Summarizing Concerns for Natural Resources Due to Climate Change and Interactions With Non-Climate Stressors in the Rocky Mountains

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Overview of Climate Change Effects on Plant and Animal Species in the Rocky Mountains

Climate change presents many challenges for ecosystems, biodiversity, and ecosystem services, particularly in combination with non-climate stressors. Progressive warming, variable precipitation, and more frequent extreme weather events produce changes in ecosystem structure and function, species distribution and abundance, and productivity (IPCC 2021; Lipton et al. 2018). Climate change affects natural resources and interacts with disturbances, such as fire, and non-climate stressors, such as habitat loss, to sometimes generate synergistic effects (Coristine and Kerr 2011). However, disturbance and land-use change also may have antagonistic interactions with climate change, for example, creating lags in species response to climate change or even species shifts to warming locations (Song et al. 2021). Vulnerability of plant and animal species intensifies with exposure to a greater magnitude of climate change, posing substantial risks to ecosystems and their services (Glick et al. 2011). The ability of wildlands to continue to provide goods and services may be disrupted when ecosystems and processes operate outside of historical climate conditions (Warziniack et al. 2024).

Climate has warmed during recent decades due to radiative forcing by emissions of radiatively-active greenhouse gases (Foote 1856; IPCC 2021; Rangwala 2024). General circulation models unequivocally predict progressive warming (fig. 1), but projected precipitation is less certain in magnitude, direction, and spatial and temporal variation (Rangwala 2024). The northern Rocky Mountains are projected to experience increased precipitation, based on agreement among most general circulation models (fig. 2; Hayhoe et al. 2018). Regardless of total precipitation, precipitation may occur more frequently in heavy precipitation events, resulting in surface runoff, flooding, erosion, and fallen trees (Hanberry et al. 2024; Rangwala 2024). Heavy rains, with water lost to overland flow, and warming trends, with greater evapotranspiration rates, will cause effectively drier conditions despite the same or even greater total precipitation, influencing resources and disturbance events such as wildfires (Rangwala 2024). Moreover, warmer temperatures will lead to more precipitation in the form of rain instead of snow, decreased snowpack, earlier snowmelt, and earlier dry conditions in soils and streams during summer, resulting in water limitations and longer fire seasons (Rangwala 2024). Nonetheless, cold-limited mountainous elevations may resist some of the impacts of warming temperatures, whereas water limitations that reduce biomass production may slow fuel accumulation and potentially reduce fire frequency or severity (Addington et al. 2018).

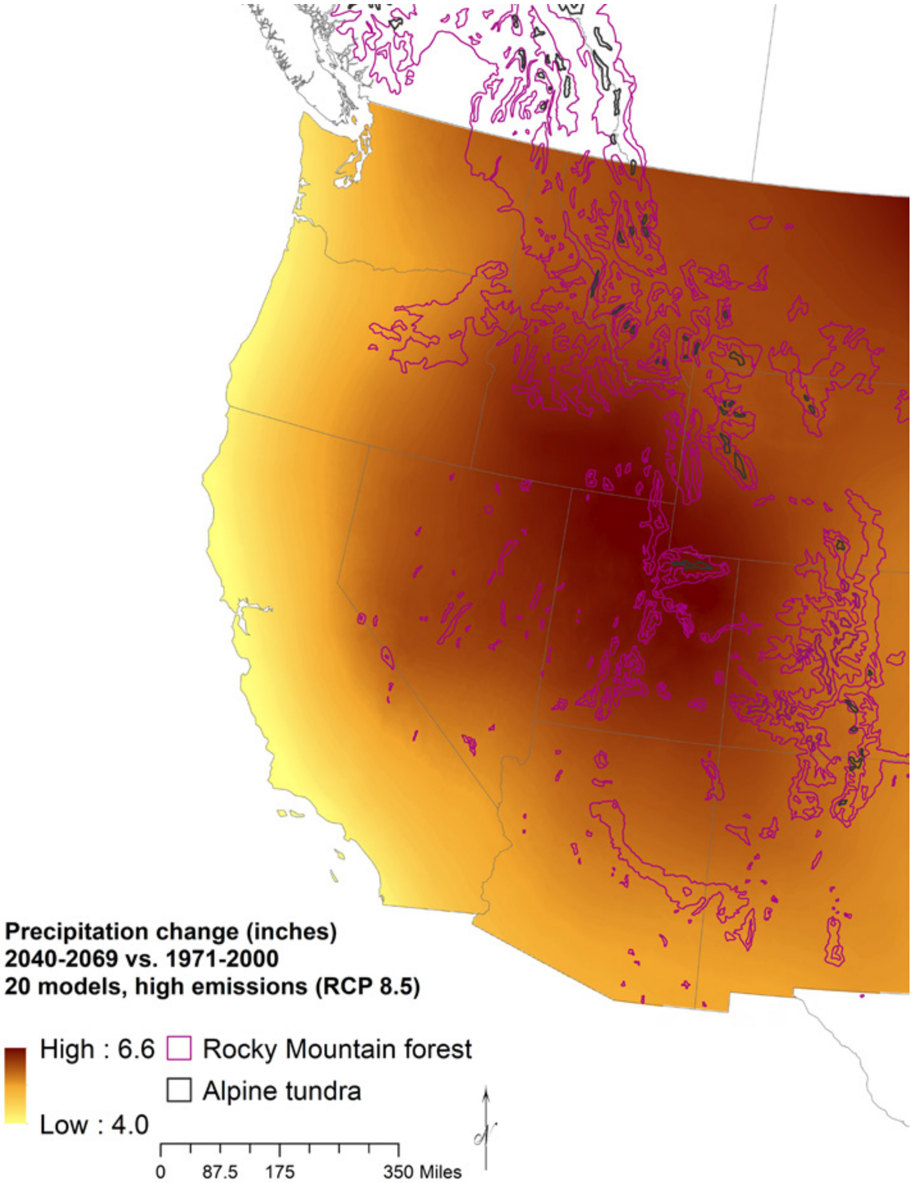

Figure 1—Projected change in mean annual temperature (°F) during 2040–2069 as compared to the baseline average during 1971-2000 for an ensemble of 20 general circulation models under the fossil-fueled representative concentration pathway (RCP8.5; Abatzoglou 2013; modified from Climate Toolbox 2022).

Climate change affects natural resources both directly and indirectly and may help or hurt species or populations over time by modifying survival, growth, and reproduction (Fornwalt et al. 2024; Smith 2024; White 2024). Direct impacts include stress or mortality from heat, drought, flooding, and cold, due to less insulative snow cover, and mistimed migration, reproduction, and hibernation activities (White 2024). Warming likely will affect growing season length, dormancy, and productivity (Fornwalt et al. 2024; Rangwala 2024). Longer growing seasons may allow for greater overall growth rates, especially for cold-limited species, creating compensation for metabolically stressful periods (Fornwalt et al. 2024; Smith 2024; White 2024). A warmer climate generally may increase growth of species in energy-limited high-elevation or high-latitude forests with short growing seasons, until exceeding species heat tolerances, and conversely, may decrease growth, particularly of trees, in water-limited forests at low elevations in the western United States (figs. 1 and 2; Fornwalt et al. 2024; Smith 2024; White 2024).

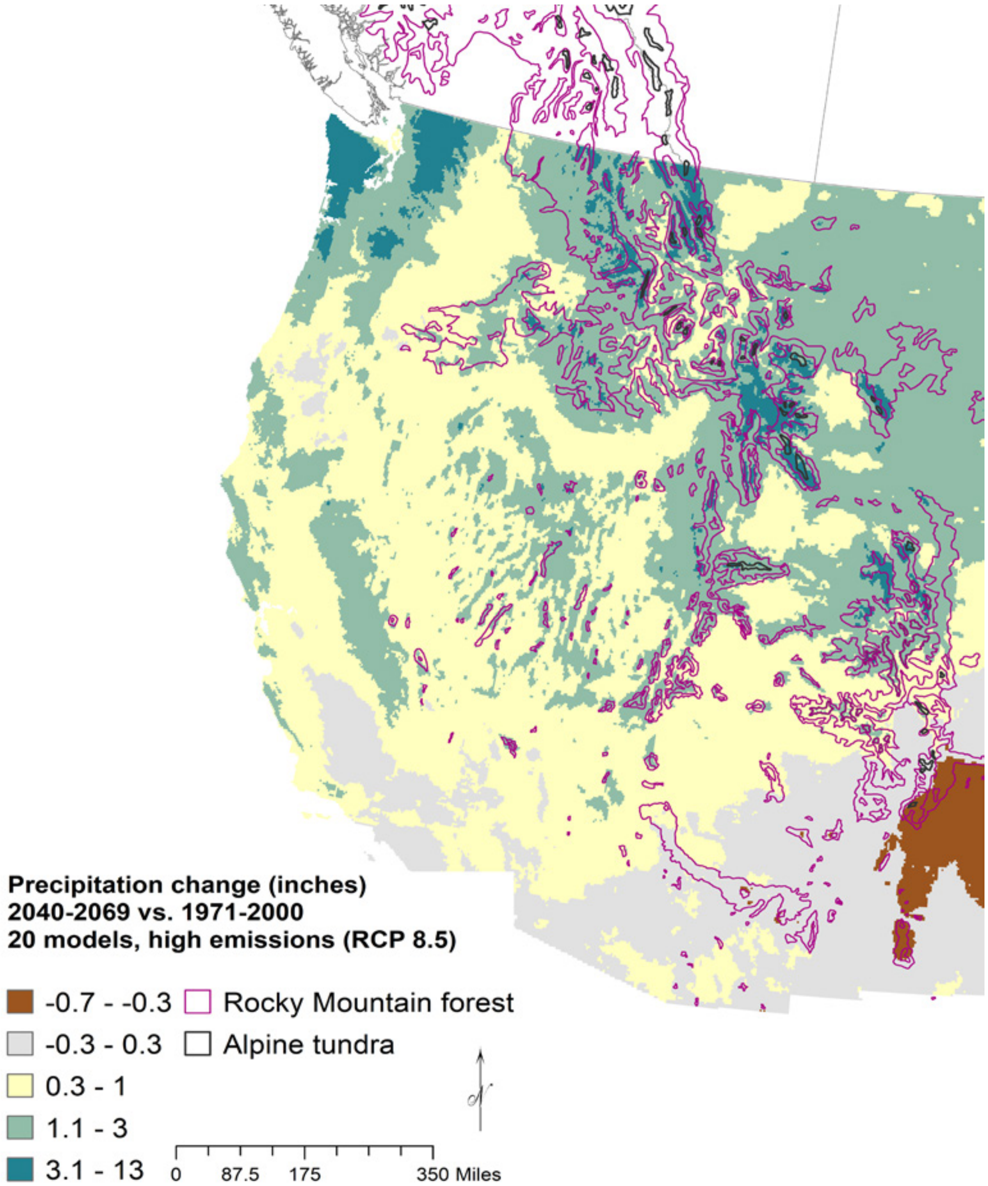

Figure 2—Projected change in mean annual total precipitation change (inches) during 2040–2069 as compared to the baseline mean annual average during 1971–2000 for an ensemble of 20 general circulation models under the fossil-fueled representative concentration pathway (RCP 8.5; Abatzoglou 2013; modified from Climate Toolbox 2022).

Climate change may have a greater influence on plant and animal species through influences on resources and biological interactions rather than direct physiological stress, excluding mortal thresholds (Keane et al. 2018). Extreme weather events such as flooding and drought can disrupt foraging and nesting resources by altering the quantity, timing, and location of resources leading to reduced survival, growth, and breeding success (Keane et al. 2022). Dietary, pollinator, or propagule dispersal specialists (i.e., dependent on a single or small number of species for food, pollination, or propagule dispersal) are more vulnerable to climate-related changes in resources than more generalist species (Glick et al. 2011). Faster-growing species that dedicate fewer resources to cold tolerance typically are able to outcompete cold-adapted species under warmer climates (Fornwalt et al. 2024; Smith 2024). Species with a greater capacity to tolerate biological stressors (such as insect outbreaks beyond endemic levels or invasive species) and increased frequency or intensity of extreme natural disturbances also may have a competitive advantage and experience relatively greater success in survival, growth, and reproduction than competitors (Decker and Fink 2015).

Species, populations, and individuals respond uniquely to climate change; therefore, climate-related changes are likely to disrupt ecosystems (Keane et al. 2018; Fornwalt et al. 2024). The ranges of plant and wildlife species are predicted to move in response to shifts in climate suitability at species-specific rates and trajectories, potentially disordering current ecosystem assemblages (Davis and Shaw 2001). Typically, species are composed of populations genetically suited to the climate of their location (Friggens et al. 2013). Populations at the southernmost or lowest elevation range edges are predicted to have greater exposure to temperature increases beyond optimal for persistence, compared to populations in the center or leading edge of the range (fig. 3a-d; Decker and Fink 2015). The degree to which individual species are able to adjust through behavioral or physiological plasticity to changing climate spaces within their occupied range is partially driven by genetic variation (Lipton et al. 2018). Some individuals and species can alter their behavior of foraging or habitat use in response to new environmental conditions (Lipton et al. 2018). Long-term strategies to adjust to climate change include shifting ranges poleward or up in elevation for montane species and selection to optimize fitness by matching genotypes with shifting climate (Friggens et al. 2013). Species with greater genetic variation and wide-ranging species that thrive under diverse conditions are likely to be less sensitive to climate change than species with limited genetic variation and narrow environmental tolerances (Decker and Fink 2015). Species with substantial dispersal ability are better able to track shifting climate envelopes than species with limited dispersal or with barriers of unsuitable habitat to dispersal (Decker and Fink 2015). Climate change may favor generalist and nonnative species with strong dispersal abilities, rapid growth rates, short generation times, and tolerance of broad and changing environmental conditions (Glick et al. 2011).

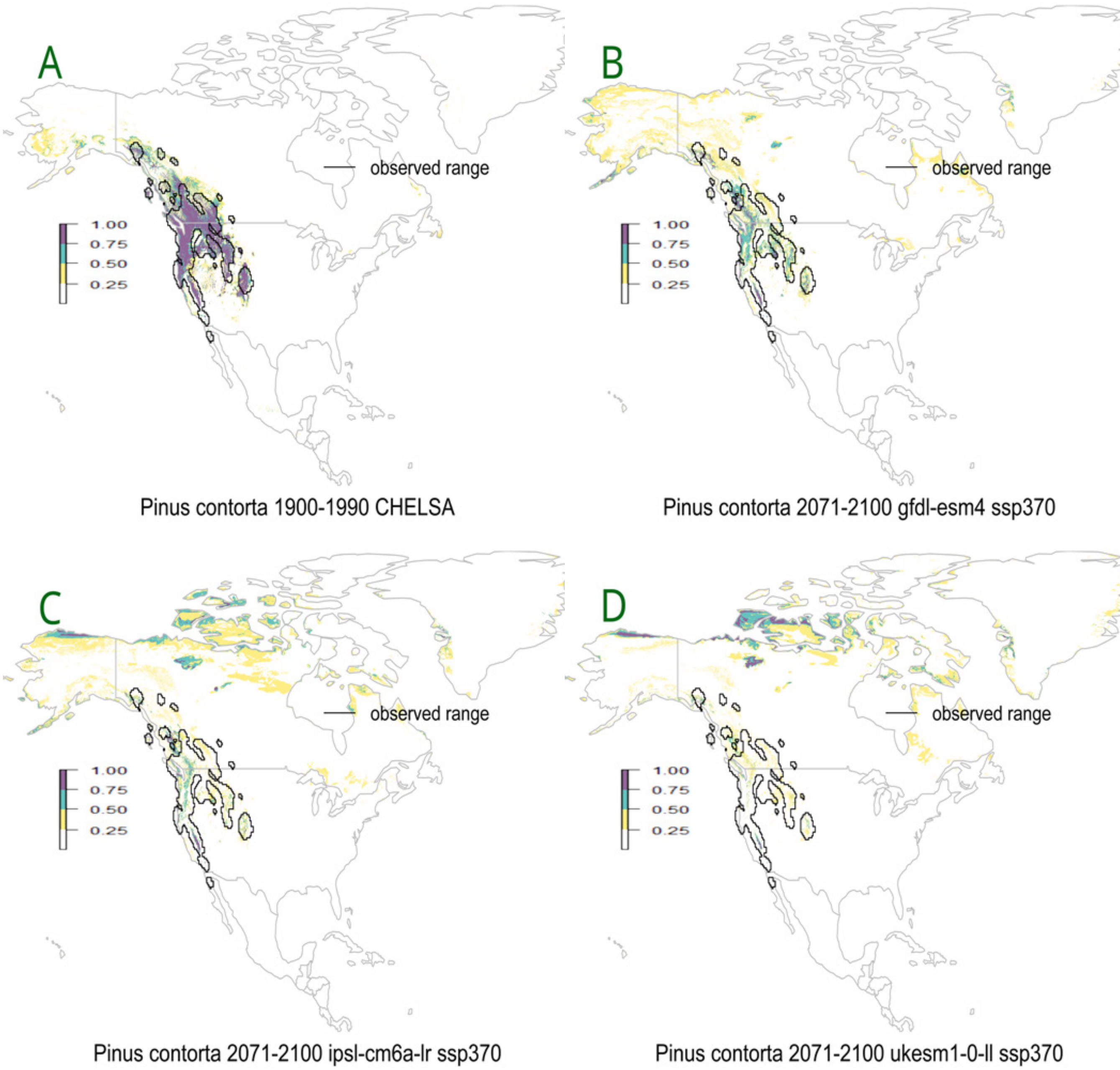

Figure 3a-d—Bioclimatic envelope, or modeled species distribution, of lodgepole pine (*Pinus contorta*) that shows observed range (black outline) from known locations and the climate envelope (temperature and precipitation of occurrences) during 1900–1990, and predicted future climate envelopes, 2071–2100, under three general circulation models and moderate emissions. Based on this model, lodgepole pine has great sensitivity to climate change.

Bioclimatic envelopes are modeled distributions of species observations based on temperature, precipitation, and other climate metrics (fig. 3, B. Hanberry 2024). However, species locations are constrained by many factors, such as disturbances, competitive interactions, and barriers to dispersal. Climate limitations are not known and indeed, climate interactions with the ecological setting and the life stage of the organism may generate a range of outcomes, from lethal to optimal for survival, growth, and reproduction (Fornwalt et al. 2024; Keane et al. 2018). Due to warmer temperatures, bioclimatic envelopes will be pushed upslope in elevation or northward in latitude (Fornwalt et al. 2024; Keane et al. 2018). In general, higher elevations have cooler temperatures and receive more precipitation and the wide range in elevations available in mountains will be to the advantage of species to readily locate to cooler conditions (Fornwalt et al. 2024; Keane et al. 2018).

Many species use seasonal cycles of climate, such as heat and chilling accumulation and precipitation patterns, as cues for blooming, reproduction, migration, or hibernation (Wolkovich and Cleland 2014). Phenology is the timing of periodic events (Lipton et al. 2018). Factors that cause or change timing and relationships among phenological events can affect species, communities, productivity, and ecosystem function (Lipton et al. 2018). Altered life cycle timing or weather patterns, such as earlier onset of bud burst and flowering, precipitation and flood events, fire seasons, emergence from overwintering, nesting, annual migration, and water availability, may cause seasonal mismatches between species and necessary food sources, or other resources, such as water, cover, and nesting opportunities (Lipton et al. 2018). Decoupling of temperature and photoperiod cues may be maladaptive for plants and animals, resulting in lessened growth, survival, and reproduction, and overall competitive disadvantage for resources (Keane et al. 2018; White 2024). Interdependencies occur among plants, insects, and birds for pollination and nesting and foraging resources (Keane et al. 2018; White 2024). Differential phenologies may disrupt the synchronicity of plant-pollinator or insect-breeding bird relationships in space or time where one partner relies more heavily on different cues; for example, temperature, day length, or snowmelt (fig. 4; Keane et al. 2018; White 2024). In addition, invasive species generally appear to be tracking climate change phenologically more closely than native species (Wolkovich and Cleland 2014).

Climate change can impact resources, species, and productivity by enhancing the growth and reproduction of insects and pathogens and increasing severe, stand-replacing fires. Recent insect outbreaks and insect-caused tree mortality may be outside of historical bounds, in that historically insects occurred in low numbers and killed weak trees with rare outbreaks (Negrón 2024; Romme et al. 2006). For example, warming has allowed mountain pine beetles (*Dendroctonus ponderosae*) to erupt at higher elevations and latitudes where winters historically were cold enough to reduce overwintering survival (Negrón 2024). A century of fire exclusion and overstory disturbance has generated dense forests with accumulated surface and canopy tree fuels (Romme et al. 2006). Warmer temperatures and more frequent drought in higher-elevation forests with abundant fuels may increase fire frequency, while lower-elevation woodlands may become fuel-limited due to reduced production (Keane et al. 2018).

Figure 4—Climate change may alter biotic relations and processes, such as mutualisms that exist between plants and pollinators, including bees, beetles, flies, wasps, ants, butterflies, and moths (Courtesy photo by B. Hanberry).

Disturbances of drought, severe wildfires, and insect outbreaks can occur in a rapid sequence (compounding), modulating both the severity of the next disturbance and effects on species (Bigler et al. 2005; Kulakowski et al. 2013; Page et al. 2014). For example, wildfires that reduce stand basal area may aid in protecting pine from future fires, beetle outbreaks, and drought, perhaps for decades or longer by reducing stress related to competition (Bigler et al. 2005). However, effects may be complex to partition. Page et al. (2014) reported that the likelihood of severe fires increased in lodgepole pine (*Pinus contorta*) stands attacked by mountain pine beetles, though typically this effect lasted less than 10 years. In contrast, mountain pine beetles did not appear to influence 57 large (> 1,140 ha) wildfire events that burned for greater than 10 days (Hart and Preston 2020). Multiple severe disturbances, from insects, wildfire, blowdowns, and logging, do not appear to favor lodgepole pine or conifers in general relative to quaking aspen (*Populus tremuloides*); conversely, aspen is not tolerant of drought (Bretfeld et al. 2016; Kulakowski et al. 2013; Rhoades et al. 2018).

Species are often less tolerant of additional stresses when already under stress from one factor (Kolb et al. 2019; Sturrock et al. 2011; Vanbergen et al. 2013). That is, cumulative stresses are likely to have synergistic interactions, resulting in greater negative impact on species (Kolb et al. 2019; Vanbergen et al. 2013). Stress can suppress immune function in animals and stressed trees generate weaker resin flow, amplifying the negative effects of disease or damaging insect exposure in populations (Goulson et al. 2015; Kolb et al. 2019). Non-climate human activities that degrade and fragment wildlands, such as agricultural and residential conversion or infrastructure development, increase species sensitivity to climate change by reducing resources that sustain plant vigor and animal health against insect or disease infection (Vanbergen et al. 2013). Many predisposing long-term factors for disease and mortality, such as previous disturbance, fire exclusion, stand structure, tree age, and site location (elevation, aspect, site quality), influence disturbance severity by altering the capacity of trees to resist stress (Sturrock et al. 2011). Inciting factors for disease and mortality are short-term conditions such as drought that weakens trees, particularly in high-density stands (Sturrock et al. 2011). Contributing factors for disease and mortality consist of attacks by insects or fungi, which are otherwise unlikely to attack and kill healthy, vigorous trees (Sturrock et al. 2011). Recent large-scale insect outbreaks may be due to a combination of climate change (drought-stressed trees, warm summers that accelerate insect growth and development, warm winters that allow insect larvae to survive) and land-use change, which reduce tree vigor, particularly in dense forest stands (Romme et al. 2006).

Aquatic Ecosystems in the Rocky Mountains

Physical (water temperature) and biological (vegetation) conditions in aquatic ecosystems provide the habitat required by native aquatic and semiaquatic species, including amphibians, fishes, macroinvertebrates, and plant and periphyton communities (fig. 5; Smith 2024). Climate change is likely to warm water temperatures, change timing and magnitude of flows, and reduce water levels, due to greater evapotranspiration and longer growing seasons (Lall et al. 2018; Warziniack et al. 2024). Water level reductions and warming, with changed flow patterns, will interact with stresses arising from poorer water quality due to sedimentation and pollutants, fragmentation and loss of shading vegetation cover, water regulation, and human water use (e.g., irrigation, diversions, reservoirs; Young et al. 2018).

Due to likely loss of cold and transitional stream reaches under warmer and drier conditions, vulnerability of freshwater ecosystems overall is greater than for terrestrial vegetation types (Decker and Fink 2015). As water temperatures change, cool- or coldwater aquatic ecosystems are likely to transition to warmwater aquatic ecosystems, with only high-elevation streams potentially resistant to these effects. Likewise, warmer water temperatures will favor warmwater fish over coldwater fish (e.g., bull trout, *Salvelinus confluentus*; Young et al. 2018). Warmer stream temperatures may allow increased invasion by nonnative fish, supplanting native fish or increasing hybridization risk (Smith et al. 2024; Young et al. 2018). Lower base flows could lead to reduced fish abundance and reduced recruitment (Smith et al. 2024; Young et al. 2018). Hot days could be a potential trigger point for fish mortality, especially if combined with low flow and low oxygen levels or of a long duration (Smith et al. 2024).

Figure 5—Climate change is likely to warm water temperatures and change timing and magnitude of flows in aquatic and wetland ecosystems. Muskrats (*Ondatra zibethicus*) are an ecohydrological indicator species and may serve as a bellwether for drying ecosystems (Ward et al. 2021; Courtesy photo by B. Hanberry).

Higher high flows and lower low flows could lead to increased erosion, which reduces water quality and affects reproduction by aquatic species, and leads to channel adjustments or breaks in stream connectivity (Young et al. 2018). Some aquatic species require floodplains created by peak flows for spawning or larval/juvenile development (Wydoski and Wick 1998). Fish may need access to thermal refugia and connectivity to access those refugia (e.g., cooler tributaries, streams with spring inputs, deeper pools, more shade; Young et al. 2018). For most species, intact connectivity within the hydrologic network will support movement and long-term migration to appropriate conditions as existing reaches become increasingly dry and warm (Young et al. 2018). Species assemblages likely will change as species migrate and as less mobile and more vulnerable community members are eliminated (Young et al. 2018).

Forests in the Rocky Mountains

Forests of the Rocky Mountains are primarily dominated by conifers and can be loosely grouped into (1) pinyon pine (*Pinus edulis*)-juniper (*Juniperus scopulorum, J. osteosperma*), (2) ponderosa pine (*Pinus ponderosa*), (3) mixed-conifer forests including ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and aspen (*Populus tremuloides*), (4) lodgepole pine (*Pinus contorta*), (5) aspen, and (6) subalpine forests including Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (Fornwalt et al. 2024). Disturbance regimes, which are modulated by climate and site-specific context, favor different tree species and drive plant community assemblages (Keane et al. 2018). For example, surface-fire tolerant ponderosa pine is a long-lived species; longevity is indicative of a species that has evolved in a system with infrequent stand-replacing disturbance events (Hanberry et al. 2020). Conversely, aspen, lodgepole pine, and many firs and spruces are short-lived species that typically respond well to stand-replacing disturbances (Fornwalt et al. 2024; Keane et al. 2018).

Fires and vegetation have synergistic and antagonistic interactions. Pinyon and juniper typically occur in warm, moisture- and fuel-limited low-elevation sites with discontinuous vegetation, resulting in infrequent fires (> 50 years between events) and fire severity determined by amount of available tree and shrub fuels (Veblen and Donnegan 2005). Generally, albeit varying in space and time, ponderosa pine forests, in particular at lower montane elevations (that is, warmer locations) with enough moisture to grow continuous fine surface fuels, had frequent (< 35 years) low-severity fire regimes, given discontinuous or at least clumped tree densities (Addington et al. 2018). Conversely, spruce and fir forests, with continuous understory to canopy and canopy to canopy fuels, at higher elevations (that is, colder locations) experienced high-severity fires, perhaps every century or so due to ignition limitations and also lack of fine surface fuels that ignite easily (Addington et al. 2018). However, fire spread is contagious and higher elevation forests experienced fires that spread upslope from grasslands and woodlands (Jack 1900). For mixed forests at intermediate elevations and temperatures or wet conditions, historical fire probabilities also were intermediate in range with mixed-severity burns occurring every 35 to 100 years (Arno 2000).

Fires, which are whole-system disturbances, have different regimes dependent on the amount, continuity, and type (that is, fine herbaceous or coarse tree) of fuels and probability of ignition. Fires can be patchy in distribution, though mixed-severity burns may remove 20 to 80 percent of the dominant trees (Addington et al. 2018). High-severity fires, with long flame lengths, occur when midstory trees are dense enough to allow fire to spread to the overstory (Urza et al. 2023). If canopies are not connected, torching of individual or grouped trees may occur, reducing overstory tree density without necessarily terminating most of the stand (Urza et al. 2023). Faster fuel accumulation due to greater productivity, which may occur under wetter conditions in water-limited forests or under warmer conditions in cold-limited forests, increases frequency of fires, whereas fuel connectivity to and among tree canopies increases fire severity; extended warm and dry conditions and abundance of fine, cured fuels increase the chance of ignition (Urza et al. 2023).

During the early 1900s, fire exclusion became standard management to prevent forest destruction and loss of valuable board feet per acre, effectively disrupting the natural fire cycle of many ecosystems (Addington et al. 2018; Keane et al. 2002; Veblen and Donnegan 2005). Euro-American settlement resulted in extensive logging and grazing by domestic livestock during the mid- to late 1800s, modifying stand structure, fuels, and fire regimes, although during initial settlement before extensive land cover change, fire frequencies typically increased (Veblen and Donnegan 2005). In general, forest changes during the past century have included increased tree density, reduced tree diameters, increased abundance and range of fire-sensitive species, and increased fuel accumulation, in particular surface and ladder tree fuels (Addington et al. 2018; Hanberry et al. 2024; Keane et al. 2002).

Reduced water availability and hotter or more extreme temperatures directly may change community composition, favoring species with drought and heat tolerance traits (Fornwalt et al. 2024; Keane et al. 2018). As climate shifts, trees are likely to migrate upslope in elevation or northward in latitude (fig. 6; Fornwalt et al. 2024; Keane et al. 2018). Growth and productivity also may shift, as soils in warmer locations become water-limited during the growing season whereas cooler locations will experience an increase in growing season length (Keane et al. 2018). The influence of drought, in combination with variable heat tolerance of individual tree species, likely will drive overall forest response to climate change and, ultimately, resistance to damage from insects and fire (Keane et al. 2018). However, climate change effects may be obscured by the slow response times of long-lived tree species, with a lag in species response relative to the rate of change (Davis and Shaw 2001). Non-climate influences such as changing land use and inherent variability among species can make it difficult to attribute changes in abundance or range to climate alone (Coristine and Kerr 2011; Song et al. 2021).

Furthermore, drought may interact with severe disturbances, particularly wildfire and insects, creating different outcomes (Davis et al. 2019). While some tree species auto-replace under severe disturbances, such as drought-tolerant lodgepole pine, compounding disturbance events that include insects may prevent lodgepole pine regeneration and allow stand replacement by quaking aspen and southern tree species (Rhoades et al. 2018). Aspen is another species that thrives on severe fires and other severe disturbances, auto-replacing typically every century, but aspen is sensitive to drought and heat (Anderegg et al. 2013; Carroll et al. 2019; Kulakowski et al. 2013). Aspen has been successful at establishing following recent high-severity wildfires upslope of its previous range within burns, but not in unburned areas, probably due to seedbed requirements (Nigro et al. 2022).

Figure 6—Spruces, firs, and Douglas-fir (*Pseudotsuga menziesii*) may increase in alpine meadows as temperatures warm. These species currently are expanding due to fire exclusion (Hanberry et al. 2020; Courtesy photo by B. Hanberry).

Extreme Events and Infrastructure Development in the Rocky Mountains

Residential development has increased adjacent to public lands (Karau et al. 2024). Wildlands are desirable amenities that supply ecosystem services of privacy, aesthetics, well-being, and recreational access (Warziniack et al. 2024; Wear and Joyce 2012). Furthermore, national forests have protected area status as an added attraction, guaranteeing reduced development and changes to the surroundings, and the benefit of investment in land management services, including wildlife support, invasive species control, and fuel treatments (Karau et al. 2024; Wear and Joyce 2012).

At the same time, the risk of wildland fire affecting homes and other structures is greatest in wildlands (Hanberry 2020). The length of wildfire season has increased due to warming temperatures, with increased number of extreme fire weather days, and fire severity has increased with fuel accumulation (fig. 7; Karau et al. 2024; Rangwala 2024). Severe wildfires are difficult to contain, particularly in areas with widespread low-density exurban housing, driving up the cost of fire containment (Karau et al. 2024). Awareness and preparation for wildland fire by communities and homeowners is a challenge near public lands, where homeowners tend to rely on public agencies to provide fire containment rather than act themselves (Busby and Albers 2010). Ideally, homeowners would limit fuel accumulation surrounding homes and fires could spread without causing extensive damage (Karau et al. 2024; Wear and Joyce 2012). Defensible perimeters protect buildings from forest fire and inversely can prevent fire spread from houses to forests (Karau et al. 2024).

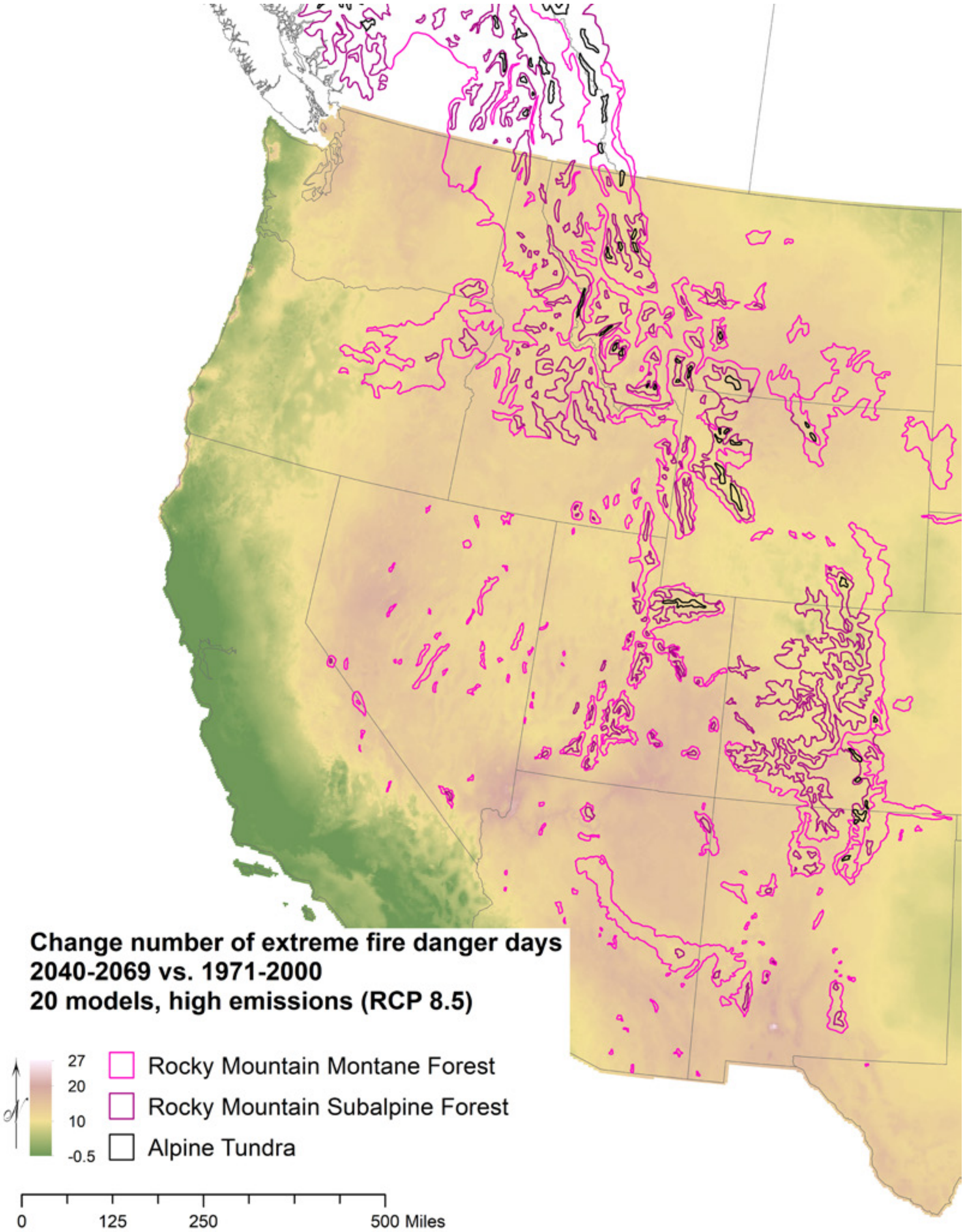

Figure 7—Projected change in the mean number of extreme fire danger days (100-hour fuel moisture below 3 percentile) during 2040–2069 as compared to the baseline mean number of extreme fire danger days during 1971–2000 for an ensemble of 20 general circulation models under the fossil-fueled representative concentration pathway (RCP 8.5; Abatzoglou 2013; modified from Climate Toolbox 2022).

As the spatial extent of recently burned wildfires increases, previously burned areas may provide fuel breaks that influence the pattern, extent, and severity of future fires (Urza et al. 2023). Fuel treatments can protect bordering infrastructure and treatment placement can take advantage of adjacency to land uses, such as roads and fields, that act as firebreaks, and leverage locations of prior treatments or fires (Urza et al. 2023). Large fires can easily overwhelm small, unconnected fuel treatments, and extreme weather conditions will overwhelm most preventive and suppression actions (Prichard et al. 2020).

Infrastructure is vulnerable to extreme weather events and stress from changing climate through flooding, drought, wildfire, extreme heat, ice, strong winds, freeze-thaw cycles, and snowmelt (Hanberry et al. 2024). The U.S. Department of Agriculture, Forest Service infrastructure portfolio consists of structures and facilities for administrative, transportation, recreation, or special uses, such as dams and camping concessions (Hanberry et al. 2024). Extreme events may cause injury and mortality and disrupt livelihoods and infrastructure networks, such as roads, water and power supplies, and health and emergency services (Mora et al. 2018). Extreme events often interact because they are spatially and temporally dependent, leading to underestimation of risk (Mora et al. 2018; Zscheischler et al. 2018). Fire may lead to postfire flooding due to loss of vegetation and debris flow due to soil erosion, intensifying vulnerability (Keller et al. 2021). On top of heat, fire, and postfire events, climate change likely will increase heavy precipitation and flooding, resulting in a cascade in which greater temperatures may produce more fires that will interact with floods (Rangwala 2024). Flooding is the most costly natural disaster in the United States, through direct rainfall, overbank flows, soil erosion, and landslides (Keller et al. 2021). Simple designs to reduce flooding hazard, by reducing susceptibility to flooding, include regularly cleaning out culverts, maintaining roads and ensuring surface drainage measures are functional, modifying bridge and culvert designs to accommodate larger flows, avoiding potential of stream diversion at road-stream crossings, and correcting scour problems at bridges (Keller et al. 2021).

Social and Economic Considerations in the Rocky Mountains

Forests on public and private lands benefit human populations through ecosystem services that encompass four primary functions: provisioning materials, such as forest products, forage, and water; regulating services, such as clean water, erosion control, climate and natural hazard control; cultural services, such as scenic and recreational opportunities, spiritual enrichment, and physical and mental health; and providing supporting services, such as nutrient cycling, pollination, and soil formation (Warziniack et al. 2024; Wear and Joyce 2012). Public land management aims to provide both market and nonmarket ecosystem services, maximizing public welfare derived from forests by maintaining and considering resources, recreation, infrastructure, natural resource extraction, scenic appeal, Tribal areas, heritage status, land status, designated areas, and socioeconomics (Arapaho-Roosevelt National Forests and Pawnee Grasslands 1997). National forests connect local residents and visitors to the land and one another, through additional opportunities such as volunteering, education, and scientific learning, contributing to the quality of life, sense of place, and scientific monitoring (Fairchild and Hanberry 2024).

Natural resource-based communities derive economic benefits from surrounding natural resources and withstand associated natural disturbances. Tourism and recreation are important for economies and for human well-being, with winter and water sports likely to be affected by climate change (Sánchez et. 2024). Demand for recreation is projected to increase with population growth; however, recreation and tourism are relatively adaptive (Sánchez et. 2024). Vulnerable populations may have relatively greater exposure to climate change effects or have sensitive characteristics, resulting in reduced adaptive capacity (Warziniack et al. 2024; Wear and Joyce 2012).

Climate change likely will exacerbate long-standing issues about sharing natural resources, including water rights (Prestemon et al. 2016; Smith 2024). Currently, water use is highly subsidized so that prices do not reflect the full cost of water, resulting in the majority of water consumption for agricultural irrigation (Prestemon et al. 2016). With increased drought and demand for water from other competitive sectors (domestic, public, commercial, and industrial water use), transfer of water rights may occur from agriculture to urban centers or for multiple objectives, such as maintenance of minimum stream flows for protection of aquatic species, recreation, maintenance of water quality, and riparian land restoration (Prestemon et al. 2016).

Management in the Rocky Mountains

Climate change is projected to significantly damage human health, the economy, and the environment (Mora et al. 2018). A number of approaches have been developed to mitigate climate change through low-carbon energy technologies and energy efficiency (Griffith et al. 2021). At the Federal level, recommendations for sustainable operations include reducing water and energy consumption and increasing water and energy efficiency, purchasing sustainable goods and services, reducing waste generation, and reusing and recycling materials. Sustainable operations include a shift toward renewable energy, with installation of solar power systems on buildings as an option to consider (USDA FS 2014). It is possible to lessen exposure of infrastructure to extreme events, such as by not building near floodplains (Hanberry et al. 2024), and diminish susceptibility by building for tolerance to extreme events.

Climate changes are likely to disrupt natural resources in ways that challenge management. Public forest management can be slow to adjust management plans by design, due to the public process of resource planning (Wear and Joyce 2012). Earlier action compared to delay or inaction will allow development of experience in incorporating climate adaptation planning into natural resource management and testing effectiveness of actions (Keane et al. 2018). Decisionmakers may wish to take active steps to anticipate and steer change in desired directions and to avoid consequences of unplanned, crisis-based responses (Timberlake et al. 2024). Integrating climate risk management into existing planning, decision, and operations workflows, in contrast to adding novel decision processes for climate adaptation alone, can make adaptation more likely to succeed by strengthening already familiar processes with new information and tools (Keane et al. 2018). Known climate change vulnerabilities can inform prioritization of projects to receive funding, capacity, and other resources (Keane et al. 2018). The feasibility of project goals may be dependent on decisions to resist, accept, or direct climate-driven changes (Timberlake et al. 2024).

Integration of climate change into existing management workflows coherently addresses adaptation along with other objectives that are regularly managed, but in some cases may prove insufficient to address the full range and magnitude of climate risk (Essen et al. 2022). Even if potential magnitude and effects of climate change are assessed and adaptive management responses are developed, adaptation measures may not occur unless management organizations have sufficient people and financial resources (Essen et al. 2022). Linking across resource sectors and agency boundaries may generate additional capacity, for example, to focus on water rights (Essen et al. 2022). Addressing the full range of future climate change may entail changes in organizational practices and procedures (Tedim et al. 2021).

Effective management for climate change retains the basic management objective to restore and maintain resources against non-climate anthropogenic stresses. The 2012 Forest Service Planning Rule codifies management principles for National Forest System lands (USDA FS 2012). Systems that are already degraded from non-climate stressors likely have lower adaptive capacity for climate change and poorly nourished animals are less resistant to drought, temperature fluctuations, fire, land-use pressure, and disease (Goulson et al. 2015; Keane et al. 2018; Kolb et al. 2019; Wear and Joyce 2012). Both conventional and climate change management strategies for aquatic systems incorporate enhancing hydrologic connectivity and stream flows and guarding streams from sedimentation and erosion (Smith et al. 2024; Young et al. 2018). However, connectivity projects will be more proactive if designed for ecosystems likely to remain, for instance, perennial streams or deep pools, or future ecosystems with anticipation of higher high flows, lower low flows, and more frequent extreme flood events (Smith et al. 2024; Young et al. 2018). Management additionally includes restoration of natural disturbance regimes, including wildland fire where practical, to enhance resources (Keane et al. 2018; Veblen and Donnegan 2005). Other benefits include reduced fire severity, reduced outbreaks of native insect and disease populations, and reduced drought stress (Keane et al. 2018; Romme et al. 2016). For example, fires that are contained could lead to more severe fire or insect disturbances but areas treated with thinning or prescribed burns may experience mostly surface fires rather than crown fires, and equally, insect outbreaks and drought stress may be limited by reduced basal area (Keane et al. 2018; Romme et al. 2016). Management that considers interacting impacts of climate and other stressors on resources, coordinated across landscape scales, can greatly support ecosystems in the future.

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