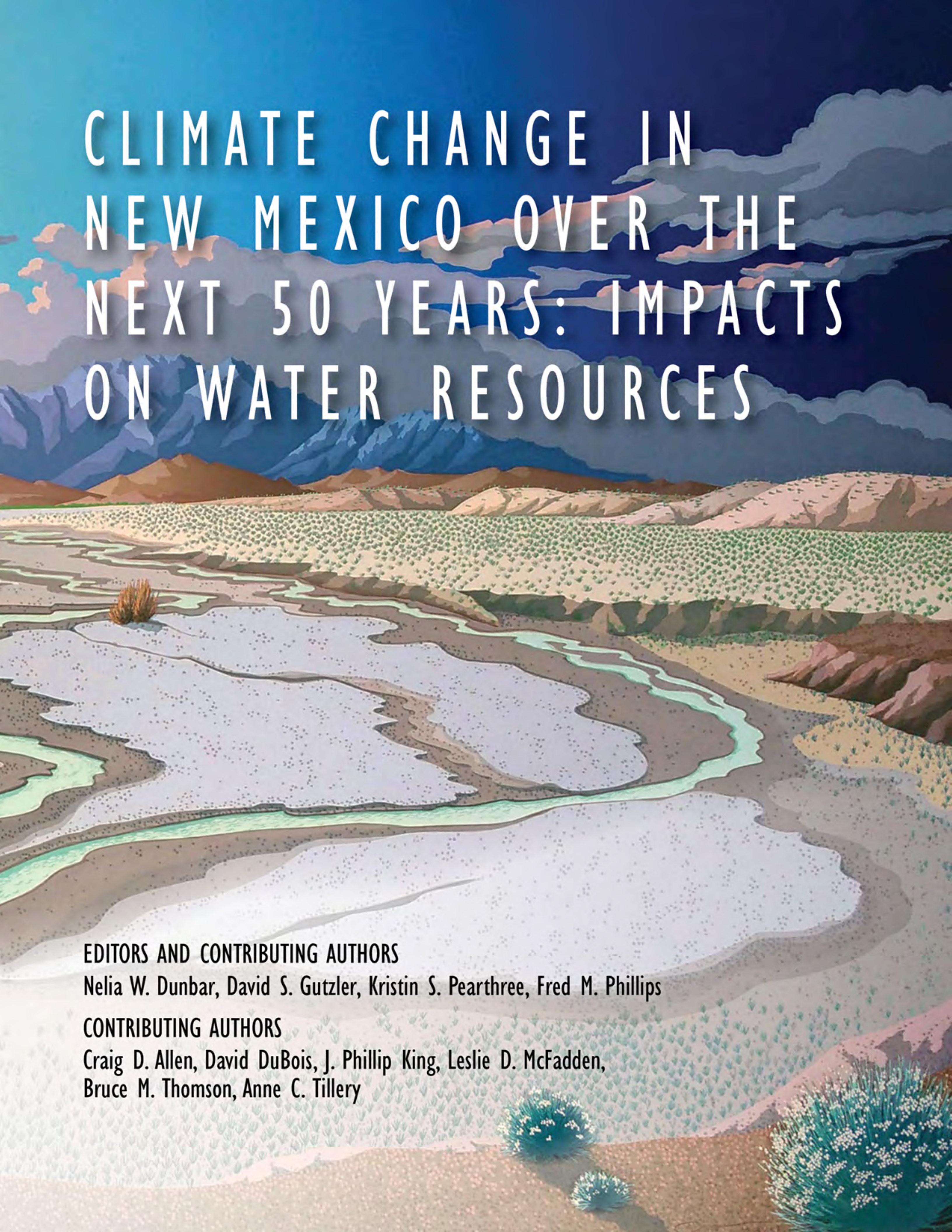
CLIMATE CHANGE IN NEW MEXICO OVER THE NEXT 50 YEARS: IMPACTS ON WATER RESOURCES



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New Mexico Bureau of Geology and Mineral Resources

Established by legislation in 1927, the **New Mexico Bureau of Geology and Mineral Resources** is a research and service division of the New Mexico Institute of Mining and Technology (New Mexico Tech). The Bureau of Geology is a non-regulatory agency that serves as the geological survey for the State of New Mexico. Through our offices, website, and publications, our staff serves the diverse population of our state by conducting research; distributing accurate information; creating accurate, up-to-date maps; providing timely information on potential geologic hazards; acting as a repository for cores, well cuttings and a wide variety of geologic data; providing public education and outreach through teaching and advising, our world-class Mineral Museum, and teacher/student training programs; and serving on geoscience-focused boards and commissions within the state. There is something at the Bureau for everyone who has ever wondered about the exceptional geology of New Mexico.

The **New Mexico Interstate Stream Commission** (NMISC) is a sister agency to, and administratively attached to, the New Mexico Office of the State Engineer. NMISC activities are overseen by eight appointed Commissioners in addition to the State Engineer, who serves as the Commission's Secretary. The NMISC oversees New Mexico's obligations and entitlements under eight interstate stream compacts to which New Mexico is a party. To ensure compact compliance, NMISC staff analyze, review, and implement projects in New Mexico and analyze streamflow, reservoir, and other data on stream systems. The NMISC is authorized by statute to investigate, develop, conserve and protect the water supplies of the state. In addition, the NMISC supports and conducts regional and state water planning efforts, implements Indian Water Rights Settlements, manages the State's Strategic Water Reserve and supports compliance with federal environmental regulations such as the Endangered Species Act. Further, Governor Michelle Lujan Grisham directed the NMISC to develop the New Mexico 50-Year Water Plan.

This report represents a collaboration between two state agencies: the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Interstate Stream Commission. The work was carried out by the Bureau at the request of the New Mexico Interstate Stream Commission in support of development of New Mexico's 50-Year Water Plan. The purpose of the report was to provide a solid and scientifically based foundation about climate change in New Mexico over the next five decades upon which to build the 50-Year Water Plan.

The Bureau appreciates the New Mexico Interstate Stream Commission's vision in supporting the development of this project. The Bureau also deeply appreciates the expertise and commitment of the eight experienced scientists who developed the core chapters of this consensus study. We hope this report will be used by many in and around New Mexico for many years to come.

ACKNOWLEDGMENTS

This report underwent review in draft form by individuals chosen for their technical expertise in the topics addressed, as well as their relevant research focus on the southwestern United States. Some reviewers provided an evaluation of the entire report and others reviewed only specific sections. The purpose of this independent review was to provide candid and critical comments to ensure that the report is scientifically sound and responsive to the study charge.

We thank the following individuals for their review of this report:

Kevin Hobbs, New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, New Mexico

Sarah Moore, United States Army Corps of Engineers, Albuquerque, New Mexico

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This article has been peer reviewed and approved for publication consistent with U.S. Geological Survey Fundamental Science Practices (https://pubs.usgs.gov/circ/1367/).

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they re-review the final draft before its release. The review of this report was overseen by Nelia Dunbar, David Gutzler, Kristin Pearthree, and Fred Phillips. They were responsible for making certain that the independent examination of this report was carried out thoroughly and fairly, and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee, the New Mexico Bureau of Geology and Mineral Resources, and the New Mexico Interstate Stream Commission.

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IV. CLIMATE CHANGE: TERRESTRIAL ECOSYSTEM RESPONSES AND FEEDBACKS TO WATER RESOURCES IN NEW MEXICO

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, 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 management of declining water availability for human use (e.g., irrigation) versus "wild" water retained 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 the 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 and water management actions, and urbanization. Important abiotic factors include topographic characteristics that affect local microclimate (e.g., elevation, slope, aspect, landform, slope position), soil and bedrock physical properties, nutrient availability, and various ecosystem disturbance processes (e.g., fire, floods, wind). Subsurface water storage in soils and fractured bedrock is increasingly recognized to be critically important for deep-rooted plants (Rempe and Dietrich, 2018; Klos et al., 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, parasites, etc. As a result, there are sharp differences in microclimate and vegetation between cooler-moister north-facing slopes versus the microclimate and vegetation found on directly adjoining hotter-drier, south-facing slopes (Fig. 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 versus 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 U.S. contains an unusual abundance and diversity

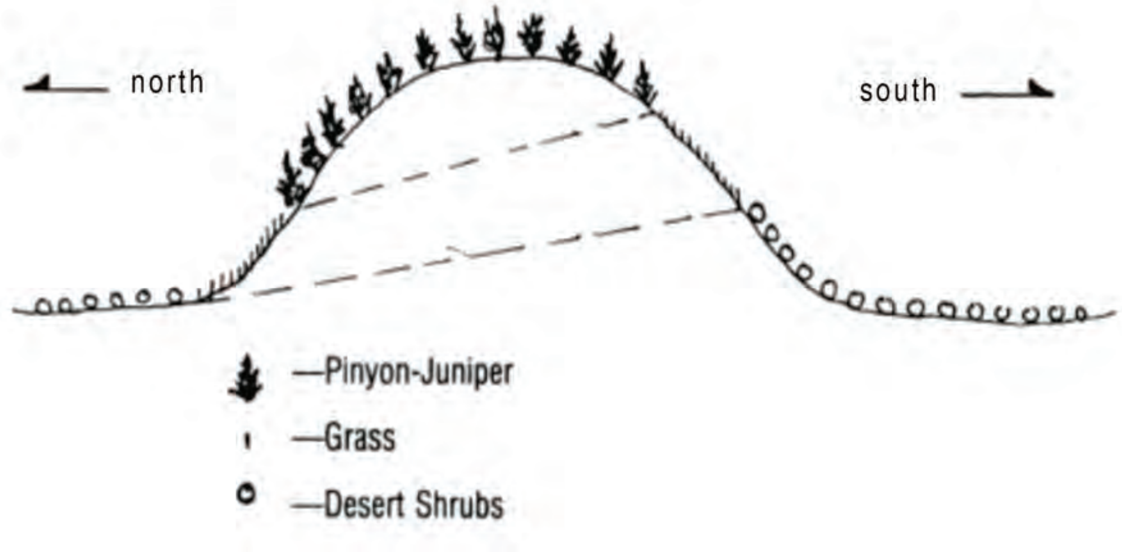

Figure 4.1. The strong effects of south versus north topographic aspect on vegetation pattern. Modified from Figure 3.1 in Dick-Peddie et al. (1993).

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., 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 versus 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 (Betancourt et al., 1990; Swetnam et al., 1999). 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 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 U.S. 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, b). 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 CE (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)—ranging from 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 (LTER) 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-foot elevational gradient from the Rio Grande to Redondo Peak. These groups are partners in a new National Park Service (NPS) Research Learning Center (the in-development website address 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 CE, ranging from a particularly wet window in the 1910s–1920s that favored a huge pulse of successful tree regeneration across the Southwest U.S. (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 (Fig. 4.2). Since ca. 2000, New Mexico and the Southwest U.S. have been in the midst of an increasingly severe regional drought (Williams et al., 2013, 2020a, b; 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 (Fig. 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, b; 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.

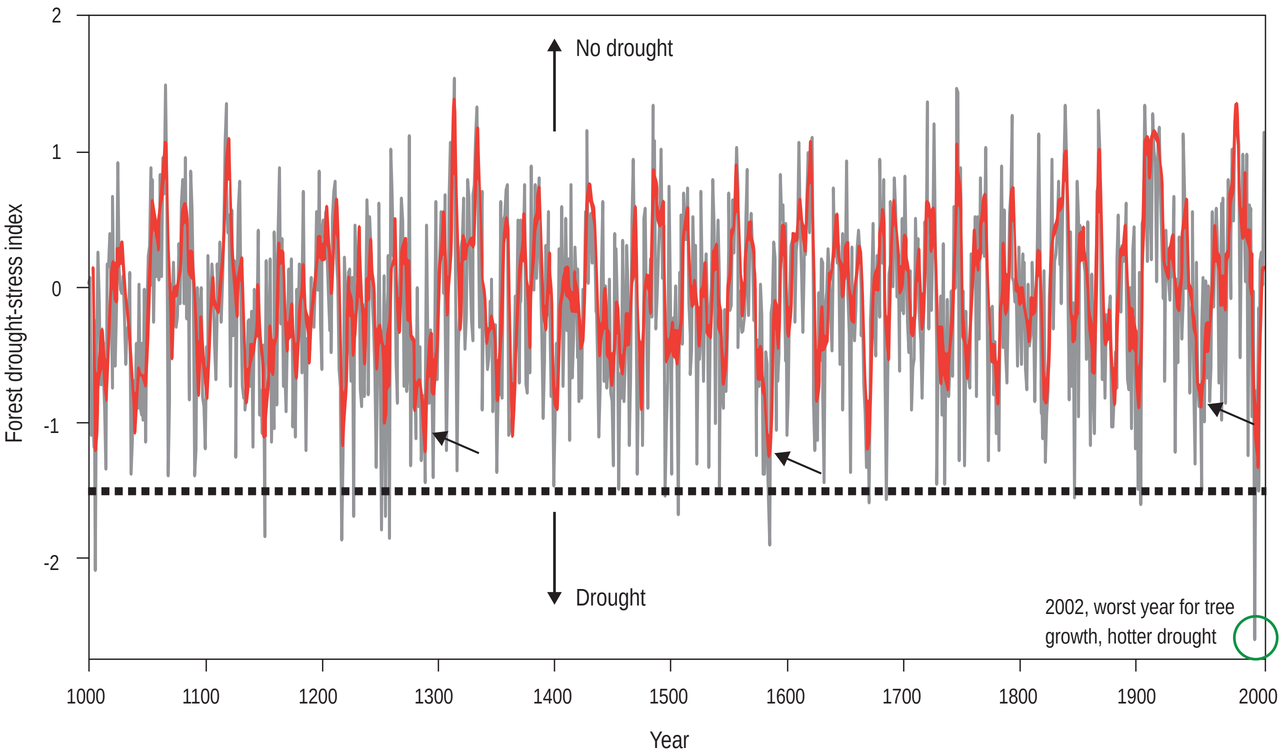

Figure 4.2. A 1,000-year reconstruction of a regional "forest drought stress index" (FDSI) from tree rings in the Southwest U.S. Annual FDSI values in gray, 10-year moving average in red, for 1000–2007. Arrows mark megadroughts in the late 1200s and late 1500s, and the well-documented 1950s historical 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 multi-year, 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 the 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, and that 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 (Fig. 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) (Fig. 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 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 Southwest U.S. plant growth (Koehn et al., 2021; Munson et al., 2021). For example, warming has amplified conifer forest drought stress in the Southwest U.S., generally squeezing tree growth in New Mexico since ca. 2000 (Fig. 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—Bailey et al., 2021).

While plant individuals, populations, vegetation communities, and ecosystems have substantial capabilities to adapt to some degree of climate change (cf. 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—*(cf. 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 (Fig. 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 (Fig. 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 [Fig. 4.5]), can greatly increase the probability that threshold-level extreme events occur. Increasingly extreme, unprecedented climate events—particularly

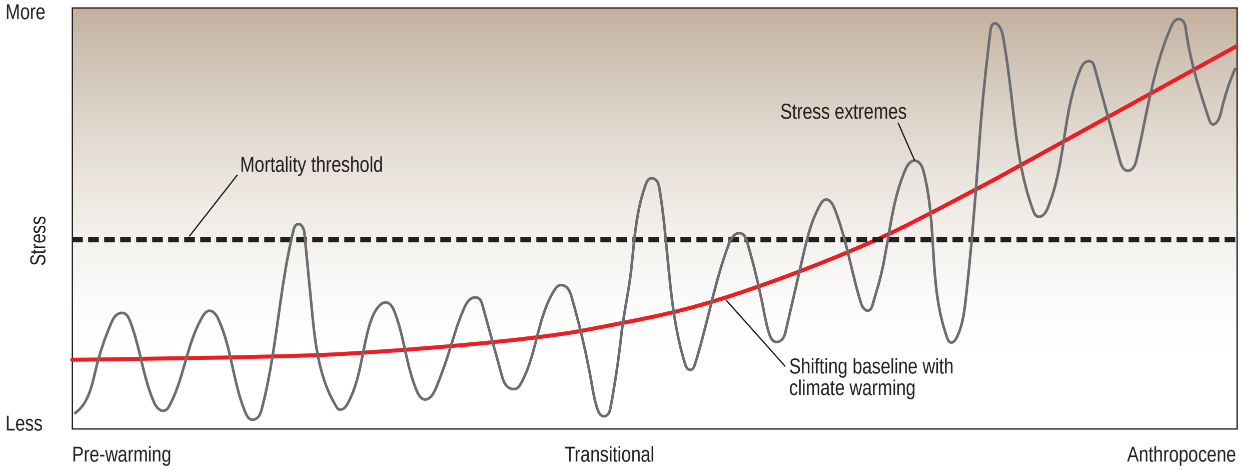

Figure 4.3. Ecosystem stress results from both general incremental trends and particular extreme events in climate (Jentsch et al., 2007). The red line indicates a shifting baseline level of forest stress through time due to an increasing trend in temperature; the gray line represents stress changes due to substantial multi-year 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).

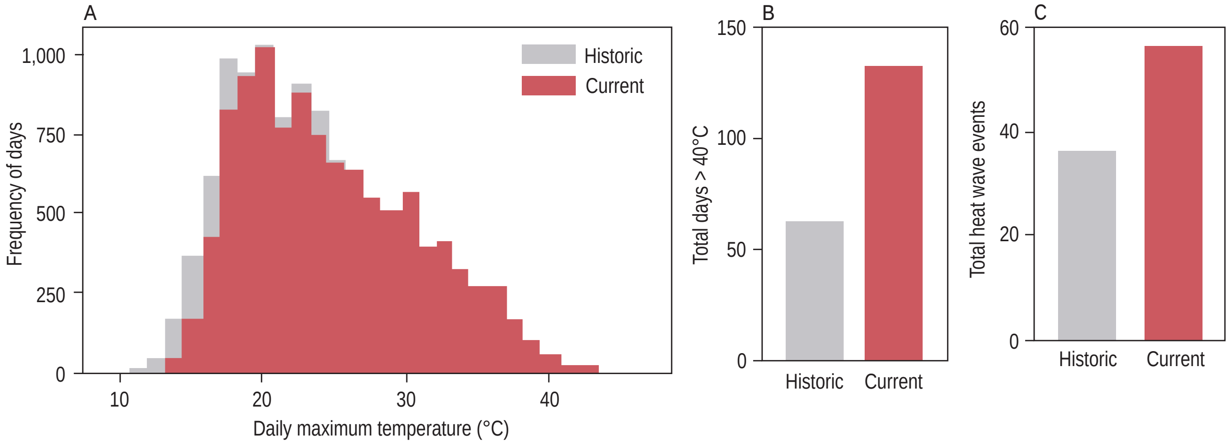

Figure 4.4. Warming greatly increases the frequency of extreme temperature days and heat waves. Daily maximum temperature (a), number of days over 40°C (b), and number of heat wave events (c) for Perth, Western Australia, for historical (1910–1939; gray) and current (1989–2018; red) 29-year periods.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

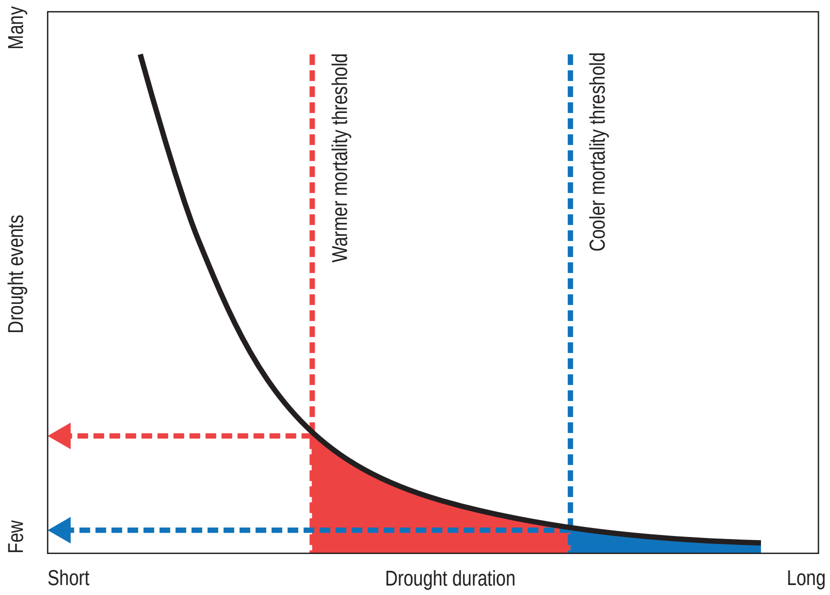

Figure 4.5. Warming greatly increases frequency of tree-killing drought events. Drought frequency (black line) increases nonlinearly as drought duration decreases, as there are many more short-duration droughts than long ones (Lauenroth and Bradford, 2009), and during cooler historical times only a few 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).

droughts and heat waves—are emerging as ever-more important drivers of severe ecosystem disturbances and abrupt vegetation changes in the Southwest U.S. (Allen, 2014; Breshears et al., 2021).

Indirect Climate Effects on Vegetation through Altered Ecosystem Disturbance Processes— Recent, ongoing climate change also 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 (Fig. 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 (Figs. 4.7a, 4.7b; Elliott et al., 2021).
2. Warming has substantially altered recent wildfire activity in the Southwest U.S. and New Mexico (Fig. 4.8), with changes in frequency, severity, area burned, 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 post-fire (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 (Fig. 4.9; Allen, 2014) dominated by resprouting angiosperm species that can regenerate after severe fire from surviving below-ground 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 post-fire floods and debris flows (Fig. 4.10); these disturbances are addressed in Chapters 6 and 9.
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 (Fig. 4.11) is contributing to declines in perennial grass cover and increases in subtropical woody shrubs (Bestelmeyer et al., 2018).

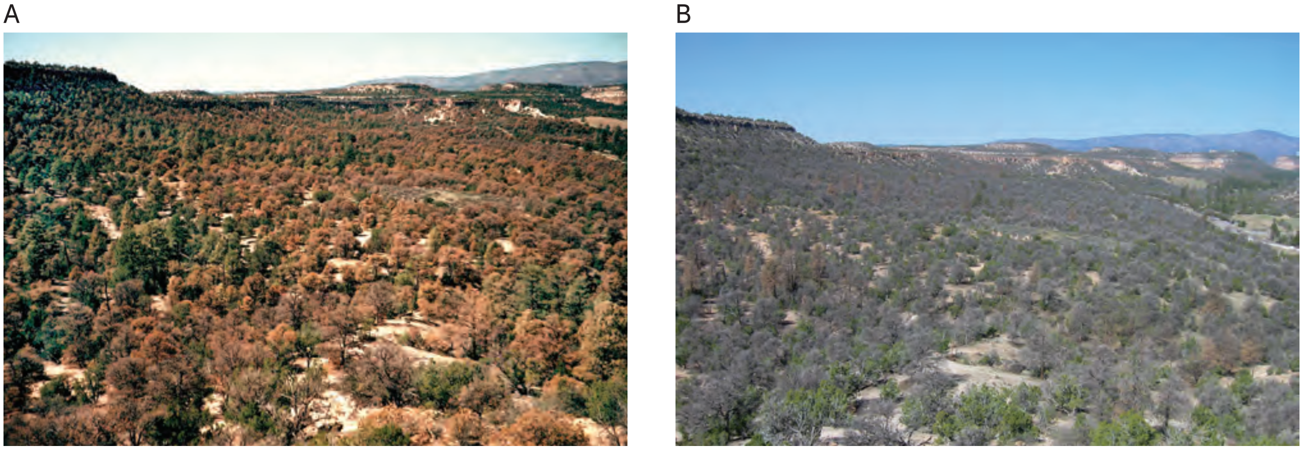

Figure 4.6. Repeat photos of landscape-scale mortality of piñon (*Pinus edulis*) from hotter drought and an associated bark beetle outbreak. (a) Rust-colored dying piñon, eastern Jemez Mountains, October 2002. (b) The same scene 18 months later, with gray piñon skeletons and remaining live junipers,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

Figure 4.7. (a) 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 4.7. (b) 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 hectares in the headwaters of the Pecos River in the Sangre de Cristo Mountains. *Photos by William deBuys (October 2020)*

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

Figure 4.8. (b) 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 2011–2013. *Photo by Craig D. Allen*

Figure 4.8. (c) High-severity fire effects in desertified piñon-juniper woodland in the southeast Jemez Mountains, taken August 2011, two 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 4.9. (a) Fire-caused type conversion from conifer forest to oak shrubland, Dalton Fire footprint near Pecos, NM. 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*

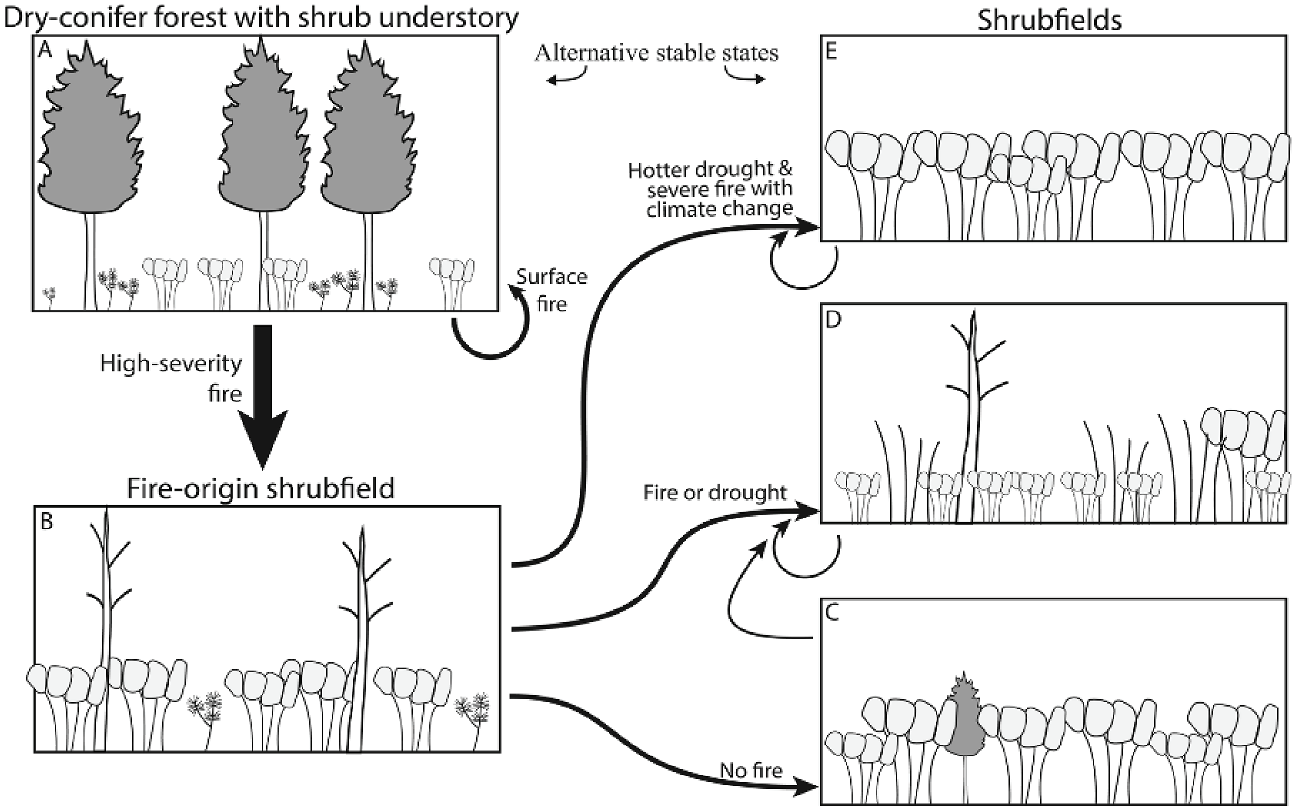

Figure 4.9. (b) Conceptual model of alternative post-disturbance stable states in dry conifer forest and shrub ecosystems of New Mexico, depending upon histories and combinations of disturbances. From Guiterman et al. (2018).

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)*

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 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 post-fire debris flows (Fig. 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 (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 (USFS) 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 U.S. 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 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" (NMEMNRD, 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, including 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, models) indicate that these warm semiarid/arid grasslands will see additional declines in perennial grasses and increases in shrubs (Fig. 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).

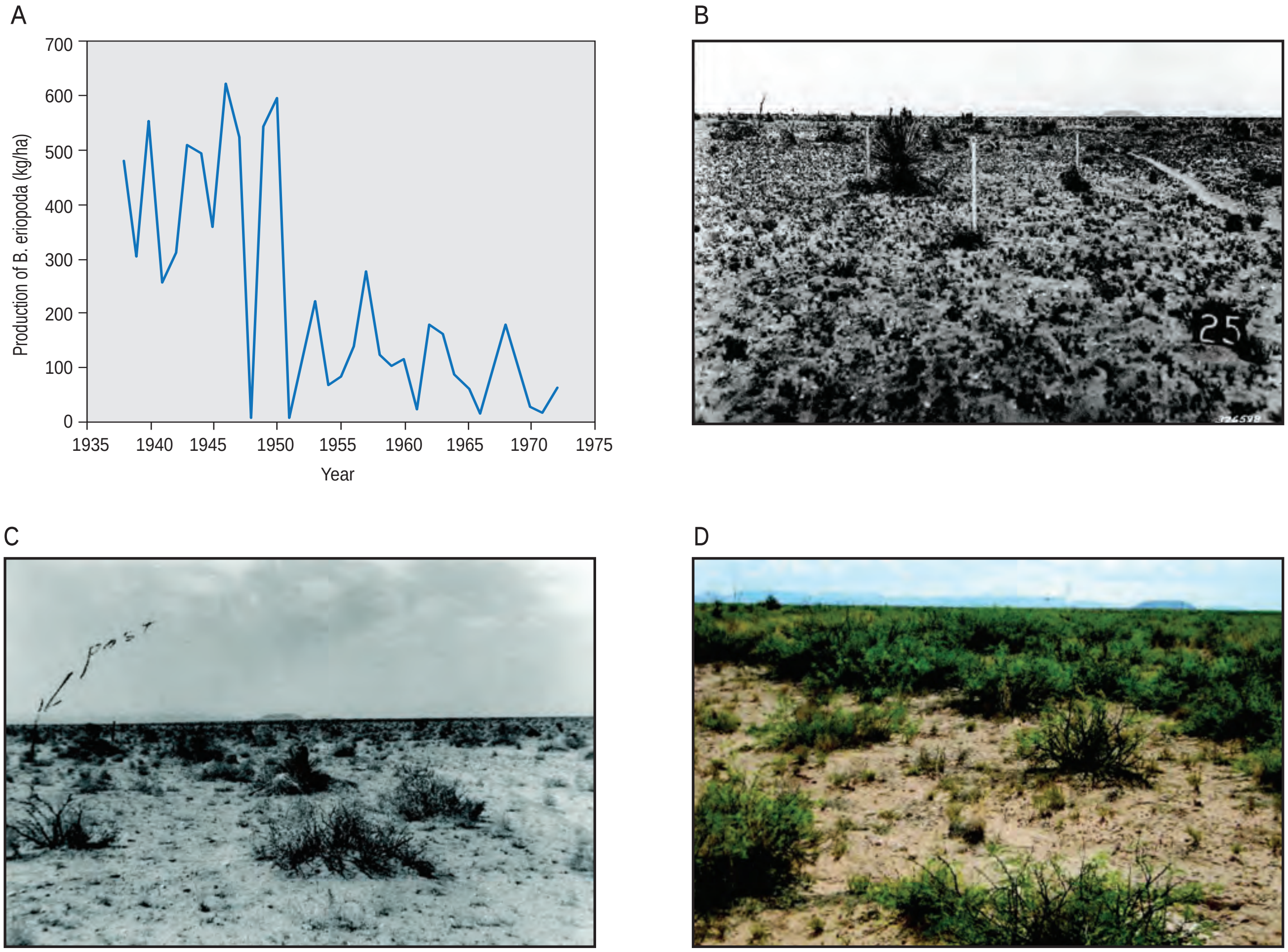

Figure 4.11. Evidence for a major historical grassland–to-shrubland transition in the Jornada Basin of southern New Mexico. (a) The initial collapse of black grama (*Bouteloua eriopoda*) production during the 1950s drought. (b) A 1936 photograph illustrating the effects of overgrazing during the 1930s 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).

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., Figs. 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, 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, leading to positive feedbacks on regional warming and aridification in the Southwest U.S. (McKinnon et al., 2021).

2. Canopy change impacts to snowpack and spring snowmelt runoff (e.g., Belmonte et al., 2021). This effect began with twentieth century declines in snowpack and water yield due to regional forest densification (cf. McDonald & Stednick, 2003; Broxton et al., 2020) but subsequently transitioning to twenty-first century declines in water yield from excessive forest cover loss from wildfire and forest dieback processes (Harpold et al., 2014; Biederman et al., 2015; Stevens, 2017; Moeser et al., 2020 [although see Bales et al., 2020, and Bart et al., 2021]). In addition, direct effects of climate warming on snowpack dynamics is a factor (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 streamflow in some water-limited systems (Bart et al., 2021).
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, affecting runoff, infiltration, 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 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 paleo-ecological 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 twenty 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, 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 that are 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, 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).

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APPENDIX A

Modeling Approaches for Projecting Changes in the Land-Surface Water Budget

In order to generate projections that have real predictive value at sufficient resolution to be useful, surface hydrologic models must have several characteristics. One is based on the observation that New Mexico is large and contains greatly varied topography and local climate. This means that Global Climate generalized models are of little value until their output is downscaled to finer resolution. Useful models must be capable of simulating the effects of climate change at the local scale (described below). A second is that models based on historical empirical observations are not likely to correctly predict future behavior when the system behaves differently than it does now. Rather, these models should be based on physical principles that are generally valid. A third is the degree of difficulty in constructing and running the model. Very highly resolved and complex models may be difficult to employ because of the computational demands (e.g., they run on only a supercomputer) and because it is very difficult to accurately supply all of the parameters that are needed to construct the model.

The basis for obtaining future projections of the hydrologic budget under changing climate usually starts with the output of GCMs that are driven by standardized greenhouse-gas emission scenarios developed by the IPCC. The coarse-resolution GCM outputs are converted to finer scales in a process called ‘downscaling’. The outputs for the historical period are statistically adjusted to match the statistics of the observations for the same period and this adjustment is then used on the climate-model outputs for the future. The downscaled sequence of climate parameters is then used to drive the state-scale water balance models. Below we review several water-balance models that have been used for estimating recharge and runoff in New Mexico.

Mass-Balance Accounting Models—To date, the only model that has been employed to empirically estimate the water balance for the entire state of New Mexico is a systems-dynamics mass-balance accounting model called the ‘New Mexico Dynamic Statewide Water Budget Model’ (Peterson et al., 2019). Such models use relatively simple equations that conserve mass or volume as hydrological flows that are routed or transferred, for example from the soil-water reservoir to the atmosphere via evapotranspiration. This type of model is also termed ‘lumped-parameter’ or ‘bucket models’ because models of this type do not attempt to spatially resolve the hydrological processes, but rather divide up the area into sub-units (e.g., counties or water-planning regions, which are treated like ‘buckets’ districts) that are treated as being homogeneous. The hydrological transfers are often quantified using empirical constants that are derived from historical studies, for example, estimation of the fraction of the snowpack that becomes runoff, based on past snow surveys and stream gaging.

Although they are a valuable tool for understanding the current water balance, their utility is limited for future projections under changing climate. This is partly because their lack of spatial resolution does not account for variations of hydrological response across a varied landscape, but more fundamentally it is because the empirical formulations that they often employ were derived by observations under constant climate and are likely to be inaccurate under different climate conditions in the future.

One-Dimensional Surface Process Models—There is a large family of models that use physical formulations (as opposed to empirical ones) to simulate the division of hydrological flows at the land surface, but only as a purely vertical process. This is reasonable to a first approximation, noting that the vertical flows in Fig. 3.1 are much larger than the horizontal flows. For the most part these models employ physics-based formulations to calculate flows and transformations and should thus have predictive power under changing climate. They are computationally straightforward and can thus be used at high spatial and temporal resolution to capture effects of topography and vegetation variation and other heterogeneities. Their main limitation is that they cannot include lateral flows of water, except on the land surface. Lateral flows are important to generating runoff and to focusing shallow subsurface flow to become recharge.

The most important of these is the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). It is commonly used in conjunction with GCMs to make coarse-resolution hydrological projections. It is also the most common hydrological model to be coupled with downscaled GCM output for finer resolution local projections. A significant limitation of VIC is that it, at least in the original version, does not explicitly quantify groundwater recharge. Rather, any excess water at the base of the root zone is directly routed to surface flow. This is a reflection of common hydrological conditions in humid regions.

A code that has been explicitly employed to compute groundwater recharge is the WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003; Döll and Fiedler, 2008). This model was incapable of realistically simulating groundwater recharge in arid and semiarid environments without arbitrary adjustments (Döll, 2009).

Only one such model has been developed and applied specifically to calculate recharge in the New Mexico environment: Python Recharge Assessment for New Mexico Aquifers (PyRANA) (Ketchum, 2016; Xu, 2018; Parrish, 2020). This model employs the dual crop-coefficient method of calculating evapotranspiration (Allen and Breshears, 1998) to obtain accurate water-balance in New Mexico's semiarid climate and is efficient to run at very high spatial and temporal resolution in order to meet the challenge of the state's irregular topography. However, in its current configuration, it does not incorporate interception of precipitation by plant leaves, which can significantly affect the land-surface-water balance, especially in forested areas.

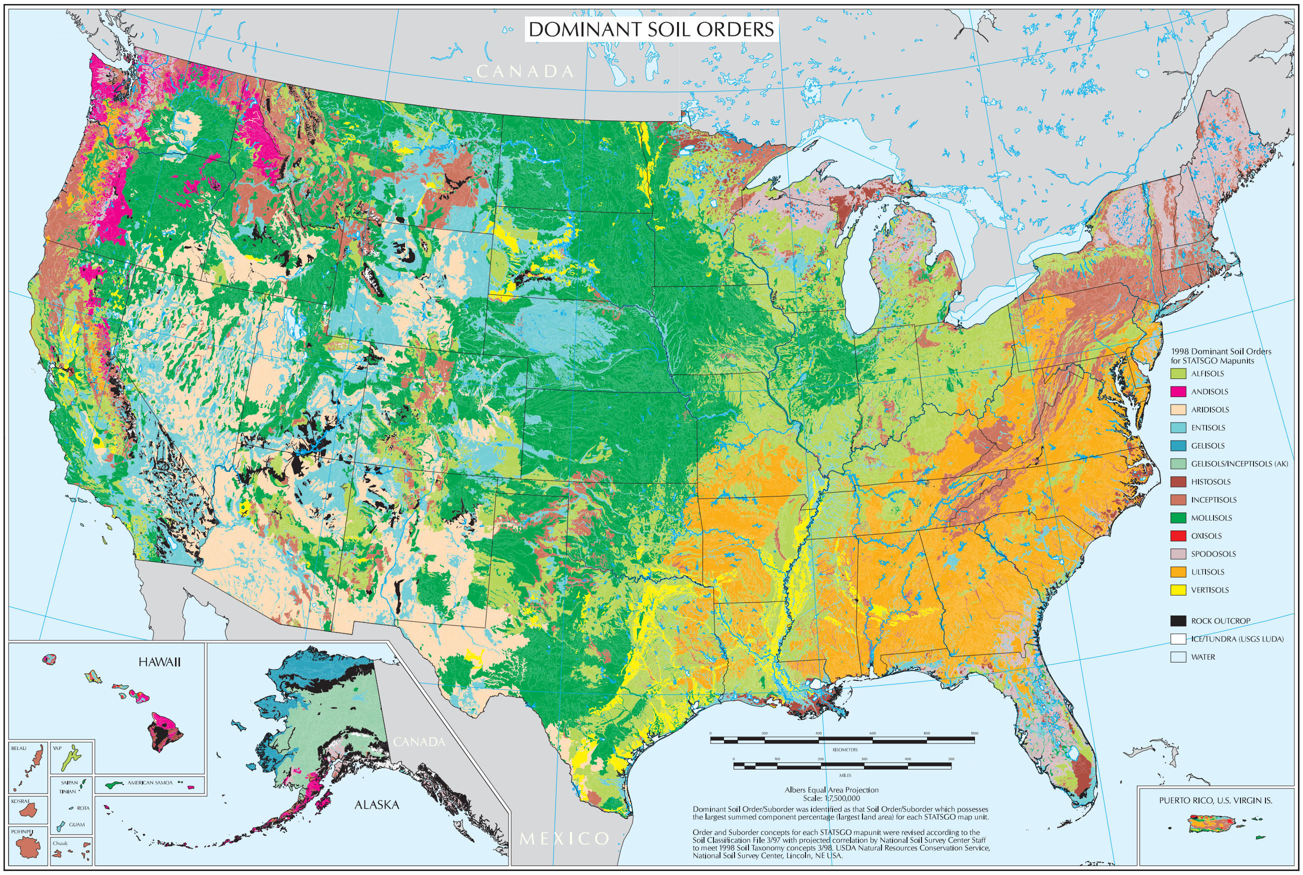
Three-Dimensional Hydrological System Models—A more complex family of models attempts to mimic the entire hydrological system, including hydrometeorological, land surface, surface-water, and groundwater components, in three dimensions. This allows them to account for some phenomena that cannot be represented in more simplified models, but at the cost of much greater computational expense. They generally can only be run on supercomputers.

The most relevant of these to our purpose is ParFlow-CLM, developed for high-resolution global simulations of the hydrological cycle under current and future conditions (Maxwell and Miller, 2005).

APPENDIX B

Soil Diversity in New Mexico and the "CLORPT" Approach in the Studies of Soil Landscapes

The map of soils of the United States at the level of soil orders (the highest taxonomic level of soil classification in the U.S. Department of Agriculture [USDA] Soil Taxonomy) (Fig. B.1) illustrates the large range of very different soil types that are present in the landscapes of New Mexico (Fig. B.2). At least six of the twelve soil orders are evident at this map scale (Entisols, Inceptisols, Aridisols, Mollisols, Alfisols, Vertisols); at least one other soil classified in another order can be found locally in some landscapes in favorable circumstances (Andisols, soils with properties that reflect weathering of volcanic parent materials). The large spatial extent of Aridisols (well-developed soils that form in an "Aridic" soil moisture regime), an order that has six suborders in New Mexico (Fig. B.3) reflects the arid climate of many areas of New Mexico. The large area with Mollisols (soils typical of grassland and prairies with a thick, darkened surface A horizon - a 'Mollic' epipedon) reflect the semiarid areas of New Mexico that support shortgrass communities. Alfisol (high base-status soils with fine textured subsurface



Dominant Soil Order/Suborder was identified as that Soil Order/Suborder which possesses the largest summed component percentage (largest land area) for each STATSGO map unit.

Order and Suborder concepts for each STATSGO mapunit were revised according to the Soil Classification File 3/97 with projected correlation by National Soil Survey Center Staff to meet 1998 Soil Taxonomy concepts 3/98. USDA Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE USA.

Figure B.1. Soil orders distribution map of the United States and Territories (http://www.nrcs.usda.gov/wps/portal/nrcs/)

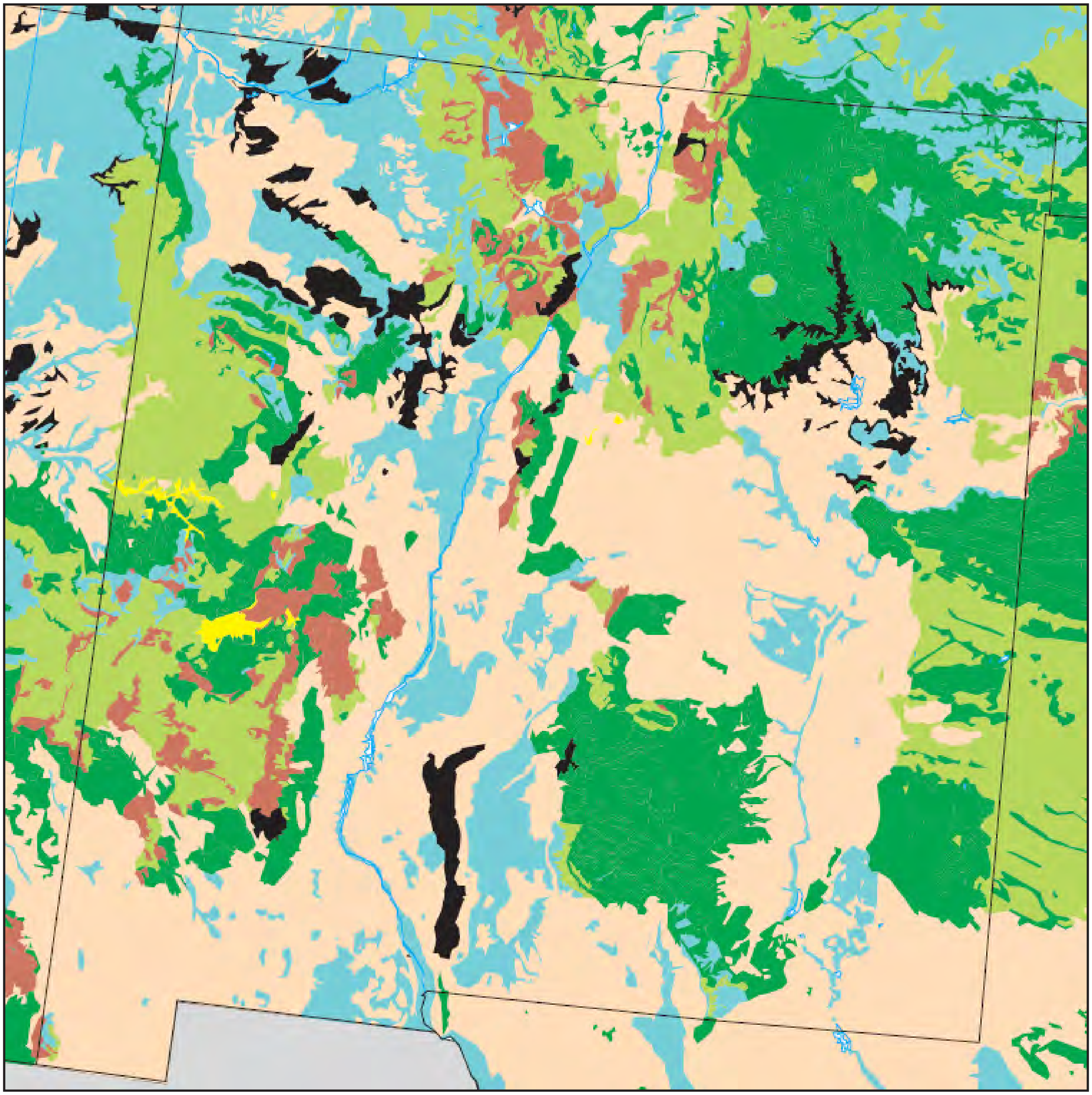


Figure B.2. Soil orders in New Mexico (http://www.nrcs.usda.gov/wps/portal/nrcs/).

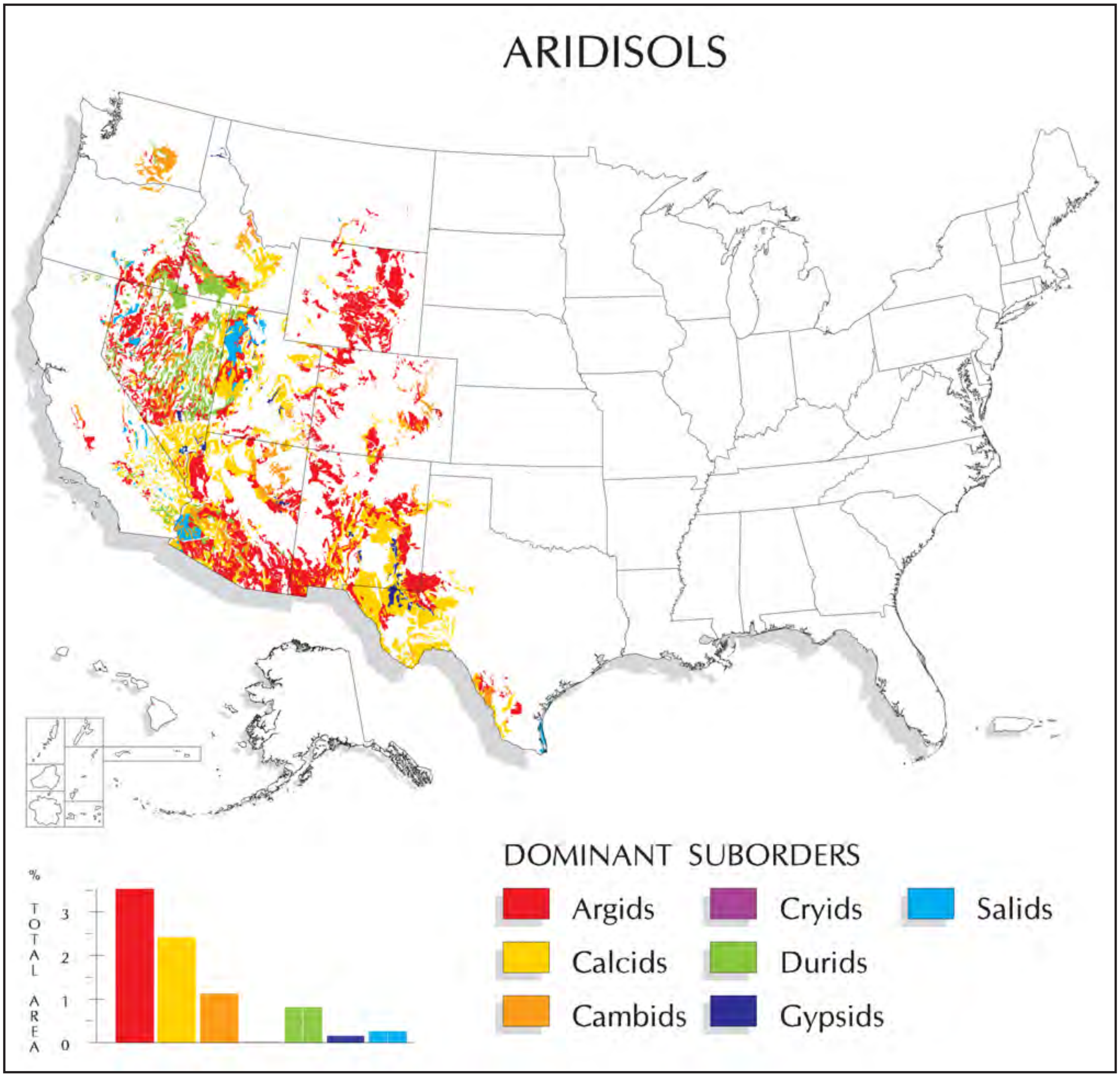


Figure B.3. Map of the suborders of Aridisols in the United States (NRCS image, https://www.nrcs.usda.gov/Internet/FSE_MEDIA/stelprdb1237729.jpg). The large spatial extent of these suborders in New Mexico as well as other regions of the western United States reflects an arid climate and associated soil-forming processes favored by an "aridic" soil moisture regime.

B horizons) can be found in areas of greater annual precipitation at typically higher elevations. Of course, at other levels of the Taxonomy or in Natural Resources Conservation Service (NRCS) soil maps of much smaller regions, literally many dozens of Suborders and much larger numbers of Great Groups, Subgroups, Series, and Types are present (USDA).

Substantial soil diversity in New Mexico reflects the highly variable topography, climate, vegetation and rock types that characterize the state. Much of this variability reflects, to a large extent, the consequences of Cenozoic tectonic processes that ultimately caused, for example, uplift of the lofty southern Rocky Mountains or the development of lower elevation dryland basin landscapes of the Rio Grande rift. Topography, climate, vegetation, and rock types constitute the most important factors that influence the many soil-forming processes and overall soil profile development.

Soil chronosequences are one of several types of sequences of soils designed to enable scientists to ascertain the influences of factors such as climate (Cl), organisms, or biotic factors (O), local and regional relief (R; essentially also characterized as “topography”), parent material characteristics (P) of processes of soil development (Jenny, 1941). A remaining attribute of soils, their age (T), enables recognition of the degree to which some processes are strongly time dependent. Although other factors certainly influence soil-forming processes, these five factors are generally regarded as the most critical ones to the extent that collectively they define the “state” of the soil (or a particular soil property) (Birkeland, 1999), and they have come to be generally known as CLORPT. This conceptual framework used in soil geomorphic research is often referred to as the “State Factor” approach (or the CLORPT approach). Through careful selection of groups of soils in circumstances such that the influences of one factor can be isolated or selectively varied, while the influences of the others are essentially held constant, different soil “functions” associated with the CLORPT factors can be determined (Jenny, 1941; Birkeland, 1999; McFadden, 2013). To identify differences amongst a group of soils that primarily reflect soil age, a soil chronosequence is established, and a time-dependent change in soil morphology (or a given property) is called a chronofunction. Soil chronosequence studies usually involve selection of geomorphic surfaces with relatively low gradients and generally low relief, features that engender geomorphically stable conditions, which in turn favor continuous soil formation and morphological property development on time scales ranging from a few hundred to several hundred thousand years (Birkeland, 1999).

Other soil sequences can be established in a given region that emphasize topography (soil toposequences, or sometimes referred to as a “catena” (Fig. B.4)). Studies of toposequences prove invaluable in the study of hillslope form and processes, as they are geomorphically unstable when compared to, for example, the surfaces of fluvial terraces (Birkeland, 1999; McFadden, 2013). Similarly, the role played by different soil parent materials (the earth materials in which soils form) substrate (e.g., weakly cemented sedimentary rocks, crystalline igneous and metamorphic rocks, alluvium) in influencing soil development can be assessed through studies of soil lithosequences (Birkeland, 1999).

Drainage Basin Hillslopes and Soils

The hillslopes of drainage basins (“watersheds”) are the major areas of aquifer recharge and the primary source of water and sediment discharge to fluvial channels in most landscapes. In New Mexico and adjacent states, substantial runoff and recharge is generated from mountainous areas (see relevant sections in this report). These include the San Juan, Sangre de Cristo, Jemez, Black Range, Sacramento, Sandia, Zuni, and Mogollon Mountains, all of which have relatively extensive high elevation areas (greater than 10,000 feet) with elevations in a few cases exceeding 12,000 feet. In many drainage basin hillslopes of these mountains, weathering of exposed bedrock or bedrock beneath a cover of hillslope sediments produces “regolith”. In some studies, formation of regolith, either in situ or mobile, by this process is referred to as “soil production” (Heimsath et al., 1997; Bierman and Montgomery, 2019). The formation of regolith occurs mainly through biogeochemical weathering of bedrock. The initial alteration of bedrock that is essential in influencing subsequent chemical weathering rates and the eventual development of soil that enables colonization by vascular plants involves the development of secondary porosity and resultant increased water-holding capacity (Graham et al., 2010). Some studies in New Mexico mountainous, and other high elevation study areas, that document chemical weathering of bedrock parent material include Egli et al. (2014) and Rea et al. (2020). On many drainage basin hillslopes, however, soils form in materials produced mainly by physical weathering of bedrock, such as talus and colluvium. In higher elevation areas subject to frequent freeze-thaw cycles, frost weathering is a key physical weathering process (Bierman and Montgomery, 2019). At lower, generally warmer elevations where frost weathering is not effective, other physical weathering processes are important. Recent studies suggest that solar insolation may actually play a key role in the development and extension of initial fractures (McFadden et al., 2005; Eppes et al., 2010), accelerated via subcritical formation and extension of cracks (Eppes and Keanini, 2017). Increases in the spatial extent and thickness of talus and colluvium are commonly observed in the hillslopes of mountain ranges with high relief, given the associated higher annual precipitation and lower temperatures, conditions that tend to favor an increase in the magnitude of physical weathering.

The character and spatial extent of soils on hillslopes are affected by several factors, such as relief, rock type, vegetation, climate and local base level. Given variability amongst these factors in diverse geomorphological settings, hillslopes exhibit different forms. For example, some hillslopes are dominated by relatively frequent occurrences of debris flows, rotational slumps, and other mass movements. In many drainage basins where mass movements are rare, a very common hillslope form observed is characterized by a smooth, curvilinear profile and is associated with a continuous mantle of soil and vegetation (Fig. B.5). Gilbert (1880) recognized the latter hillslope form as being one that develops in effectively wetter and colder climate regimes. These conditions are conducive to weathering and slope material production sufficient to exceed the rate of transport of weathered material on the hillslope. In the nearly 150 years since this publication, a large

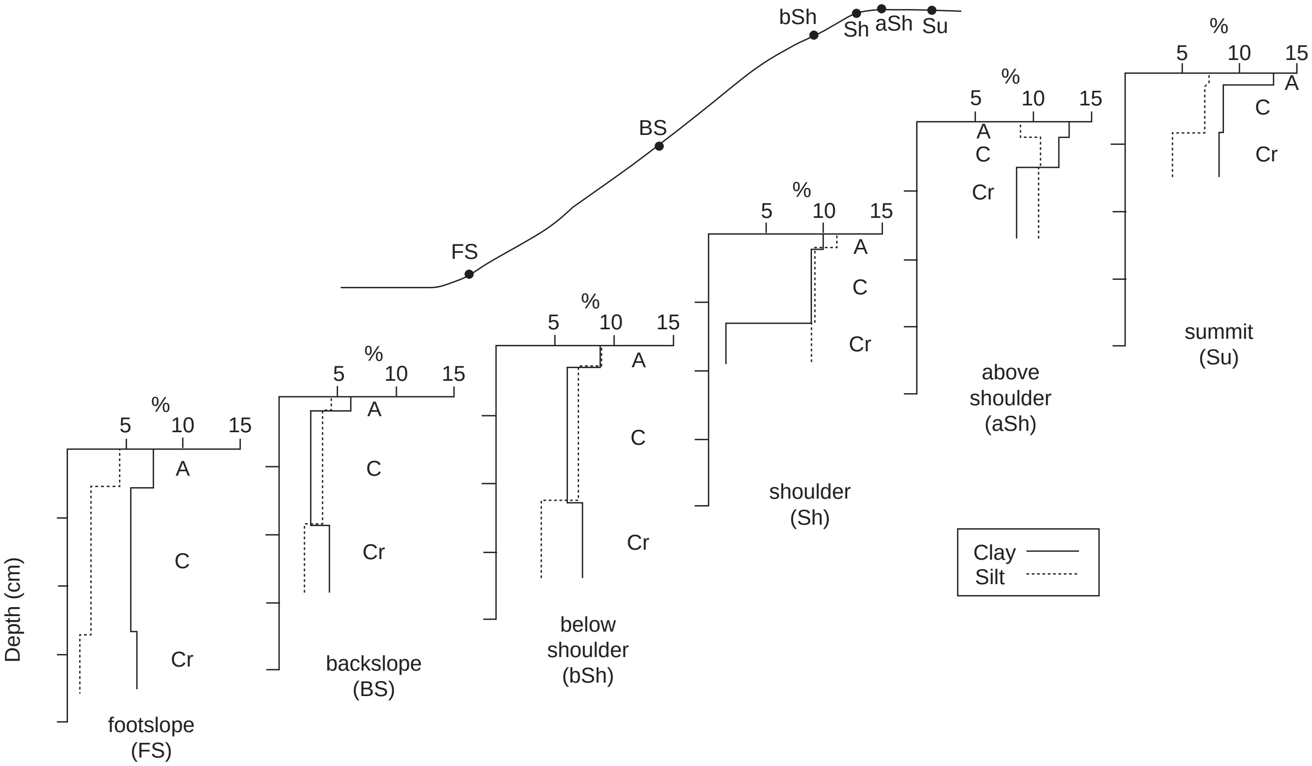


Figure B.4. A cross section (no vertical or horizontal exaggeration) showing a soil toposequence on a transport limited hillslope from a study site on the Colorado Plateau in NE Arizona. Soil horizons with depths and textural data for soils located at various hillslope positions are shown in the different plots. See text discussion of soil toposequences. After McFadden (2013).

body of published research has both confirmed and extended Gilbert's research (e.g., Heimsath et al., 1997), and these smooth hillslopes are commonly referred to as transport-limited hillslopes dominated by diffusive transport of slope materials. In contrast, typically steeper hillslopes dominated by exposure of bedrock and discontinuous weathering mantles (including soils) are now often referred to as detachment- or weathering-limited hillslopes (Fig. B.6) (Bierman and Montgomery, 2019). Gilbert noted that such hillslopes are common in generally arid climates, and he recognized that in these circumstances, the magnitude of weathering and production of colluvium and/or soils was not sufficient to exceed the rate of hillslope erosion by runoff or mass movements (e.g., creep).

In geomorphically favorable circumstances, where colluvium has accumulated in zero order drainage basins or where colluvium, sheetwash-derived sediment or debris-flow sediment has accumulated at base of hillslopes, the soil profiles are often generally thicker than those forming in bedrock. For example, published detailed NRCS soil maps of the higher elevations (8,400 to 10,500 feet) of the Sandia Mountains (Hacker, 1977) identified

Figure B.5. Smooth, soil and vegetation mantled "transport limited" hillslopes formed on weakly cemented sandstones of the Dixon Member, Tesuque Formation, Santa Fe Group. The hillslopes face to the northeast (hillslope aspect) and the area is located 35 km southwest of Taos, New Mexico at an elevation of approximately 2070 m. *Photograph by Leslie D. McFadden*

Figure B.6. Steep, bedrock dominated "detachment-limited" hillslopes formed on southwest-facing hillslopes formed on the same bedrock and in the same area as the hillslopes shown in Figure 6.5. *Photograph by Leslie D. McFadden* the “Shallow to Deep Soils” of the Kolob-Rock Outcrop Association. This association includes large areas of exposed bedrock or very thin soils (Rock Outcrop, including extragrade “Lithic” subgroups with typically thin, weakly developed A-C profiles with bedrock at shallow depths) and the thicker Kolob soils, many of which occur in thick hillslope materials and commonly exhibit B horizons. In the Sandia Mountains, these more well developed, thicker soils occur in the Alfisol, Mollisol and Inceptisol orders. Soils classified in these orders are also common in higher elevation settings in the Jemez Mountains (e.g., Nyhan et al., 1978) and in the Front Ranges in Colorado (Birkeland et al., 2003). Recent extensive geomorphological research in glaciated and unglaciated basins in the southern San Juan Mountains also show that relatively thick soils (some exceeding 100 cm) with weakly developed B horizons have formed in latest Pleistocene unconsolidated morainal till and younger Holocene alluvial deposits at elevations between 10000 and 11000 feet. Soils formed directly on steep hillslopes, however, exhibit thin soils with A-C-Cr profiles (Aldred, 2020).

Steep hillslopes commonly favor rates of erosion that enable only thin soils to form, or entirely preclude the development of soils. Additionally, the relatively low permeability of bedrock (as compared to, for example, gravelly alluvium) favors a low infiltration-to-runoff ratio, which also limits weathering and soil development. This is especially the case in dryland climates. Many other hillslopes are not so steep, and thick soils can form on these hillslopes. Their development can be attributed to the following: (1) the moister climate at higher elevations characterized by higher annual precipitation and cooler temperatures that favor deeper average depths of soil water movement and soil development in relatively permeable parent materials; (2) increasing vegetation density at higher elevations provides canopy cover and a root network that increases soil strength and cohesion, which results in increased resistance to erosion (see Chapter 4 of this publication); (3) the entrapment and incorporation of eolian dust in soils that produces net soil accretion; (4) incision of gullies into colluvial deposits and debris fan-aprons temporarily isolates soils from subsequent runoff and erosion; (5) colluvial materials, commonly far more permeable than bedrock, favor deeper soil water movement and, ultimately, development of thicker soils; and (6) thicker forest soils with thick O, A, Bw and C horizons often have relatively high infiltration rates and generally low runoff (e.g., Martin and Moody, 2001). In addition, the presence of thick soils that retain soil water provide insulation that increases soil water retention in deeper subsurface horizons. At the soil-bedrock contact, these circumstances have been proposed to favor increased chemical weathering of bedrock. As is described in Chapter 4, the presence of a continuous soil mantle is also conducive to the colonization of soil-stabilizing herbaceous plants, such as grass.

The body of soil geomorphological research conducted on drainage basin hillslopes in New Mexico is relatively limited; however, over two dozen papers in this area have been published in only the last twenty-five years (e.g., Davenport et al., 1998; Phillips et al., 1998), presumably largely reflecting the presence of a large national laboratory (LANL) and the establishment of the Santa Catalina-Jemez Mountains Critical Zone Observatory (CZO) in the Jemez Mountains (e.g., Olyphant et al., 2016). As is the case in other CZOs throughout the United States and also many other studies of hillslope geomorphology, one conceptual approach that has been adopted in the study of soil component of the critical zone is referred to as steady-state soil production (McFadden, 2013; Richter et al., 2020). The recent development and refinement of soil production represents an important extension of the definition of soil geomorphology as initially proposed by McFadden and Knuepfer (1990). The derivation of the soil production function (spf) that combines the hillslope sediment flux equation with the conservation of mass for a column of soil requires that the spf is essentially applicable only on soil mantled hillslopes with convex-up form and characterized by exclusively diffusive slope transport (i.e., abiotic and biotic creep) (Heimsath et al., 1997). In addition to the application of the steady-state spf in soil geomorphological research of hillslopes in the Jemez Mountains, this approach has been utilized in a few studies in other New Mexico mountains, including a study focusing on biochemical weathering processes in bedrock (Rea et al., 2020) and in studies of drainage basin patterns on hillslopes formed on uplifted basin fill sediments in the semiarid region west of Socorro (Gutiérrez-Jurado and Vivoni, 2013). As will be described below, however, recent studies of soils and hillslopes in some semiarid settings in New Mexico and elsewhere in the southwestern U.S. (Persico et al., 2011; McFadden, 2013; McAuliffe et al., 2014) show that steady state has been disrupted and/or that gullying and rilling (advective sediment transport processes) have played important roles with respect to erosion and sediment transport. In addition, soil-forming processes other than "production" of soil via bedrock weathering affect hillslope soils, including variable eolian sediment flux and the development of mechanically strong petrocalcic horizons not subject to creep. These geomorphic processes somewhat limit the usefulness of the conceptual framework provided by the spf in study of many landscapes subject to climate and other environmental changes.

Soil Chronosequence and Other Geomorphic Studies

Ultimately, over longer time spans, hillslopes must inevitably retreat, thereby ultimately limiting periods of geomorphic stability that enable sustained soil development and the overall magnitude of soil development. Processes of runoff, erosion, interflow, locally intensive bioturbation, and the difficulty of determining the ages of soil parent materials on hillslopes greatly complicate interpretation of strongly topographically dependent trends in soil-forming processes. However, studies of soil formation on the basis of soil chronosequence studies can in appropriate circumstances be used to evaluate some important aspects of soil development on hillslopes.

Some of the most well regarded soil chronosequence studies have been conducted in the landscapes surrounding Las Cruces in southern New Mexico, known as the Desert Project (Holliday et al., 2001). Desert Project research shows that many soil-forming processes are strongly time dependent (e.g., the development of pedogenic carbonate morphology) (Gile et al., 1981). The availability of numerical age dates for different soil parent materials or soil materials provided the basis for determining rates of soil development in this dryland region. Since these studies, new geochronological methods have been developed that provide numerical age information to help determine rates of soil development (e.g., Phillips et al., 1998). One of the most significant contributions of Desert Project research, however, was the recognition of the role of dust as a principal source of pedogenic calcium carbonate, rather than the production of dissolved calcium via chemical weathering of aluminosilicate minerals in the initial soil parent materials.

Other soil chronosequence studies in New Mexico also revealed key time-dependent soil properties including the important role the incorporation and pedogenic alteration of dust plays in the development of soil properties in addition to soil carbonate accumulation. Many other studies of soil chronosequences elsewhere in the southwest show similar results (c.f., Birkeland, 1999). Other studies that demonstrate the significant impact of dust entrapment and accumulation on soil formation in New Mexico and adjacent regions include studies of soils formed on volcanic flow surfaces (Eppes and Harrison, 1999; Van der Hoven and Quade, 2002; McFadden, 2013), and on eolian landforms (Wells et al., 1990; Reheis et al., 2005; Ellwein et al., 2018).

The entrapment and accumulation of dust in dryland soils not only plays a primary role in pedogenic carbonate accumulation, but also ultimately plays a fundamental role in the mode of soil profile development in sparsely vegetated landscapes (McFadden, 2013). In contrast to soil profile development in more humid climates (Fig. B.7a) (dominated by chemical weathering and net mass loss below the soil-atmosphere interface), dryland soil development is commonly characterized by the net **addition** of eolian sediment via cyclic soil inflation and accretion (Fig. B.7b). The formation and evolution of soils of desert pavements that dominate the landscapes of many very hot and arid regions is attributable to this mode of profile development; however, this mode of soil development can also be recognized in the soils of the semiarid foothills of the Sandia Mountains, as described below (Persico et al., 2011). A recently published study of lacustrine sediments from a site in central Arizona (Staley et al., 2021) shows that eolian dust accumulation has been occurring during much of the last 1.3 Ma, demonstrating that this process likely has strongly influenced soil development in drylands of the southwest throughout much of the Quaternary.

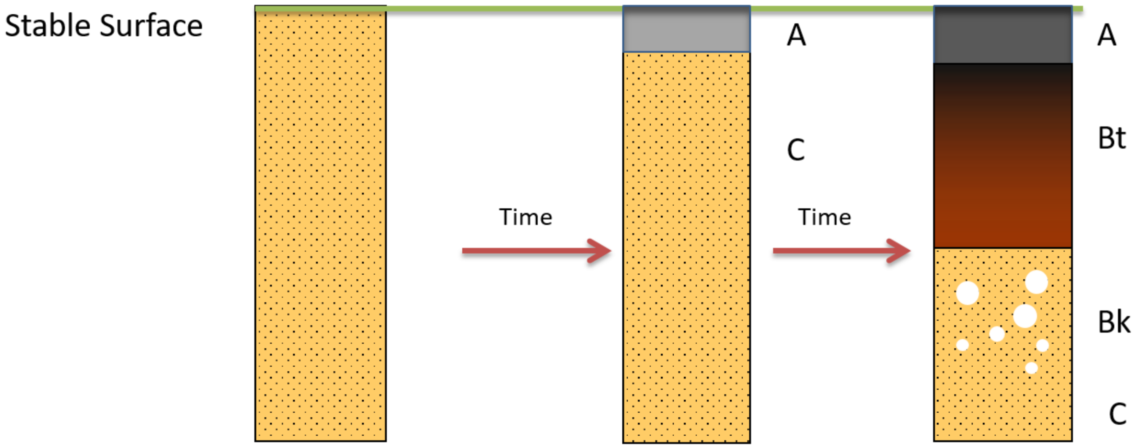


Figure B.7a. Time dependent development of the classical A/B/C soil profile developed in the 19th century by Russian soil scientists and ultimately adopted as a profile model by scientists worldwide in the 20th century. The lower case letters "t" and "k" indicated the presence of soil clay and calcium carbonate in the associated soil horizons. After Figure 1a from McFadden (2013).

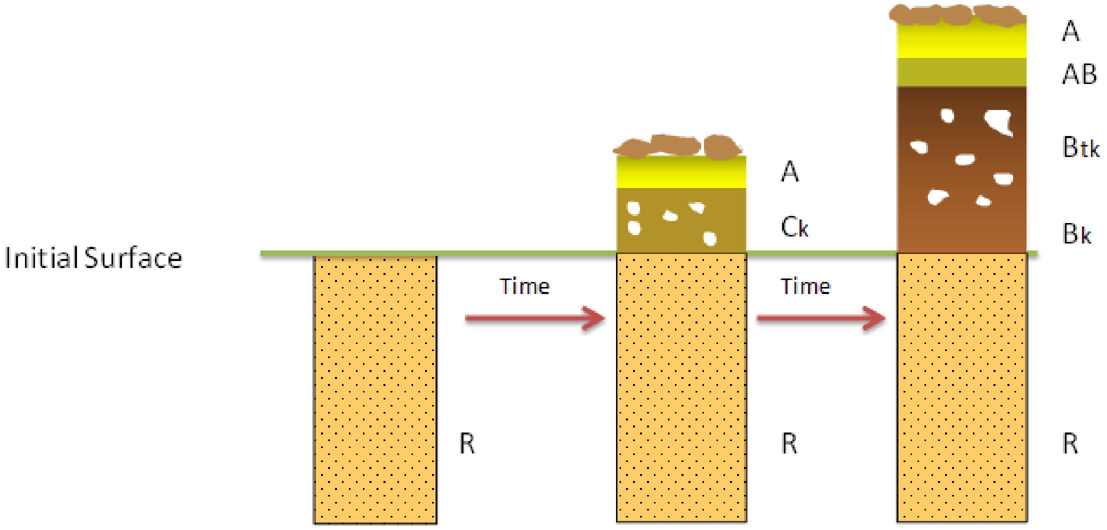


Figure B.7b. Time dependent development of a "cumulative" soil profile dominated by net accretion of slowly accumulating and pedogenically modified sediment. The light-brown irregularly shaped objects represent coarse fragments or gravel that are maintained as the surface during development of the soil. This example of a cumulative soil represents development of a dryland soil below a "desert pavement"; "R" represents fresh and/or slightly weathered bedrock. After Figure 1b, McFadden (2013).

Contributions of Soil Geomorphological Research to the Evaluation of Rates and Processes of Pedogenesis on Hillslopes in New Mexico

As noted above, the geomorphic and hydrological processes that characterize hillslope environments (e.g., interflow, soil creep) as compared to those on stable geomorphic surfaces appropriate for soil chronosequence studies complicate the interpretation of soil formed on hillslopes (Birkeland, 1999; McFadden, 2013). Certain hillslopes, however, provide more favorable circumstances. Glacial moraines found in mountainous regions subject to alpine glaciation are a good example. Unlike most hillslopes formed on bedrock, the hillslopes of a moraine initially have the same age, eliminating “T” as a soil state factor. Moreover, in some cases, morainal sediments can be dated using radiocarbon or cosmogenic surface age methodologies. The relatively limited relief, common parent material and vegetation of moraines enables development of soil toposequences. On some hillslopes formed on bedrock, dendrochronological methods and cosmogenic surface age dating also can be used in the study of hillslope soils and geomorphic processes (McAuliffe et al., 2006; Scuderi et al., 2008; McAuliffe et al., 2014).

Studies of soils of glacial moraine toposequences (Muhs and Maat, 1993; Birkeland, 1999; Birkeland et al., 2003) in the Rocky Mountains of central Colorado show that the entrapment and incorporation of dust plays a key role in soil development, despite the moist conditions and development of organic matter-rich O and A horizons. Soils in the southern San Juan Mountains formed in latest Pleistocene moraines and post-glacial colluvium and alluvium with B horizons are also strongly influenced by eolian dust (Aldred, 2020). Late Pleistocene soils formed in tundra covered soils on bedrock at elevations up to 12,000 feet in the Uinta Mountains with A-Bw-C profile development are also dominated by dust accumulation. These studies also demonstrate that soils on latest Pleistocene moraines with A-B-C profile development require at least several thousand years to form, a conclusion consistent with that of the numerous aforementioned soil chronosequence studies conducted in New Mexico and adjacent regions.

With the exception of the Jemez Mountains region, to date there have been relatively few soil geomorphic studies in high elevation mountains in New Mexico. For example, Google Scholar for publications in this area of research turned up between 0 and a maximum of 3 papers (for a given mountain range) over the last few decades based on studies in the Sangre de Cristo, Sandia, Sacramento, Black Range, and Mogollon Mountains. Although their focus is not on the development of soil properties, at least some of the published studies, such as the studies of Gierke et al. (2016) and Rea et al. (2020) in the Sacramento Mountains and Persico et al. (2011) in the Sandia Mountains foothills acknowledge the significance of dust accumulation in development of soils in their study sites.

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. The Sandias are composed mainly of the 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 Fig. 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 (Figure B.8) (McFadden, 2013). These smooth, soil-mantled hillslopes (Figure 5.6) have been stable for tens of thousands of years, but ongoing shifts in climate will likely strip away the soil. As noted above, the numerous studies in the Jemez Mountains provide important contributions to the understanding of the role played by soils in the critical zone. Several of these studies also focus on soil hydrology, and in particular the impacts of wildfire on surface soil horizon alteration and erosion potential (e.g., Martin and Moody, 2001) (see Chapters 4 and 6). Employing “constitutive mass balance” analysis of a strongly developed soil atop the Pajarito Plateau, Eberly et al. (1996) strongly suggest that dust accumulation has influenced the development of soils on the hillslopes of the Jemez Mountains and other mountain ranges elsewhere in the southwest United States.

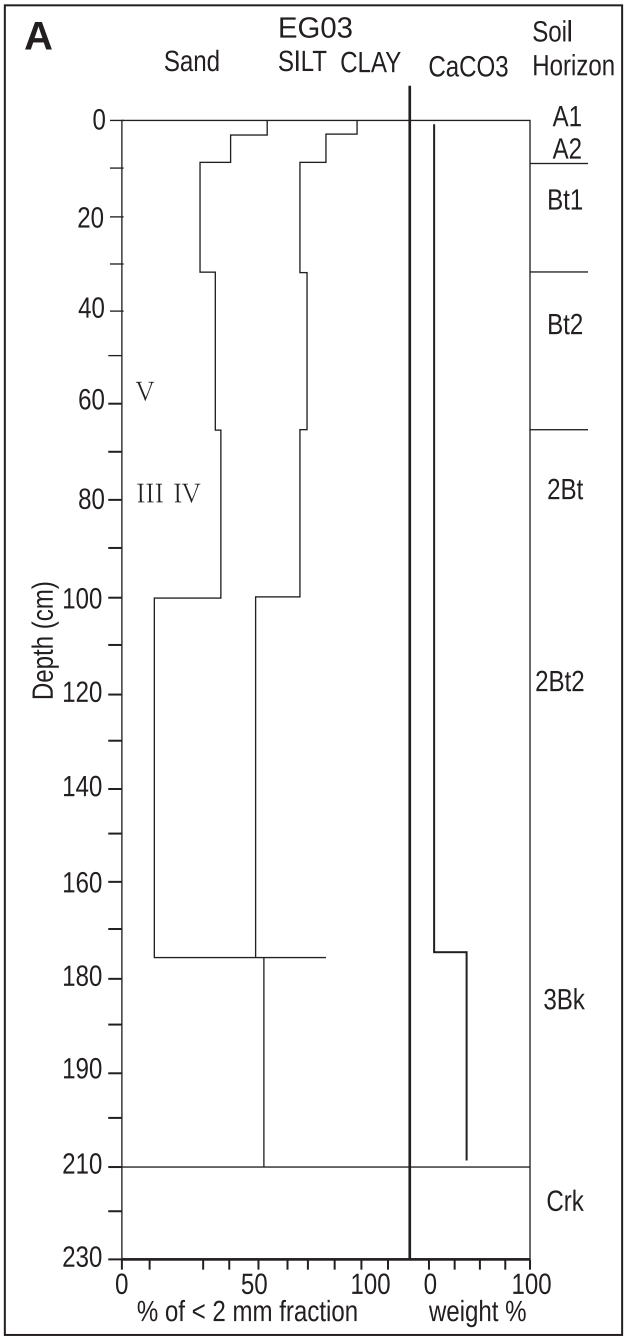


Figure B.8. Changes in particle size and soil carbonate concentrations in a thick soil on an “aplite” hillslope located in the foothills of the Sandia Mountains, New Mexico. The graph shows that soil-forming processes over tens of thousands of years have caused the accumulation of a great deal of clay and silt in the soil “B” horizon, most of which is derived from windblown dust. Only small patches of much thinner and weakly developed soils are found on the core-stone hills. Development of such soils are responsible for the emergence of smooth, curvilinear hillslopes (see text). Roman numerals signify depths at which samples for optical luminescence studies were taken. Modified after figure 8 in Persico et al. (2011).

APPENDIX C

The Clausius-Clapeyron Relationship

Most discussions of the effects of a warming climate on extreme precipitation start with a presentation of the Clausius-Clapeyron equation, which describes the saturation vapor pressure of water as a function of temperature (Donat et al., 2016; Lu et al., 2018; Lynker Technologies, 2019; Meredith et al., 2019; Kappel et al., 2020; Kunkel et al., 2020; Tabari, 2020; Fowler et al., 2021). The saturation vapor pressure of water is proportional to the maximum water content that the atmosphere can hold.

$$ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Where

- P_1 & P_2 are the vapor pressure of water at temperatures T_1 & T_2
- ΔH_{vap} is the Enthalpy (Heat) of Vaporization of water (40.7 kJ/mol)
- R is the universal gas constant (8.314 J/(mol °K))

This relationship, plotted in Figure C.1, shows that a slight increase in temperature results in a large increase in atmospheric water content at warm temperatures. For example, increasing air temperature by only 1°C (1.8°F) allows the atmosphere to retain approximately 7% more water vapor. Consequently, increased temperature allows for the potential for much-increased water content in the atmosphere. This relationship directly implies the potential for increased precipitation from rainfall events as temperature increases.

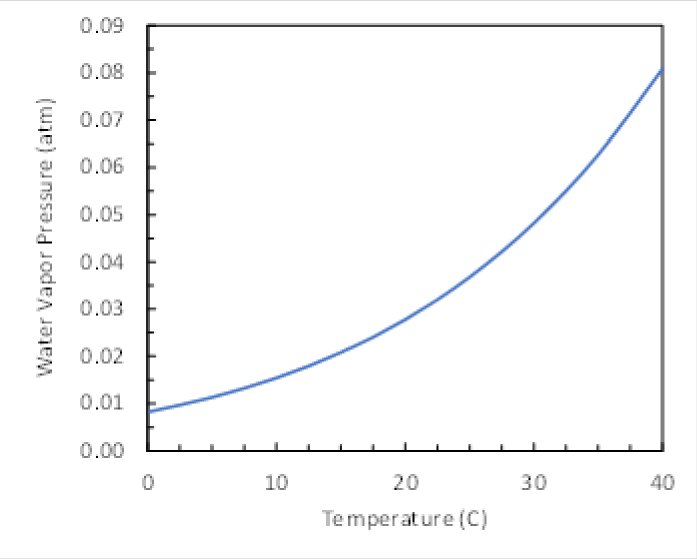


Figure C.1. Relationship between saturation water vapor pressure (over a flat surface of liquid water) and air temperature.

Of course, most of the time the actual vapor content of the atmosphere is much less than the saturation vapor pressure (the "holding capacity" of the air). This statement is equivalent to noting that most of the time the relative humidity (which is the actual vapor content expressed as a percentage of the saturation value plotted in Fig. C.1) is considerably less than 100%. On dry summer days in New Mexico, the relative humidity can be as low as 5%; on these days the temperature is typically very hot, but there just is not much water vapor in the air. For purposes of assessing future rare occurrences of extremely high precipitation, however, the huge increase in saturation vapor pressure at temperatures near 40°C in Fig. C.1 provides a compelling reason to expect that the most extreme precipitation events will be more intense in a warmer climate.

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Doug West, *Arroyo Salado*, serigraph, 1993

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