow different paths (such as winter storm tracks shifting north or south due to Pacific Ocean variability) or when temperature change affects the water balance at the surface (such as by changing how much snow accumulates or by changing surface evaporation rates).

Specific information, with supporting illustrations, on selected aspects of New Mexico's past and future climate is summarized here:

- The average temperature across New Mexico has risen by more than 2°F from 1970 to 2020 (Figure 1.2), in parallel with global temperatures.
- Annual precipitation shows no obvious long-term trend in the instrumental record, but interannual and decadal-scale swings are large (Figure 1.2). Decadal averages of precipitation values peaked in the 1980s and have since declined for the 3 subsequent decades. The decadal average of statewide precipitation for 2011–2020 was very close to the average for the drought decade of the 1950s. Four of the five lowest annual statewide precipitation values since 1931 have occurred since the turn of the twenty-first century.
- Based on projections of the climatic response to global emissions of greenhouse gases, New Mexico temperatures are likely to increase significantly in coming decades (Figure 1.3). The projected increase in temperature is described in more detail in Chapter 2.
- The record of past drought in New Mexico reflects the pronounced natural variability of precipitation, a considerable fraction of which can be explained by natural fluctuations of Pacific Ocean temperatures (such as the El Niño cycle). New Mexico has experienced extended periods of wetter or drier conditions for many centuries (Figure 1.4), and these fluctuations are expected to continue in future decades. Intermittent profound drought periods—the dry half of natural variability such as we are experiencing today—are endemic to the Southwest. The first few years of the ongoing drought epoch are shown as declining values at the end of the time series in Figure 1.4. The approximate frequency of swings between drought and pluvial (wetter) conditions in this figure (approximately twice per century) suggests that New Mexico's climate might transition back toward an epoch of wetter conditions sometime in the next few years, but we currently have no reliable way to predict when such a swing might take place.
- Snowpack has been declining over the past several decades in association with warming temperatures and increases in dust blowing onto snow (Livneh et al., 2015), promoting earlier snowmelt. When snowpack becomes dust-covered, the snow's ability to reflect solar radiation decreases, causing more solar radiation to be absorbed and therefore more rapid melting. Observed snowpack in the headwaters of the Rio Grande has declined >20% over an epoch of both drought and pluvial conditions (Figure 1.5, top curve). Snowmelt runoff (not shown in this graph) has been occurring earlier as average spring temperatures rise. Streamflow in major rivers (for example, the Rio Grande headwaters, shown in the bottom curve of Figure 1.5) so far has not exhibited long-term trends as clearly as the trends in snowpack or temperature. However, flow deficits during recent drought years have been lower than flows in earlier severe drought episodes, suggesting that the effects of declining snow and rising temperature are starting to become evident as a worsening of low-flow conditions during severe droughts.

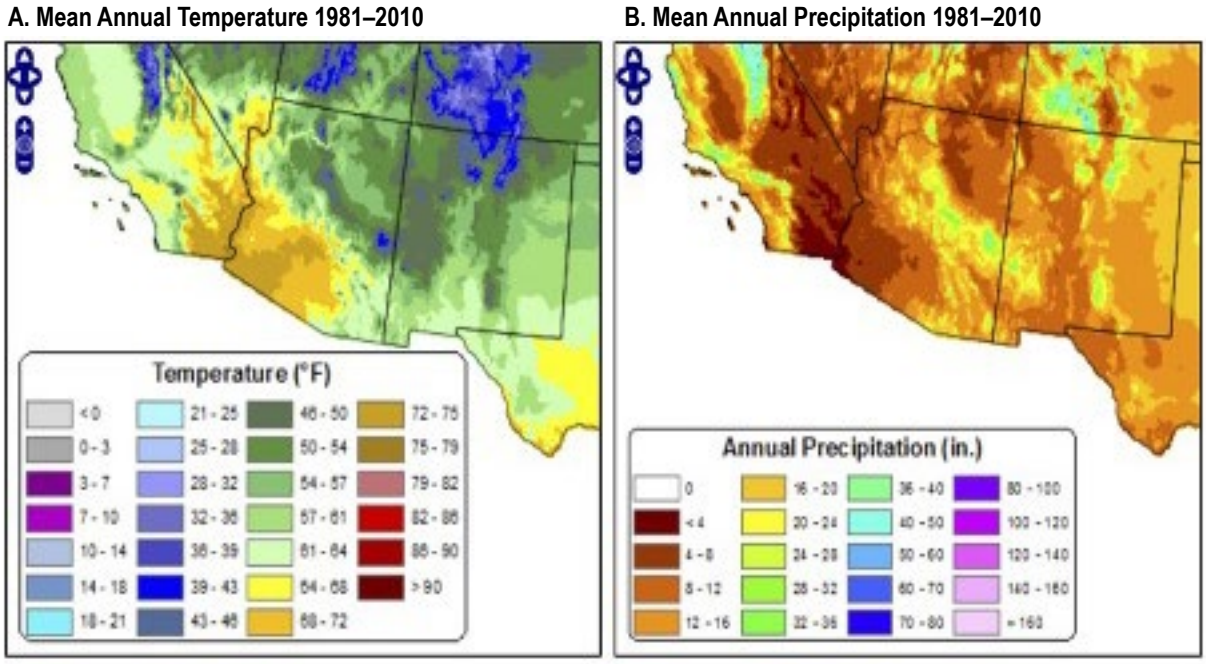


Figure 1.1. 30-year average "normal" values of observed mean annual temperature (A) and observed mean annual precipitation (B) from 1981 to 2010. From PRISM group at Oregon State University in 2021.

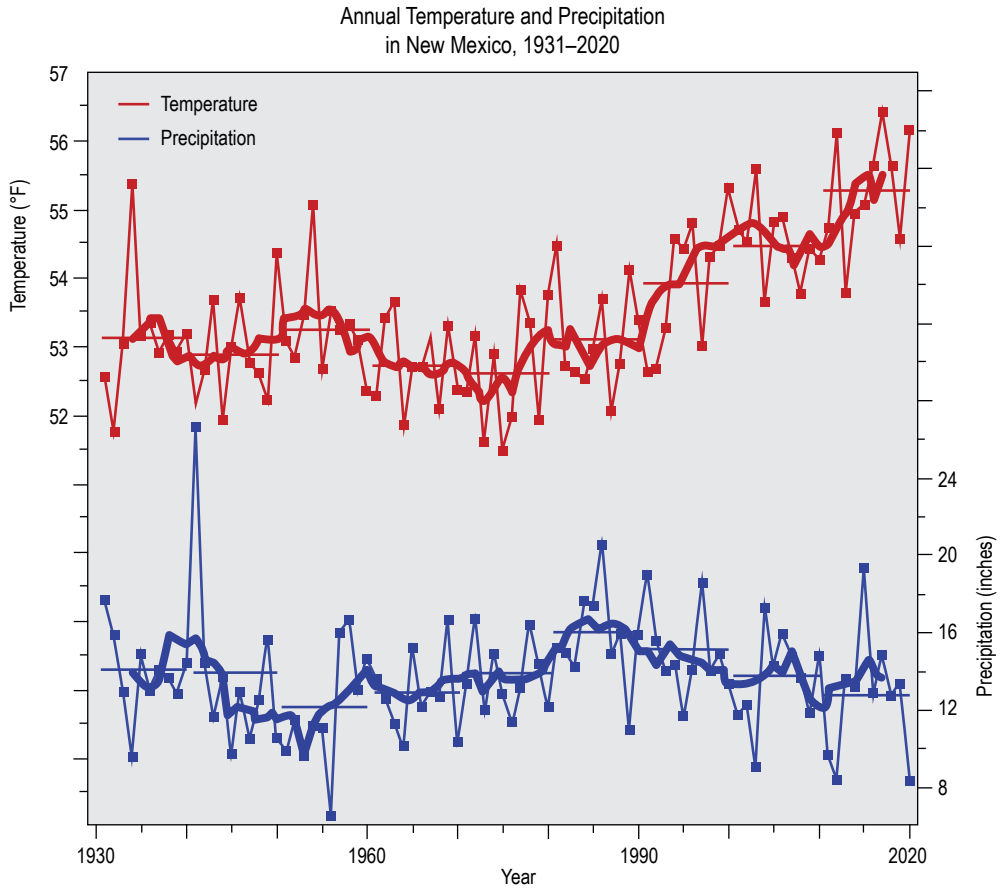


Figure 1.2. Observed annual temperature (red) and precipitation (blue) averaged over the state of New Mexico, 1931–2020. Horizontal lines depict 10-year decadal averages for each calendar decade. Updated from Chermak et al. (2015) and Gutzler (2020).

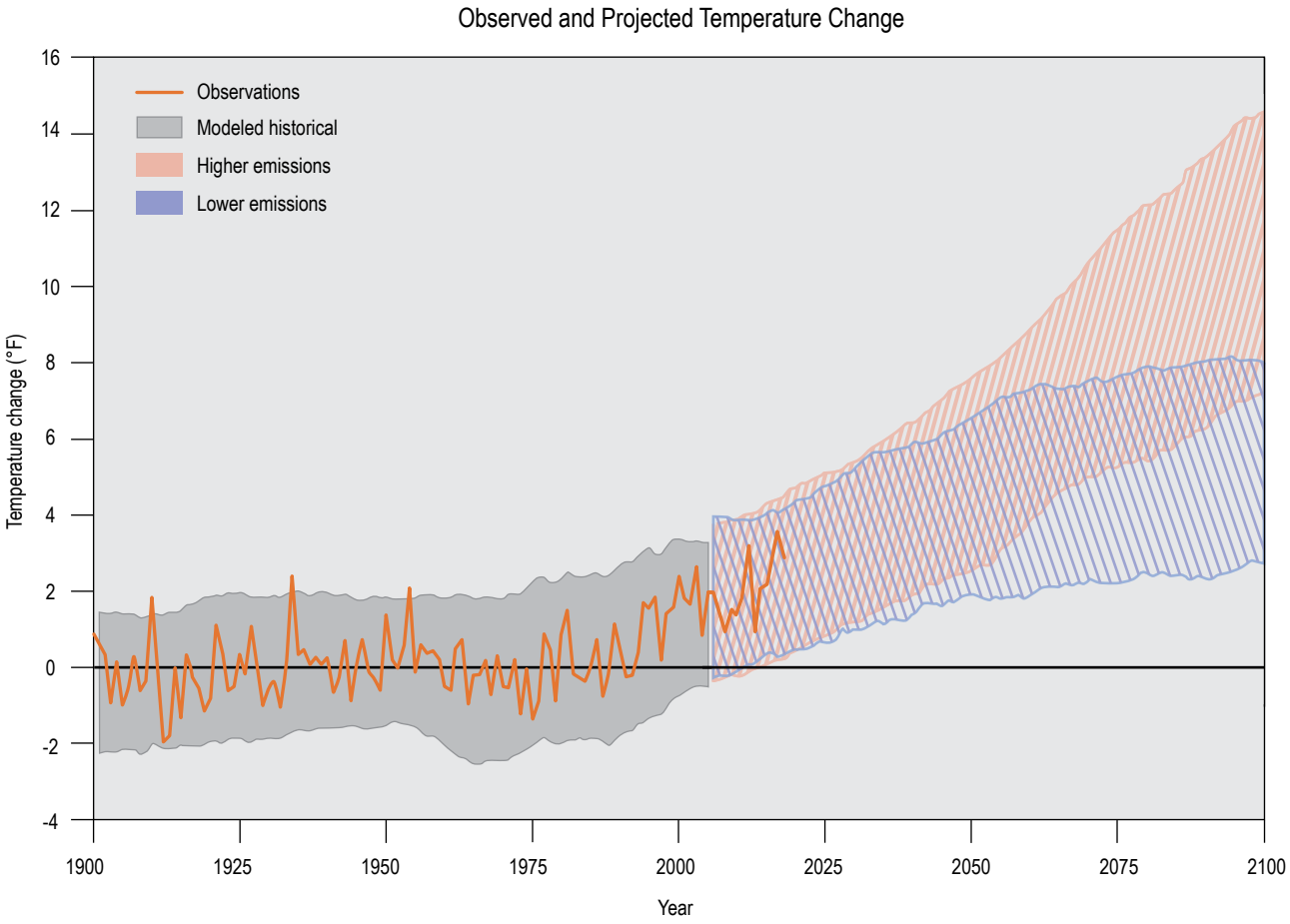


Figure 1.3. Observed and projected changes (compared to the 1901–1960 average) in near-surface air temperature for New Mexico (USGCRP, 2017). Observed data are for 1900–2018. Projected changes for 2006–2100 are from global climate model simulations of possible futures, one in which greenhouse gas emissions increase at an accelerated rate (higher emissions) and another in which greenhouse gas emissions increase at a rate similar to that observed today (lower emissions). Shading indicates the range of annual temperatures from a large set of CMIP5 global climate models. Observed temperatures are generally within the envelope of model simulations of the historical period (gray shading), serving to validate the model simulations. Historically unprecedented warming is projected during the twenty-first century, as discussed in more detail in Chapter 2.

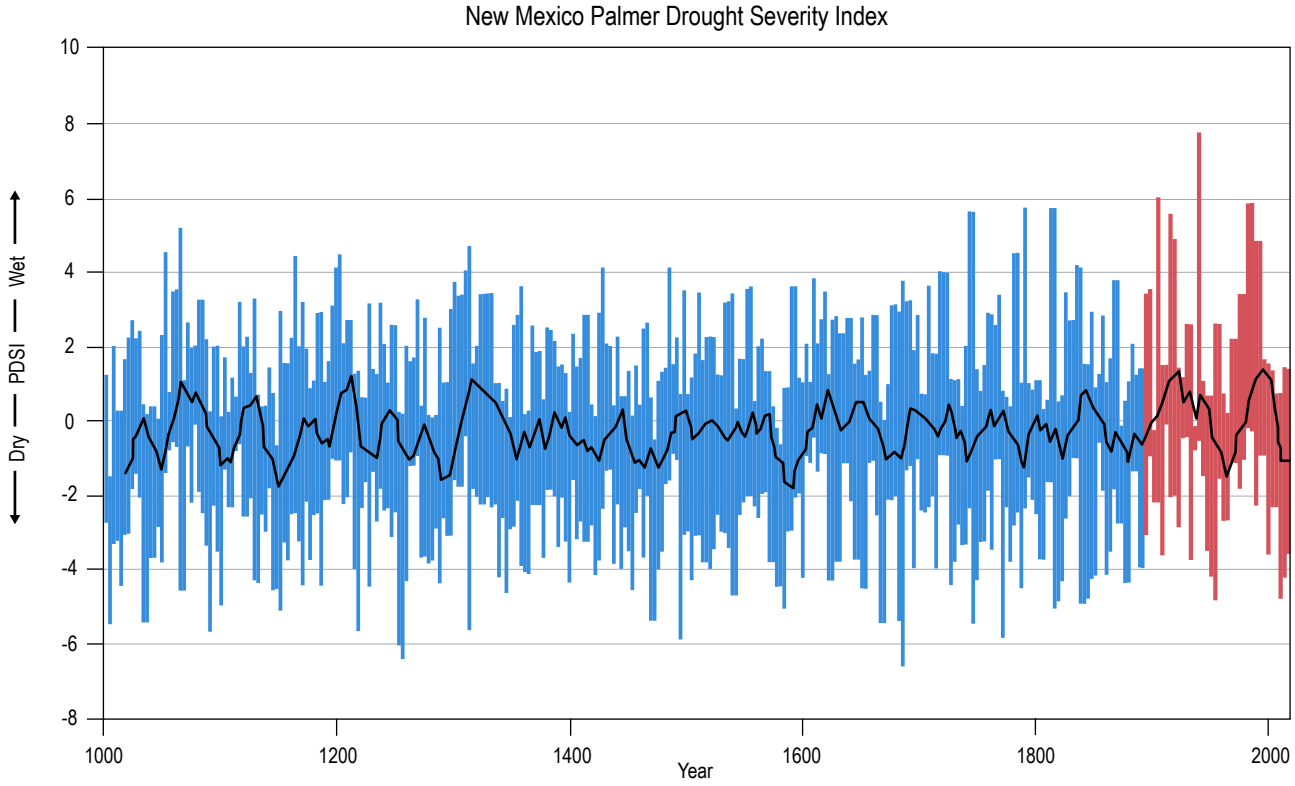


Figure 1.4. Time series of the Palmer Drought Severity Index (PDSI) from the year 1000 to 2018 (USGCRP, 2017). This index uses temperature and precipitation data to estimate relative dryness. Values for 1895–2018 (red) are based on measured temperature and precipitation. Values prior to 1895 (blue) are estimated from indirect measures such as tree rings. The thick black line is a running 20-year average. In the modern era, the wet (pluvial) periods of the early 1900s and the 1980s–1990s and the drought period of the 1950s are evident. The extended historical record (red) indicates episodic occurrences of similar extended pluvial and drought periods.

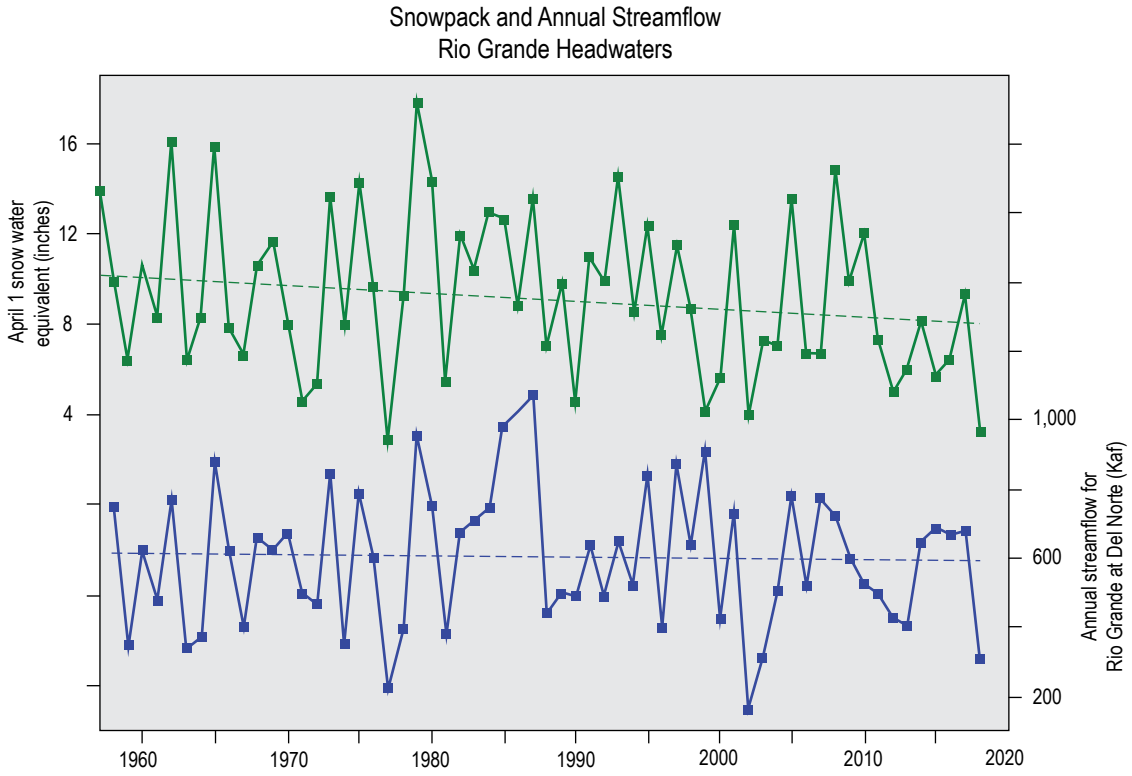


Figure 1.5. Observed April 1 snowpack (green) and annual streamflow (blue) in the Rio Grande headwaters. Kaf = thousand acre-feet. From Gutzler (2020).

Sandia Mountains; *photo by Matthew Zimmerer*

II. OUR CLIMATE FUTURE

David S. Gutzler and David DuBois

Global climate models driven by increasing greenhouse gases project an average temperature increase across the state of New Mexico of between 5° and 7°F over the next 50 years. This regional temperature increase follows the trend observed over the past half century, at a somewhat amplified rate, with the northwest corner of the state projected to experience a slightly higher rise during the same period. Although all models indicate significant increases in temperature, these models do not consistently project a significant change in average annual precipitation across the state, mirroring the absence of a clear trend in recent historical observations. However, some consistent differences in seasonality of precipitation emerge. During the winter, the northern mountains may receive somewhat more precipitation, whereas the southern parts of the state may be drier. Spring precipitation, critical for snowmelt runoff and ecosystems, may decline. Also in the southern part of the state, a trend toward somewhat stronger monsoonal activity may result in more summer precipitation, perhaps shifting toward somewhat later in the year.

The coupled trends of increasing temperature with no clear increasing trend in precipitation lead to a confident projection of increasingly arid conditions, including decreased soil moisture, stressed vegetation, and more severe droughts. Snowpack and associated runoff are projected to decline substantially by 2070, generating diminished headwater streamflow. Warmer temperatures will also cause lower river flows due to increased evaporation as rivers flow downstream. The impacts of climate change on New Mexico's resources are, unfortunately, overwhelmingly negative.

INTRODUCTION

As discussed in the previous chapter, New Mexico is characterized by a semiarid climate with enormous natural variability of precipitation and streamflow. Observations from the past half century show a clear and pronounced warming trend, together with exceptionally wet conditions in the late twentieth century, followed by decades of historic drought continuing to the present day. In this chapter we summarize projections of future climate for the next half century, out to 2070. Evidence derived from model projections suggests a high likelihood of continuing temperature increases coupled with pronounced precipitation variability. Projections of precipitation change are made with much lower confidence, with diminished precipitation in spring representing the most likely seasonal trend. Large interannual and decadal variability of precipitation should continue, and extremes in precipitation are projected to intensify regardless of any trend in the total annual precipitation. Effects of projected temperature and precipitation changes on surface-water supplies are most pronounced for temperature-related variables, including diminished snowpack and snow-fed streamflow (with continuing high interannual and

decadal variability), increased evaporation rates from open-water surfaces, diminished groundwater recharge, drier soils, increased frequency of wildfire-conducive weather, and a general trend toward more arid conditions. Episodic droughts, when they occur, will become much more severe as temperatures increase.

PREVIOUS ASSESSMENTS OF TWENTY-FIRST CENTURY CLIMATE PROJECTIONS FOR NEW MEXICO

New Mexico is projected to become hotter and more arid over the next 50 years as the result of human-caused climate change. This expectation results from multiple generations of global climate model projections made over the past 15 years (Watkins et al., 2006; Seager et al., 2007; Gutzler and Robbins, 2011; Llewellyn and Vaddey, 2013; U.S. Bureau of Reclamation, 2011, 2016, 2021b; USGCRP, 2014, 2018; IPCC 2014a, 2021). The validity of these projections has been reinforced by continuing observations of persistent hot, dry environmental conditions in the first 2 decades of the twenty-first century (Chapter 1). A strong, long-standing scientific consensus from these reports indicates that New Mexico should plan for a hotter, more arid climate, with a rate of change dependent on global policy to mitigate greenhouse gas emissions.

This section reviews the evidence derived from global climate model projections to support the more specific projections outlined in the sections that follow. As discussed in Chapter 1, New Mexico has a semiarid climate with diverse spatial variability and sharp gradients in temperature, precipitation, and vegetation in mountainous regions.

Several previous water resource assessments carried out for the state of New Mexico have highlighted the likelihood of more arid conditions in future decades as climate changes. Watkins et al. (2006) used tree-ring analyses and high-resolution climate models to highlight both past severe droughts and likely future trends toward warmer, drier conditions across the state. A decade later, a team of researchers from three New Mexico universities assessed risks to water security in the southern Rio Grande Valley in New Mexico, a region of intensive irrigated agriculture (Chermak et al., 2015). Each of these studies warned that projected decreases in water supply associated with a warmer, more arid regional climate pose substantial risks to the public welfare and the economy of the state.

The climate change findings in these statewide studies relied on and reached conclusions consistent with national climate assessments that also examined historical and projected future climate change across the Southwest (USGCRP, 2014, 2017, 2018). A consistent theme derived from all of these studies is the near-certainty of warmer temperatures and the high likelihood of drier overall conditions and deeper droughts for the state of New Mexico and all of the southwestern United States over the next 50 years.

In this chapter, we update the assessments cited above to provide climate projection information in support of the topical sections to follow. In the years since the Chermak et al. (2015) and 4th National Climate Assessment (USGCRP, 2017, 2018) reports, new products have been derived from global climate model projections by coupling projected climate change to surface hydrologic models to simulate regional changes in streamflow and soil moisture (variables that will also be discussed in following sections). In addition, new analyses of historical observations have confirmed that many of the hydrologic changes expected to accompany warming temperatures, such as declining snowpack, are already apparent in recent observations (Figure 1.5).

We first present global-climate-model-based projections for temperature and precipitation. For this bulletin we use output from the widely-used CMIP5 (Coupled Model Intercomparison Project, Phase 5) archive[1] used for international (IPCC, 2014a) and national (USGCRP, 2017) assessments. CMIP5 models simulate historical climate using observed, time-varying greenhouse gas concentrations and continue into the future using several future scenarios that differ by the assumed increase in greenhouse gas concentrations used to drive the model. The RCP 4.5

1. Output from the next generation of global climate simulations, CMIP6, is newly available for analysis and is the centerpiece of the recently released IPCC (AR6) assessment (IPCC, 2021). However, this chapter employs CMIP5-based results that have been thoroughly vetted, down-scaled, and used for hydrologic modeling over the past 8 years. Preliminary results from CMIP6 suggest that the newest generation of global climate models projects warming that may occur at a somewhat faster rate compared to CMIP5.

scenario is considered to be a mid-range assumption, and RCP 8.5 is a higher-emissions scenario that generally leads to higher temperatures and greater overall large-scale climate change. Each global climate model also simulates natural variability that influences regional climate associated with oceanic phenomena such as El Niño, fluctuations of the monsoon circulation, and other climatic processes.

Global climate models are run at a horizontal resolution of 50–100 miles (depending on the model), which is appropriate for large-scale climate but much too coarse to properly resolve individual thunderstorms, narrow mountain ranges, and other important features of local climate and topography. Here we use results from an ensemble of 20 CMIP5 simulations that have been downscaled and bias-corrected by the MACA (Multivariate Adaptive Constructed Analogs) project (Abatzoglou and Brown, 2012). In the MACA dataset, the global model output is downscaled to 1/24 degree (roughly 2.5 miles) using a statistical procedure based on historical observations and actual topographic features to introduce realistic high-resolution spatial variability to the coarse-resolution model output. We emphasize that these are "off-the-shelf" modeling results, not developed specifically for this bulletin. Detailed regional climate modeling customized to the needs of New Mexico water resources assessment is beyond the remit of our working group.

DOWNSCALED CMIP5 TEMPERATURE PROJECTIONS

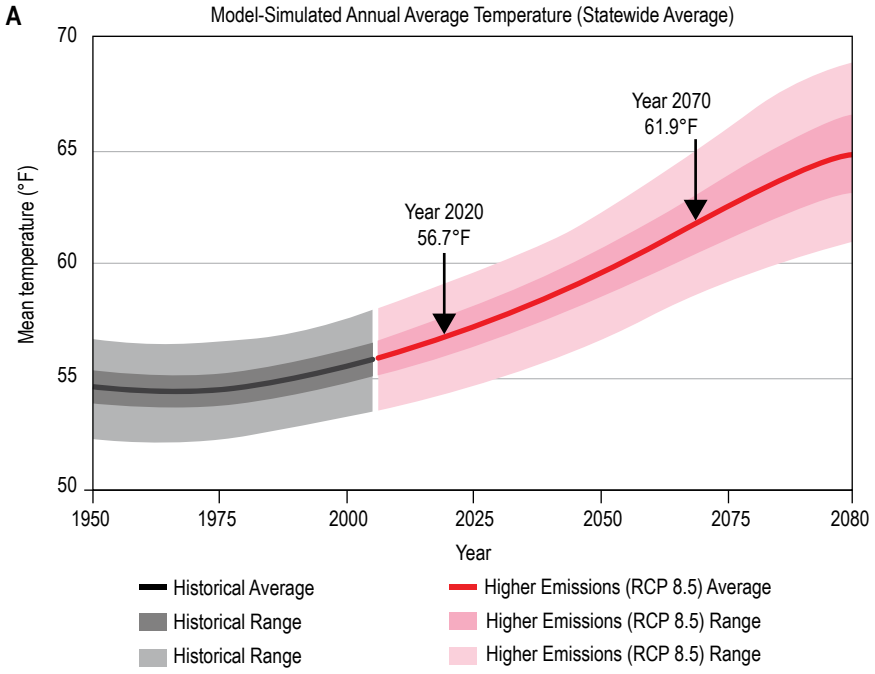
The MACA-downscaled simulations, spatially averaged statewide, consistently simulate significant increases in temperature in decades to come. Figure 2.1A shows annual temperature, averaged over 20 simulations driven by the high-emissions (RCP 8.5) scenario, from 1950 to 2070. The red portion of the time series indicates that the average increase in annual statewide temperature projected by these models is approximately 5°F by mid-century and 7°F from 2000 to 2070, with relatively modest model uncertainty represented by the dark pink shading about the average. These projections represent with high likelihood a staggering increase in temperature that would have profound consequences for life (and water resources) in New Mexico. This projected trend continues the observed warming trend from the past half century at a somewhat amplified rate. The corresponding set of projections generated by the lower emissions scenario (RCP 4.5) continues warming at about the same rate that has been observed over the past half century.

Temperatures are projected to rise all across New Mexico as shown in Figure 2.1B, with the largest increases in the northwestern part of the state. All of southwestern North America is expected to experience a significant increase in temperature during the twenty-first century, extending the observed warming trend at a rate depending on future atmospheric greenhouse gas concentration increases (USGCRP, 2017; IPCC, 2021).

DOWNSCALED CMIP5 PRECIPITATION PROJECTIONS

Unlike temperature, there is no clear trend in projected statewide total annual precipitation toward either wetter or drier conditions. The multi-model ensemble precipitation change for the high-emissions scenario (Figure 2.2) exhibits an insignificant (nearly flat) average trend, with an envelope of variability among the different models of nearly 50%. The map of ensemble-average precipitation change associated with Figure 2.3 (not shown) is nearly featureless across New Mexico. Furthermore, inspection of the 20 individual simulations included in the ensemble average (not shown) reveals that some simulations project increases in precipitation across the state, whereas other simulations project decreases. We conclude that, at least on an annual statewide basis, the suite of CMIP5 models included in the MACA archive do not exhibit a clear and significant trend in future precipitation—a continuation of the absence of a clear trend in recent historical observations (Figure 1.2).

Projected trends in precipitation stand out somewhat more clearly when separated by seasons. In winter (Figure 2.3A), frontal systems propagating eastward off the Pacific Ocean tend to track farther north on average, so the southern part of the state exhibits a tendency toward less precipitation while the northern mountains tend to receive somewhat more, averaged over all 20 simulations in the MACA model archive. The spring season (Figure 2.3B) exhibits a general statewide drying trend. For much of the state, spring is already the driest season of the



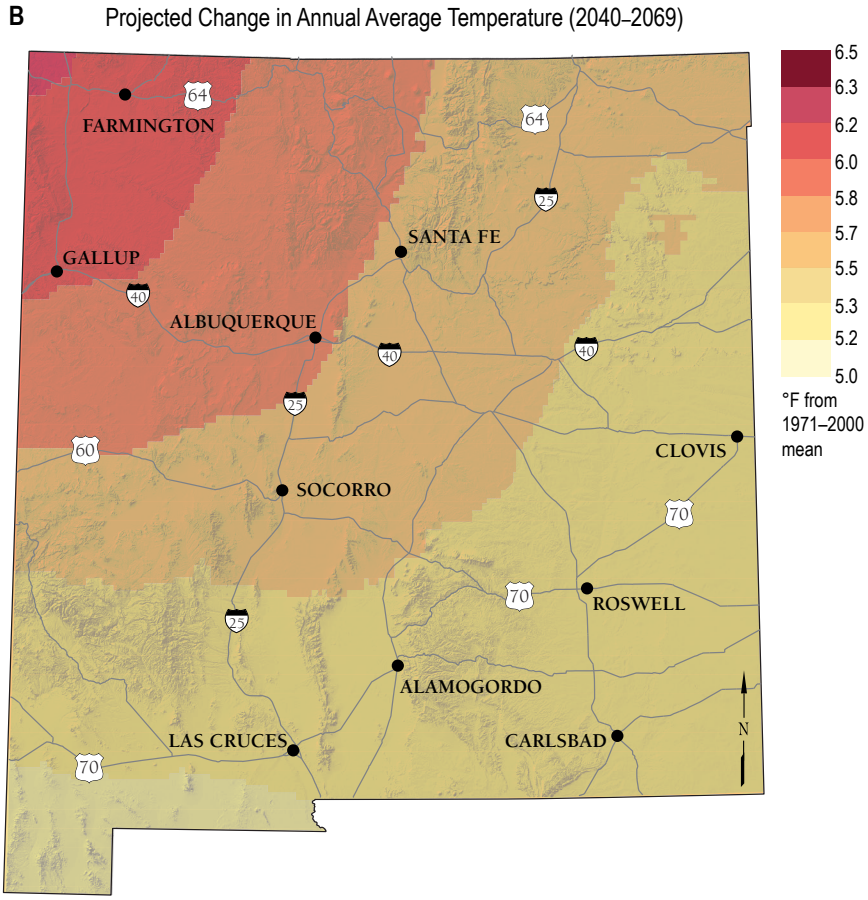


Figure 2.1. (A) Annual average temperature simulated by 20 CMIP5 climate simulations by different models, spatially averaged over the state of New Mexico. The black portion of the time series represents model output that has been bias-corrected so that the statistics of temperature match observations over the historical period, when models were forced by observed atmospheric greenhouse gas concentrations. The red portion of the curve represents future conditions, with the models all forced by the same high-emissions (RCP 8.5) greenhouse gas scenario. The thick central line is the 20-model average; the envelope of annual model variability is denoted by the gray and pink shading. The inner, darker gray and pink shading includes half of the simulations (the interquartile range). (B) Annual average temperature change simulated by the same ensemble of simulations used for Figure 2.1A. Temperature change is defined as the difference between two 30-year averages: 2040–2069 minus 1971–2000. The central years of these averaging periods are 70 years apart, so this plot represents 70-year temperature changes across the state.

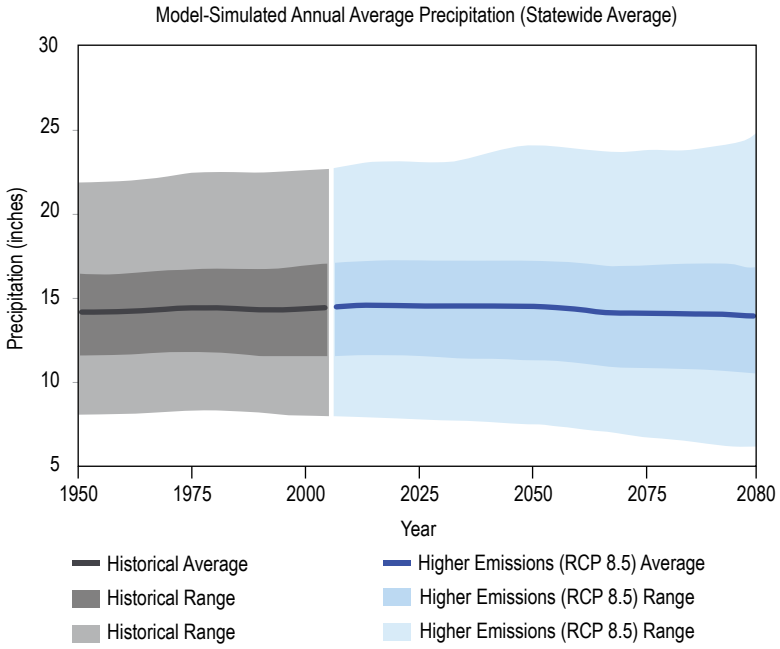


Figure 2.2. Annual average precipitation simulated by 20 CMIP5 global climate models, spatially averaged over the state of New Mexico, corresponding to the temperature time series in Figure 2.1A.

year, so the trend toward less spring precipitation (combined with hotter temperatures) represents a clear trend toward aridity.

Summer precipitation (Figure 2.3C) includes a modest trend toward stronger monsoon precipitation in the southwestern corner of the state, combined with a trend toward less precipitation in the northeast. The latter feature is part of a more general geographical trend toward drier summers in central North America. The trend in autumn precipitation averaged over 20 simulations is generally small, with some tendency for increasing precipitation in southwestern New Mexico, where the trend toward spring dryness and autumn wetness is associated with a projected tendency for the monsoon season to shift toward later dates, both in terms of its onset and its end (Cook and Seager, 2013).

However, the 70-year changes shown in Figure 2.2, averaged over 20 simulations, typically represent rather small average trends among different individual simulations, each of which includes large natural variability. With this in mind, we emphasize that the maps shown in Figures 2.1 and 2.3 suggest broad guidance regarding future climate change and should not be interpreted as providing specific local guidance (as would be indicated by a daily weather forecast map).

To illustrate how modest the projected trends are compared to interannual variability, Figure 2.4 shows precipitation time series derived from four different simulations, which were selected to show a wide range of projected changes. Figure 2.4A shows results for winter and summer precipitation for a single 1/24-degree grid cell in the Sangre de Cristo Mountains northeast of Taos at a surface elevation of approximately 10,000 ft (location denoted by the blue x in Figure 2.3A). Figure 2.4B depicts the same information for a grid cell southwest of Deming in the southwestern part of the state (denoted by a red x in Figure 2.3A).

For the Sangre de Cristo Mountains, the 20-model average in Figure 2.3 shows a modest upward change in winter and a downward change in summer. But these trends can be difficult to pick out in individual simulations (Figure 2.4B) within the "noise" associated with simulated natural variability.

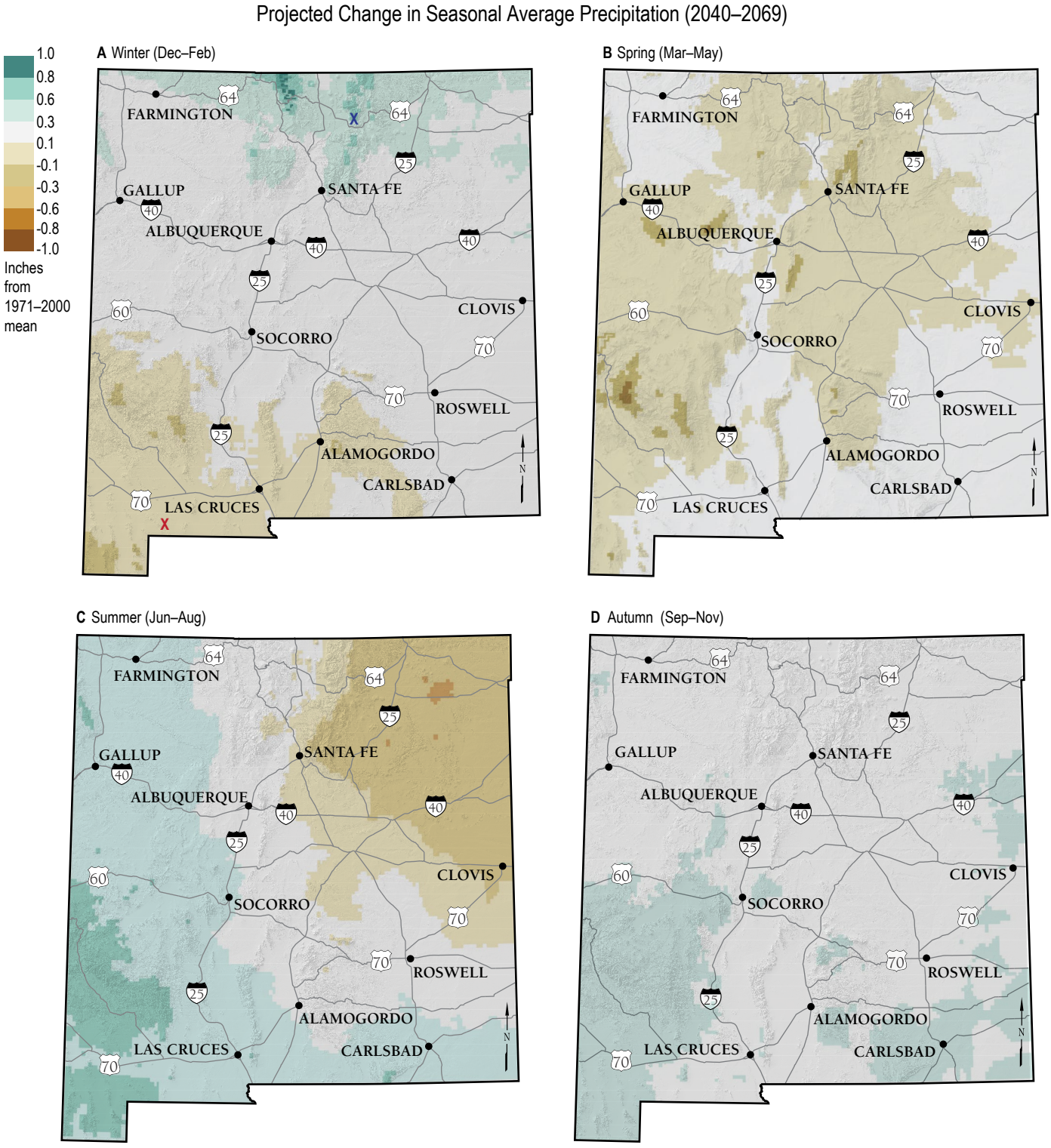


Figure 2.3. Seasonal average precipitation changes simulated by the same ensemble of climate simulations used for Figure 2.1 for (A) winter, (B) spring, (C) summer, and (D) autumn. As in Figure 2.1A, each map shows differences between two 30-year averaging periods 70 years apart: 2040–2069 minus 1971–2000. The color scheme is the same for each plot, with green colors indicating increasing precipitation and brown colors indicating decreasing precipitation. In panel (A), the blue and red x symbols denote the locations associated with time series shown in Figure 2.4.

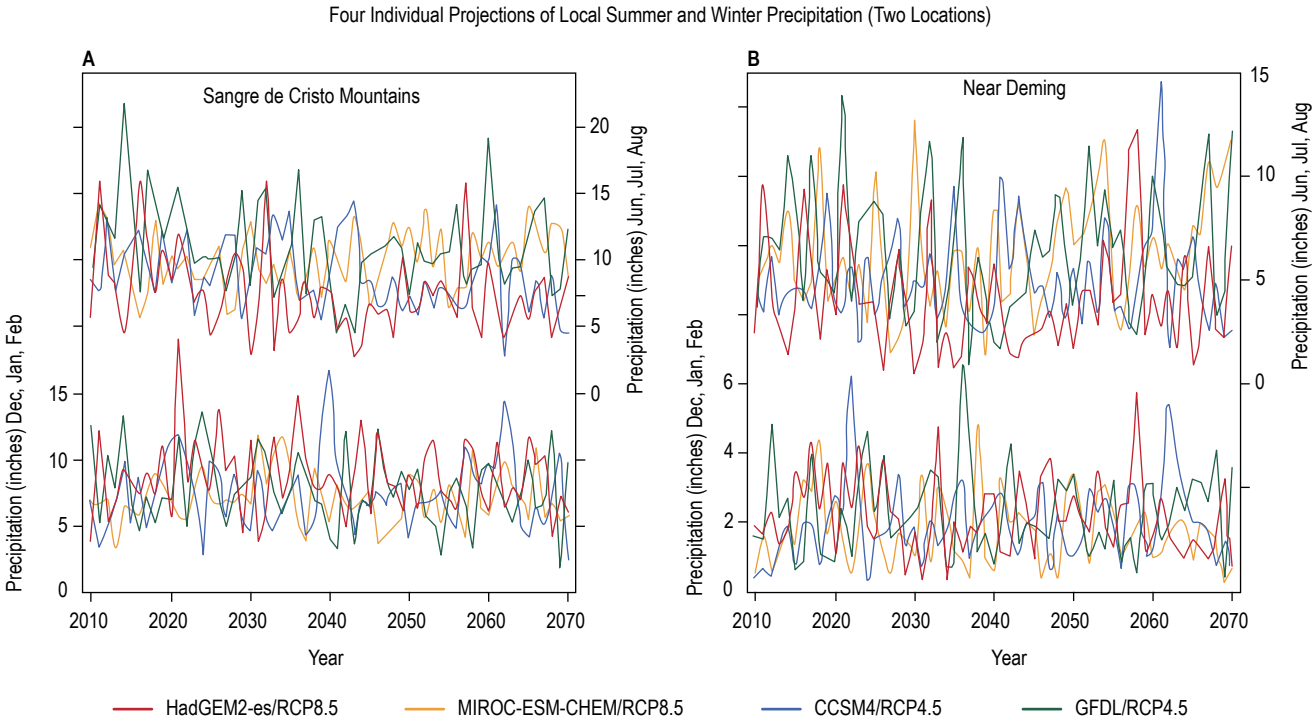


Figure 2.4. Time series of seasonal average precipitation changes from four global climate model simulations for two individual model grid-cell locations. (A) Grid cell located at 36.6N, 105.4W, in the Sangre de Cristo Mountains in north-central New Mexico (marked by a blue x in Figure 2.3A). (B) Grid cell located at 32N, 108W, near Deming in southwestern New Mexico (marked by a red x in Figure 2.3A). Each panel contains two sets of four curves. The upper set of curves in each panel shows annual values of summer (Jun–Aug) precipitation, and the lower set of curves shows annual values of winter (Dec–Feb) precipitation. Individual simulation results are color coded: red = HadGEM2-es/RCP8.5, orange = MIROC-ESM-CHEM/RCP8.5, blue = CCSM4/ RCP4.5, green = GFDL/RCP4.5.

Careful statistical analysis picks out these trends, however, leading to the smooth, large-scale features on the maps in Figure 2.3.

The same general character is true of the individual time series for the grid cell near Deming. In particular, the relatively weak overall increase in summer monsoon precipitation shown in Figure 2.3C, which represents a possible welcome respite from the general story of increasing aridity across most of the state, is seen to be a small average trend among disparate, highly variable projected time series (upper set of curves in Figure 2.4B).

Extreme precipitation values derived from CMIP5 model projections show a significant tendency for heavier extreme daily precipitation (Figure 2.5, adapted from the most recent National Climate Assessment [USGCRP, 2017]). As discussed in more detail in Chapter 9, trends in extreme precipitation are difficult to estimate from observations and challenging to simulate in global climate models. Nevertheless, there are strong physics-based reasons to expect that the risk of extreme precipitation should increase in a warming climate. The assessment of projected trends in 1-day extreme precipitation amounts shown in Figure 2.5, averaged over large regions of the United States to improve statistical significance, indicates that CMIP5 simulations project such an increase nationwide.

PROJECTIONS OF OTHER HYDROLOGIC VARIABLES

The chapters that follow in this bulletin consider many climate-related variables that affect water resources in the state. In this subsection, we present a brief introductory overview of several of these variables, focusing on those that can be simulated directly from the same global climate model simulations that have been used in this chapter to assess temperature and precipitation changes.

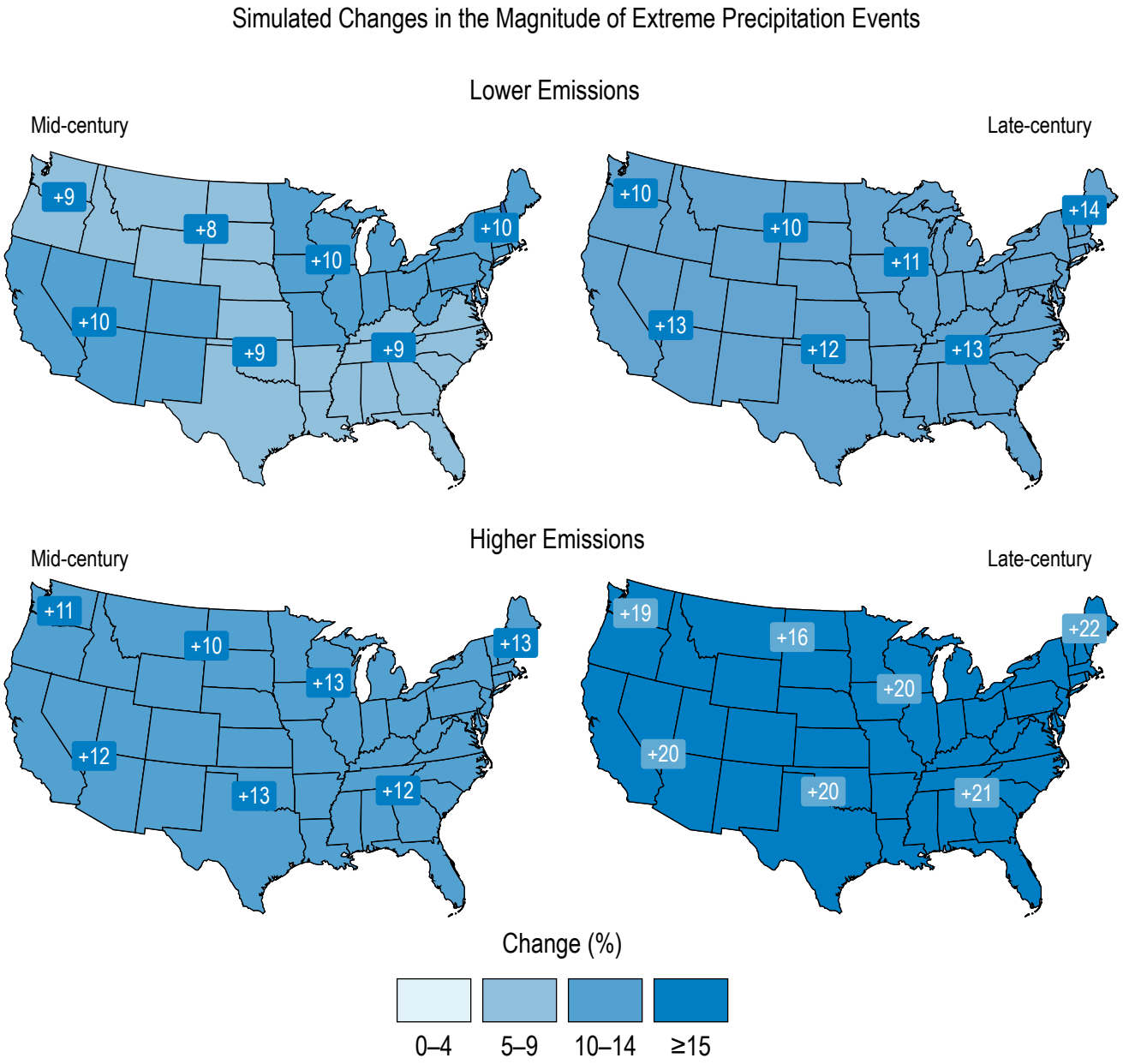


Figure 2.5. Projected change from a historical baseline period (1901–2005) in the magnitude of extreme precipitation events, here defined as the 1-day precipitation maximum expected once every 20 years, derived from statistically downscaled CMIP5 global climate model simulations (using an average of CMIP5 models but a different statistical downscaling technique than the MACA post-processing used for Figures 2.1–2.4; USGCRP, 2017, Figure 7.7). Results from a lower emissions scenario (RCP 4.5) are on the top; higher scenario results (RCP 8.5) are on the bottom. The left-side maps show changes as a percentage of present-day 20-year return values expected by mid-century; late-twenty-first-century changes are shown on the right. All changes projected nationwide are positive, indicative of higher 20-year return values of maximum daily precipitation.

Evapotranspiration and Soil Moisture—As temperature rises, the capacity of the near-surface atmosphere to accommodate water vapor increases strongly. Hence moist surfaces and open water tend to generate higher evaporative surface-water losses in a warmer climate. This tendency can be quantified by the potential evapotranspiration (PET), which is a measure of how much water would evaporate over a large area covered with uniform vegetation if there were unlimited water available at the surface. PET can be interpreted as the demand for water by surface vegetation. It is also a function of the humidity and air pressure of the overlying atmosphere so it is not just a measure of temperature. The estimate of changes in PET driven by the temperature and precipitation changes already discussed suggests that the average annual value of PET will be 3 to 9 in. higher by mid-century, relative to its late-twentieth-century value (Figure 2.6A).

The projected increases in PET are associated with projected declines in soil moisture. The increase in PET depletes the moisture available to withdraw from the surface, leading to drier soils. Based on nearly the same set of high-emissions simulations used for the temperature and precipitation projections shown here, the U.S. National Climate Assessment (USGCRP, 2017) projected significant declines in soil moisture centered on New Mexico (Figure 2.6B), especially in the winter and spring seasons. The pattern of spring soil moisture decline is very similar to the spatial pattern of temperature increase in Figure 2.1B, with greatest changes in the northwestern quadrant of the state. Chapter 3 of this bulletin assesses soil moisture changes in New Mexico in more detail, and subsequent chapters on ecosystem changes highlight the importance of the projected decrease in soil moisture across the state.

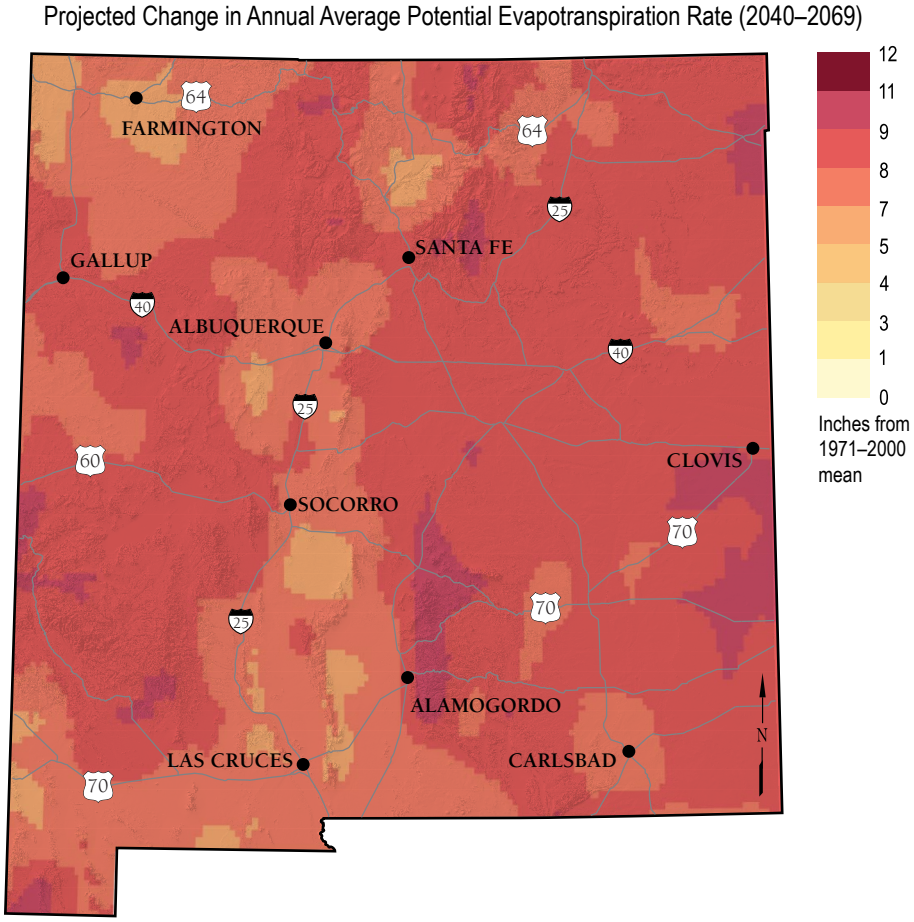
Evaporation of surface water from reservoirs is increasing as temperatures rise, similar to PET but without any limiting factors associated with dry soils and sparse vegetation. Open-water evaporation increases with temperature more strongly than evaporation from surrounding land surfaces. The U.S. Bureau of Reclamation (henceforth Reclamation; 2015) projected that evaporation from Elephant Butte Reservoir will increase at a rate of about 8 in. per year for every degree (Celsius) increase in annual average daily maximum temperature (Tmax). Therefore, if Tmax increases by 5°F (approximately 3°C), this estimate would imply an additional 2 ft of annual evaporative loss. This would constitute a 30% increase in evaporative water loss over the present-day rate, and the lake would then evaporate more than one-third of its average annual inflow. Such an increase in evaporation would provide a strong incentive to minimize storage (hence reservoir surface area) at Elephant Butte to prevent additional evaporative loss.

The trend toward aridity illustrated in Figure 2.6 has crucially important implications for assessing episodic droughts in the warmer climate of the twenty-first century. Drought, by definition, is an anomalously dry period. Droughts are often associated with lack of precipitation or streamflow (less water reaching the surface) but are also affected by evapotranspiration (more water leaving the surface). Tree-ring studies across southwestern North America have shown that profound droughts lasting multiple decades have occurred once or twice per century for at least 1,000 years (as discussed by Gutzler, 2004; Watkins et al., 2006; and many others; see Figure 1.4). In terms of precipitation, the current multi-year drought in New Mexico fits into this picture of recurring precipitation deficits, but increases in temperature have increased the severity of this drought (Weiss et al., 2009).

In the nearer-term past, observations by Navajo elders also provide a picture of increasing aridity in the twentieth century (Redsteer et al., 2018). Small increases in temperature and changes in precipitation type (rain versus snow) can have large impacts on the arid to semiarid environments of the Navajo Nation (Redsteer et al., 2018). These authors suggest that climate change and resulting water scarcity may result in younger generations of Navajo people moving away from reservation lands.

Water shortages associated with past severe droughts have caused large-scale landscape change, vegetation mortality, and social disruption, as discussed in more detail in subsequent chapters of this bulletin. The trend toward aridity will tremendously amplify the impacts of future droughts by changing the underlying longer-term climatic conditions upon which temporary drought conditions are superimposed. Various measures of drought, such as the Palmer Drought Severity Index shown

A



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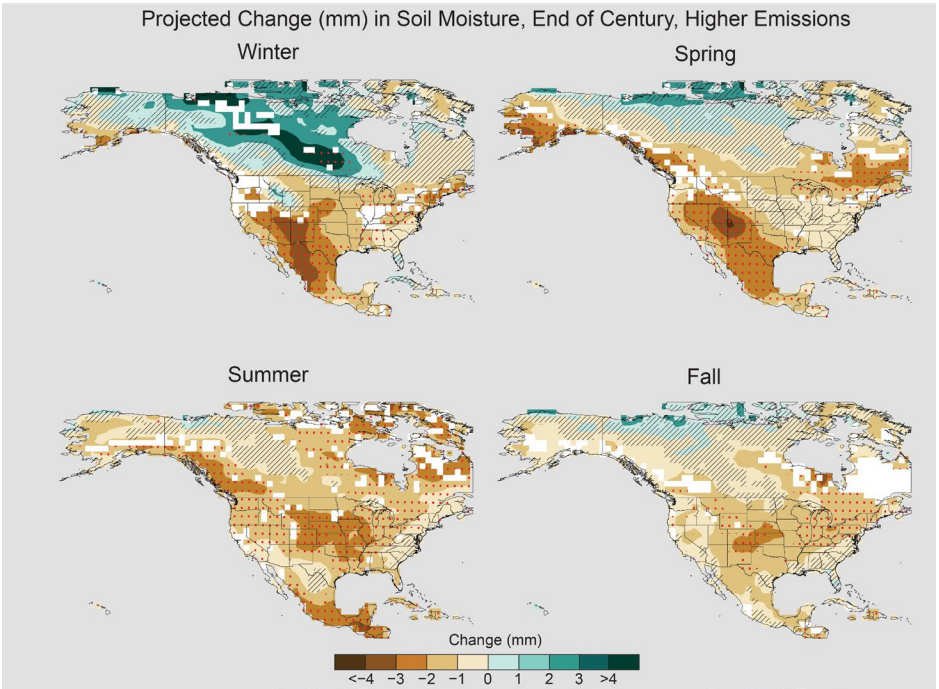

Figure 2.6. (A) Projected change in annual rate of potential evapotranspiration (inches from 1971–2000 mean), derived from the same projections used for Figures 2.1B and 2.3. (B) Projected changes in seasonal soil moisture by the end of the twenty-first century across North America, adapted from USGCRP (2017).

in Figure 1.4, are projected within the next few decades to reach, and then surpass, levels of dryness associated with the worst Southwestern droughts in the historical record (Gutzler and Robbins, 2011; Williams et al., 2013).

Snow and Snowmelt Runoff—Snowpack at high elevations is projected to decline very substantially by 2070 across the southwestern United States (USGCRP, 2017; Mote et al., 2018), continuing a long-term decrease in snowpack that has been observed (including in the Rio Grande headwaters by Chavarria and Gutzler [2018]) over the past half century. The projected decrease in snowpack occurs as the result of warmer temperature, despite possible increases in total winter precipitation (Figure 2.2), as shown in Figure 2.7 for the Rio Grande headwaters, as an example.

Surface-water supplies from major rivers are projected to decrease over the next half century, based on global climate model projections coupled to surface hydrologic models. Reclamation (2011, 2014a, 2021b) has generated streamflow simulations from downscaled global climate model projections using successive generations of CMIP simulations. Gutzler (2013) used an early generation of these simulations (CMIP3) to estimate future near-term trends in flow in the upper Gila River. Snowmelt runoff in the Gila headwaters was projected to decline by about 8% averaged over the 30-year period centered in 2035, a trend that would be expected to continue farther into the future.

More recently, Bjarke (2019) assessed newer CMIP5-based snowmelt runoff in the Rio Grande headwaters in southern Colorado, using Reclamation's (2014a) projections which, in turn, used many of the same simulations assessed in the MACA archive and shown earlier in this section (the Reclamation projections were downscaled and bias-corrected using a different statistical method). A sample of these projections (Figure 2.7) illustrates how snowpack and snowmelt runoff are projected to evolve. The four colored lines represent downscaled projections derived from the same four global climate model simulations used to illustrate precipitation change near Deming and in the Sangre de Cristo Mountains in Figure 2.4. In Figure 2.7, temperature and precipitation (panel A) and April 1 snowpack (panel B) are averaged over downscaled grid cells corresponding to the headwaters of the Rio Grande. Streamflow during the snowmelt runoff season is shown (panel B) for a simulated point on the mainstem of the Rio Grande corresponding to the Del Norte gage in southern Colorado. Eleven-year running averages have been implemented to emphasize variability on the scale of a decade or more.

As before, temperature projections for all four simulations (the lower set of curves in Figure 2.7A) indicate warming, with simulations driven by the higher-emissions scenario (red and orange lines) warming the most. Precipitation projections (upper set of curves in Figure 2.7A) generally show slight decreases, especially in the higher-emissions scenarios, but not all projections show such a decrease, as would be expected given the average increase in winter precipitation seen in southern Colorado in Figure 2.3A. Snowpack on April 1 (lower set of curves in Figure 2.7B), near the historical average peak snow date in the Rio Grande headwaters, shows a clear decrease in three of the four simulations. Snowpack declines more than precipitation in general due to the increase in temperature that is consistent across the simulations.

Finally, streamflow in the snowmelt runoff season (upper set of curves in Figure 2.7B), which results from both melting snowpack and late spring precipitation, exhibits substantial decadal variability (as do observed flows in the historical record) and a wide range of projected long-term trends. The red and green curves show substantial long-term declines consistent with both decreasing snowpack and diminished precipitation. Streamflow projected by the blue and orange curves, in which snowpack declines but total precipitation does not, exhibits smaller long-term change.

Reclamation (2014a) and Bjarke (2019) showed that the overall average of nearly 100 simulations is a very slight decrease in Rio Grande headwaters streamflow volume but with a huge range in the twenty-first century projections. Peak snowmelt runoff occurs earlier in nearly all simulations.

Can we narrow the range of uncertainty in projected runoff by selecting the simulations in which we should have the most confidence? Assessing similar projections for the Upper Colorado River basin, Udall and Overpeck (2017) estimated that

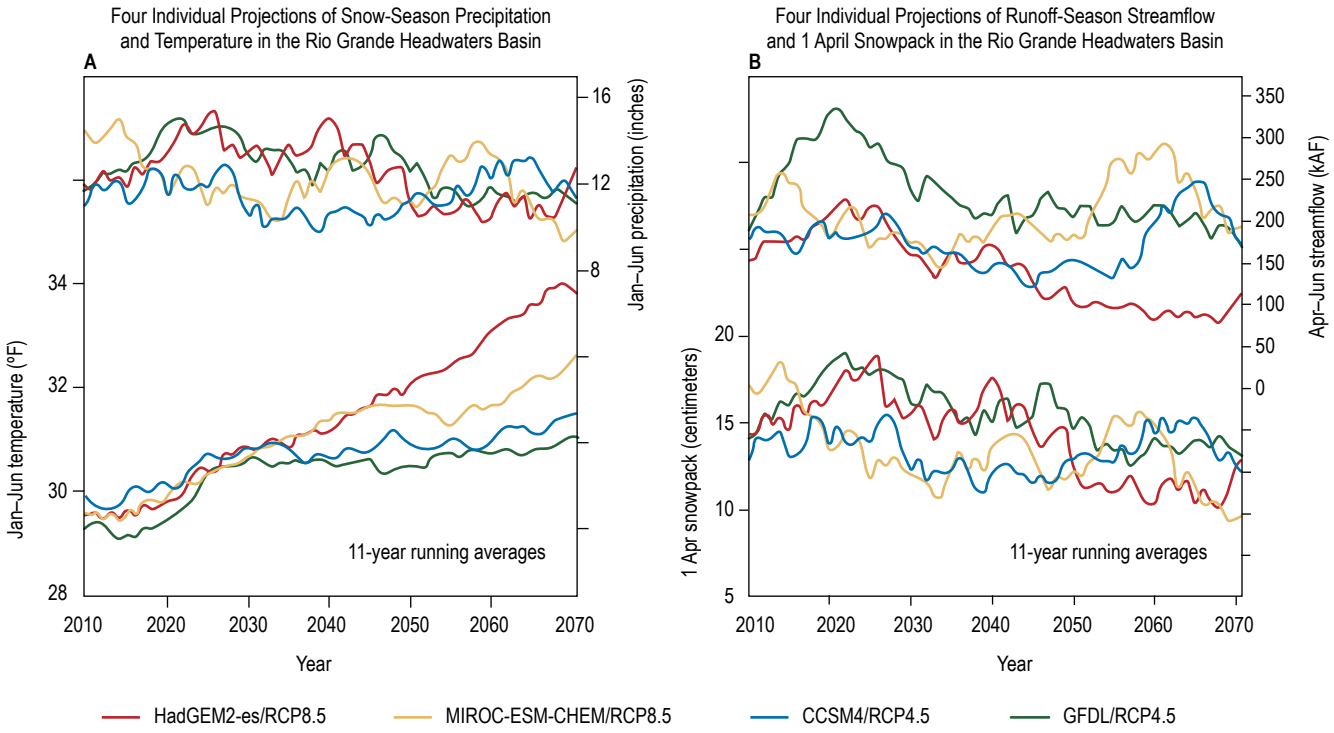

Figure 2.7. (A) Projected January–June temperature (bottom set of curves) and precipitation (top set of curves) in the Rio Grande headwaters basin in southern Colorado, derived from the same four downscaled projections used for Figure 2.4 with the same color coding. (B) Projected April 1 snowpack (bottom set of curves) and April–June streamflow in thousand-acre-feet (KAF) at a point on the river corresponding to the Del Norte stream gage (top set of curves) and corresponding to the precipitation and temperature projections shown in (A). An 11-year running average centered on each year has been applied to all time series to emphasize variability on decadal and longer time scales.

the temperature effect on diminished snowpack was likely to be so large, and projected with so much more confidence than precipitation change, that policymakers should place more weight on projections of declining snowmelt runoff regardless of precipitation uncertainties. Bjarke (2019) also argued that sharply diminished streamflow was more likely, because the Reclamation simulations that project increasing runoff uniformly failed to simulate the decline in snowpack and the changes in snowpack–runoff relationships observed during the half century of the simulations that reproduced the late twentieth-century historical period. Chavarria and Gutzler (2018) and Bjarke (2019) highlighted spring precipitation as an increasingly important component of headwaters flow as snowpack diminishes, so the relatively confident projection of decreasing spring precipitation (Figure 2.3B) portends diminished river flow as temperature increases and snowpack declines. Musselman et al. (2021) made a similar point, showing that earlier snowmelt (driven by warming temperature) correlates with diminished snowmelt runoff.

In summary, recent research suggests that the projection of just a small decrease in headwaters streamflow, derived from averaging together a large ensemble of widely varying CMIP5 simulations with different precipitation projections, may represent an overly optimistic vision of future Rio Grande flow. And notwithstanding the uncertainty in headwaters flow, increased PET in a warmer climate makes projections of lower river flows downstream much more likely because flows will diminish as the river flows south (Townsend and Gutzler, 2020).

KEY GAPS AND RESEARCH NEEDS

The projections assessed in this chapter are mostly derived from global climate models run globally, so the well-documented general limitations of current models apply to the region-specific results

emphasized here. The simulation of clouds and cloud-related processes represent the single biggest uncertainty in global climate modeling. Uncertainties in cloud simulation lead directly to the precipitation uncertainties discussed below. But, in addition, the effect of clouds in modulating temperature (so-called cloud feedbacks) is also a key uncertainty in model projections. Although surface temperature changes are simulated and projected with much more confidence than precipitation changes, uncertainties associated with clouds have been shown to represent the primary reason that models differ with regard to how much global warming to expect in future decades as greenhouse gas concentrations continue to increase.

Projecting precipitation across the Southwest remains a key uncertainty in model projections. New Mexico is located on the southern periphery of the winter storm track—the average band of latitude where winter frontal systems move eastward from the Pacific Ocean across the North American continent. The winter storm track is projected to shift northward as global temperatures rise, leading to the pattern of projected winter precipitation change shown in Figure 2.3 (decreasing precipitation to the south, increasing precipitation to the north). However, the average shift of the winter storm track varies from one model simulation to another, leading to uncertainty in how much (or even whether) we can expect winter precipitation to decline across New Mexico.

With regard to winter precipitation, we note that the results assessed in this chapter are derived from CMIP5 global models, which were generated about a decade ago. During the time that this bulletin was generated in early 2021, the next generation of global models (CMIP6) was assessed by the IPCC as part of its 6th Assessment report. CMIP6 models are somewhat more consistent than CMIP5 models were in projecting diminished winter precipitation across southwest North America, including New Mexico (Gutiérrez et al., 2021). More detailed assessment of CMIP6 results will be helpful to address the question of reduced winter precipitation in New Mexico and the headwaters of the San Juan River and Rio Grande in southern Colorado.

In summer, precipitation across central and western New Mexico is supplied by the North American monsoon circulation. Global climate models, with their coarse spatial resolution (using model grid cells typically about 50 miles on a side) have difficulty resolving the mountainous topography and small-scale thunderstorm clouds that are integral to the monsoon. Hence model projections of the future monsoon circulation have been variable and uncertain across generations of models, with different models projecting quite different future conditions and little consensus over even the sign of projected precipitation change. Uncertainties regarding summer monsoon projections remain in the current (CMIP6) generation of global climate models.

The uncertainties in projecting summer precipitation extend to understanding extreme precipitation values (which typically occur in summer) as well as projecting average or total precipitation. Chapter 9 of this bulletin assesses extreme precipitation in more detail, including key research needs and gaps.

Additional snowpack and snowmelt runoff research will be critical for improving estimates of future flows in major snow-fed rivers across New Mexico. Our state features several of the southernmost snow-dominated rivers in North America. Rivers such as the Gila, Pecos, and Rio Grande are among the most sensitive rivers in the world to the effects of diminishing snowpack as winter and spring temperatures increase. Current research efforts are aimed at quantifying the total water content of snowpack in high-elevation mountains and improving our understanding of the processes that determine how much snow water on hillslopes reaches valley bottoms to become river flow, as well as how these processes will change as temperatures increase and the overall quantity and seasonal duration of snow diminishes.

Each of the uncertainties described above could to some extent be addressed in projects that refine the results of global models by customized application of higher-resolution regional models. Such New Mexico-specific modeling efforts were not possible for this bulletin given our time and budget constraints. However, it is certainly possible to formulate projects that address specific New Mexico hydrologic projections using existing modeling and expertise.

El Vado reservoir, Rio Arriba County; *photo by Matthew Zimmerer*

III. LAND-SURFACE WATER BUDGET

Fred M. Phillips and Bruce M. Thomson

All water that we use in New Mexico originates as rain or snow falling onto the landscape, which either goes to groundwater or surface water or returns to the atmosphere. Of the precipitation that falls on the state, 1.6% runs off into streams and rivers, and 1.8% infiltrates into the ground, recharging subsurface aquifers. Much larger proportions are transpired by plants (78.9%) or evaporated (17.7%). The impact of climate change on all of these pathways will affect our state's water budget. Notably, because of the larger percentages of water lost to evaporation or transpiration, even very small changes in these factors will result in large changes to runoff and recharge. As mentioned in Chapter 2, the climate will continue to warm over the next 50 years without a likely increase in precipitation, leading to greater statewide aridity. Hydrological modeling indicates declines in both runoff and recharge going forward, amounting to 3% to 5% per decade for both quantities. Historical trends in runoff indicate significant year-to-year variability, as do trends in soil moisture and recharge. But all are generally decreasing, consistent with the results of climate models that project a drying climate. Combining the historical trends with modeling of future changes, significant decreases in runoff and recharge seem very likely.

INTRODUCTION

Over the coming 50 years, the climate of New Mexico will almost certainly become warmer and likely drier than at any previous time in human history (see Chapter 2). How will this change affect the availability of water for human needs? To answer this question, we must recognize that ultimately all water that we use originates as rain or snow falling over the landscape. This precipitation on the landscape is divided (partitioned) to end up in different flows: some as streams or rivers that are easily accessed by people for various uses, some as groundwater that supports flow in streams and springs and can be pumped directly, and some that returns to the atmosphere as water vapor. In order to understand how human-caused climate change will affect the availability of water, we have to understand how this partitioning works, which is a way of stating that we have to understand the water budget.

THE LAND-SURFACE WATER BUDGET IN A SEMIARID CLIMATE

The hydrological budget consists of flows of water (in all phases: gas, liquid, solid) through different parts of the environment, such as through streams or within aquifers. It is the division of the water into these different flows that determines how much is available for human or ecosystem use. At the center of this division is the land surface, which is principally the surface of the soil but is actually best thought of as extending down from the tops of the highest vegetation to the base of the root zone (Figure 3.1). The input of water comes from the atmosphere as either rain or snow. This water may wet the leaves of a plant, never reaching the ground, or may reach the ground and either soak into the soil or else run off from the surface into a stream or arroyo. The water that wets the leaves returns to the atmosphere by evaporation and does not enter

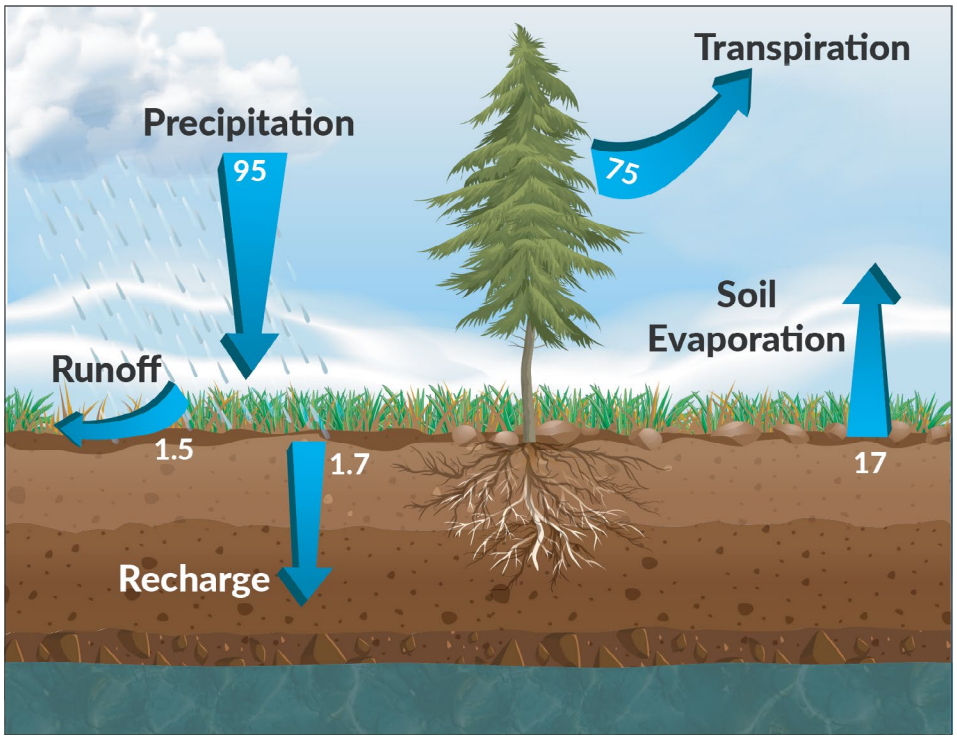

Figure 3.1. Average water budget of New Mexico, based on analysis of Peterson et al. (2019). Values are in millions of acre-feet per year. Evapotranspiration has been separated into evaporation and transpiration based on the analysis of Jasechko et al. (2013).

the local hydrological system. The water that soaks in becomes part of the soil-moisture reservoir. Over time, the soil moisture may do one of three things: (1) be evaporated from the soil surface; (2) be absorbed by roots, move upward as plant sap, and be vaporized back into the atmosphere through stomata on the plant leaves (transpiration); or (3) trickle downward through the soil until it escapes past the base of the root zone and becomes groundwater recharge. It is usually difficult to distinguish between water lost to the atmosphere through evaporation and that lost by transpiration; hence the combination of evaporation and transpiration is often referred to as evapotranspiration.

The division of the hydrological flows depends more than anything else on the aridity of the locality, which is commonly quantified by the aridity index. The aridity index is defined as the ratio of average potential evapotranspiration to average precipitation, over an entire year. Potential evapotranspiration is the amount of water, per unit area, that could be lost to the atmosphere over a large area covered with dense, uniform vegetation if there is unlimited water available at the surface. As Figure 3.2 illustrates, over the large majority of New Mexico, the aridity index varies from a high of about 8 to a low of about 0.5, meaning that the atmosphere could potentially evaporate up to eight times as much water as the soil actually has to offer (Seager et al., 2018). The relatively cool and moist tops of the highest mountains in the state may have aridity indexes as low as 0.5 (i.e., two times as much precipitation falls as can be evapotranspired). These areas of low aridity index are a very small fraction of the area of the state, but they generate a large majority of the runoff and recharge.

Under a climate as arid as New Mexico's, two flows strongly dominate the water budget: precipitation and evapotranspiration (in other words, actual evapotranspiration, not the amount that could potentially evapotranspire given an unlimited water supply). Precipitation onto the land

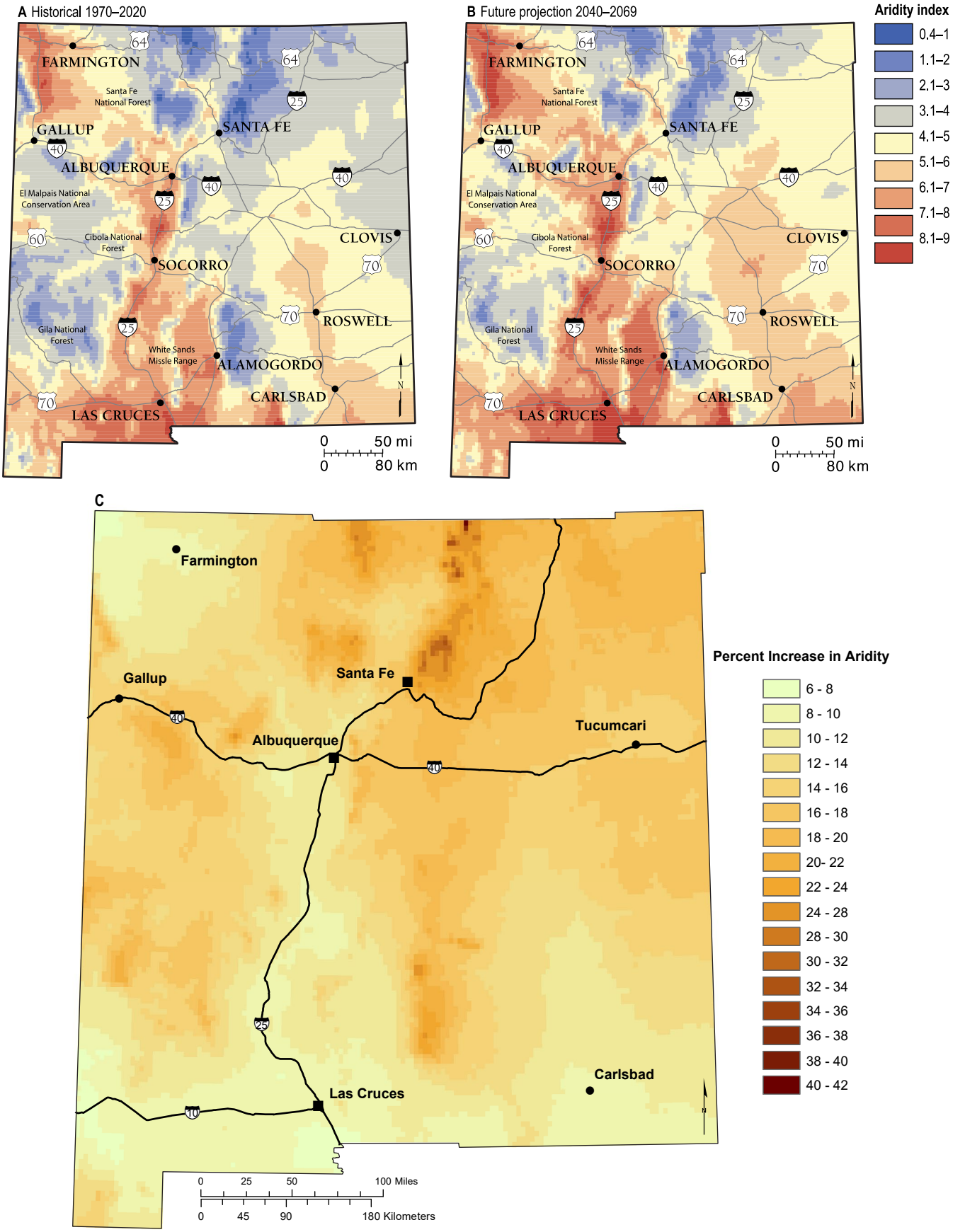

Figure 3.2. Aridity index over New Mexico. (A) Average aridity index from 1970–2000 data. (B) Average aridity index from 2040–2069 projections, generated from 20-model ensemble RCP 8.5. (C) Percent increase between 2040–2069 and 1970–2000 aridity indexes. Aridity index is defined as the ratio of average potential evapotranspiration to average precipitation.

surface of New Mexico amounts to about 95 million acre-ft/yr (Figure 3.1). Of this, about 91.8 million acre-ft/yr, or 96.6%, returns to the atmosphere as evapotranspiration (Peterson et al., 2019). The remaining 3.4% (3.2 million acre-ft) is about equally divided between runoff and recharge. When considering the effects of climate change on the water budget, this carries two implications. The first is that evapotranspiration is highly predictable. Even if precipitation changes, evapotranspiration will nearly always equal, but be slightly less than, precipitation over most of the state. This is because water evaporates and transpires readily when the climate is so arid. The second is that the terms in which we are most interested for water resources—runoff (supplying streamflow) and recharge (supplying groundwater)—will be very sensitive to even small changes in the relative magnitudes of precipitation and evapotranspiration. For example, if a climate change such as lower temperature and increased precipitation caused 1.7% less precipitation to be evapotranspired and become runoff instead, the total state runoff would double! Small changes in the land-surface water budget can thus have a major impact on human society.

The utility to humans of the different divisions of the hydrological cycle differ greatly. Water that evaporates from leaves and soil, comprising about 20% of the precipitation that falls on the land surface in the Southwest (Jasechko et al., 2013), provides few direct benefits to humans. The main one is a cooling effect—a significant part of the reason that the monsoon season in New Mexico is cooler than the earlier part of the summer. The water that is transpired through plant leaves (currently about 79% of precipitation) is essential for plant growth because it carries nutrients to the leaves and is necessary for photosynthesis. Rain falling on agricultural fields, along with irrigation water, is necessary for crop production. On natural lands, the transpiration component of the water budget supports all plant life and, based on the plants, animal life. Benefits to humanity are obvious, ranging from grass for livestock grazing to the aesthetic appreciation of a beautiful vegetated landscape. The tiny fraction that runs off from the soil (1.6%) or recharges groundwater (1.8%) yields the largest relative benefit to society. Essentially all water that we use for human consumption, industry, and irrigation comes from these two components. The main purpose of this chapter is to explore how future climate change will affect the partitioning of precipitation into these two flows.

EFFECTS OF CLIMATE CHANGE ON THE LAND-SURFACE WATER BUDGET

Global climate change, as projected in previous chapters, will reduce both runoff and groundwater recharge in New Mexico. Change in precipitation cannot be projected with confidence, but most models project that it will decrease rather than increase across most of New Mexico (see Chapter 2), while variation from year to year will remain high. Temperature, however, will certainly continue to rise. As temperature increases, the ability of the air to hold water vapor also increases (in other words, for a constant mass of water vapor in the air, the relative humidity goes down as the temperature goes up). This will cause liquid water to be lost more rapidly from leaves and soil and thus dry out the landscape, even if precipitation does not decline. Dry soil "sucks in" precipitation faster than wet soil, causing less runoff. Recharge cannot occur until the whole thickness of the upper soil layer is quite wet, and if the soil becomes drier, recharge will happen less frequently.

Phenomena related to the timing and frequency of precipitation events complicate the simple scenario presented above. First, seasonality of precipitation plays a strong role. In warm, semiarid climates, recharge is much more likely if most of the precipitation falls in the winter when temperature is cold and plants are not active so evapotranspirative demand is low (Small, 2005). But in lowland settings where winter snow does not persist, runoff may be favored by a shift toward intense summer convective storms that dump precipitation so rapidly that the water flows away before it has a chance to sink into the soil. Second, groundwater recharge and runoff are favored by relatively large precipitation events that are clumped together in time, and they are reduced when precipitation falls in a large number of small events that are evenly spaced in time (Small, 2005). We refer to this as the clumping effect. When precipitation events are small and evenly spaced, they tend to be absorbed by the soil and largely evapotranspired back to the atmosphere. The soil dries out. It rarely becomes wet enough to produce

recharge. When rain does fall, it tends to be absorbed by the dry soil rather than run off. In contrast, when precipitation falls in fewer events and they are clumped together, by the end of those stormy periods the soil becomes wet and later storms are likely to produce both runoff and recharge.

The implication of these findings is that more information beyond projections of evapotranspirative demand and precipitation is needed to estimate future trends in runoff and recharge. Changes in the seasonality of precipitation, the frequency and clumpiness of precipitation events, and the size of storms are also important. The forcing exerted by all of these factors on the land-surface water budget must then be used to drive hydrological models that realistically incorporate snowmelt, runoff, infiltration, soil-water storage, and interaction with plant roots that draw out the soil water to be transpired. The uncertainties associated with quantifying and modeling all these processes make the task of projecting runoff and recharge a difficult one.

Dynamical models of the atmosphere and ocean that are used to assess future climate (such as the projections of temperature and precipitation described in Chapter 2) do not simulate in any detail the surface-water processes described above. Global climate models are designed to simulate atmospheric weather on very large spatial scales, for which the fine details of recharge and runoff at the surface—which are so important for local water resources—are just a secondary influence. In order to assess changes in local and regional water resources that result from large-scale climate change, a different class of surface hydrologic models must be developed and implemented. Such models include more detailed hydrologic processes (as conceptualized in Figure 3.1) at much finer horizontal resolution, using downscaled output from a global climate model as the driver for hydrologic simulations (see the first part of Chapter 2 for a more complete discussion of this topic). These are the types of models that are required for state water-resource planning at the 50-year time scale.

We divide the models that are commonly used for detailed, local water-budget projections into three categories, in order of increasing complexity: mass-balance accounting models, one-dimensional surface-process models, and three-dimensional hydrologic systems models. Detailed information on the characteristics of these types of models is unnecessary for the typical reader of this bulletin, but we have included an appendix (Appendix A) containing such a description for the use of state water-planning specialists, who will ultimately have to choose the most suitable type of model for their planning objectives.

INFORMATION AVAILABLE FOR PROJECTING CHANGES IN RUNOFF AND RECHARGE

We have two principal methods for projecting changes in the land-surface water balance over the next 50 years. The first is implementing the various numerical models discussed in Appendix A, which require input (principally temperature and precipitation) from downscaled global climate model simulations. The advantage of these is that many of them can give detailed projections of changes over the varied landscapes of New Mexico. One disadvantage is that they depend on global climate model simulations of future conditions, which can vary widely due to different scenarios of change in greenhouse gases and different model structures. The alternative is attempting to discern trends from recent records of hydrological responses (for example, runoff from stream gages or water levels in wells) over the past 50 years. These cannot supply detailed spatial projections, but, if reliable trends can be detected, they have the advantage of being grounded in actual observed climate-hydrology variations. If a certain amount of global warming has produced some specific change in the water balance (for example, less runoff), then it does not seem likely that additional warming will reverse that trend. More speculatively, the rate of change can be extrapolated into the future to estimate future hydrological flows and water resources.

Figure 3.2 shows the projected change in the aridity index over New Mexico for the RCP 8.5 scenario. The aridity index increases everywhere, which means that precipitation will increasingly partition into more evaporation and transpiration and less into runoff and recharge. The percent increase in aridity index is largest in the most humid areas of the state, particularly the mountain ranges, some of which will experience a 40% increase in aridity. The northeast plains also show a large increase. Since the

humid areas are the ones that produce most of the state's runoff and recharge, this pattern implies a large reduction in water supply.

Modeled Changes in Runoff—Numerous studies have attempted to simulate changes in streamflow in the southwestern United States. Of these, the most important for our purposes is the Reclamation report "West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment" (Llewellyn and Vaddey, 2013). This study employed the VIC model (described in Appendix A), driven by downscaled and bias-corrected global climate model scenarios as discussed in Chapter 2, to simulate water supply and demand on the Rio Grande through 2100. The median precipitation projection from the global climate models decreased by about 10% between the mid-twentieth century and 2100, but projected Rio Grande discharge at the Colorado border decreased by 30% over the same period (Figure 3.3 [Llewellyn and Vaddey, 2013, Figure 31C]). This difference is largely due to an increasing proportion of precipitation and snowpack being partitioned into evapotranspiration as the watershed warms. Results for tributaries to the Rio Grande in New Mexico were virtually the same as for the Colorado portion. The study did not attempt to simulate changes in groundwater recharge throughout the drainage basin, but did indicate that groundwater levels along the Rio Grande Valley would decrease due to reduced input from the river and associated flood irrigation.

Other studies have arrived at similar conclusions. Udall and Overpeck (2017) also used VIC combined with the Reclamation global climate model projection datasets to estimate median reductions in Colorado River discharge of 25% to 35% by century's end (Figure 3.4, indicated by the green probability density curves). Although the Upper Colorado River impinges on only a small portion of New Mexico (the San Juan River drainage), it directly adjoins the headwaters of the Rio Grande in Colorado, and projections

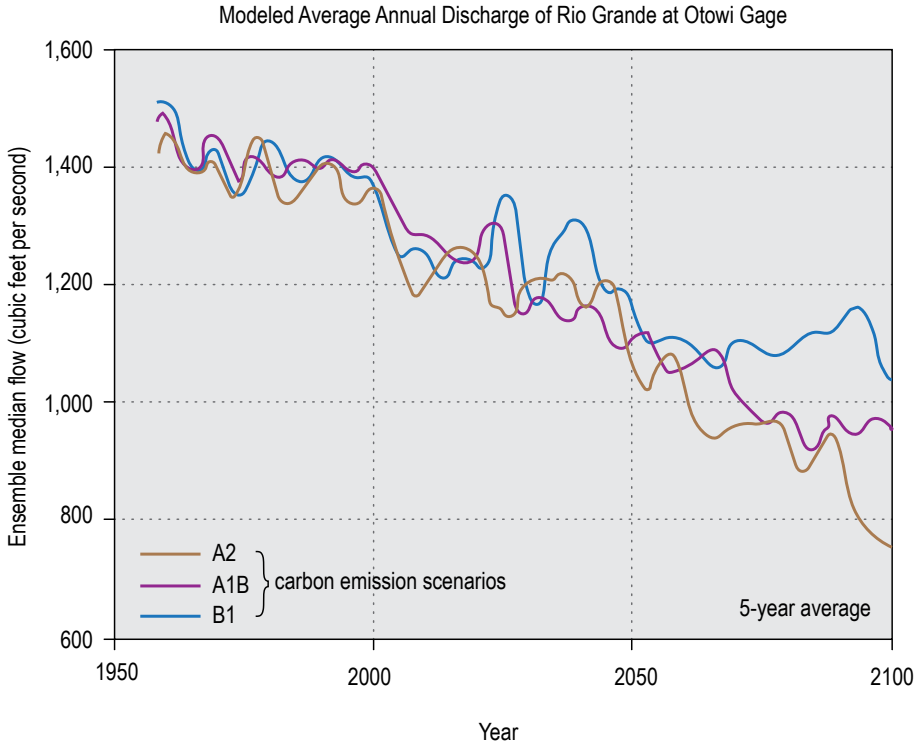

Figure 3.3. Modeled 5-year average discharge of the Rio Grande at the Otowi gage in cubic feet per second from 1950 to 2100 (Llewellyn and Vaddey, 2013). A2 represents high, A1B represents moderate, and B1 represents low carbon-emission scenarios.

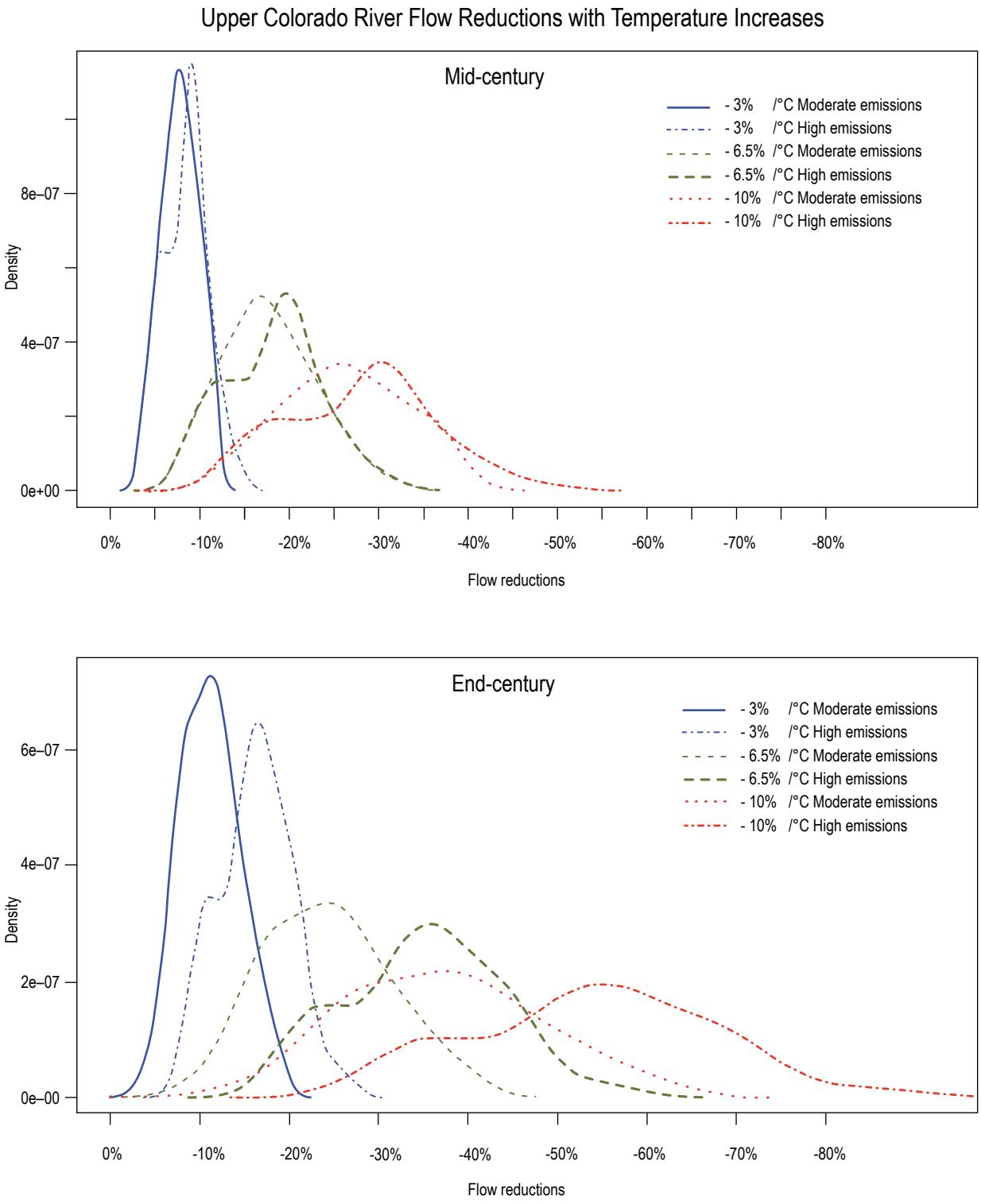

Figure 3.4. Probability density function (unitless) for flow in the Upper Colorado River as a function of greenhouse gas emissions and the sensitivity of runoff to temperature, from Udall and Overpeck (2017). The percentages in the legend are percent reduction in runoff per degree Celsius of warming and range from a reasonable lower limit to a reasonable upper limit, with the most likely value (-6.5% per degree) in the middle. The moderate emissions scenario corresponds to SRES A1B/RCP4.5 and the high emissions scenario to SRES A2/RCP8.5.

for it thus provide useful information for assessing changes in the Rio Grande. Garfin et al. (2013) used a similar methodology to arrive at similar reductions of discharge but over a much wider area of the Southwest. Jiménez-Cisneros et al. (2014) presented a global synthesis of the projections from 16 global models (5 General Circulation Models and 11 Global Hydrological Models) that indicates widespread reductions in streamflow (10% to 30%) over the Southwest. Elias et al. (2015), on the other hand, used a highly specialized snowmelt model (Snowmelt Runoff Model) to project changes in the discharge of the Rio Grande. They attempted to bracket the entire range of possible future climates, in some cases using projections of future precipitation as high as 40% above that of the twentieth century. These yielded limiting maximum estimates of runoff as much as 25% greater than historical, but for more reasonable precipitation changes (12% to 23% reductions in precipitation), runoff decreased by 0% to 24% in most of the basins comprising the Upper Rio Grande. Projected reductions of flow in the Upper Colorado River basin are attributed to increased evaporation of snowpack (Milly and Dunne, 2020).

***Modeled Changes in Recharge*—**Fewer studies have attempted to project changes in recharge than changes in runoff. Most studies that do so calibrate their models against historical records of base flow (flow during periods when there is little or no precipitation) in rivers and streams. This is not appropriate for much of New Mexico because there are no perennial streams over much of the state. Models must then be calibrated against long-term, water-level records from wells, which is much more difficult.

The difficulties of projecting recharge in arid and semiarid environments are illustrated by the global study of Döll (2009), which used the WaterGap Global Hydrology Model to project recharge increases in the Southwest of approximately 100% by the 2050s for most of the global climate model climate projections. As discussed in Appendix A, this model was not constructed with arid climates in mind. The authors had to perform arbitrary modifications of the input data to achieve even remotely reasonable recharge values; thus the confidence in this projection is low.

Meixner et al. (2016) compiled the results of four previous studies for Southwestern aquifers that used the WAVES model. They also heuristically estimated recharge changes for four other aquifers. Their best estimate of the future changes was a decrease of 10% to 20% in recharge, but with a quite wide range of uncertainty. One of the studies included, by Crosbie et al. (2013), was in the High Plains of eastern New Mexico. Crosbie et al. (2013) projected a median decrease in recharge on the High Plains of 12% by 2050, but the changes ranged from -50% to +24% depending on the amount of precipitation predicted by the global climate model climate models.

The Meixner et al. (2016) study was extended by Niraula et al. (2017), who performed quantitative recharge projections over the entire U.S. West using standard global climate model climate projections linked to the VIC model. For the Southwest, the average recharge change from 10 global climate model scenarios through 2050 was a decrease of 4.0% ± 6.7%. For New Mexico, the model averages showed small decreases in recharge over most of the state but small increases in some of the northern mountains. This large uncertainty in the projected recharge change results from the underlying variability in the global climate model simulations. The magnitude of the recharge change is also surprisingly small and may reflect inherent limitations in the VIC hydrological model used (see below).

Condon et al. (2020) employed a relatively detailed and realistic hydrological systems model, ParFlow-CLM, to examine the effect of increased atmospheric demand on groundwater resources over a substantial portion of the United States. They did not consider the effects of withdrawals from wells. Although they did not explicitly present their simulations in terms of changes in the recharge rate, they did present modeled changes in the water-table elevation by the end of the present century. In New Mexico, water-table depth under natural conditions is most closely tied to recharge. The eastern parts of the state showed negligible changes in water-table depth, but most of the state showed declines ranging from 0.5 m to 2 m, depending on location and the severity of the warming scenario. These changes in the water table are of similar magnitude to other climate-sensitive areas of the United States. Most importantly, they are consistent with a significant reduction of recharge in all scenarios, rather than the increase in recharge indicated by a minority of studies.

***Modeled Changes in Runoff and Recharge*—**Very few New Mexico-specific studies have investigated future changes in both runoff and recharge from the same model. One of these is Bennett et al. (2020), which applied the INFIL model to the Pajarito Plateau (the location of Los Alamos National Laboratory) in north-central New Mexico to project climate-driven changes between 2040 and 2069 and the historical data. The INFIL model is similar to the PyRANA model described in Appendix A. As with other studies described above, this study used a range of global climate model simulations, from small temperature increase to large and from drier to wetter conditions (precipitation), to drive the hydrological model. The change in runoff varied from –11 to +21 mm/yr and recharge from –9 to +6 mm/yr. In general, both modeled runoff and recharge had a tendency to increase at higher elevation and to decrease at lower elevation. The researchers concluded, "Our major findings indicate that the amount of available water for processes such as infiltration and runoff is sensitive to changes in the seasonal distribution of precipitation that may not be reflected in the aridity index. We also find that the delivery in terms of the form and rate of precipitation is as important, if not more important, than the overall amount of precipitation…" As discussed in the introduction to this chapter, although a significant increase in the aridity index over the next 50 years is strongly indicated, secondary changes such as small increases in precipitation amount, seasonality, and clumpiness can strongly influence runoff and infiltration in ways different than the aridity index changes alone would suggest. This study confirms that inference.

***Analyses of Historical Runoff Trends*—**Most of the modeling studies cited above have attempted to bracket possible changes in hydrological flows by using the full range from the global climate model outputs in terms of temperature and precipitation. Others have used medians of many outputs bracketed by standard deviations or other statistical measures of variability. As noted, either method tends to produce projections of runoff or recharge with very large uncertainties (often larger than the projected change). One approach to additionally constraining projections is to examine historical data.

The influence of anthropogenic global warming caused global temperatures to begin to rise above natural background fluctuations in the 1970s (Chapter 2). However, it is only in the past 20 years that the signal has become unequivocal. Nearly all hydrologists now accept the principle that the hydrological system no longer fluctuates around a stable mean value and that many parts of the system are now varying around a mean that is veering in one direction or the other (Milly et al., 2008). If the effects of warming on processes such as runoff and recharge are large, they might produce observable anomalies over this period. By analyzing data collected over the past 50 or 20 years, we can hope to find trends that might support better selection of global climate model outputs to drive hydrological models. This is important because unnecessarily wide bounds on hydrological projections render the projections less valuable for planning purposes.

As discussed in Chapter 2, the mean annual temperature of New Mexico is very clearly increasing at a relatively linear rate of about 0.7°F per decade. This has resulted in an increase of about 2.7°F since the 1980s. Any changes in precipitation are much more difficult to detect (Figure 1.1). According to the USGCRP (2017) and Garfin et al. (2013), annual precipitation has increased slightly (0% to 5%) over most of New Mexico when comparing averages from 1986 to 2015 with those from 1901 to 1960. However, it has decreased by about the same amount in the area of the Rio Grande headwaters in Colorado; recall that precipitation across New Mexico was particularly high in the 1980s and 1990s. Most of the increase has been in the fall, but spring precipitation, important for snowpack and runoff, has decreased markedly statewide. In contrast, Slater and Villarini (2016) detected a signal of decreasing precipitation over New Mexico. Udall and Overpeck (2017) found a slight decrease in annual precipitation over the Upper Colorado River basin since the 1980s, although the trend was small in comparison to the year-to-year fluctuations. In general, any long-term changes in precipitation are small enough that over the interval of detectable global warming they are difficult to separate from normal fluctuations.

Reanalysis of weather data from 1979 to 2014 has indicated a fairly strong trend of decreasing atmospheric relative humidity of about 1.5% per decade over New Mexico (Douville and Plazzotta, 2017). This can plausibly be posited to drive increased evapotranspiration, shifting the land-surface water

balance away from runoff and recharge. However, Yang et al. (2018) have cautioned that runoff is much more sensitive to changes in precipitation than to changes in atmospheric water demand and that many localities with apparent increases in the aridity index are in fact experiencing increases in runoff. Given this warning, it is prudent to examine the scanty evaluations of trends of runoff that are available for our area.

At the large scale of the entire western United States, Gudmundsson et al. (2021) indicated that runoff has decreased between 1971 and 2010 at about 4% per decade. They compared this finding with runoff simulated by models that include global warming forcing and by ones that exclude its effects. Those including the observed global warming forcing predict a decrease in runoff, albeit smaller than the actual, whereas those that exclude it indicate an increase in runoff. This allows the runoff decline to be clearly attributed to global warming. At the scale of the Upper Colorado River basin, Xiao et al. (2018) found that the discharge of the Colorado River at Lees Ferry decreased by 17% between 1920 and 2014, or about 1.4% per decade, which they principally attributed to warming. At the headwaters of the Rio Grande, Chavarria and Gutzler (2018) did not find a significant decline in annual discharge, which they attributed to recent small increases in precipitation during the snowmelt season, but they did detect a significant decline in spring snowpack that they project will drive reductions in Rio Grande flow in the near future as temperature continues to increase. In contrast, annual discharge of the Rio Grande at Otowi, south of the Colorado border, has decreased by almost 20% per decade since 1985. However, this dramatic reduction is clearly strongly influenced by variations in snowfall that are driven by sea-surface temperature patterns that fluctuate over decades (Pascolini-Campbell et al., 2017). Since 1997, within a relatively stable ocean-temperature regime, the flow at Otowi has decreased by 4% per decade, about the same as was inferred for the entire U.S. West by Gudmundsson et al. (2021). However, this decline is small in comparison to the standard deviation of annual flows, which is about 30%. In summary, changes in runoff over the watersheds that include New Mexico are difficult to separate from natural year-to-year variability, but to the extent that they can be separated, they consist of declines in runoff, not increases.

Trends in soil moisture, which are a measure of the partitioning of precipitation into subsurface infiltration, have been relatively little studied. Unlike streamflow, soil moisture is not routinely monitored, and the monitoring that has been done mostly covers only a few decades or less, so there are much less data on which to base evaluation of trends with time. Instead of actual observations, global reanalyses of meteorological and remote-sensing data using land-surface and atmospheric models are often used to reconstruct environmental conditions. Deng et al. (2020) used the output of the ERA-Interim/Land reanalysis by the European Centre for Medium-Range Weather Forecasts to evaluate trends in soil moisture over the period 1979 to 2017. In the area of New Mexico, they inferred a reduction of water content of the soil (top 5 cm) of 3% to 5% volumetrically per decade. Soil drying was the predominant trend worldwide. Deng et al. (2020) felt that the main driver of this drying was increasing temperature. For the Upper Colorado River basin, Scanlon et al. (2015) used standard land-surface model outputs to evaluate changes in soil moisture storage from 1980 to 2015. Focusing on their results from the 1997 to 2015 interval for the reasons described above reveals a steady decline in soil moisture storage amounting to about 22 mm water depth. This is roughly equivalent to 5% to 10% of the typical water storage capacity of the soil and thus appears similar to the result from Deng et al. (2020). Total basin water storage includes both soil moisture and groundwater and can be monitored using satellites. Scanlon et al. (2018) estimated that between 2002 and 2014, the Rio Grande basin lost between 2.2 and 3.5 km^3 (1.8 to 2.8 million acre-ft) of water storage, equivalent to 4.5 mm over the basin. However, the VIC simulation for the same period only registered 0.5 km^3 loss. Similar underestimates by the VIC model were found for other basins worldwide.

Two conclusions can be drawn from this summary of observational evidence. The first is that over the area of interest to the state of New Mexico,

any recent trends in precipitation, runoff, and soil moisture/recharge are small enough that, with only about 20 years of clear temperature signal, they are difficult to separate from natural year-to-year and decadal fluctuations. The second is that insofar as they can be separated from natural variability, the simulations almost universally indicate soil drying and reduction in runoff primarily as the result of water lost to the atmosphere through increased evapotranspiration caused by warmer air temperatures. There is very little evidence to support an upward trend in these parameters. Thus, responding to the concern of Yang et al. (2018) that the projected strong increase in aridity index might not necessarily correspond to reductions in runoff and recharge, the available observational evidence does indeed support the modeled projections of quite significant downward trends in surface water, groundwater, and soil moisture over the next 50 years. The observed evidence indicates that New Mexico is at high risk of significant increases in surface aridity in a warming climate.

SUMMARY OF FUTURE WATER-BALANCE CHANGES

Published studies on climate-driven changes in the water balance in New Mexico watersheds have yielded projections with wide uncertainty bounds. In general, the median hydrological model output generated by using as input multiple runs by multiple global climate models indicates declines in both runoff and recharge over the next 50 years, typically amounting to 3% to 5% per decade for both quantities. However, the published uncertainties around these median projections are generally quite large, often two to three times the projected median change, with the uncertainty encompassing both large increases in runoff and recharge and large decreases. Such large uncertainties render the projections of limited value for water-resource planning and management. In most cases, this wide uncertainty does not arise from the variability inherent within the hydrological models used to make the projections, but rather from the variability in projected precipitation in the global climate model simulations used to drive the hydrological models. Although there is generally a fairly strong clustering of global climate model precipitation outputs within the bounds of no precipitation change to a decline of about 5% per decade, some individual runs from some models fall well outside these bounds, indicating either a large increase in precipitation or a fairly drastic decrease. Inclusion of these extreme runs widens the uncertainty bounds of the runoff/recharge output a great deal.

We have attempted to evaluate the value of these wide uncertainty bounds by comparing model projections (both global climate model outputs in terms of precipitation and hydrological model outputs in terms of runoff and recharge) with actual data from the period of detectable global warming—the past 50 years. These data show that any inferred changes in precipitation since about 1970 are quite small and can be either negative or positive, depending on the geographical area and the time intervals compared. The available data thus do not support the validity of global climate model outputs showing either substantial increases or decreases in precipitation over the New Mexico area. One cannot a priori rule out such shifts over the coming 50 years, but we suggest that for planning purposes we should not place much confidence in these outlier simulations. Instead, the lack of precipitation trends over the past 50 years of pronounced warming argues that models in the median cluster are most likely to provide reliable projections for the next 50 years.

Evaluation of the data for changes in runoff or recharge yields somewhat stronger evidence for trends. Although once again the trends depend on location and time interval, there is significant support for declines of 3% to 5% per decade for both runoff and recharge. These decreases are on the order of the projections from the hydrological models driven by the median global climate model outputs. Declines in runoff and recharge with increasing temperature can be expected so long as precipitation is not actually increasing (Yang et al., 2018). Given the likely existence of these declines during the first 50 years of global warming, their continuation into the next 50 years also seems likely.

KNOWLEDGE GAPS

The summary in this chapter of water-balance research under global climate change pertaining to New Mexico shows both strengths and weaknesses in our state of knowledge. Strengths include an ever-increasing capability in global climate modeling, data to drive such models that enable a highly sophisticated approach to the problem, and the accumulation of about 50 years of hydroclimatic data against which to compare the outcomes of global climate model simulations. Weaknesses are:

1. *Lack of adequate soil-moisture and groundwater-level data*—The availability of long-term data for temperature, precipitation, and surface-water runoff is at least adequate, along with other basic hydrometeorological data. However, these present only part of the information needed to understand changes in the surface-water balance over time. Two critical components, soil moisture and groundwater level, are largely missing. We note that although groundwater is monitored at numerous localities in New Mexico, these are nearly all selected in response to heavy pumping. For assessing changes in groundwater recharge, water levels in remote areas with minimal human extraction are needed, but repeat water-level measurements are rarely performed in such settings.

   Using traditional methods, collection of soil-moisture data has been labor intensive and typically yields only a point measurement of a parameter that can vary a lot over short distances. However, newer technologies such as the Cosmic-ray Soil Moisture Observing System (COSMOS; Zreda et al., 2012) can sense soil moisture at a large spatial scale and a time scale of a few minutes and telemeter the data to a central location. Another relatively simple but very powerful technology is the use of fixed Global Positioning System receivers to monitor vertical changes in the land-surface elevation, from which changes in soil-water and groundwater storage can be evaluated (Larson et al., 2008; Borsa et al., 2014). As hydrological changes due to global warming increase, the state of New Mexico is increasingly going to need regional hydrology and climate data against which to calibrate and compare the results of models. Ensuring that adequate datasets of all relevant parameters are available in order to make use of these model results for management purposes would be a wise investment.

2. *Criteria for evaluation of global climate model output*—Traditionally, atmospheric modelers have tended to use strongly inclusive measures to quantify the possible spread of model outputs (e.g., global climate model outputs used as input to hydrological models, wettest and driest global climate model runs; see Elias et al., 2015). Although such wide bounds are conservative in the sense of bracketing the entire range of possibilities, they render the model output of limited practical value for management purposes because they do not adequately distinguish between possible outcomes and likely outcomes. With a current database of about 50 years of observable warming of global temperature, it is quite likely (though not provable) that model runs which have succeeded in predicting the regional hydroclimatic history over that time period will also be more successful at predicting the following 50 years. We suggest that effort be invested in developing a set of quantitative criteria for evaluating the output of global climate model runs and, on that basis, selecting the ones most likely to predict future climate (a procedure commonly known as post-processing).

3. *Lack of New Mexico-focused hydrological models*—A large number of the studies reviewed above are global in scope. Others cover the entire United States or the western United States. Such models inevitably make compromises in attempting to reproduce the hydrological effects of global warming under climate regimes ranging from cold and humid to hot and hyperarid. They typically do not have adequate spatial resolution to simulate processes on the highly varied topography of New Mexico. When regional-scale modeling has been performed, it has often by default used the VIC model even though there are indications that VIC systematically underestimates the magnitude of the hydrological response to climate change (Scanlon et al., 2015; Niraula et al., 2017). Given that New Mexico is one of the most water-short states in the union and that the water supply is shrinking under climate change,

development of a state-scale model should be a priority. As discussed above, a wide variety of models are potentially available, ranging from simple, straightforward, and capable of being run on a laptop to highly comprehensive, complex, and requiring supercomputers. We suggest a thorough evaluation process in light of in-state capabilities, model suitability for management objectives, and availability of data to parameterize models, followed by a comprehensive projection of changes in the hydrological system of New Mexico over the next 50 years using the selected model or models.

Bland Canyon, Jemez Mountains; *photo by Craig D. Allen*

IV. TERRESTRIAL ECOSYSTEMS

Craig D. Allen

Climate is a fundamental driver of ongoing and future vegetation changes in New Mexico. Future changes in vegetation will affect the distribution and abundance of water resources in New Mexico. Major shifts in climate and vegetation across New Mexico's landscapes have occurred in the past, but the scale and rate of recent and projected climate change is probably unprecedented during the past 11,000 years. Recent warming, along with frequent and persistent droughts, have amplified the severity of vegetation disturbance processes (fire, physiological drought stress, and insect outbreaks), driving substantial changes in New Mexico vegetation since the year 2000. Ongoing and projected vegetation changes include growth declines, reduced canopy and ground cover, massive tree mortality episodes, and species changes in dominant vegetation—foreshadowing more severe changes to come if current warming trends continue as projected. Such major alterations of New Mexico vegetation likely will also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water supply shortages for people, such climate-change-driven water stress could lead to increasing conflict between managing declining water availability for human use (e.g., irrigation) and retaining "wild" water for the maintenance of historical ecosystems.

INTRODUCTION

Ongoing climate change—a mix of both natural climate variability and directional anthropogenic climate change—is a major driver of recently changing vegetation patterns in New Mexico, ranging from drought-induced forest die-offs and extreme wildfires to desertification of grasslands. Vegetation changes, in turn, affect various ecosystem processes that interact with and modify the geomorphology and hydrology of our landscapes. In this way, climate-induced vegetation changes have consequences for the water resources of New Mexico that affect all state citizens. Ecohydrology is the interdisciplinary scientific field that addresses interactions between ecosystems and hydrology. This chapter reviews the effects of climate change on terrestrial ecosystems in New Mexico, focusing on vegetation and associated linkages to ecohydrology to provide important context for statewide assessment of water-resource issues. Although important, aquatic ecosystems and biodiversity considerations are outside the scope of this chapter.

Globally, the main limiting environmental factors that determine the distribution and productivity of dominant vegetation types are combinations of water, temperature, and sunlight (Boisvenue and Running, 2006). In warm tropical rainforests, sunlight limitation (from intense inter-plant competition for canopy space and clouds) is usually the main constraint on vegetation productivity, while in cold Arctic and high alpine settings, temperature is most limiting. However, in semiarid, warm-temperate regions like New Mexico, water is generally the most limiting factor, with seasonally varying temperature

constraints (e.g., frost and extreme heat) being important secondary drivers. Ongoing regional climate change toward warmer temperatures and more severe droughts therefore threatens vegetation types that are sensitive to hotter, drier conditions.

The modern spatial distributions of New Mexico's diverse plant species and vegetation communities (Dick-Peddie et al., 1993) are generally structured by these same broad climate factors of precipitation and temperature, although at local sites the patterning of vegetation is substantially modified by other abiotic and biotic environmental factors and human land use practices. Major human land use practices include agriculture, livestock grazing, forestry activities, fire suppression, watershed modifications, water management actions, and urbanization. Important abiotic factors include topographic characteristics that affect local microclimate (e.g., elevation, slope, aspect, landform, and slope position), soil and bedrock physical properties, nutrient availability, and various ecosystem disturbance processes (e.g., fire, floods, and wind). Subsurface water storage in soils and fractured bedrock is increasingly recognized to be critically important for deep-rooted plants (Klos et al., 2018; Rempe and Dietrich, 2018; Bales and Dietrich, 2020). Key biotic factors also interact to influence local vegetation patterns, including soil microbiota, competition between plants, herbivory by animals, insect and disease pests, and parasites. As a result, there are sharp differences in microclimate and vegetation between cooler-moister, north-facing slopes and directly adjoining hotter-drier, south-facing slopes (Figure 4.1). At even finer spatial scales, similar microclimate and understory vegetation contrasts also occur between the cooler ground-surface conditions underneath tree or shrub canopies and plants adapted to exposed, hotter conditions in open intercanopy sites.

PALEO-ENVIRONMENTAL AND HISTORICAL PERSPECTIVES ON CLIMATE–VEGETATION RELATIONSHIPS IN NEW MEXICO

Climate is a fundamental driver of vegetation patterns and processes. But how do we rigorously determine how ongoing and projected climate changes are likely to alter future vegetation? One approach is to reconstruct the linkages between past climate variability and vegetation, providing evidence to infer likely future changes.

Past climate–vegetation relationships are particularly well documented for many thousands of years in New Mexico because the southwestern United States contains an unusual abundance and diversity of paleo-environmental data sources that allow reconstruction of detailed information on linkages between climate and vegetation through time (Swetnam and Betancourt, 1998; Swetnam et al.,

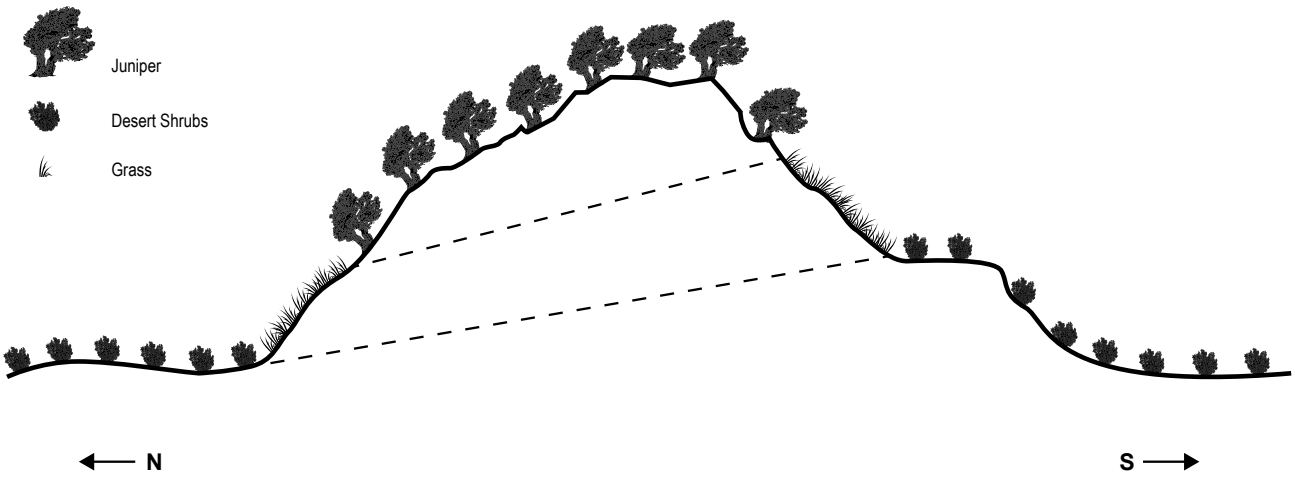

Figure 4.1. The strong effects of south versus north topographic aspect on vegetation pattern. Modified from Figure 3.1 in Dick-Peddie et al. (1993).

1999). For example, ancient lake sediments from the Valles Caldera (Jemez Mountains) provide multiple lines of evidence for major oscillations in climate and water balance (between colder-wetter and warmer-drier) across multiple glacial–interglacial cycles over hundreds of thousands of years in northern New Mexico, with close linkages between climate and vegetation patterns (Fawcett et al., 2011). For the last 40,000 years, plant macrofossils preserved in packrat middens provide powerful species-specific information on major changes in the biogeographic distribution of vegetation and climate across the Southwest (Swetnam et al., 1999; Betancourt et al., 2016). Similarly, the pollen, macrofossils, charcoal, chemical isotopes, and numerous other paleo-environmental indicators found in the sediments of multiple New Mexico mountain lakes and bogs reveal greater detail on linked changes in climate and vegetation over the past 20,000 years, particularly as the world transitioned from the last ice age (the Pleistocene epoch) to the Holocene epoch about 12,000 years ago (e.g., Anderson et al., 2008b). These paleo-sediment studies also provide long-term perspectives on the environmental effects of relatively recent historical land-use changes like Euro-American livestock grazing and fire suppression in New Mexico (Allen et al., 2008; Brunelle et al., 2014). Overall, these deep-time paleo-environmental studies consistently document that warmer periods in southwestern North America tend to be more arid, resulting in the drying of lake and bog environments, transitions to vegetation communities dominated by species better adapted to warm and dry conditions, and more fire activity.

Tree-ring research in the Southwest and New Mexico provides well-replicated and diverse paleo-environmental evidence that is spatially widespread, precisely located, and dated at annual to seasonal resolution. Tree-ring widths, wood density, and isotope measurements are used to produce calibrated reconstructions of past precipitation (Touchan et al., 2011), temperature (Salzer and Kipfmueller, 2005), tree drought stress (McDowell et al., 2010; Williams et al., 2013), annual streamflow (Routson et al., 2011; Margolis et al., 2011), and floods (McCord, 1996). Additionally, tree-ring-dated fire scars and other dendroecological observations document the environmental histories of New Mexico's forest fires (Falk et al., 2011; Swetnam et al., 2016; Margolis et al., 2017); insect outbreaks (Swetnam and Lynch, 1993); and forest establishment, growth, and mortality (Guiterman et al., 2018). The southwestern United States is the most intensively sampled region of the world in terms of tree-ring reconstructions of climate and fire history, with numerous chronologies extending back more than 1,000 years before present (Grissino-Mayer, 1995; Cook et al., 2007; Woodhouse et al., 2010; Williams et al., 2013). Southwestern climate reconstructions based on tree-ring analyses universally document high natural variability in precipitation at all timescales—annual, decadal, and even centennial (Grissino-Mayer, 1995; Williams et al., 2020a, 2020b). There also has been recent success in separating cool-season precipitation from warm-season monsoonal precipitation in tree-ring reconstructions for New Mexico (Griffin et al., 2013), comparing reconstructed seasonal precipitation and Rio Grande streamflows back to 1659 (Woodhouse et al., 2013), and in assessing cool- versus warm-season precipitation effects on past fire occurrence (Margolis et al., 2017). Similarly, tree-ring temperature reconstructions for the Southwest also show significant variability through time (Salzer and Kipfmueller, 2005). These often well-replicated tree-ring studies quantitatively demonstrate the effects of both climate variability and human land uses on diverse forest ecosystem patterns and processes (Swetnam and Betancourt, 1998; Swetnam et al., 2016; O'Connor et al., 2017; Guiterman et al., 2019; Roos et al., 2021).

In addition, substantial historical ecology research (Allen, 1989; Swetnam et al., 1999) and numerous environmental history studies (Rothman, 1992; deBuys, 2015) have documented relatively recent (Anglo-American era, since ca. 1850) vegetation changes in New Mexico using historical observations and multiple other lines of evidence (Allen and Breshears, 1998). These include General Land Office Survey field notes (Yanoff and Muldavin, 2008), repeat photography of century-old ground-based landscape photographs (Fuchs, 2002; deBuys and Allen, 2015), photo-interpretive mapping of vegetation from stereographic aerial photographs as far back as 1935 (Allen, 1989; Miller, 1999), and compilation and interpretation of diverse historical maps and text documents (e.g., Hillerman, 1957; Scurlock, 1998). These historical ecology studies are particularly useful in documenting and illustrating the major effects of extended droughts versus extended

wet periods upon New Mexico's forest and rangeland vegetation (Swetnam and Betancourt, 1998; Allen and Breshears, 1998).

Finally—and most powerfully—direct measurements of climate and vegetation changes from a variety of long-term monitoring and research efforts over roughly the past century provide a solid foundation of quantitative observational data to assess recent and ongoing linkages between climate and vegetation in New Mexico. The effects of climate on vegetation change and ecosystem dynamics in New Mexico have been particularly well-studied through long-term ecological research at three large and environmentally varied fieldwork localities that collectively represent a big portion of New Mexico's diverse landscapes:

1. the USDA Jornada Experimental Range (established 1912) and associated Jornada Long-Term Ecological Research site (run by New Mexico State University since 1982) in southern New Mexico's Chihuahuan Desert, focusing on subtropical desert grasslands and shrublands and rangeland issues in general (https://jornada.nmsu.edu/ltar; https://lter.jornada.nmsu.edu/)
2. the USDI Sevilleta National Wildlife Refuge (established 1983) and associated Sevilleta Long-Term Ecological Research site (run by the University of New Mexico since 1988) extending from the Rio Grande to adjoining low mountains in central New Mexico at the intersection of four biomes: Colorado Plateau Shrub Steppe, Great Plains Short Grass Prairie, Chihuahuan Desert, and Piñon–Juniper Woodland (https://www.fws.gov/refuge/Sevilleta/; https://sevlter.unm.edu/)
3. the Jemez Mountains, a volcanic "sky island" in northern New Mexico at the southern end of the Rocky Mountains, where the Valles Caldera National Preserve (est. 2000), Bandelier National Monument (est. 1916), and the USGS New Mexico Landscapes Field Station have collectively fostered long-term ecological monitoring and research since the 1980s on diverse montane forests, woodlands, grasslands, and streams along a 6,000-ft elevational gradient from the Rio Grande to Redondo Peak. These groups are partners in a new National Park Service Research Learning Center (the in-development website is: https://www.nps.gov/rlc/jemezmountains/index.htm)

All three of these large research landscapes are characterized by diverse, intensive, long-term studies and datasets; multidisciplinary research teams; and abundant published scientific research documenting ongoing vegetation and ecosystem responses to climate variability and change.

These recent observations of linked climate–vegetation variability include documentation of multiple wet and dry periods since 1900, ranging from a particularly wet window in the 1910s to 1920s that favored a huge pulse of successful tree regeneration across the Southwest (Pearson, 1950; Swetnam and Betancourt, 1998) to the regionally severe 1950s drought that caused great stress to vegetation and water resources in New Mexico (Hillerman, 1957; Thomas, 1963; Allen and Breshears, 1998). More recently, another wet period from the late 1970s to mid-1990s was a time of abundant water resources and extremely productive tree growth (Figure 4.2). Since ca. 2000, New Mexico and the Southwest have been in the midst of an increasingly severe regional drought (Williams et al., 2013, 2020a, 2020b; Cook et al., 2021). Although this current multi-decadal period of lower precipitation is not unusual relative to past patterns of natural precipitation variability, the drought stress effects on both vegetation and water resources are increasingly amplified by substantial recent climate warming (Figure 1.1; McKinnon et al., 2021). This is one of the two most severe regional megadroughts in the past 1,200 years (Williams et al., 2020a, 2020b; Cook et al., 2021). The ongoing "hotter drought" in New Mexico is consistent with projected climate changes for the Southwest (Chapter 2; Williams et al., 2013; Cook et al., 2015, 2021). As New Mexico's environment has undergone this period of substantial warming and aridification, long-term ecological monitoring and research programs here have been able to precisely document and interpret the direct and indirect impacts of warmer "global-change-type drought" on both vegetation and water resources in New Mexico.

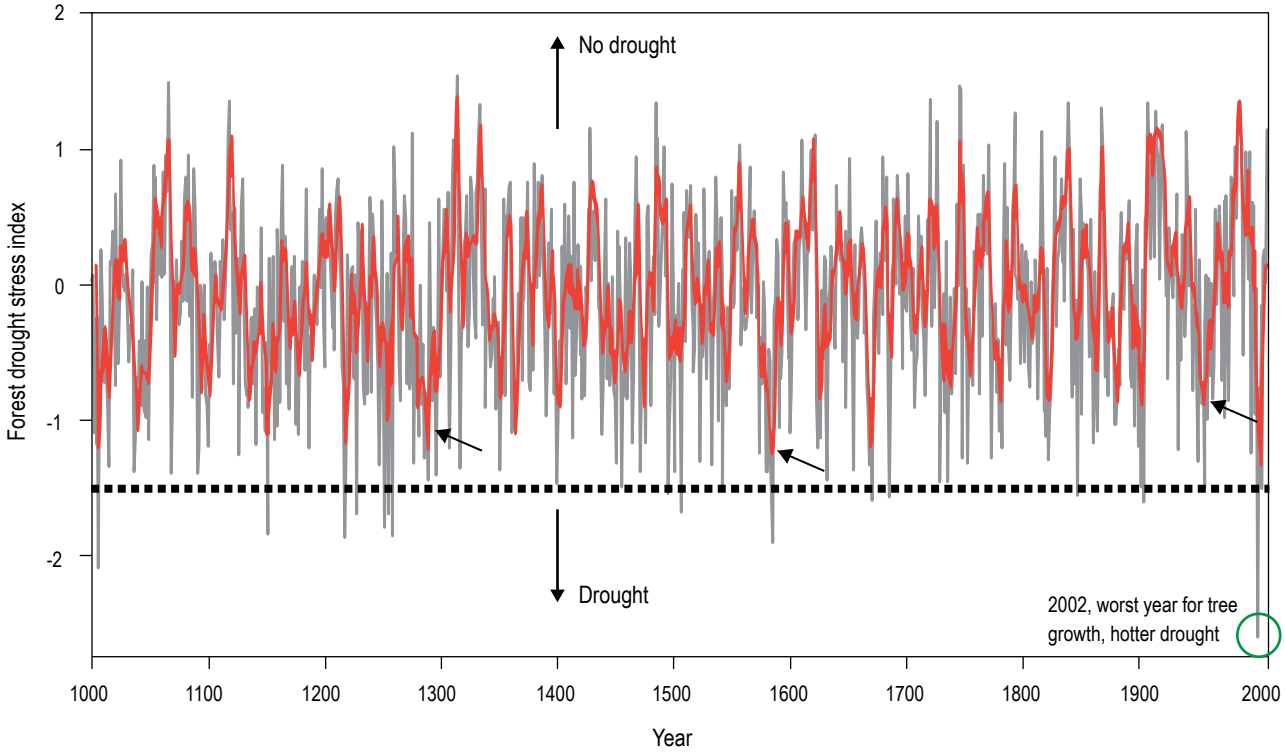

Figure 4.2. A 1,000-year reconstruction of a regional forest drought stress index (FDSI) from tree rings in the southwestern United States. Annual FDSI values are in gray and 10-year moving averages are in red for 1000–2007. Arrows mark megadroughts in the late 1200s and late 1500s, as well as the well-documented 1950s historical drought. The -1.5 FDSI dashed line indicates an approximate historical threshold for tree mortality. The green circle highlights the unprecedentedly extreme FDSI in 2002, reflecting amplified drought stress from recent warming, which triggered extreme regional tree die-offs and wildfires. Modified from Williams et al. (2013) and Allen (2014).

DIRECT AND INDIRECT CLIMATE EFFECTS ON VEGETATION AND ECOHYDROLOGY

As described in Chapters 1–3, climate change in New Mexico is projected to continue recent trends toward warmer and thus generally more arid conditions as well as to amplify wet, dry, and hot extremes.

Climate variability and directional climate changes in precipitation and temperature modulate New Mexico's vegetation cover in two general ways:

1. **Directly** through moisture and temperature effects on plant reproduction, growth and productivity, and mortality; and
2. **Indirectly** by altering ecological disturbance processes such as fires, insect and disease outbreaks, and floods.

Direct Climate Effects on Vegetation— Climate changes directly alter New Mexico's vegetation through effects on the demography of plant populations, including:

1. *Reproduction*—Plant populations in warm, semiarid regions like New Mexico are characterized by episodic reproductive success linked to relatively infrequent, often multiyear periods of favorable climate to sufficiently support abundant flowering, seed development (e.g., Parmenter et al., 2018), germination, and seedling establishment. As a result, many dominant plant species establish primarily in pulses during favorable climate periods, resulting in episodic, even-aged cohorts of the dominant vegetation, whether southwest U.S. trees (e.g., Swetnam and Betancourt, 1998) or grasses (e.g., Neilson, 1986; Collins et al., 2014). Note that the range of climate conditions that

support successful vegetation regeneration (the regeneration niche) is generally narrower than the broader climatic range in which adult plants can grow and persist. Due to warming-induced aridity, the regeneration niche is likely now shrinking for many plant species (e.g., Bailey et al., 2021).

2. *Growth*—The moisture and temperature conditions of both the atmosphere and soils directly control plant growth and productivity (Figure 4.1); globally, soil moisture stress dominates vegetation productivity, particularly in semiarid ecosystems (Liu et al., 2020). In mostly semiarid New Mexico, the high natural variability in precipitation (and soil moisture; Figure 4.2) drives the similarly high variability in growth of both woody and herbaceous vegetation (Rudgers et al., 2018; Koehn et al., 2021). When water is not a limiting factor, slightly warmer temperatures can be beneficial for plant growth (e.g., longer growing seasons); in addition, the substantially elevated atmospheric concentrations of CO_2 can support increased water-use efficiency of photosynthesis (and thus good plant growth) when water stress is not extreme (De Kauwe et al., 2021). Also, atmospheric CO_2 enrichment tends to favor C3 plants like woody conifers and shrub species over C4 plants like many warm-season grasses (Archer et al., 2017; although see Reich et al., 2018). However, warming over the last several decades has been enough to increase the frequency and severity of more arid atmospheric and soil conditions, thereby decreasing the supply of plant-available water (Breshears et al., 2013) and even beginning to approach thermal limits of photosynthesis (Duffy et al., 2021). These climate warming effects apparently are increasingly overcoming CO_2 enrichment benefits (Peñuelas et al., 2017; Jiao et al., 2021; although see Lian et al., 2021)—particularly in spring—and thereby reducing southwestern U.S. plant growth (Koehn et al., 2021; Munson et al., 2021). For example, warming has amplified conifer forest drought stress in the Southwest, generally squeezing tree growth in New Mexico since ca. 2000 (Figure 4.2; Williams et al., 2013), particularly in the warmer and drier low-elevation portions of the elevation distribution of individual tree species (McDowell et al., 2010). Similarly, warming-amplified drought stress and increases in precipitation variability also are linked to observed declines in the growth and productivity of perennial grasses in arid desert grasslands of New Mexico (Gherardi and Sala, 2015; Bestelmeyer et al., 2018; Rudgers et al., 2018; Munson et al., 2021).

3. *Mortality*—Extremes of drought and/or heat can lead to pulses of amplified vegetation mortality, which can rapidly change the sizes, ages, and species composition of the dominant vegetation (Allen et al., 2010; McDowell et al., 2020). While drought- and heat-induced vegetation mortality is a natural response to historical climate variability (e.g., Allen and Breshears, 1998), the emergence of hotter global-change-type droughts in recent decades (Breshears et al., 2005) is linked to increasing observations of more extensive and severe episodes of tree mortality in diverse ecosystems regionally and globally (Allen et al., 2015 [especially Appendix A of that paper for New Mexico observations]). While forest die-offs have received the most attention scientifically, hotter drought events also are causing mortality pulses in Southwestern shrublands and grasslands (Jacobsen and Pratt, 2018; Winkler et al., 2019). Climate variability, particularly oscillation between increasingly wet and dry climate extremes, leads to "structural overshoot" of woody plants during growth-favorable (wet) climate windows at both individual and stand scales, which can increase vulnerability to forest dieback during the inevitable subsequent swing to an unfavorable climate window (hotter drought; Allen, 2014; Jump et al., 2017; Zavala, 2021).

Because each plant species has its own particular set of climate requirements, changes in climate cause demographic changes in plant populations that drive wide-ranging incremental shifts (both contractions and expansions) in the biogeographic distribution, abundance, and community dominance of essentially all plant species (e.g., Collins et al., 2014; Rudgers et al., 2018).

Expected direct effects of future climate warming on New Mexico's vegetation include:

1. The vegetation communities historically found on warmer, drier south-facing slopes will tend to "shift" (through colonization) onto adjoining north-facing slopes;

2. More warm/dry- (xeric-) adapted plants from lower-elevation sites will shift their distributions upslope (Kelly and Goulden, 2008; Brusca et al., 2013); and
3. Less cold-tolerant plants from southerly portions of New Mexico will shift their distributions northward and perhaps upslope (although note the recent documentation of warming temperature and dryness constraints on alpine tree establishment in northern New Mexico by Bailey et al., 2021).

While plant individuals, populations, vegetation communities, and ecosystems have substantial capabilities to adapt to some degree of climate change (Allen et al., 2015), these adaptive capacities are limited and may be overwhelmed by the speed and magnitude of projected climate change—warming in particular.

Thresholds—*(see also Chapter 1 "critical threshold" or "tipping point" events)* Climate variability and change is one important driver of nonlinear threshold dynamics in ecosystem patterns and processes (Turner et al., 2020). Prominent New Mexico examples include drought-induced tree mortality, wildfire behavior, and water and wind erosion processes (Allen, 2007; Field et al., 2010; Bestelmeyer et al., 2018). Abrupt vegetation transitions can result from both incremental climate changes and unprecedented climate extremes (Figure 4.3; Allen et al., 2015); such vegetation changes from aridification may be reversible or not (Berdugo et al., 2020; Munson et al., 2021). Note that even modest incremental shifts in the average value of a climate variable (e.g., daily maximum temperature) can result in substantial increases in the probability of the most extreme events at the far tail-end of the distribution (Figure 4.4)—e.g., the extreme heat records set in June 2021 in the Pacific Northwest and Canada. Similarly, a shift in the sensitivity of a climate-related threshold (e.g., a warming-caused decrease in the duration of drought needed to trigger tree mortality [Figure 4.5]), can greatly increase the probability that threshold-level extreme events occur. Increasingly extreme, unprecedented climate events—particularly droughts and heat waves—are emerging as ever more important drivers of severe ecosystem disturbances and abrupt vegetation changes in the southwest United States (Allen, 2014; Breshears et al., 2021).

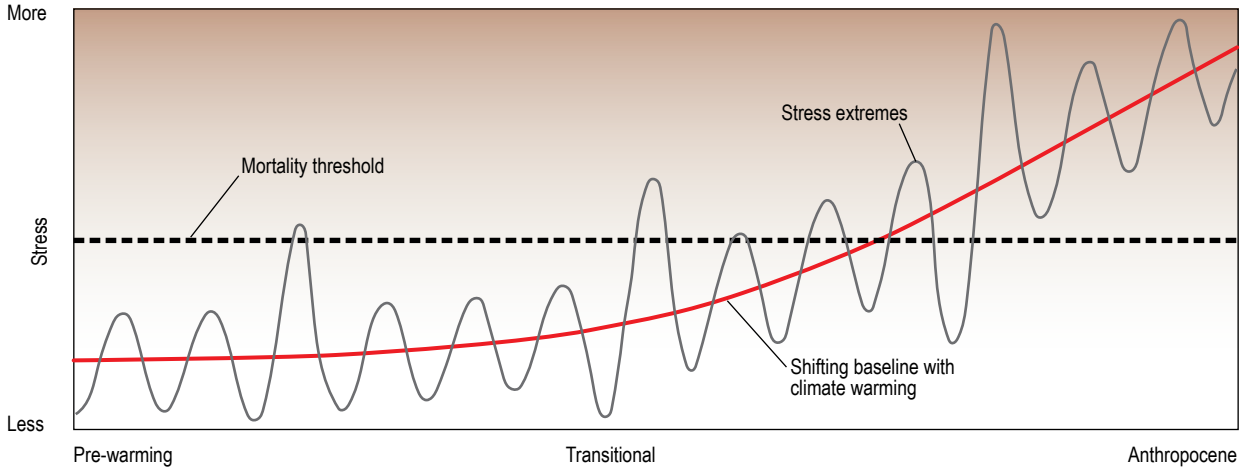

Figure 4.3. Ecosystem stress results from both general incremental trends and particular extreme events in climate (Jentsch et al., 2007). The red line indicates a shifting baseline level of forest stress through time due to an increasing trend in temperature; the gray line represents stress changes due to substantial multiyear oscillations in precipitation and temperature that are inherent in the climate system, producing stress events like extreme droughts and heat waves. Atmospheric warming increases both baseline and extreme drought stresses through time, thereby driving elevated tree mortality vulnerability. Increasing temperature alone drives greater forest drought stress (Adams et al., 2009; Williams et al., 2013), and because temperature is increasing chronically, so is forest stress. Swings in forest drought stress push forests closer (or further) from the historical mortality threshold (dashed black line), but given the chronic increase in forest stress associated with ongoing anthropogenic warming, the frequency, magnitude, and duration of these swings above the mortality threshold increase through time. If unabated, chronic warming eventually will cause even relatively wet periods to exceed the mortality stress threshold for present-day forests. From Allen et al. (2015).

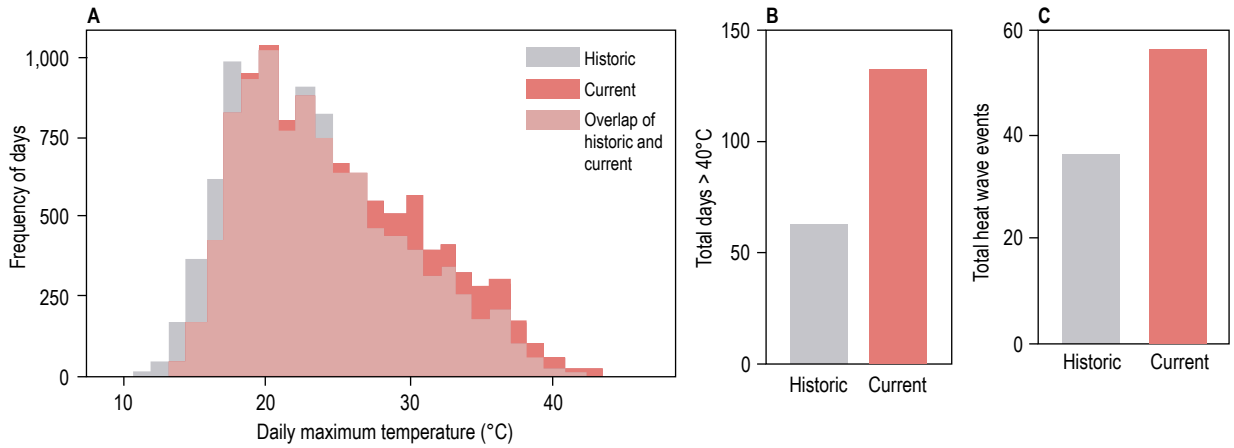

Figure 4.4. Warming greatly increases the frequency of extreme temperature days and heat waves. Daily maximum temperature (A), number of days over 40°C (B), and number of heat wave events (C) for Perth, Western Australia, for historical (1910–1939; gray) and current (1989–2018; red) 29-year periods. A small change in the overall distribution has led to more than a doubling of days over 40°C and a 59% increase in heat wave events. From Breshears et al. (2021).

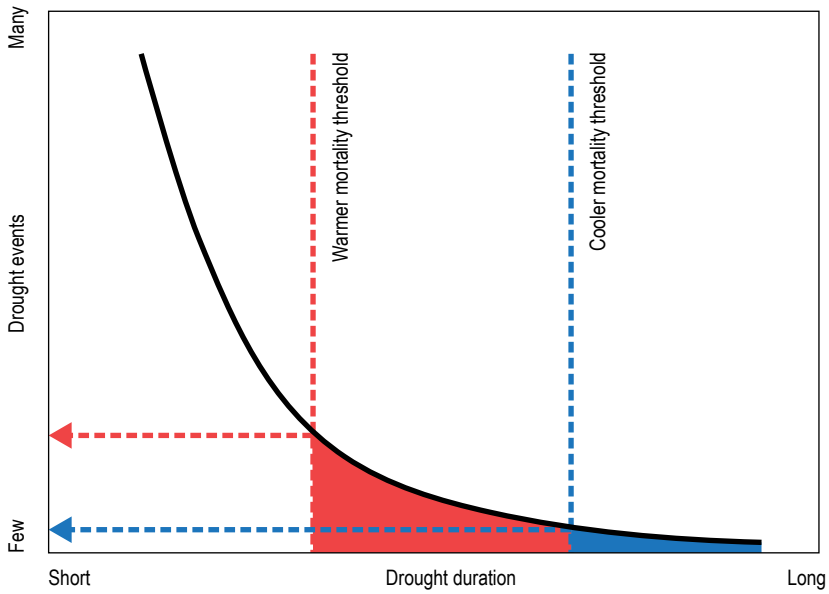

Figure 4.5. Warming greatly increases frequency of tree-killing drought events. Drought frequency (black line) increases nonlinearly as drought duration decreases, as there are many more short-duration droughts than long ones (Lauenroth and Bradford, 2009), and during cooler historical times only a few extremely long-duration drought events were long enough to exceed the historical tree mortality threshold (blue dashed vertical line). Under warmer recent and future drought conditions, trees die faster (red dashed vertical line, warmer mortality duration threshold) than with cooler droughts (blue dashed vertical line, cooler mortality duration threshold), resulting in more tree-killing drought events at the minimum-duration mortality threshold for hotter drought (horizontal red arrow line) than for cooler drought (horizontal blue arrow line). This cumulatively translates into more total tree-killing droughts under hotter drought conditions (filled red + blue areas) than under cooler drought conditions (filled blue area only) because many additional shorter duration droughts become lethal with warming (Adams et al., 2009). From Allen et al. (2015).

Indirect Climate Effects on Vegetation through Altered Ecosystem Disturbance Processes—Recent, ongoing climate change is indirectly but profoundly altering vegetation patterns by amplifying a variety of ecosystem disturbance processes that also affect water and watersheds. Documented effects of these climate-amplified disturbances on vegetation in New Mexico include:

1. More extreme pulses of tree mortality and forest die-offs (Figure 4.6) from physiological stress due to hotter drought (Breshears et al., 2005; Williams et al., 2013; Allen et al., 2015 [Appendix A of that paper]), often with associated bark beetle and other insect outbreaks (Raffa et al., 2008; Anderegg et al., 2015)—also including novel insect outbreak dynamics linked to recent warming (Figures 4.7a, 4.7b; Elliott et al., 2021).
2. Warming has substantially altered recent wildfire activity in the Southwest and New Mexico (Figure 4.8), with changes in frequency, severity, area burned, and seasonality and longer fire seasons (Westerling et al., 2006; Abatzoglou and Williams, 2016). Wildfire activity has recently increased upslope into cooler-wetter forest types (Higuera et al., 2021) as well as downslope into semiarid woodlands (Floyd et al., 2000, 2021; Romme et al., 2009). Recent increases in the extent and frequency of high-severity fire (Parks and Abatzoglou, 2020) are strongly filtering which species are able to regenerate postfire (Johnstone et al., 2016; Coop et al., 2020). One result is an increase in vegetation "type conversion" from gymnosperm conifer forests that require nearby fire-surviving trees for seed regeneration to shrublands and grasslands (Figure 4.9; Allen, 2014) dominated by resprouting angiosperm species that can regenerate after severe fire from surviving belowground roots, tubers, etc. (Guiterman et al., 2018; Coop et al., 2020).
3. High-severity wildfires also cause extreme alterations of watershed vegetation cover and surface soil properties that can trigger postfire floods and debris flows (Figure 4.10); these disturbances are addressed in Chapters 6 and 11.
4. Ongoing warming-induced aridification and disturbances drive widespread reductions in vegetation cover below critical thresholds in many New Mexico landscapes (Davenport et al., 1998; Breshears et al., 2009; Field et al., 2010), resulting in generalized upland soil erosion by water (Wilcox et al., 2003) and wind (Munson et al., 2011; Duniway et al., 2019); these disturbances are addressed in Chapter 5.
5. Warming-induced desertification of desert grasslands (Figure 4.11) is contributing to declines in perennial grass cover and increases in subtropical woody shrubs (Bestelmeyer et al., 2018).

Note the importance of synergistic interactions among ecosystem disturbances, both within and across spatial scales (Allen, 2007; Turner et al., 2020). For example, warming drives the increased atmospheric vapor pressure deficit (Williams et al., 2013), leading to greater drying of vegetation and

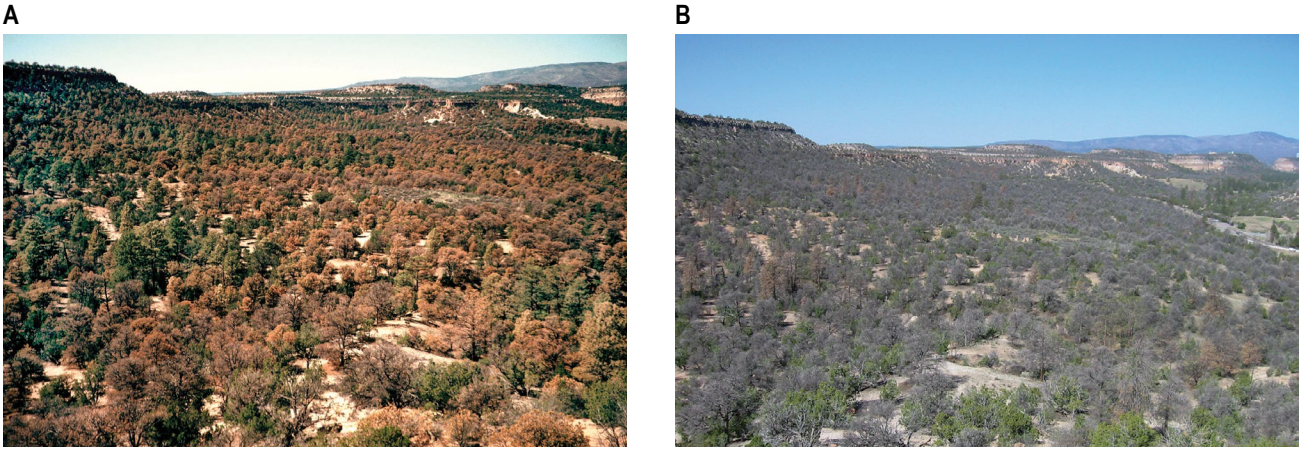

Figure 4.6. Repeat photos of landscape-scale mortality of piñon (*Pinus edulis*) from hotter drought and an associated bark beetle outbreak. (A) Rust-colored dying piñon, eastern Jemez Mountains, October 2002. (B) The same scene 18 months later, with gray piñon skeletons and remaining live junipers, May 2004. *Photos by Craig D. Allen*

Figure 4.7a. Novel insect outbreak dynamics. Aerial photo of Janet's Looper outbreak during 2017–2019 in the Sangre de Cristo Mountains near Santa Fe, with red-rusty-gray tree canopies from winter herbivory of Douglas fir and Engelmann spruce tree needles by caterpillars (inset photo) of this inconspicuous moth. Recent warmer winters allowed the first recorded outbreak of this native insect in northern New Mexico. *Photos by U.S. Forest Service*

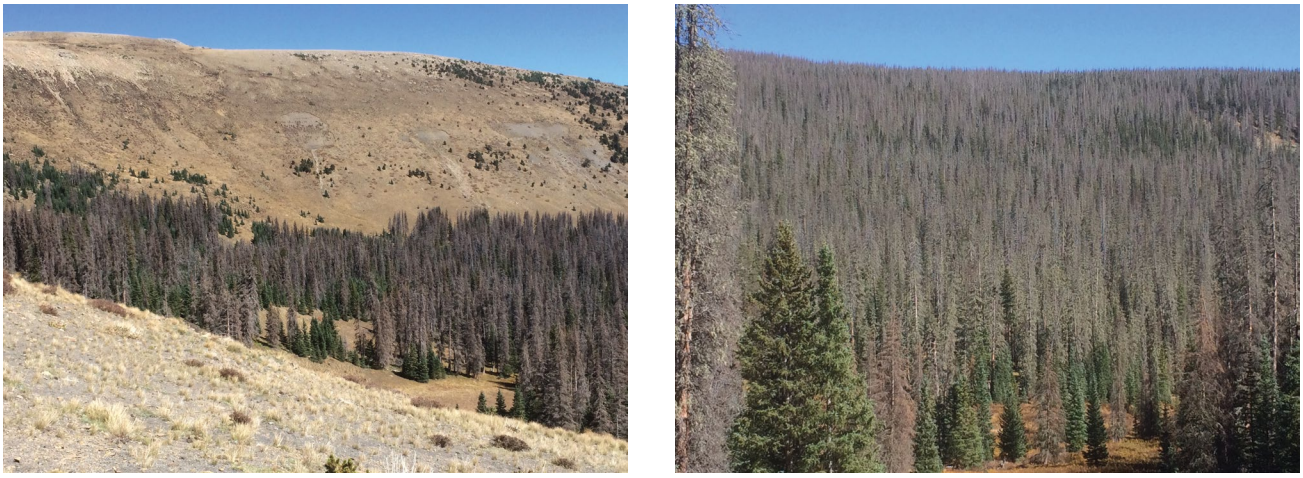

Figure 4.7b. Novel insect outbreak dynamics. Photos of extensive and unusually high-elevation Engelmann spruce (*Picea engelmannii*) mortality at and near upper treeline, caused by a combination of warming-amplified drought stress and an associated outbreak of the native spruce bark beetle (*Dendroctonus rufipennis*) killing over 80% of mature spruce trees across thousands of acres in the headwaters of the Pecos River in the Sangre de Cristo Mountains. *Photos by William deBuys (October 2020)*

Figure 4.8a. Start of the Las Conchas fire, June 26, 2011. *Photo by Craig D. Allen*

Figure 4.8b. Upper Cochiti Canyon in the Jemez Mountains seven weeks after being burned in the 2011 Las Conchas fire. High-severity fire affected almost the entire Cochiti Canyon watershed, from upper-elevation mixed-conifer forests along the rim of the Valles Caldera down to near the confluence with the Rio Grande. This extensive loss of vegetative cover across the watershed led to substantial flooding from 2011 to 2013. *Photo by Craig D. Allen*

Figure 4.8c. High-severity fire effects in desertified piñon–juniper woodland in the southeast Jemez Mountains in August 2011, 2 months after being burned in the Las Conchas fire. Note complete exposure of soil surface from fire consumption of all live and dead plant cover. *Photo by Craig D. Allen*

Figure 4.9a. Fire-caused type conversion from conifer forest to oak shrubland in the Dalton Fire footprint near Pecos, New Mexico. There is evidence that the increasingly large extent of post fire conversions of forests into potentially quite persistent shrublands is a novel recent development in New Mexico conifer ecosystems. *Photo by Craig D. Allen*

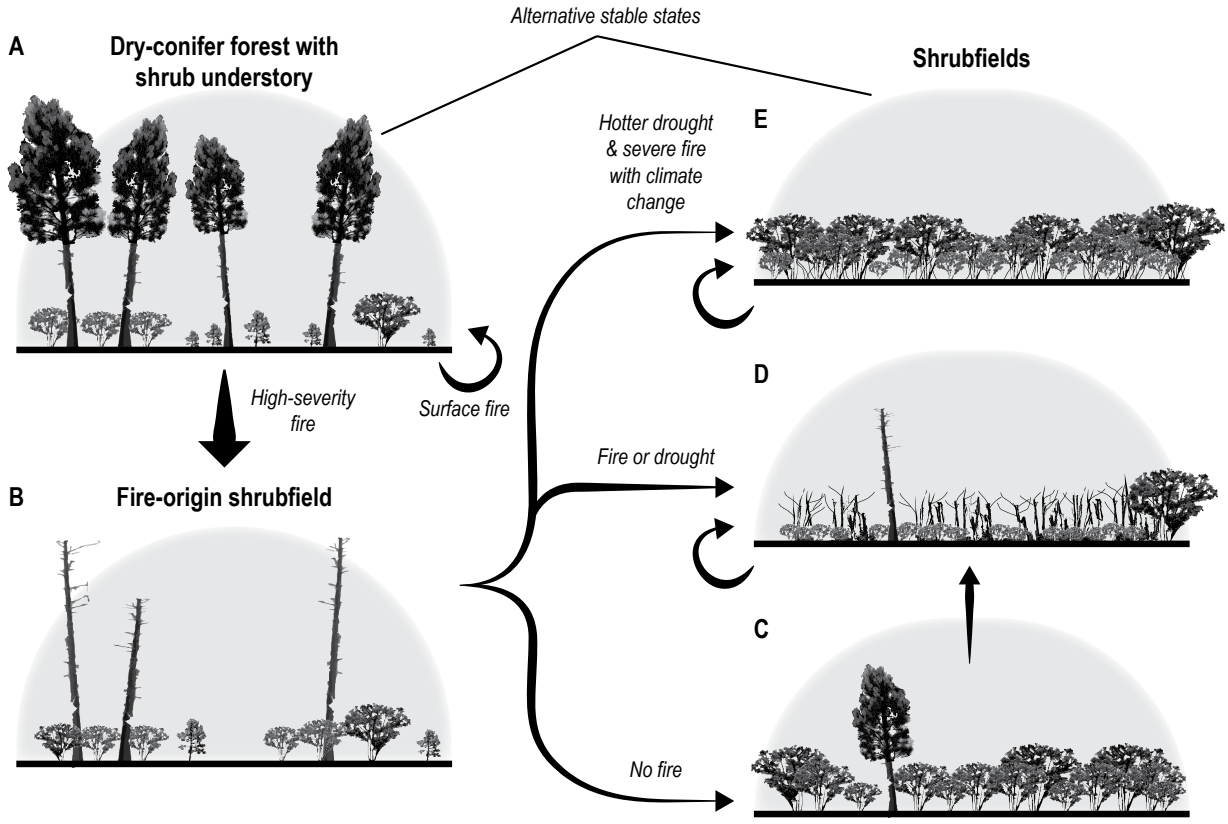

Figure 4.9b. Conceptual model of alternative post-disturbance stable states in dry conifer forest and shrub ecosystems of New Mexico, depending upon histories and combinations of disturbances. From Guiterman et al. (2018).

Figure 4.10. Gullies eroded by debris flows in upper Santa Clara Canyon, triggered by the 2011 Las Conchas fire. *Photo by Craig D. Allen (2015)*

soils that can amplify multiple individual disturbance processes (e.g., dieback, fire, erosion), which in turn also can interact with each other through diverse feedbacks (Allen, 2007) such as postfire debris flows (Figure 4.10).

ANTICIPATED EFFECTS OF ONGOING AND FUTURE CLIMATE CHANGE ON NEW MEXICO'S ECOSYSTEMS

Aquatic Ecosystems—Although aquatic ecosystems are outside the scope of this chapter, several broad assessments of climate change effects on the aquatic ecosystems of New Mexico are listed here. The New Mexico State Wildlife Action Plan (New Mexico Department of Game and Fish [NMDGF], 2016) reviews the characteristics and climate change vulnerabilities of New Mexico's diverse aquatic ecosystems, including a broad range of perennial systems (cold- and warm-water streams, lakes, cirques, ponds, marshes, cienegas, springs, seeps, cold- and warm-water reservoirs) and ephemeral systems (marshes, cienegas, springs, playas, pools, tinajas, kettles). In a separate effort, the U.S. Forest Service recently conducted an Aquatic-Riparian Climate Change Vulnerability Assessment (ARCCVA) of ongoing and potential effects of climate and drought at subwatershed scale (HUC12) for perennial and intermittent/ephemeral waters on all lands of Arizona and New Mexico (Wahlberg et al., 2021), built upon existing data for over two dozen intrinsic and climate-related indicators associated with watershed condition, riparian and aquatic habitat, and the presence of warm- and cold-water fish that represent both impact risk and adaptive capacity. The ARCCVA geodataset can be downloaded at: https://www.fs.usda.gov/detailfull/r3/landmanagement/gis/?cid=stelprdb5201889&width=full.

Biodiversity Considerations—New Mexico harbors an exceptional diversity of plants and animals, ranking fourth in the United States in the number of species (https://nhnm.unm.edu/). Climate change will have a broad range of effects on the plant and animal biodiversity of New Mexico that are beyond the scope of this chapter; however, several key sources of information relative to climate change effects on biodiversity in New Mexico are noted here. Natural Heritage New Mexico (https://nhnm.unm.edu/), a division of the Museum of Southwestern Biology at

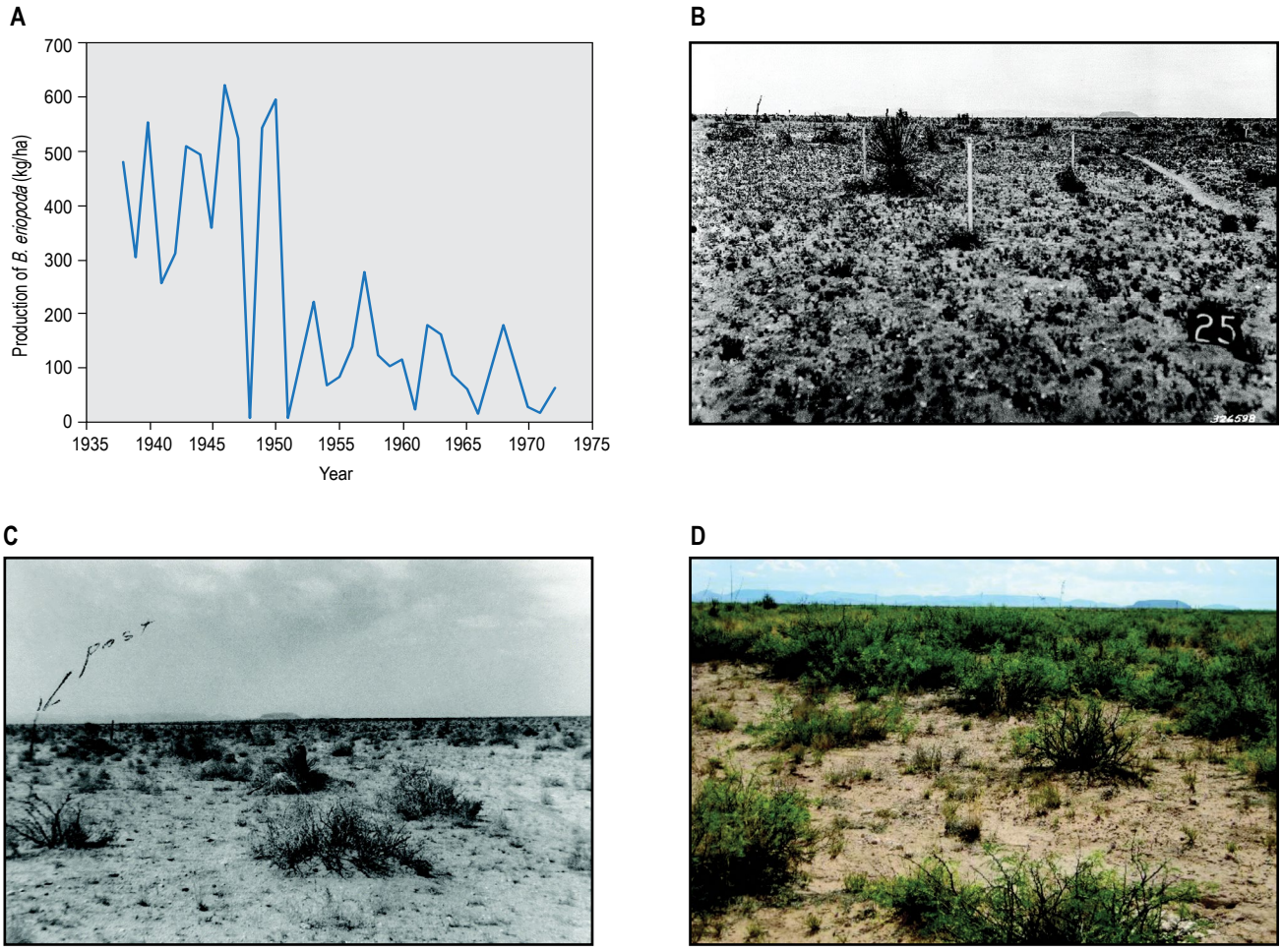

Figure 4.11. Evidence for a major historical grassland-to-shrubland transition in the Jornada Basin of southern New Mexico. (A) The initial collapse of black grama (*Bouteloua eriopoda*) production during the 1950s drought. (B) A 1936 photograph illustrating the effects of overgrazing during the 1930s drought. (C) The appearance of small honey mesquite (*Prosopis glandulosa*) shrubs in 1956. (D) The site in 2009, dominated by mesquite shrubs and with evidence of significant soil erosion exposing an indurated petrocalcic soil horizon (caliche). From Bestelmeyer et al. (2018).

the University of New Mexico, does climate-change-related research on the conservation and sustainable management of New Mexico's biodiversity and serves as a portal for acquiring and disseminating biodiversity conservation information for New Mexico. The New Mexico State Wildlife Action Plan (NMDGF, 2016) reviews the climate change vulnerabilities of New Mexico's terrestrial and aquatic ecosystems, with a focus on habitats for wildlife and fish. This State Wildlife Action Plan (SWAP) also addresses the climate change vulnerabilities of animal "species of greatest conservation need." Much additional detailed information on climate change implications for New Mexico's biodiversity is contained in a SWAP-associated online background document (Friggens, 2015). The New Mexico Rare Plant Conservation Strategy (New Mexico Energy, Minerals and Natural Resources Department, 2017) is focused on 235 rare and endangered plant species in New Mexico, including 109 endemic species that only occur in New Mexico and nowhere else in the world. The overall goal of the New Mexico Rare Plant Conservation Strategy is to protect and conserve New Mexico's rare and endangered plant species and their habitats, which are distributed among 135 Important Plant Areas (IPAs) across the state. The associated New Mexico Rare Plant Conservation Scorecard provides an analysis of the current conservation status of the 235 rare plants and addresses threats such as climate change.

***Forests and Woodlands*—**Future climate warming and increased precipitation variability are anticipated to directly depress regional woody-vegetation productivity (Williams et al., 2013; Munson et al., 2021) and promote Southwest forest die-offs from hotter droughts (McDowell et al., 2015; Goulden and Bales, 2019). In concert with the associated intensification of ecosystem disturbances, particularly high-severity wildfire (Bowman et al., 2020; Pausas and Keeley, 2021), ongoing warming in New Mexico montane forests and upland woodlands is expected to increasingly constrain tree regeneration (Davis et al., 2019; Rodman et al., 2020; Bailey et al., 2021; Nolan et al., 2021) and further amplify widespread vegetation type conversion from tree-dominated forests and woodlands to non-forest ecosystems (Allen, 2014; Guiterman et al., 2018; Coop et al., 2020; Davis et al., 2020). Drier, low-elevation distributions and ecotone margins of individual tree species and particular vegetation communities will tend to respond to growing drought and heat stress with early, rapid, and pronounced mortality-induced upslope range retraction (Allen and Breshears, 1998; Davis et al., 2019; Parks et al., 2019).

***Grasslands and Shrublands*—**Long-term research in southern New Mexico's desert grasslands finds that projected future climate warming and increased variability of wet/dry years will affect grass production and grass–shrub relationships (Peters et al., 2010; Gherardi and Sala, 2015; Gremer et al., 2015; Petrie et al., 2018). Multiple lines of evidence (from climate/vegetation monitoring, experiments, and models) indicate that these warm, semiarid/arid grasslands will see additional declines in perennial grasses and increases in shrubs (Figure 4.11; Archer et al., 2017; Bestelmeyer et al., 2018), reflecting a documented ongoing conversion of New Mexico's temperate drylands (e.g., desert and plains grasslands) to subtropical drylands (Schlaepfer et al., 2017; Bestelmeyer et al., 2018). However, in some grassland settings there may be drying of deep soils that could reduce shrub cover (Schlaepfer et al., 2017).

***Riparian Forests*—**As perennial streamflows decline and become more intermittent and ephemeral, riparian gallery forests of cottonwoods in areas like the Middle Rio Grande probably will become increasingly vulnerable to growth reductions and dieback from more variable and generally lower water-table depths (Rood et al., 2013; Thibault et al., 2017; Condon et al., 2020; Varney et al., 2020; Kibler et al., 2021). Meanwhile, opportunities for post-flood pulses of native riparian tree regeneration will diminish (Molles et al., 1998; Perry et al., 2012). Reductions in riparian vegetation canopy cover will have substantial warming effects on stream temperatures (Wondzell et al., 2019).

Overall, globally as well as regionally in New Mexico, currently there are substantial uncertainties regarding the specifics of how rapidly and profoundly New Mexico ecosystems will reorganize in response to these direct and indirect climate change effects as well as the particular outcomes of potentially novel post-disturbance vegetation trajectories (e.g., Figures 4.7a, 4.7b, 4.8b, 4.8c, and 4.9a). In addition, we should expect that many of the newly transformed vegetation communities that are emerging today will be ephemeral and subject to further reorganization as ongoing climate change drives continued direct and indirect ecosystem responses for the foreseeable future (Jackson, 2021).

Ecohydrological Impacts of These Climate-Induced Vegetation Changes Include—

1. Effects on the hydrological cycle of decreased vegetation cover such as increased evaporation, drier soils, and decreased transpiration that lead to positive feedbacks on regional warming and aridification in the southwest United States (McKinnon et al., 2021).
2. Variable effects of forest canopy change to snowpack and spring snowmelt runoff (e.g., Moeser et al., 2020; Bart et al., 2021; Belmonte et al., 2021). Twentieth-century declines in snowpack and water yield occurred as regional forest densification drove greater canopy snow interception, sublimation, and transpiration (McDonald and Stednick, 2003; Broxton et al., 2020); meanwhile, twenty-first-century declines in snowpack and water yield are observed from large forest cover losses due to more severe wildfire and forest dieback processes (Harpold et al., 2013; Biederman et al., 2015; Stevens, 2017 [although see Bales et al., 2018, for increased streamflow with reduced forest cover]), combined with direct effects of climate warming on snowpack dynamics (Milly and Dunne, 2020).

3. Direct or indirect reductions in forest biomass (e.g., through drought-induced dieback, fire, or mechanical thinning treatments) can substantially alter evaporation and transpiration, with potential to increase soil moisture (Belmonte et al., 2022) and streamflow (Bales et al., 2018; Bart et al., 2021) in some water-limited forest ecosystems.
4. Fire-driven changes in watershed runoff and erosion processes. These are addressed in Chapter 6 and Chapter 9.
5. Changing connectivity of upland bare soil surfaces that will affect runoff, infiltration, and geomorphic wind/water erosion processes (both directly through changes in vegetation cover and indirectly through disturbances). These are addressed in Chapter 5.
6. Recent warming-related land cover changes (woodland tree dieback and shrub encroachment) in New Mexico that alter site-level biophysical conditions (including aerodynamic conductance, albedo, and canopy conductance) in ways that can further increase surface temperatures (Duman et al., 2021), with potential for further intensification of surface warming with expected future reductions in soil water availability.

SUMMARY OF ECOSYSTEM IMPACTS AND RESPONSES

Climate is a fundamental driver of ongoing and future vegetation and ecosystem changes, with resulting effects on ecohydrological patterns and processes that will affect the distribution and abundance of water resources in New Mexico (Wilcox, 2010). While paleoecological evidence clearly demonstrates major past shifts in climate-vegetation across New Mexico's landscapes, the large magnitude and rapidity of recent and projected climate change is thought to be unprecedented during the past 11,000 years at least and probably much longer. Recent chronic warming, along with increasingly unprecedented episodes of extreme, hotter drought stress, have already driven substantial changes in New Mexico's vegetation over the past 20 years, foreshadowing massive reorganization of vegetation distributions and reductions in vegetative ground cover if current warming trends continue as projected (e.g., Jennings and Harris, 2017; Triepke et al., 2019). Such major alterations of New Mexico's vegetation would also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water-supply shortages for people, such climate-change-driven water stress could lead to increasing conflict between management of declining water availability for human use (e.g., irrigation) versus "wild" water retained for the maintenance of historical ecosystem values and services (e.g., Grant et al., 2013; NMDGF, 2016; Wahlberg et al., 2021). However, through collaborative translational approaches (Jackson, 2021), thoughtful anticipatory planning (Bradford et al., 2018), and forward-looking ecosystem management actions (e.g., Schuurman et al., 2020), there is also the potential for creative, adaptive conservation strategies that increase resilience to water shortages for both New Mexico ecosystems and our intimately linked human societies.

KNOWLEDGE GAPS, UNCERTAINTIES, AND STRATEGIC AREAS WHERE NEW MEXICO MIGHT WANT TO INVEST IN FURTHER RESEARCH

1. Further research is needed on the hydrological responses (e.g., changes in watershed evapotranspiration and in timing and magnitude of surface-water runoff) to observed and anticipated watershed vegetation changes and ecosystem disturbances. For example, watershed research in California's Sierra Nevada shows that direct or indirect reductions in forest biomass (e.g., through drought-induced dieback, fire, or mechanical thinning treatments) can substantially alter evaporation and transpiration in overgrown forests, with potential to increase both forest resilience and streamflow in some water-limited systems (Bart et al., 2021). Are these findings potentially relevant to our somewhat similar but also substantially different higher-elevation montane forest watersheds in New Mexico and southern Colorado?
2. The usefulness of today's complex, process-based models used to project vegetation dynamics in response to changes in climate drivers is currently limited by large uncertainties from several sources, including the lack of realistic ecosystem disturbance processes. Thus one

essential research need is to develop and incorporate more realistic, well-parameterized, and better-validated representations of ecosystem disturbance processes (e.g., climate-induced vegetation mortality, insect pest outbreaks, and wildfire) into process-based vegetation models, including synergistic interactions among disturbance processes.

3. A general complementary approach to constrain the large uncertainties associated with projections of future vegetation dynamics from current process-based models is the development of empirical models that are directly based upon observational data. One southwest U.S. example is the "forest drought stress index" of Williams et al. (2013), which is an empirical model of climate relationships to forest growth that also turns out to be strongly predictive of the regional extent of climate-related, tree-killing bark beetle outbreaks and high-severity fires.
4. Further research is needed to sort out variability in findings regarding the effects of shrub dominance on deep soil moisture and potential shrub-related aquifer recharge in some desert landscapes (Sandvig and Phillips, 2006; Schlaepfer et al., 2017; Schreiner-McGraw et al., 2020).
5. Long-term ecological monitoring and research that is field-based in and representative of the diverse range of New Mexico landscapes is needed to adequately document, sufficiently understand, and effectively address: (1) current uncertainties and the expectation of many further tipping-point surprises over the rate, magnitude, patterns, and drivers of ecosystem reorganization in New Mexico relative to projected climate changes over the next 50 years; (2) associated ecohydrological responses; (3) modeling needs for better parameterization and validation of climate-ecosystem process models; and (4) effective societal adaptations to anticipated climate change impacts to land and water resources (Bradford et al., 2018).

Mesa Portales, Sandoval County; *photo by Kevin Hobbs*

V. SOILS

Leslie D. McFadden, Anne C. Tillery and Craig D. Allen

Soils play a strong role in determining how New Mexico's diverse landscapes will respond to climate change. Soil cover acts like a sponge, holding in water that falls as rain or snow. The presence of soil supports vegetation and substantially reduces runoff and erosion. Soil enhances other processes such as infiltration of water and aquifer recharge. Soils can be damaged by a warming climate. Loss of vegetation in the Northwestern High Desert and Eastern Plains, where soils are not well developed and are easily damaged, will lead to dustier conditions in much of the state. On mountain hillslopes, the loss of vegetation cover in response to ongoing climate change will increase soil erosion, which then increases hillslope runoff. This in turn causes additional increases in soil erosion and bedrock exposure, which can largely prevent widespread recolonization by most plants, including trees. Soils on mountain hillslopes that face south, which are typically hotter and drier, will be damaged sooner by a warming climate than those on generally north-facing hillslopes that are slightly cooler and moister. Soils take many thousands of years to form, so these hillslopes will increasingly support sparse forests or, in some circumstances, be entirely deforested. These changes are already well underway in some mountains in New Mexico.

INTRODUCTION

This chapter considers how climate change will impact soils, landscapes, and water resources in New Mexico. In this chapter, studies of soils and their relationships in diverse landscapes, climatic regimes, and geologic settings are described to illustrate how such studies provide the basis for evaluating the impacts of ongoing climate changes on New Mexico's diverse landscapes over the next 5 decades. For general information on soil types across the state of New Mexico and landmark soil studies on rates and processes in soil formation across New Mexico, see Appendix B. Many recent studies have concluded that sustained periods of drought and extensive wildfires are causing significant erosion of hillslopes and soils in areas of New Mexico (see Chapters 4 and 5). The absence of soils on hillslopes is important because soils store water over large and continuous areas of hillslopes, and this fundamental aspect of soils supports recruitment by vascular plants. Moreover, the root networks of plant communities established in soils increase surface cohesion and enhance the infiltration/runoff ratio, thereby reducing erosion.

Two major questions concerning soils in New Mexico should be addressed:

1. Will climate-driven loss of soils, trees, and other vegetation in diverse landscapes of New Mexico (e.g., stable landforms of the Eastern Plains, hillslopes of mountain ranges) result in permanent changes to our landscapes, including increased runoff, irreversible soil erosion, and large-scale exposure of bedrock?
2. If soils over extensive areas of different landscapes are removed by erosion, how long will it take to form a new soil?

The loss of soils from landscapes impacts water resources because soils play an important role in the hydrologic cycle. The surfaces of most of Earth's landscapes are associated with a soil, or loose, unconsolidated sediment formed through weathering processes that break down bedrock. When it rains or snows, water can either move into the soil or sediment (infiltration) and sink through the soil or sediment (percolation) or it may accumulate at the surface and move downslope across the surface (runoff). Some of the water that moves below the soil may ultimately join deeper groundwater, a process referred to as recharge (see Chapter 3). Surface runoff may also cause erosion of soil, sediment, or even bedrock. In some circumstances, the saturation of the soil or weathered rock can trigger different kinds of mass movements, such as debris flows, slumps, or slow downhill soil "creep" (see Chapters 4 and 5). Eroded material is eventually transported to streams or rivers that ultimately deposit the sediment onto river floodplains and into lakes, reservoirs, and oceans.

The magnitude of runoff, infiltration, and recharge following precipitation on hillslopes is dependent on several variables including the steepness of the slope, the types and amounts of vegetation, the types and thicknesses of the soil and/or weathered surface materials, the amount of water in the soils prior to a precipitation event, and the overall surface area that is capable of producing runoff (Bierman and Montgomery, 2019). Thus, the distribution of various soil and sediment characteristics on hillslopes (such as soil thickness) plays an important role in the processes that directly or indirectly impact water resources in New Mexico. For example, future changes in climate that affect the spatial extent of soils in New Mexican landscapes (e.g., through increases in soil erosion; see Chapter 6) will have immediate impacts on water resources, as the removal of soil will strongly impact surface hydrological processes as well as substantially increase hillslope erosion (see Chapter 6) by increasing the proportion of runoff relative to infiltration. Climate changes that result in increases in soil temperature, evapotranspiration, and the depth of soil moisture movement will also have a significant impact on water resources, although these impacts will likely play out over longer time scales.

In considering these important questions, it is useful to understand the nature of the soils that exist in the diverse landscapes of New Mexico. A few key factors most strongly influence the rates, processes, and magnitude of soil development in our landscapes. Two important factors are relief (or topography) and parent material (the materials in which a soil forms; Jenny, 1941; Birkeland, 1999). Also, the length of time a soil has been forming is important, as many soil properties change with time. Finally, an especially important factor is climate. A conceptual approach that has been used for several decades to demonstrate how these soil-forming factors affect the development and evolution of soils on different kinds of landforms or in different climate regimes is called the Factors of Soil Formation or the CLORPT (climate, organisms, relief, parent material, and time; Birkeland, 1999) approach. Appendix B provides helpful background materials concerning the scientific study of soils and landscapes, including (1) overviews of the CLORPT approach, (2) studies that show the lengths of time over which many types of soils form, and (3) different hillslope types and how surface processes associated with hillslope affect soil development. In this chapter, studies of soils and their relationships in diverse landscapes, climatic regimes, and geologic settings are described to show how they provide the basis for considering the impacts of ongoing climate changes on New Mexico's diverse landscapes over the next 5 decades. Studies of how soil landscapes responded to changes in climate during the past few centuries extending to about 15,000 years ago (i.e., including global changes in climate following the last great ice age and those that have occurred since then) are also essential for increasing the reliability of predictions largely made on the basis of numerical modeling. Such studies are essential in predicting the consequences of ongoing climate changes that are already impacting the landscapes of New Mexico and which may well ultimately cause irreversible changes over the next several decades and beyond.

IMPACTS OF CLIMATE CHANGE ON SOIL LANDSCAPES IN NEW MEXICO

An increasing number of studies address the direct impacts of climate change on soil properties and soil formation, especially considering the potential contributions of carbon from the uppermost, organic-rich soil horizons to the atmosphere (e.g., Varney

et al., 2020). In New Mexico, where global climate models indicate a high probability of significant warming (see Chapter 2), some likely impacts on soil development and water resources can be predicted. Although changes in average annual precipitation over the next several decades will likely be relatively minor (see Chapters 1 and 2), increases in annual temperature and therefore soil temperatures in dryland environments, coupled with diminished vegetation cover, favor decreases in soil organic matter. This decrease is related to processes such as increased carbon mineralization caused by increased microbial activity and elevated carbon dioxide in the uppermost soil horizons (e.g., Pritchard, 2011), slight decreases in the average depth to which soil moisture will descend, and diminished soil-water availability (see also Birkeland, 1999; McFadden, 2013). Coupled with predicted increases in the frequency, intensity, and length of droughts (see Chapters 2 and 9), studies indicate that these changes will in turn change the rate at which carbonate (sometimes called caliche) forms in soils (McFadden and Tinsley, 1985; McFadden et al., 1991; Breecker et al., 2009).

***Impacts on Eolian Landscapes and Eolian Processes*—**Climatic changes over the next 50 years are likely to substantially influence the distribution and thickness of many soils in New Mexico. For example, windblown (eolian) sediments cover many areas of New Mexico, especially in northwestern New Mexico and in large areas of the Eastern Plains. At present, these particular eolian landscapes have been stabilized by vegetation (Lancaster and Marticorena, 2008), which has enabled formation of relatively weakly developed soils. A future loss of the plant community, mainly in response to warmer, sustained periods of drought, will likely lead to widespread destabilization of eolian landforms (Muhs and Maat, 1993; Madole, 1994; Forman et al., 2008; Ellwein et al., 2018). Although the presence of more well-developed soils will slow destabilization (Ellwein et al., 2018), research shows that destabilization—essentially a form of desertification (the transformation of a vegetated landscape to a largely barren desert)—is already underway in parts of northeastern Arizona (Bogle et al., 2015). Desertification of the vast eolian landscapes on the Colorado Plateau, a large part of which occurs in northwestern New Mexico (Figure 5.1) will allow large quantities of dust to be transported long distances by wind. The deposition of such dust on top of the snowpack on downwind mountain ranges has already led to early melting of snowpack (Painter et al., 2012).

Once these eolian landforms are destabilized, stabilization at some future time will require, at minimum, changes to an effectively less arid climate that enables colonization of active eolian landforms. Formation of soils that provide increased resistance to destabilization will require at least a few thousand years, as shown by results of studies of soil development in eolian landscapes in different parts of the American Southwest (Wells et al., 1990; Ellwein et al., 2018)

The extensive drylands of eastern New Mexico are dominated by soils that have either fine-grained/thin-surface horizons or thicker and more organic-matter-rich horizons, as in short-grass prairie soils. Such soils are especially vulnerable to deflation (erosion by wind of loose sediment) when subjected to extended drought-caused losses in vegetation and/or certain types of ground disturbance and/or heavy tilling. Lambert et al. (2020) reported that given the expansion of agriculture in many parts of the U.S. Great Plains, increases in drought and associated crop losses are already causing increases in erosion and dust emission. Farmers in Curry County and other parts of eastern New Mexico, observing drought-stricken fields, are concerned that future increased windiness could result in significant erosion and dust emission, essentially establishing a "new Dust Bowl" (*Albuquerque Journal,* Jan. 2, 2021). The rapid decline of the Ogallala Aquifer may force the abandonment of agriculture in parts of eastern New Mexico (Rawling, 2018), which will further increase deflation and dust emission, especially if warm season grasses are unable to effectively recolonize such landscapes in the increasingly warmer and more arid climate (e.g., Winkler et al., 2019).

Some researchers attribute the development of large areas characterized by small sand dunes formed around clumps of vegetation in arid regions of south-central New Mexico to increases in grazing pressure coupled with drought on formerly grassland-dominated landscapes (Gile et al., 1981). Even if grazing pressure on these landscapes is reduced over the next several years, given the inexorable increase in temperature and drought length and severity, reestablishment of native grasslands is unlikely, as noted above. Whether the substantial diminishment of

plant cover occurs on sandy or finer-textured surfaces of landscapes in the drylands of New Mexico, a significant increase in deflation of unconsolidated surficial materials by seasonally strong winds is virtually assured. Accordingly, the response of large regions of eastern and south-central New Mexico to the next 50 years of climate and environmental change is almost certainly increasing desertification, accompanied by increasing dust emission and increased erosion on hillslopes, as described in the following section.

***Increased Erosion on Hillslopes*—**Over the next 5 decades, climate change will alter the soils that currently exist on the hillslopes of New Mexico. Climate change substantially affects many hillslope processes in hot, arid landscapes that have basin-wide impacts on soil and landscape evolution (Bull, 1991; Figure 5.1). Bull (1991) proposed that significant increases in temperature and aridity would cause increases in hillslope runoff and erosion by reducing vegetation cover. Such a climate change occurred during the transition between the cooler climate of the late Pleistocene (the last glacial period of the 2.6-million-year Pleistocene Epoch) and the much warmer Holocene (approximately the last 12,000 years, referred to as an interglacial period). The soil and weathered rock eroded from hillslopes ultimately caused ephemeral streams to deposit the sediment on alluvial fans.

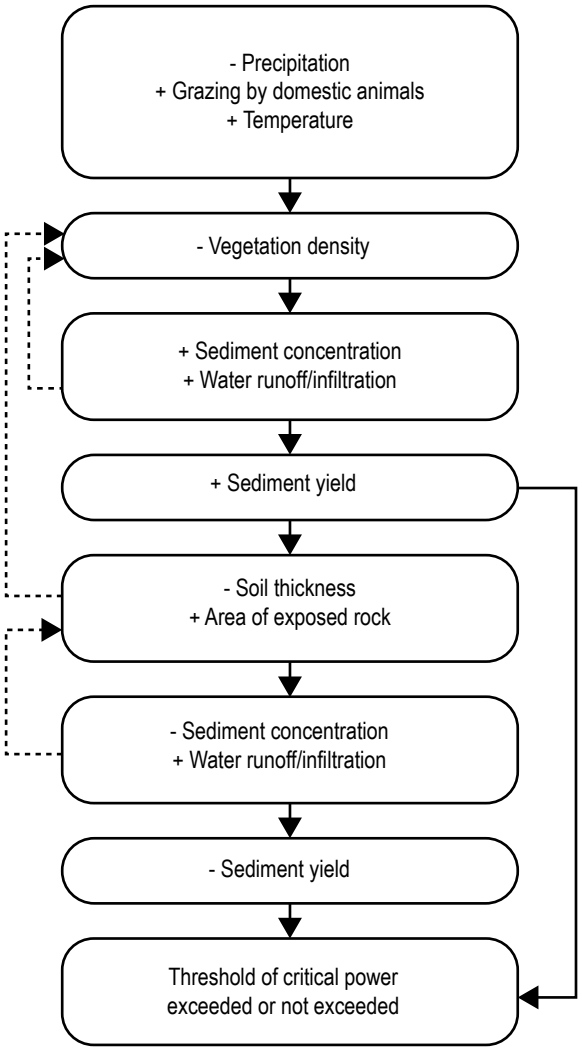

Figure 5.1. A flow diagram showing increases (+) and decreases (-) in variables involved in processes associated with sediment transport on hillslopes and deposition on alluvial fans in deserts (after Bull, 1991). "Critical power" signifies the power associated with water flowing in a stream channel needed to transport the sediment load. Feedbacks are indicated by dashed lines.

Substantial increases in average annual global temperature have occurred during all previous glacial-to-interglacial sequences, and changes in climate of a smaller magnitude have occurred during the Holocene. Paleoclimatic research in the southwestern United States also demonstrates that during previous interglacial periods there have been shorter intervals of increased warm temperatures (Fawcett et al., 2011), a pattern somewhat analogous to present circumstances. Geomorphological and paleoclimatological studies, in addition to providing insight into the behavior of eolian landscapes, provide insight into how an increasingly warmer climate in New Mexico over the next several decades might affect hillslopes and soils.

An important aspect of the Bull (1991) model is that diminished hillslope vegetation substantially increases the erosion of soils, thus increasing bedrock exposure. Ongoing research in the eastern Mojave Desert provides important new insights concerning

the impacts of climate change on hillslopes associated with rocks resistant to chemical weathering in a high desert setting (Persico et al., 2016; McAuliffe et al., 2019; Persico et al., 2019; Persico et al., 2022). This body of research generally confirmed the Bull (1991) model, showing that climate changes after the end of the last ice age caused substantial increases in erosion, substantial loss of soil mantle, and substantial increases in bedrock exposure on hillslopes. However, these responses to climate change are most strongly expressed on south-facing hillslopes, and they occurred several thousand years following the end of the Pleistocene Epoch. The contrast between north-facing and south-facing hillslopes in the same geographic area are illustrated in Figures 5.2A and B. The south-facing hillslopes have large areas of bedrock and/or a thin layer of unconsolidated, weathered material that can move downslope under the influence of gravity (colluvium) over the bedrock (Figure 5.2B). Isolated remnants of much thicker but stabilized colluvium on which a soil has developed that supports warm-season grass occur on these hillslopes. Field studies show that these hillslopes once had a continuous cover of colluvium and soil. Because soil horizons in many dryland soils contain a large amount of accumulated eolian dust (McFadden, 2013; Persico et al., 2022), the timing of the accumulation of the dust can be dated. This enables determination of the timing of the formation of the soil and the age of the formerly continuous hillslope cover of colluvium. The dates show that the soils started forming over 20,000 years ago, at a time when paleobotanical studies show that a piñon–juniper woodland with intercanopy grass

A

B

Figure 5.2. (A) Smooth vegetation and soil-mantled, north-facing hillslopes in a semiarid region of the eastern Mojave Desert, California. Such hillslopes are regarded as transport-limited slopes. See text for details. (B) Close-up of a sparsely vegetated and locally bedrock-dominated detachment-limited or weathering-limited hillslope located on south-facing hillslopes only a few hundred meters from north-facing hillslopes shown in Figure 5.2A. *Photo by Les McFadden*

was present. The warming and increasingly more arid climate after the end of the ice age caused the loss of the woodland. However, the only extensive alluvial deposit and associated river terrace present in this area is about 3,000 years old. This indicates that the presence of a grass community in the semiarid climate of the Holocene acted to resist erosion until well into the Holocene.

On smooth, curvilinear, north-facing slopes (Figure 5.2A), the soil is nearly continuous and supports a grass-dominated vegetation community. This type of hillslope develops when the rate of weathering and soil formation exceeds the rate of hillslope erosion. Why did the north-facing hillslopes respond so differently than the south-facing hillslopes, despite the fact that they have identical rock types and are subject to the same regional climate? The answer is that in the northern hemisphere, south-facing hillslopes receive a greater amount of sunlight than north-facing hillslopes. Burnett et al. (2008) showed that this topographically driven difference in climate (referred to as topoclimate) is large enough to cause differences in soil temperature and moisture content. Thus, although the north-facing hillslopes lost the piñon–juniper woodland at the beginning of the Holocene, the slightly cooler and moister conditions (mesic conditions) enabled the retention of a grass community. Accordingly, in marked contrast to the warmer and drier south-facing hillslopes (xeric conditions), the continuous grass cover greatly minimized erosion.

This research demonstrates how considering hillslope aspect allows assessment of the varied impacts of climate change on the magnitude of erosion and sediment production from hillslopes that have different kinds and thicknesses of soils and contrasting plant communities. Research in dryland regions shows that the development of moderately developed soils that support plant communities and resist erosion requires many thousands of years (Appendix B). Once stripped from hillslopes, their reestablishment will require substantial lengths of time—as long as many thousands to tens of thousands of years.

Changes in climate during the last 12,000 years (since the end of the last glaciation) have resulted in episodes of increased wildfire frequency and severity on the higher-elevation, forested hillslopes of the Southern Rocky Mountains, Jemez Mountains, and Sacramento Mountains (Anderson et al., 2008a; Fitch and Meyer, 2016; Frechette and Meyer, 2009; see Chapters 4 and 5). Both tree-ring (dendrological) studies and assessment of fire-related alluvial deposits show these episodes are correlated with periods of climate warming and/or drought severity over the past 5,000 years. Observed increases in sediment deposition during the Holocene in these areas are interpreted to reflect increased erosion of hillslope soils (see Chapter 6 for extended discussion of impacts of wildfires on hillslopes and river channel responses). The strongly correlated radiocarbon-dated fire-related deposits and paleoclimatic evidence for periods of warming and/or extended droughts show that the erosional response of hillslopes to periods of wildfire is extensive and occurs over a short period of time. Numerous studies in the Bandelier National Monument area located on the Pajarito Plateau (see Chapters 4 and 6) also provide evidence of the impacts of recent warmer temperatures, drought, land use, and wildfire on hillslopes and soils (see Chapters 4 and 6 and associated citations).

Fitch and Meyer (2016) demonstrated that climatic differences related to hillslope aspect strongly influenced the postfire erosion response to the 2002 Lakes fire in the Jemez Mountains of New Mexico. Whereas fire-related alluvial deposits constituted over three-quarters of the fan sediments derived from north-facing basin hillslopes, fire-related deposits made up only about 40% of fan sediments from the south-facing and more xeric basin hillslopes. The researchers concluded that south aspects produce more runoff and sediment given their sparser vegetation and increased bedrock exposure; the north-facing and more mesic hillslopes mantled by soil produce much less runoff and sediment unless they are severely burned. The researchers also concluded that the magnitude of the erosion and deposition produced by this fire was larger than any other postfire response in the Jemez Mountains in the last several thousand years. They attributed this to extreme drought and fuel loading associated with fire suppression.

Effects of Bedrock Type on Hillslope Erosion— Research in semiarid, piñon–juniper-dominated hillslopes in different areas of the southwestern United States demonstrates that the type of bedrock in drainage basins strongly influences rates of weathering, soil development, vegetation, and erosion

(McFadden and McAuliffe, 1997; Persico et al., 2011). Accordingly, climate changes affect drainage basins associated with different rock types in different ways. For example, studies show that the sandstone of the Jurassic Morrison Formation and the Bluff Sandstone are especially sensitive to changes in climate, as they are rapidly weathered by wetting–drying cycles (McAuliffe et al., 2006; McAuliffe et al., 2014). When rainwater soaks into this kind of bedrock, the water interacts with some of the clay minerals that bind the sand grains together. The clay absorbs the water and expands, but when soil temperatures increase, this causes loss of the water from clay (a process called dehydration) and the clay shrinks. Over time, many expansion–contraction cycles cause weakening of the clay cement and disintegration of the sandstone bedrock (Tillery et al., 2003). This process favors the rapid weathering of the clay-cemented sandstone and the formation of weakly developed soils in only a few decades on north-facing hillslopes (McAuliffe et al., 2006; McAuliffe et al., 2014) because, as noted above, north-facing hillslopes favor cooler temperatures and a moister, mesic environment than do south-facing, xeric hillslopes. The mantle of soils on the former hillslopes is continuous and able to support a piñon-pine community on a smooth, curvilinear hillslope. Geoscientists who focus on studies of the origin and evolution of landscapes refer to this type of hillslope as transport-limited (Figure 5.3; Appendix B). The south-facing hillslopes in these areas that formed on the same sedimentary rocks are very different; they are generally much steeper and have a much greater area of exposed bedrock and much less vegetation cover. This kind of hillslope is referred to as weathering-limited (Figure 5.4; Appendix B). As in the eastern Mojave Desert study area, the contrasts in hillslope form and soils in the northeastern Arizona site and their responses to climate change also can be attributed to differences in aspect-related temperature and soil moisture—conditions that in turn influence soil development and hillslope character (Burnett et al., 2008).

Figure 5.3. Smooth, soil- and vegetation-mantled, north-facing, transport-limited hillslopes with a piñon forest formed on Jurassic sandstone in a semiarid climate in northeastern Arizona. After Figure 9 in McFadden (2013).

Evaluation of soils and vegetation, studies of tree-ring growth (Scuderi et al., 2008; McAuliffe et al., 2006; McAuliffe et al., 2014), and studies of erosion associated with large monsoon storms (Wawrzyniec et al., 2007) show that smooth, soil- and vegetation-mantled hillslopes are very quickly changing into steeper and sparsely vegetated hillslopes (Figure 5.5). On the basis of detailed dendrological, soil, and other studies, McAuliffe et al. (2006; 2014) attributed this change to sustained periods of drought during the last few centuries that were abruptly followed by monsoonal storms and/or tropical cyclones. Their studies documented substantial losses of perennial grasses and perennial herbaceous plants caused by the 1999–2002 drought in this area and over much of the Southwest. Substantial reduction, or even complete loss, of these plants and their root networks allowed significant soil erosion and bedrock exposure that was caused by an unusually large monsoonal storm (Wawryzniec et al., 2007). Longer droughts and warmer temperatures over the next 50 years will likely accelerate similar changes to hillslopes in southwestern drylands on similar rock types. In New Mexico, the smooth, soil- and vegetation-mantled hillslopes shown in Figure B.5 in Appendix B are northwest-facing, whereas the southwest-facing hillslopes formed on identical sedimentary rocks in the same field area are essentially bare of soil and vegetation and have many steep cliffs (Figure B.6 in Appendix B). Geologic maps of New Mexico (New Mexico Bureau of Geology and Mineral Resources, 2003) show that rocks like the sedimentary rocks of northeastern Arizona—rock types that are very sensitive to climate warming and droughts—are also present in New Mexico. Over time, as climate change reduces vegetation and soil erosion accelerates, the northwest-facing hillslopes will assume the form of the southwest-facing hillslopes. Given the results of the studies in northeastern Arizona, these changes will occur rapidly, likely over decades to centuries.

The study by Persico et al. (2011) in the foothills of the Sandia Mountains provides another example of the important role rock type plays in soil- and hillslope-forming processes as they are affected by climate changes (see Appendix B, Figure B.8). The Sandias are composed mainly of Sandia Granite and are characterized by bedrock-dominated (weathering-limited) core-stone hillslopes, which consist of bare, fractured, ellipsoidal blocks of granite, as illustrated in the lower left corner of Figure 5.6. Core-stone hillslopes have small patches of thin, weakly developed soils between the large core-stones. Where small, tabular bodies (geologists call these features dikes) of a rock type called aplite (a fine-grained, granite-like igneous rock) occur in the granite, the aplite breaks down to large blocks that accumulate on hillslopes below the dikes. The blocks efficiently entrap windblown dust, a process that eventually causes the formation of a thick, well-developed soil (as described in Appendix B, Figure B.8; McFadden, 2013). These smooth, soil-mantled hillslopes (Figure 5.6) have been stable for tens of thousands of years. Ongoing shifts in climate that reduce vegetation cover will accelerate erosion of these soils, although far more slowly than the very rapid soil erosion rates of soils formed on the sedimentary rocks in the northeast Arizona study area. The results of the Persico et al. (2011) study indicate the soils could potentially persist for several thousand years, unless the hillslope vegetation and soils are subjected to wildfire, as discussed in the following section and in Chapters 4 and 5.

***Changes to High-Elevation Soils and Hillslopes: The Next 50 Years*—**What insights do soil studies at lower-elevation, piñon–juniper forests in a semiarid climate provide about the possible impacts of the next 50 years of climate change on forested, higher-elevation settings in New Mexico? There is little doubt that there will be continued changes in vegetation in response to future increases in temperature, drought, and wildfires (see Chapter 4). As many studies have already demonstrated, this will both substantially reduce soil infiltration and canopy cover and increase soil erosion. This and other research suggests that at higher-elevation settings, many hillslopes with continuous soil mantles and vegetation will begin to shift to hillslopes with discontinuous soils, generally thinner soils, and larger areas of exposed bedrock. In some areas, virtually complete loss of soils and most vegetation is possible. As noted in the introduction to this chapter, such changes will have large impacts on surface hydrology, shallow-subsurface water flow, groundwater recharge, and the behavior of streams and rivers. Hillslopes in many areas of the state will become bedrock-dominated hillslopes that are largely incapable of enabling widespread recruitment of plants better adapted to future, higher-average temperatures. More xeric conditions are a virtual certainty.

Figure 5.4. Steep, bedrock-dominated, south-facing, weathering-limited hillslopes formed on Jurassic sandstone in a semiarid climate in northeastern Arizona. These south-facing hillslopes are located less than 50 m from the north-facing hillslopes shown in Figure 5.3. *Photo by Les McFadden*

Figure 5.5. Recent erosion and exposure of Jurassic sandstone on east-facing hillslopes located between hillslopes shown in Figures 5.3 and 5.4. Erosion is rapidly removing a once-continuous soil associated with formerly transport-limited hillslopes and transforming them into steep, bedrock-dominated, detachment-limited hillslopes. The seated geologist is examining recently exposed roots associated with cliffrose plants that are established on remnants of the soil visible on the right side of the photograph. The geologist at right is standing on a calcite-cemented concretion that is more resistant to weathering and erosion than the clay-cemented bedrock. This observed very rapid change in hillslope form is most likely caused by the impacts of recent decade- to centennial-scale climate changes. After Figure 11 in McFadden (2013). *Photo by Les McFadden*

Local bedrock types are, as described above, an important factor. Rocks that are less resistant to weathering and erosion are abundant in the landscapes of New Mexico, and they will likely respond to climate changes rapidly, leading to major losses of associated soil mantle after the stabilizing vegetation canopy has withered. Recolonization may take considerable time (see Chapter 4). As soils are eroded on hillslopes, exposed bedrock will generate more runoff than soil- and vegetation-covered hillslopes do. Increased runoff will erode the remaining soils, further increasing bedrock exposure and constituting self-reinforcing positive feedback. Trees may eventually be able to colonize certain areas of these future hillslopes, but the forests will likely be sparse (see Chapter 4). Formation of new soil takes a minimum of several centuries—more likely, many thousands of years. Even those plant species adapted to future warmer conditions will be unable to quickly recolonize cooler, higher-elevation environments that lack substantial soil cover.

What conditions would potentially prevent or perhaps minimize soil erosion in higher-elevation hillslopes subject to drought and wildfire? Such conditions would be present on those hillslopes with thick deposits of coarse colluvium, talus, and glacial till. These parent materials (1) favor accumulation of fine, windblown sediment and development of soils over a generally greater thickness; (2) have generally higher infiltration rates and permeability relative to bedrock; and (3) have relatively lower erosion potential. To some extent, the abundance of colluvium and talus on these hillslopes reflects the presence of steep, bedrock-dominated topography

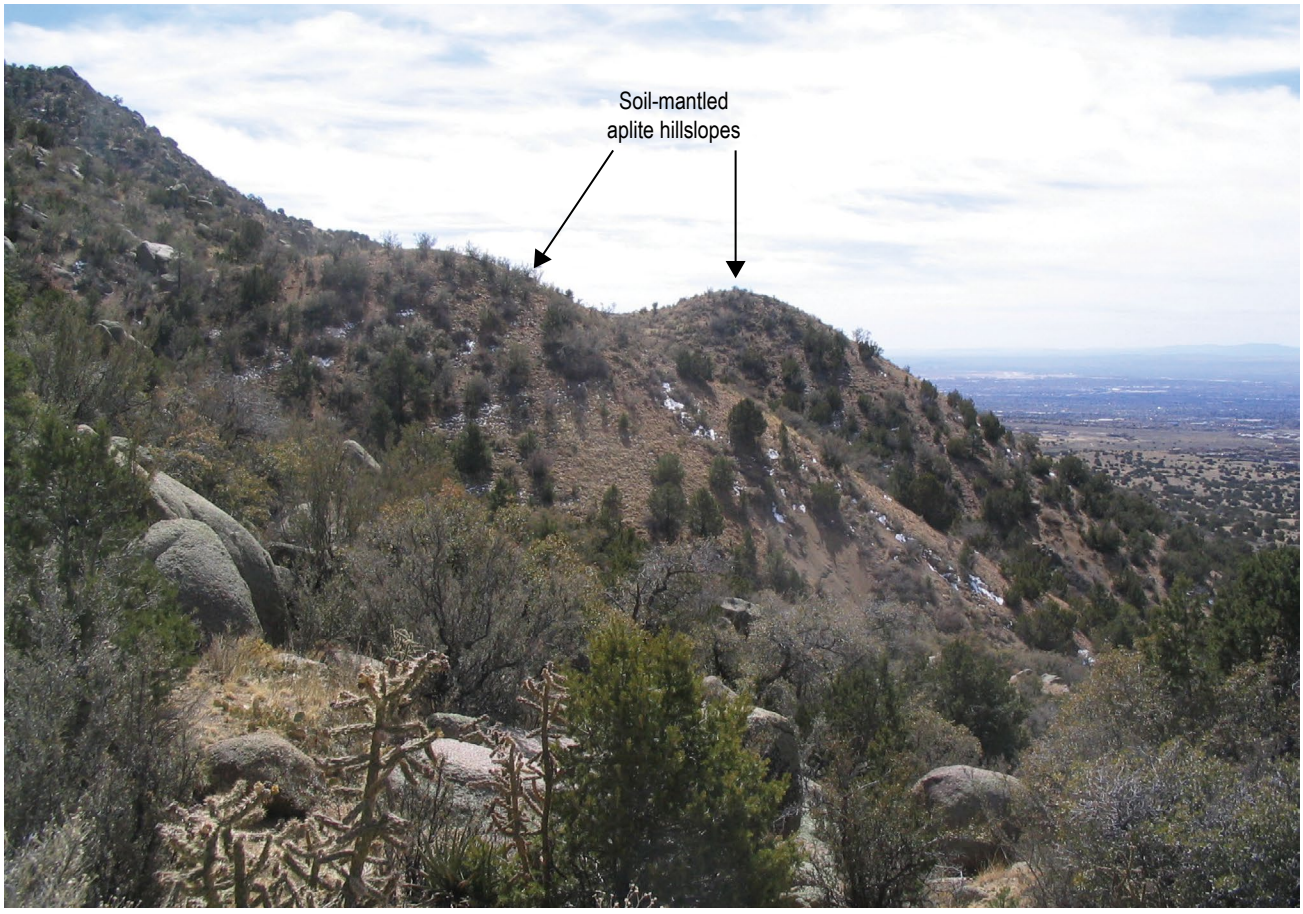

Figure 5.6. Core-stone-dominated hillslopes (in left foreground) are the dominant kind of hillslope in the Sandia Mountains foothills formed on granitic rocks. Two smooth, soil-mantled, transport-limited hillslopes are labeled. Understanding how such soils and hillslopes form provides the basis for predicting how they have responded to past climate changes and how they may respond to the next 50 years of climate change. *Photo by Les McFadden*

in much of the highest elevations of these mountain ranges (Figure 5.7). Such mountain ranges, including the Sangre de Cristo and San Juan Mountains, have been subject to alpine glaciation during at least the last few million years. The legacy of long durations of glacial climate on the surface processes during the Pleistocene greatly complicate study and evaluation of the soils and landforms of high-elevation mountains as well as the impacts of ongoing climate changes in these areas (Aldred, 2020). For example, shattering of bedrock in high-elevation alpine zones is an efficient mechanism for producing large volumes of colluvium, talus, and scree—angular rock debris that accumulates along and at the base of hillslopes (Bierman and Montgomery, 2019). Frost shattering undoubtedly was an important weathering process at elevations that in the currently warmer climate of the Holocene are no longer subject to this kind of weathering. The combination of high relief and strong rock types such as granite is also conducive to the generation of steep, bedrock-dominated hillslopes, especially in high-elevation mountains that supported large glaciers during the Pleistocene. Many hillslopes in formerly glaciated mountains in New Mexico formed as a result of the deposition of glacial till and resultant development of ridges and hummocky landforms called moraines in the Pleistocene (see Appendix B). The presence of soils that have formed in the last 12,000 years on hillslopes composed of bouldery, morainal sediment or talus that resist erosion and stripping following wildfires may enable recolonization by some plants, including trees (see Chapters 4 and 5 for an in-depth overview of ecological succession and wildfire impacts).

Figure 5.7. Alpine hillslopes, Sangre de Cristo Mountains. The steepest, largely unvegetated hillslopes in the midground are an excellent example of rock-dominated, detachment-limited hillslopes (see Appendix B for explanation). The dominance of such hillslopes at the highest elevations of this mountain range is largely attributable to previous periods of glaciation. Frost shattering is a key physical weathering process operating on such hillslopes, and the products of this process (talus and colluvium) are accumulating on the hillslopes. The lower-elevation, smooth and vegetated hillslopes in the background are examples of transport-limited (or weathering-limited) hillslopes (see Appendix B). Photograph taken from the summit of Wheeler Peak at an elevation of 13,160 ft. *Photo by Les McFadden*

These changes in the soils and geomorphology of higher-elevation hillslopes may result eventually in the development of increasingly sparse vegetation on hillslopes that are characterized by a discontinuous, patchy pattern of soil cover and a more extensive exposure of bedrock. These conditions will be irreversible over time scales of thousands or more years. The climate of New Mexico has been subject to major glacial-to-interglacial changes during the last 2.6 million years. Throughout the western United States, major mountain plant communities responded by migrating to higher altitudes during changes to warmer conditions and to lower altitudes during changes to cooler temperatures (Betancourt et al., 2016). The average elevation change of these shifting communities was as much as 2,500 ft (Spaulding, 1990). We should expect New Mexican plant communities to shift upward in elevation in response to future warming. Of course, migration to higher-elevation hillslopes will not be a practical option for those plant communities that already occupy the highest elevations of any mountain range or where yet-higher-elevation hillslopes are completely dominated by bedrock. In the state's highest mountains, soils and sediments that can support plants may survive the aftereffects of wildfire (see Chapter 4 for an extended discussion of ecological dynamics and related topics).

It is highly likely, however, that in 50 years hillslopes will exhibit the initial, if not a more advanced, stage in a transformational shift from soil-mantled to more bedrock-dominated slopes. Cooler and effectively moister conditions exist at increasingly higher elevations in mountain ranges or, in the northern hemisphere, at increasingly more northerly latitudes. Thus, species of trees that now exist at lower elevations and are subject to a warming climate (see Chapter 2) could potentially thrive in higher-elevation settings (or at more northerly latitudes). However, the changing nature of the hillslopes, as specifically reflected in the diminished cover of soil, will likely favor the development of a sparser, patchy forest. The results of soil geomorphological research strongly suggest that the changes in hillslope character described in this chapter will be irreversible on human time scales.

SUMMARY

1. Soils influence how New Mexico's diverse landscapes have responded and are responding to climate change.
2. Soil cover acts like a sponge, holding water during times of rain and snow. Because many soils retain much of this infiltrated water, they also support vegetation. The presence of vegetation intercepts rain, reducing runoff, and the presence of soils increases evapotranspiration and favors shallow-subsurface flow. Lack of soils substantially increases surface runoff and reduces recharge.
3. In the drylands of New Mexico, loss of vegetation due to climate change increases erosion, in many cases caused by wind. In the Eastern Plains, large amounts of dust will be produced. The landscapes of northwest New Mexico contain many windblown deposits of sand (e.g., sand dunes). Those dunes not stabilized by well-developed soils are undergoing reactivation. Desertification will only increase as temperatures rise in New Mexico over the next 50 years, resulting in many negative agricultural and health impacts.
4. At the end of and following the last ice age, climate changes characterized by increases in global temperature occurred; for New Mexico this resulted in increased frequency and intensity of drought and wildfires as well as overall aridity. Studies that show how New Mexico's landscapes responded to those climate changes provide deep insights into how ongoing climate changes and future changes will affect New Mexico water resources over the next 50 years and beyond.
5. On mountain hillslopes, the loss of substantial vegetation cover in response to ongoing climate change is increasing soil erosion. On some hillslopes, soil erosion is increasing the area of exposed bedrock, which then increases hillslope runoff. This in turn causes additional increases in soil erosion and bedrock exposure.
6. Hillslopes that have effectively hotter and drier topoclimate (e.g., generally south-facing) will respond sooner to a warming climate than hillslopes with slightly cooler and effectively moister topoclimates (e.g., generally north-facing).

7. Bedrock-dominated hillslopes largely prevent widespread recolonization by most plants, including trees. (Other impediments to recolonization are presented in Chapter 4.)
8. Soils can take many thousands of years to form, so loss of soil on hillslopes will lead to fewer or more sparse forests or, in some circumstances, total lack of tree colonization. These changes are already well underway in some mountains in New Mexico. This is the future for most of our mountain landscapes over the next several millennia.

KNOWLEDGE GAPS

1. New Mexico's high-elevation mountain ranges provide much of the surface flow to our rivers and groundwater recharge to our aquifers. Therefore, more soils and geomorphic research in high-elevation mountains is essential. Unfortunately, outside of the Jemez Mountains, a survey of the relevant literature in peer-reviewed journals and other publications reveals that relatively little soils and geomorphological research on the mountains of New Mexico has been conducted. Accordingly, future research efforts in these mountains should include characterization and evaluation of hillslope-aspect-related contrasts in soils, plant communities, and geomorphology. Data provided by these studies can be input into numerical models to calculate the net soil loss from hillslopes as functions of topography, vegetation, and other variables. Models which determine potential soil loss and sediment delivery have been successfully used to calculate potential soil erosion and sediment production from drainage basins in the upper Santa Fe Municipal Watershed (Lewis, 2018).
2. New Mexico's upland forests are a precious state resource. Ongoing paleoclimatic and paleobotanical research (Fawcett et al. 2011; Staley et al., 2022) is shedding new light on the impacts of episodic intervals of increased warming during past interglacial periods on forest communities—a pattern of climate change that serves as a potential analogue for present and future warming. More such research is needed.