

Chapter 7

NATURAL ECOSYSTEMS I. THE ROCKY MOUNTAINS

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INTRODUCTION

Background and Purpose

This assessment of climate-change effects on Rocky Mountain terrestrial ecosystems is prepared from information generated by a workshop focused on terrestrial systems of the Rocky Mountains, and held in Boulder, CO, on 29-30 September 2000 at the National Center for Atmospheric Research. It is a compilation of this workshop's discussion along with material from earlier workshops.

Because individual participants brought different disciplinary and geographic knowledge of the Rocky Mountains to this workshop, they were asked to provide insights on aspects of Rocky Mountain ecosystem sensitivity to climate change for which they had expertise. Specific future climate scenarios were provided in advance to provide some structure for the members' considerations. Modified versions of those scenarios are discussed later in this report.

The purpose of this chapter is to sum up the best thinking on possible impacts of future climate change on Rocky Mountain terrestrial ecosystems. To a large extent, this document

consists of acknowledged suppositions derived from “first principles” logic superimposed on years of experience in this region. Ideas contributed to this report are derived from perspectives covering a wide range of spatial and temporal scales. In this sense, this document is complementary to the Thompson et al. (1998) assessment of “... Potential Future Changes in Climate, Hydrology, and Vegetation in the Western United States” that is based on a common data set and a fixed scale. This report has not benefited from in-depth data analyses of particular issues such as hydrologic or vegetative responses to past climate changes. Nor does it fully utilize the rich ecological literature available for this region. No aspect of this report is, by any means, complete or authoritative. Rather, it aggregates the judgment of a score of people with long experience in the Rocky Mountain region who, by sharing their joint experience

and cautiously evaluating the evidence, make prudent extrapolations for the future.

The group considered it important to consider regional problems with landuse change, fire suppression, exotic-species invasions, habitat loss of threatened and endangered species, outbreaks of forest pests, and air and water pollution. These issues are ongoing, all too tangible realities, threatening the integrity of Rocky Mountain ecosystems now. Climate change, by comparison is presently an uncertain threat. Nevertheless, workshop participants hewed to the task of focusing on climate change itself, and were unanimous in their opinion that significant change will result from the interaction of climate change with present environmental issues if the projected changes occur.

This report is divided into 12 main sections starting with a brief description of the physical geography of the region and its sources and patterns of variation. Next are sections on hydrology, geomorphology, vegetation as an aggregation of plant cover, and individual species responses as members of the flora and fauna. After brief consideration of timbering, livestock production, and recreational activities in the region, the report terminates with an agenda for needed research and a summary.



Figure 7.1. The Rocky Mountain Province and surrounding physiographic provinces according to Hunt (1967) extended to the southern New Mexico border between the Rio Grande and edge of the Great Plains. Published with permission of W.H. Freeman and Company.

REGIONAL GEOGRAPHY

Domain

The geographical domain of this analysis is the Rocky Mountain Province (Hunt 1967) within the conterminous U.S. (Fig. 7.1). This Province is bounded by the Great Plains to the east, and by the Sierra-Cascade, Columbia Plateau, Basin and Range, and Colorado Plateau Provinces to the west. Technically, the Rocky Mountains terminate at their southern limit in northern New Mexico near Albuquerque and the mountains that continue southward to the Texas border are, in fact, part of the Basin and Range Province (Hunt 1967). For the purpose of this report, the Rocky Mountain domain extends to the Texas border to include the mountains east of the Rio Grande.

The Wyoming Basin is included in this domain according to Hunt (Fig. 7.1) along with many smaller valleys and basins lying between the scores of distinct mountain ranges comprising this cordillera. Except for parts of Montana, where several disjunct mountain ranges extend outward into the plains, the eastern boundary is relatively distinct where abrupt increases in slope and changes in lithology mark the junction of the Great Plains with a more-or-less continuous series of mountain flanks. This report does not include the Black Hills which are considered part of the Great Plains. The western boundary is more arbitrary where this Province abuts other provinces containing other mountain systems (Fig. 7.1).

Regional Heterogeneity

The heterogeneity of the Rocky Mountain Province can best be described in hierarchical terms. At the largest scale, this region extends 17° in latitude, or about 1,900 km (1,181 mi), from the Texas-New Mexico border to Canada. A latitudinal range of this extent imposes not only latitudinal variation in mean temperature at a prescribed elevation, but also significant effects on growing-season length, frost-free periods, and photoperiods. In addition, significant variability in the climatic regime exists within the Rocky Mountains (Bryson and Hare 1974). The northwestern portion of the Province is dominated by a Pacific maritime influence with mild winters and relatively high levels of precipitation for a given elevation. The Central Rocky Mountains are characterized by a relatively even precipitation regime, although winter snow often exceeds summer rain. The Eastern Rocky Mountains generally experience a more continental climate similar to that of the Great Plains, with significant precipitation from summer convective thunderstorms. The Southern Rocky Mountains are more generally aligned with the bimodal regime of the Colorado Plateau, with spring droughts and abundant late-summer thunderstorm activity associated with monsoonal flows from the Gulf of Mexico.

At a smaller spatial scale, the elevational dimension of this Province generates an even stronger axis of heterogeneity than does latitude. Base elevations of the mountain ranges of the Rockies extend from only a few hundred meters

in the northwestern Rockies to elevations of greater than 1,200 m (3,937 ft) in the Central Rockies. Maximum elevations in the central Rockies reach 4,000 m (13,123 ft), and individual mountain-range relief varies from a few hundred meters to almost 3,000 m (9,842 ft).

Steep temperature and precipitation gradients result from these elevational extents that, in turn, enforce strong altitudinal gradients in the occurrences of plants and animals. Such variation in occurrence of dominant plants is often characterized in terms of elevational "zones." Boundaries between these zones vary with latitude but typically zonation starts with vegetation describable as a grassland or desert system at the mountain base, and then changes to woodland, then to several forest types, and finally to alpine tundra at the highest elevations (Fig. 7.2). The changes in dominant plant zones and associated animals vary more with elevation at any latitude, than they do along the entire latitudinal gradient of 1,900 km (1,181 mi). The exact locations of these zonal boundaries vary with slope aspect, with boundaries occurring at lower elevations on north-facing slopes than on south-facing slopes (Fig. 7.2).

As a third component of complexity, local and regional variations in geology lead to distinct landforms, soils, and geomorphological processes. The Rocky Mountains is a collective term for a large number of distinct geologic events. Accordingly, individual mountain ranges within the Rockies may be block-faulted uplifts, thrust-faulted overthrusts, broad synclinal folds, or of extrusive or intrusive igneous origin. Broad exposures of rocks ranging from igneous and metamorphic pre-Cambrian basement rocks to Cenozoic or Tertiary volcanics to Tertiary sediments or Quaternary alluvium all occur and interact with regional climate to form distinct soils. At yet a smaller scale, the presence or absence of Pleistocene glaciation is another source of variation. Where glaciation has occurred along the latitudinal axis of the Province, it dominated at higher elevations and in valleys. Glaciated terrains typically have steeper valley walls but more gently graded valley floors than do areas shaped by fluvial erosion.

At a scale of 100s to 1000s of meters, topographic variation imposed by geological structure and geomorphological processes create

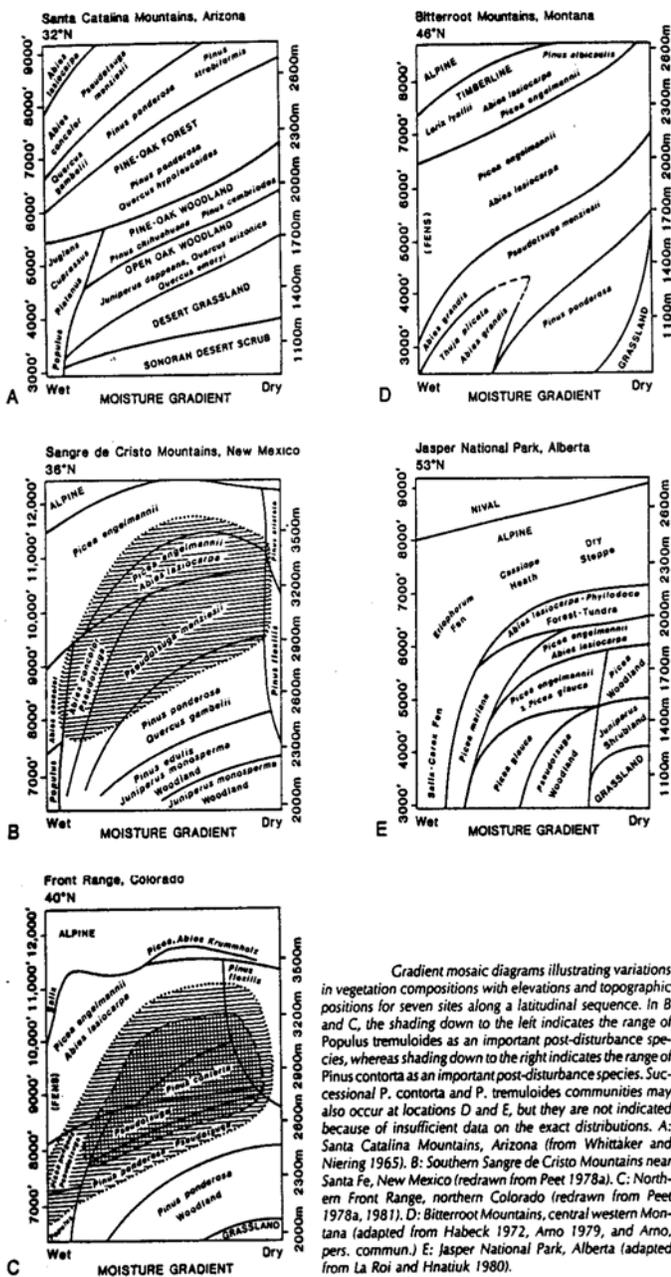


Figure 7.2. Gradient mosaic diagrams for portions of the Rocky Mountain cordillera extending from 32°N in Arizona (not part of the Rocky Mountains but illustrative for this purpose) through 53°N (part of the Rocky Mountains but beyond the limits of this assessment). This figure was created by Peet (1988) and is published here with the permission of Cambridge University Press. Mosaic diagrams illustrate the distribution of vegetational units in terms of elevation (Y axis) and moisture availability (X axis). The moisture axis represents a number of factors including slope aspect and position with mesotopography of the mountainous landscape. For the purposes of this paper, the X axis may be viewed as a north- to south-facing slope gradient. Note the downward shift of analogous zonal boundaries with elevation. Peet's original caption is retained here to add further information to this figure.

patterns in resource availability for the biota (Fig. 7.3). South-facing slopes are warmer than north-facing slopes; steep slopes shed more water than do shallow slopes, ridges are intrinsically drier than drainages, lower portions of catchments benefit from vadose water more than do upper portions of catchments, water is distributed and stored differently when slopes parallel the dip slope of sedimentary rocks than when they cut across them. Thus, at the scale of hundreds to thousands of meters, topographic variation leads to differential vegetation, animal habitat and, sometimes, propensity for fires or disease outbreaks.

Topography is not the only source of variation at this scale of 100s to 1000s of meters. Historical imprints left by past disturbances mark ecosystems at this and even larger scales. For example, a slope favoring subalpine fir might be occupied by lodgepole pine because of a fire that took place 100 years previously. That imprint will last until succession allows fir to reestablish itself, or yet another disturbance event intervenes. Of course, some of the most obvious historical imprinting has been left in these mountains by clear-cutting and roads associated with forest management (Fig. 7.3).

This recognition of heterogeneity is important because it highlights the difficulty of generalizing at any scale in this region. Assessments of any potential environmental change are made more difficult by the extremes in spatial heterogeneity in mountainous regions than they are in regions of more gentle topography. Similarly, designs of experiments or monitoring systems and models of impacts derived from climate-change projections have to be made in the context of this multiscale heterogeneity. It is essential to match the scale of the phenomenon in question to the appropriate scale of heterogeneity in this and all mountainous regions.

About 25% of the nation's surface water emanates from the Rocky Mountain region (Stohlgren 2000, Chapter 3), providing water supplies to arid and semi-arid regions of at least equal size to the east and west. Most of this water arrives as snow in the winter and is key to natural resources and economic

activities of the region. Thus, the distribution of snowfall and consequent pattern of hydrologic river, tunnel, and aqueduct arteries is another layer of critical geographic variation superimposed on the others outlined above.

The social-economic fabric of this region reflects the variability of its natural geography. The region encompasses parts of seven western states, each with its markedly differing political legacies and styles. The most productive portions of the region are generally privately held. But the majority of the area is publicly owned, containing 15 National Park System units, 16 national forests, and hundreds of other agency, state, and conservation lands. The region has historically supported livestock, mining, timbering, and tourism industries but major nodes of industrial production and information/services such as Albuquerque, Colorado's Front Range strip, Salt Lake City, and Boise have grown up in the region (Riebsame 1996). These urban centers extend tentacles of influence along roads and highways into foothill and riparian zones and around recreational facilities at higher elevations. Parts of the Rocky Mountain region are growing 2-3% per year (Stohlgren 2000) while other parts are demographically and economically stagnant.

The Rocky Mountain region includes extensive wilderness areas, nevertheless the hand of humankind has fallen heavily on this region. Despite our American mythology and contemporary wishful thinking, human effects were profound and ubiquitous throughout the Holocene up to the EuroAmerican period (Wagner and Kay 1993). It is possible that many elements of the continent's megafauna were

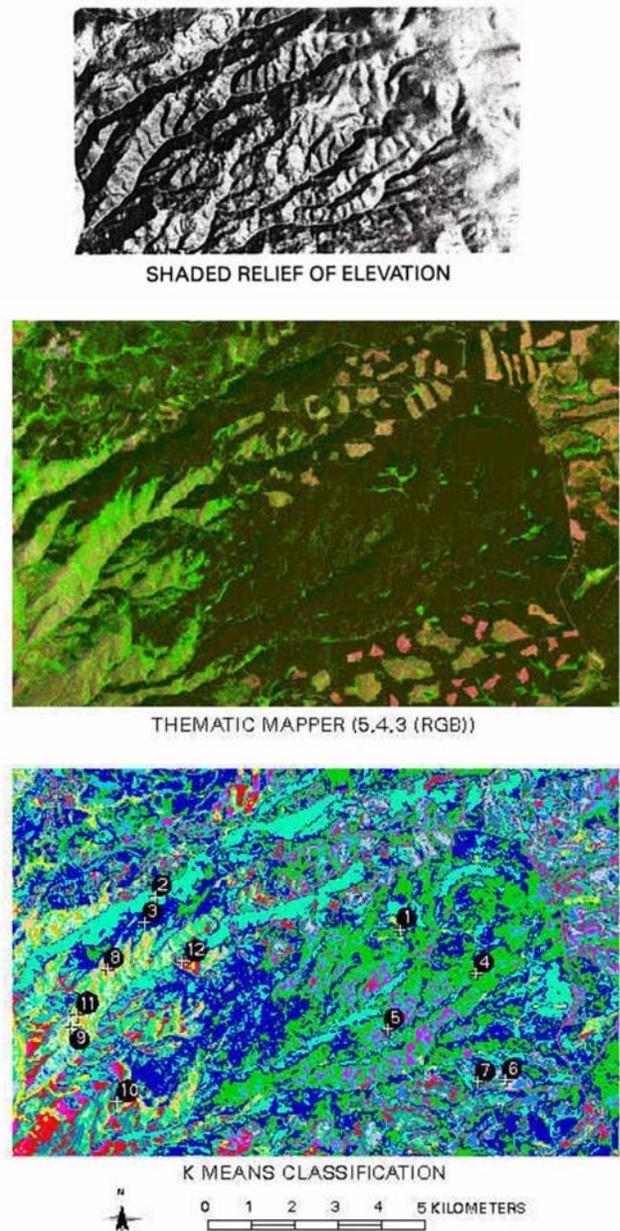


Figure 7.3. (A) Shaded relief visualization of topography for a 12,500 ha (30,888 ac) area centered on the Savage Run Wilderness Area of the Medicine Bow Mountains, south-central Wyoming. The right edge of this image is approximately centered on a broadly arching ridge of these mountains at 3,000 m (9,840 ft) and extends down in elevation to the left to about 2,200 m (7,216 ft). Terrain incision by streams flowing from east to west (right to left) deepens downslope. These west-running drainages create strong topographic patterns with distinct north-slope-south-slope contrasts. (B) A Landsat Thematic Mapper-derived Image of the areas. The TM bands 5/4/3 have been presented as red/green/blue. The dark green, triangular area in the center is the wilderness area. The areas on the right half of the image surrounding the wilderness area have been mostly clear-cut. Some of the vegetation to the left of the image is non-forest. (C) The same area as A but with spectral differences enhanced to show vegetational patterns. Numbered crosses are centered on examples of the following and cover types: (1) non-forested riparian, (2) coniferous forest on mesic, north-facing slopes dominated by Engelmann spruce, subalpine fir, and lodgepole pine; (3) coniferous forest on dry-mesic sites dominated by the same species as 2; (4) lodgepole pine forests on comparatively flat terrain, on broad ridgetops, or on south-facing slopes; (5) rock outcrops, exposed soil, open woodlands with limber pine or lodgepole pine, and the margins of clear-cuts; (6) post-harvest vegetation developing after clear-cutting in the 1980s; (7) post-harvest vegetation developing after clear-cutting prior to the 1980s; (8) aspen, typically in moist environments or on the margins of coniferous forests at lower elevations; (9) foothill meadows and forblands; (10) foothill shrubland dominated by big sagebrush and bitterbrush; (11) foothill shrubland dominated by mountain mahogany, and (12) on image-processing and landcover classification.

hunted to extinction by Clovis people who arrived about 11,500 BP (Martin 1984). Whether this overkill hypothesis is correct or not, the fact that many species of large mammals were lost in a wave of extinctions about this time is incontestable (Pielou 1991). Ecologists can surmise that the loss of both herbivorous and carnivorous species from ecosystems of that time must have had severe “top-down” effects on vegetation and other members of the fauna.

The role of Native Americans in shaping ecosystem structure and function prior to the Euro-American period is inadequately known and hotly contested. There is evidence in some areas like the Northern Rocky Mountains that Native Americans curtailed the sizes of large ungulate populations, particularly elk (Kay 1998), which transmitted effects to forage species and carnivorous elements of those ecosystems (Keigley and Wagner 1998). Native Americans probably also influenced fire regimes in the Rocky Mountains (Wagner and Kay 1993). How these impacts were geographically distributed and varied over this period is poorly known but throws into doubt our concept of what “normative conditions” were as comparisons with the present (Callicott et al. 1999).

Whatever impacts Native Americans might have had, they were dwarfed by the actions of Euro-Americans. Beginning in the mid-19th century, all the lands of the region became managed in one fundamental way or other through mining, grazing, logging, recreation, road construction, fragmentation,

fire suppression, near elimination of beaver and grizzly, diminution of cougar and golden eagle populations, probably futile persecution of the coyote, and the temporary extirpation of gray and Mexican gray wolves. Even the most remote wilderness areas are, at the least, affected by altered air and precipitation quality. As we assess the potential impacts of climate change, we recognize that no place in the Rocky Mountain region is without the influence of human action.

CLIMATE CHANGE OVER THE ROCKY MOUNTAIN REGION

Historical Climate Change

Contemporary and future climate change is best viewed in the context of historical climate change in this region. Reconstructions of general climate changes across the entire western U.S. for the last 18,000 years and the climatology underlying those changes are provided by Thompson et al. (1993). This is an excellent foundation source for the larger area encompassing the Rocky Mountain region. Considerable paleoecological work of high quality has been done in the Rocky Mountains themselves (for reviews see Thompson 1988, Thompson et al. 1993, and for more recent work see Whitlock and Bartlein 1993, Feiler et al. 1997). But inferences about climate in these publications are usually stated in relative terms (cooler-warmer, wetter-drier); numerical values for temperature and precipitation over the last 22,000 years are difficult to obtain.

Temperature differences between the present and the most recent glacial maximum (22,400 to 12,200 yr BP) have been estimated as 9°C (16.2°F) by Fall (1988) for Colorado, as 7° to 13°C (12.6-23.4°F) by Mears (1981) for the Wyoming Basin, and as ~10-15°C (18.0-27.0°F) in the Greater Yellowstone Ecosystem (GYE)

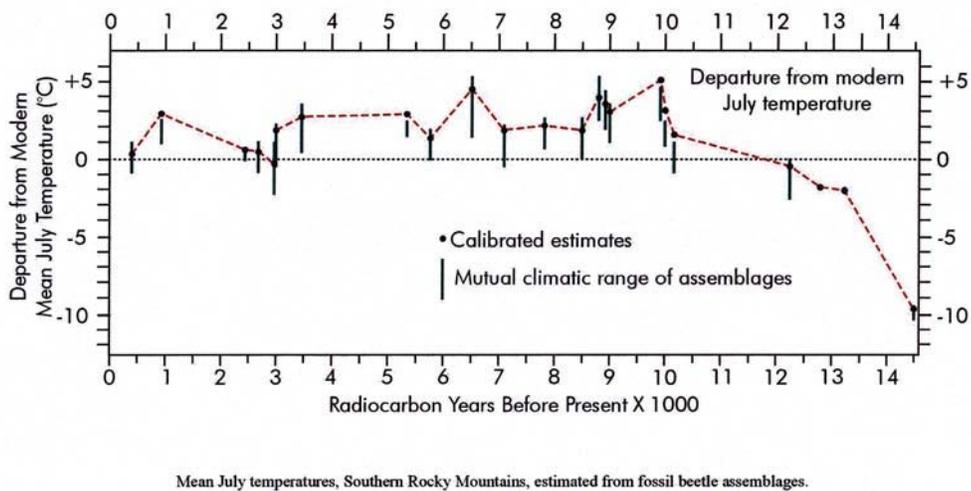


Figure 7.4. Mean July temperature departures from modern values for the Southern Rocky Mountains for the last 14.5k yr estimated from fossil beetle assemblages (Elias 1996).

(Porter et al. 1983). Based on fossil insect evidence, Elias (1996) estimated that mean July temperatures were 9-10°C (16.2-18.0°F) colder than today during the last glacial maximum (Fig. 7.4), and that mean January temperatures may have been as much as 23°C (41.4°F) colder than today. With closure of the most recent Ice Age, rapid deglaciation was complete by 14,000 to 15,000 yr BP in the southern part of the cordillera (Fall 1988) and by 10,000 to 11,000 yr BP in the Yellowstone Plateau area (Whitlock 1993). During this late glacial period, pollen studies suggest that temperatures were 3-4.5°C (5.4-8.1°F) cooler than the present and the treeline had ascended to about 500 to 700 m (1,640-2,296 ft) below the modern treeline (Fall 1988). However, the fossil insect evidence (Fig. 7.4) suggests that modern summer temperature levels were reached as early as 12,000 yr BP in the Rocky Mountain region (Elias 1996).

With the beginning of the Holocene (12,000 BP), conditions generally warmed but fluctuated irregularly across this region as well as the rest of the globe. Terms such as the “Medieval Warm Epoch” (MWE) supposedly characterizing the 11th-13th Centuries, and “Little Ice Age” characterizing the period 1550-1850 A.D. have been applied to climatic deviations that may not have behaved in the same way at the same time or with the same amplitude in other areas including the Rocky Mountains. Thus, we are advised by Bradley (2000) to refer to the MWE as the “Medieval Climatic Anomaly” and view the Little Ice Age as possibly having a longer time span than that normally applied and demonstrating different conditions than inferred elsewhere.

Based on pollen evidence, temperatures were warmer than present for the southern Rockies from 9,000 to 4,500 yr BP when upper treeline may have been 300 m higher than it is presently (Fall 1988). Fossil insect evidence indicates that warmer-than-modern summer temperatures existed in this region as early as 10,000 yr BP (Fig. 7.4), and persisted until about 3,500 yr BP (Elias, 1996). The pollen evidence suggests that regional temperatures cooled below current levels 4,500 to 3,100 BP (Fall 1988), warmed slightly between 3,000 to 2,000 yr BP, then cooled again during the Little Ice Age between 1550 and 1850 AD. Temperatures have been warming slowly since the end of the Little Ice Age. In

general, precipitation regimes varied with temperature, becoming wetter in warm periods and dryer in cold periods.

There is evidence that temperature changes in recent millennia may sometimes have been rapid (Fall 1988, Graumlich 1993, Hughes and Graumlich 1996, Elias 1996, Schuster et al. 2000), sometimes as much as 10°C (18.0°F) in a few years (Grootes et al. 1993, Alley et al. 1993, Alley 2000). According to Schuster et al. (2000), climate changes during the Holocene in the topographically complex and latitudinally extended Rocky Mountains have been abrupt—sometimes decadal in scale—bi-directional and unpredictable.

In summary, the Rocky Mountain region has experienced wide swings in temperature, perhaps in the order of 10°C (18.0°F) for summer temperatures, and poorly documented precipitation variation throughout the Holocene. These changes are of amplitudes equivalent to those forecast for the next century.

It has been the common wisdom that the rates of change for projected new climates will be faster than those experienced in the past. In fact, the past millennia have been highly variable. But any generalizations turn on whether these were random or oscillatory variations around relatively unchanging, or slowly changing, mean secular trends over time scales of a century or more. As discussed in Chapter 3 (cf. Fig. 3.19), the proxy temperature evidence for North America shows abrupt interannual and decadal variation from 1000-1998, but superimposed on a gradually declining net trend to about 1900. Since 1900, instrumental data show a rise, still with abrupt short-term variations, to mean levels far above anything experienced in the preceding millennium. More data and synthesis of existing data are needed to adjudicate the rate of change over defined ranges.

Present and Future Climate Change

The Global Perspective

The dominance of opinion on the evidence for global warming has been reinforced in recent months by the continuing trend of increasing global surface temperatures, e.g. (http://www.ncdc.noaa.gov/ol/climate/research/1999/ann/triad_ann99_pg.gif), new data on heat

accumulation in the oceans (Levitus et al. 2000), on river and lake ice melting (Magnuson et al. 2000), by a number of world-wide biological indicators (Hughes 2000), and by the weight of reaction of the scientific community (National Assessment Synthesis Team [NAST] 2000), Intergovernmental Panel on Climate Change (IPCC)). In fact, on 26 October 2000, the IPCC increased its estimate of the upper limit of possible global temperature change for this century to 6°C (10.8°F) (<http://www.ipcc.ch/>).

Scientific opinion that at least some of this warming is related to human influence on the atmosphere has recently been strengthened by model and statistical results by Andronova and Schlesinger (2000), Delworth and Knutson (2000) and Crowley (2000). Concern that climate changes might be more rapid and step-like than previously thought has also been heightened in the scientific community as illustrated by the 97(4) special issue of the Proceedings of the National Academy of Science published in February 2000. While general climate models generally concur in predicting further global climate change as a result of the balance of changing radiative forcing factors, there remains considerable disagreement as to the magnitude of the change, and especially how changes will be distributed on different parts of Earth's surface (Kerr 2000). In addition, it is becoming increasingly apparent that changes in landcover/landuse might mitigate or augment mesoscale climate changes in significant, but still unrealized, ways (Couzin 2000).

The Western United States Perspective

In spite of serious uncertainties about regional climate change, Chapter 8 of the NAST 2000 report (Smith et al. 2000) makes the following summarizing statements about the 20th Century climate change for the "western United States." It is important to note that this chapter covers all of the southwestern United States and only includes the Utah, Colorado, and New Mexico Rockies:

- "In the 20th century, temperatures in the West rose 2°F to 5°F (1.1 to 2.8°C).
- The region generally became wetter, with some areas having increases of greater than 50%. A few areas, such as Arizona, became drier and experienced

more droughts. But, the length of the snow season in California and Nevada decreased by about 16 days from 1951 to 1996."

Prognoses based on selected scenarios for the coming century made in the same chapter include the following:

- "During the 21st century, temperatures will increase throughout the region, at a rate faster than that observed, with two GCMs projecting increased temperatures of about 3°F (1.7°C) to over 4°F (2.2°C) by the 2030s and 8°F (4.4°C) to 11°F (6.1°C) by the 2090s.
- The two GCMs also estimate increased precipitation, particularly during winter, and especially over California. However, parts of the Rocky Mountains are estimated to get drier and one of the two models has most of the region getting drier in the 2030s. And there is a slight chance the climate over much of the West could become drier for certain time periods during the 21st century.
- Under the GCM scenarios, runoff is estimated to double in California by the 2090s, but the climate models also suggest there could be more extreme wet and dry years in the region."

As noted, these statements only applied to the southern Rockies. The part of the Rocky Mountain Province occurring in Wyoming and central Montana (Fig. 7.1) is putatively covered by the NAST chapter for the Great Plains, but in fact is not discussed (Joyce et al. 2000). The Rocky Mountains of Idaho and western Montana are putatively covered in the NAST chapter on the Pacific Northwest (Parson 2000) but where "interior forests" are discussed, they are lumped with mountains much farther west.

Moreover, these projected increases are based on GCMs (general circulation models) that do not resolve topography even at the scale of the Rocky Mountain cordillera, that have limited capacity to project precipitation trends, and whose outputs differ among themselves to varying degrees (cf. Table 3.8). Only two GCMs out of a possible ten or so were chosen to make these projections. Some models are better at some processes and some at others. Moreover, these models are designed for making global

estimations and are being pushed beyond their bounds of design or resolution to make regional projections. NAST itself makes clear the limitations of GCMs for projecting climate changes at the regional level (MacCracken et al. 2000). Contributors to this report view the specificity of the projections reported by NAST with some reservation, but do consider that some extent of warming is not only possible, but likely.

The Rocky Mountain Regional Perspective

In reviewing evidence for 20th-century climate trends in the Rocky Mountain region specifically, it should be noted at the outset that it is particularly difficult to detect trends in the western United States in general and the Rocky Mountain region in particular because of wide swings in short-term climate at several scales. As discussed above, weather varies widely on an inter-annual basis at any particular station. Stohlgren (Chapter 3) analyzed data for Estes Park, CO over the 1931-1993 period. During that interval, annual temperature varied from the average by +/- 0.6°C and precipitation varied by +/-29.6%. In addition to inter-annual variations, sub-decadal and decadal variations occur in relationship with both the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillations (PDO) as discussed in Chapter 3. Further complicating the analysis, the precipitation patterns for the northern half of the Rocky Mountain region (north of 40°N) oscillate inversely to the southern half (cf. Cayan et al. 1998, Dettinger et al. 1998, and discussion in Chapter 3).

In the face of this apparent climatic noise, four types of analyses pertaining to changes within the last 100 years are available: temperature and precipitation data over the last 100 years, streamflow data for undammed Rocky Mountain region streams, glacier recession rates, and upper treeline changes.

Trends in 20th-century climates in the Rocky Mountain/Great Basin region were analyzed by Baldwin in Chapter 3. His results show increases in mean, annual minimum temperatures of 0.62°C (1.12°F), 0.40°C (0.72°F), and 0.54°C (0.97°F) for the Northern, North-central, and West-central Rockies respectively, all significant at $p < 0.01$, during the 20th century. The trends in minima were not significant at $p = 0.05$ in the East-central and Southern Rockies (Table 3.5). Mean,

annual maxima increased significantly only in the Northern Rockies, at 0.67°C (1.21°F) per 100 years. Trends in annual, average temperatures were the same in the five subregions (Fig. 3.20). Baldwin's analyses also showed that 20th-century annual precipitation rose significantly in the Northern and North-central Rockies, but not significantly in the West-central, East-central, and Southern subregions (Fig. 3.23).

Kittel had similar results with slightly different subdivision of the Rocky Mountain chain. He found significant, positive trends for mean, minimum temperatures, and for annual and seasonal precipitation in his Northern and Central Rockies subdivisions. There were no such trends in the Southern Rockies (Figs. 3.22, 3.26).

Collectively, these results indicate temperature and precipitation increases from approximately the latitude of northern Utah northward to the Canadian border. And combined with Kittel's evidence of more pronounced trends in the Canadian Rockies, they are consistent with poleward increases in temperature change, and more pronounced increases in nighttime minima. In Chapter 4, Baldwin et al. analyzed streamflow timing in three streams of the West-central and North-central Rockies. They found the contemporary dates of peak run-off have advanced 10-15 days over those of 1950-1970. Dettinger (2000) reported similar advances in streams of the northern-U.S. Rockies that he attributed to "... spring temperatures which have warmed significantly since 1945 ... in this region ..."

A warming climate will increase evapotranspiration (PET). Without a commensurate increase in precipitation to balance a higher PET for an area, a regional decline in annual stream discharges could reasonably be expected. In Chapter 4, Baldwin et al. analyzed trends in 20th-century flow in four streams with headwaters in the Rocky Mountain system. Three showed significant increases in flow over the period (Fig. 4.2), and a fourth showed increase but the test fell short of significance. A fifth, the San Juan in southern Colorado, was well short of significance. Lettenmaier et al. (1994) similarly recorded flow increases in streams of the northern-U.S. Rockies, and Kittel et al. (2002) reported similar increases in streams of the Canadian Rockies. However

the Chapter 4 analyses found no trends toward increase in 20th-century flows of the Colorado River and its tributaries, largely in Colorado.

We conclude that the evidence points to increase in the flows of a number of streams, during the 20th century, in the western and northern portions of the Rocky Mountain system. These are portions of the Intermountain West in which precipitation increases over the same period have been documented. However, streams of the southern Rockies, where no precipitation increase has occurred, show no net trends in streamflow during the 1900s.

These levels of temperature change are less than the 1.1 to 2.8°C (1.98-5.04°F) increase reported for the western U.S. by the NAST Report (Smith et al. 2000). Precipitation increases occurred only in the northern regions. The rates of temperature increase, where they occurred, were linear in form over this 100-year period. Thus, they may represent changes related to continued warming at the end of the Little Ice Age—although temperature trends in the early part of the 1900s were downward (Kittel et al. 2002)—or they may be related to the onset of the Industrial Revolution around the mid-19th century, or both factors may have been involved. The present increase in atmospheric CO₂ content becomes noticeable in ice core records by 1850. The combined radiative forcing function of CO₂ and other greenhouse gases, along with slight increases in solar forcing (Lean et al. 1995) and the counter-balancing effect of increasing aerosols, accelerated to their present levels of annual increase around 1980 (Shine et al. 1990, Schimel et al. 1996). However, Mann et al. (1998) reported evidence of earlier temperature increases for the northern hemisphere.

In this region, hydrographs primarily reflect melting of the winter snowpack. A shift from precipitation as snow to rain together with warming temperatures would be expected to accelerate the timing of stream runoff.

Two other sets of observations provide supporting evidence for subregional warming in the Rocky Mountain region. The first is evidence for accelerated melting of glaciers in Montana and Wyoming (Fagre and Peterson 2000, Schuster et al. 2000). The second set of observations are changes in krummholz tree growth to more erect forms (Hessl and Baker 1997a) and in-filling between krummholz

patches by tree regeneration (Hessl and Baker 1997b). Moir et al. (1999) also recorded trees in-filling subalpine meadows.

One well-documented example of climate change in the region is actually one for cooling in the Front Range area of Colorado. Chase et al. (1999) and Stohlgren et al. (1998b) have shown that the foothill-plains areas at the base of the Front Range have cooled since the early 1930s, probably because of increased latent energy in the area due to irrigation and other landuse changes. This is an example of how landcover can modify climate at the mesoscale.

In summary, these lines of evidence support the probability that the northern portions of the Rocky Mountains have warmed slightly, particularly at night and in the winter, over the last 100 years. And they point to increases in precipitation in the same region.

Climate Scenarios for Possible Future Change

The National Assessment Synthesis Team (NAST 2000) has prepared scenarios for consideration at the national level for the latter decades of the 21st century (MacCracken et al. 2000), and with appropriate caveats for smaller areas, particularly the Rocky Mountains. Downscaling these models is problematic as there is typically wide variation in temperature for areas as small as the Rocky Mountain region, and even greater variation in precipitation. General circulation models (GCMs) necessarily operate at relatively coarse spatial scales that do not represent ground and atmospheric conditions well at the scale of hundreds of kilometers.

Beyond the typical constraints and limitations associated with these models, the Rocky Mountains must be considered a particularly difficult area for downscaling. The extraordinary heterogeneity discussed above is homogenized by these models, with the entire Rocky Mountain region exhibiting less relief than is typical for an individual small range within the region. While relatively sophisticated downscaling techniques were employed to increase the spatial resolution of the projections, in many cases these represent extrapolation, rather than interpolation, and the base simulations fail to capture topographic features known to have significant influence on the climate of the Rocky Mountains (Mock

1996, Bartlein et al. 1997). Nor can these models take into account mesoscale landcover/landuse effects such as demonstrated by Stohlgren et al. (1998) for the Colorado Front Range, which are changing faster in the Rocky Mountains than in many other areas of the country.

A climate-change scenario by Thompson et al. (1998) exemplifies these kinds of problems. These authors demonstrated a scenario based on the NCAR GENESIS AGCM (atmospheric circulation model) for a 2xCO₂ global climate at 4.4° lat. by 7.5° long. Output from this global model was scaled down by the NCAR RegCm regional climate model to a grid of 60 x 60 km (37.3x37.3 mi). Output from that grid was further interpolated onto a 15 km (9.3 mi) grid on the basis of topography for driving hydrologic and vegetation models. Methodological problems notwithstanding, results from this approach are the state-of-the-art and their results must be taken seriously, if with some reserve.

Thompson et al. showed model output for January and July mean temperatures and precipitation totals distributed to 15 km grid units and mapped present versus potential anomalies at 60 km. This latter output shows the northern Rockies warming by 3°C (5.4°F) and the southern Rockies by 1-2°C (1.8-3.6°F) in January, and all of the Rockies warming by 3°C (5.4°F) in July. It also shows a complex pattern of precipitation change for January, with most areas increasing by 0 to 10 mm (0-0.39 in) except for Montana, western Colorado and northern New Mexico which decrease by 10-20 mm (0.39-0.78 in). In general, this model projects an increase in July precipitation by 0 to 30 mm (0-1.18 in) north of 41°N and decreasing by 30 mm (1.18 in) south of 41°N.

As a basis for deliberations in this workshop, Assessment Team members posed a set of climate-change scenarios for consideration of possible effects on Rocky Mountain ecosystems (Table 7.1). Selection of these scenarios began with the model projections set

forth in Table 3.9, but with three modifications: (1) The Hadley projections were used as a base because they are more conservative than those of the Canadian model. (2) Because the historical climate analysis of Chapter 3, and that of Kittel et al. (2002), showed more pronounced 20th-century temperature and precipitation change in northerly subregions of the Rockies than in the southerly and eastern subregions, scenarios for the Northern, North-central, and West-central subregions (cf. Fig 3.18) were given 1°C (1.8°F) higher temperature projections and slightly higher precipitation increases than the East-central and Southern Rockies subregions. (3) Some authors have suggested that increased temperatures in the West might elicit summer-precipitation increases through strong, northward extension of summer monsoons. Hence, scenarios are posed with increased summer precipitation in Table 7.1.

Snowpack, a central variable in ecosystem function in this region, was adjusted to reflect temperature changes combined with precipitation seasonality. For example, the first scenario for the northern group is warmer but also wetter (Table 7.1). This was considered to

Table 7.1
Scenarios for Assessment of Ecosystem Sensitivity to Climate Changes Within Rocky Mountains

Subregion ¹	Scenario	°C Mean Temperature Increase ²	mm/day Precip. Change	Snowpack
Northern, North-central, West-central Rockies	1 Winter	+4.5	+2.0 to +3.0	No change
	Spring	+2.5	0.0 to +0.5	
	Summer	+4.0	0.0 to +0.5	
	Fall	+3.5	+0.5 to +1.5	
Northern, North-central, West-central Rockies	2 Winter	+4.5	0.0 to +0.5	Reduced to none
	Spring	+2.5	+0.5 to +1.5	
	Summer	+4.0	+2.0 to +3.0	
	Fall	+3.5	0.0 to +0.5	
East-central and Southern Rockies	1 Winter	+3.5	+1.0 to +1.5	Reduced
	Spring	+1.5	-1.0 to -0.5	
	Summer	+3.0	-1.0 to -0.5	
	Fall	+2.5	-0.5 to +0.5	
East-central and Southern Rockies	2 Winter	+3.5	-1.0 to -0.5	Reduced to none
	Spring	+1.5	-0.5 to +0.5	
	Summer	+3.0	+1.0 to +1.5	
	Fall	+2.5	-1.0 to -0.5	

¹Subregions are same as those shown in Fig. 3.18.

²Temperature increases are expected to result more from elevations in night-time minima than from day-time maxima.

lead to no net change in the snow pack. But with warmer temperatures and less winter precipitation, a reduction or elimination of the snowpack was posed. Both scenarios for the southern Rockies led to declines or elimination of the snowpack.

The climate changes shown in Table 7.1 are working values prepared to aid in estimating ranges of ecological responses. The values are not a formally derived set of climate-change projections for the Rocky Mountain region.

HYDROLOGIC RESPONSES TO CLIMATE-CHANGE SCENARIOS

General Patterns of Change

The importance of changes in seasonality and amount of water resources in the arid and semi-arid western states was noted by the compilers to the NAST report (Smith et al. 2000), and discussed in Chapter 4 of this report. Any permanent changes in the amount, timing and form of precipitation; the spatial and temporal extent of snowpack; the temporal variation in stream discharge, or the timing and total volume of stream discharge would affect every aspect of the Rocky Mountains and much of the regions surrounding them. The importance of snowpack to life in and around the Rocky Mountains cannot be overemphasized. It is an important determinant of the mesoscale climatology of the region, a control of vegetation and animal life at the landscape scale, as well as being the primary source of ground and surface water (Liston 1999).

Based on the stream hydrograph data presented above and general principles, some general predictions can be deduced:

(1) If winter precipitation changes to rain, or if precipitation seasonality shifts from winter to summer, then:

- (a) Temporal extent and volume of snowpack will decrease, and mountain catchments will discharge more water more evenly through winter and spring.

As a result:

- Peak flows will be lower and earlier in the year.
- Lower hydrographic peaks will influence aquatic communities,

geomorphic processes, and water management strategies.

- Water available for mountain vegetation will decline earlier in the growing season.

- (b) Geomorphic processes will shift from cryoturbation (snow and ice abrasion) and avalanche-related processes to fluvial erosion and deposition processes.
- (c) Glacial melting will accelerate.

(2) If annual or growing-season precipitation is less than the water demand created by higher temperatures, then:

- (a) A larger percentage of incoming water will be lost to evaporation and transpiration (ET). As a result:
 - A smaller percentage of water will be available for runoff to downstream ecosystems and socio-economic uses.
 - Vegetation will undergo moisture stress for longer periods of time, with the result that
 - Vegetation will be more combustible for longer periods.
- (b) Fluvial erosion rates will decline.
- (c) Glacial melting will accelerate so that glacial contribution to streamflow, especially in late summer, may increase in the short term, but decrease in the long term.

(3) If global warming intensifies the hydrologic cycle in general, then:

- (a) Cloudiness would increase and it would produce:
 - Increased orographic precipitation.
 - Reduced solar radiation in the mountains which would:
 - Steepen precipitation gradient between mountains and lowland.
 - Reduce night-time reradiation, particularly at high elevations, and reduce night-time cooling.
 - Daytime cooling and night-time warming.
- (b) More water available for streamflows.

Thompson et al. (1998) projected how some hydrologic features of the Rocky Mountains

would react to their climate-change projections. They projected that Yellowstone Lake might experience the following: average temperature would increase from the present 11.6° to 13.2°C (20.9-23.8°F); ice cover would decrease from the present 196 days to 152 days; concomitant longer periods of mixing would appear throughout the water column and less snow cover and ice thickness would result during the winter.

Several hydrologic simulation models have been exercised for altered climate conditions for well-parameterized Rocky Mountain catchments. Perhaps the first was a relatively simple simulation by Revelle and Waggoner (1983) in which they forecast a reduction in streamflow throughout the United States of 40-70%. Later, Running and Nemani (1991) simulated a climate projection with FOREST-BGC coupled with MT-CLIM for the Swan Range area of Montana. Their model indicates that an increase in air temperature of 4°C (7.2°F) and an additional 10% precipitation would net a decrease in snowpack duration by 19-69 days, depending on location in the landscape, and a decrease in outflow by as much as 30%. Nash and Gleick (1991) used a "conceptual model" to simulate effects of temperature and precipitation change on stream discharge in several sub-basins of the Colorado River. Flows would decrease with temperature increases and vary as anticipated with higher or lower amounts of precipitation. According to this model, flows would be more sensitive to precipitation changes than to temperature changes. Rango and van Katwijk (1990), using a non-distributed snowmelt model (SRM), simulated snowmelt runoff scenarios for two Rocky Mountain catchments. Simulating a 3°C (5.4°F) warming, with or without a 10% change in overall precipitation, leads to a simulated outcome of 20-40% decrease in runoff in months of peak water demand.

These hydrologic results confirm intuitive conclusions that soil-moisture availability, water yield, time of peak flow, and amount and duration of snowpack would be affected by the annual cycle of water-budget variables as would be expected from first principles. The amounts to which these variables would change and their timing change are dependent on details of the models and assumptions about intervening events such as forest disease or fire on the catchments being simulated. It is important to

discriminate between probable trends for Rocky Mountain hydrology in general, and outcomes for actual catchments in particular.

A Case Study: The Loch Vale Simulation

Baron et al. (2000) examined the sensitivity of hydrologic and ecologic components of the Loch Vale headwater catchment in Colorado using RHESSys (Regional Hydrologic-Ecological Simulation System) with a TOPMODEL hydrological component. This area has undergone cooling in the past 40 years (Chase et al. 1999), so they ran the simulations at -2° (-3.6°F), +2° (+3.6°F), and +4°C (+7.2°F) in conjunction with -10% and +10% precipitation and various degrees of direct CO₂ effects on water-use efficiency. These simulations are quite similar to the range of scenarios presented in Table 7.1. In general, cooling led to greater snowpack, slightly less runoff, evaporation, and transpiration. The +4°C (+7.2°F) simulation projected a snowpack reduced by 50% and a runoff peak advanced by 4-5 weeks. These results are particularly useful in their representation of high-elevation catchments where evapotranspiration effects of plants are less important to the water budget. Forested catchments might be expected to show a lesser yield at higher temperatures because of higher evapotranspiration losses.

These simulation results support some of the projections made by other model simulations described above. In summary, more data synthesis of past trends and responses to climatic deviations as well as more simulation exercises of this type are needed to fully explore the range of response that might be expected within the range of scenarios tabulated above. If climate changes of sufficient magnitude do occur, there is every reason to think that hydrologic responses will result in this semi-arid region.

GEOMORPHIC RESPONSES TO CLIMATE-CHANGE SCENARIOS

Geomorphic responses to climate change have been overlooked among the "key issues" listed in Smith et al. (2000) for the western United States, but consideration of them is important to the ecosystem orientation of this assessment. Such processes logically follow on hydrology inasmuch as the movement of water

is intimately linked with the many processes by which materials are moved.

Geomorphology (sometimes termed earth surface processes) is the science addressing the form of the land surface and the processes underlying those forms (Summerfield 1991). It is the branch of geology that describes and predicts how processes like weathering and fluvial, glacial, colluvial (mass movement in response to gravity), and aeolian erosion reshape the surfaces provided by tectonic uplift, vulcanism, and sedimentary aggradational processes. Climate is a fundamental variable controlling the relative importance of surface processes. As climate changes, the net sum of processes will change as well. In fact, many of the principles of geomorphology such as “open systems,” “disequilibrium,” “entropy,” and “multiple controlling factors” are shared with ecologists and soil scientists.

Consideration of climate change is very much part of geomorphology (Eybergen and Imeson 1989, Bull 1991) although it is primarily used in retrospective analysis. In this respect, there is a close relationship between geomorphology and paleoecology. But, surface processes are pervasive in mountainous environments—the kind of environment being assessed here. These processes have influences on soil formation, plant longevity, and even the welfare of animal population conditions. For example, deer, mountain goat, grizzly bear, and even wolverine activities have been shown to be greater around avalanche tracks than surrounding terrain covered with older vegetation (Krajick 1999). Erosion dominates over aggradation for the most part in mountainous landscapes although alluvium deposition and reworking are critical processes in mountain valleys. Erosion is brought about by glacial, fluvial, and colluvial processes. Changes in snow distribution by wind (Hiemstra et al. 2000) and increases or decreases in rain will alter the rates of all of these forms of erosion and consequent deposition within and beyond mountain landscapes. This is a large topic with a rich literature (e.g. Menounos and Reasoner 1997) that can only be highlighted in passing here.

The tools are available to predict how climate warming might accelerate glacial retreat and enhance deposition of glacial debris, reduce

freeze-thaw (cryoturbation) activity at high altitudes, reduce snow avalanches and debris torrents down steep mountain slopes, accelerate fluvial incision of channels in some cases, and aggradation in others (e.g. Eybergen and Imeson 1989, Bull 1991, Hiemstra et al. 2000). All of these processes are dependent on the altitude, local climate, slope steepness and form, and the lithology of the terrain in question. Thus, generalization is only possible in the broadest terms. Inclusion of geomorphic processes in any detail would require specification of local conditions.

Workshop members did not have the expertise to provide professional opinions on how climate change might influence dominating, recurrent surface processes in the Rocky Mountain region so that any such analysis is inappropriate here. However, changes in geomorphic regimes should be incorporated in more holistic analysis of climate-change effects in a more thorough assessment effort.

VEGETATION

Vegetational Zonation: A Construct for Generalization About

Climate-change Effects

In this assessment, the plants of the region are differentiated as “flora” and as “vegetation.” Flora is the total species list of a designated area. Vegetation is the plant cover of the area. Floras are inclusive listings of all the taxa in an area regardless of the ecological importance or environmental preferences of any taxon. Vegetation is described in terms of the physical structure imposed by the plant cover in terms of form (evergreen or deciduous trees, shrubs, herbs, etc.), and in terms of the identities of dominant species. A focus on plants as vegetation is imperative because vegetation defines the primary energetic and biogeochemical functions of the landscape in which it occurs, influences hydrologic budgets and geomorphic processes, provides fuel for fire and substrates for pests, and, to a large extent, determines habitat for animal and microbial life.

There are three primary axes of variation in the distribution of vegetation in the Rocky Mountains: elevation, geology and climate. As described earlier, dominant plant species tend to

sort out along complex environmental gradients associated with elevation, forming loosely structured “zones” or “bands.” The zones have transitions between them termed ecotones, and the elevational position of the ecotones vary with latitude and moisture gradients associated with the effects of slope-aspect (Fig. 7.2). We emphasize that vegetation zones are mental constructs providing a convenient structure for general discussion over broad areas. Closer inspection of vegetation in any particular place reveals that vegetation is better described in some places and at some scales as gradients, and in other places and scales as complex patch mosaics.

Three points to note in Fig. 7.2 are that:

(1) Where the zones have the same character (e.g. alpine zone), their boundaries move down in elevation with increasing latitude;

(2) The effect of slope-aspect increases with latitude; and

(3) The nature of the zones themselves changes with latitude through the addition and loss of dominant species.

The first point indicates that temperature is a strongly controlling factor, and that the cooler temperatures associated with higher elevations can compensate for the higher mean annual temperatures of lower latitudes. The second point reflects the influence of topographic shading on direct solar radiation, with increasingly significant effects at higher latitudes.

The third point is more complex. In part such latitudinal changes stem from insufficient elevation effects to compensate for very large latitudinal effects on temperature, but also in part from differences in climate regime (seasonality of precipitation and temperature and differences in climate variability) which do not vary smoothly with latitude. For example, given similar mean annual temperatures and precipitation amounts, the Pacific maritime, Great Basin, and Arizona monsoon climates support different vegetation adapted to the peculiarities of those regimes.

Zonal generalizations about vegetation assume a dominance of climatic variables and minor role for edaphic (soil) variables. A caveat is appropriate here. The Rocky Mountains were rejuvenated in the Pliocene and sculpted by ice in the Pleistocene so that many, but not all, slopes are steep, surfaces relatively young, and soils

relatively immature in the region. Consequently the physical and chemical properties of Rocky Mountain soils are strongly determined by soil parent material—underlying rocks—and less modified by climate as would be the case in older terrains. Due to the high level of variability in geology of these soil parent materials, the properties of the immature soils are also quite variable, producing sometimes dramatic spatial heterogeneity throughout the Rocky Mountains. This spatial variability of soil properties, in turn, constrains the possible migration of plant species in response to changes in climate.

This last caveat notwithstanding, the zonal structure of Rocky Mountain vegetation provides a convenient conceptualization for discussing vegetation change resulting from warming and altered precipitation patterns. It provides a general language for making vegetation-change projections based on simplistic, first-order logic and on the expert opinions of the workshop participants. The most general projection that can be made for a warmer, dryer scenario is that all of the boundaries will move upward in elevation in response to warming. If such were to occur, forested zones could be eliminated from low mountains as the lower treeline ascends past the summit, and alpine zones could be extinguished from medium-sized mountains as the upper tree line ascends over the summit in climatological terms (but see discussion of treeline below). A corollary of this upward shift is that as any zone moves upward, the space that it occupies decreases because the amount of land area diminishes rapidly with elevation.

A second, general projection can be made with a scenario involving more precipitation, particularly in the summer. In such a case, a bi-directional change of zones both upward and downward—a spreading of the forested zone (Stohlgren et al. 1998a, 1998b)—would likely occur.

The third most general projection is that if the upward shift of forested zones is the dominant result, it will tend to cause shifts in the character of the zones. Pine-oak woodland and pinyon-juniper zones would become more widespread in the montane zones of the southern Rockies, while Douglas-fir, lodgepole pine, and ponderosa pine would infiltrate upper montane and subalpine zones in the northern Rockies. Everywhere, this movement upward would

be achieved at the expense of area occupied by Engelmann spruce and subalpine fir. These very general projections are consistent with predictions made with continental-scale models for vegetation change in response to a 2xCO₂ climate (Neilson and Chaney 1995, Neilson et al. 1998).

Application of Climate-change Scenarios to Vegetation at the Regional Level

Climatic Variables Affecting Plant Function

The zonal structure of Rocky Mountain vegetation provides a conceptual framework for discussing vegetation change resulting from warming and altered precipitation patterns, but is too simplistic to capture the variability of response to be expected. The current (and probable future) climatic controls on the distributions of the dominant species of these zones are: (1) soil moisture availability during the growing season as compared to evaporative demand, (2) the length of growing season and temperature or heat, and (3) the climatic variability, specifically including frequency of spring droughts and growing-season frost. The future-climate scenarios included in our analysis (Table 7.1) are insufficiently detailed with regard to these basic drivers. Soil- moisture calculations require integrating the difference between precipitation and potential evapotranspiration, while considering the soil-moisture holding capacity. Clearly, such calculations cannot be completed on the given scenarios, or in the absence of soils data, and much simpler methods will have to suffice.

The Jensen-Haise equation (1963) relates potential evapotranspiration to air temperature in a simple function

$$PET = 0.245 \times 10^{-4} \times R_s (0.025 T_a + 0.08)$$

where PET = potential evapotranspiration (mm/day), R_s = shortwave radiation (KJ m²/day), and T_a = average daily air temperature in degrees C. Depending on the levels of radiation (assumed unchanged although cloudiness might increase), it is possible to estimate the increase in PET for a given increase in temperature as has been done for the discussions in the following sections.

The frequency of occurrence of droughts and frosts cannot be determined from the scenarios and have to be estimated very generally. Nor

can this informal analysis take into account the possible direct effects of increased CO₂ on water-use efficiency of all the plants involved. Interestingly, the scenarios considered appear to accentuate the existing differences in climate between the northern and southern Rocky Mountains (Dettinger et al. 1998), thereby requiring separate treatments.

East-central and Southern Rocky Mountains

In the East-central and Southern Rocky Mountains, the scenarios call for increasing temperatures (+1.5 to +3.0°C) and variable precipitation (-45 to +90 mm/yr). Under Scenario 1 (increased winter precipitation, decreased growing-season precipitation), the increase in summer temperature of +1.5 to +3.0°C is likely to increase PET on the order of 0.5 to <1 mm/day depending on the actual temperature. Given the projected decrease in growing season precipitation of -0.5 to -1.0 mm/day, the net effect is a growing-season decrease in the water budget of -1.0 to -2.0 mm/day. Even if offset by the most favorable precipitation estimates (+90 mm in winter), the net effect is a significant decrease in soil-available water, or an increase in soil drought. In addition, thinner or rockier soils will be unable to store the additional winter precipitation, leading to no net increase in soil-available water against a very significant increase in PET. The result will be a very significant drying. Only those species that can disperse upward in elevation will be able to secure the necessary cooler-wetter conditions. The degree of change in climate would probably be too significant to allow vegetation change to be ameliorated by latitudinal migration except in isolated cases. The net effect would likely be significant decreases in productivity, losses of area in forested ecosystems, and some local losses of native species.

Under Scenario 2 (+1.0 to +1.5 mm/day increased precipitation in summer), the situation is much more favorable. While on an annual basis the increase in PET will far outstrip the increase in precipitation, water balance should actually be more favorable in the summer season, resulting in increased available soil water during parts of the growing season than at present. A reasonable expectation is that total water available over the course of the year will still decline significantly, but the impact will be much

less than under Scenario 1. Water available to plants will depend much less on soil-water holding capacity and more on growing-season precipitation. The summer precipitation regime will more closely match the current Arizona monsoon regime that presently dominates the Southern Rocky Mountains. Despite the less severe conditions, high-elevation subalpine ecosystems are likely to be lost from the Southwest.

Northern and Western Rocky Mountains

In the Northern and Western Rocky Mountains, the scenarios are significantly different from those of the Southern Rockies. Both scenarios (1 and 2) call for an increase in precipitation from 225 to 495 mm/yr. However, similar to the Southern Rocky Mountains, the difference in seasonality between Scenarios 1 and 2 leads to large differences in projected vegetation change.

Under Scenario 1, winter precipitation and temperature both increase, with relatively little expected impact on snowpack. Given this scenario, high-elevation sites which already achieve maximum soil-water holding capacity (field capacity) will enter the growing season with roughly the same amount of water as at present; lower-elevation sites not having excessively thin or rocky soils may achieve higher rates of soil-water recharge and enter the growing season with higher soil moisture than at present. During the growing season, the slight increase in precipitation (0.0 to +0.5 mm/day) is sufficient to offset most of the effect of higher temperatures, and possibly have a net, positive change at high elevations. The expected result is possibly higher soil-moisture availability on sites with sufficient water-holding capacity, offset by a slightly unfavorable shift in PET versus precipitation. The result would be a slight drying at high elevations (due to soil storage limitations) and relatively little change at mid elevations. Under these circumstances, relatively more drought-tolerant species such as Douglas-fir might expand into higher elevations while maintaining populations in their current elevation zone. Intermountain basins will experience milder, wetter winters with hotter, drier summers, possibly benefiting early-season crops and exacerbating late-season irrigation demands on water.

Under Scenario 2, precipitation increases predominantly in the spring and summer (+1.0 to +3.0 mm/day), with winter precipitation increasing only slightly. Accompanied by a significant increase in temperature, especially in winter (+4.5C), the result is a significant reduction in snowpack with frequent winter rain events. Despite the loss of snowpack, mid- and high-elevation forests are likely to enter the growing season with relatively high soil moisture availability due to winter rain with low PET conditions. In addition, increased summer precipitation will be significantly more than that required to offset the increased PET due to increased temperatures, leading to higher soil-water availability during the growing season. Even in the absence of increased water-use efficiency due to higher CO₂ concentrations, vegetation in the Northern Rockies would experience more favorable conditions for growth. Given milder winters, the growing season may lengthen, and in combination with increased moisture, increases in productivity should occur.

Given similar scenarios, Romme and Turner (1991) and Bartlein et al. (1997) project forest vegetation in the Greater Yellowstone area similar to what now occupies western Montana and northern Idaho. However, the shift to a summer maximum precipitation regime is a significant change for many parts of the Central Rockies, and shifts in species composition more similar to those characterizing the Arizona monsoonal or Pacific maritime areas might occur. Accordingly, ponderosa pine, Gambel oak, and quaking aspen may all increase their importance and move into the Central Rocky mountains. Under these conditions, the diffuse boundary between mixed-grass prairie and sagebrush steppe in the Wyoming Basin might move westward from its present location between the Bighorn and Medicine Bow Mountains (Driese et al. 1996)

Intrazonal Changes in Response to Climate Change

Complexities at Subzonal Scales

The zonal view of vegetation is convenient, particularly for generalizing over 1,900 km of latitudinal variation for collective assemblages. It is not a particularly good way to examine

the distribution of individual species (e.g. Stohlgren et al. 1997). But intrazonal variation, and even the possible breakdown of zones as presently defined may also occur with climate changes. The zones graphed in Fig. 7.2 are not as monolithic as they appear. These are conceptual diagrams, not views of mountain slopes. Some of the variability denoted by the horizontal axis—the moisture gradient—can occur at relatively fine scales of tens to hundreds of meters. Depending on their lithology and geomorphologic processes, mountains may have expansive planar slopes or may be dissected into fine-grained sub-catchments. Depending on topographic grain, xeric sites on south-facing slopes or rocky ridges may be as much as kilometers or as little as tens of meters away from mesic sites on north-facing slopes, or from hydric sites in the bottoms of these sub-catchments. More subtle vegetational changes in response to climate change are likely to occur at this scale of tens to hundreds of meters than at the zonal scale.

An example of the complex grain at relatively small pattern scale is exhibited in Fig. 7.3. The upper panel of this figure is a shaded relief image of the topography for an area in the Medicine Bow Mountains of 12,500 ha (30,888 ac) centered on an unlogged wilderness area. As explained in the caption, the elevation decreases from upper right to lower left and terrain becomes increasingly dissected as elevation drops to the left. Three environmental factors are illustrated here. First, elevation and its attendant macroclimatic properties decrease from upper right to lower left. Second, the terrain is dissected by downcutting streams running from right to left with the extent of dissection increasing downslope. Third, the east-west-running stream channels create sharply contrasting north- and south-facing slopes. Thus, the topography of this area creates some complex variations in microclimate and soil properties at a relatively fine scale of tens to hundreds of meters.

The second panel in Fig. 7.3 is a Landsat-TM derived image for the same area. The relatively undisturbed, non-forested vegetation of the wilderness area extends from the darkly colored wilderness area to the lower left corner. The shadows cast by north-facing slopes make them appear darker than the rest of the image. This

topographic variation is better revealed in the third panel in which more detailed separation of the spectral signals of this image are exhibited as colored polygons, each polygon representing a different vegetation type. Some of the variations in the unlogged area stem from elevational differences, some from topographic effects. The drainage incisions have produced more-or-less linear features paralleling the direction of the stream channels. The second panel indicates that the wilderness area is surrounded in the right two-thirds of the figure by a system of clear-cut plots. The patterning described above applies to non-logged areas. The patchwork surrounding the wilderness area patterning illustrates another form of spatial heterogeneity that, along with roads, is a dominant aspect of much of the Rocky Mountains.

The complex pattern demonstrated in Fig. 7.3, both logged and non-logged, is the kind of environment in which intrazonal changes may occur. Some crude projections can be made on intrazonal change but they are locally specific and replete with caveats. For example, different properties of the vegetation will change at different time scales. Clearly, mature trees have experienced considerable climate change already over their 100- to 500-year life spans as is evidenced in variations in their tree rings and correlations with past climate changes. These adult trees can endure a considerable amount of climatic variation and persist. More problematic is seedling establishment and sapling growth (Stohlgren et al. 1998a). Regeneration is highly variable in the West and climate effects are more likely to affect regeneration processes than mortality processes so that while forests may appear to be unaffected in terms of responses by adult trees, changes in reproduction may have already taken place that may not be seen for decades without very careful demographic studies. While climate-driven processes can be slow and subtle, changes could be accelerated by disturbances, extinctions, or invasions of exotic species. In contrast to forests, response times in mountain meadow species will generally be faster than for forests (see discussion below).

It is within intrazonal changes that the different precipitation scenarios come into play. The situation is further confounded by considerations of increased water-use efficiency (WUE) brought about as a direct effect of higher

CO₂ itself. Comprehensive models of climate effects on vegetation performance take this into account although little is known, in fact, about the long-term effect of CO₂ in this respect. For an assessment as generalized as this one, the direct CO₂ effect is not considered.

A warmer scenario with more precipitation in the winter, or with less precipitation in the summer, would intensify the summer drought period. Given the site preferences of species today, those members of a given zone occupying xeric sites would expand their area of occupation at the expense of those occupying more mesic sites within that zone. For example, ponderosa pine might give way to limber pine, Douglas-fir to ponderosa pine, subalpine fir to Douglas-fir at low elevations, or to lodgepole pine at higher elevations in landscapes like that shown in Fig. 7.3. Lodgepole pine, a widespread dominant from 38.5° lat. (central Colorado) northward (excepting the Utah mountains) would lose some ground it presently occupies to competition from other species at a specific elevation because its relatively high, spring frost tolerance would no longer provide a crucial advantage in competition with other species. These kinds of shifts are projected by Neilson and Chaney (1995, 1998) on a broad areal basis. The point here is that these shifts can interplay in relatively small areas at the same time.

A warmer scenario, or even no temperature change, but with a shift in precipitation to summer, would favor other species in competitive interactions across the landscape. Under these circumstances, white fir and trembling aspen could expand their area of occupation in middle-elevation landscapes at the expense of the pines, while ponderosa pine and Gambel oak could expand their share of landscapes at lower elevations. The same kinds of shifts in relative importance of species over a landscape could be predicted on a smaller scale for dominant species composing the alpine zone.

Embedded within the forest matrix, meadows dominated by graminoids and forbs occur in valleys, dry slopes, and sites of past fires at all altitudes (Peet 1988 [Fig. 7.2], Debinski et al. 1999). The vegetative structure of meadows varies over short distances along xeric-mesic gradients (e.g. vegetation Type 1 in Fig. 7.3). Because of the shorter life-spans of the herbaceous and shrubby species, composition

of meadow vegetation could change more rapidly than that of the surrounding forests under altered climatic conditions (Harte and Shaw 1995). Under the right conditions, these meadows are highly invasive by trees and could disappear. In dry meadows, that change could result under warmer, wetter conditions; in wetter meadows, tree invasion could be fostered by shortened periods of saturated soil moisture. Under still drier conditions, these meadows could expand in area but would also undergo large shifts in composition. For example dry slopes occupied by sagebrush could expand to cover other slopes and dominate more area at the expense of grasses and forbs at intermediate altitudes. All of these possible dynamics would be very much altered by fire (see later section).

Debinski et al. (2000) found that mesic meadows (meadows at the midpoints of moisture gradients) support the highest plant diversity and they also show the largest inter-annual and seasonal variability in spectral response. Because spectral responses are linked with productivity, one might expect major changes in productivity along these moisture gradients under conditions of climate change. For this reason, mesic meadows may be important indicators of environmental change that could be detected with remotely sensed data.

The upper treeline, where trees give way to dwarfed krumholz forms, and ultimately to alpine tundra, is an area of intense study because it is an ecotone at which it would seem to be particularly easy to detect changes. There is a copious literature on treeline and its causal factors. Space does not allow lengthy review of this, and the focus here is on evidence for change in the Colorado Front Range.

While it is intuitive to infer that any increase in temperature would cause treeline to move upward, available evidence suggests that it has not occurred rapidly in recent years in the Front Range. Weisberg and Baker (1995a, 1995b) have extensively measured changes in growth form, seedling establishment, and leader extension in the krumholz zone. They found little seedling-establishment and sapling-density increase, but did find increased growth extension in the short krumholz trees. So far, there seemed to be no general expansion at the expense of tundra at

that locale. Hessl and Baker (1997a, 1997b) also found no evidence of change in recent years.

Patterns of snow deposition, both too much and too little, wind-driven snow-crystal scour of coniferous needles, soil moisture and, in some places, inadequate soils, control treeline and may prevent rapid change. This is an issue that is very much site-bound and must be evaluated locally. If it is true that upper treeline will be intransigent to climate change, that has important implications for the generalizations about zonal “shifts” and how vegetation zones below treeline could be “compressed.”

Nevertheless, the northward elevational decline of treeline, and the post-Pleistocene elevational shifts described above in the Historical Climate Change section remain as persuasive, circumstantial evidence that the overall positioning of the zone is climatically determined. And they are a reasonable basis for the hypothesis that treeline will ultimately rise with increasing temperatures.

Within the alpine tundra, snow distribution and depth of snow cover is a dominating influence on vegetative patterns (e.g. Walker et al. 1993), animal distributions, and ecosystem processes (e.g. Seastedt and Vaccaro 2001). Any scenario lessening the distribution, depth, or length of coverage in the snow cover will have short-term effects on tundra vegetation structure and function. For example, winter-time soil activity is relatively high under deep snow in the Front Range alpine tundra. A lessening of the snow cover would reduce rates of organic matter decomposition and nitrogen mineralization (Brooks et al. 1996, 1998). The impact of more snow is being experimentally tested at Niwot Ridge in the Colorado Front Range. Shifts in vegetation due to the imposition of an artificial snowfence have brought about changes in the vegetation that are obvious to any observer, and ecosystem functions are likely to reflect this as well.

A larger question is whether climate warming, particularly at nighttime, would be as great at altitudes over 4,000 m (13,120 ft) because of the lesser depth and mass of overlying atmosphere and its radiative properties. A counter-argument to this possibility is that the atmosphere is so well mixed that local elevation means little; advection processes are greater than local radiative processes. This argument

is supported by recently quoted Chinese data from much higher elevations in the Himalayan Mountains. There they found not only “...a linearly increasing annual temperature trend of $\sim 0.16^{\circ}\text{C}$ per decade from 1955 to 1996, and an increasing winter trend of $\sim 0.32^{\circ}\text{C}$ per decade, they also report evidence that the rate of warming has increased with elevation.” (Thompson et al. 2000).

A Case Study: The Greater Yellowstone Ecosystem:

Romme and Turner (1991) took several climate-change scenarios for the Greater Yellowstone Ecosystem of northwestern Wyoming and adjacent Montana and projected how the alternative scenarios would alter vegetation distribution and some of the signature plants and animals of the region. The methods used were relatively simple rule-based applications of GIS but the results seem plausible for an equilibrium outcome. This kind of simulation does not take into account the influence of intervening changes in disturbance patterns, influences of soil types, or lags in the migration rate of plants. These authors used three climate scenarios:

- “1) Warm, dry—temperature and PET increase, precipitation decreases or remains unchanged, and WUE [water-use efficiency] increases only slightly; plants are subjected to elevated temperatures, CO_2 and drought stress.
- “2) Intermediate—temperature and PET increase; precipitation decreases or remains unchanged, and WUE increases sufficiently to compensate for increasing PET; plants are subjected to elevated temperatures and CO_2 , but there is no change in drought stress.
- “3) Warm, wet—temperatures and CO_2 increase, precipitation increases, and WUE increases significantly; plants are subjected to elevated temperatures and CO_2 , but to reduced drought stress.”

Fig. 7.5 is a simplified synopsis of the outcomes of these projections in terms of vegetation zones now and with the three different scenarios. Starting at the top of Fig. 7.5, the first point is that the alpine zone can go no higher and its elevational range, and thus

area, is greatly reduced according to all three scenarios. The whitebark pine zone, a species critical to grizzly bear habitat, increases in elevation and is reduced in elevational range and area. The forested zone in general increases in elevation and maintains the same range under Scenario 1, increases in upper elevational range in Scenario 2, and increases in both upper and lower elevational range in Scenario 3. Thus, with a warmer-wetter scenario, the forested zone expands above and below, reducing shrub and herbaceous areas at both ends of the elevational gradient. This has profound implications for grazing/browsing and other kinds of animals. Finally, the low-elevation, shrub/grassland zone increases in elevation and elevation range in Scenario 1, is about the same for Scenario 2, and decreases to only the lowest elevations in Scenario 3. This projection approach is relatively simple from a technical point of view and yet provides some insight on how vegetation, and

thus animal habitat, might react to different kinds of climate change.

Others have modeled the possible redistribution of individual species, perhaps a more realistic approach from an ecological point of view although without an explicit elevational output such as used by Romme and Turner. Plants attain their distributions, in our opinion, mostly in terms of their unique environmental requirements and dispersal qualities, not as components of integrated vegetational types. For example, Thompson et al. (1998) and Bartlein et al. (1997) calculated climatic envelopes for nine species occurring in or around the Greater Yellowstone Ecosystem (GYE)—lodgepole pine, whitebark pine, Gambel oak, western larch, Douglas-fir, Engelmann spruce, ponderosa pine, western red cedar and big sagebrush. Based on the co-occurrence of species distributions with January and July temperatures, and January and July precipitation, they created response surfaces that then could be mapped over the region in terms of those variables under a 2xCO₂ climate.

This approach assumes that species distributions are individualistic, in equilibrium with the current climate, and that competitive relations between them or dispersal limitations will not restrict redistribution. It also assumes that other climatic variables or combinations of the four determinant variables will not be more important than the ones used. It also cannot take into account how soil properties may create lags in establishment of different species, or how changes might be accelerated or delayed due to fire. These are equilibrium models, not temporally dynamic models. As such, they are not designed to consider processes affecting rates of change. Outputs by this method are small-scale maps of projected individual species distributions.

The combined research from both of these publications produced some very enlightening results for the eight target species. The projected distributions of lodgepole pine, Douglas-fir, and Engelmann spruce were mostly reduced along their margins. Whitebark pine was almost entirely eliminated from the region. Gambel oak expanded north to the Canadian border and southeast to south-central Wyoming. The projected western larch distribution was reduced in the northern part of its range but expanded to the southeast, centering on the Wyoming-Idaho

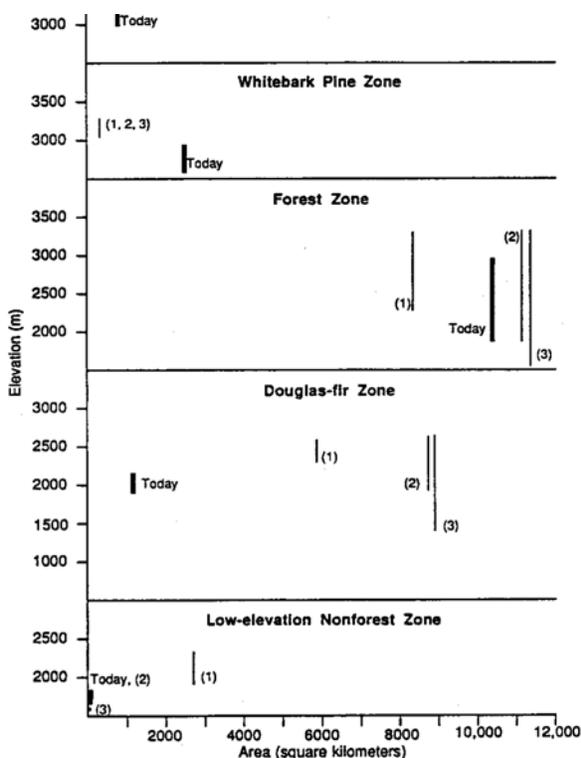


Figure 7.5. Present and projected elevational ranges of vegetation zones in Yellowstone National Park and the adjacent mountains along its eastern border. Scenario (1) is elevated temperature, CO₂, and drought stress. Scenario (2) is elevated temperature, but no change in drought stress. Scenario (3) is elevated temperature and CO₂, but reduced drought stress. From Romme and Turner (1991); see text for details. Published with permission of Conservation Biology.

border. Ponderosa pine range was reduced by this projection throughout much of its range in northern Idaho but became more prominent in much of central Montana and lower margins of western-Wyoming mountains where it is only sparsely found today. Western red cedar range was projected to shift from Idaho and western Montana farther east in Montana and in the Teton and Wind River Ranges of Wyoming, and the Overthrust Belt of Idaho and western Wyoming. Big sagebrush range contracted in the Great Basin, Columbia Basin, and eastern Wyoming and Montana according to this projection but expanded into eastern Colorado, Alberta, and Manitoba. The climate scenarios employed by Bartlein et al. (1997) and Thompson et al. (1998) most closely matched Scenario 2 (Table 7.1) as used in this report, and their projections are qualitatively in agreement with ours for that scenario.

More sophisticated vegetation distribution models than these are possible and needed to better evaluate possible outcomes for other parts of the Rocky Mountains. The individual species approach is preferable but considerations of competitive relations, dispersal pathways, and the interacting roles of potential changes in disturbance regimes also need to be considered.

Disturbance Regimes in Response to Climate Change

Disturbance Regimes

All ecosystems are subject to natural destructive disturbances by a host of agents: trampling, over-grazing, windstorms, floods, landslides, avalanches, insect or disease outbreaks, and fire. The frequency of occurrence of these disturbances depends on geographic location of a site and—particularly in the case of forest insects, disease, and fire—on the physiological condition and age of the forest, and on the weather. Thus, there is an important intersection between potential climate change and its resultant weather with disturbance in the Rocky Mountain region. For this reason, disturbance phenomena--their contemporary regimes and their relationships with weather--deserve careful consideration in this assessment.

The complex of factors responsible for a disturbance event—topographic location,

geographic context, infection, ignition-event frequency, growth rate of a stand—all lead to a characteristic frequency of occurrence of the disturbance event, albeit with large variance. This is considered the “disturbance regime” for that location. These regimes may or may not have characteristic frequencies related to climate oscillations (Swetnam and Betancourt 1990, 1998, Swetnam and Lynch 1993, Parsons et al. 1999, Veblen et al. 2000). Meadows and shrublands also are disturbed by fire, but their recovery dynamics are typically more rapid than those of forests.

Fire

Fire has been part of the Rocky Mountain environment throughout the Holocene and probably before. Records dating back to 17k yr BP show a correspondence between fire frequency and climate change over the Holocene (Millsbaugh et al. 2000). More recent tree-ring records demonstrate that fire frequency in the southwestern U.S. (including New Mexico) varied not only with ENSO cycles but with multi-decadal-scale variation in the amplitude and/or frequency of ENSO events (Swetnam and Betancourt 1998). Currently, larger fires and more numerous fires are associated with dry years related to La Niña following wet periods related to El Niño in the Rocky Mountains. The wet years lead to the accumulation of more fine fuels and the dry years lead to higher temperatures and drying of those fuels (Veblen et al. 2000). Farther north in the Rockies, the Pacific North America pattern plays a stronger role in creating fire weather. For example, in the Canadian southern Rockies mid-tropospheric surface-blocking events during large fires are teleconnected to upper-level troughs in the atmospheric circulation over the North Pacific and eastern North America (Johnson and Wowchuk 1993). Thus, the fire regime for any given location has to be viewed in an appropriate time frame. The regime at the decadal scale may vary at the interdecadal scale and at the millennial scale. These demonstrated relationships between fire and climate strongly suggest that a fire disturbance regime is likely to be shifted with the kinds of secular climate change projected for the future.

It is difficult to know what the natural fire regime for forests might be today. Fuel accumulation, and thus stand age, is dependent

on a historical legacy of past disturbances. There were fire and insect outbreaks prior to European settlement, but the regime has been strongly impacted by human management effects since the late 19th century. Management, including cutting and grazing, but particularly fire suppression, has confounded the present situation (Veblen et al. 2000). Cutting and grazing may reduce fire probability, but suppression certainly increases the potential for more widespread and intense fire events.

Aside from the effects of fire suppression, human-caused ignition and the interactions of blowdowns and insect attacks on fire probability, it seems likely that all of the summer-dry scenarios for climate change could, at least in the short term, contribute to increases in fire probability. They would do so mainly by intensifying dry periods. The relative impact of increased fuel desiccation is likely to be greatest in mesic spruce-fir forests where summers currently are relatively moist compared to the intense summer drought typical of ponderosa pine and other low-elevation forest types. It is well documented that large areas of subalpine forest have burned during infrequent, exceptionally dry years that have occurred during the past several centuries (Romme 1982, Kipfmüller and Baker 2000). These historically documented patterns of extensive fires in the subalpine zone will in all likelihood be repeated under future conditions of more severe summer drought. In the longer term, shifts toward more xeric vegetation under summer-dry regimes could reduce productivity and fuel loading although that relationship is not documented. If the scenario for summer-wet conditions were sufficiently large, it would tend to reduce fuel flammability and could reduce fire frequency. Of course, vegetation productivity would also increase and species composition would be likely to change as well.

A key determinant of the probable influence of climatic trends on future fire regimes is the degree of year-to-year variability in moisture availability. Fire history studies in the Rocky Mountains have demonstrated that decadal and longer average weather conditions have less influence on fire regimes than do extreme oscillations occurring over 2- to 5-year periods (Swetnam and Betancourt 1998, Veblen et al. 2000).

A Case Study: The Colorado Front Range

Veblen et al. (2000) have recently published a detailed history of fire in ponderosa pine forests of the montane zone (~1,830--2,790 m) of the northern Colorado Front Range. Over 700 fire-scarred trees, mostly ponderosa pine, from 41 sites were sampled from which 525 sections yielded 909 cross-dated fire scars. Fire dates extended from 1,450 AD to the late 20th Century. The resulting record can be divided into three historical periods: pre-EuroAmerican settlement (pre-1850), early European settlement (1851--1920), and the fire suppression period (1920-present).

The first period was marked by frequent surface fires in the lowest elevation (c. 1900 m) ponderosa pine woodlands, near the ecotone with the Plains grassland. In higher-elevation forests (above ca. 2,400 m, 7,872 ft), where ponderosa pine co-occurs with Douglas fir, the pre-EuroAmerican fire regime was characterized by a much lower fire frequency and included extensive stand-replacing fires as well as some surface fires. The second period was marked by a much higher fire frequency in both the lower and upper montane zone, and the third period by very low frequency, small-sized fires.

Although increased ignitions by humans during the mid- and late-19th century probably contributed to the increased burning, this was also a period of increased year-to-year climatic variability. ENSO cycles became more marked in the latter half of the 19th century, concurrent with EuroAmerican settlement and probably increased fuel conditions favorable to the spread of fire. Tree-ring evidence shows that years of widespread fire tend to be preceded 2 to 4 years by above-average moisture during the El Niño years and to coincide with drought associated with La Niña years. With suppression through most of the 20th century, recent fire occurrence has been well outside the historical range of variability in this region. As a result of the exclusion of surface fires that formerly killed many tree seedlings, the lowest elevation ponderosa pine forests have increased in density.

In the upper montane zone, stands are typically even-aged as a result of abundant tree establishment following the widespread stand-replacing fires of the late 1800s. Both situations have resulted in a montane landscape

of more homogeneous stand structure and increased fuel continuity that now has the potential for sustaining more extensive crown fires. This poses a difficult management situation. Managers must now take into account the relationship between buildup of fine fuels during El Niño periods together with subsequent high temperatures and fuel drying imposed by subsequent La Niña periods, all superimposed on large areas of extensive forests primed to burn through decades of fire suppression.

How will climate change influence this already complicated situation? It seems that any of the scenarios are likely to encourage burning in that warmer temperatures help to produce more fuel in wet periods and to dry fuels in dry periods. How interdecadal fluctuations in ENSO amplitude are altered in a new climate regime will be a very important consideration in this regard. A climate change bringing more precipitation during warm phases of those fluctuations might diminish fires, but more precipitation would also alter the vegetation to such an extent that past experience in these ponderosa pine forests and woodlands would have less value for predicting outcomes.

Insects and Disease

It is more difficult to specify general rules for how climate change might interact with the greater diversity of disturbances caused by insect outbreaks and diseases. The literature is extensive on each of these so the level of generalization must be more superficial than for fire.

Large areas of forest in the Rocky Mountains are attacked and trees killed by bark beetles and defoliating insects such as mountain pine beetle, Douglas fir beetle, spruce beetle, and western spruce budworm (Amman 1977, Frye et al. 1974, Schmid and Mata 1996, Veblen 2000). In the southern Rocky Mountains the mountain pine beetle (*Dendroctonus ponderosae*) primarily attacks live ponderosa and lodgepole pines. During epidemics, nearly 100% of overstory trees can be killed by mountain pine beetles over many square kilometers (Schmid and Mata 1996). Numerous mountain pine beetle outbreaks have occurred during the 20th century throughout the southern Rocky Mountains (Roe and Amman 1970). It is widely believed that increased stand densities associated with fire exclusion in this

century have increased the susceptibility of stands to outbreaks of mountain pine beetle (Roe and Amman 1970, Schmid and Mata 1996). However, there are no long-term studies (e.g. based on tree-ring records) of the frequency or duration of outbreaks to examine this hypothesis. Also this hypothesis ignores the fact that the larger trees (i.e. those most susceptible to beetle attack) were removed from stands that subsequently have experienced outbreaks. Occurrence of extensive outbreaks in the late 1800s and early 1900s (Roe and Amman 1970) indicates that not all outbreaks can be attributed to the stand structural changes resulting from modern fire exclusion.

The extensive research on mountain pine beetle has shown that the larval stage is vulnerable to low temperatures during winter, and hence the species is limited to lodgepole pine stands generally below ~ 3,000 m (9,840 ft, cf. Amman 1973). U.S.D.A. Forest Service biologist J.A. Logan (Pers. Comm.) suggests that rising temperatures would allow the species to move up to higher elevations where it would attack and eliminate whitebark and limber pines. The nuts of these species are important foods for the threatened grizzly bear in the North-central and Northern Rockies.

The Douglas-fir bark beetle (*Dendroctonus pseudotsugae*) can cause widespread mortality of Douglas-fir in the southern Rocky Mountains, and its epidemics appear to have arisen during and expanded following outbreaks of western spruce budworm (Schmid and Mata 1996). Outbreaks have been observed to last 5 to > 10 years, and intervals between outbreaks in the same areas may be on the order of 15 to 35 years (Hadley and Veblen 1993, Schmid and Mata 1996).

The spruce beetle (*Dendroctonus rufipennis*) in the southern Rocky Mountains mainly infests Engelmann spruce (Alexander 1987, Schmid and Mata 1996). Endemic spruce beetle populations infest fallen trees and scattered live trees, but during outbreaks can kill most canopy spruce over extensive areas. Spruce < 10 cm (3.7 in) in diameter usually are not attacked, nor are the subalpine fir, and their accelerated growth following the death of canopy trees can be used to date outbreaks (Veblen et al. 1991). Stands containing large (i.e. > 55 cm (21.7 in) diameter) spruce and especially those in valley- bottom

sites are the most susceptible to outbreaks. Blowdowns or accumulated logging debris are usually the immediate triggers of outbreaks (Schmid and Frye 1977) which is an important distinction from outbreaks of mountain pine or Douglas fir beetle. Tree-ring records document the occurrence of regionally extensive outbreaks of spruce beetle in the mid-19th century and earlier prior to any significant impact of Euro-Americans on the subalpine forests of northwestern Colorado in the form of either logging or fire suppression (Baker and Veblen 1990, Veblen et al. 1991, 1994).

The western spruce budworm (*Choristoneura fumiferana*) primarily defoliates Douglas-fir and white fir in the southern Rocky Mountains (Schmid and Mata 1996). Extensive defoliation by budworm over several years can produce high levels of tree mortality. Given the apparently greater susceptibility of stands with suppressed understories of Douglas-fir saplings, it is likely that fire exclusion during this century is creating a more homogeneous landscape of increased susceptibility to budworm outbreaks. Studies from Montana to New Mexico suggest that since the early 1900s budworm outbreaks have become increasingly severe and synchronous over larger areas (McCune 1983, Anderson et al. 1987, Swetnam and Lynch 1993, Hadley and Veblen 1993). Increased 19th century burning in the upper montane zone also would have created extensive areas of post-fire, even-aged stands that more or less synchronously become susceptible to budworm outbreaks (Hadley and Veblen 1993).

Weather profoundly affects the life cycles of insect pests as well as the capability of trees to respond to insect attacks, yet the effects of climatic variation on the occurrence of insect outbreaks are poorly understood (Swetnam and Lynch 1993, Logan et al. 1995). For example, mortality of mountain pine beetle is increased by cold winters so that, as commented above, cool temperatures are believed to be the major restriction on mountain pine beetle outbreaks at high elevations (Logan et al. 1995). Generally, warmer temperatures promote bark beetle outbreaks both through their favorable influence on the life cycle of the insect and through drought-related declines in the trees' abilities to withstand attack (Frye et al. 1974, Amman 1977).

Logan and Powell (2000) have written an especially interesting treatise on how bark beetles might react to climate change. Through careful analysis of heat requirements for life-history steps, they concluded that bark beetle responses to warming would be highly non-linear. Once warming passed a critical level (at a given elevation), the life-history processes would pass over a cusp and the population could enter an infestation phase. From their analysis it appears that as a specific elevational level gradually became warmer, the heat budget would build up and changes in beetle population levels would be small to nil. But after the heat budget reached a critical point, the population would pass across a cusp of life-cycle viability permitting completion of its life cycle at that elevation and thus allowing it to attack the trees at that elevation. This kind of analysis would be desirable for all of the insect pests of concern in this region as it integrates life history, physiology, stand conditions and climate in a way permitting better predictive modeling of possible outcomes to climate warming.

Although it has long been believed that drought pre-disposes Douglas-fir stands to outbreaks of western spruce budworm (Cates and Alexander 1982), recent research from New Mexico suggests that wet periods may favor outbreaks. For example, in northern New Mexico tree-ring records of outbreaks from 1690 to 1989 indicate a tendency for outbreaks to coincide with years of increased spring precipitation (Swetnam and Lynch 1993). This contrasts with findings for the northwestern U.S. and eastern Canada where shorter-term records indicate an association of budworm outbreaks with periods of moisture deficit (Swetnam and Lynch 1993). Although the mechanisms relating budworm population dynamics and tree susceptibility to attack are not clear, there is strong evidence that climatic variation influences the occurrence of budworm outbreaks. However, non-climatic changes in stand structures still play an equal or greater role.

Clearly, insect outbreaks are important modes of wide-spread disturbance in the Rocky Mountain region. The relationship between these insects and stand condition and weather are complex. Stand condition, in turn, is related to fire history and logging practices. Fitting individual species climatological envelopes to

projected spatial distributions only provides a “potential” new range for that species. The complex dynamics of fire and insect epidemics must be factored in to generate projections that are ecologically satisfactory. The workshop participants cannot make meaningful projections on this complicated set of interacting forces. It can only point out the importance of the factors and point toward the need for better-directed research to develop such projections.

Among forest diseases, the exotic species white pine blister rust is of most general concern. This rust has decimated much of the western white pine range and more recently has infected the whitebark pine that is primarily restricted to high elevations. It is unknown whether the recent infection of this high-elevation species might have been enabled by a warming climate. As mentioned above, the loss of whitebark pine is of particular concern as a critical food resource for the threatened grizzly bear (Koteen 1999). Whitebark pine is also a nursery plant for subalpine fir, so that blister rust might influence vegetation dynamics indirectly (Callaway 1998).

BIOTA

Species-level Effects

In contrast to the previous section on vegetation, this section addresses the biotic

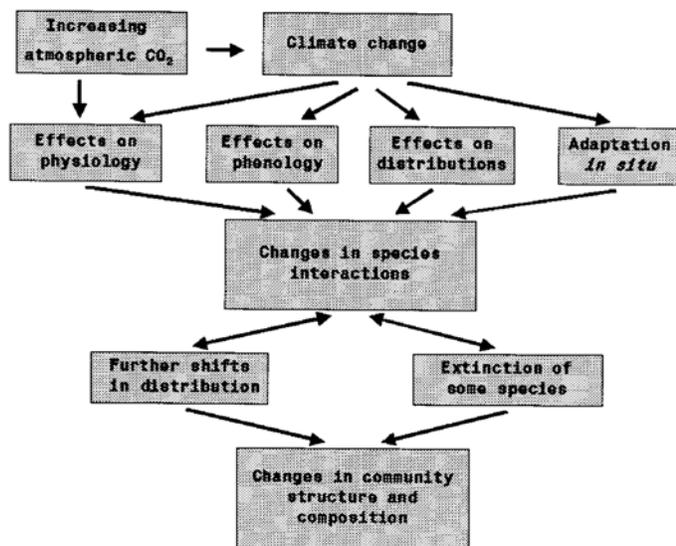


Figure 7.6. Projected causal sequences from atmospheric- CO_2 increases and climate change through effects on individual species, species interactions, and ultimate changes in community structure and composition.

resources of the Rocky Mountain region from a species-level point of view. Projecting how individual species might react to a change in climate is a complex process requiring a multifaceted set of considerations. Hughes (2000) has written on evidence for species changes world-wide and produced a causal linkage diagram of key processes from which Fig. 7.6 is abstracted. The top of Fig. 7.6 illustrates that increases in CO_2 and change in climate variables are linked while the first contributes to the second. CO_2 itself has a direct effect on plant physiology. Climate variables also have effects on phenology, distributions, and adaptations *in situ* (second tier of Fig. 7.6). The third tier illustrates how changes in physiology, phenology, distributions and adaptations collectively influence species interactions. Changes in interactions can cause further shifts in distribution and lead to extinction of some species (fourth tier). Shifts in distribution and extinction of species lead to changes in community structure and composition (fifth tier).

Hughes’ approach is a logical way to conceptualize potential climate impacts on individual members of the biota. While this cannot be done in this report, elements of this approach will be followed. In the following, the biota is divided into several groups based on the way the groups tend to be studied and managed.

Flora

There is no defined flora for the Rocky Mountains as described in this report although one could be compiled with considerable effort. Floras tend to be organized by states and none of the Rocky Mountain states fall entirely into the Rocky Mountain region. Ronald L. Hartman, Curator, Rocky Mountain Herbarium estimates that a flora for the region, as defined here, would be in the order of 5,000 to 5,500 vascular plant species (Pers. Comm.). For perspective, this is a moderate-sized flora, not quite equal to the flora of the entire state of California—a state with extraordinary environmental diversity and endemism. As is typical of any flora, most species are quite uncommon and a relatively few are dominants or occur with high fidelity in particular habitats or vegetation types (Stohlgren et al. 2000). A

small number of species in this flora are listed as threatened and endangered by the U.S. Fish and Wildlife Service (see below).

Assessing the possible influence climate change might have on this flora as a whole cannot be made in this brief report even if the requisite information were available. The ranges of most species are not well known, much less their environmental requirements. Work is underway in developing environmentally-based distribution models for some species (Bartlein et al. 1997, Thompson et al. 1998, Fertig and Reiners 2001) but the number of species receiving this attention is a small fraction of the entire flora. Furthermore, there is evidence for low fidelity of species to environmental complexes and for large persistence in the face of environmental change (Stohlgren et al. 2000). The influence of landuse change and invasive exotics will probably be more important than climate change for the majority of the members of the Rocky Mountain flora. On the other hand, a more careful evaluation of restricted groups within the flora, such as members of alpine tundra, bog or wetland groups, might reveal some important trends in vulnerability to climate change.

Fauna

As with the flora, there is no single terrestrial faunistic list for the Rocky Mountains as defined here. The situation with animals is complicated by the migratory habits of many of the birds. A very crude estimate for Wyoming alone, provided by D. Keinath, Heritage Zoologist with the Wyoming Natural Diversity Database, is 370 species of birds, 24 species of reptiles, 12 species of amphibians, and 117 species of mammals for a total of 523 vertebrate species (Pers. Comm.). This faunistic list probably represents Idaho and Montana fairly closely but the numbers in the more southerly states of the Rocky Mountain region are undoubtedly higher because of the latitudinal enrichment effect and wider range of environmental conditions found in Utah, Colorado, and New Mexico. A crude way to arrive at an estimate for the entire region might be to double the numbers found in Wyoming for a total of about 1000 vertebrate species. Numbers would likely increase for all classes of vertebrates but the increase would probably be proportionally higher for amphibians and reptiles. The number of invertebrate species

has to be orders of magnitude higher than for vertebrates.

Climate-change impacts on vertebrates and invertebrates would probably be associated with climate-change effects on their habitats. Habitats are based, in part, on vegetation discussed earlier but also on spatial proximity to other resources such as water or cover. For most vertebrates, enough is known about their habitats through development of habitat models for wildlife management and through the Gap Analysis Program to permit crude modeling at coarse scales for climate-change impacts on these species. Such models can be obtained through the National Gap Analysis Program (<http://www.gap.uidaho.edu/Projects/States/>). Much less is known about invertebrate habitat requirements except for certain pest species, but climate change would almost certainly affect these ectothermic species directly by operating through their physiologies.

A small proportion of the fauna is of exotic origin although most exotic invasives are invertebrates. An even smaller proportion of the fauna is threatened and endangered and will be discussed in the next section.

Threatened and Endangered Species

Conservation biology is a general term used for consideration of and planning for maintenance of species as part of the “biodiversity” of a defined area. There are two issues that need to be separated—biodiversity as a quantitative property of a designated area, versus the host of specific protection measures on behalf of threatened and endangered species. “Biodiversity” is often simplified to mean species richness—the number of species, usually within a taxonomic group like reptiles—occurring in a defined area. By this usage, higher species richness is synonymous with higher “biodiversity.” This quantitative measure of an ecosystem variable is quite different from more highly focused concerns with threatened and endangered species whose populations are in a precarious state or are close to extinction.

Within the United States, individual State Heritage Programs maintain records on the status of species with respect to their vulnerability to extinction, but the responsibility for taking action as well as maintaining status

records falls with the U.S. Fish and Wildlife Service. Species monitored for their viability status include vascular plants and vertebrate animals and a relatively few invertebrates such as butterflies and mollusks. Most invertebrates, non-vascular plants, and microbes are excluded from these listings. They are kept by state, and not in terms of the region in which they are found. In fact, many species, particularly animals, are found in more than one region. Thus, listings of endangered species of the Rocky Mountain region strictly delimited are not readily available.

The lack of systematic data on invertebrates is unfortunate for purposes of evaluating the ecological impacts of climate change. Although less is known about these groups on a species-by-species basis, given the fact that many invertebrates have short generation times and high reproductive rates, and sometimes have tight associations with members of the vegetation, the effects of regional climate change could take place quickly and dramatically among the invertebrates. Identifying key invertebrate species to monitor for such changes is strongly recommended.

State heritage programs list species status in more complex terms than those issued by the U.S. Fish and Wildlife Service, thus more complete information about endangered species can be found at the state level. The addresses for these programs are:

Montana—<http://nris.state.mt.us/mtnhp/>

Idaho—<http://www2.state.id.us/fishgame/cdchome.htm>

Wyoming—<http://uwadmnweb.uwyo.edu/wyndd/>

Utah—<http://www.utahcdc.usu.edu/ucdc/>

Colorado—<http://www.cnhp.colostate.edu/>

New Mexico—<http://nmnhp.unm.edu/>

The legal status of species is set by the only agency mandated by Congress to enforce laws protecting endangered non-marine species: the U.S. Fish and Wildlife Service. According to these listings, the Rocky Mountain states are home to 14-27 threatened and endangered animals and 2-22 vascular plant species (Table 7.2). Naturally, many, if not most, of these species occur in more than one state so the total animal species found primarily in the mountains is nine and the total plant species is six.

Compared with the total floral and faunal lists, the number of species listed as threatened or endangered in the Rocky Mountains is small. The nine animals listed are: Uncompahgre fritillary butterfly (*Boloria acrocneuma*—one of the few invertebrates listed), Mexican spotted owl, Preble’s meadow jumping mouse, woodland caribou, bald eagle (which has come close to delisting), grizzly bear, gray wolf, lynx, and jaguar. However, some of these species, like the grizzly, bald eagle, gray wolf, and lynx are signature species of the Rocky Mountains as well as of wildness in general in America. The bald eagle, grizzly bear, and gray wolf also play important functional roles in the ecosystems in which they are found. The list would be extended to ten if one wishes to differentiate the Mexican gray wolf from the gray wolf of the north. Petitioning for further listings by the U.S. Fish and Wildlife Service is anticipated

for isolated populations of martens and flying squirrels on single mountain ranges or systems (G. Beauvais, Pers. Comm.). These are boreal-subalpine Holocene isolates for which climate change would be particularly endangering and as such, illustrate the problems for genetically differentiated populations of any taxonomic species.

The number of threatened and endangered plant

Table 7.2

Numbers of Threatened and Endangered Plant and Animal Species in the Rocky Mountain States and (parentheses) in Mountainous Habitats Plus Wyoming Basin Within the RMGB Region¹

State	Plant Species	Animal Species
Montana	2 (1)	14 (4)
Wyoming	2 (1)	15 (5)
Colorado	12 (7)	20 (7)
New Mexico	14 (1)	27 (4)
Idaho	3 (1)	21 (5)
Utah	22 (2)	21 (3)

¹Source: U.S. Fish and Wildlife Service listings updated September 1, 2000.

species is only seven and none of them could be said to be signature species for the region. They include: Penland alpine fen mustard (*Eutrema penlandii*), North Park Phacelia (*Phacelia formosula*), water Howellia (*Howellia aquatilis*), Sacramento Mountains thistle (*Cirsium vinaceum*), heliotrope milk-vetch (*Astragalus montii*), Maguire daisy (*Erigeron maguirei*), and blowout penstemon (*Penstemon haydenii*).

The primary concern for most of these species is habitat loss and habitat fragmentation, both of which result primarily from management decisions and disturbances. For grizzly and gray wolf (and possibly jaguar) the primary cause of death is human "predation." Of course, human-caused mortality is also a function of access, which, in turn, is related to fragmentation. One concern related to climate change is the loss of area occupied by whitebark pine, due to restriction to even higher elevations. Such a loss would be a detrimental reduction in grizzly bear food resources, as commented above. This situation is already exacerbated by the loss of whitebark pine to white pine blister rust. Whether the spread of the rust is being augmented by subtle, ongoing changes in climate is unknown. There is a potential here for a three-way interaction. It is important to note that the grizzly's present range is highly restricted by human intervention. This species would be prospering in a wider climatic range extending well into the Great Plains if it were not for human predation.

A second climate-related concern is for the lynx. The lynx is a high-elevation predator dependent on deep and long-lasting snowpacks. Without snow, the lynx tends to be outcompeted by other predators like coyotes, foxes and bobcats, and can even be victim to direct attacks by the bobcat (Beauvais 1999). This relationship with snow is exacerbated by increasing penetration of mountainous areas in the winter by recreational snow machines. Where the snow machines create packed snow trails through the subalpine zone, predators like coyotes can enter a foraging area normally dominated in the winter by lynx, wolverine, and marten (Beauvais 1999). Any reduction in snowpack depth, spatial extent, or duration would be a particular threat to the lynx.

A third species of concern is the Uncompahgre fritillary butterfly. It currently

lives on one mountain pass (Mt. Uncompahgre) in Colorado and is undoubtedly strongly affected by the local climate. If the region becomes warmer, the butterfly's principal host plant, the snow willow (*Salix nivalis*), could potentially be lost from the area. There is not much area for either the plant or the butterfly to move up the mountain if the climate were to warm.

Not enough is known about the environmental requirements of the seven listed plant species to comment on their possible status in the face of climate change.

Invasive Exotic Species

In some ways, the impact of exotic invasive plants, animals, and microbes may be greater in the Rocky Mountain region than will be climate change. This judgment will depend on an individual's viewpoint. The effort required by a farmer to adapt to temperature and precipitation may be less onerous than that required for coping with invasive pest species. In contrast, loss of snowpack will be more serious than weed invasions to a ski-area operator. The spread of invasive exotics has accelerated rapidly in the latter half of the 20th Century and the ultimate accommodation of exotics to the Rocky Mountain environment is yet to be seen. The ranges of many of these organisms have not yet found their limits. How impacts and ranges of invasives will react to climate change is less well known than for natives for which there is little information as well.

There are many information sources on invasive exotics but none are delimited to the Rocky Mountain region itself, and none are complete with regard to all taxa. A number of databases exist but each has its own taxonomic and geographic limitations. For an entry to these databases see: <http://www.invasivespecies.gov/databases/main.shtml>. One of these, "The Invaders Database" from the University of Montana, contains listings of exotic plants in Washington, Oregon, Idaho, Montana and Wyoming (<http://invader.dbs.umt.edu/>). This lists 447 total exotic species for Idaho, 82 of which are noxious. Similarly Montana has 489 total, 80 noxious, and Wyoming has 220 total, 48 noxious. This gives the magnitude of plant-species numbers involved. Most of these plant exotics are problems within agricultural parts of these states,

some are very critical in rangeland ecosystems, but relatively few invade forests or tundra ecosystems. Numbers do not tell the entire story, however. The advance of only a single exotic into an ecosystem can radically alter its normal structure and function. The advance of just one species—leafy spurge on to the northern mixed-grass prairie or chestnut blight into the eastern deciduous forest—have had impacts of enormous ecological significance.

There is generally less known about the environmental limits of invasive species than there is for most members of the native flora and fauna, partly because there is little known about the historical distribution of exotics. Further, their potential distributions are, for the most part, still unrealized in the U.S. Were these known, it might be possible to model individual species responses to climate changes in the same way described for forest trees and other members of the flora and fauna (Scott et al. 1996, Bartlein et al. 1997, Thompson et al. 1998, Fertig and Reiners 2001). A concerted effort to identify those exotic species known, or suspected, to be the greatest threats to Rocky Mountain ecosystems; a series of long-term monitoring plots to detect their spread; and development of a database on their environmental limits, would be valuable starts toward projecting how their distributions and roles might change with an altered climate.

Spatial Relationships

Particularly when investigating how individual species might respond to climate change, it is important to be realistic about the heterogeneous nature of the terrain and land cover. Fig. 7.3 provides an example of that kind of complexity for both natural variability and management-imposed variability (Knight and Reiners 2000). The latter leads to increasing fragmentation through dissection of old forest into more isolated and smaller fragments in a matrix of younger forests, openings, and edge (Baker 2000). Especially under the latter case of human-disrupted landscape patterns, we cannot assume that species will interact freely or disperse according to translocation of suitable climatic environmental space somewhere else. Migration, dispersal, and gene exchange depend on topological relationships between points in environmental space. For example,

habitat suitability might be related to patch size or core/edge relationships. Ability to migrate in response to climate change to translocated environmental conditions involves appropriate connectivity across landscapes that may or may not be satisfied in the increasingly fragmented landscape (Pitelka 1997, Malanson and Cairns 1997, Collingham and Huntley 2000). This means that a component of landscape ecology must be implemented in model building in order to predict species movements across landscapes.

Such consideration of spatial relations increases the complexity of the task before us. It is in this context that we begin to perceive the chaos that may be expected if climate changes to the degree and with the velocity predicted by some models. Ecosystems across the region may eventually reach some kind of accommodation with the new conditions, replete with the same form of temporal dynamics at multiple scales with which we are familiar. But, it is likely that a quasi-transition period over a period of rapid climate change will bring many surprises. Species will probably appear in new locations and become extinct in others asynchronously with their associates in present-day assemblages. Adaptations we postulate for heat or water stress by particular plants or animals may prove to be misplaced if and when changes actually occur. Over time the apparent new assemblages may be surprising, and temporary. We should be prepared to find that our understandings about how nature functions are incorrect.

NATURAL RESOURCES

Timber

If forested zones were to shift upward in response to temperature increases alone, the areas occupied by merchantable as well as non-merchantable forests would necessarily shrink. However, as illustrated in the Greater Yellowstone Ecosystem case, if warming were offset by more precipitation, particularly in the summer, the area occupied by forest might even expand upward and downward. Thus, the area for potential harvesting is scenario dependent. Quite unknown is whether there will be a lasting direct effect of CO₂ on water-use efficiency of long-lived plants.

Except for moist areas of Montana and Idaho, forest productivity in the Rocky Mountains is relatively low. As old-growth timber has already been largely cut in the Rockies, and as the forests tend to be used increasingly for recreational activities, forest harvest is tending to become less important over most of the region. Market forces and political agendas will probably have a greater influence on the future of timbering in this region than will climate change.

Livestock Production

Warmer and drier climate scenarios would suggest that rangelands would expand in the Rocky Mountains at the expense of forests. Of course, these expanded rangelands could be of lower productivity and of quite different character than the present ones. Scenarios for warmer and wetter conditions could have the opposite effect of reducing rangeland area in this zone as forests expand. To a certain extent, and for other reasons, this has already been the case with the expansion of juniper over large areas of former rangeland at the bases of mountains in this region (Goodloe 1993).

As with the timber industry, the future of livestock production in the Rocky Mountain region is likely to be controlled more by market forces and political attitudes about grazing on public lands than by climate change. These factors, together with impacts of invasive species, are likely to interact in ways too complex to address in this report.

Recreation

The Rocky Mountain region has been a locus for recreation since the arrival of the mountain men and women in the early 19th century. Hunting and fishing were the original, dominating recreational uses early in Post-EuroAmerican settlement, but other uses have grown over time. These include hiking, backpacking by foot and horse packing, camping, touring by automobile, skiing and, more recently, roving by all-terrain vehicles in the summer, and by snow machines in the winter. These recreational usages vary historically, geographically, and seasonally but the dominant trend has been an increase in all of them.

Recreation and tourism are primary activities in the region that represent significant financial

interests and active political activity. Conflicts occur between recreational and non-recreational usages. Thus, management is going to be the primary determinant of how these activities are changed in the future. Climate change will likely play some role in altering the context of management conflicts but other drivers will be primary.

NEEDED RESEARCH

Research needs have been suggested throughout this assessment but are revisited here as integrated format. As a preface, it must be said that workshop members realize that examining ecosystem components or regional land uses in sequential order is a misrepresentation of how the ecosystems of the region actually work. Topography, lithology, climate, soils, vegetation, animals, hydrology, etc. all work together in space and time in complex ways. Textual presentation requires this kind of linearization of environmental elements, but one of the prerequisites for coordinated research on this problem would be designing a program that permitted and required integration of these components and phenomena. A principal research need is a holistic research design.

A physiographic region like the Rocky Mountains is, by virtue of its geographic extent alone, heterogeneous. The altitudinal variation superimposed on the horizontal extent intensifies the variability embodied in this area as a unit of study and integration. A research need is a programmatic design providing for informational management of this three-dimensional geographic variation. This can be achieved with a digital geographic database, probably in a GIS framework, with which knowledge gained in a local area can be extrapolated appropriately, and with which phenomena generated by broader functions such as mesoscale climate can be interpolated appropriately to local areas. If this region is to be dealt with as a whole, a geographic data center is necessary.

Related to gaining control of geographic variables is the requirement to maintain a time-varying perspective on systems at any spatial scale. Some temporal phenomena like diurnal and annual cycles are obvious, but virtually every phenomenon has its characteristic time scalar. Such scalars may range from hours for

population turnover times of soil microbes to decades for fire return times, to centuries for generation times of Engelmann spruce. Thus, a temporally varying as well as spatially varying mind-set is mandatory for research in this region, particularly with respect to a time-varying phenomenon like weather and the possible secular change in climate variables.

Various phenomena occur at different spatial scales and their observation, representation, and modeling require different resolution (grain, or areal extent of data units) for appropriate research. An integrated program must maintain a sure understanding of which extents and grains are appropriate for different issues, and how to properly scale up or down as the case requires. This will require a relatively sophisticated scale-awareness of all involved in a concerted program.

In keeping with recognition of different scales of operation, the project will require projects that are extensive in scope (in both space and time) and intensive projects that are highly focused in scope. For this kind of research, results of intensive studies gain value as they may be properly extrapolated into the broader system, whether it is a site, catchment, elevational zone, mountain range, or the entire region.

Advances in prediction of climate change and its effects, or of any kind of perturbation, cannot be made without modeling. Modeling of virtually all processes of interest is needed and will play a role complementary to that of spatial database management, analysis, and extrapolation.

Some, but not all, kinds of data can be gathered by different forms of remote sensing. Remote sensing extends from animal and environmental telemetry to low-level aerial photography and lidar surveys, to high-level aerial photography and satellite-borne remote sensing. Remote-sensing technologies should be integrated into a research plan in order to gather necessary spatial data and used in such a way to integrate phenomena across spatial and temporal scales.

The extensive environmental literature on the Rocky Mountains has scarcely been touched by this assessment. Much is known that needs to be organized in literature search and database

organization that will include a digital cross-referencing system. The same is true for data. A system archiving data with rigorous metadata standards is needed for this region. The data-archiving systems being developed for the Long-term Ecological Research Program or by the National Center for Ecological Analysis and Synthesis are possible models.

Some locations are better than others for characterizing ecosystem functions. Managed forests and rangelands have value because of their accessibility, presence of sites with known histories and age classes, and amenability to disturbance experiments. National Parks and USFS Research Natural Areas (RNAs) and national monuments are more limited in this regard but have special value as long-term records and management histories that are supposed to represent pre-EuroAmerican settlement. Of course, national parks have much greater extent than do RNAs. Wilderness areas feature the most pristine conditions of the region but are very limited for access, treatment, and even monitoring studies. An integrated research program on the Rocky Mountain region should take into account the special character of each of these management resources

A regional research program should include surveys for meaningful indicator phenomena that might provide signals of change for small amounts of effort. Indicator phenomena might include the presence or absence of species, changes in population properties such as abundance or age-class structure, alterations in interactive behavior of species with one another, nitrate concentrations in streamwater, as well as standard physical measurements of weather, snowpack, hydrology, etc.

Many of the components of a regional research program require technological methods that may be remote from organisms themselves. A program should not be based purely on measurements of physical properties and derivative model outputs. A program must have a philosophy that organismal-level ecological research—research that might be termed “natural history”—needs constant support. It is from research at that level that we will learn vital information about the biological elements that drive many of the broader processes.

The topics addressed in this assessment (climate-change effects on hydrology, vegetation,

disturbance regimes, floral and faunal elements) are natural foci for an integrated research program. Not discussed in this assessment are other important topics that, in a sense, are a derivative of the set reviewed. These include potential feedbacks between landcover change and mesoscale climate, changes in the amount and chemical character of primary productivity, interactions between terrestrial and aquatic ecosystems, and biogeochemical functions such as net carbon exchange with the atmosphere or nitrogen cycling.

In much of this discussion, effects of climate change are described as moving from one state to another. Neither was the past, nor will be the future, anything like a steady state when viewed from a sufficiently large temporal window. Clearly periodic and aperiodic variations occur at multiple time scales. These sources of variation combined with the nonlinear dynamics characteristic of ecological systems, inability of species to respond to rapid climate change, and lack of adaptations to new climates and habitat conditions together add to the complexities of developing predictive models needed to project the effects of climate change on Rocky Mountain systems. Hence there is a critical need for further research on the biota itself, and on developing system-level models, both in the context of climate-change effects.

SUMMARY

The Rocky Mountain region is large in extent and complicated by its extensive altitudinal gradients and local variations in structural geology, lithology, climate, and history. This heterogeneity makes generalization about possible responses of ecosystems to climate change difficult. The Rocky Mountains have undergone climate changes of great amplitude through the Pleistocene and Holocene and may be experiencing a warming trend that is differentially manifested throughout the region. Whether this warming is linked to greenhouse-induced mechanisms is presently impossible to tell.

Scenarios for warming and drying, and warming with more moisture in, alternatively, the winter or summer, were devised to provide a framework for considering ecosystem responses. Because the Rocky Mountain region is basically semi-arid, changes in the water budget anywhere

in its domain will be of more importance than temperature change *per se*. On the other hand, temperature and precipitation cannot be separated as they both have controlling influences on water budgets. Warming is likely to reduce snowpack depth, extent, and duration under any scenario, but stream discharge timing and volume will be affected differently by the different scenarios. It is possible that changes in precipitation amount and timing may be more important than changes in temperature for altering hydrologic regimes. Regrettably precipitation is difficult to model and high-elevation precipitation gages are so limited as to make validation of precipitation models at high elevations almost impossible.

Climate changes are likely to cause changes in geomorphic processes throughout the region but inadequate attention was directed to this area to produce any suggestions of trends in this regard. Soil responses likewise were not considered in this assessment.

Potential responses by vegetation, and thus habitat, to climate change are highly likely, but variable in time and space, given evidence for such changes in the past. This may be manifested as shifts in elevational location of entire vegetational zones, as breakdowns in zones and the boundaries between them, and most probably, as variations in the species composition and distribution of zonal elements across landscapes within zones. In the most general terms, a warmer, dryer scenario suggests translocations of zones upwards with loss of some higher zones off the tops of lower mountains. Of course for hydric systems, such a change would reduce the amount of watershed area nourishing them and they might be totally eliminated from the landscape. Warmer and wetter scenarios, particularly with higher summer precipitation, might lead to expansion of forested zones upward into the alpine zone and downward into the shrub or grassland areas now below the lower treeline.

The responses of vegetation to climate change will be highly influenced by changes in disturbance regimes, particularly of fire and insect outbreaks. The fire regime has already been altered beyond the range of natural historical variability by grazing, logging and, especially, fire suppression. It is becoming increasingly clear that fire occurrences and

extents are related to intra-decadal oscillations in climate associated with ENSO and PDO. This climate relationship ensures that fire will be influenced by any of the scenarios, or intensification or buffering of the ENSO and PDO cycles themselves. There is evidence that insect outbreaks are also climate-related but other factors such as the distribution of forest stands by age class, and thus tree vigor, will modify climate effects.

Climate change will be implemented through alterations in species populations throughout the Rocky Mountain region. The flora (ca. 5,000-5,500 vascular plant species) and fauna (ca. 1,000 vertebrate species) are likely to react individualistically to changes in climate along with related changes in fire, insect outbreaks, landuse change, and further invasion or naturalization of exotic species. Predicting the responses of individual species requires considerable knowledge about those species but methods are in place to begin to do this. Some model results have been published for tree species and there is no reason why more cannot be done with other members of the flora and of the vertebrate fauna. Invertebrate species are less well known across most groups but a few, particular species such as the Yellowstone checkerspot butterfly (*Euphydryas gillettii*) which is diagnostic of wet meadows near riparian areas (Debinski 1994), would have great utility in this regard. Sheer numbers of invertebrate species prohibit investigations of all of them, but critical or diagnostic species might be especially useful for analysis and prediction because of their associative fidelity with plant species, physical conditions, or vegetation types.

Species deserving particular attention are threatened and endangered species, of which there is actually a relatively small number in this region (nine vertebrate and one invertebrate animal and seven vascular plants). Shifts in environmental gradients across Rocky Mountain landscapes are likely to lead to rapid growth in the numbers of recognizably threatened species.

Invasive exotic plant and animal species may be a threat to Rocky Mountain ecosystems equal, in some cases, to potential climate change. Exotic species are a present-day reality that must be considered regardless of climate change. They will vastly exacerbate our abilities to predict and manage for the anticipated chaotic shifts

in future species composition and occurrences when superimposed on climate-change effects.

Considerable research has been published and is ongoing in the Rocky Mountain region focused on, or relevant to, climate-change questions. This assessment uncovers but a small part of the scientific resources available in this region. There is good potential for organizing a more coordinated method for integrating research bearing on climate change if that were a national goal. A series of research needs concludes this assessment. This list may help to conceptualize a coordinated research system to better help society to predict and recognize changes ongoing and looming in the future due to a changing climate.

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ACKNOWLEDGEMENTS

We extend our appreciation to reviewers Michael B. Coughenour, Department of Rangeland Ecosystem Science at Colorado State University, and Stephen T. Jackson, Department of Botany, University of Wyoming, who made excellent suggestions for strengthening this chapter. However, they should not be held responsible for any of its short-comings, or for any of their comments not heeded.