Synthesis of Knowledge: Fire History and Climate Change

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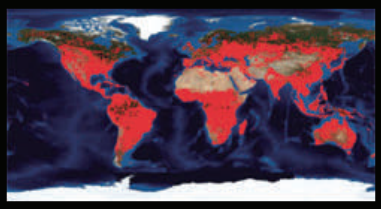
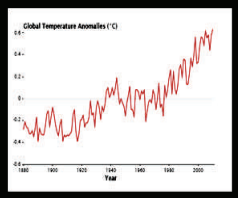
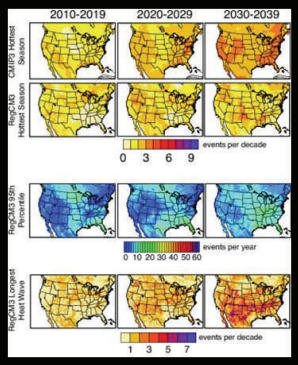
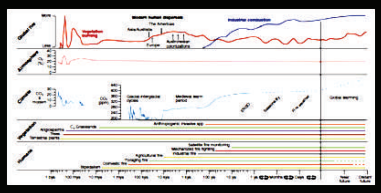
JFSP Project 09-02-1-09

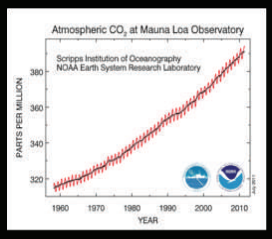


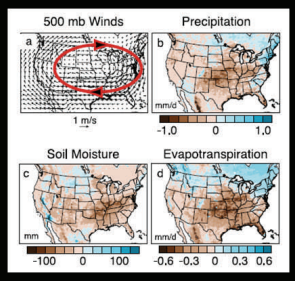






A SUMMARY OF KNOWLEDGE FROM THE Joint Fire Science Program





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Abstract

This report synthesizes available fire history and climate change scientific knowledge to aid managers with fire decisions in the face of ongoing 21st Century climate change. Fire history and climate change (FHCC) have been ongoing for over 400 million years of Earth history, but increasing human influences during the Holocene epoch have changed both climate and fire regimes. We describe basic concepts of climate science and explain the causes of accelerating 21st Century climate change. Fire regimes and ecosystem classifications serve to unify ecological and climate factors influencing fire, and are useful for applying fire history and climate change information to specific ecosystems. Variable and changing patterns of climate-fire interaction occur over different time and space scales that shape use of FHCC knowledge. Ecosystem differences in fire regimes, climate change and available fire history mean that using an ecosystem specific view will be beneficial when applying FHCC knowledge.

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Cover Page Image Sources		
Source: Flannigan et al. 2009 Fig. 2. MODIS active fire detections for 2007	Global Temperature Anomalies 1880-2010. Source: NASA GISS	Source: Diffenbaugh & Ashfaq 2010 Figure 2.14a: Projected changes in heat extremes in the coming decades
Source: Bowman et al. 2009 (AAAS) Fig. 1. Qualitative schematic of global fire activity through time.		Source: Diffenbaugh & Ashfaq 2010 Figure 2.14b: Changes in summer (a) 500 mb winds, (b) precipitation, (c) total soil moisture, and (d) evapotranspiration
LANDFIRE: Fire Regime Condition Class (provided by Brian Tolk)	Monthly mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii. Source: NOAA ESRL	

Preface

Fire is a climate influenced ecosystem process recorded in paleoclimate and paleoecology records covering a long span of Earth history. Human use and management of fire increased human influence as climate warmed and modern societies emerged from the last ice age into the modern era. Modern fire management practices developed over the last century during relatively stable climate. As we entered the 21st Century, scientific evidenced mounted that human activities are now influencing climate to a significant extent. This report synthesizes available scientific information on fire history and climate change to describe likely impacts of 21st Century climate change on fire management. We accompany the report with an online bibliographic database found at: **https://www.zotero.org/groups/jfsp_fire_history_and_climate_change/items/order/creator**

Fires are local events, with regional scale characteristics, governed by global scale climate patterns. Fire functions in an interactive zone of the Earth's atmosphere and vegetated landscapes (fuels). Fire modifies the atmosphere and influences ecosystem structure and function. Fire has played this role in Earth history for ~ 420 million years. Climate varied and changed during that time, affecting ecosystems, fire and their interaction. As climate warmed from ice age conditions in the last 10,000 years, human influence from land use change, agriculture and industrialization has increased. Humans have modified fire regimes and are modifying climate. Fire history records how climate, humans and other factors have shaped fire regimes in the past and help us understand how changing climate may modify fire regimes in the future.

Climate in the 21st Century will differ significantly from the 20th Century climate under which modern fire management developed. The magnitude and speed of projected 21st Century change will strongly influence ecosystem characteristics and fire regimes. Observed climate change is already affecting fire. Continuing increases in greenhouse gas (GHG) emissions will accelerate climate change and fire impacts. Managers are required to include climate change in their fire planning and to include consequences of changing fire regimes in strategic natural resources planning. This synthesis report will help managers plan for fire under changing climate.

The available body of relevant information is expanding rapidly, in articles that directly address fire history and climate, and in the broader arenas of climate and ecosystem science that are necessary to support the fire context. More than 40% of the over 1,000 references cited in the bibliography that accompanies this report were published in 2010 and 2011. This flow of supporting science will continue to provide managers with an unprecedented volume of science to inform their decisions. Improved understanding of fire history under past variable and changing climate will in turn improve our planning for fire during 21st Century climate change.

While empirical measures of weather, ignition and fuels will change as climate changes, the fundamental fire combustion process will function largely as it has through Earth history. 21st Century climate change is modifying the envelope within which managers conduct fire business, but not the business itself. Fire regimes will change, fire seasons will be longer, peak season periods of heat and drought will amplify, fuel conditions and ignition patterns will change in varying ways. Perhaps of greatest impact, the role of fire will become even more important in natural resource management as climate change mitigation and adaptation responses count on the benefits of carbon sequestration and ecosystem resiliency that fire can rapidly alter.

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Chapter 1: Introduction

A century ago, in August 1910, fires burned more than 3 million acres in the northern Rocky Mountains of the United States and set the stage for fire management in the 20th Century (Egan 2009). Edward Beals (Beals 1914) reflecting on the August 1910 and other historic fires noted *"…Climate is defined as the sum of weather conditions affecting animal and plant life, and …climate in connection with forests may be considered…advance information about the weather [that] can be used to advantage in reducing fire losses in forested areas."* A few years before, in March 1908, the Swedish scientist Svante Arrhenius wrote: *"… any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°… The question, however, is whether any such temperature fluctuations have really been observed on the surface of the earth. The geologists would answer: yes*." (Arrhenius 1908 page 53). Arrhenius explained the now well-documented (IPCC WG I 2007) correlation between the greenhouse gas (GHG) carbon dioxide (CO_2) and temperature at the Earth's surface. At the time of the August 1910 "Big Burn", the atmospheric concentration of CO_2 was ~300 parts per million volume (ppmv) and it is now[1] more than 390 ppmv. As emissions from fossil fuel consumption and land use change continue to increase, current projections are that atmospheric CO_2 will reach 600 ppmv, double pre-industrial levels, by mid-21st Century. Carbon dioxide concentrations of ~ 900 to 1100 ppmv, approaching a four-fold increase, are expected by the end of the Century (Kiehl 2011). Changing climate is now setting the stage for fire management in the 21st Century.

Climate is the description of the average weather and its variability over a given time period, commonly 30 years. Climate in the 21st Century will differ significantly from 19th and 20th Century climate (IPCC WG I 2007). Observed 20th Century warming is highly correlated with increases in human-induced emissions of heat trapping GHG (IPCC WG I 2007). The first decade of the 21st Century, 2001 – 2010, was the warmest decade in the 130-year period of recorded global temperature (NOAA NCDC 2011). Nine of the 10 warmest years on record occurred in the period 2001 to 2010 (1998 was the other), with 2010 tied with 2005 as the warmest on record, with a global mean annual surface temperature (MAT) 1.34^{o}F warmer than the 30-year average MAT from 1951 to 1980 (NASA 2011). During the past 30 years, global surface temperatures have increased approximately 0.16^{o}C (0.29^{o}F) per decade. Since 1895, when records began for the contiguous United States, temperature has increased at an average rate of 0.12^{o}F per decade and precipitation by 0.18 inches per decade. 2010 was the 14th consecutive year with MAT above the long-term average (NOAA 2011). The expected 2°F to 10°F warming in the 21st Century will be considerably greater than the 1.5^{o}F observed increase in the 20th Century (Karl, Melillo, and Peterson 2009). CO_2, the most important GHG (Hofmann, Butler, and Tans 2009), showed growth in 2010, reaching a concentration of 390 ppmv by years end (NOAA ESRL 2011). Even if anthropogenic GHG emissions had been reduced to zero by 2010, inertia in the Earth system would result in continued warming through the 21st Century and beyond (Gillett et al. 2011). In reality, increases in atmospheric CO_2 continued accelerating in 2010.

[1] Updated CO_2 information may be accessed at http://www.esrl.noaa.gov/gmd/ccgg/trends/

Continued business-as-usual energy consumption will result in an atmospheric CO_2 concentration of ~1000 ppmv by 2100 (IPCC WG I 2007). The Earth last experienced 1000 ppmv CO_2 concentration ~ 35 million years ago (Ma) when the tropics were 5 to 10°C warmer and the polar regions 15 to 20°C warmer than present (Kiehl 2011). In the past, biomes changed when Earth experienced warmer temperatures and higher CO_2 concentrations (Salzmann, Haywood, and Lunt 2009), and fire regimes changed as climate and vegetation changed (Bowman et al. 2009). 21st Century fire regimes will likewise change as ecosystems experience to changing 21st Century climate (Flannigan et al. 2009; Krawchuk et al. 2009; Pechony and Shindell 2010).

Climate change is a statistically significant variation in the mean state of the climate or in its variability that persists for an extended period (typically decades or longer) (IPCC WG I 2007). Climate has changed over time scales of decades to millions of years during the Earth's history (Cronin 2009). Predictions of 21st Century Climate Change are based on projected GHG concentrations in the atmosphere that will result from past, present and future GHG emissions. Recorded atmospheric concentration of CO_2, the principal GHG, has increased by over 24% during the 50 years of active measurement (US Department of Commerce 2010) and an estimated 40% since 1750 (IPCC 2007). Global GHG emissions (CO_2 plus other GHG) due to human activities increased 70% between 1970 and 2004 (IPCC 2007). GHG emissions in the first decade of the 21st Century are tracking at the high end (most carbon intensive) of the range of emissions scenarios (Le Quéré et al. 2009), used by the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (AR4) issued in 2007 (IPCC WG I 2007). The various scenarios are based on different socioeconomic conditions and patterns of energy use (Nakicenovic and Swart 2000). Managers and planners need to be aware that current global GHG emissions and emissions trends will result in 21st Century warming that exceeds the temperature increases currently being considered by policy makers (Rogelj et al. 2010). As models have improved over time, the remaining uncertainty about the precise magnitude and timing of 21st Century climate change is largely due to uncertainty about future global GHG emissions (Anderson and Bows 2008).

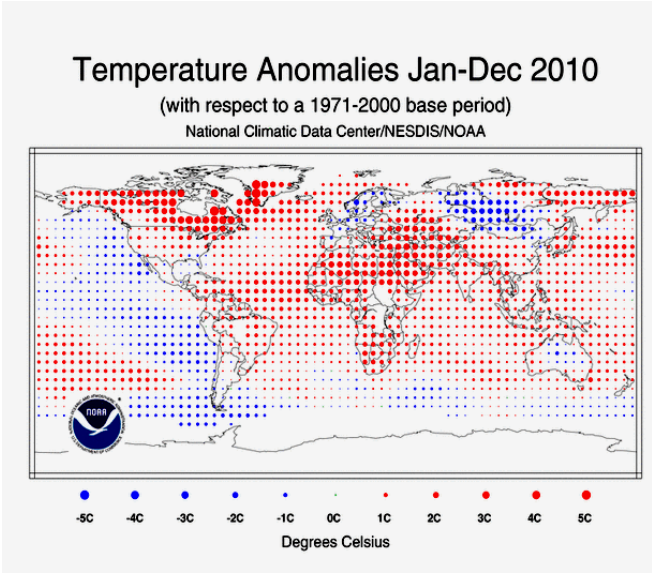

Figure 1.1: Source: NOAA http://www.noaanews.noaa.gov/stories2011/20110112_globalstats.html Last accessed July 12, 2011

Climate largely determines ecosystem differences, and ecosystems of different climates differ significantly (Bailey 2010). Projected climate change will strongly influence ecosystem characteristics and fire regimes (Flannigan et al. 2009). Land managers will need to plan and

manage for these changing conditions (Joyce et al. 2009; West et al. 2009; US Government Accountability Office 2007). Mitigation and adaptation are the common categories for planning and managing climate change responses (IPCC 2007). Mitigation involves actions to reduce the concentration of GHG in the atmosphere and adaptation involves actions that address minimizing the negative effects of climate change on ecosystems and societies. Changing fire regimes will affect both mitigation and adaptation, meaning land managers will be involved in both aspects of climate change response. For example, management that enhances the long-term retention of carbon in ecosystems and reduces fire emissions to the atmosphere will benefit mitigation (Hurteau, Koch, and Hungate 2008). Management that contributes to increased ecosystem resilience will benefit adaptation (National Academy of Science 2010).

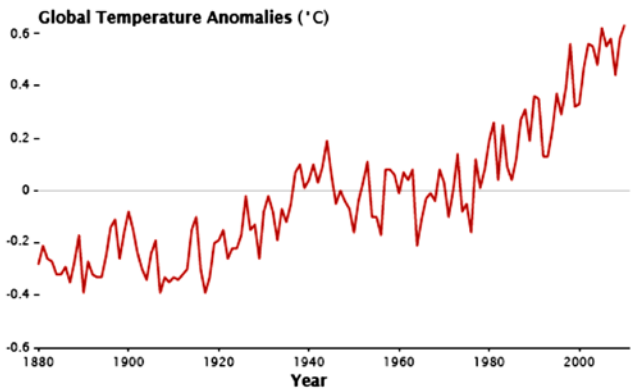

Figure 1.2: Global Temperature Anomalies 1880-2010. Source: NASA http://www.giss.nasa.gov/research/news/20110112/ Last accessed July 12, 2011

The Great Fire of 1910 burned 3 million acres of the recently created Bitterroot, Cabinet, Clearwater, Coeur d'Alene, Flathead, Kaniksu, Kootenai, Lewis and Clark, Lolo, and St. Joe national forests (Egan 2009). A two-day wind driven blow-up (August 20–21, 1910) killed 87 people, including 78 firefighters (Beals 1914). The three million acres burned rank the Great Fire of 1910 with previous large fires in 1825 in Maine and New Brunswick, 1871 in Wisconsin and Michigan and 1898 in South Carolina (National Interagency Fire Center). The importance of the 1910 Idaho and Montana burn on fire policy has been noted by several authors (Pyne 1982; Pyne 2001; Busenberg 2004; Stephens and Ruth 2005; Stephens and Sugihara 2006). The year 1910 is also a useful reference for discussing the converging paths of fire history and climate science. At that time, much of the wildland acreage of the United States had recently come under modern jurisdictions, with the establishment of the Forest Reserves (later National Forests) under the 1891 Forest Reserve Act, the 1897 Organic Act, and the 1911 Weeks Act. The role that atmospheric GHG concentrations played in warming our planet had been identified (Arrhenius 1908). By 1910, we had begun to practice both modern forest management with Pinchot and others in the United States and modern meteorology, including weekly forecasts issued by the U.S. Weather Bureau (Huffman 1977; Lorenz 2006; Pietruska 2011). Looking forward a century from 1910 we can see the impacts of demographic change and begin to witness the impacts of climate change on wildland fire management. Looking backward a century from 1910 we can see growing changes between the landscape traversed by the Lewis and Clark Voyage of Discovery and that burned in 1910 (Ambrose 1996). Looking forward two Centuries, climate will be significantly different from that experienced in the two Centuries since Lewis and Clark traversed the area of the Great Fire of 1910 (National Research Council 2010). Looking back two Centuries, and more, from 1910 we see the changes associated with European settlement of the United States, view fire in a pre-European dominated landscape and gain a sense of how our current landscape evolved under

climate and demographic change over the past ~12,000 years of the Holocene epoch (Delcourt and Delcourt 1997; Delcourt and Delcourt 1988).

The Great Fire of 1910, and the Palouser[2] wind that drove it, also produced scientific studies and human narratives on the mixture of climate, fuels, weather and fire that define Earth as a fire planet. *"It is the plan of this work to investigate ... climatic causes for forest fires ... in order to discover whether or not the last three years are usual or unusual..."* (Lennon 2000; Beals 1916; Koch 1978; Pyne 1990; Larsen and Delavan 1922). Those post-1910 studies were steps in the development of modern fire weather forecasting, fire behavior, fire effects, fire danger and many other technologies that form the basis of our understanding of fire in relation to weather. Science is now extending our 20th century understanding of the relationship of fire and weather into the realm of relationships between fire and climate variability, as exemplified by ENSO (El Nino-Southern Oscillation), and climate change (Crimmins 2006; Trouet et al. 2009; Thuiller 2007). Developing widely applicable ecosystem classification systems and relating them to fire regimes has greatly enhanced our ability to understand the interrelationships between climate, ecosystems and fire that are necessary for our ability to plan and manage for fire during 21st Century climate change (Holdridge 1947; Bailey 1985; Grossman et al. 1998; Lugo et al. 1999; Host et al. 1996; Brown and Smith 2000; Bailey 2006; Hostetler, Bartlein, and Holman 2006; US Government Accountability Office 2007).

Fire occurs in the vegetation that grows in the thin boundary layer where the Earth interacts with its atmosphere. Fire has been occurring and influencing Earth's ecosystems since at least 420 million years ago (Mya), when terrestrial vegetation arose and the Earth's atmosphere became sufficiently oxygenated for combustion to take place with the presence of lightning and other ignition sources (Bowman et al. 2009; Scott and Glasspool 2006). Fire has been a presence on Earth while climate varied and changed and humans rose to dominance to use and change the way fire influenced ecosystems. Fire has been a feature of the long interaction of atmosphere and vegetation that has modified atmospheric chemistry and produced a richly diverse mosaic of terrestrial vegetation (Marlon et al. 2009). Atmospheric oxygen concentrations of 15% or higher demarcate the times in geologic history when fire was present in the Earth's landscapes (Marynowski and Simoneit 2009). Fire played a critical role in human ascendancy and enabled humans to join climate as important ecosystem drivers (Pausas and Keeley 2009; Bowman et al. 2011). Human activities are also causing climate change, which will result in different climate in the 21st Century than experienced in the 19th and 20th Centuries (National Research Council 2010). Climate change will alter the geographic distribution of wildfire and lead to increased fire activity in many parts of the world (Krawchuk et al. 2009; Flannigan et al. 2009).

We follow this Introduction with eight chapters covering: the current status of climate change science; the importance of fire regimes for understanding climate change impacts; the interrelationships among ecosystems, climate and fuels; the importance of understanding variability, change, scale and pattern for interpreting climate-fire interaction; fire history and climate change from an ecosystem perspective; scientific progress we can expect in the upcoming decade; some recommendations for managers for using fire history to inform their decision making under 21st Century climate change, and concluding thoughts.

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[2] A strong, dangerous, katabatic wind that descends from the mountains into the Palouse River valley in northern Idaho and eastern Washington. http://www.superglossary.com/Definition/Weather/Palouser.html

Our approach to *Chapter 2: Climate Change – State of the Science* recognizes that an unprecedented volume of already synthesized information on climate change is readily available. After briefly relating the history of climate change science and available syntheses products, we discuss currently available synthesis documents, and provide information on how they can be accessed. As wildland ecosystems evolved under the influence of demographic and climate change during the Holocene, the frequency, intensity, seasonality, extent, and other characteristics of fire that define fire regimes (Agee 1996) have also changed. Fire regimes constitute a means for understanding and summarizing the many components of fire as they vary through time. The fire regime concept closely parallels how climatology constitutes a means for understanding and summarizing how the many components of weather vary though time. As such, understanding fire regimes becomes a critical link for understanding the relationship between fire history and climate. As climate changes during the 21st Century and beyond, fire regimes serve as a critical bridge for interpreting the impacts of climate change on ecosystems through the empirical extension of fire history information. For these reasons, we provide an overview of fire regime theory and literature in *Chapter 3: Fire Regimes*. We build on this foundation in *Chapter 4: Ecosystems, Climate and Fuels* to consider how climate has historically affected ecosystems and fuels in relation to climate to aid our understanding of the potential impacts of future climate change. We find that Bailey ecoregions are a particularly useful basis for understanding current ecosystem, climate and fuels and their historic development, as well as for linking fire history/climate change information to a large array of existing and expanding fire information sources such as, for example, LANDFIRE. Fire history is greatly enriched by an expanding array of paleoecological studies and information bases that portray the evolution of ecosystems and fire over time, and particularly during the past 12,000 years since North America emerged from the last glacial period of Earth history. Fire is a disturbance process that is integral to most ecosystems at various time and space scales (Levin 1992). In *Chapter 5: Variability, Change, Scale and Pattern*, we examine the importance of scale for understanding variability and change in both ecosystems and the atmosphere, and in their interaction. We specifically address *Fire-Atmosphere Interaction* in order to provide information at three specific "scales": Short (synoptic to seasonal), Intermediate (annual to interannual), and Long (decadal to centennial). In *Chapter 6: Fire History and Climate Change - The View from Ecosystems (East and West)* we provide a historical perspective of fire in the United States. That history derives from a variety of sources ranging from historical and anecdotal accounts through tree ring data and sediment cores. Fire history sources are not evenly distributed around the United States. Some areas have multiple sources of measurement data while others must rely more on written history. We expect that fire history will be most useful for contemplating climate change impacts when organized on an ecosystem basis. *Chapter 7: Scientific Progress Expected in the Next Decade* looks out to the science horizon, and a bit over, to point out areas of expected progress and emphasize areas of continuing uncertainty. In *Chapter 8: Recommendations for Managers* we provide some specific suggestions so managers can use both available and expected information about fire history and climate change to better understand potential fire regimes in the face of climate change, and use this information to help shape fire and fuel management decisions in the 21st Century. Chapter references for literature cited and five Appendices (A through E) follow the main body of the report. Appendix D provides additional links to expanded bibliographic information associated with this effort, including an online bibliographic database.

Chapter 2: Climate Change – State of the Science

The purpose of this chapter is to provide historical context for the current state of climate change science, with an emphasis on references to more recent journal articles, historically important scientific literature and major synthesis documents. A large, and rapidly growing, amount of scientific literature on climate change and an unprecedented collection of climate change syntheses are available for this purpose.

Science involves the systematic combination of what we know from observation and what we understand from analyses of those observations. We use what we know and understand about the past and the present as a basis for what we expect in the future. When we predict future events, there will always be an element of irreducible uncertainty (Stewart 2000). That uncertainty cannot be resolved until the event either occurs or does not occur at the predicted time. Since climate is not a single event but a statistical measure of a large ensemble of meteorological events, climate prediction involves statistical analyses that yield a range of potential climate outcomes (e.g. 2° to 11° C warming) that we expect for the future (Stainforth et al. 2005). Gains in climate change knowledge over the past few decades have substantially reduced the uncertainty of climate change projections and thus decreased the range of expected future climate outcomes (IPCC WG I 2007).

Basis for Climate Change Science

Three areas of knowledge form the basis for current climate change science. **First** is the instrumental record that includes surface meteorological conditions, available for ~140 years, and atmospheric Carbon Dioxide (CO_2) concentrations, available for ~50 years (Compo et al. 2011; Keeling et al. 1976). The instrumental record provides clear observational evidence of global greenhouse gas (GHG) and surface temperature increases and trends. The geographic and temporal coverage of instrumental observations has increased significantly since the mid-1950s, especially with the advent of satellite observing technologies. **Second** is the paleoclimate record of observations from tree rings, ice cores and several other techniques, which now provide a rapidly increasing body of knowledge that extend GHG and temperature observations backward in time and allow us to see how ecosystems evolved over the geologic history of the planet. CO_2 and CH_4 (methane) GHG concentrations have increased over the last several thousand years of the Holocene epoch (~10,000 years ago to present) (Ruddiman, Kutzbach, and Vavrus 2011). Earth has experienced significantly different GHG concentrations, climates, and fire regimes over the past 420 million years (Bowman et al. 2009). Our rapidly expanding paleoclimate knowledge base is perhaps the most useful component for increasing our understanding of fire history and climate change. The **third** area of knowledge involves our ability to explain how various forcing factors, including GHG growth, affect the coupled circulation and energy fluxes of Earth's atmosphere and oceans, called the General Circulation, to influence weather and climate. Our knowledge of the General Circulation allows us to combine instrumental and paleoclimate observations with other information sources to provide an integrated understanding of past climate, present climate, ongoing climate change and projections for additional climate change likely in the 21st Century and beyond. This is the realm of General Circulation Models (GCMs).

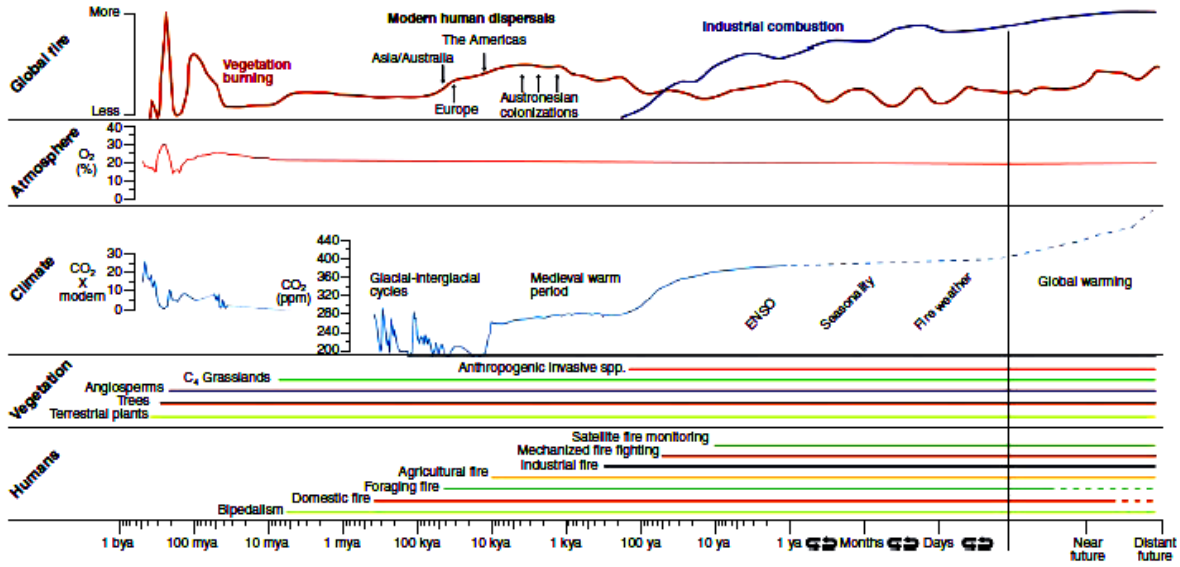

Figure 2.1: Global fire, climate and demographic history. Source: Bowman et al Science 2009

We understand and can numerically describe (model) the General Circulation of the Earth's atmosphere and oceans. General Circulation movements of the atmosphere (wind) and oceans (currents) are constantly redistributing heat received from the sun (solar radiation) and unevenly captured or reradiated by Earth. The General Circulation of the atmosphere determines all of the weather and climate variables (temperature, precipitation, wind, etc.) we experience. Major forcing factors determining the General Circulation and its variation are:

1) solar radiation -- generated, received and captured
2) orbital geometry of the Earth -- eccentricity, obliquity and axial precession
3) plate tectonics -- placement of continents and oceans and land surface height
4) albedo (reflectance due to vegetation cover, snow cover, etc.) of the land surface (includes Anthropogenic Land Cover Change (ALCC))
5) chemical and thermodynamic nature of our atmosphere and oceans (includes greenhouse gas (GHG) emissions and aerosols)

The first three forcing factors are stable over time scales of individual human lives, but have varied over geologic time scales[3] of Earth history. General Circulation forcing factors 1, 4 and 5 have varied over multiple time scales during both Earth history and human societal history (Kiehl 2011).

[3] Geologic time is divided in to Eons, Eras, Periods, Epochs, and Ages. Eons last half a billion years or more and Ages millions of years. We are currently in the Holocene Epoch, which began 11,700 years ago. See: http://en.wikipedia.org/wiki/Geologic_time_scale and http://en.wikipedia.org/wiki/Holocene (last accessed July 6, 2011)

The Sun is the source of energy that heats the Earth by absorption of incoming and reflected radiation (IPCC WG I 2007). Total solar irradiance (TSI) from the Sun is the Earth's dominant energy input, providing 10,000 (10^4) times more energy than any other source (Kopp and Lean 2011). There are only three ways to cause a lasting increase in the Earth's surface temperature (Pearson 2010):

1) increasing heat from the Sun (forcing factors 1 and 2 above)
2) reflecting less sunlight back into space (forcing factor 4 above)
3) trapping more heat in the atmosphere (forcing factor 5 above)

Radiative forcing, reported in Wm^{-2}, is a measure that allows comparison of variability in these three factors and comparison of their contribution to observed surface global temperature change (IPCC WG I 2001).

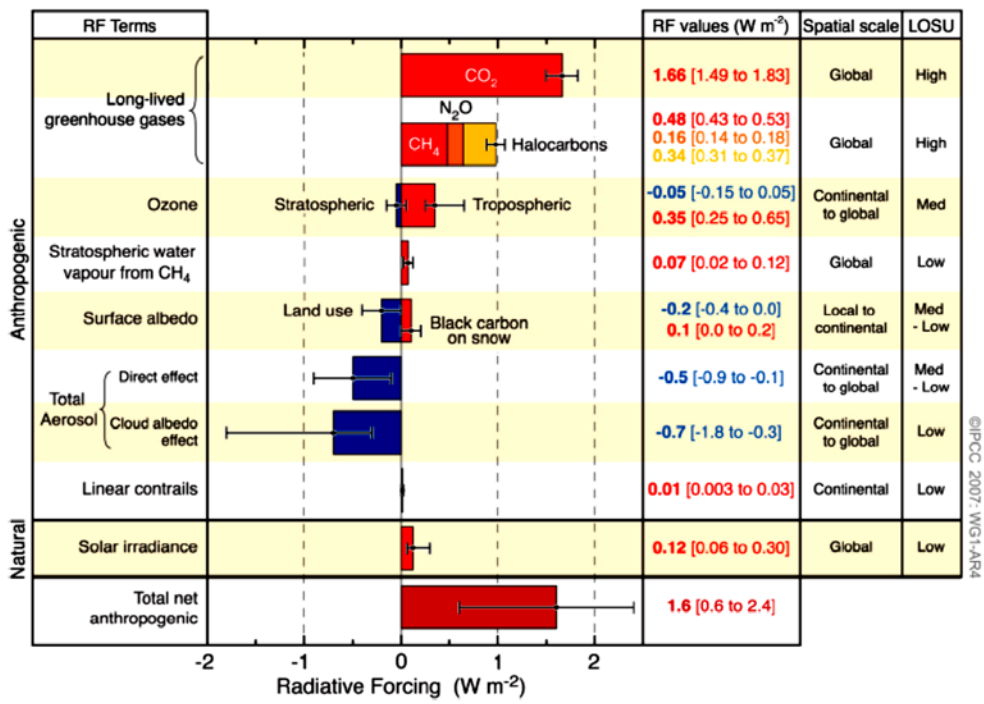

Figure 2.2: A comparison of the difference in radiative forcings from 1750 to 2005.
Source: IPCC, 2007, Figure SPM 2

Measured variability of incoming solar radiation over the 11-year maximum to minimum sunspot cycle is about 1 Wm^{-2}, with a measured 30 year drift of 0.017 Wm^{-2} $decade^{-1}$ that is associated with changes in energy from the sun (Gray et al. 2010). Solar forcing appears to have dominated long-term regional climate changes during the pre-industrial era (Shindell et al. 2003). Solar activity during the current sunspot minimum has fallen to levels unknown since the start of the 20th century, with solar activity expected to continue to decline in the years ahead, contributing to some regional winter cold periods within an overall warming climate (Lockwood et al. 2011).

Albedo-related radiative forcing changes due to anthropogenic vegetation changes (mainly conversion of forest to agriculture land use) from pre-agriculture times to present are now estimated as -0.09 Wm^{-2} (Myhre, Kvalevåg, and Schaaf 2005). In comparison, radiative forcing from trapping of heat by GHG is currently increasing at the rate of 0.30 Wm^{-2} $decade^{-1}$ (Hofmann, Butler, and Tans 2009), and has increased by about 2.7 Wm^{-2} since 1750 as measured by the Annual Greenhouse Gas Index (AGGI) (Hofmann et al. 2006). Variability in solar radiative forcing is therefore smaller than estimated radiative forcing due to changes in albedo (forcing factor 4 above) and much smaller than estimated radiative forcing from heat trapping GHG and aerosols (forcing factor 5 above). Albedo-related radiative forcing changes are inherently more regional in scale than those associated with solar variability and GHG (Pielke Sr. et al. 2002).

Past climate change occurring over millions (~10^5 to 10^7) of years has resulted from plate tectonics (forcing factor 3 above). Modern (Holocene epoch) biomes, and the climatic factors governing them, depend heavily on the distribution of oceans and landmasses, and the topography of those landmasses, all resulting from plate tectonics (Prentice and Webb III 1998; Prentice et al. 1992). Modern land distributions and mountain building began to be shaped with the breakup of the super continent Pangaea starting ~ 225 to 200 Mya during the transition from the Permian to the Triassic, and proceeded through the Jurassic (150 Mya) reaching a recognizably modern distribution in the Cretaceous (65 Mya), when a period of warmer temperatures began (Keating-Bitonti et al. 2011)[4]. Climatically driven, latitudinal dependent biogeographic provinces sorted terrestrial biota on Pangaea where topographic barriers were largely absent. Pangaean biogeographic provinces changed as biota migrated in response to ~ 20,000-year climate variations caused by cyclical variations in the Earth's orbit (Whiteside et al. 2011).

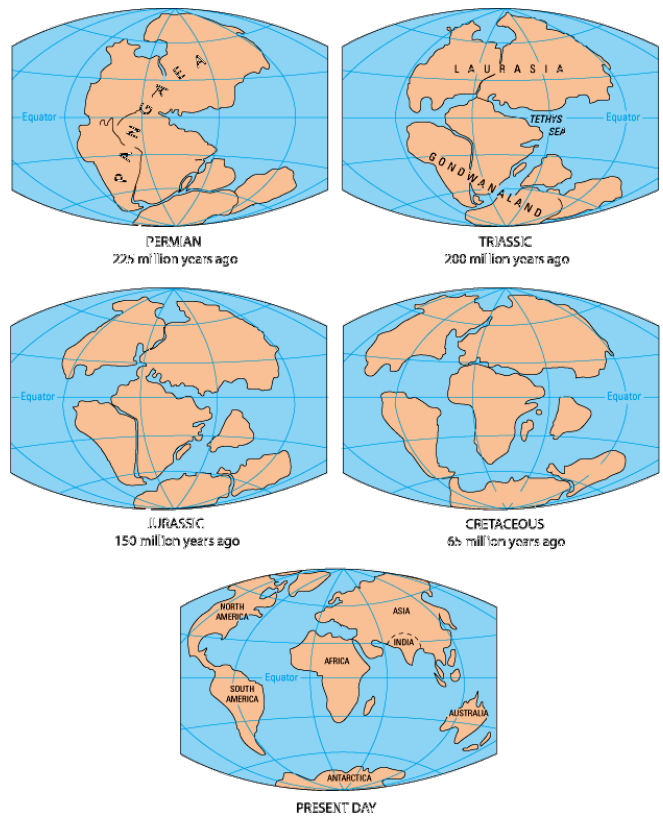

Figure 2.3: The supercontinent Pangaea began to break up about 225-200 million years ago, eventually fragmenting into the continents as we see them today. Source:USGS http://pubs.usgs.gov/gip/dynamic/historical.html

[4] For additional description of these changes, see http://pubs.usgs.gov/gip/dynamic/historical.html.

Earth Orbit Variability

The Earth rotates around an axis that tilts relative to the plane of its elliptical orbit around the Sun. These orbital factors give us our days, seasons, and annual climate cycles, and vary over long periods. Climate change occurring over tens to hundreds of thousands (10^4 to 10^5) years has resulted from quasi-periodic oscillations in the Earth's movement around the Sun (orbital parameters - forcing factor 2 above) (Zachos et al. 2001). The orbital *components* and their perturbation periods are[5]:

- *eccentricity* (400,000 and 100,000 years) - The shape of the Earth's orbit changes from a nearly perfect circle to an oval shape on a 100,000-year cycle
- *obliquity* (41,000 years) - Earth's axis is tilted, and the angle of the tilt varies between 22 and 24 degrees every 41,000 years
- *axial precession* (23,000 years) – gravity-induced slow change in the Earth's rotational axis relative to the Sun over the span of 19,000 to 23,000 years, observed as a movement of the equinoxes relative to fixed stars

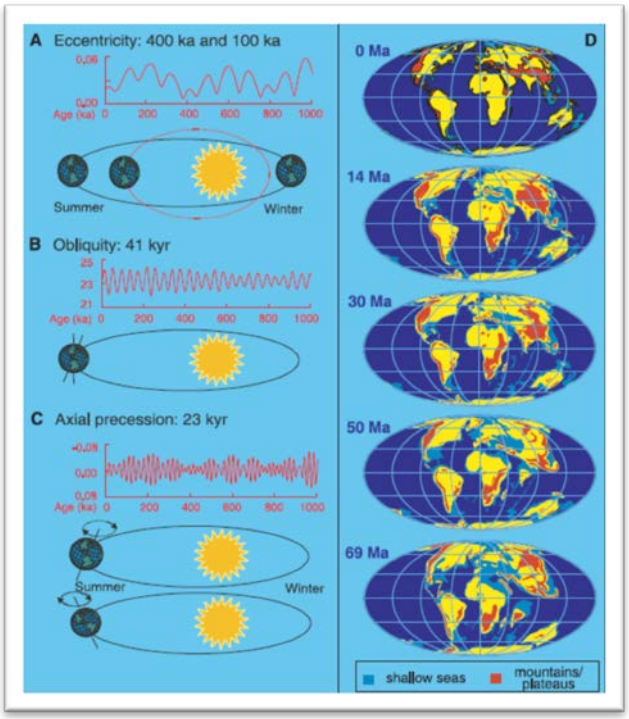

Figure 2.4: Plate tectonic and orbital forcing components

General Circulation Models (GCMs) accurately account for orbital variations (factor 2) and plate tectonics (factor 3), which are important factors needed to study the paleoclimatic record of Earth. The time scale of their variability means, however, that they are not important factors driving short-term 21st Century climate change. The important factors determining 21st Century climate change relate to natural events and anthropogenic causes acting via GHG, aerosol and albedo forcing factors, with a minor contribution related to variation of solar radiation. The amount of surface warming or cooling produced during a solar minimum to maximum cycle is 0.1°C, compared to warming produced by an ENSO (El Nino Southern Oscillation) event of 0.2°C and cooling following large volcanic events of ~0.3°C (Lean and Rind 2009). All of these natural events affect climate, often in a cyclical manner (warming then cooling), for a limited period. ENSO and other observed periodic patterns of ocean and atmosphere circulation, such as the North Atlantic Oscillation (NAO), are known to have significant influence on weather and short-term climate variability (Hurrell and van Loon 1997). ENSO type events have been associated with changes in fire patterns and are considered to be a potentially important feedback mechanism of climate change (Swetnam and Betancourt 1998; Beckage et al. 2003; Kitzberger et al. 2007; van der Werf et al.

[5] See http://earthobservatory.nasa.gov/Features/Paleoclimatology_Evidence/ for further detail

2008; Macias Fauria, Michaletz, and Johnson 2011; Jinbao Li et al. 2011; Wenhong Li et al. 2011). ENSO and similar events are features of the General Circulation that affect weather patterns from periods of weeks to several years, and lie in the computational zone between Numerical Weather Prediction (NWP) technologies that support daily weather forecasts and GCM technologies that provide long-term climate simulations. As discussed elsewhere in this synthesis, improvements in computational and observational capacity are expected to yield significant improvements in our ability to predict short-term climate variability caused by ENSO type patterns and close the coverage gap between NWP and GCM in the decade ahead (Keenlyside and Ba 2010; Meehl et al. 2009; Scroxton et al. 2011).

While it is important to understand the broad context under which long-term climate change occurs, our primary focus is on those General Circulation forcing factors that directly relate to the current rapid warming. Primary among these are anthropogenic emissions of GHG which are causing atmospheric warming at the rate of ~0.2°C per decade and this rate is accelerating (Easterling and Wehner 2009). Previous uncertainty about the relative importance of various contributors to the forcing factors has been reduced as a result of:

- improved accuracy of Total Solar Irradiance (TSI) monitoring from satellite systems (Kopp and Lean 2011),
- improved quantification of Anthropogenic Land Cover Change (ALCC)[6] emissions (Reick et al. 2010), and
- improved understanding of how atmospheric chemistry favors removal of non-CO_2 GHG but long term retention of CO_2 (Montzka et al. 2011).

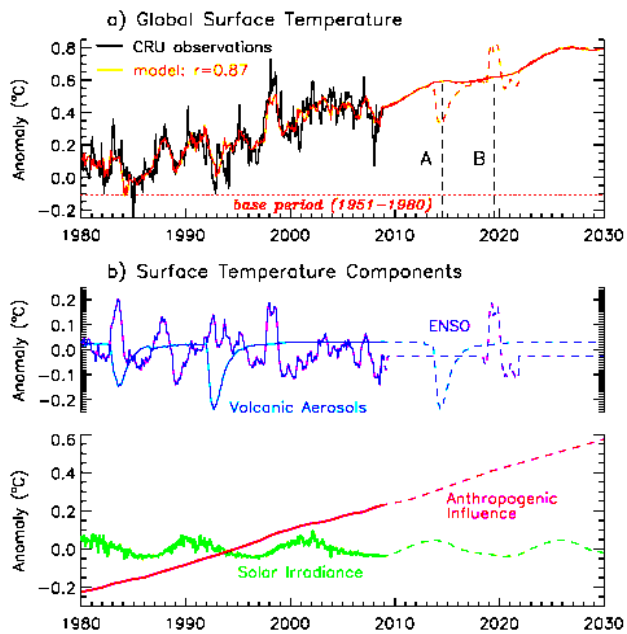

Figure 2.5: Comparison of natural and anthropogenic forcing function of the atmospheric General Circulation. Source: Lean and Rind 2009

Carbon Dioxide

The role of CO_2 as the dominant GHG and continuing primary cause forcing surface temperature increases is now clearly established (Lacis et al. 2010). The more variable impact of aerosols is gradually becoming better understood (Kaufmann et al. 2011; Solomon et al. 2011). The two main causes of anthropogenic GHG gas emissions over human history are anthropogenic land cover change (ALCC) and fossil fuel consumption (Kaplan et al. 2010). ALCC was the major

[6] Readers may be more familiar with the terminology Land Cover and Land Use Change (LCLUC), but we use ALCC here as due to its more common usage in cited studies describing long-term history of human induced changes in vegetative cover.

contributor of GHG emissions for most of human history through the early days of the industrial revolution. Current estimates are that tropical land-use change emissions, consisting of a gross tropical deforestation emission partially compensated by a sink in tropical forest regrowth, are more than offset elsewhere to yield an overall total forest sink of 2.4 ± 0.4 Pg C yr^{-1} globally for 1990–2007 (Pan et al. 2011). The influence of fossil fuel emissions became increasingly dominant from the beginning of large-scale industrialization (~ AD 1850) onward (Vitousek et al. 1997). The Earth will warm by 2^oC above pre-industrial temperature levels when a cumulative total of 3,670 Pg C[7] of anthropogenic CO_2 is emitted to the atmosphere, with about half of that amount already having been emitted since ~1750 when industrialization began (Allen et al. 2009). The growth rate of atmospheric CO_2 has increased from ~1 ppmv yr^{-1} prior to 1970 to more than ~2 ppmv yr^{-1} at present. Atmospheric CO_2 concentration is now increasing exponentially; it has been doubling every 30 years since about 1930 and on track to reach 560 ppmv (double pre-industrial levels) by 2050 (Hofmann, Butler, and Tans 2009). The exponential growth of CO_2 emissions driven by fossil fuel consumption, and the persistence of CO_2 in the atmosphere, cause it to be the main forcing factor for the 21st Century climate change (Solomon et al. 2010). CO_2, and other GHG, do not condense and precipitate from the atmosphere, while water vapor does. CO_2, and other noncondensing GHG, account for 25% of the total terrestrial greenhouse effect, and serve to provide the stable temperature structure that sustains current levels of atmospheric water vapor and clouds via feedback processes that account for the remaining 75% of the greenhouse effect. While CO_2 is not subject to removal from the atmosphere by chemical reactions, the other noncondensing GHG are. Methane (CH_4), the second most important anthropogenic influenced GHG, is subject to greater (and not fully explained) observed variability than CO_2 (Heimann 2011; Kai et al. 2011; Aydin et al. 2011). Without the radiative forcing supplied by CO_2 and the other noncondensing greenhouse gases, the terrestrial greenhouse would collapse (Lacis et al. 2010). CO_2 growth and persistence means we are committed to irreversible warming in the 21st Century, and for centuries beyond, with CO_2 likely to exceed 1,000 ppmv by 2100 (Gillett et al. 2011; Solomon et al. 2009).

Climate Change Prediction

Quantitative climate change prediction is based on our knowledge of atmospheric chemistry and atmospheric dynamics (motion). The roots of both of those aspects of modern atmospheric science date to the same era when the Big Burn of 1910 (Egan 2009) was shaping future fire management in the United States. Swedish scientist Svante Arrhenius combined his interests in atmospheric chemistry and cosmology to explain how water vapor and certain trace gases in the atmosphere acted like the glass panels in a greenhouse to warm our atmosphere and make Earth habitable, concluding that a doubling of CO_2 would cause a 4^oC increase in global surface temperature (Arrhenius 1908). Current estimates are that a doubling of CO_2 will result in a 2° C to 4.5^o C warming (IPCC 2007) which is likely to occur by the mid 21st Century (Betts et al. 2011). Observations of modern and past climates help us understand climate dynamics and provide a baseline for predicting future responses to GHG emissions (Zachos, Dickens, and Zeebe 2008). The current state of the science of climate dynamics, represented in GCM climate simulations (also called global climate models by some), built upon a practical need to better navigate by winds and currents at a time when wind power drove ocean commerce. Hadley, in 1735, "… *explained the trade winds and prevailing westerlies by noting that heating should*

[7] 1 Petagram (Pg) = 10^{12} (1 trillion) kg = 10^9 (1 billion) metric tons = 2,204.62 billion pounds

produce a direct meridional cell in each hemisphere. The equatorward current at low levels should be deflected by the Earth's rotation to become the trade winds." (Lorenz 1967). In the 275 years since Hadley described this theory, we have seen the industrial revolution replace wind and water power with fossil fuel power, human population expand exponentially and human enterprise continue to alter the albedo of the Earth's surface. As human society and ecosystems have co-evolved in the 10,000 years since the peak of the last glacial period, plate tectonic and orbital factors determining the General Circulation have remained relatively stable. Measured perturbations in received solar radiation have been minor. Effects of human activity, manifested as changes in atmosphere/ocean chemistry and in land cover, are the basis for attributing observed and expected future climate change to anthropogenic causes (Hegerl and Zwiers 2011; IPCC WG I 2007). Those changes are altering the thermodynamic drivers of the General Circulation. Science is increasingly able to quantify the causes and amount of thermodynamic alteration, and numerically describe (model) resulting and future changes of the circulation patterns of the atmosphere and oceans, which determine patterns of weather and climate. These are the two bases for quantitative climate change prediction. Thermodynamic forcing caused by past, present and future GHG emissions serves as input to the GCMs to describe future climate conditions.

NWP and GCM Development

Our understanding of atmospheric dynamics has grown from the early 20th Century work of Norwegian scientist Vilhelm Bjerknes and his colleagues at the Bergen (Norway) School, who developed the frontal model of extratropical cyclones that remains the centerpiece for today's public forecasts that ascribe daily weather conditions to the movement of pressure systems and fronts. Shortly after Arrhenius provided his greenhouse explanation, Bjerknes began applying mathematical equations governing the motions of the atmosphere that, if solved in real time, would advance weather forecasting (Gedzelman 1994; Lorenz 2006). Soon after, Lewis Richardson proposed how those three dimensional equations could be solved through time using numerical methods (Richardson 1922). Richardson's methods for Numerical Weather Prediction (NWP) had no practical application until modern digital computers became available after World War II. Weather forecasts were one of the first uses of the new digital computers starting in 1950 (Lorenz 2006). Those NWP methodologies are the basis of both current daily weather predictions and the General Circulation Models (GCMs) used for climate change forecasting (Phillips 1956). By the mid-1960s several groups were conducting general circulation model research, which developed the ancestors of GCMs used today (see Edwards (Edwards 2011) for a definitive history). NWP (weather forecasts) and GCMs (climate models) diverged during this period of development because of lack of sufficient computer capacity. As each advance in computing capacity became available, meteorologists focused on improving operational weather forecasts (out to 96 hours/4 days) and used additional computing capacity to increase spatial and temporal resolution of the computations to reduce forecast errors. The long-term nature of climate forecasting (30 years to centuries) required GCM scientists to parameterize many variables to gain the computational stability necessary for computer runs over long time periods required for climate modeling. GCMs remained more of research than operational or policy interest until observational evidence of increasing atmospheric CO_2 indicated to the research community that the potential for anthropogenic climate change was a serious possibility (Keeling et al. 1995).

The IPCC

The concern raised by scientists over the potential for substantial climate change from recorded increases in CO_2 led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by two United Nations Organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) (Revelle 1982). The purpose of the IPCC was to assess "*the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change*." (http://www.ipccfacts.org/history.html). In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted as the basis for a global response to the climate change problem with the goal of preventing "dangerous" human interference with the climate system (http://unfccc.int).

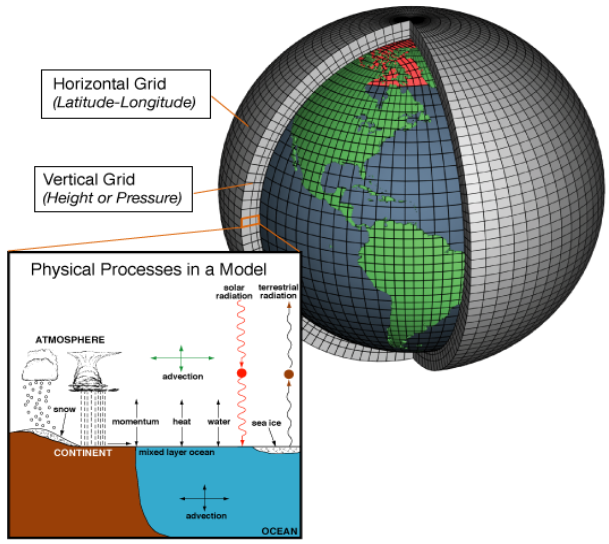

Figure 2.6: Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To "run" a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Source: NOAA http://celebrating200years.noaa.gov/breakthroughs/climate_model/modeling_schematic.html

The IPCC has been an essential sponsor of GCM development and improvement, in addition to issuing four comprehensive and authoritative assessment reports (AR)[8] and various additional reports in support of the UNFCCC process. While several individual laboratories in different countries continue development of their own GCMs, the IPCC through its continuing assessment process and supporting functions uses these various GCMs to support integrated GCM-based products. As models are improved, the outputs from many of the available individual GCMs used by IPCC have increasingly converged through the four assessment reports issued to date (IPCC WG I 2007), eliminating earlier concerns that the GCMs "did not agree". IPCC model comparison efforts are strongly supported by the Coupled Model Intercomparison Project (CMIP) organized by the World Climate Research Program (WCRP). This project integrates data from 23 models, run by 16 modeling groups, from 11 countries (Meehl et al. 2007).

[8] IPCC released the First Assessment Report (FAR) in 1990, the Second Assessment Report (SAR) in 1995, the Third Assessment Report (TAR) in 2001, and most recently, Assessment Report 4 (AR4) in 2007. AR5 is currently in development and de for publication in 2014 (http://www.ipcc.ch/activities/activities.htm)

GCMs

So how do GCMs actually work? They basically apply a system of equations (the Navier-Stokes equations[9]) that describe the motion of fluids in time and space. These analytical equations, along with equations and parameterizations that represent myriad physical processes, are translated into numerical models, which are then solved for a series of time steps at points (grid points) on a three-dimensional lattice that represents the Earth's atmosphere (Fig. 2.6). A typical modern GCM grid lattice using ~20 vertical levels and a horizontal grid point spacing of ~100 km models the atmosphere at 2.5 million grid points. At a typical time step of ~10 to 20 minutes, a one-year simulation requires processing data 27,000 times at each of the 2.5 million grid points. For climate simulations extending a century forward, extremely large and fast computer systems are necessary.

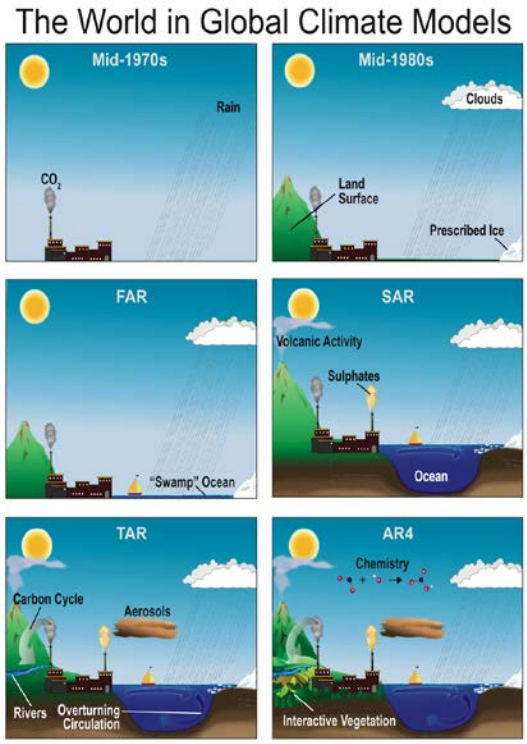

Figure 2.7: The complexity of climate models has increased. Source: Climate Change 2007: Working Group I: The Physical Science Basis http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-1-2.html

Supercomputer speeds have increased by a factor of over a million since the 1970s, enabling remarkable progression of GCM technology (Figs. 2.6 and 2.7). This progress has permitted a corresponding increase in model complexity (by including more and more components and processes), in the length of the simulations, and in spatial resolution (IPCC WG I 2007). As GCMs have added more Earth system components they are now, on occasion, called atmosphere-ocean general circulation models (AOGCMs) and, with inclusion of carbon cycle and other dynamics, Earth system models (ESMs) (Hibbard et al. 2007). We will retain the simple GCM terminology in this synthesis, unless we need to emphasize a specific point regarding model development. Each succeeding IPCC AR has relied on both higher resolution and more complete GCMs.

Several important processes that control climate sensitivity or abrupt climate change (e.g., clouds, vegetation, and oceanic convection) depend on very small spatial scales that, even with decades of computational advancement, are still treated by using simplified parameters to represent complex biophysical processes or with less than desirable resolution even within the most powerful GCMs. Likewise, GCM outputs do not approach the time and space scales of weather forecasts that fire and other land managers are accustomed to working with. Improvements are expected in the decades ahead (see Chapter 7 of this synthesis), particularly in

[9] The Navier–Stokes equations, named after Claude-Louis Navier and George Gabriel Stokes, describe the motion of fluid substances http://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations

shorter range (months to decadal time scales) climate simulations that will help those managers, and including more physical and biological processes in the actual computations (see Chapter 7 of this synthesis).

Longer term (beyond several decades) climate projections will not be as likely to improve because the greatest uncertainty in the use of GCMs for climate prediction does not derive from shortfalls of the models themselves, but from uncertainty in needed input to the models of future GHG emissions that are dependent on socio-economic and policy factors (Knutti et al. 2008). Climate science frequently refers to "business as usual" as the default emissions scenario, meaning no effective international treaty will come into affect that would mitigate GHG emissions expected from fossil fuel energy consumption associated with normal population growth and economic development. Although the IPCC is developing alternative approaches in support of CMIP modeling, it has relied on emissions scenarios to drive GCMs in all four assessments issued to date (Moss et al. 2010).

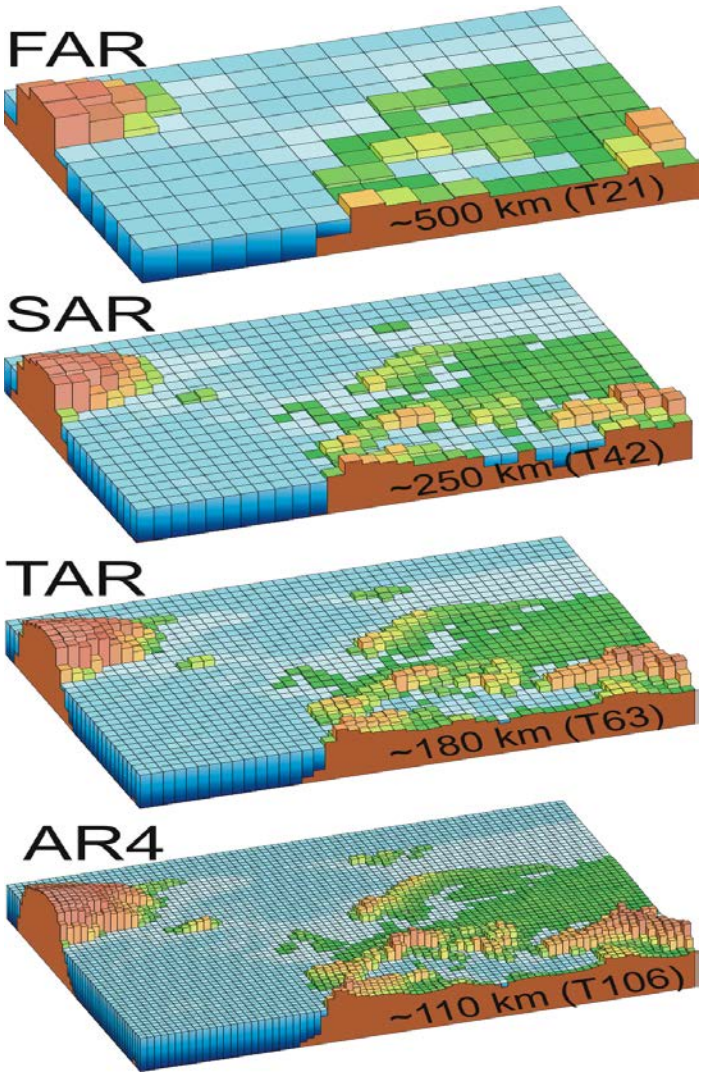

Figure 2.8: Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). Source: Climate Change 2007: Working Group I: The Physical Science Basis http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-1-2.html

Emissions Scenarios

The IPCC has used data from a study of emissions scenarios for future GHG emissions commonly referred to as SRES (Special Report on Emission Scenarios), to generate radiative forcing data for GCM input (Nakićenović and Swart 2000). The SRES scenarios incorporate a wide range of the main demographic, economic, and technological driving forces of GHG to produce 40 scenarios grouped under four storylines or "families". Four "families" or groups of scenarios (A1, A2, B1, and B2) represented low, high, low and medium population growth

respectively. Other characteristics used to define different scenarios were GDP growth, energy use, land-use change, resource availability, technological change and change of energy source. In practice, only a few of the 40 scenarios have been used because it was not practical to multiply the already huge computational load of GCM runs by 40. The SRES also did not include a "business as usual" or a "best guess" scenario. Business as usual is a terminology meant to indicate that economic, population and energy use growth take place driven solely by business dynamics and in the absence of carbon reducing technologies and/or policies. In the decade since SRES release, business as usual has been the norm and GHG emissions have systematically exceeded most of the SRES scenarios. SRES did identify 6 'marker scenarios' (A1FI, A1B, A1T, A2, B1 and B2), but practical computational costs and capacity resulted in IPCC AR4 consideration of only 3 of these scenarios (A1B (*A balanced emphasis on all energy sources*), A2 (*A world of independently operating, self-reliant nations, with continuously increasing population*) and B1 (*An emphasis on global solutions to economic, social and environmental stability*)) by all of the participating complex GCM modeling groups. The highest emissions scenario A1F1 (*fossil fuel intense*) was run only under simplified GCMs. The 'likely range' of warming for the B1, A1B and A2 scenarios is 1.6–5.9◦C relative to pre-industrial, and with the A1FI projection considered, the likely range extends to 6.9◦C relative to pre-industrial (Betts et al. 2011). The IPCC is preparing a new approach to providing emission inputs to the GCM runs in preparation for AR5 that should more accurately represent actual radiative forcing measures (Pitcher 2009). This new emissions estimation approach identifies radiative forcing characteristics to support CMIP GCM runs and brings a new term, Representative Concentration Pathways (RCPs), selected from the scientific literature (Moss et al. 2010). In 2010, global CO_2 emissions were 96% of those estimated by the A1F1 scenario, and concern remains that even the A1F1 scenario (the most carbon intense used by the IPCC) underestimates high-end 21st Century GHG concentrations. Recent GCM runs using carbon futures that enhance the A1F1 scenario by increasing population growth and fossil fuel consumption yielded 2100 global mean temperatures 0.5°C to 1.2°C greater than projected for the IPCC A1F1 scenario (Sanderson et al. 2011).

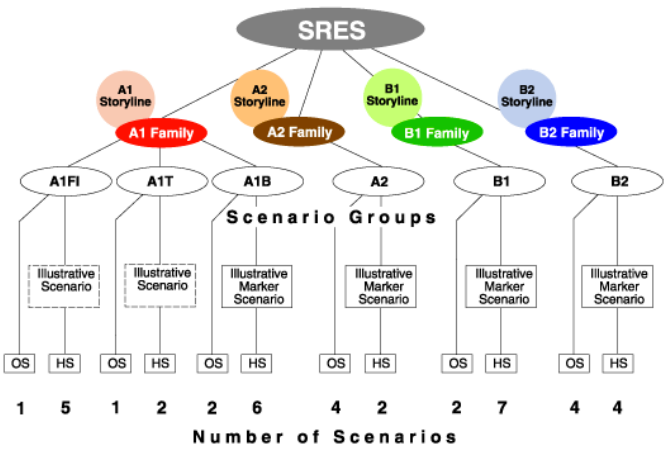

Figure 2.9: Schematic illustration of SRES scenarios. Four qualitative storylines yield four sets of scenarios called "families": A1, A2, B1, and B2. Altogether 40 SRES scenarios have been developed by six modeling teams. All are equally valid with no assigned probabilities of occurrence. The set of scenarios consists of six scenario groups drawn from the four families: one group each in A2, B1, B2, and three groups within the A1 family, characterizing alternative developments of energy technologies: A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel). Source: (Nakićenović and Swart 2000)

There are three approaches for predicting the future. One involves process models that use numerical solutions of physical equations and supporting input information to provide quantitative predictions of future conditions that may be entirely different from those existing at present or in the past. As discussed above, GCMs represent this approach. The second approach is to project current conditions unchanged into the future, or to, perhaps, extend current trends into the future allowing for some change from the present. The third approach uses knowledge and understanding of current and past conditions and processes to project what systems would look like in the future, when certain variables are expected to change. This empirical approach, heavily used in natural resource science and management, can be especially useful if there is sufficient information on a range of past conditions. A good example is using fire history information to inform how future fire regimes are likely to evolve as climate changes in the 21st Century. While not so much in the public eye as GCM technology, information relating paleoclimate and paleo-vegetation to fire regimes has grown tremendously over the past several years and now offers the opportunity to inform projections of future fire regimes.

Paleoclimate

We have to look back 35 million years to see the last time atmospheric CO_2 concentrations reached 1,000 ppmv (Kiehl 2011; Keating-Bitonti et al. 2011). Paleoclimate observations (tree rings, ice cores, sediment cores, pollen, and charcoal, for example) have now provided a good record of the climate history of Earth, especially during the Cenozoic Era, which began 65 Mya (Long et al. 1998). The modern distribution of our continents and oceans, the diversification of mammals and plants (including the evolution of grasses) and the geologically recent appearance of humans characterize the Cenozoic Era. Continuing climate change has also characterized the Cenozoic. Paleoclimate studies covering the Quaternary Period (1.8 Mya to today) and the Holocene Epoch (11,000 years ago to today – the time since the last glacial maximum) of the Cenozoic Era have greatly increased our understanding of how past changes in our atmosphere, oceans and land cover have related to changes in climate (Geological Society of London 2010).

Era	Period	Epoch	Began (Ma)
Cenozoic	**Quaternary**	**Holocene**	**.01**
		Pleistocene	1.8
		Pliocene	5.3
		Miocene	23
		Oligocene	34
		Eocene	54
	Tertiary	Paleocene	65
Mesozoic	Cretaceous		145
	Jurassic		200
	Triassic		251
Paleozoic	Permian		299
	Carboniferous		359
	Devonian		416
	Silurian		443
	Ordovician		488
	Cambrian		542

Figure 2.10: Geological timescale
Source: adapted from Pausas and Keeley, 2009

During the Cenozoic Era, the Earth's climate has experienced the warm extreme of ice-free poles and the cold extreme of continental ice sheets and polar ice caps. Our current ecosystems and human civilization have co-evolved during the Holocene Epoch. This period has seen increasing human impacts on climate change through ALCC and fossil fuel GHG emissions. From 8000 years ago to the start of the industrial revolution (circa AD 1750), atmospheric CO_2 increased by ~22 ppmv (Ruddiman

2007). Inefficient agriculture and growing human populations led to extensive clearing of forestland by fire, with associated increases in atmospheric GHG concentration (Springer et al. 2010; Bowman and Haberle 2010; McWethy et al. 2010).

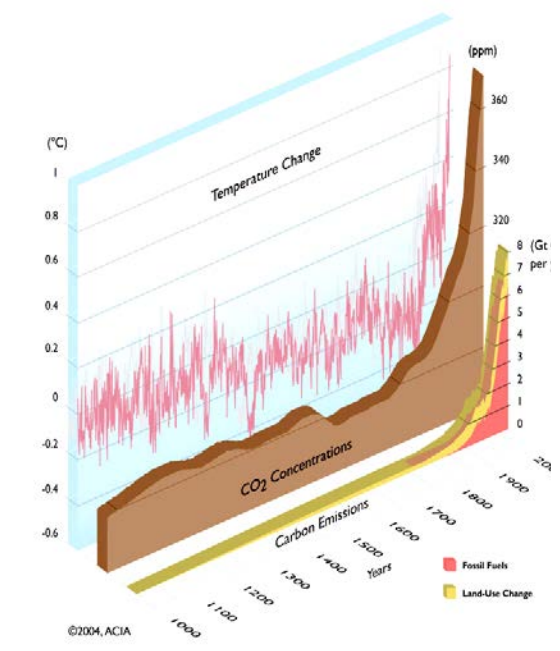

Figure 2.11: This 1,000-year record tracks the rise of carbon emissions due to human activities (fossil fuel burning and land clearing) and subsequent increase in atmospheric carbon dioxide concentrations, and air temperatures. Source: AC IA 2005

Increases in agricultural efficiency and a large decrease in per capita land use followed (Kaplan et al. 2010). Exponential population growth began ~ AD 1500, continuing until present. Events that decreased population locally or regionally, such as the European conquest of the Americas with accompanying fire reduction and reforestation (Nevle and Bird 2008), are reflected in ice core CO_2 records (Faust et al. 2006), but those and other local emission reductions were offset by increased emissions in other parts of the world (Pongratz et al. 2011). Paleoclimate records are also helping to explain historical susceptibility of human societies to climate variability as regional and seasonal manifestations of climate change (Büntgen et al. 2011; Hegerl et al. 2011). By AD 1850, ALCC during the Holocene had produced an increase in atmospheric CO_2 of ~ 25 ppmv (Kaplan et al. 2010). Western hemisphere ALCC is likely the main driver of a steep increase in atmospheric CO_2 between AD 1750 and 1850 (Reick et al. 2010). Fossil fuel emissions gained significance after 1850 and are now responsible for a rapidly growing 84% of global GHG emissions, with ALCC responsible for the remaining 16% (Raupach et al. 2007). Current projections are for CO_2 to increase from the current level of 390 ppmv to reach atmospheric concentrations of ~ 900 to 1100 ppmv by the end of the 21st Century (IPCC WG I 2007). The last time Earth experienced ~1000 ppmv CO_2 levels was 35 Mya when paleogeography did not differ much from current alignments and solar radiation was ~0.4% less than today. At that time of the Cenozoic mean annual temperatures were 5° to 10°C warmer in the tropics and 15° to 20°C warmer at the poles than they are today (Kiehl 2011). While anthropogenic GHG increases, and associated surface warming, have occurred throughout the Holocene, the current rate of increase is unprecedented.

Measurements of CO_2 concentrations in air trapped in ice cores show a strong correlation between changes in atmospheric CO_2 (and methane) concentrations and changes in surface temperature for the past 420,000 years (Petit et al. 1999). A comparison of CO_2 from ice cores and surface temperatures with estimated and measured carbon emissions shows more short-term variability in the temperature record compared to the smoother CO_2 and carbon curves. The ice core data show that CO_2 concentrations at some times in the past were higher than pre-industrial

levels. Nonetheless, the long-term changes in CO_2, carbon emissions and temperature correlate well and the rates of increase in all these variables since the mid-1800s are unprecedented.

Deeper drilling of ice cores is providing longer periods of record and improved analysis techniques are providing higher resolution and measures of more atmospheric variables trapped in the air bubble and ice cores. Ice core data are producing increasingly more detailed evidence of past abrupt climate change events, adding significantly to our knowledge of climate variability and change during the Holocene (Steffensen et al. 2008). Ice core contents of various atmospheric trace gases and other variables, such as soot and pollen, are used to explore past fire events and fire regime changes such as those that occurred during the Younger Dryas climate event of ~8,000 years ago (Alley et al. 1997). We apply this understanding of the importance of past interactions between CO_2 and climate to the rapidly expanding record of paleoclimate measurements that quantify the Earth's past climate, including information of varying fire regimes in relation to past climate (Bijl et al. 2010; Bowman et al. 2009). While ice core data are a critical source for our increasingly detailed descriptions of past climate, other paleoclimate approaches have added more significantly to our specific understanding of the relationship of past fire regimes to climate. Of particular importance to understanding past fire in relation to climate are techniques that employ tree ring widths (dendrochronology) and fire scars (Swetnam 1993), sediment cores (Brunelle and Whitlock 2003), pollen (Delcourt et al. 1998) and charcoal (fusain) studies (Whitlock and Larsen 2001). Because these studies are typically based on samples from one or a few sites, they have tended to be site specific, but syntheses of data from different investigators and research groups are providing increasing information at regional through global scales (Enache and Cumming 2009; Swetnam and Anderson 2008; Marlon et al. 2008). Our knowledge of fire during the last ~500 years in certain regions (such as the western United States) has been greatly enhanced by findings showing regional fire histories based on fire scar tree ring data (Brown et al. 2008; Heyerdahl, Morgan, and Riser II 2008; Sherriff and Veblen 2008). Charcoal studies, extend our record of direct fire evidence back many millennia, with developing regional and global coverage (Crickmay 1935; Scott 1989; Enache and Cumming 2009; Power et al. 2008). A very useful, but still not complete, source for paleoclimatological data sets is World Data Center for Paleoclimatology (http://www.ncdc.noaa.gov/paleo/paleo.html) maintained by

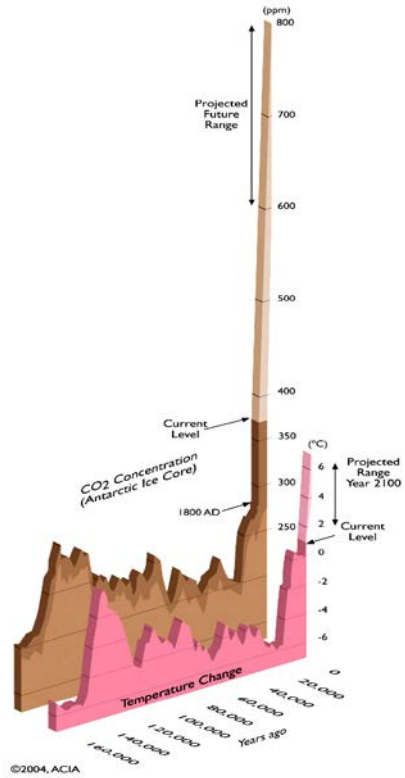

Figure 2.12: This record illustrates the relationship between temperature and atmospheric carbon dioxide concentrations over the past 160,000 years and next 100 years. Source: ACIA 2005

NOAA. Paleoclimate studies affirm the strong correlations, and feed-backs between fire and atmosphere and vegetation conditions. This is consistent with our understanding of current fire regimes and fire-atmosphere interactions (Harrison, Marlon, and Bartlein 2010). These studies show that fire has been prevalent since the atmosphere became sufficiently oxygenated (13% to 35%) to support combustion and there was fuel to burn (Scott and Glasspool 2006; Belcher et al. 2010). Fire has been a major factor in GHG emissions for the last 420 million years (My) of Earth history (Pausas and Keeley 2009). Paleoclimate studies show that fire in turn influenced atmospheric CO_2 prior to the rise of humans and increasingly during the Holocene with human use of fire a principal tool for ALCC (Grasby, Sanei, and Beauchamp 2011; Marlon et al. 2008). Fire associated with ALCC forest clearing is considered a main cause of GHG emissions through most of recorded human history, while others considered climate the other important driver of fire (Michael Williams 2008; Pechony and Shindell 2010). There is a rich and growing library of paleoclimate-based information that help us understand fire history and fire regimes in relation to varying atmospheric CO_2 concentrations, including levels were last at levels being experienced in the 21st Century.

Instrumental Record

The instrumental record that informs current climate change science is well described elsewhere (IPCC WG I 2001) and is being continually augmented (NOAA NCDC @ http://www.ncdc.noaa.gov/oa/ncdc.html, CDIAC @ http://cdiac.ornl.gov/, NASA GISS @ http://data.giss.nasa.gov/gistemp/), so will be only briefly covered here. Instruments have measured temperatures at the surface of the Earth for over 130 years. Observed temperatures have increased 0.8^{o} C globally since 1880 (IPCC WG I 2007), with two-thirds of the warming occurring since 1975, at a rate of ~0.15-0.20°C per decade (http://earthobservatory.nasa.gov). Seven of the eight warmest years since 1880 have occurred since 2001 and the 10 warmest years have all occurred since 1995 (NOAA NCDC http://www.ncdc.noaa.gov), with 2010 approaching or equaling the 2005 record (Hansen et al. 2010). Methodology concerns with earlier reporting (Hansen et al. 1981) have been resolved (Thorne et al. 2011). Global surface temperatures have risen at an increasing rate over the last two decades, with temperatures in the United States increasing by a comparable amount (Karl, Melillo, and Peterson 2009). The 2009 Copenhagen Accord (http://unfccc.int/) agreed that to avoid "harmful" warming '*the increase in global temperature should be below 2 degrees Celsius…with an intent to consider a lower 1.5◦C target in 2015*' (New et al. 2011). A comprehensive reanalysis of the historical instrumental meteorological records is now available in numeric and map based formats for all global weather events from 1871 to the present day, and from the earth's surface to the jet stream level (Compo et al. 2011).

Carbon dioxide (CO_2) is the leading GHG and its current atmospheric concentration of ~390 ppmv (http://www.esrl.noaa.gov/gmd/ccgg/trends/) is higher than it has been in at least 800,000 years (National Research Council 2010). The importance of the concentration of CO_2 in the atmosphere, and the suspicion that global fossil fuel consumption was affecting that concentration, lead to the establishment of a long term monitoring program for atmospheric CO_2 at Mauna Loa Observatory in Hawaii in 1957 (Keeling 1973). At the beginning of the 20th Century, Arrhenius noted that global coal combustion (then the major source of GHG emissions) had reached about 900 million tons and he estimated that it would take about 3,000 years for atmospheric CO_2 concentration to double (Arrhenius 1908).

Growth in global fossil fuel use by the middle of the 20th Century lead Charles Keeling to estimate CO_2 emission values from 1800 to 1969, and conclude that atmospheric CO_2 concentrations had increased by 18% over the projections of Arrhenius (Keeling 1973). Based on the long-term record at the Mauna Loa observatory in Hawaii, annual average CO_2 concentration rose by 3.4% between 1959 and 1971 (Keeling et al. 1976). More recent Mauna Loa CO_2 measurements[10] show that atmospheric CO_2 concentration rose from 315.98 ppmv (parts per million volume) in 1959 to 387.50 ppmv in 2009, a 22.6% increase in 50 years and an increase of 45% over levels estimated for 1800. In the years since the Mauna Loa observations began climate change science has established an unequivocal relationship between atmospheric CO_2 and global temperature throughout Earth history (Solomon et al. 2009). Successive international scientific assessments (IPCC 2007) have, with increasing certainty, attributed ongoing global warming to anthropogenic forcing caused by emission of GHG, principally CO_2.

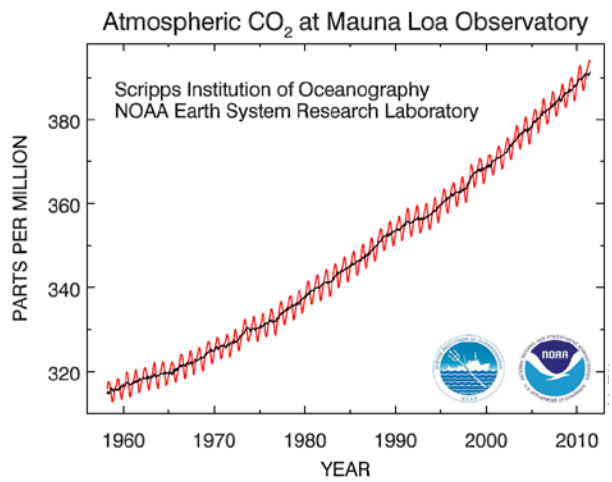

Figure 2.13: Monthly mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii. The carbon dioxide data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. They were started Scripps Institution of Oceanography in March of 1958 at a NOAA facility. NOAA started its own CO_2 measurements in May of 1974, and they have run in parallel with those made by Scripps since then. The black curve represents the seasonally corrected data. Source: http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html#mlo_full

21st Century Climate

Since the exceptional atmospheric persistence of CO_2 means that irreversible warming for more than 1,000 years is nearly certain (Solomon et al. 2010), the cumulative emissions of CO_2 are of paramount importance (Bowerman et al. 2011). Because CO_2 is so long lived in the atmosphere compared to non-CO_2 GHG and aerosols, an immediate cessation of anthropogenic emissions, followed by washing of aerosols out of the atmosphere, would result in an immediate upward spurt in global surface temperatures resulting from a rapid dimunition of aerosol cooling relative to GHG warming effects (Armour and Roe 2011). Changes in the heat trapping capacity of the Earth's atmosphere have been closely associated with changes in surface temperatures during the past 400 years and throughout much of earth's history (Mann, Bradley, and Hughes 1998; Petit et al. 1999; Joos and Spahni 2008). For example, a 4° C to 6° C global warming took place over a 400,000-year period about 40 Mya. This coincided with a doubling of atmospheric CO_2 (Bijl et al. 2010). With continuation of current emissions we will experience a similar CO_2 doubling and 4° C warming this Century after ~ 300 years.

[10] ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt

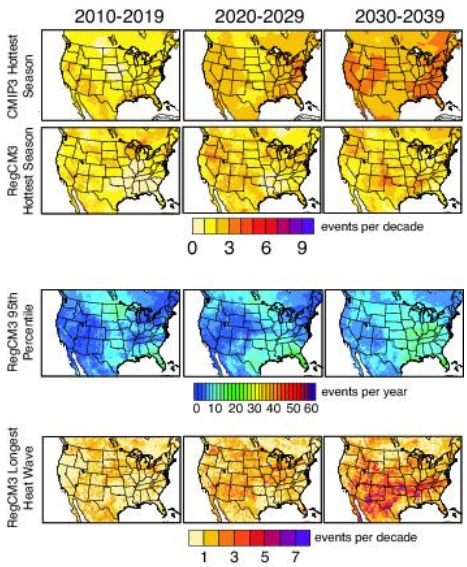

Figure 2.14a: Projected changes in heat extremes in the coming decades. The top two rows show the decadal occurrence of the 1951–1999 hottest-season threshold in the CMIP3 and RegCM3 ensembles. The third and fourth rows show the decadal occurrence of the 95th-percentile daily maximum threshold and the historical hottest heat wave threshold for the RegCM3 ensemble. Source: (Diffenbaugh and Ashfaq 2010)

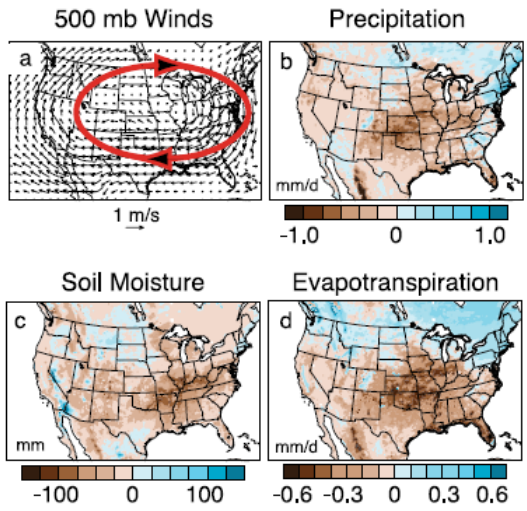

Figure 214b: Changes in summer (a) 500 mb winds, (b) precipitation, (c) total soil moisture, and (d) evapotranspiration in the RegCM3 ensemble. Changes are calculated as 2030–2039 minus 1980–1999 for June-July-August. The ellipse and large arrows in upper left Figure are added for emphasis.
Source: (Diffenbaugh and Ashfaq 2010)

The average mean annual temperature at the Earth's surface was 14°C (57°F) in the 20th Century (http://www.ncdc.noaa.gov/cmb-faq/). The instrumental record shows that 20th century, atmospheric carbon dioxide increased more than an order of magnitude faster than any sustained change during the past 22,000 years (Joos and Spahni 2008). Atmospheric carbon dioxide is the "principal control knob" governing our Earth's temperature, and its accelerating atmospheric concentration increase over the first decade of the 21st Century correlates with measured increases of global surface temperature and increasingly with measured climate related changes in fire regimes in the United States (Lacis et al. 2010; Westerling et al. 2006).

GCM outputs are continually improving in terms of resolution and completeness of process inclusion. In the opening of this chapter, we directed the reader to the IPCC AR4 and other scientific consensus reports for more in depth coverage of climate change science and the model outputs available. Now to illustrate the type of information available, we show some model results for the United States that focus on summer heat and drought, variables shown to be of importance to fire (Heyerdahl et al. 2008). Drier conditions existed over the central United States and northern Rockies during the mid-Holocene (~ 8,000 to 3,000 years ago). These

periods were dominated by changes in large-scale atmospheric processes, such as enhanced anti-cyclonic circulation aloft over mid-continent, attributed to insolation[11] forcing and insolation-induced changes in sea surface temperature (Diffenbaugh et al. 2006). Recent studies indicate a similar shift towards more anti-cyclonic atmospheric circulation over the United States during the warm season with resultant intensification of hot extremes (Diffenbaugh and Ashfaq 2010). A permanent 21st Century heat regime shift, in which the coolest warm-season of the 21st century is hotter than the hottest warm-season of the late 20th century, is increasingly likely (Diffenbaugh and Scherer 2011). Figures 2.14 a, b illustrate this potential.

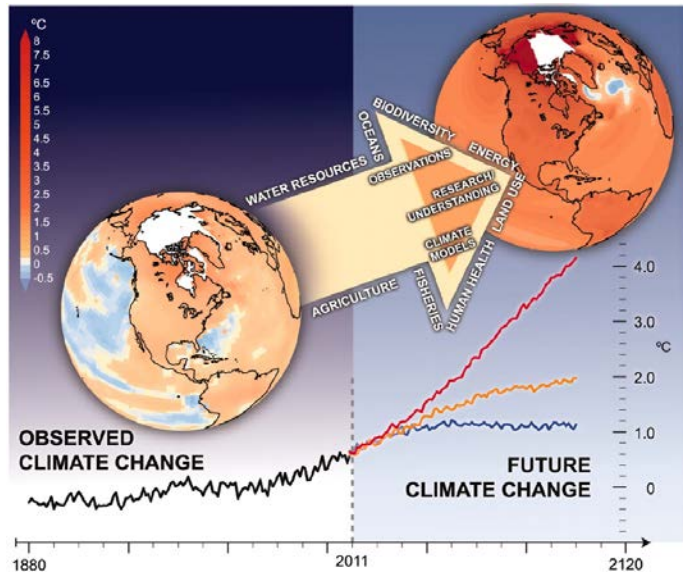

Figure 2.15: Climate data from observations and climate model simulations are critical for understanding the past and predicting the future. Source: J T Overpeck et al. Science 2011; 331:700-702 Published by AAAS

Climate Information Growth

While we have emphasized the enormous growth of climate change science by focusing on instrumental, paleoclimate and model supported knowledge; we may be hiding a fundamental facet of the state of climate change science by our focus on the "trees" rather than the "forest". The volume of worldwide climate data is expanding rapidly and becoming directly available to a wide user community that goes far beyond climate science specialists (Overpeck et al. 2011). Major growth in model and remote sensing (satellite) data will greatly supplement in situ (observational) data over the next 30 years. Data volume is expected to expand from the Terabyte (1 Tb = 10^{12} Bytes) to the Petabyte (1 Pb = 10^{15} (2^{50})

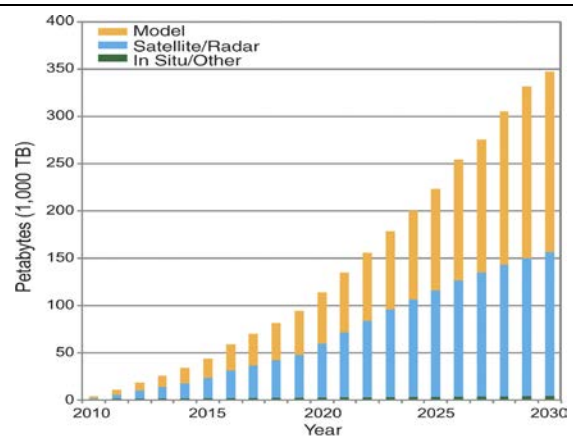

Figure 2.16: The volume of worldwide climate data is expanding rapidly, creating challenges for both physical archiving and sharing, as well as for ease of access and finding what's needed, particularly if you are not a climate scientist. Source: J T Overpeck et al. Science 2011;331:700-

[11] Insolation is a measure of solar radiation energy received on a given surface area in a given time. http://en.wikipedia.org/wiki/Insolation

Bytes) range, specifically from ~ 1 Pb to 350 Pb, compared to the Gigabyte (1 Gb = 10^9 (2^{30}) Bytes) volumes we are used to commonly deal with. These data must meet the needs of a wide range of users (including those concerned with fire) and be useful for purposes beyond traditional climate change science (or within a significantly enlarged concept of what is included in climate change science). *"… two major challenges for climate science revolve around data: ensuring that the ever expanding volumes of data are easily and freely available to enable new scientific research, and making sure that these data and the results that depend on them are useful to and understandable by a broad interdisciplinary audience*." (Overpeck et al. 2011). Meeting those challenges will enable us to apply our knowledge, based on observation, understanding and modeling of past and present climate, to help us understand fire history and fire regimes, and to shape fire and fuel management decisions in the face of 21st Century climate change.

Further Reading

The reader seeking a more comprehensive understanding of the development of climate change science over the last few decades should begin by accessing:

- Assessment (4) reports issued to date by the Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/),
- Synthesis and Assessment Products (21) issued to date by the United States Global Change Research Program (USGCRP; http://www.usgcrp.gov/usgcrp/default.php)
- America's Climate Choices publications series issued by the National Research Council of the National Academies (NRC; http://americasclimatechoices.org/).
- State of the climate in 2010. The *State of the Climate* report is peer-reviewed and published annually as a special supplement to the Bulletin of the American Meteorological Society (BAMS). (BAMS; http://www.ncdc.noaa.gov/bams-state-of-the-climate/2010.php)

IPCC AR4 WGI
Frequently Asked Questions

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) Working Group I (WGI) Report "The Physical Science Basis" (IPCC WG I 2007) is the most useful, currently available, comprehensive reference for the state of the science of climate change. The Report extracts information from its 11 component Chapters to provide a Frequently Asked Questions section that serves as an excellent source for understanding the basics of climate science. The 19 questions are listed below, and the complete answers to them can be found by clicking **HERE**.

What Factors Determine Earth's Climate?
What is the Relationship between Climate Change and Weather?
What is the Greenhouse Effect?
How do Human Activities Contribute to Climate Change and How do They Compare with Natural Influences?
How are Temperatures on Earth Changing?
How is Precipitation Changing?
Has there been a Change in Extreme Events like Heat Waves, Droughts, Floods and Hurricanes?
Is the Amount of Snow and Ice on the Earth Decreasing?
Is Sea Level Rising?
What Caused the Ice Ages and Other Important Climate Changes Before the Industrial Era?
Is the Current Climate Change Unusual Compared to Earlier Changes in Earth's History?
Are the Increases in Atmospheric Carbon Dioxide and Other Greenhouse Gases During the Industrial Era Caused by Human Activities?
How Reliable Are the Models Used to Make Projections of Future Climate Change?
Can Individual Extreme Events be Explained by Greenhouse Warming?
Can the Warming of the 20th Century be Explained by Natural Variability?
Are Extreme Events, Like Heat Waves, Droughts or Floods, Expected to Change as the Earth's Climate Changes?
How likely are Major or Abrupt Climate Changes, such as Loss of Ice Sheets or Changes in Global Ocean Circulation?
If Emissions of Greenhouse Gases are Reduced, How Quickly do Their Concentrations in the Atmosphere Decrease?
Do Projected Changes in Climate Vary from Region to Region?

Chapter 3: Fire Regimes

Fire regimes are a critical foundation for understanding and describing effects of changing climate on fire patterns and characterizing their combined impacts on vegetation and the carbon cycle (Grissino Mayer and Swetnam 2000; Clark 1988; Schoennagel, Veblen, and Romme 2004; Pechony and Shindell 2010). In general a fire regime characterizes the spatial and temporal patterns and ecosystem impacts of fire on the landscape (Bradstock, Williams, and Gill 2002; Morgan et al. 2001; Brown and Smith 2000; Keeley et al. 2009). The two most important factors for determining fire regimes are vegetation type (or ecosystem) and weather and climate patterns. Fire history provides evidence of past relationships between fire and climate. That evidence makes it clear that changing climate will profoundly affect the frequency and severity of fires in many regions and ecosystems in response to factors such as earlier snowmelt and more severe or prolonged droughts (Westerling et al. 2006; Bowman et al. 2009; Flannigan et al. 2009; Littell et al. 2009; Morgan, Heyerdahl, and Gibson 2008; Kitzberger et al. 2007). Changing climate will alter the growth and vigor of existing vegetation, with resulting changes in fuel structure and dead fuel loads.

General Concepts of Fire Regimes

Fires in wildland vegetation display a range of fire behavior and fire characteristics that depend on factors such as the vegetation composition and fuel structure, stage of succession after previous fires or other disturbances, types of past management, climate and weather patterns, terrain, and landscape patterns (Morgan et al. 2001; Taylor and Skinner 2003; Wotton, Nock, and Flannigan 2010). The concept of a fire regime provides an integrated way of classifying the impacts of these diverse spatial and temporal patterns of fire and impacts of fire at an ecosystem or landscape level (Hardy et al. 1998; Morgan et al. 2001; McKenzie, Miller, and Falk 2011). Understanding the historic and potential fire regimes of different types of vegetation and the factors that can alter these fire regimes is important for understanding and predicting potential interactions between fire and climate. Not only does climate (as reflected in dominant weather patterns) directly affect the frequency, size and severity of fires, it also affects fire regimes through its influence on vegetation vigor, structure, and composition.

On a local to regional scale, fire regimes may also be affected by terrain features, slope exposure, management regimes, landscape pattern, and ignition loads (both from lightning and from human impacts) (Taylor and Skinner 2003; Odion et al. 2004; Frost 2000; Agee 1993). At a minimum, fire regimes may be distinguished by how often fires typically occur (frequency, fire interval, fire rotation) and some assessment of impact on the ecosystem (e.g. mortality of overstory or surface vegetation). Some fire regime classifications include additional features such as fire characteristics (e.g. surface fire, crown fire, ground fire), the typical extent (or size) of fires (patch size), fire severity (impact of fire on the ecosystem; degree of mortality, depth of burn, fuel consumption, etc;), intensity or other measures of fire behavior (see box 3-1 for a discussion of terminology related to severity and intensity); seasonality, topographic position, and the degree of variability in fire characteristics within an ecosystem or fire regime type.

We do not have a consistent, agreed-upon and generally accepted fire regime classification as yet. This is partly a reflection of local and regional differences in vegetation and climate, and therefore in the types of fire regimes that occur. The ability to classify details of fire regimes also depends on the temporal and spatial scales being addressed and the types of data available. The fire regime characteristics of interest may also depend on the goals of a specific research study, the specific responses of individual ecosystems to fire (e.g. chaparral systems that may be dominated either by obligate seeders or by sprouting species), or the needs of managers in a particular area.

Text Box 3.1: Fire severity and fire intensity

In discussing fire regimes it is important to recognize that there has been an evolution in the use of the terms "intensity" and "severity" in the fire effects and fire ecology literature. In the past, many authors used "intensity" to represent the ecosystem effects of fire (e.g. (Heinselman 1981), Kilgore, 1981). This usage can easily be confused with "fire-line intensity", which has a very specific meaning with reference to fire behavior (the energy released per unit length of a fire front per unit time; generally in reference to flaming combustion). Measures of other physical factors that are aspects of fire intensity may include characterization of aspects of heat transfer, such as air temperature, soil temperature, or even cambial temperature; and characteristics of the flaming front (flame length, depth of flaming front, residence time or rate of spread, etc.). When combined with fire-line intensity, such factors can help to better explain effects of fire on vegetation and soils. Because factors such as duff moisture, fire rate of spread or residence time affect ecosystem impacts such as depth of burn, and duration and intensity of heating of stems, branches and foliage, fire-line intensity may not show a strong correlation with fire effects or severity, or with carbon emissions. This is especially true where there are extensive areas or localized pockets of smoldering combustion or where slow rates of spread lead to deeper heat penetration into the soil. In much of the literature, fire effects have been evaluated after a fire event with little or no information on the actual fire behavior. Recent authors (e.g. (Keeley 2009) and others) have urged the use of the term "severity" to describe the effects of fire on soil (sometimes called burn severity; see (Jain and Graham 2004) or on fuels and vegetation (sometimes called fire severity). Fire severity descriptors may include characterization of fuel consumption (what is burned), vegetation mortality, and measures such as bark char and foliage scorch. These latter are indicators of how the fire behaved and are often related to mortality. Intensity is then reserved for description of fire-line intensity, and may be supplemented with information of other important physical characteristics of fire (e.g. residence time, rate of spread, depth and duration of soil heating), all of which can help to explain the severity and secondary ecosystem effects of the fire. Fortunately, this is increasingly common practice. Although severity may be characterized in different ways, most often qualitatively, the use of this terminology lends more clarity to descriptions and discussions of fire regimes and ecosystem fire effects. There are valuable discussions of some of these issues in (Keeley 2009; Keeley et al. 2009; Jain and Graham 2004).

Fire Regime Classification

The general temporal and spatial patterns of fire behavior and effects within a particular vegetation type or ecosystem over multiple fire cycles (decades to centuries) determine the fire regime over a specific period for any given ecosystem. Fire regimes are useful for comparing the

relative role of fire among ecosystems, for describing the degree of departure from historical conditions, and for projecting the potential effects of management activities, changing climate, or changing ignition patterns.

Before describing how fire regimes are classified, it is important to understand some of the terminology used to describe them (adapted from (Agee 1993; Dickmann and Cleland 2002; Keeley 2009)).

Ground fire: A fire that burns in surface organic materials such as peat or deep duff layers. Ground fires typically undergo a large amount of smoldering combustion and less active flaming than other types of fires. They may kill roots of overstory species because of prolonged high temperatures in the rooting zone.

Surface fire: Fires that burn only the lowest vegetation layer, which may be composed of grasses, herbs, low shrubs, mosses, or lichens. In forests, woodlands, or savannas surface fires are generally low to moderate severity and do not cause extensive mortality in the overstory vegetation.

Understory or sub-canopy fire: A fire that burns trees or tall shrubs under the main canopy. Depending on structure, this may also be called a surface fire.

Crown fire: A fire that burns through the upper tree or shrub canopy. In most cases the understory vegetation is also burned. Depending on species, a crown fire may or may not be lethal to all dominant vegetation. An example of this would be many shrub and broadleaf tree species that sprout from roots, root crowns or stem bases after their tops are killed. A crown fire may be continuous or may occur in patches within a lower severity burn.

Stand replacement fire: A fire that is lethal to most of the dominant above ground vegetation and substantially changes the vegetation structure. Stand replacement fires may occur in forests, woodlands and savannas, annual grasslands, and shrublands. They may be crown fires or high-severity surface fires or ground fires.

Mixed-severity fire: The severity of fires varies between nonlethal understory and lethal stand replacement fire with the variation occurring in space or time. In some vegetation types the stage of succession, the understory vegetation structure, the fuel condition and/or the weather may determine whether a low or high-severity (or surface or crown) fire occurs. In this case individual fires vary over time between low-intensity surface fires and longer-interval stand replacement fires. In others, the severity may vary spatially as a function of landscape complexity or vegetation pattern. The result may be a mosaic of young, older, and multiple-aged vegetation patches.

Fire frequency: The number of times that fires occur within a defined area and time period.

Fire return interval (or fire interval): The time between fires in a defined area, usually at the scale of a point, stand or relatively small landscape area. This is called Mean Fire Interval (MFI) in the LANDFIRE system, where it refers to the average number of years between fires in representative stands (Barrett et al. 2010).

Fire rotation (interval): the time required to burn an area equal to a defined area of the landscape. The entire area may not burn during this period; some sites may burn several times and others not at all. This is the same as fire cycle.

There have been numerous fire regime classifications for North America suggested in the literature. These vary in the number of types of fire regime described, the characteristics used to develop the classifications, and the types of ecosystems represented. The majority of classification systems focus primarily on forests, and few incorporate grasslands, desert vegetation, shrub ecosystems such as chaparral, or ecosystems with deep organic ground fuels (such as peat). A summary of several of these classification systems (Table 3.1) illustrates some of this diversity of classifications. Heinselman (Heinselman 1973; Heinselman 1981) described 6 fire regime types; three for varying frequency and severity of surface fires, and three for differing frequency of crown fires. Kilgore (Kilgore 1981) adapted this somewhat, and included a category for variable fire regimes that are dominated by frequent low-"intensity" surface fires with infrequent stand-replacement or high-'intensity' fires. Frost (Frost 2000) took a rather more complex approach. He mapped fire frequency regions at the time of European settlement for the eastern and western US. In developing these maps, he used a combination of landscape structural characteristics, fire frequency, and effects of fire on different vegetation layers. He then characterized fire regimes based on periodicity (regularity of the fire intervals), seasonality (the primary season of burn), frequency (seven classes of fire return intervals), and ecosystem effects (10 categories representing effects of fire on understory and overstory vegetation). The latter included categories such as light surface fire, grass reduction fires, understory thinning fires, canopy thinning, canopy replacement, and ground fires. The result was a characterization of over 30 different fire regimes.

Brown and Smith ((Brown and Smith 2000); the "flora volume" of Table 3.1), use a simplified scheme that includes only three basic fire regimes. Nonetheless, this publication provides an excellent overview of the spatial patterns, frequency, and impacts of fire in major ecoregions of the US. Hardy et al. (1998) describe fire regimes in terms of the typical time between fires and whether fires are low-severity (with little impact on vegetation or soils and low fuel consumption), high severity (stand replacement fires where above-ground parts of dominant vegetation are killed) or mixed severity (where fires may occur at a range of severities on the landscape, in either space or time, as a function of weather, fuels, and other factors). The scheme proposed by Morgan et al. (2001) differs from that of Hardy et al. (1998) in distinguishing between non-lethal fires (e.g. grassland fires and some surface fires in forest systems), and stand replacement fires in forests and shrublands. The reasoning for this is that the Hardy et al. (1998) scheme does not work well for distinguishing stand replacement fires where vegetation mortality is high, from fires where aboveground parts of vegetation are burned, but belowground parts regenerate, or herbaceous vegetation recovers rapidly from seed. The fire regime classifications discussed above were all designed for North America—and primarily for the conterminous United States. Notably missing from these is specific mention of ground fires and smoldering fires in deep organic layers such as peat, which are common across the boreal zone (e.g (Turetsky et al. 2004; Turetsky et al. 2011)), and in some moist subtropical systems, such as the pocosin soils of the southeastern US (Reardon, Hungerford, and Ryan 2007) or the deep peat soils in Malaysia (de Groot et al. 2007). One of the first mentions of ground fire regimes was by Malcolm Gill (Gill 1975) in Australia, who had no experience with them, but recognized "below-ground fires" as important in other parts of the world. The large difference in approaches to classifying fire regimes described above speaks to a need for a broader consensus on the appropriate variables to include for describing fire regimes at various spatial and temporal scales, and perhaps for different purposes.

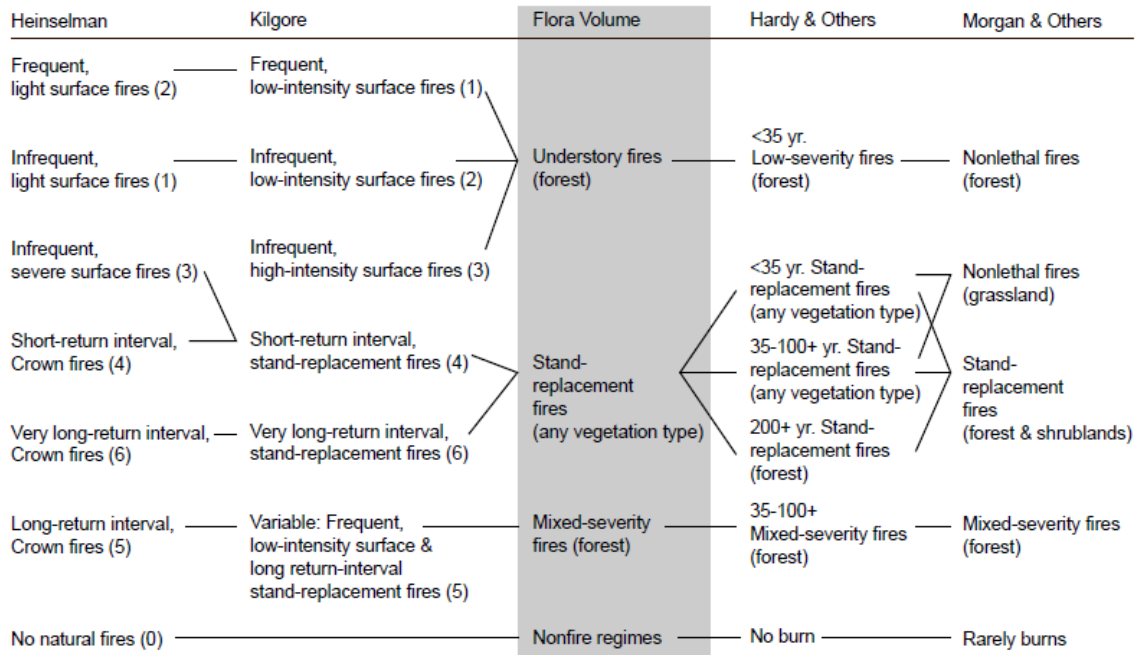

Table 3.1: Comparison of North American fire regime classifications by (Heinselman 1981) Kilgore (1981), Hardy and others (1998), Morgan and others (1998), and Brown and Smith (2000). Lines connect similar fire regime types. In parentheses, forest includes woodlands and grassland includes shrublands. Adapted from Figure 1-1 in Brown and Smith, 2000.

Spatial and Temporal Scale of Fire Regimes

Fire regimes can be viewed over a wide range of temporal and spatial scales, ranging from several years to thousands of years and local to broadly regional. Knowledge of historical temporal and spatial patterns of fire is a key to characterizing and understanding fire regimes. The term "fire history" typically refers to some measure of past records or data that relate to the frequency of fire in a stand or a landscape, although inferences sometimes are drawn about the type or severity of these fires. It is when we move beyond simple fire history to describing the varying characteristics of fire across the landscape, and the interactions of fire with ecosystem structure and processes, that we move into the realm of fire regimes.

Recent fire history (spatial and temporal patterns of fire on the landscape) has been recorded on fire maps or fire atlases, but these are often incomplete, and may only cover certain ownerships or parts of the landscape. In the past several years efforts have intensified to map fires that have occurred since (or shortly before) the advent of satellite remote sensing. Canada's large fire database[12] is the first nationwide effort of this sort. This database contains point locations for all fires larger than 200 ha from 1959-1999 and represents about 97% of the area burned during that

[12] http://cwfis.cfs.nrcan.gc.ca/en_CA/lfdb

period (Stocks et al. 2002). The Canadian National Fire Database includes fire perimeters for all large fires, since 1980 and is annually updated[13] (Parisien et al. 2006). In the United States, the Monitoring Trends in Burn Severity (MTBS) Project[14] is using satellite data to map all large fires from 1984 to the present (Figure 3.1). This collaborative project also maps an index of fire severity (differenced Normalized Burn Ratio (dNBR)) within the fire perimeters using moderate resolution satellite data obtained before and after fires. The goal of this project is to provide nationally consistent data on fire perimeters and severity for all recent large fires in the United States (Eidenshink et al. 2007). Databases such as these provide a sound basis for quantifying fire occurrence, size, and (for the US) severity for use in modeling fire climate and fire vegetation interactions over the past several decades. The Alaska Fire Service has developed an excellent geospatial database of all fires since 1934[15].

For fire location and size data prior to 1984 in the conterminous US, we will need to continue to rely primarily on the databases that are maintained by federal and state agencies. Unfortunately, these databases are often incomplete. They typically include data such as point locations for fire starts, area burned, and perhaps a general description of vegetation at the point of ignition. For fire perimeter maps, it becomes necessary to go to local offices, where maps of varying quality and reliability are stored.

A longer period of record than the 30 to 100 years available for various products in Agency databases is required for understanding long-term interactions between fire and climate. As we go back further in time, fire history can only reliably be determined for portions of the landscape where some sort of fire indicators are recorded--either on the trees themselves (e.g. dendrochronology-based fire scar analysis), in stand structure (age distribution of stands where fire can be assumed to be the dominant disturbance factor), in charcoal deposits in soils, lakes, bogs, or ocean sediments (sediment charcoal analysis), or can be inferred from vegetation changes over long time periods (e.g. through pollen records). While each of these methods has its limitations, approaches using dendrochronology and sediment charcoal and pollen data can provide excellent insights into trends in vegetation, fire and fire/climate interactions over hundreds to thousands of years, and provide perspectives on variability, drivers of fire regimes, and fire/climate/vegetation interactions that are not possible from analysis of historical fire records which typically span decades rather than centuries or millennia (Whitlock et al. 2010). Numerous recent studies based on tree ring data or on historical fire records have shown strong relationships between past climate and fire frequency or extent (Brown et al. 2008; Heyerdahl, Morgan, and Riser II 2008; Heyerdahl, Brubaker, and Agee 2002; Heyerdahl, Brubaker, and Agee 2001; Kitzberger et al. 2007; Swetnam and Baisan 2003; Swetnam and Baisan 1996; Westerling et al. 2006). Such information can be used to extrapolate fire history to periods before actual fire data are available (Falk et al. 2011; Grissino Mayer and Swetnam 2000). Results of ecosystem specific studies relating fire to climate are discussed in Chapter 6.

[13] http://cwfis.cfs.nrcan.gc.ca/en_CA/nfdb/poly
[14] http://www.mtbs.gov/
[15] http://afsmaps.blm.gov/imf_firehistory/imf.jsp?site=firehistory

While fire history data are quite useful for understanding past fire regimes, changes in fire management policies and practices, demography, and climate mean that we cannot expect the same fire regimes to continue into the future. Models based on past relationships between fire and climate, fire and demographic change, and fire and management policies, or on past relationships between vegetation and climate show promise for helping us to project fire regimes into a future of changing climate and social environments. These concepts are discussed in detail in later chapters.

LANDFIRE fire regimes

Although there are numerous fire regime classifications presented in the literature, we will use the basic classification scheme of Schmidt et al. (2002) as modified in the current version of LANDFIRE ((Barrett et al. 2010); Table 3.2). This updated fire regime approach explicitly distinguishes between "stand replacement severity" and lower severity fires for all types of vegetation, improving its usefulness in grasslands and shrublands.

We emphasize the LANDFIRE classification because both the historic fire regimes (Figure 3.2) and an assessment of departure of present fire regimes from the historic patterns (Figure 3.3) can be mapped for all US wildland ecosystems as part of the development of the LANDFIRE project and associated data bases. From inspection of Figures 3.1 through 3.4 broad regional variations in fire regimes, fire patterns, and departure from historic fire regimes are visible. For example,

Text Box 3.2 LANDFIRE

The Landscape Fire and Resource Management Planning Tools (LANDFIRE) is a vegetation, fire, and fuel characteristics mapping and modeling system that is sponsored by the United States Department of the Interior (DOI) and the United States Department of Agriculture, Forest Service (USFS). LANDFIRE was initiated based on the need for consistent national geospatial data to support prioritization of hazardous fuel reduction, ecological conservation activities, and strategic resource management initiatives[1], fire management planning, as well as stewardship of public and private lands, and natural resource management. As the LANDFIRE databases and models were developed and implemented nationally over the past decade, it became clear that these products were useful for a broad range of purposes in addition to fire management, including climate change research, carbon sequestration planning, and eco-regional assessments. The participating agencies have committed to periodically update LANDFIRE data for the entire United States to ensure the availability of both current and historic data, and to continue to improve the quality of data products into the future. http://www.landfire.gov

Maps and geospatial databases of vegetation (Figure 3.2), fuels and fire regimes (Figures 3.3 and 3.4) are essential for understanding and modeling ecological relationships between wildland fire and landscape structure, composition, and function, and for managing wildland fire hazard and risk with an ecosystem perspective. Prior to LANDFIRE, there were no standard methods for creating these maps, and spatial data representing these important characteristics of wildland fire were lacking in many areas. LANDFIRE provides an integrated approach for mapping vegetation, fuels and fire regimes based on extensive field sampling, remote sensing, ecosystem simulation, and biophysical gradient modeling to create predictive landscape maps of fuels and fire regimes. The biophysical models incorporated into LANDFIRE rely on 38 mapped variables that describe gradients of physiography, spectral characteristics, weather, and biogeochemical cycles. (Rollins 2009; Rollins, Keane, and Parsons 2004).

large fires in the past 10 years have been concentrated in the western states, Alaska, Georgia and Florida. During this period, no large fires were observed in other areas of the East. Examination of the fire, fire regime and vegetation maps shows that a high degree of departure of vegetation from historic conditions is not necessarily associated with increased hazard of large fires. This is especially evident in the eastern United States. Further, forested areas historically characterized by frequent low to moderate severity or mixed severity fires (FRG I and III; Figure 3.3) typically show at least moderate departure from historic conditions (FRCC II or III; Figure 3.4). Chapter 6 will discuss observed changes in vegetation and fire regimes in more detail for the various ecoregions of the US.

Group	Frequency	Severity	Severity description
I	0 – 35 years	Low/ mixed	Generally low-severity fires replacing less than 25% of the dominant overstory vegetation; can include mixed-severity fires that replace up to 75% of the overstory
II	0 – 35 years	Replacement	High-severity fires replacing greater than 75% of the dominant overstory vegetation
III	35 – 200 years	Mixed / low	Generally mixed-severity; can also include low-severity fires
IV	35 – 200 years	Replacement	High-severity fires
V	200+ years	Replacement / any severity	Generally replacement-severity; can include any severity type in this frequency range

Table 3.2: Fire regime groups used in the current LANDFIRE data bases. These groups have been modified from earlier versions (Hardy et al. 2001, Schmidt et al. 2002) to include low-severity fires in Fire Regime III and fires of any severity in Fire Regime V. Adapted from FRCC Guidebook, Version 1.2.1 (Anon. 2010).

The LANDFIRE classification is also useful because it includes a general description of both typical fire frequencies, and fire severities, which are probably the most important types of information for detecting fire regime changes over time in ecosystems. Such data are a necessity if we are to evaluate and project effects of climate at regional to landscape scales. Further, the LANDFIRE databases are readily available to managers, and will be updated to reflect fire and other disturbance patterns. These data are freely available for download from www.landfire.gov, and can be integrated into geospatial databases for use in LANDFIRE analyses or other applications (such as analyses of potential climate change impacts). Another advantage of using

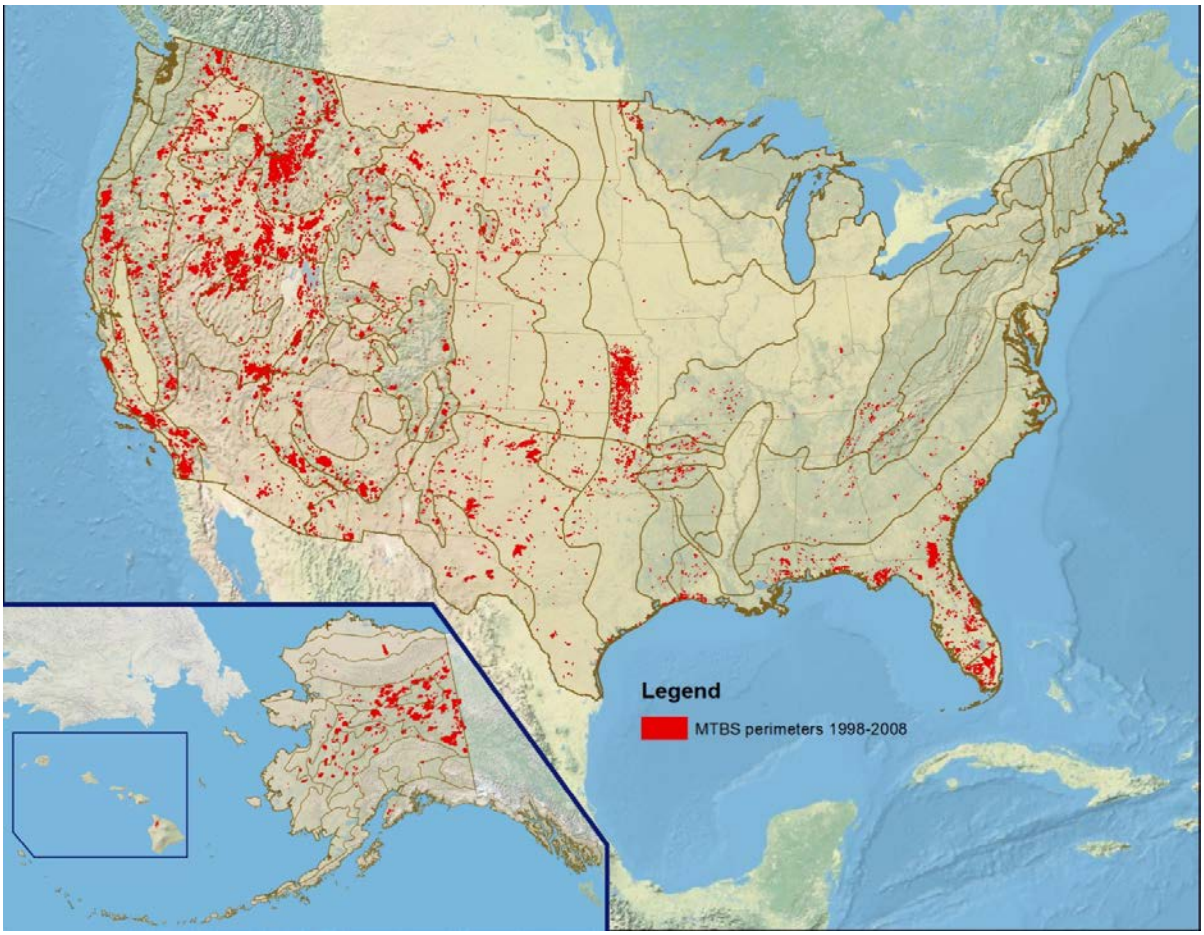

Figure 3.1: Burn perimeters of all large fires in the United States from 1998 to 2008 as mapped, primarily from remote sensing data, for the Monitoring Trends in Burn Severity (MTBS) project. The database includes burns over 500 acres in the East, and burns over 1000 acres in the west. These thresholds were selected because they capture a high percent of the total burned area. The individual pixels have been enlarged to enable ready visibility of these data at a national scale. The map shown here includes an overlay of the Bailey ecoregions and the state boundaries.

the LANDFIRE classification is that the LANDFIRE databases also include geospatial data on the Bailey ecoregions and provinces ((Bailey 2008) Figure 3.5), which we will refer to throughout this synthesis.

However, we will also use various terminology discussed above as needed to clarify the capacity of various vegetation types to regenerate above-ground vegetation from living roots or fire-adapted seeds after fire, distinguish between surface fire, ground fire, and crown fire, or discuss other aspects of fire regime such as seasonality that are appropriate to specific ecoregions or ecosystems.

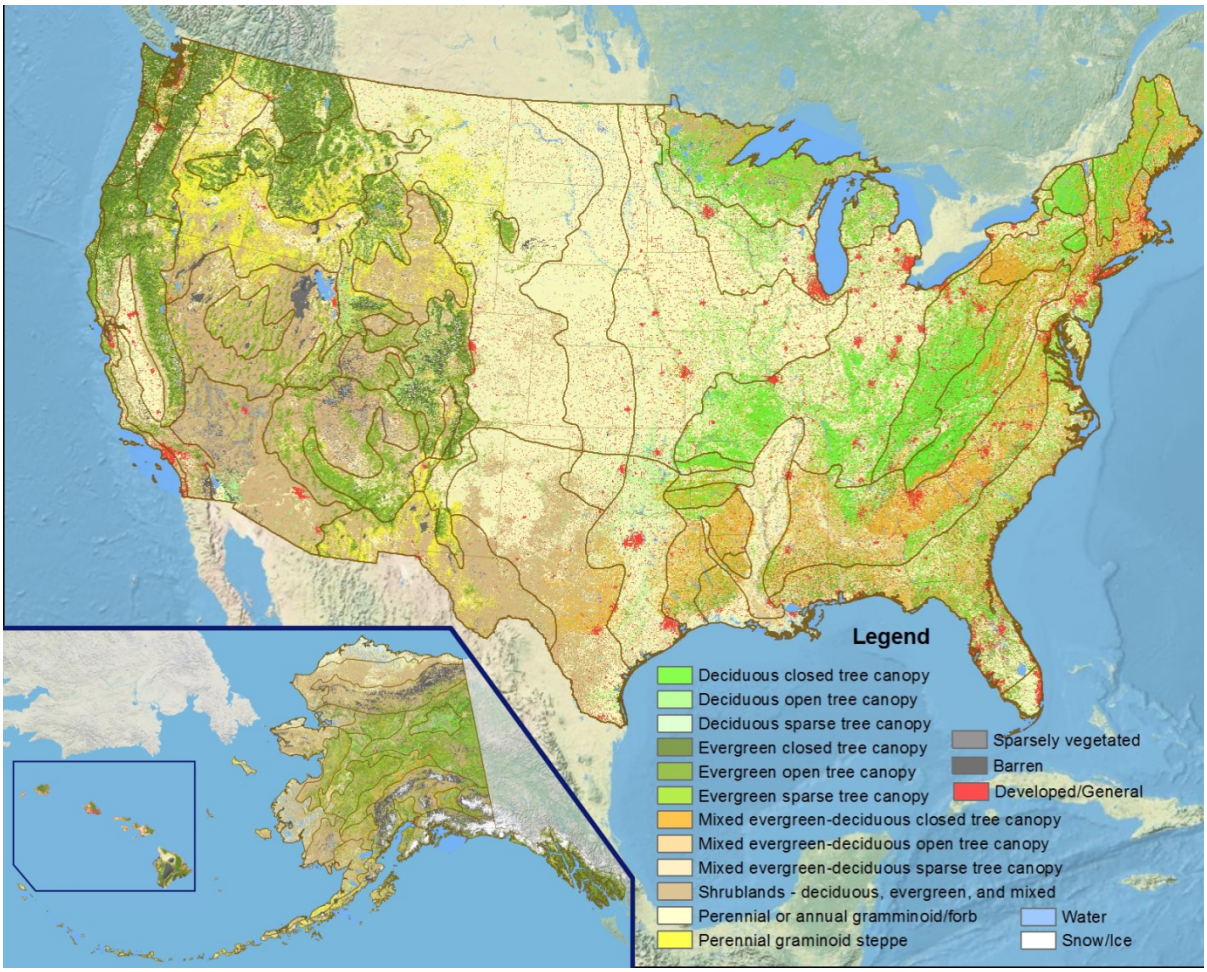

Figure 3.2: Existing vegetation as mapped from LANDFIRE data. For the purposes of this map, the many vegetation types in the LANDFIRE data base have been grouped into types of vegetation that are likely to have similar fire regimes, based on overstory type, openness of canopy, and dominant life form (e.g. grass, shrub, evergreen vs. deciduous trees). For reference, the vegetation groups are overlaid on outlines of the Bailey Ecoregions defined in Figures 3.5 and 4.X).

Regional Patterns in Fire Regimes

Malamud and colleagues report that the size of wildfires and their severity patterns show distinct regional differences across the United States (Malamud et al. 2005). This study used high-resolution Forest Service wildfire statistics based on 31 years (1970-2000) of wildfire data consisting of 88,916 fires ≥1 acre on the National Forest System. To facilitate spatial analysis of the biophysical factors that drive wildfire regimes, the researchers classified the wildfire data into ecoregion divisions (areas of common climate, vegetation, and elevation). In each ecoregion, they asked: What is the frequency-area distribution of wildfires?

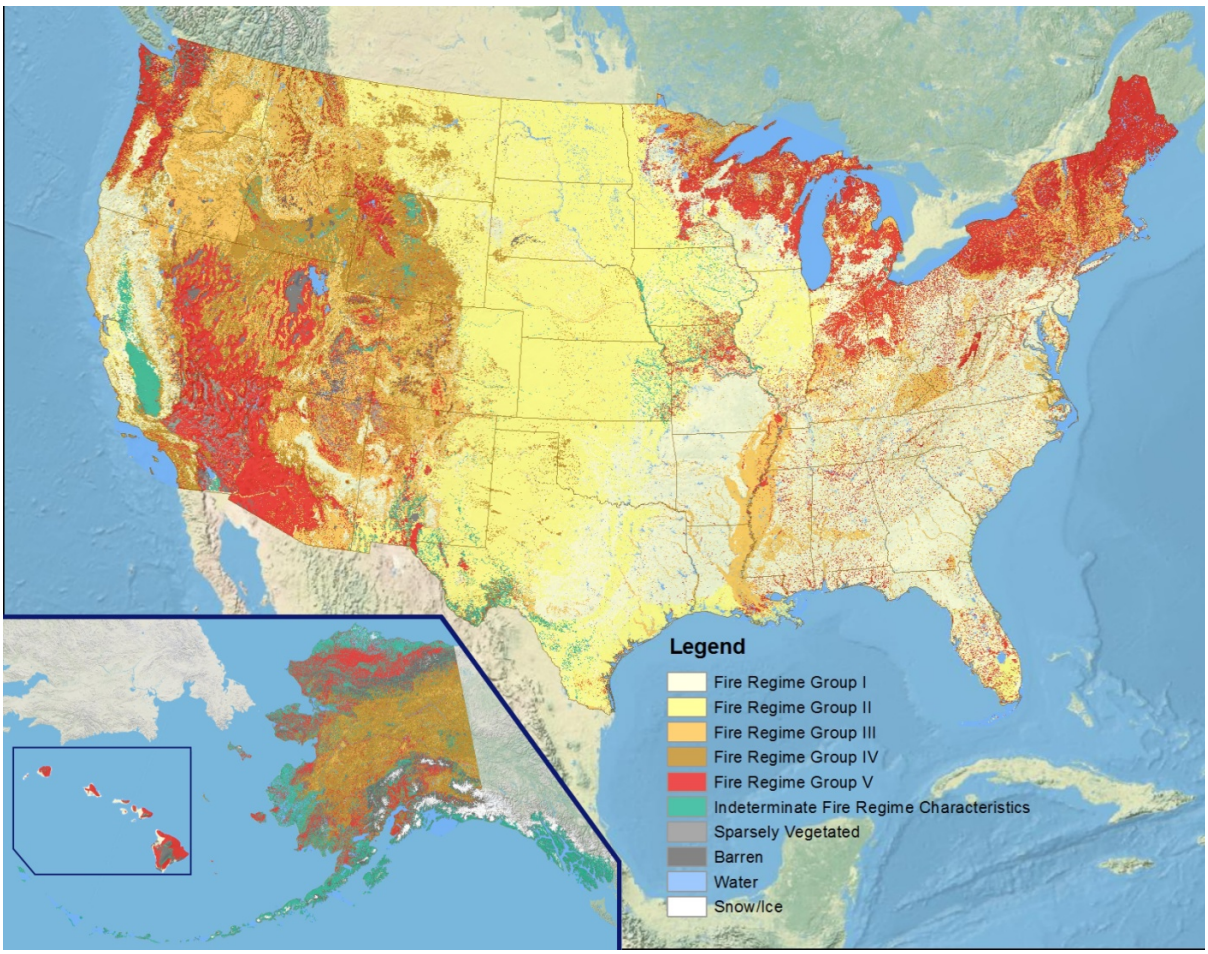

Figure 3.3: Historic fire regime groups (FRG) across the United States as used in LANDFIRE. FRG I (0 to 35 year frequency, low to mixed severity; typical of perennial grasslands; FRG II (0 to 35 year frequency, replacement severity; annual grasslands and some forest types with frequent surface fire); Fire Regime III (35 to 200 year frequency, low to mixed severity; many forests and shrublands such as chaparral); Fire Regime IV (35 to 200 year frequency, replacement severity; mostly forests, some shrublands with non-sprouting shrubs); Fire Regime V (200+ year frequency, any severity; some moist forests, tundra, desert)

The study compared area burned, number of fires, and the wildfire recurrence interval and created maps to display wildfire patterns and risk for the entire conterminous United States. These parameters were calculated at the ecoregion division level. They found a relatively higher proportion of large fires in the west compared to the east (Figure 3.6 A), although analysis at the Ecoprovince level undoubtedly would have also shown a relatively high proportion of large fires in Bailey's Ecoprovince 232 Outer Coastal Plain Mixed Forest Province, which includes most of Florida and neighboring regions (see Figures 3.1 and 3.5). They also found the longest fire intervals in the Pacific Northwest, around the Great Lakes, and in the extreme Northeast (Vermont, New Hampshire and Maine) (Figure 3.6 B). Fire intervals also appear quite long throughout the Eastern US and in some mountain areas of the Interior West. The generally lower fire frequency and lower incidence of large fires in most of the eastern US may be due to in part

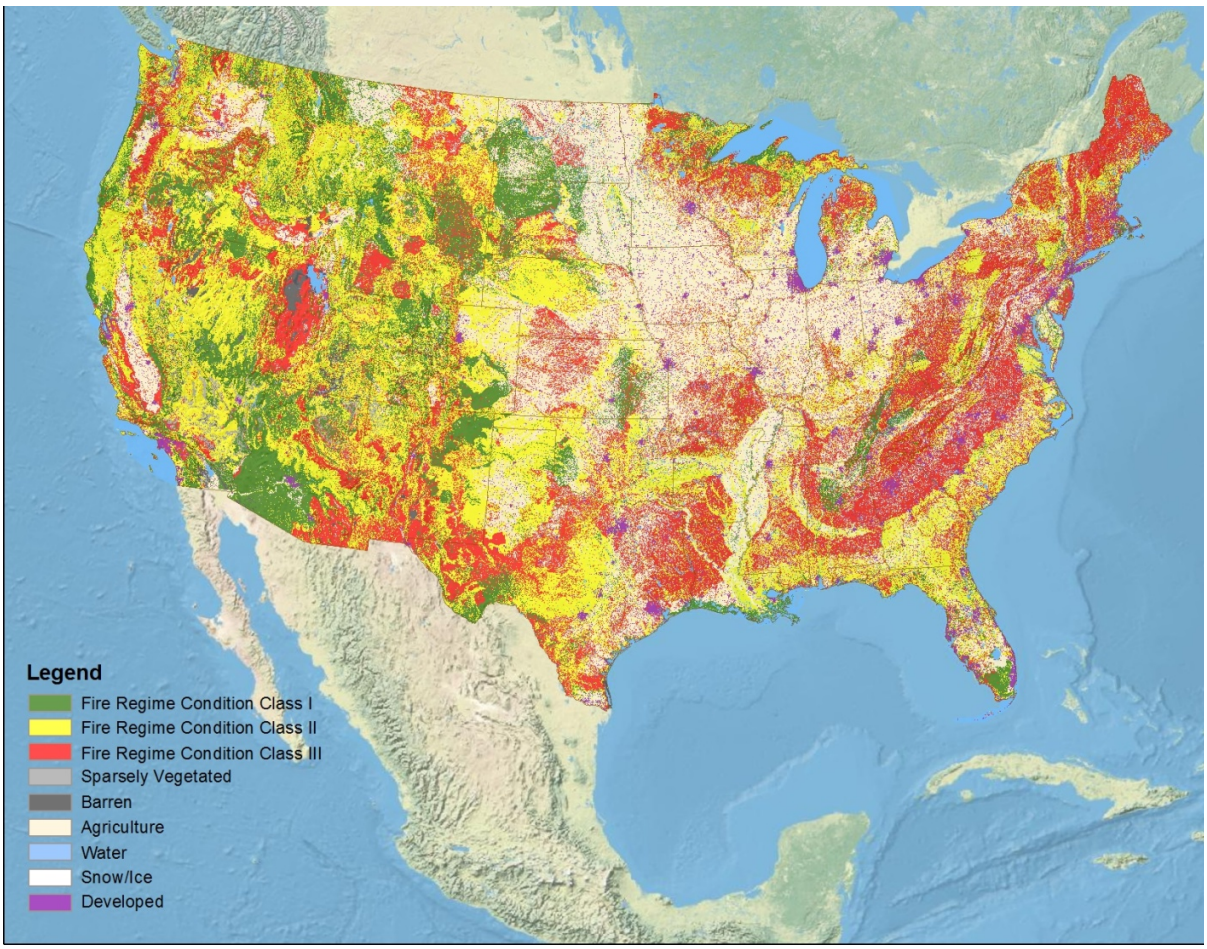

Figure 3.4: Fire Regime Condition Class (FRCC) for the conterminous United States as used in LANDFIRE national database. FRCC is a metric of the degree of departure of current vegetation from the historical vegetation reference conditions simulated in LANDFIRE (Hann and Bunnell 2001; Hardy et al. 2001; Barrett et al. 2010; Holsinger and others 2006). The three condition classes describe low departure (FRCC 1), moderate departure (FRCC 2), and high departure (FRCC 3). Variables used in calculating FRCC are changes in species composition, structural stage, and canopy closure compared to modeled historical (pre-European) conditions (Barrett and others 2010); Holsinger and others 2006) (Rollins et al. 2007). The departure of current vegetation conditions shown in the LANDFIRE FRCC is only one component of the FRCC characterization described in Barrett et al. (2010) for doing local and regional assessments.

greater population density and increased forest fragmentation. However, the differences among ecoregions are most likely primarily due to natural drivers, with frequent drought, flammable vegetation, and steep terrain producing conditions more conducive to large wildfires in much of the western US, and considerable summer rainfall and dominance by deciduous tree species in much of the East. The fire return interval differs markedly among ecoregions. For example, the fire cycles (typical fire return intervals) ranged from 13 years for the Mediterranean Mountains Division (M260) to 203 years for the Warm Continental Division (210).

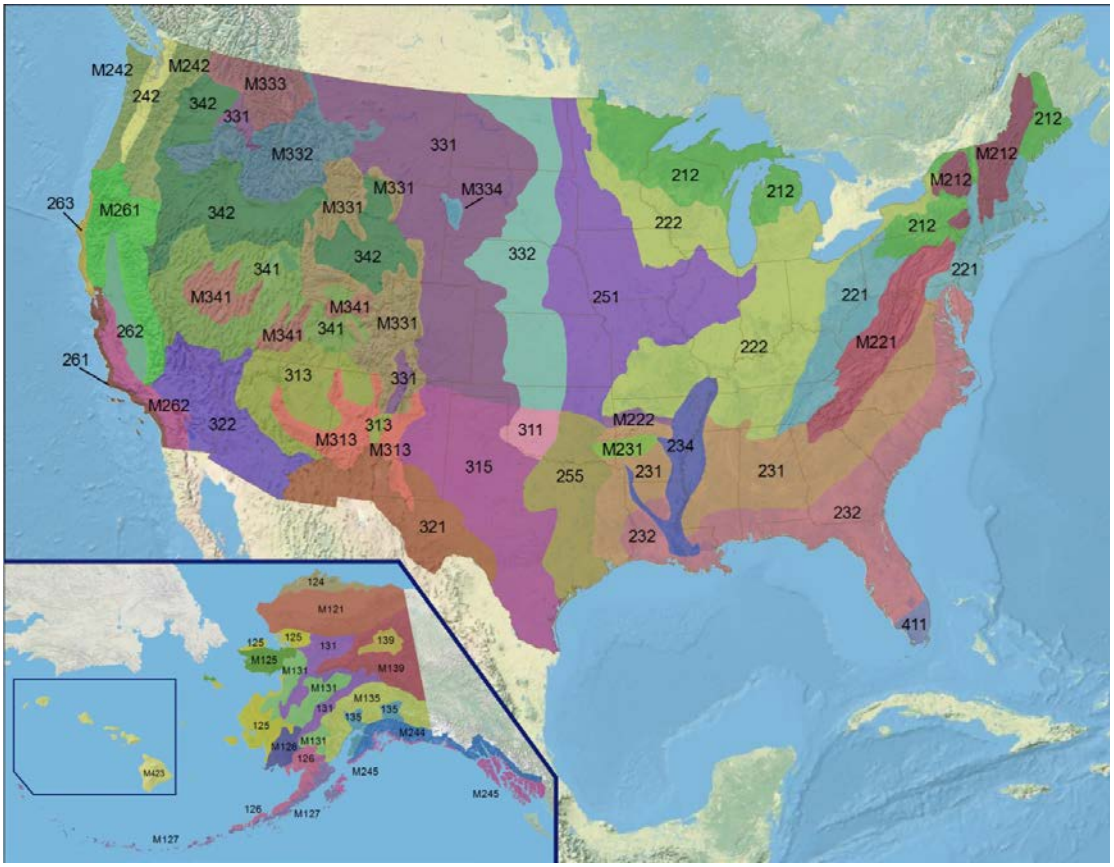

Figure 3.5: Ecoprovinces of the United States (Bailey 2008), mapped from the LANDFIRE database. Details on this map and the hierarchical system it represents are in the following chapter. The numbered Provinces, which are characterized by their dominant vegetation complexes are subdivisions of the 5 Domains and 14 major Divisions listed below. The M designator represents mountain areas within each Division. The domain and division boundaries are based on climate regimes, and topography:

100 POLAR DOMAIN
- 120 Tundra Division
- 130 Subarctic Division

200 HUMID TEMPERATE DOMAIN
- 210 Warm Continental Division
- 220 Hot Continental Division
- 230 Subtropical Division
- 240 Marine Division
- 250 Prairie Division
- 260 Mediterranean Division

300 DRY DOMAIN
- 310 Tropical/Subtropical Steppe Division
- 320 Tropical/Subtropical Desert Division
- 330 Temperate Steppe Division
- 340 Temperate Desert Division

400 HUMID TROPICAL DOMAIN
- 410 Savanna Division
- 420 Rainforest Division

In other studies, gradients similar to those observed by Malamud et al. (2005) have been described and related to climate and vegetation. Turner and Romme (1994) describe wildfire occurrence gradients as a function of altitude and latitude. They attribute these gradients to broad climatic variation and note western and central regions tend to have frequent fires with forest

stand structures dominated by younger trees, whereas the eastern region experiences longer inter-fire intervals and older stand structures. A statistical forecast methodology developed by Westerling et al. (2002) exploits these gradients to predict area burned by western United States wildfires, by ecoregion, a season in advance. Littell et al. (2009) found that climate drivers of synchronous fire differ regionally. They identified four distinct geographic patterns of Bailey Ecoprovinces across the West, each associated with a unique set of climate drivers of annual area burned by wildfire. For example, in northern mountain ecoprovinces (M332, M333), dry, warm conditions in the seasons leading up to and including the fire season are associated with increased area burned, suggesting that fuel condition that is dry vs. wet, was the key determinant of regionally synchronous fires. In contrast, in the southwestern dry ecoprovinces (313, 315, 321, 322), moist conditions the seasons prior to the fire season are more important than warmer temperatures or drought conditions in the year of the fire, suggesting that fuel abundance determined large fire years (See Figure 3.5 for Ecoprovince locations).

Chapter 6 includes a detailed discussion of fire regimes for major vegetation types in each ecoregion of the US.

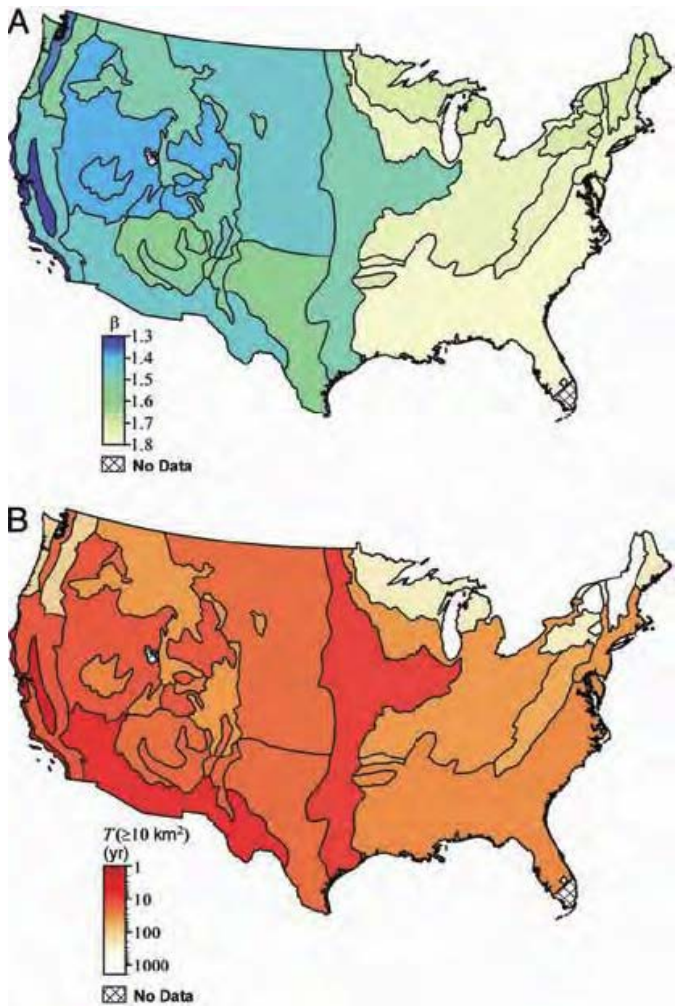

Figure 3.6: Wildfire patterns across the conterminous United States for years 1970 to 2000 for U.S. Forest Service wildfires, classified by ecoregion division. (A) Ratio of large to small wildfires. The darker the color, the greater the number of large fires. (B) Fire recurrence interval. The legend goes from dark red to white, representing “high” to “low” hazard (from Malamud et al. 2005).

Chapter 4: Ecosystems, Climate and Fuels

Ecosystem Classification --- Bridging Fire History, Fuels and Climate Change Information

Terrestrial vegetation is the product of long-term biosphere-atmosphere interaction and an essential descriptor in ecosystem classification systems (Moorcroft 2003; Holdridge 1947; Bailey 1983). Vegetation is a fundamental component of terrestrial ecosystems and the principal fuel burned in fires through much of Earth history (Kempes et al. 2011; Bowman et al. 2009). Further, vegetation, in its role as fuel, is an essential descriptor for fire regimes (Hardy et al. 1998). While fire regime knowledge (as discussed in Chapter 3) offers the most direct link between climate, fuels and fire, a great deal of extremely useful existing and forthcoming information regarding climate and ecosystems does not consider fire per se but rather looks at the larger context of climate and ecosystem change. Those with a specific focus on fire need to incorporate scale dependent information from this larger realm of climate-ecosystem knowledge, particularly when decadal, centennial, or millennial long-term views are taken. Just as fire regimes form a foundation for understanding and describing effects of changing climate on fire patterns and impacts, ecosystem classifications are a foundation for understanding and monitoring broader ecosystem impacts of climate change, in which fire regime impacts are embedded. Ecosystem classification is particularly useful for interpreting fire history in relation to observed climate change that took place over the longer time scales of the post-glacial Holocene epoch ecosystem evolution that produced current ecosystems.

Ecosystem classification systems are a valuable tool for translating climate change projections into ecological impacts (Emanuel, Shugart, and Stevenson 1985). Ecosystem classifications allow for standardized application of climate information to aid understanding of ecosystem location and function, where ecosystems were located during different climate conditions in the past and how ecosystems may change under different climate conditions in the future (Holdridge 1947; Delcourt, Delcourt, and Webb III 1982; Iverson and Prasad 1998; Littell et al. 2011). Standardized classifications are important for ecosystem planning nationally and globally, relating ecosystem characteristics to fire regimes and fire planning (Bailey 2008; Grossman et al. 1998; Bailey 2010; Littell et al. 2009; Rollins, Keane, and Parsons 2004; Rollins 2009).

Terrestrial ecosystems have gained heightened importance in climate change planning because of their role in carbon cycling, where they serve as a major sink for atmospheric CO_2 (Pan et al. 2011). When fire consumes ecosystem fuels it impacts the carbon cycle in addition to emitting GHG and aerosols, including albedo impacting black carbon (Chapin III et al. 2006; van der Werf et al. 2006; Kuhlbusch 1998). Managers seeking to apply results of scientific studies about fire history and climate change for fire and fuels planning will broaden their base of applicable current and future information by using ecosystem classification as a bridge to other resource issues and by identifying the important ecological role of fire to the wider scientific community. Those managers also will communicate with the larger natural resources community as it seeks to address the changing role of fire in accelerating carbon cycling and other ecosystem impacts in response to 21st Century climate change (US Government Accountability Office 2007; US CCSP et al. 2008; National Research Council 2010). Participants at our user workshop (see

Appendix A) agreed that the audience of this synthesis should include natural resource managers as well as fire managers. Ecosystem classification is a bridge for integrating fire history, fuels and climate change information for use among fire and other natural resource managers. The Bailey system (Bailey 2009) offers the best vehicle for wide information and audience coverage. After review of existing and probable future availability of climate change information, we expect that information will likely be most applicable at the Bailey Division level for the near future. It is certainly desirable to apply information at the Province level but caution should be exercised when doing so, both because of lack of resolution of downscaled climate change information and the increasing influence of factors such as vegetation type, landform, land use, altitudinal gradient, and aspect at finer spatial scales.

Understanding how ecological processes and other factors within ecosystems interact and vary across a range of spatial and temporal scales is important for relating climate change impacts to fire managers and other natural resource managers (a more detailed discussion of change, variability, pattern and scale relationships follows in Chapter 5). Scale typically suggests a level of detail in describing or defining a landscape or timeframe over which ecological events or processes occur. We believe it is important to consider the history of fire as a natural process described in the context of a spatial and temporal hierarchy. Delcourt and Delcourt (see Figures 4.1 and 4.2) used a hierarchical construct with spatial and temporal ordinates to illustrate the comparison of fire regimes, climate fluctuations, biotic responses, vegetational patterns, and landscapes at differing scales in the paleoecological record (Delcourt and Delcourt 1988; Delcourt, Delcourt, and Webb III 1982). The resultant time space mapping provides a crosscutting reference between climate, fire regimes and ecosystem classification for interpreting paleo as well as more recent fire history.

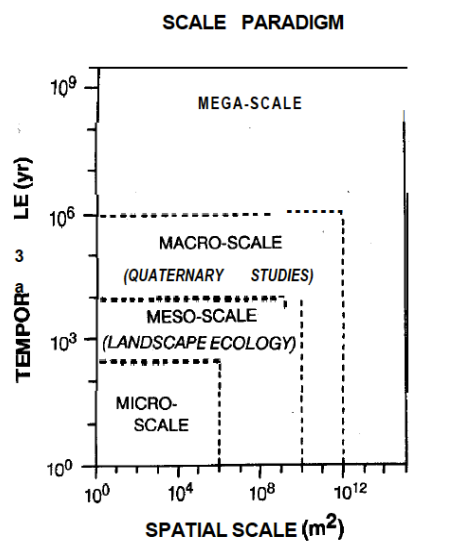

Figure 4.1: Spatial-temporal domains for a hierarchical characterization of environmental forcing functions, biological responses and vegetation patterns. Source: (Delcourt and Delcourt 1988)

Ecological Classification Use in Holocene Paleoecology Studies

Environmental changes during the Holocene epoch (from ~12,000 years Before Present (BP) to present) have influenced the development of natural landscapes over centennial to millennial time scales. Human cultural evolution has resulted in the transformation of much of the planet from natural to cultural landscapes over the past 5,000 years. Knowledge of Holocene landscape changes enables fire managers, land managers and others to understand and have a context for anticipating future ecosystem trends on local, regional, and global scales (Delcourt and Delcourt 1988).

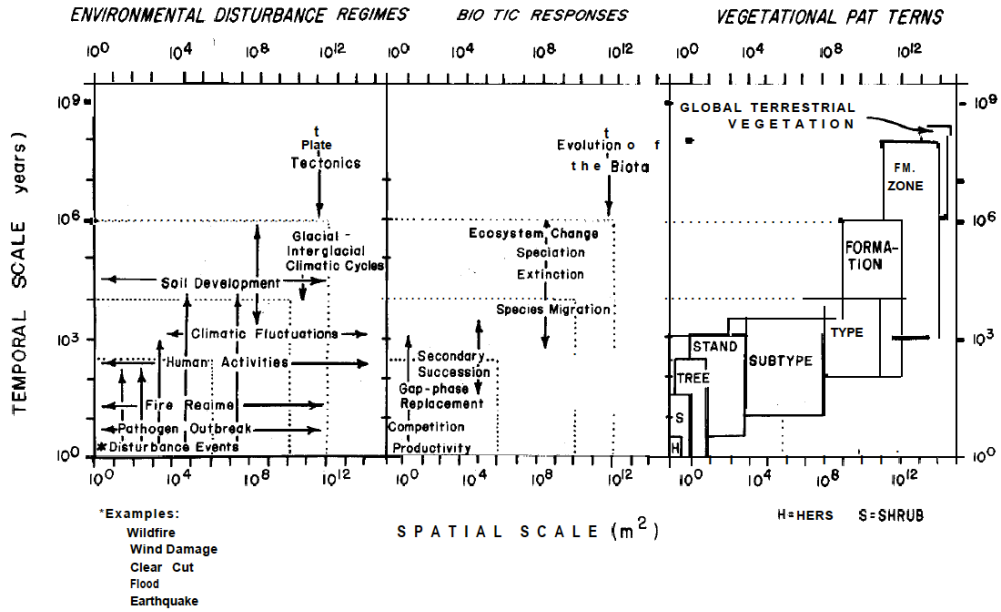

Figure 4.2: Environmental disturbance regimes, biotic responses, and vegetational patterns viewed in the context of four space-time domains. Source: (Delcourt and Delcourt 1988)

Paleoecology studies consider landscape ecology scales in evaluating changes in ecological pattern and process on natural landscapes through time. The Delcourts (1988) describe broad *"…spatial-temporal domains for a hierarchical characterization of environmental forcing functions, biological responses, and vegetational patterns..."* and diagram *"…Environmental disturbance regimes, biotic responses, and vegetational patterns viewed in the context of four space-time domains."* They suggest an operational scale model consisting of micro, meso, macro, and mega scales of spatial-temporal domains to incorporate landscape ecology (see Figs 4.1 and 4.2). The bounds placed on the dimensions of these domains represent a generalized overview for the purpose of illustrating relationships. The Delcourts divide the Macro scale (10^6 to 10^{12} m^2; 250 to 250 million acres) into Macro, Meso and Micro regions, which roughly bracket Domains, Divisions, Provinces and Sectors used by Bailey. The Delcourts (Delcourt, Delcourt, and Webb III 1982) had earlier provided a tabular hierarchy (see Figure 4.3) of space-time domains for time dependent vegetation change, noting *"…The idea of a space-time hierarchy can be illustrated through the example of wildfire, an environmental disturbance that is effective over several spatial and temporal scales…* (Christensen 1981)*."*

Hierarchical level of resolution		Area m^2	Metric side - m	Geodetic Side	Map scales	Vegetational unit
Mega Scale	Global land area*	1.5×10^{14}				Global forest vegetation
		10^{14}	10,000,000	90°	1:20,000,000	
	Continent					Formation zone
		10^{12}	1,000,000	10°	1:2,000,000	
Macro Scale	Macro Region					Formation and large type
		10^{10}	100,00	1°	1:200,000	
	Meso Region					Type
		10^8	10,000	7.5’	1:20,000	
	Micro Region					
		10^6	1,000	30”	1:2,000	Subtype
Micro Scale	Macro Site					
		10^4	100	3.75”	1:200	
	Meso Site					Stand
		10^2	10		1:20	
	Micro Site					Individual Tree
		10^0	1		1:2	

** The planet Earth has a combined land, ice and water area of 5.1×10^{14} m^2*

Figure 4.3: Spatial hierarchies of vegetational units. The typical range in spatial coverage for each vegetational unit is expressed in terms of orders of magnitude for area in square metres. Note that specific examples of vegetational units may partially overlap in area with units at adjacent spatial scales. Adapted from: (Delcourt, Delcourt, and Webb III 1982)

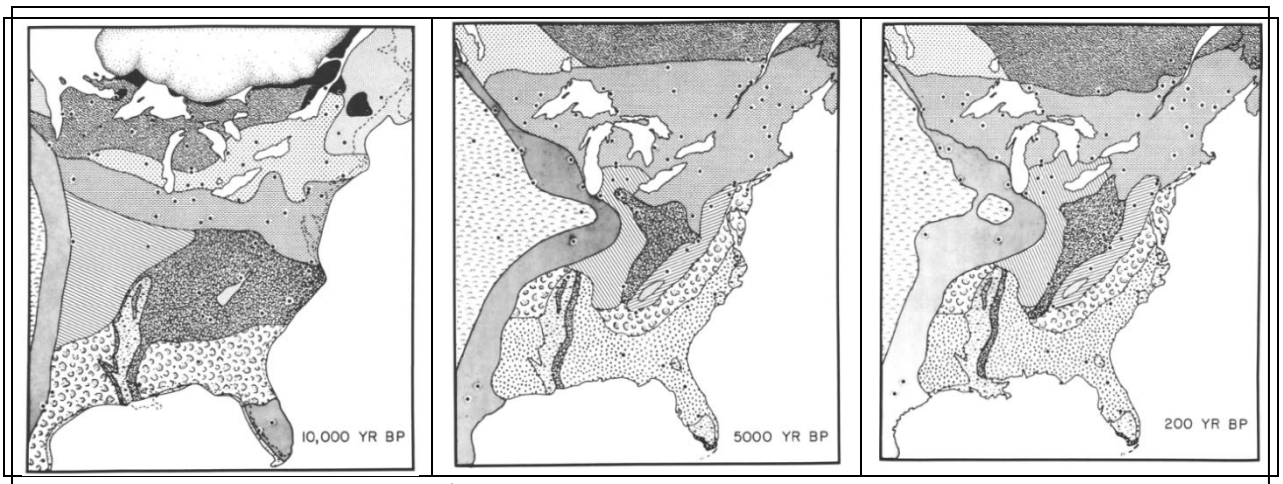

Figure 4.4: Paleovegetation maps for 10,000 BP, 5,000 BP, and 200 BP. The black dots represent locations of sites from which pollen data were used to reconstruct the past vegetation. Source: (Delcourt, Delcourt, and Webb III 1982)

Paleovegetation maps of the eastern United States depict ongoing vegetation change during the Holocene (see Figure 4.4 for examples). Late Holocene (5000 BP and 200 BP) maps resemble current Bailey Division and Province patterns, Indicating relative ecosystem level stability during that period.

The majority of the boreal and temperate vegetation types of eastern North America have been sustained over the past 5,000 years. The spatial patterns for most major forest types, including boreal forests, deciduous forests and southeastern evergreen forests have been maintained during this time, while some vegetation types have changed at the forest stand level primarily due to migration and establishment of species (Delcourt, Delcourt, and Webb III 1982).

Bailey's Ecosystem Classification

Bailey's classification of ecosystems is particularly appropriate for relating climate change information to ecosystems because it identifies the influence of climate and other environmental factors, e.g. landform and elevation that function to create the wide range of ecosystems on the planet. Bailey provides a comprehensive examination and review of the earlier work of several investigators to characterize, delineate and classify the ecoregions of the world (Bailey 1983). Climate is the most significant factor delineating Domain, Divisions and

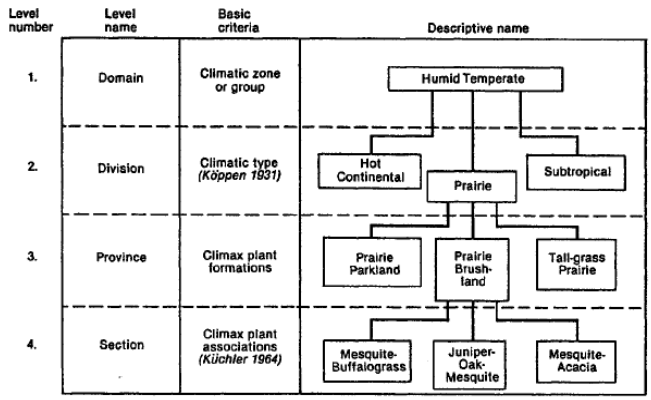

Figure 4.6: A hierarchy to the 4th level for ecosystem regions within the Humid Temperate Domain. Source: (Bailey 1983)

Provinces (Bailey 2004). Combining ecosystem classification with fire regimes has been used to highlight areas of the country in which historic fire exclusion has lead to concerns with ecosystem health and fire risk (Bailey 2010). Appendix F provides Bailey system descriptions to the Province level.

In the Bailey system, the most important climatic regime factors determining the distribution of ecosystems are daily and seasonal fluxes of energy (as represented by temperature) and moisture (precipitation and evapotranspiration). At the macroscale or subcontinental scale, ecosystems are defined and controlled primarily by the macroclimate…i.e. the climate that prevails at a scale just beyond the modifying influence of landform and vegetation. The effects of latitude, continental position and elevation combine to form the climatic zones used as the basis for defining ecosystems, also known as ecoregions (Bailey 2004).

Seasonal differences generally increase with latitude, altitude and continentality. As the climatic regime changes, so does the hydrologic cycle, as reflected in the stream flow of rivers located in different climatic regions. For example, no water flows in creeks located in the warm, dry summer region of California during summer and fall, but in winter and early spring, groundwater contributes to stream flow.

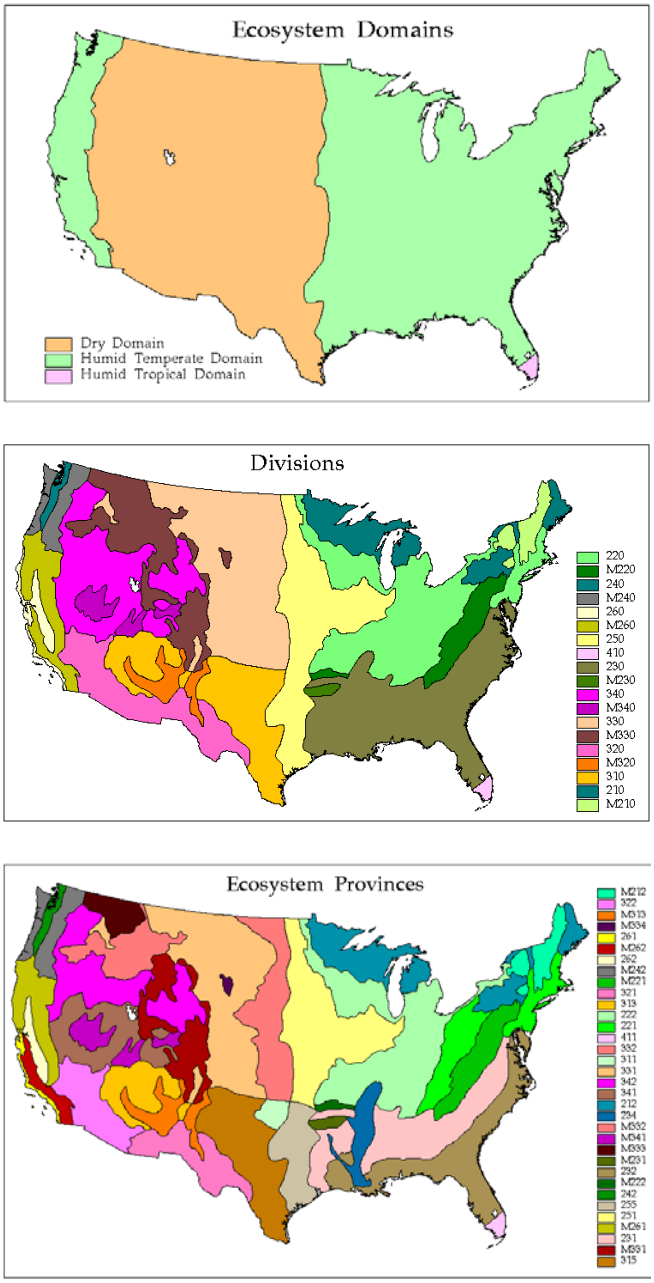

Figure 4.5 a,b,c: Bailey Ecoregion System: Domains, Divisions, and Provinces. Source: http://www.fs.fed.us/land/ecosysmgmt/ Downloaded June 1, 2011

Climate acting over time profoundly affects landforms and erosion cycles. Such effects are evident when we contrast the angularity of arid land topography of the Colorado Plateau with the rounded slopes of the humid Blue Ridge Mountains. Plants and animals have adjusted their life patterns to the basic environmental cycles produced by the climate. Whenever a marked annual variation occurs in temperature and precipitation, a corresponding annual variation occurs in the life cycle of the flora and fauna. Climate helps to determine the distribution, frequency, and density of lightning ignitions.

Bailey describes a hierarchical order of ecoregions (Figures 4.5 and 4.6) established by defining successively smaller ecosystems within larger ecosystems (Bailey 1983).

Domains - Subcontinental areas, termed Domains, are identified on the basis of broad climatic similarity, such as having dry climates. Climate is emphasized at the broadest level because of its overriding effect on the composition and productivity of ecosystems from region to region. Domains are quite heterogeneous and are further subdivided into Divisions, again on the basis of climatic criteria.

Divisions – Divisions correspond to areas having definite vegetational affinities (prairies or forest) and falling within the same regional climate, generally at the level of the basic climatic types of Koppen (1931) or of Thornthwaite (Agee 1993; Thornthwaite 1948). Within a division, one or several climatic gradients may affect the potential distribution of the dominant vegetation strata. Within the arid zone, for example, deserts that receive only winter rain (Sonoran Desert) can be distinguished from those that receive only summer rain (Chihuahuan Desert). Within the steppe zone, a semiarid steppe (short-grass prairie) climate that has a dry summer season and occasional drought can be distinguished from and arid semi-desert (sagebrush) climate that has a very pronounced drought season plus a short humid season. A southern (coniferous forest) climate and northern (forest-tundra) climate can be distinguished within the Subarctic Division of the Polar Domain.

Provinces - Divisions are subdivided into **provinces** on the basis of the climax plant formation that geographically dominates the upland area of the province. Boundaries drawn on the basis of this broad criterion are often coincident with the major soil zones which, therefore serve as supplemental criteria for establishing the limits of provinces. Highlands are distinguished due to the influence of altitude where the climactic regime differs substantially from that of adjacent lowlands. Thus, further differentiation is made according to landform to distinguish mountains with altitudinal zones from lowland plains e.g. highland province and lowland province.

Sections - Provinces are further subdivided into sections on the basis of differences in the composition of the climax vegetation type. The summer green deciduous forest of eastern North America is fairly homogeneous, its main structural features from east to west and north to south; but, five discrete climax associations can be recognized on the basis of floristic composition: oak-hickory, beech-maple, Appalachian oak, mixed mesophytic, and maple-basswood. Sections correspond generally to the potential natural vegetation types of Kuchler (Kuchler 1964; Küchler 1985).

Topographic Influence - Landform with its geologic substrate, surface shape and relief modifies climate regime at all scales within macroclimatic zones. It is the cause of the modification of macroclimate to local climate. Landform provides the best means of identifying local ecosystems. These interactions are most important in fire-prone ecosystems in steep terrain where vegetation regulates physical processes. Fire behavior and pattern are influenced by effects of topography and firebreaks. Vegetation-landscape patterns viewed at any point in time reflect both short- and long-term relations among fire, vegetation, soil, hydrology, and geomorphic factors. Landforms, especially in areas of high relief, may strongly influence fire regimes (Morgan et al. 2001).

Topographic variation (e.g. aspect, slope position, and elevation) influences precipitation, runoff, temperature, wind, and solar radiation, which in turn affect flammability through fuel production and moisture (Daly, Neilson, and Phillips 1994; Dague 1930). Climate and topography are two important controls on spatial patterns of fire disturbance in forests globally, via their influence on fuel moisture and fuel production. Climate and topography have been demonstrated as key

drivers of fire disturbance patterns (Swetnam and Betancourt 1998), (Taylor and Skinner 1998). However, fire does not necessarily respond consistently to these controls across space and time. Climatic and topographic controls on fire may interact with each other adding further complexity to the processes that drive fire patterns (Rollins, Morgan, and Swetnam 2002). Furthermore, the majority of research on spatial patterns of fire has been carried out in the western U.S. in dry ponderosa pine forests or in wet subalpine and boreal forests. Flatley examined influence of topography in the southern and central Appalachian Mountains and concluded moisture appears to influence topographic patterns of fire, with drier elevations, slope positions and aspects burning most frequently (Flatley, Lafon, and Grissino-Mayer 2011).

Ecosystems, Fire Regimes, Fuels, Ignition and Climate

The spatial and temporal relationships of fire, ecosystems and climate are reasonably well understood at the domain and division level where climatic influences (primarily temperature and precipitation) are relatively homogeneous. At the province and section level the influence of climate is more difficult to apportion in comparison to the influence of other factors such as landform, vegetation type and structure, ignition sources (lighting), seasonality, etc (Bailey 2010; Malamud, Millington, and Perry 2005; Morgan et al. 2001).

Morgan describes the complex nature of the interaction of fire, climate and ecosystems that provides key insight and perspective about the spatial and temporal relationships and limits of our understanding (Morgan et al. 2001). Fire has a profound influence on ecosystem structure, composition and function at temporal scales from years to decades and centuries, and from spatial scales from local to regional and continental. Because fire regimes will be sensitive to changing climate, understanding the relationship of temporal and spatial scales and links to ecosystem classification at the Division and smaller scales, will be crucial to managing fuels, fire risk, and ecological impacts of fires upon ecosystems now and in the future (Lenihan et al. 1998; Clark 1988; Flannigan, Stocks, and Wotton 2000; Hessl 2011; Marlon et al. 2009).

Many aspects of fire will be affected by changes in climate, as has been evidenced in the past, with fire regime response to climate change varying over time and space (Malamud, Millington, and Perry 2005; Bailey 2010; Morgan et al. 2001). Fire will be a catalyst for change in vegetation, perhaps prompting more rapid change than would be expected based on plant response to the changes in temperature and moisture availability. Thus fire may be more important than the direct effects of climate change on species fitness and migration (Flannigan et al. 2009). Fires may be more frequent where climate warms; and fires may become more severe and more extensive as predicted for boreal forests (Overpeck et al. 2011; Kasischke, Williams, and Barry 2002; IPCC WG II 2007; Goldammer and Price 1998; Weber and Flannigan 1997). Changes in regional and local fire regimes will be affected by changes in ignition (lightning), vegetation change and land use patterns and land management practices. Climate change appears likely to affect lightning and its capacity for fire ignition. Lightning producing convective storms are expected to become more frequent and intense with 21st Century warming. One study suggests a 30% increase in global lightning activity for the warmer climate and a 24% decrease in global lightning activity for the colder climate. This implies an approximate 5–6% change in

global lightning frequencies for every 1°C global warming/cooling (Price and Rind 1994; Christian et al. 2003; Keeley 1982; Macias Fauria and Johnson 2006; Reeve and Toumi 1999).

*"1. **Alteration of fuel condition.** This pathway might occur where ignition sources and fuels are plentiful but fuel moisture is high, such as moist temperate and boreal forest (Meyn et al. 2007). Changes in the length of the fire season (e.g. a longer or shorter snow-free season) (Westerling et al. 2006) a shift in the fire season (Turetsky et al. 2011), higher frequency or longer duration of drought/pluvial events (Ze'ev Gedalof, Peterson, and Mantua 2005), or increased/decreased frequency of fire weather conducive to fire spread (Podur and Michael Wotton 2010), could all alter fuel condition."*

*"2. **Changes in fuel loading**. Episodic or incremental increases in fuel loading as a result of other disturbances (e.g. insect outbreaks or mortality events) or changes in the density or connectivity of fuels as a result of warmer and/or wetter conditions are likely to occur in many regions. In systems dominated by fine fuels (grasslands, shrublands, or woodlands), this pathway could develop in a matter of months or seasons (Meyn et al. 2007). Future aridity and associated decreases in productivity might lead to reduced fire activity in places where fuel continuity is already limited, particularly semi-arid forest or woodland environments. In systems dominated by coarse woody fuels (continuous forests), increases in fuel volume would take decades but could lead to increased fire severity and increased emissions as larger volumes of biomass are consumed. This transition to higher fuel loads is likely to occur in semi-arid forests where precipitation is projected to increase or areas subjected to widespread mortality events (Allen and Breshears 1998), (van Mantgem et al. 2009). Fuel loads may change as a result of climate change altering species composition, vegetation structure, age class, density, and decomposition rates, or as a result of changing fire regimes themselves (de Groot et al. 2003), (de Groot, Pritchard, and Lynham 2009), (Malanson and Westman 1991), (Soja et al. 2007). Similar changes are possible in the absence of climate change, for example as a consequence of land-use change or invasive species."*

*"3. **Changes in ignitions**. Where ignitions are limiting, for example semi-arid forest environments with little convective activity, fuels are dry enough to carry a fire but ignitions are relatively infrequent. Projected warmer temperatures and increased convective activity may translate into increased lightning activity and increases in wildfire (Price and Rind 1994). Although these pathways are not completely independent (e.g. fire in the forests of the coastal Pacific Northwest are likely limited by both ignitions and fuel condition)."*

Source: (Hessl 2011)

Changes in ignition, fuel condition and fuel loading are three pathways through which Hessl (Hessl 2011) proposes climate change may alter fire activity in the future, contending that these are the primary trajectories likely to occur with climate change. Analysis of the trends from one landscape to another can help understand the relative roles of land use, climate, vegetation, and topography and their complex interplay. The relative influence of land use and other human influences can be separated from the influence of climate and local site conditions (Morgan et al. 2001; Malamud, Millington, and Perry 2005; Lenihan et al. 2003; Bailey 2010; Lertzman, Fall, and Dorner 1998). Ecosystem classifications are based on climate and vegetation, which interact with fire and vary over space and time. The direct and indirect effects of fires on ecosystems vary across temporal and spatial scales.

Considerations of change, variability, pattern and scale, which have emerged as central concepts for understanding the interweaving of climate change, fire regimes, and ecosystem classifications, are discussed in detail in Chapter 5. Table 4.1 provides a transition to Chapter 5 by conceptual temporal linking of Bailey's scales (which are spatial but not temporally variable) to fire and climate/weather scales (which display both temporal and spatial variability). For example, regional drought may encompass the province or division ecosystem scale, extend over many months to years, and result in multiple fire seasons over several years.

Table 4.1 - Conceptual Scales

Bailey Ecosystem	Temporal	Climate/Weather	Fire
Localized Province/Section	Days- Weeks	Local fire weather (1-5 days) Local dry spells	Fire Event
Province through Division	Several Months through Years	Seasonal/Interannual (El Nino, La Nina, PDO...regional climate) Extended Drought *(months to years)*	Fire Season through Multiple Fire Seasons
Domain/Division/Province	Multiple Years (*varies by Ecosystem)*	Climate Change (*decades and longer*)	Fire Regime Change

Bailey's ecosystem classification system provides a standardized hierarchical method of describing ecosystems that enables the application and interpretation of interaction of climate and ecological processes. At the smallest scale (sections) ecosystems are described within the context of larger systems (provinces, divisions, domains). This perspective enables assessing the geographic patterns and connection between actions at one scale and effects at another scale. Standardized classifications are important for ecosystem planning nationally and globally (Bailey 2008; Grossman et al. 1998), and for relating ecosystem characteristics to fire regimes (Bailey 2010; Littell et al. 2009) and fire planning (Rollins, Keane, and Parsons 2004; Rollins 2009). Ecosystem classification systems facilitate understanding of ecosystem evolution, i.e. where ecosystems were located in the past (Delcourt and Delcourt 1988) and how ecosystems may change under future climate conditions. It is important to note that although ecosystem classification systems are contemporary descriptions of ecosystems fixed in time, multiscale classification systems provide the standardized foundation of geographic patterns upon which future changes in ecosystems can be projected, analyzed and characterized. Future ecosystem

species assemblages may not have an antecedent legacy, which adds additional complexity to future projections.

Fire regimes are not static. Fire regimes will change as climate varies. Fire will be a catalyst for change in vegetation, perhaps prompting more rapid change than would be expected based on plant response to the changes in temperature and moisture availability. Fire may be more important than the direct effects of climate change on species fitness and migration (Flannigan et al. 2009). The expected increase in ignition from lightning associated with climate change coupled with increasing fuel abundance and changing fuel condition (fuel moisture) suggests pathways by which climate may influence interaction of fire and ecosystems in the future.

Chapter 5: Change, Variability, Pattern and Scale

In this Chapter we discuss change, variability, pattern and scale relating fire to the major Earth system components (terrestrial ecosystems and the atmosphere/oceans) affecting it. Ecological classification systems, ecosystem disturbance theory and scale considerations are particularly useful for understanding the scales at which climate patterns influence ecosystem patterns and shape fire regimes (Bailey 1983; Bailey 2010; Turner 2010; Falk et al. 2011). Statistical measures of fire variability, such as Wildland Fire Area Burned (WFAB) and climate variability such as the Palmer Drought Severity Index (PDSI) are linked through use of ecological classification at appropriate scales (Maxwell and Soulé 2009; Littell et al. 2009). Ecological classification is also employed both in paleoecological studies to map the pattern and scales of ecosystem change in response to climate change and for designing the National Ecological Observing Network (NEON)[16] to monitor and map patterns of ecosystem responses to future climate change (Delcourt and Delcourt 1988; Adams and Faure 1997; Lowman, D'Avanzo, and Brewer 2009). Weather pattern classifications, which correlate synoptic scale[17] weather patterns with fire conditions, are the basis for fire weather forecasting (Schroeder et al. 1964). Severe fire conditions have long been associated with extended periods of hot, dry weather that are caused when normal day to day weather variation ceases as systems stagnate over a particular region and atmospheric Rossby Wave[18] blocking patterns set in (Beals 1916; Skinner et al. 2002; Stenseth 2002; Girardin et al. 2009; Lau and Kim 2011). Observed increases in the duration and intensity of summer heat waves and drought are likely an early example of 21st Century climate warming that are expected to amplify (Barriopedro et al. 2011; Diffenbaugh and Ashfaq 2010; Anderson 2011). Evidence is expanding that these regional scale patterns of interannual atmospheric variability are in turn manifestations of variability in larger scale patterns of coupled atmosphere-ocean (AO) circulation, with the El Nino Southern Oscillation (ENSO) as the best-known example (Alencar, Nepstad, and del Carmen Vera Diaz 2006; Hessl, McKenzie, and Schellhaas 2004; Schoennagel et al. 2005; Trouet, Taylor, et al. 2009). Variability and change of AO patterns affect fire in many areas of the world (Heyerdahl, Morgan, and Riser II 2008; Heyerdahl et al. 2008; Yocom et al. 2010). Better information about changes in the variability of ENSO and other coupled AO patterns is becoming available from improved satellite observation and GCM simulations (Giorgi and Francisco 2000; Tebaldi and Knutti 2007). Concepts of change, variability, pattern and scale help inform our understanding of how fire-atmosphere interactions impact fire regimes for specific fire prone regions of the United States (Abatzoglou and Kolden 2011; Moritz et al. 2010; Moritz and Stephens 2008; Swetnam and Anderson 2008). We consider these concepts in combination with fire regime and ecosystem classification to be

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[16] A map of ecological domains used in NEON can be found at http://www.neoninc.org/domains/overview

[17] The synoptic scale in meteorology (also known as large scale or cyclonic scale) is a horizontal length scale of the order of 1000 kilometres (about 620 miles) or more. http://en.wikipedia.org/wiki/Synoptic_scale_meteorology

[18] Atmospheric Rossby waves are large-scale meanders of the jet stream and a major influence on surface weather systems. These meanders govern cyclones and anticyclones that are responsible for day-to-day weather patterns at mid-latitudes.

critical components for applying fire history and climate change information in 21st Century fire planning and management.

Fire – Global Process, Regional Characteristics, Local Events

Fire is a global ecosystem process consisting of local combustion events with organizing regional characteristics. Fire is an example of disturbance, or relatively discrete event disrupting an ecosystem, happening over relatively short intervals of time (hours to months) and altering ecosystem state and trajectory. Fires arise from a combination of abiotic (ignition source) and biotic (adequate fuel) conditions subject to climate forcing. Changes in both ignitions and fuel conditions are expected to result from 21st Century climate change (Hessl 2011). Disturbance **regimes**, in contrast to disturbance **events**, refer to the spatial and temporal dynamics of disturbances over a longer period of time. Disturbance regimes include characteristics such as spatial distribution, frequency, return interval, size, intensity, and severity (Turner 2010). Fire interactively links atmosphere, biosphere, and human Earth system components through time and at local, regional and global spatial scales (Lavorel et al. 2007). Those interactions may be categorized as top-down (>10^4 ha) and bottom-up (10^{-4} - 10^4 ha)[19] regulation respectively represented by 1) synchrony of fire- and non-fire years at regional and larger scales for climatically similar areas, and 2) spatial heterogeneity in fire occurrence, extent, or severity (Falk et al. 2011). This bimodal view is also reflected in weather/climate and fire event/fire regime couplings, and indicates the scale above which climate change information is likely to be most applicable for fire use.

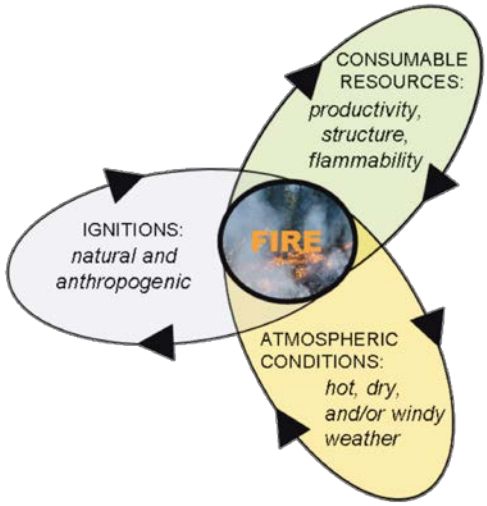

Figure 5.1: The pyrogeography framework includes vegetation resources to consume, atmospheric conditions, and ignition agents. Each of these components is spatially and temporally variable, as illustrated by arrows, and it is their coincidence that results in fire activity. Variation in their coincidence generates different fire regime types (e.g., frequent low-intensity surface fire versus infrequent high-intensity crown fire). Source: (Max A. Moritz, Krawchuk, and Parisien 2010)

Fuel availability and atmospheric components of the combustion process combine to make fire possible for some period of time at some location on Earth throughout the year. Throughout the fire history of Earth, characteristics (e.g. intensity, area burned, fuel consumed, carbon emitted) of fire events have been determined by local conditions existing at the time of the events.

[19] 10^4 hectares = 10^8 meters^2 approximates the boundary of Bailey Divisions and Provinces and centers on the mesoscale region used in paleoecology studies (Delcourt and Delcourt 1988)

However, those existing local fuel and atmospheric conditions are themselves variable in response to both local and larger scale forcing factors. The cumulative impacts of fire events, as described by fire regimes and fire statistics, vary over time in response to climate variability, climate change and other larger scale forcing factors. Paleoecological studies show that past climate variability has impacted fire regimes over large areas of the United States that are now expected to experience significant 21st Century drought (Swetnam and Anderson 2008; Stahle et al. 2011). Combining knowledge that 21st Century global climate change is altering fire regimes with knowledge that fire control mechanisms influenced by climate variability (such as ignition, fire spread, fuel moisture and fuel production) are likely to change, points to information pathways fire planners can follow (Flannigan et al. 2009; Gedalof 2011).

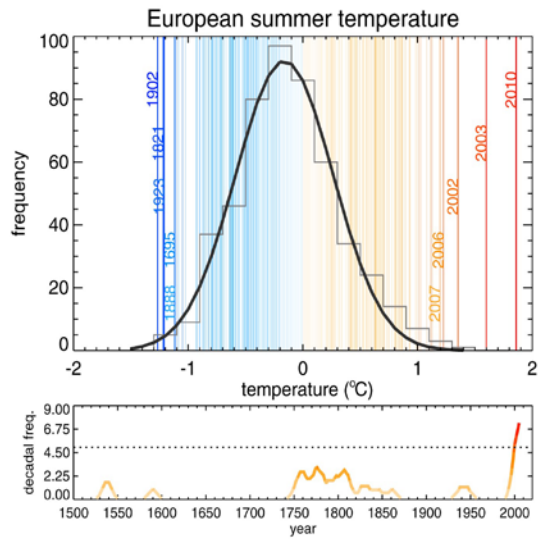

Figure 5.2: European summer temperatures for 1500-2010. The five warmest and coldest summers are highlighted. Grey bars represent the distribution for the 1500-2002 period with a Gaussian fit in black. The bottom panel shows the running decadal frequency of extreme summers, defined as those with temperature above the 95th percentile of the 1500-2002 distribution. A 10-yr smoothing is applied. Dotted line shows the 95th percentile of the distribution of maximum decadal values that would be expected by random chance. Source: (Barriopedro et al. 2011)

Numerical descriptions of interactions between weather and vegetation condition, such as the National Fire Danger Rating System (NFDRS), track developing fire potential (Bradshaw et al. 1984). When shown in map form[20], characteristic regional scale fire patterns display variability and change that help to inform fire planning. Planners use known seasonality of regional fire occurrence and severity risk (Roads et al. 2005), which on average vary for given regions of the Earth in cadence with annual global climate cycles modulated by interannual variability (Schultz 2002). Modulation of the average annual fire signal for a given region results when atmosphere-ocean systems (El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multi-Decadal (AMO) and North Atlantic Oscillation (NAO) are examples) synchronize to produce extended periods of heat and drought that yield greater concentrations of vigorous fire events than usually experienced under average fire regime conditions for a given region (Carmona-Moreno et al. 2005).

Climate variability that increases normally experienced regional fire season lengths, through earlier starts and/or later closures, expands the seasonal fire risk window and has resulted in

[20] For example see http://www.wfas.net/images/firedanger/fd_class.png (last accessed June 1, 2011)

increases in overall fire activity and large fire events in recent years (Westerling et al. 2006; Spracklen et al. 2009). Since anthropogenic activities are modifying both the average state and variability of climate, we observe and project 21st Century climate change both as trends of atmospheric variables such average temperature and as temperature variability expressed by a change of the probability distribution of temperature (Sierra et al. 2010). Utilization of increasingly available climate change information for fire management and planning purposes will benefit from recognition of scale dependent patterns of atmospheric and ecosystem change and variability shown to impact fire regime characteristics.

Individual fire events result from the interaction of atmospheric and ecosystem components that supply the oxygen, ignition source (now often human supplied) and fuel needed to initiate and support combustion at a given place and time (Moritz, Krawchuk, and Parisien 2010; Pausas and Keeley 2009). These interactive linkages take place at different temporal and spatial scales, and are subject to variability in the component parts. Local conditions during the time and over the location of a fire determine ongoing event characteristics. Variability in those local conditions affects the vigor and impact of a given fire event, and is subject to larger scale forcing factors. When viewed globally, the accumulation of fire events over periods of years or longer is strongly correlated with ecosystem classifications and synchronized with seasonal climate and weather cycles (Bond, Woodward, and Midgley 2005). Observed variability may in turn prove to be a signal of change or simply variation that in time proves to be not statistically significant. Climate and fire regime "change" can thus only be attested to in hindsight, when sufficiently long record lengths (normally 30 years for climate) become available to account observed variability as statistical change. While local atmospheric and vegetative (weather and fuel) conditions drive fire behavior and other fire characteristics during fire events, those events, in turn, cause measurable and lasting variance in the atmosphere and vegetation. Over time, the cumulative effects of multiple fire events can result in changes in the atmosphere, ecosystems and fire regimes (Delcourt, Delcourt, and Webb III 1982; Page et al. 2002; Beerling and Osborne 2006; Arora and Boer 2005; Agee 1998; Johnstone et al. 2010; Bowman and Haberle 2010; Kasischke et al. 2010).

Pattern and Scale in Fire History

Paleo-fire history studies provide an increasingly comprehensive record of fire variability and change linked to climate and ecosystem variability and change (Belcher et al. 2010; Marlon et al. 2008; Enache and Cumming 2009). The combustion process itself has not changed since land plants began to diversify and evidence of fire appeared during the Silurian period (443 to 417 Mya) of Earth history (Pausas and Keeley 2009). Fire events have since been oxidizing biomass wherever vegetation grows. Fossil charcoal records, which had dated earliest fire to the late Devonian (417 to 354 Mya), now show that wildfires have been occurring on Earth for ~ 420 million years, since there was sufficient vegetation to serve as fuel and sufficient atmospheric oxygen to support the combustion process (Scott 2000; Scott 2008). Atmospheric O_2 concentration has varied during the 540 million years of the Phanerozoic[21] eon, resulting in significant variation in fire activity (Berner and Canfield 1989). Since terrestrial vegetation arose on Earth, the atmosphere has supplied the oxygen (current atmospheric O_2 concentration of

[21] The Phanerozoic is the current eon of geologic time, during which abundant animal life has existed. http://en.wikipedia.org/wiki/Phanerozoic

20% exceeds the minimum 13% required for combustion), and the lightning (currently estimated as ~ 44 flashes per second occurring globally) ignition source needed for combustion to be supported (Scott and Glasspool 2006; Christian et al. 2003). Paleoecology and paleoclimatogy studies combine to extend our understanding of antecedent conditions backward through the ~ 420 million years of Earth history where fire has functioned as a major shaper of ecosystem evolution (Bowman et al. 2009).

Fire has been a common but variable part of the evolution of existing terrestrial ecosystems, both shaping and shaped by changing ecosystems (Whitlock, Moreno, and Bartlein 2007; Bond and Keeley 2005). Fire history traditionally focused on one or more, local scale fire events, but has more recently expanded our knowledge of larger scale climate controls on vegetation composition and fire regimes (Whitlock and Bartlein 2003). The paleo record of fire history prior to 5,000 years ago (before human dominance), includes examples of occurrence of scale relevant fire regime change consistent with our current understanding. For example, recorded increases in charcoal deposits from increased burning of grasses are associated with grassland replacement of woodlands facilitated by increased fire size and frequency during a shift of climate conditions towards more monsoonal structures (Keeley and Rundel 2005). The paleo record associates the regional scale appearance 8 Mya of savannahs, as a major terrestrial biome, with climate-coupled fire accelerated forest loss and grassland expansion through multiple positive feedback loops that promoted drought and more fire (Beerling and Osborne 2006). During the Holocene, humans have increasingly changed the occurrence envelope of combustion events by supplying alternative ignition sources, among many other practices (Lavorel et al. 2007).

Individual fire events add up to a fire history on Earth that has been closely aligned with regional to global scale climate variability and change through geologic time, as recorded in tree ring and other paleo records (Scott 2000; Swetnam and Betancourt 1998; Bowman et al. 2009). Paleo studies have proven to be an invaluable source for increasing our understanding of the historic relations between climate and fire (Marlon 2009). Early breakthrough paleo studies, for example of fusains and fire scars, while limited in ability to provide spatial and temporal scale information by sample size and analytical resolution, form the scientific foundation for what is now a growing catalogue of paleo records relating past fire and climate (Crickmay 1935; Dieterich and Swetnam 1984). Paleo information about both climate and fire is providing increasingly wider spatial coverage and finer temporal resolution that correlates fire with atmospheric conditions present when combustion took place (Stahle et al. 2011; Swetnam and Anderson 2008; Marynowski and Simoneit 2009).

While each fire event results from the local scale interaction of atmosphere and ecosystem components at the time of the event, antecedent and post-ignition conditions, deriving from a variety of scale dependent interactions of atmosphere and ecosystems components, govern the eventual impact of each fire (Hostetler, Bartlein, and Holman 2006). Scale dependent atmosphere-ecosystem interactions also govern post-ignition fire development and ecosystem impacts (Flannigan et al. 2005; Randerson et al. 2006; Abatzoglou and Kolden 2011). Those interacting atmosphere and ecosystem components in turn display ongoing temporal and spatial variability and change. McKenzie et al (McKenzie, Miller, and Falk 2011) note: "…*spatial and temporal scales of fire are intuitively observable and comprehensible by humans, although*

reconciling them quantitatively with the spatiotemporal domain of "normal" ecosystem processes introduces profound challenges, chiefly because of the different rates and scales at which processes occur. Planning at scales that are too fine will fail to account for disturbances that arise outside small management units; planning at scales that are too coarse…will not account for local patterns of spatial and temporal variability.... fires occur as "events" over time spans of days to months, the postfire ecosystem response can unfold over decades to centuries." 21st Century climate change is a forced global scale disturbance that, by definition, arises outside of management units and interacts with ecosystems to yield impacts realized at all scales of/on those management units. This is the tension inherently faced by managers/observers seeking to employ past, present and future climate variability and change information to inform place based fire planning under 21st Century climate change.

Observer Perspective

Discussions of scale, variability and change can relate to the scale of observer, the process observed and the scientific framework employed by the observer. As we look backward or forward in time, and upward in spatial scale, from the fire event, discussion becomes more dependent on atmospheric and ecosystem observations, processes and frameworks. Fire scientists are expanding knowledge of fire history from past local scale fire events to patterns with regional to larger scale linkages to past climate (Swetnam and Baisan 2003; Swetnam and Anderson 2008; Whitlock, Moreno, and Bartlein 2007; Whitlock et al. 2010). Climate scientists are, in turn, providing knowledge of the underlying atmospheric pattern drivers that forced past warming periods, such as the Medieval Climate Anomaly (MCA) (Trouet, Esper, et al. 2009; Xoplaki et al. 2011; Graham et al. 2007; Bird et al. 2011). Increased occurrence, duration and amplitude of these atmospheric forcing patterns will likely be a manifestation of 21st Century climate change (Schär et al. 2004; Xie et al. 2010; Liang Xu et al. 2011; Woodhouse et al. 2010). Correlating fire history and other ecosystem histories with past climate change, such as observed high fire occurrence associated with severe summer

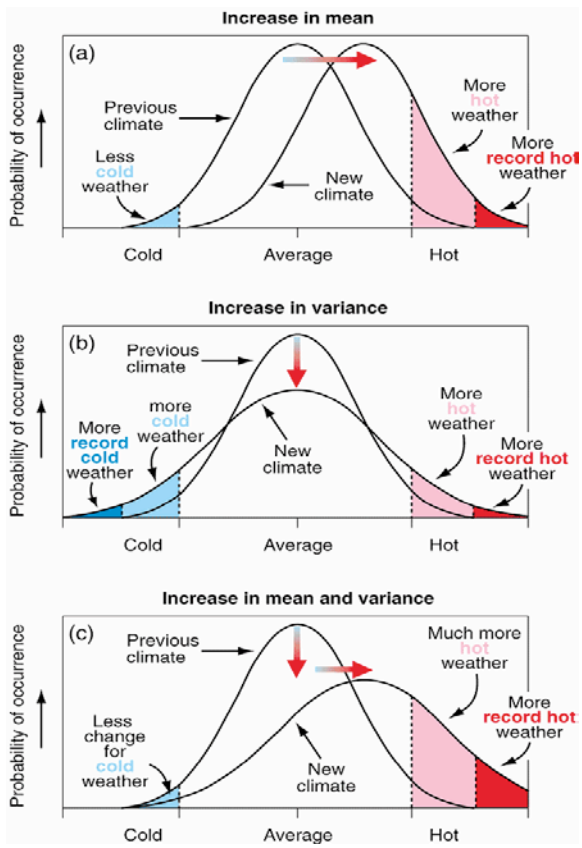

Figure 5.3: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: (IPCC WG I 2001)

droughts in the northern Rockies during the MCA, informs our understanding of fire-climate interaction at regional and larger scales (Umbanhowar Jr. 2004; Miao et al. 2007; Whitlock, Shafer, and Marlon 2003; Brunelle et al. 2005). Recent fire outbreaks and regional scale vegetation desiccation, with resulting ecosystem impacts, have similarly been associated with atmospheric patterns that force increased occurrence, duration and amplitude of record-breaking summer heat waves (Pereira et al. 2005; Della-Marta, Haylock, et al. 2007; Yurganov et al. 2011; Xu et al. 2011; Lewis et al. 2011; Barriopedro et al. 2011; Lau and Kim 2011). These observations of both lengthier periods of hot weather and increased numbers of record hot weather events demonstrate statistical climate change in the making, with both increasing mean and variance of recorded temperature (Schär et al. 2004; Della-Marta, Haylock, et al. 2007; Kuglitsch et al. 2010).

Fire and Weather Patterns

Fire history informs our understanding of antecedent forcing of current conditions. Large fires and fire complexes have long been known to be associated with regional scale drought and synoptic scale weather patterns (Beals 1916; Crimmins 2006; Schroeder and Buck 1970; Skinner et al. 2002; Pereira et al. 2005). Even though large fires result from only a very small percentage of total fire ignitions, they are the cause of high fire suppression costs, result in large area burned, significantly impact the atmosphere, serve as ecosystem shapers, and display strong climatic forcing (Calkin et al. 2005; Balshi et al. 2009; Abatzoglou and Kolden 2011; Wiedinmyer and Neff 2007; Fromm et al. 2010; Bond, Woodward, and Midgley 2005; Yang, He, and Gustafson 2004; Moritz 1997; Heyerdahl, Brubaker, and Agee 2002). Large fires in extreme fire years drive area burned statistics (a surrogate measure of fire impacts) and correlate with atmospheric circulation patterns and climatic processes (Abatzoglou and Kolden 2011; Gedalof, Peterson, and Mantua 2005). Statistically significant regional scale increases in large fire activity in the western United States starting in the mid-1980s are associated with climate change forcing from warmer spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006). We have now accumulated sufficient data to view two regional scale climate variations (increased frequency, intensity and duration of summer heat waves and earlier spring snowmelt) as manifestations of ongoing

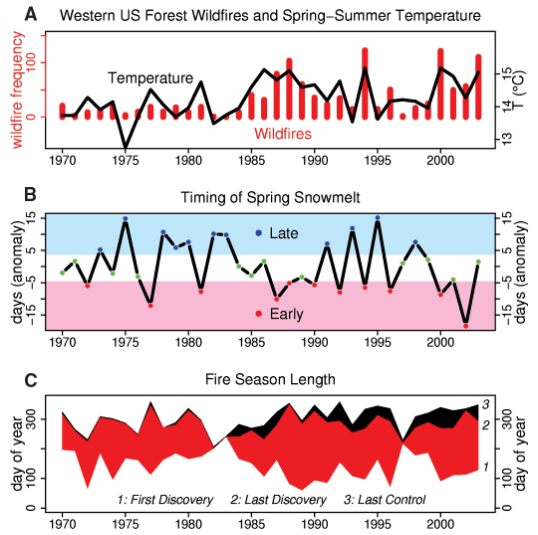

Figure 5.4: A) Annual frequency of large (9400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western United States (line). (B) First principle component of center timing of streamflow in snowmelt dominated streams (line). Low (pink shading), middle (no shading), and high (light blue shading) tercile values indicate early, mid-, and late timing of spring snowmelt, respectively. (C) Annual time between first and last large-fire ignition, and last large-fire control. Source: (Westerling et al. 2006)

climate change that fire history associates with increased fire activity.

Pattern and Scale Concepts

The concepts of pattern and scale are central to our understanding of: ecosystem processes, ecosystem classification, invasive species and biodiversity, weather and climate, demographic influences, fire history and fire regimes (Levin 1992; Gosz and Sharpe 1989; Holdridge 1947; Adams and Faure 1997; Bailey 1985; Powell, Chase, and Knight 2011; Lorenz 2006; O'Neill et al. 2010; Delcourt, Delcourt, and Webb III 1982; Grissino Mayer and Swetnam 2000; Morgan et al. 2001). Scale considerations are thus necessary for understanding how present climate influences ecosystems and fire, for interpreting fire history recorded during past climate conditions, and for applying fire history knowledge to describe expected changes in fire regimes resulting from 21st Century climate change (Whitlock and Bartlein 2003; Whitlock, Moreno, and Bartlein 2007; Whitlock et al. 2008; Whitlock et al. 2010). A scaling issue inherent in providing and applying climate change information useful to fire managers is that while climate change is an integrative global scale response to GHG and other forcings, biological systems respond to local conditions (Parmesan et al. 2011). Those local conditions describe the sum of measured component parts that are themselves subject to variation and change in space and time. Local and regional conditions existing at the time of an individual disturbance event (a fire for example) influence responses to the event, which may be quite different to responses that would be experienced under a new disturbance regime, or at different local and regional scales (Clark 1996; Powell, Chase, and Knight 2011). Disturbances, with fire being a ubiquitous example, play important roles in landscape ecology, an ecology subfield that focuses on the reciprocal interactions between spatial pattern and ecological processes (Hessburg and Agee 2003; Turner 2005). Processes operating at various temporal and spatial scales generate landscape patterns (Urban, O'Neill, and Shugart Jr 1987). Fire has been an important process coupling biotic and abiotic ecosystem components, for example insect outbreaks and snow pack retention in evolving landscape patterns for over millions of years of Earth history, while the combustion

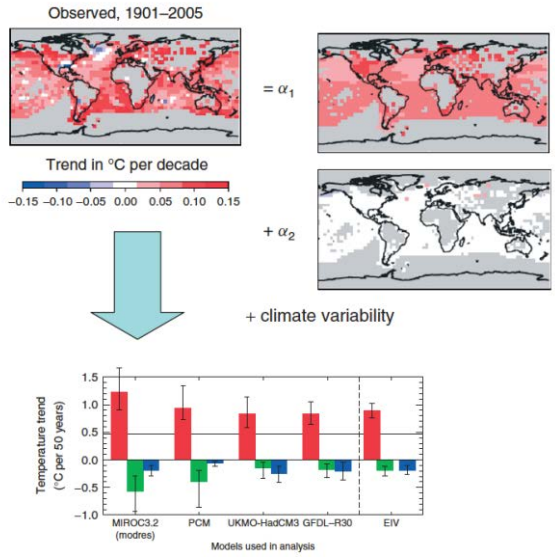

Figure 5.5: Schematic for detection and attribution. The observed change (shown here: pattern of temperature change over the 20th century, left) is composed of a linear combination of fingerprints for all forcings combined (top, right) and for natural forcings only (center right, this combination allows rescaling of natural vs anthropogenic fingerprints in simulations of the 20th century) plus residual, unexplained variability. Source: (Hegerl and Zwiers 2011) (Reprinted with permission from Ref 2. Copyright 2007 Cambridge University Press)

process itself has not undergone change (Pugh and Small 2011; Clow 2010; McKenzie, Miller, and Falk 2011).

Atmosphere and Ecosystem Change and Variability

Concepts that relate event variability to regime change are similar for the atmosphere and ecosystems. Fires and weather are the respective events, or realizations, whose ensemble[22] statistics define fire regimes and climate, and whether or not they are changing over time. You can not reverse calculate from the climate or fire regime statistics to get the actual distributions of fire and weather events that produced them, although some information can be gained by applying power law approaches (McKenzie, Miller, and Falk 2011). Climate change projections based on ensemble forecasts[23] provide envelopes containing multiple projected outcomes (events), which derive from slightly varying initial condition inputs (Tebaldi and Knutti 2007). We can use future climate and fire regime projections as envelopes that inform us about the shape, based on historical distributions, of future weather and fire event statistics. In doing so, we need to assure that pattern scaling information used to describe future variability and change of fire, atmosphere and ecosystem interactions applies reasonably linearly across the scales that are used (Mitchell 2003). Climate scientists attribute observed and projected climate change signals to parts due to external forcing and internal variability, with such factors as GHG emissions, solar cycles and orbital variation assigned to external forcing and ENSO, PDO, and NAO assigned to internal variability (Hegerl and Zwiers 2011). We can likewise view the Bailey classification system scale transition from Division to Province as a transition in dominance from external climate forcing to internal variability (due to terrain and other factors), or a division between Macro (10^{11} m^2) and Meso (10^9 m^2) ecosystems (Bailey 1983; Bailey 1985; Rowe and Sheard 1981). This line of reasoning points to an expectation that GCM climate change predictions resulting from GHG and other external forcing factors will reasonably allow for projection of change and variation of Bailey Division scale patterns through the 21st Century. Province and smaller scale change and variation will require climate information associated with ENSO and other factors that contribute to internal climate variability.

Since fire is a nexus of coupled atmospheric and ecosystem processes, the scale concepts governing fire and these contributing processes guide our application of information needed to describe fire regime changes resulting from climate change. Scale recognition is also critical when applying this information for fire planning and management, since information may only be available at scales that are not normally preferred for a particular fire activity (Saxon et al. 2005). While scale considerations are necessary, they can also be complex and confusing when they traverse multiple disciplines and uses. In view of this inherent communication problem, we sought a practical common ground, for discussion and information display, in the widely used

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[22] An ensemble (also statistical ensemble or thermodynamic ensemble) is an idealization consisting of a large number of mental copies (sometimes infinitely many) of a system, considered all at once, each of which represents a possible state that the real system might be in. http://en.wikipedia.org/wiki/Statistical_ensemble

[23] Ensemble forecasting is a numerical prediction method that is used to attempt to generate a representative sample of the possible future states of a dynamical system. http://en.wikipedia.org/wiki/Ensemble_forecasting

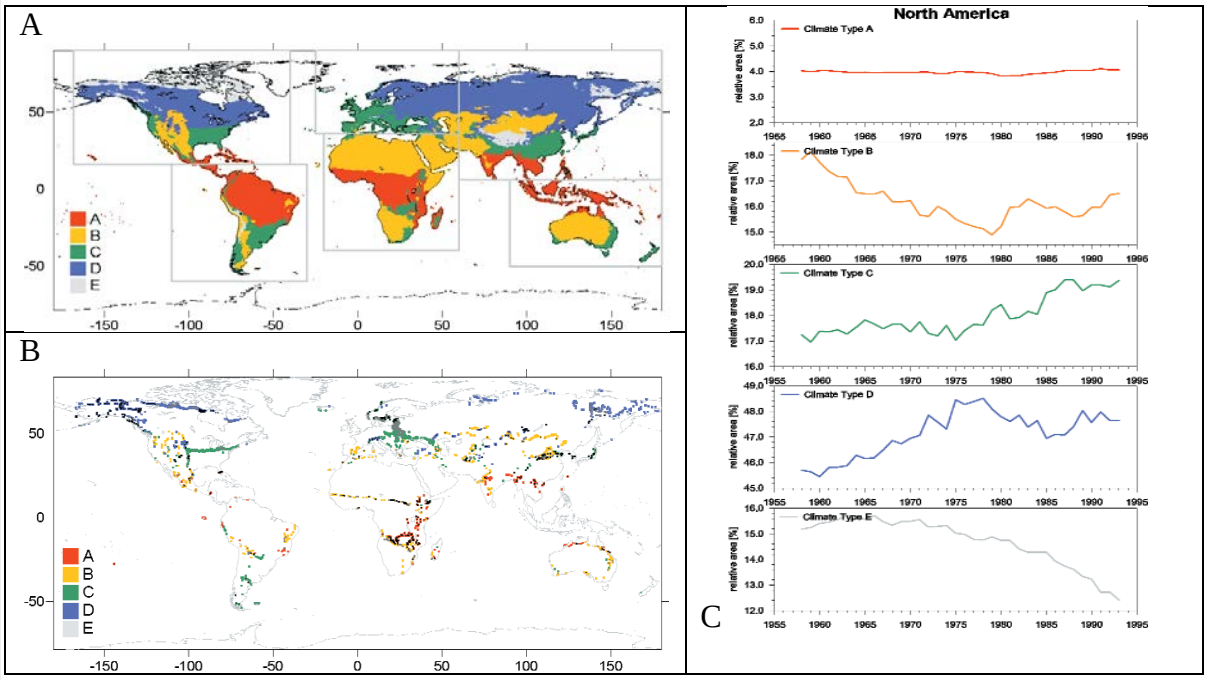


Figure 5.6: Characterizing Global Climate Change by means of Köppen Climate. a: Spatial distribution of the five main Köppen climate types determined for the period 1951 – 2000. Rectangles indicate the continental sub-regions for which selected results are presented. b: Köppen climate types for the period 1986 - 2000 for gridcells with different Köppen climates within the periods 1951 – 2000 and 1986 – 2000, respectively. c: Time series of the relative area (percentage of the resp. continental land area excluding Greenland and Antarctica) occupied by the main Köppen types. Source: (Beck et al. 2005)

Bailey system[24] for classifying ecosystems. Consensus agreement reached at our February 2010 Workshop (see Appendix A) was that fire history and climate information at the Bailey Division level would serve as a useful and sufficient scale for information focus, while information at the Domain level was useful only for broad discussion purposes, and information, when available, at the Province level would be most preferred.

To illustrate the information scale consequences involved in Domain-Division-Province discussions (see Figures 5.5a, b, c), consider that Bailey's system is derived from the Köppen climate classification system with the Bailey Division equivalent to the Köppen climatic type (Bailey 1983; Ackerman 1941; Kottek et al. 2006; von Köppen 1931; von Köppen and Geiger 1930). Beck et al. (2005) applied 50 years (1951-2000) of digitized climate data in sliding 15-year intervals using the five main Köppen climate types (which are equivalent to Bailey Domains - see Figure 5.5d). He demonstrated the temporal variability in the mapped types (see Figure 5.5e) and graphing (see Figure 5.5f) changes in relative climate type area for each continent (see Figure 5.5g for North America). Beck found *"…Most striking for North America appear distinct reductions of polar E and as well dry B climates. Simultaneously the area occupied by the temperate C and boreal D climate types increases."*

[24] http://www.fs.fed.us/land/ecosysmgmt/index.html

How do the Bailey Domain, Division and Province level scales compare with scales employed in paleoecology, atmospheric and fire fields? A recent study of wildfire area burned (WFAB) in the western United States from 1916 to 2003 employed Palmer Drought Severity Index (PDSI) and WFAB statistics at the Bailey Province level (Littell et al. 2009; Karl 1986). They concluded that WFAB is substantially controlled by climate, with current season temperature and dryness having the greatest effect in most Provinces but previous year moisture and PDSI drought being better WFAS predictors in others. For managers, knowledge of climate-fuel interactions at the Bailey Province level will help refine larger scale (Division and Domain level) information deriving from climate change patterns. For example, the management impacts of fire related ecosystem change that result from the interaction of elevated CO_2 levels, warmer temperatures, nitrate deposition and fire on invasive species competition are informed by integrating global scale external forcing (e.g. CO_2 growth) with internal climate variability (e.g. ENSO) through Province/Section scale (fire event) processes (Dukes et al. 2011). Even the largest individual fire events rarely burn beyond or cross more than one or two Bailey Provinces.

Ongoing research is helping us to better determine patterns of where and when the relative weight of human influence is greater than that of past climate change, or where human influence is a major factor in observed changes in historical patterns of global biomass burning (Ruddiman, Kutzbach, and Vavrus 2011; McWethy et al. 2010; Marlon et al. 2008). While fully acknowledging the importance of human influences, we concentrate this synthesis on fire as it relates to atmospheric and ecosystem process interactions described at different time and space scales. Descriptions of the pattern and scale of ecosystem (and fire regime) responses to past

IPCC (IPCC WG I 2001) Definitions

Climate change: Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Patterns and Indices of Climate Variability – *"Climate variability is not uniform in space; it can be described as a combination of some "preferred" spatial patterns. The most prominent of these are known as modes of climate variability, which affect weather and climate on many spatial and temporal scales. The best known and truly periodic climate variability mode is the seasonal cycle. Others are quasi-periodic or of wide spectrum temporal variability. Climate modes themselves and their influence on regional climates are often identified through spatial teleconnections, i.e., relationships between climate variations in places far removed from each other."* (A. Kaplan in Blunden, J., D. S. Arndt, and M. O. Baringer, Eds., 2011: State of the Climate in 2010. *Bull. Amer. Meteor. Soc.*, **92** (6), S20–S26)

climate change better inform our understanding of how fire regimes are likely to change in response to 21st Century climate change (Guetter and Kutzbach 1990; Flannigan et al. 2005; Spracklen et al. 2009). Such descriptions help us understand the patterns and scales of interaction between atmosphere and ecosystem processes (Mitchell 2003). Bailey classifications and fire regimes are well correlated (Malamud, Millington, and Perry 2005; Bailey 2010).

The terms "variability" and "change" also depend on the scale of the process described, and the processes themselves. Climate variability (see box for IPCC Definition) refers to variations in the mean state and other statistics of the climate on all temporal and spatial scales beyond that of individual weather events. Climate change refers to a statistically significant variation either in the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Weather (temperature, wind direction and speed, humidity, sky cover, etc.) "changes" minute to minute, hour to hour, day to day and location to location. But unless the statistical envelope that describes the long term mean and variability of those weather components changes over time, what we call changeable weather in our every day language is just inherent variability in weather patterns and component variables. The Intergovernmental Panel on Climate Change (IPCC)[25] and The American Meteorological Society (AMS)[26] provide online glossaries for reference. The IPCC defines climate change as referring to *"…a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer."* It defines climate variability as referring to"… *variations in the mean state and other statistics --- of the climate on all spatial and temporal scales beyond that of individual weather events."* No comparable glossaries are as readily available from the ecological community to offer definitions of the terms "change" and "variability". For fire, we often observe that fire behavior, spread, intensity, fuel consumption and all other fire variables "change" over the period of a fire event or incident, when "variation" is a more accurate description of what is going on.

Time Scales of atmospheric Effects on Fire

Atmospheric and fire processes are coupled across time and space scales used to describe patterns of climate, weather, ecosystems and fire (Macias Fauria, Michaletz, and Johnson 2011). Climate can impact fire by changing the three components of the pyrogeography framework (see Figure 5.1) affecting fire through changes in weather, ignition and fuel (Hessl 2011). She examines a broad array of factors, including influences on fuel, to derive general relationships of fire-climate-vegetation interaction at different time scales. At short time scales (several hours to days) local weather conditions, temperature, relative humidity, precipitation and wind speed influence how fires burn by affecting fuel conditions and heat transfer for combustion of those fuels (Albini 1976; Anderson 1982; Rothermel 1983). On time scales of weeks to months, meteorological variables may influence the duration of the fire season, frequency of lightning ignitions, and the abundance of fine fuels (Goldammer and Price 1998; Wotton and Flannigan 1993). On scales of years to decades, climate may influence fire regimes by altering net primary

[25] Intergovernmental Panel on Climate Change (IPCC) AR4 Annex 1 Glossary (last accessed June1, 2011 http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf

[26] American Meteorological Society (AMS) Glossary of Meteorology (last accessed June 1, 2011) http://amsglossary.allenpress.com/glossary/browse

productivity, decomposition, vegetation structure, vegetation composition, density, fuel loading, and fuel connectivity across a landscape (Meyn et al. 2007).

Given that climate and weather clearly interact with wildfire over a range of spatial and temporal scales, Gedalof (Chapter 4 in McKenzie, Miller, and Falk 2011) conceptually models climate interaction with processes of vegetation development and topography, to characterize regimes and patterns of wildfire throughout North America.

Gedalof described timescales of atmospheric effects on fire,

- Short (synoptic to seasonal)
    - Fine fuel moisture,
    - Ignition frequency, and
    - Rates of wildfire spread,
- Intermediate (annual to interannual)
    - Relative abundance and continuity of fine fuels, as well as
    - The abundance and moisture content of coarser fuels,
- Long (decadal to centennial)
    - Assemblage of species that can survive at a particular location,

These are a useful construct for conveying information about climate/weather impacts on fire, and one we now employ to transition to considerations of atmosphere/climate/weather scale, variability and change of import to fire. Adapting the Gedalof timescales to atmospheric processes yields

- Short (synoptic to seasonal)
    - Traditional fire weather (Schroeder and Buck 1970)
    - Seasonal fire planning aids (Roads et al. 2005);
- Intermediate (annual to interannual)
    - El Nino Southern Oscillation (ENSO) (Schoennagel et al. 2005)
    - Pacific Decadal Oscillation (PDO) (Le Goff et al. 2007)
    - Atlantic Multidecadal Oscillation (AMO) (Sibold and Veblen 2006)
    - North Atlantic Oscillation (NAO) (Goodrick and Hanley 2009); and
- Long (decadal to centennial)
    - Climate induced ecosystem changes that cause revisions of Bailey ecosystem Domain, Division and Province maps (Saxon et al. 2005).

The various Intermediate scale atmosphere-ocean coupled circulation patterns (referred to as "oscillations" by atmospheric scientists – see box and Appendix E) drive fire activity trends on a multi-year basis, underlie fire-weather teleconnections, and are increasingly recognized as critical links for understanding year to year regional weather "anomalies", including those associated with prolonged summer heat waves and drought (Cooke et al. 2007; Simard, Haines, and Main 1985; Mote and Kutney 2011; Della-Marta, Luterbacher, et al. 2007; Della-Marta, Haylock, et al. 2007). 21st Century changes in these Intermediate scale circulation patterns are seen as key elements leading to increased summer heat waves and droughts and help us to better

understand historic patterns of fire-ecosystem interactions (Meehl and Tebaldi 2004; Diffenbaugh and Ashfaq 2010; Kaye 2011). Short time scale atmospheric prediction derives from Numerical Weather Prediction (NWP) technology (see Chapter 2 discussion) with improving accuracy in multi-day fire weather forecasts that inform fire event management, and extended length forecasts inform seasonal fire planning (Pereira et al. 2005; Roads et al. 2005). Long time scale atmospheric prediction derives from General Circulation Model (GCM) technology (see Chapter 2 discussion) with improving resolution (space and time) and increasingly realistic modeling of contributing Earth system component interactions that determine climate change.

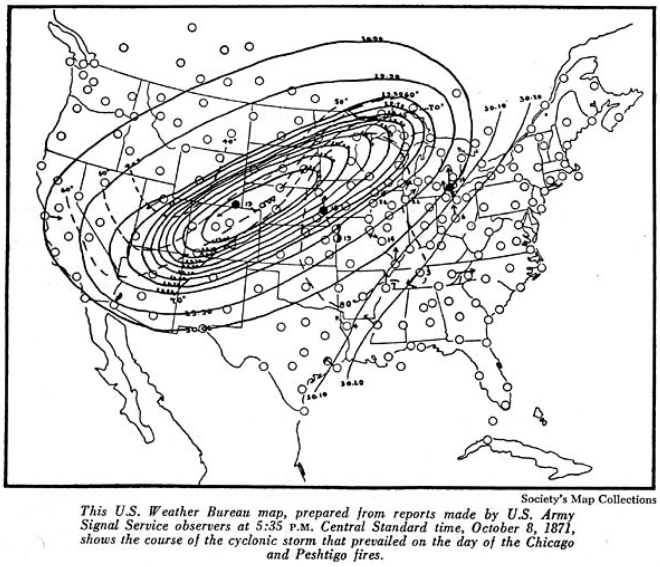


Figure 5.7: U.S. Weather Bureau Map for 5:35 pm CST October 8, 1871. Source: This image courtesy of the Wisconsin Electronic Reader

Much of our discussion of ecosystem scale, both in the present and in the past, has had a spatial focus, whereas discussion of atmospheric scaling places more focus on temporal scale issues. This is because if weather and/or climate never changed with time or place we would have little concern with them, although biodiversity and other ecosystem components would be different (Cadena et al. 2011). Initial human observation of weather/climate was from a small fixed place orientation in space over hours to years of time. It was not until commercial 18th Century ocean spanning navigation took hold that we began to place our locally observed time varying weather and climate in a global context of moving atmospheric systems that could be monitored and tracked in space and time (see Chapter 2). The advent of meteorological instrumentation and the telegraph provided the opportunity to display in map format moving pressure driven weather systems. The deadliest fire in American history (Peshtigo, Wisconsin) and the most infamous urban fire (Chicago) started on the same October 8, 1871 evening, both driven by the same synoptic weather system (Flesch 2009; Schroeder et al. 1964). Schroeder (1964) analyzed surface and upper-air weather patterns and computed daily fire load indexes for a 10-year period (1951-1960) using a pre-cursor of the NFDRS to categorize critical fire weather patterns for the contiguous 48 States aggregated into 14 regional groups. Schroeder concluded, *"…periods of critical fire weather are associated with a relatively few synoptic weather patterns and types."* A high amplitude example of one of those types created the drought, high temperatures and high winds that produced the Peshtigo and Chicago fires (Lorimer and Gough 1988; Schulte and Mladenoff 2005).

In the ensuing five decades after Schroeder's pioneering work, synoptic weather typing produced comprehensive information about synoptic scale weather patterns related to fire activity in various regions of the world (Schroeder et al. 1964; Crimmins 2006; Amiro et al. 2004; Skinner

et al. 2002; Pereira et al. 2005; Takle et al. 1994; McCutchan 1978; Benson, Roads, and Weise 2008). By having linked synoptic scale weather patterns to various aspects of the fire business, improvements in general weather forecasting, resulting from advancements in Numerical Weather Prediction (NWP) (see Chapter 2), satellite observation, radar, lightning detection and other incremental improvements, have lead directly to improved fire weather information. For fire planners, improved accuracy of 24 to 96 hour range forecasts and progression into seasonal outlooks[27] were of critical importance. Those seasonal outlooks are transitional between the Short (synoptic to seasonal) and Intermediate (annual to interannual) timescales.

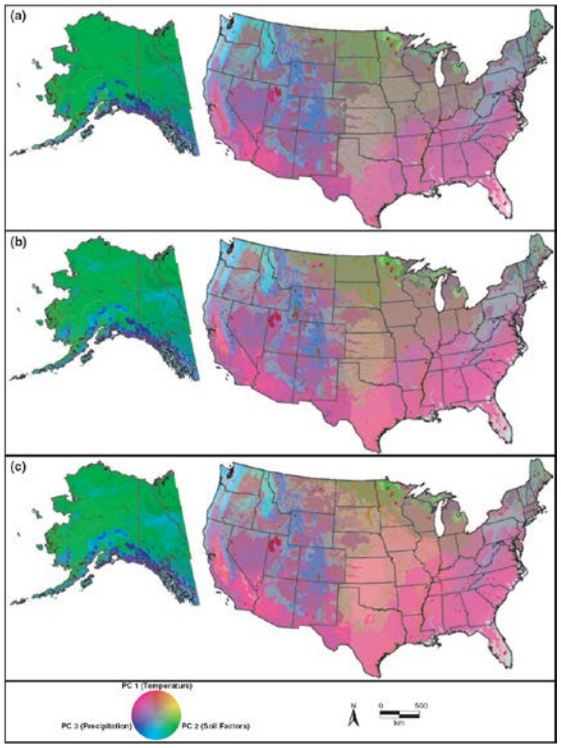


Figure 5.8: Five hundred domains in the continental USA and north-western Canada are depicted in colours reflecting the relative dominance of temperature factors (red), edaphic factors (green) and precipitation (blue). Colour assignments are consistent regardless of when or where each domain occurs. (a) Current conditions. (b) Scenario B2, moderate greenhouse gas increases. (c) Scenario A2, rapid greenhouse gas increases. Source: (Earl Saxon, Barry Baker, et al. 2005)

PDSI is a variable familiar to the fire community that is subject to large multi-year to decadal variations with demonstrated United States summer drought teleconnections to ENSO (Taylor and Beaty 2005; Dai, Trenberth, and Karl 1998; Rajagopalan et al. 2000). A recent study of global drought during the last millennia statistically links United States drought to ENSO with expected 21st Century increases in aridity. While the United States has avoided prolonged drought during the last 50 years, persistent droughts are expected during the next 20 to 50 years (Dai 2011). Monitoring variability and change of PDSI patterns over the next several decades will provide a crucial linkage between patterns of climate change that manifest through changes in ENSO (and other Intermediate scale atmospheric patterns) variability and ensuing changes in Intermediate to Long scale ecosystem and fire patterns. Several studies have found relationships among regional fire history, PDSI and Intermediate scale atmospheric oscillatory patterns, although for some fire regimes short (synoptic) scale factors are more dominant (Trouet et al. 2006; Trouet et al. 2009; Hessl, McKenzie, and Schellhaas 2004; Keeley 2004).

Long scale (decadal to centennial) patternsof climate forced ecosystem change resulting from a

[27] See National Wildland Significant Fire Potential Outlook http://www.predictiveservices.nifc.gov/outlooks/monthly_seasonal_outlook.pdf - last accessed June 1, 2011

21st Century doubling of CO_2 concentrations are projected to affect a substantial portion of global forests and Bailey ecoregion patterns (Melillo 1999). Holocene records (see Chapter 4 discussion) demonstrate ecoregion variability and change associated with climate change. GCM outputs for CO_2 scenarios have been used to model future eastern U.S. forest tree distribution patterns with substantial resultant, yet variable, change (Iverson and Prasad 2002). Iverson and colleagues have since refined and expanded their efforts, with increasing tree mortality attributed to drier and hotter conditions (Iverson and Prasad 1998; Iverson et al. 2010). With the rate of 21st Century climate change outstripping previous Holocene change rates, *"…the rate of migration typical of the Holocene period (50 km/century in fully forested condition), less than 15% of the newly suitable habitat has even a remote possibility of being colonized within 100 years."* (Iverson, Schwartz, and Prasad 2004). Considering (see Chapter 2 discussion) that global GHG emissions continue to exceed those envisioned in the IPCC scenarios used by GCM, with irreversible climate change and a potential quadrupling of CO_2 concentrations by the end of the 21st Century, significant ecosystem change will inevitably result. While fire is well understood in regard to Short (synoptic to seasonal) atmosphere patterns, and is increasingly being understood in relation to Intermediate (annual to interannual) scale atmospheric forcing, fire is not generally incorporated in models of Long (decadal to centennial) term climate forcing of ecosystem change (Solomon et al. 2010). It is recognized that *"…climate change can effect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides"*, and fire regimes are likely to change in response to Long-term climate forcing, there has been little or no work that explicitly incorporates fire as an expediter of decadal to centennial scale ecosystem adjustment to 21st climate change (Dale et al. 2001; Flannigan et al. 2009).

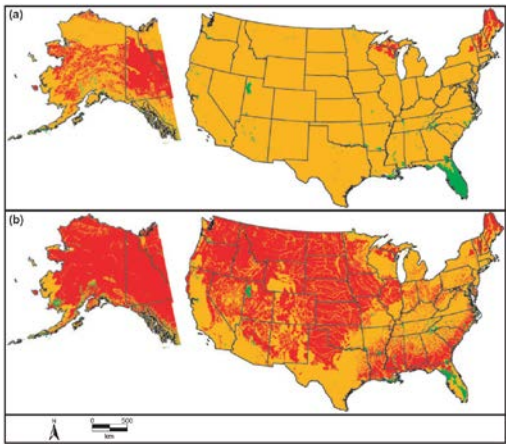


Figure 5.9: Current locations of domains that disappear from the study area are shown red, those that decrease are shown orange and those that increase are shown green. (a) Scenario B2, moderate greenhouse gas increases. (b) Scenario A2, rapid greenhouse gas increases. Source: (Earl Saxon, Barry Baker, et al. 2005)

21st Century Patterns

What patterns can we expect to see for U.S. ecosystems by the end of the 21st Century as they respond to climate change? Saxon et al. (2005) considered that question by mapping the distribution of 500 environmental domains in the year 2100 for GCM projections under the IPCC A2 (reaching concentrations of 735–1080 ppm CO_2 in 2100) and B2 (reaching concentrations of 545–770 ppm CO_2 in 2100) scenarios (see Chapter 2 discussion and (Nakićenović and Swart 2000)), with the A2 scenario concentrations more closely matching CO_2 emissions trajectories currently being experienced. The 500 environmental domains used are based on climatic, edaphic and topographic attributes that are the foundation of Bailey and other widely used biogeographic ecoregions, but, unfortunately for our purposes, are not identical. They determined *"…that 500 domains are enough to separate large uniform areas, such as the south-*

eastern Atlantic seaboard, without creating excessive numbers of units in small heterogeneous areas, such as the Rocky Mountains." Their results (see Figures 5.8, 5.9, 5.10) show significant environmental domain change for B2 scenario projections and almost nationwide domain change for A2 scenario projections by the year 2100.

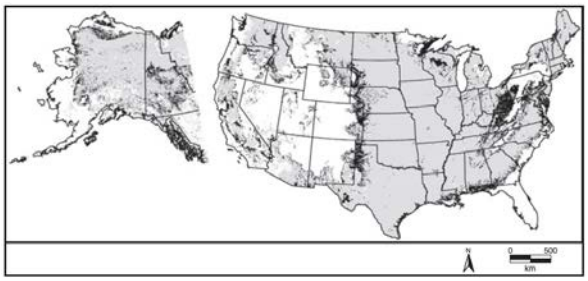


Figure 5. 10: Future locations of domains that have no current analogue in the study area. (White) Future locations of domains that currently exist, although not necessarily at these locations (Grey) Non-analogue domains that appear under both Scenario A2 and Scenario B2. (Black) Addition non-analogue domains that appear under Scenario A2 only. Source: (Saxon et al. 2005)

In this Chapter we have attempted to provide an overview of the change, variability, pattern and scale considerations that influence fire and its interactions with the atmosphere and ecosystems. We have noted the importance of fires that have occured through a considerable period of Earth history as local events and that fit within a larger context of fire as global process. Fire has exhibited regional scale patterns in time and space that relate to climate change and variability. We suggest that that the Bailey Division scale is currently the most appropriate spatial scale for which meaningful climate change information is likely to be available for fire planning use. We further suggest that it is useful to consider atmospheric information at the Short (synoptic to seasonal), Intermediate (annual to interannual), and Long (decadal to centennial) scales suggested by Gedalof (McKenzie, Miller, and Falk 2011). There is a long and valuable record of information on fire-atmosphere interactions that can inform our understanding of the factors governing fire events, their cumulative impact over time, and how they are being affected by 21st Century climate change. Our understanding of variability, change, pattern and scale gained from long observation of fire-atmosphere interaction at the Short scale is helping us to identify how Intermediate scale atmospheric patterns, such as those associated with ENSO, effect patterns of annual through interannual fire variability. At Long time scales, we remain dependent on knowledge of historic changes in ecosystem pattern and variability in response to climate change to infer that fire (and other disturbances) will play an increasing role in the future. Future ecosystem changes can be mapped and monitored at the Bailey Division level.

Chapter 6: Fire History and Climate Change - The View from Ecosystems

Introduction

In this Chapter, we focus on fire history from an ecosystem perspective. We divide our discussion of fire history of the United States broadly into the Eastern and Western clusters. For the purposes of this synthesis document, the boundary between Eastern and Western is the Domain boundary between the Bailey's Humid Temperate Domain (200) and the Dry Domain (300) shown in figure 6.1. This ecological boundary is west of and roughly parallel to the Mississippi River. The East-West boundary divides the central grasslands primarily along two different Bailey's divisions, the Prairie Division 250 to the east and the Temperate Steppe Division 330 to the west. The boundary between Humid Temperate and Dry Domains broadly reflects the climatic differences between the eastern, west coast and interior western US. Population density is also reflected by these climate domain footprints, with ~85% of the U.S.

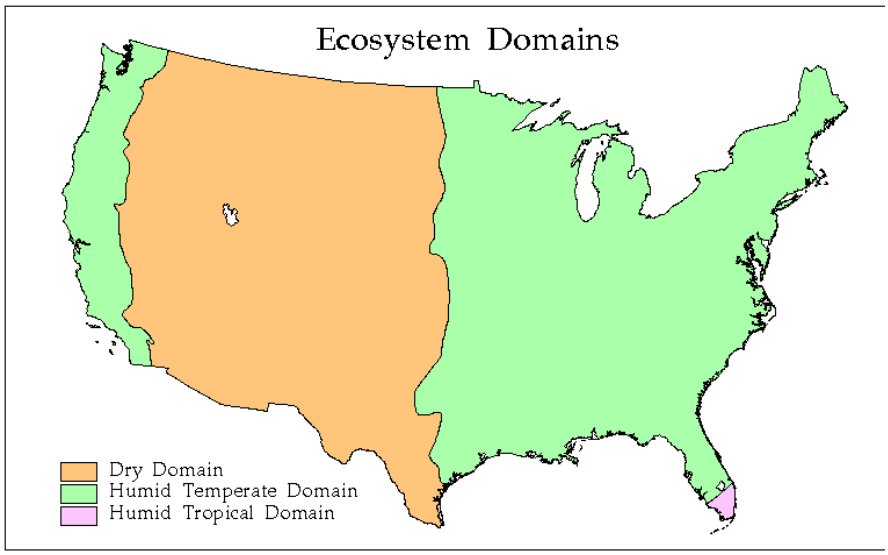


Figure 6.1: Bailey Ecosystem Domains, General Dilineation of Eastern and Western US Fire History

population resideing in areas mapped as eastern ans west coast Bailey Humid Temperate Domains. Thus, the ecosystem view starting at the Bailey domain level aligns with the climate and demographic drivers of fire history. We will discuss fire patterns in Alaska and Hawaii in the section on the Western US. The boundary between Humid Temperate and Dry Domains broadly reflects the climatic differences between the eastern and western US.

While an ecosystem perspective is facilitated by using a Bailey, or other, ecosystem classification, history additionally requires a time perspective. When undertaking this review and synthesis of fire history in the United States the question arises as to how far back in time it is relevant to examine fire history and changing fire regimes. While longer time periods were

covered in earlier Chapters, we will restrict this fire history Chapter to the Holocene epoch, which includes the period of time since the last ice age (about 12,000 years before present (BP)) and sufficiently covers the development of all terrestrial ecosystems currently found on Earth. Looking at fire history over this extended period also gives insight into the changes in fire regimes as they relate to past climate and vegetation and to human impacts in different regions. Changing climate and human expansion combined to alter North American fire regimes as the last ice age ended. Significant additional changes in historic fire regimes began ~ 400 to 500 years ago in the Eastern US with the onset of European settlement. With westward expansion, beginning ~ 200 years ago, fire regime changes became more rapid in the Western US. Contemporary land use change, such as urban development, continues to alter fire regimes.

Fire History of the eastern United States may be viewed as being segmented chronologically into six somewhat overlapping time periods: the **Holocene** beginning about 10-12 thousand years BP at the end of the last ice and continuing today, the **pre-European settlement** period extending into the 1500's, the **Early Settlement** period (1500s- 1800s), the **Industrialization/Agriculture** period, (1800s-1900s), the **Fire Suppression** period (1920s-1980s) and the **Fire Management** period (1980's-present).

The Holocene Epoch began as Earth exited its latest glacial period. The Holocene Epoch has witnessed the rise of human civilization, the increase in human populations and associated impacts of the human species, from Native Americans to European settlers, associated agricultural and industrial expansion, including all written history and the overall transition

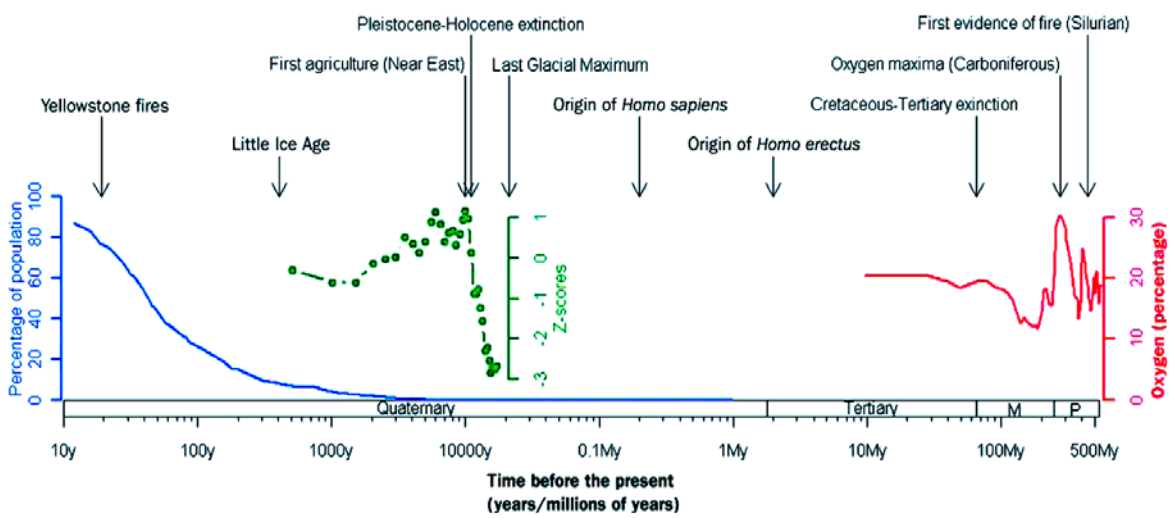


Figure 6.2: Temporal position of key moments in the history of life (time in logarithmic scale). The blue line denotes the proportion of the human world population relative to 2006 (left y-axis). The red line is the atmospheric oxygen concentration (percentage; right y-axis) from 10 million to 550 million years BP. Green dots are the standardized global charcoal values (Z scores) averaged at 500-year intervals (standardization over the interval 4000 to 100 years BP; which indicates changes in the fire regime from 170,000 to 500 years BP. Abbreviations: BP, before the present; M, Mesozoic; P, Paleozoic. Source: (Pausas and Keeley 2009)

toward urban living in the present era. Figure 6.2 provides a broad temporal context from which

to view the history of fire and the evolution of human populations and helps set the scope of this synthesis of fire history and climate change.

The increase in human populations associated with Holocene drying has raised a debate about whether major modifications to vegetation in the last 6000 to 7000 years are more the result of human activities than they are of climatic changes. Similarly, it is often difficult to distinguish between ignitions arising from humans versus natural lighting sources in Holocene fire-regime changes. How landscapes might have looked without any human impact is very difficult, if not impossible, to know, because human presence on the landscape predates contemporary vegetation and climate; the rise in human civilization occurred simultaneously with Holocene warming, and both climate-driven and human driven changes have shaped our current landscape. (Pausas and Keeley 2009)

Native Americans used fire extensively throughout the Holocene in the eastern US. Inhabitants of North America throughout the Early Holocene (12,500-10,500 BP) and Mid-Holocene (10,500-9,500 BP) used fire for hunting animals, collecting nuts, and encouraging pioneer plant species. They burned the landscape during the fall and winter when smaller mobile bands congregated for communal hunts of mastodon, bison, and caribou. They used ring fires to trap game within a circle where they could be more easily hunted and point fires to drive game towards a natural barrier such as a river where they could be captured more easily. In the late Holocene fire was used to clear and maintain areas for maize, grasses to attract game and pasturage, ease of travel, and on occasion for defensive and warfare purposes (Fowler and Konopik 2007).

CULTURAL PERIOD	CHARACTERISTIC USE OF FIRE
Clovis (12,500 - 10,500 BP)	Hunting megafauna
Paleo-Indian (10,500 - 9,500 BP)	Hunting
Archaic (8,000 – 2,800 BP)	Hunting, clearing fields and maintaining ecotones
Woodland (2,800 – 1,300 BP)	Preparing seedbeds, encouraging pioneer species
Mississippian (1,300 – 400 BP)	Clearing maize fields

Table 6.1: Characteristic Use of Fire by Native Americans in the South. Source: (Fowler and Konopik 2007)

The use of fire by Native Americans throughout the Holocene is an important part of the history of fire in the US and information about their use of fire provides valuable understanding and perspective on their influence on the role of fire in ecosystems. Questions remain regarding the population density of Native Americans in North America prior to European settlement. The population estimates for Native Americans give insight to the spatial scale of fire use and the extent of their influence on ecosystems and fire regimes. Current estimates of Native American

population in North America in 1492 span a range from 3.7 to 4.4 million at the low end to a controversial high of 18 million (Denevan 1992; Hamel and Buckner 1998).

The Native American population was reduced by roughly 90 percent in the 1500s due to epidemic disease outbreaks that accompanied European settlement. With the major Native American population collapse, fields needed for food crops and grazing were abandoned along with the use of fire to maintain those fields and open areas. Huge open agricultural areas and depopulated villages were noted by Desoto's expedition in the Carolinas in 1540. With the substantial decline in burning, vast areas in riparian bottomlands reverted to forest (Hamel and Buckner 1998).

Native Americans used fire throughout North America for thousands of years and influenced the ecosystems and fire regimes of the areas they inhabited. Native American use of the natural environment was limited to meeting personal and communal needs rather than intense market oriented production. In estimating the impact of Native Americans on fire regimes in U.S. Day (Day 1953) considered the duration of occupation of the landscape, population density, population concentration and movement, and local patterns of settlement and location of village sites in the northeastern US. Over the past 300 years the influence of Native American burning appears to be increasingly less significant compared to the impact of European settlement and the influence of modern era human activities notably agriculture, industrialization, and contemporary land use. (Pyne 1982)

Fire History Sources

Sources of fire history information include historical and anecdotal accounts, scientific studies, and contemporary fire records. Primary fire history sources include: Historical and anecdotal accounts of Native Americans, explorers, and settlers; studies of paleoclimatology, dendrochronology, lake and bog sediment cores, and contemporary fire records maintained by Federal and state governmental agencies including the National Interagency Fire Center (NIFC), non-governmental fire centers, professional organizations and associations, the academic community, scientific organizations and associations, and conservation organizations.

Written records span only a very small portion (about 500 years) of fire history of the Holocene Those written records provide a very limited perspective on older fire history and fire regimes and the evolution of current fire regimes. Studies of past fire history and fire regimes begin with an understanding of the types of information available and the methods used to acquire and analyze the data. Many natural systems and processes, notably wildfire, are dependent on or influenced by climate. The study and understanding of past climates also provides insight into past fire history. Recent advances in ecological and paleoecological science are providing new understanding of fire history and ecosystem response that is improving our ability to project what potential effects of changing climate on future vegetation and fire regimes will be.

Paleoclimatology (the study of climate prior to instrumental records) provides fundamental insight into essential elements of fire climatology and wildfire activity. Fire history information is provided through several types of proxy data; with tree-ring and charcoal sediment based records proving particulalrly useful. These data sources describe fire regimes at multiple temporal and spatial scales. Tree-ring data provides temporally precise, short-term reconstructions of fire events, usually spanning the last 400 years or less. Charcoal records from

sediments can reconstruct much longer fire histories, but with less temporal and spatial precision than tree-ring records. Because charcoal particles can be carried aloft to great heights and also transported great distances by water, the source of the charcoal may be from distant fires as well as local fires (Day 1953; NOAA (www.ncdc.noaa.gov/paleo/)).

The study of past wildfire activity is greatly facilitated by the study of natural systems and processes which are climate-dependent and which incorporate into their structure a measure of this dependency. These natural systems and processes provide a proxy record of climate. Studies of proxy data are the foundation of paleoclimatology. Ice core data provide measures of biomass burning and are of great importance for understanding Holocene and earlier histories of climate change and ecosystem responses. Knowledge of past climate and related fire history begins with an understanding of the types of proxy data available and the methods used in their analysis (Bradley 1999).

Table 6.2 lists the major types of climatic data available for determining the biological, terrestrial and historical components most relevant to fire history. Each line of evidence differs according to its spatial coverage, the period to which it pertains, and its ability to resolve events accurately in time. The value of proxy data to paleoclimatic reconstructions is very dependent on the minimum sampling interval and dating resolution. These factors determine the degree of detail and interpretation of information that can be derived from the record.

Archive	**Minimal sampling interval**	**Temporal range (order : yr)**	**Potential information derived**
Historical records	day/hr	~ 10^3	T, P, B, V, L, M, S
Tree rings	year/season	~ 10^4	T, P, B, V, M, S
Lake sediments	yr (varves) to 20 yrs	~ 10^4 - 10^6	T, P, B, V, L, M, C_w
Corals	yr	~ 10^4	C_w, L, P, T
Ice cores	yr	~ 5 x 10^5	T, P, C_a, B, V, M, S
Pollen	20 yr	~ 10^5	T, P, B
Speleotherms	100 yr	~ 5 x 10^5	C_w, T, P
Paleosols	100 yr	~ 10^6	T, P, B
Loess	100 yr	~ 10^6	P, B, M
Geomorphic features	100 yr	~ 10^6	T, P, V, L
Marine sediments	500 yr	~ 10^7	T, C_w, P, B, L, M

T = temperature
P = precipitation
C = chemical composition of air (C_a) of water (C_w)
B = information on biomass and vegetation patterns
V = volcanic eruptions
M = geomagnetic field variations
L – sea level
S = solar activity

Table 6.2: Paleoclimatology Proxy Data Characteristics. Source:(Bradley 1999)

Holocene Epoch to pre- European Settlement (12K years BP – 1500s)

Power et al. (2008) provides a comprehensive paleoclimatology study of fire regime change over the past 21,000 years based on over 4000 radiocarbon dates from 405 sites around the globe. Power et al. focus on the role of climate rather than human activity affecting past fire activity. There is in general a positive correlation between human population and fire incidence during the mid-to-late Holocene. During the Holocene, fire activity varied with long-term changes in global use (Power et al. 2008). Global sedimentary charcoal records of fire activity since the last glacial period were synthesized to describe changes in fire activity associated with global and regional climatic controls. Charcoal abundance was used as an indicator of fire occurrence. In North America, charcoal records indicate fire activity during the glacial decline period, from 21,000 to 11,000 BP, was less than we currently experience. However, Marlon Marlon et al. (2006) notes periods of abrupt climate change about 14,000, 13,000 and 11,700 BP marked by large increase in fire activity. These changes in fire activity were not associated with changes in human population.

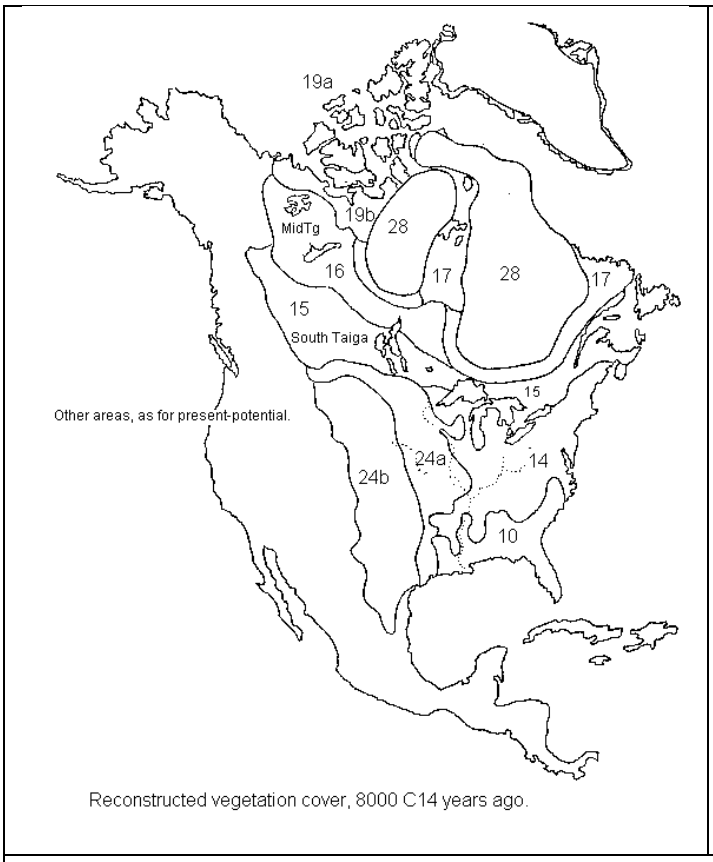
Between 12,000 and 9,000 years BP there was a significant change in fire regimes. 12,000 years BP fire increased from glacial times at sites in northeastern and western North America. By 9,000 years BP, regional charcoal record summaries show greater than-present fire throughout eastern North America with varied fire regimes in western North America. Fire activity varied by region with greater than current levels of fire activity experienced in northeastern North America, while less were experienced in central North America (Marlon 2009). Fire history from a period of significant climate change thus highlights regionally based variability in fire regime responses.

11000-7000 years BP (early Holocene)

This period experienced rapid changes with retreating ice sheets, rising sea level and surface temperature, vegetation changes with reforestation of regions formerly covered by glacial ice., greater than present solar radiation with warmer and drier summers in the Northern Hemisphere. 9000 years BP regional summaries show greater than present fire throughout eastern North America. Predominantly greater than present fire occurred in northeastern North America while less-than present fire occurred in central North America. Records from North America show shifts towards increased fire peaking around 8000 years BP. In western North America these patterns have been attributed to the regional changes caused by increased annual and summer solar radiation. In eastern North America fire began to decrease around 8000 years BP. (Marlon 2009)

6000 years BP to Present (middle to late Holocene)

The middle to late Holocene was a period of changing large-scale controls of fire as summer solar radiation decreased in the Northern Hemisphere, most glacial ice had disappeared and sea levels were approaching near modern position. Seasonal variations were still large enough to induce large regional climatic effects. In addition, increasing human populations may have had a localized role in modifying fire regimes in certain locations. 6000 years BP regional summaries show less-than-present fire in eastern North America. (Marlon 2009)



Reconstructed Vegetation Map Key
10 - warm temperate evergreen forest),
14 - cool temperate forest
15 – southern taiga
16 - mid taiga
17- open boreal woodlands
18 - Semi-arid temperate woodland or scrub (18a = woodland, 18b = scrub),
19 - tundra (19a = sparse tundra, 19b=dense tundra),
23 - Temperate semi-desert (23a=grassy temperate semi-desert, 23b= shrub-dominated temperate semi-desert)
24 - Temperate and montane steppe (24b=sparser, short-grass steppe, 21a=dense tall-grass steppe).
28- Ice sheet and other permanent ice.

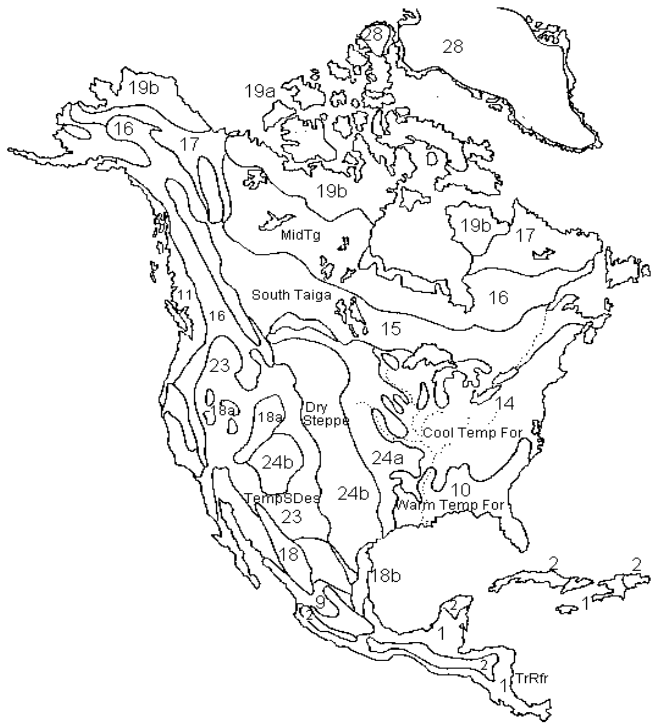
adapted from Adams and Faure, 1997

Figure 6. 3: Reconstructed Vegetation Cover about 9000 BP. Source: (Adams and Faure 1997)

The major factors governing regional climate change since the last ice age are changes in the seasonal and latitudinal distribution of solar radiation, the disappearance of the Northern-Hemisphere ice sheets (and related changes in land-sea geography) changes in sea-surface temperature patterns and variability and changes in atmospheric composition. Decreasing summer solar radiation in the Northern Hemisphere through the late Holocene led to reduced fire activity ~ 3000 year BP as compared to 6000 years BP. By 3000 years BP dominant controls of fire regimes were similar to modern era. Fire was greater than present in the summer-wet regions of the Western US. Sites in North America show near-modern fire regimes around 3000 years BP (Whitlock and Bartlein 2003; Marlon 2009; Marlon, Bartlein, and Whitlock 2006). During the mid-to late Holocene, from 8,000 to 3,000 BP, many sites indicate greater-than-present or near-present activity except for eastern North America (Marlon 2009).

Reconstructed Vegetation Maps – 8,000 and 5,000 years BP

Adams and Faure developed a set of preliminary, broad-scale vegetation map reconstructions for the world at the last glacial maximum (18,000 years ago), the early Holocene (8000 years ago), and the mid-Holocene (5000 years ago) (Adams and Faure 1997). The maps were produced through consultation with an extensive network of experts and a range of literature and map sources (Marlon 2009).



Reconstructed Vegetation Map Key
10 - warm temperate evergreen forest),
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24 - Temperate and montane steppe (24b=sparser, short-grass steppe, 21a=dense tall-grass steppe).
28- Ice sheet and other permanent ice.

Figure 6. 4: Reconstructed Vegetation Cover about 6000 BP. Source: (Adams and Faure 1997)

The reconstructed vegetation maps of 8000 and 5000 years ago are presented here to illustrate the influence of changing climate and the evolution of ecoregions showing similarity to contemporary ecoregions described by Bailey.

Pollen data show that the eastern US was already heavily forested by 8000 years ago (Delcourt and Delcourt 1987). In the southeastern US, oaks generally seem to have been much more important a forest component than today, with a predominance of deciduous and mixed forest throughout the region by around 9000 years ago. In the central and western US, the prairie extends eastwards and northward under evidence of drier than present conditions with incursion into the forests.

During the earlier Holocene, woody vegetation in the southwestern uplands seems to have been less widespread than today, with less Juniper-Pine woodland, presumably due to drier conditions. Scrub vegetation such as chaparral seems to have been more widespread relative to woodland (relative to the present-natural) about 9000 and 6000 years ago.

In the eastern US the general picture at 6000 years ago resembles that at 9000 years ago fairly closely, thus much of the discussion is broadly applicable to both time periods.

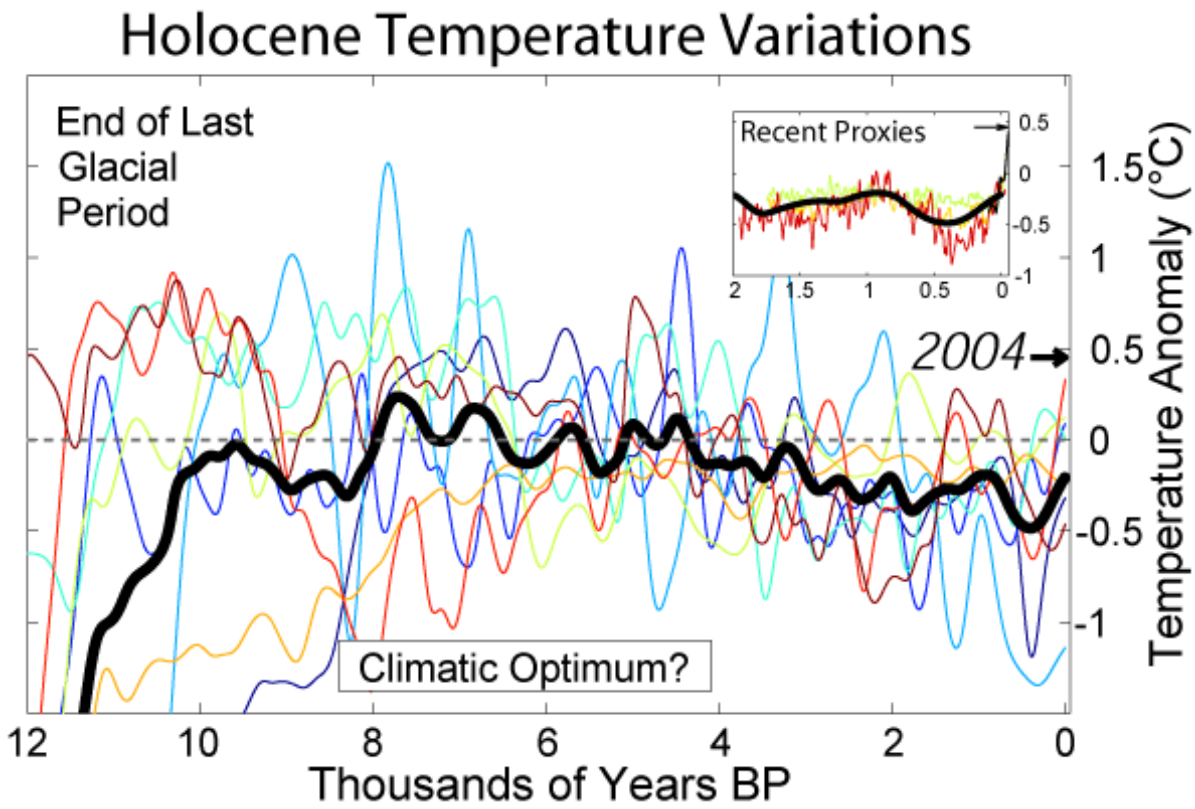

Figure 6.5: Holocene Temperature Variation. Source: (NOAA Paleoclimatology data sets, compiled by R. A. Rhode)

The warmer and drier climate and increased fire frequency associated with Holocene glacial retreat advanced the dominance of oak in the pre-European settlement forests throughout much of the eastern United States. Residues from biomass burning found in Greenland ice cores indicate a peak in fire frequency occurred in areas of eastern Canada, between 6,000 and 3,000 BP. Eastern North America appeared to be drier with more fire. This peak in burning appears related to a combination of warm, dry summer climates and also to the amount of combustible vegetation and species present in the forests and woodlands that grew following the earlier retreat of the Laurentide ice sheet from the area (Abrams 1992; Whitney 1996). The Laurentide Ice Sheet was a massive sheet of ice that covered hundreds of thousands of square miles, including most of Canada and a large portion of the northern United States, between 95,000 and 20,000 years BP. It extended to modern day New York City and Chicago.

In the Central US about 5,000 years ago, various pollen-bearing sites indicate that the prairie-to-forest boundary was still further northeast than its present/historical position, at about the same position as at 8,000 years ago. Lake level evidence from the Midwest suggests there was greater dryness, peaking between 7,700 and 4,000 years ago. Temperature variations during the Holocene show reasonable correlation with the pollen and charcoal proxy data (Bartlein, Prentice, and Webb III 1986).

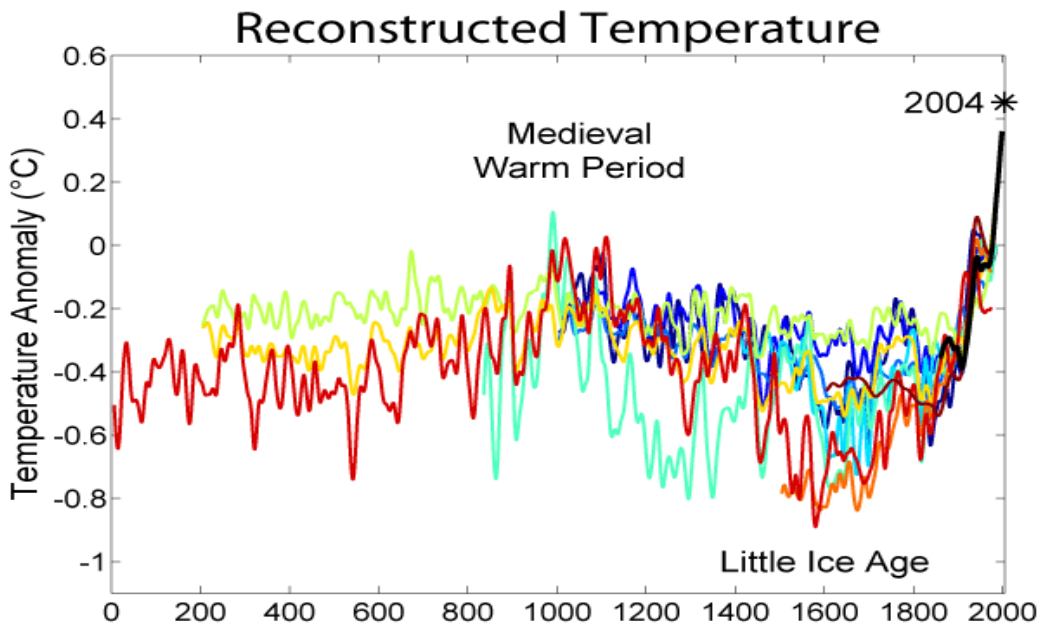

Figure 6.6: Little Ice Age – The cold period between 1550 AD and 1850 AD. Source: (NOAA Paleoclimatology data sets, compiled by R. A. Rhode; http://www.ncdc.gov/paleo)

Holocene Climate Optimum was a warm period during roughly the interval 9,000 to 5,000 years B.P. This warm period was followed by a gradual decline until about 2,000 years ago. Climate has been fairly stable over the Holocene. Ice core records show that before the Holocene there was global warming after the end of the last ice age and cooling periods, but climate changes became more regional at the start of the Younger Dryas, a period of cold climactic conditions and drought between approximately 12,800 and 11,500 BP.

Note three particularly cold intervals: one beginning about 1650, another about 1770, and the last in 1850, each separated by intervals of slight warming. These periods were named because they had significant impact on people in North America and Europe as well as other parts of the planet.

Interpretation of fire patterns over the past 6000 years

The charcoal records indicate two important climate signals when viewed from a global perspective. The First, the continuous increase in biomass burning between the last ice age and present, and Second, the shift from low to diverse fire activity about 12,000 cal yr BP. The relatively few charcoal records for the last glacial period show a consistent pattern of low fire during the glacial period from 21,000 to 16,000 BP. Many sites indicate greater than-present or near-present fire activity during the Holocene with the exception of eastern North America from 8000 to 3000 year BP, where fire activity was less than present. Most available records show low fire activity when the climate was globally colder and drier than at present. The cold, dry climate, in combination with lower-than-present CO_2 levels, would result in an overall reduction in terrestrial biomass and thus a decrease in fuel availability. When the troposphere is colder and

drier than present there would be less convection, a reduction in lightning activity and thus fewer ignitions. (Power et al. 2008; Marlon 2009).

Springer et al. (2010) examined environmental changes in stalagmites and alluvium in caves in the mountainous Buckeye Creek basin in southwestern West Virginia and compared this data to nearby independent archaeological record of Native American presences in the forested watershed. The climatic record derived from the stalagmites is consistent with the pollen records for the region during much of the Holocene. The stalagmite data track aridity associated with North Atlantic Ocean ice rafting events during cooler periods associated with reduced solar radiation.

History of Climate Change in National Fire Policy

Before we address Eastern and Western fire history in more detail we need to briefly examine the history of recent national level fire management policy regarding climate change. Over the past 16 years, Federal wildland fire management policy has evolved in response to fire suppression management technology and continuing growth in the scientific understanding of wildland fire and its interaction with ecosystems and with the human environment. These changes, for the most part, began with issuance of the "Federal Wildland Fire Policy" (1995), and include the "National Fire Plan" (2000), "The Healthy Forest Initiative" (2002), "Healthy Forests Restoration Act" (2003), "10 Year Comprehensive Strategy" (2006), and the "FLAME Act (2009). Over this period fire policies have incorporated an increasingly broader understanding of the natural role of fire in ecosystems, the effectiveness of fuel management at reducing wildfire severity and improving access for suppression, the need to protect communities and resources, and the need for a comprehensive intergovernmental strategy to encompass federal, state, tribal and private lands. Further, the development of polices and legislation supports direct participation, at the broadest reach of the fire management community, at the state, county, local, and tribal government level, conservation organizations, and private landowners. However, only recently, in the updated "A National Cohesive Wildland Fire Management Strategy"[28] (March 2011) was climate change specifically noted as a factor to be considered in fire management planning.

Fire History – Eastern United States

Fire history in the Eastern United States discussed in this synthesis emphasizes the significant influence of climate change on fire, fire regimes, vegetation patterns and ecosystems. Although this synthesis of fire history begins with the end of the last ice age about 12,000 years ago, it is important to note that about 18,000 years ago vegetation and associated fire activity in the Eastern US were much different from the forests described by the first European explorers when they arrived in the 1400s. With the retreat of glacial ice, climate and vegetation changed significantly from arid-cool (18,000 years BP) to the current humid-temperate domain of the Eastern US (7,500 to 5,000 years BP) (Williams 1998; Delcourt, Delcourt, and Webb III 1982).

[28] A copy of "A National Cohesive Management Strategy" may be accessed at: http://www.forestsandrangelands.gov/strategy/national.shtml

Climate change, natural disturbance, fire, and humans have constantly affected vegetation patterns on the landscape. The history of fire in the Eastern US is rich with human history and the scientific and anecdotal information that portrays the influence and significance of each of these factors. Table 6.3 describes the use of fire during five major time periods by each group of human inhabitants that had a significant impact on Eastern ecosystems particularly the south.

Pre-European Settlement

Before European settlement, fire was widespread and frequent throughout much of the eastern United States (Pyne 1982; Nowacki and Abrams 2008). Widespread fire led to vegetation patterns different from those that would be controlled by climate alone, a common occurrence throughout the world (Bond, Woodward, and Midgley 2005).

The diversity of plant communities, local and regional climatie, soil and landform conditions of the eastern United States supported a range of pre-settlement fire regimes. These ranged from frequent low intensity fires in prairies to intense stand-replacing burns on Pine Barrens, to the northern hardwood forests that rarely burned. Most pre-settlement fire regimes were characterized by low- to mixed-severity surface burns, which maintained the vast expanses of oak and pine forests that dominated much of the eastern United States often in open "park-like" conditions (Wright and Bailey 1982; Frost 2000). Plant communities were principally fire dependent, being formed under and maintained by recurrent fire, with their continued existence dependent on recurring fire (Frost 2000; Wade et al. 2000). Prime examples include tall grass prairies, aspen parklands, oak dominated central hardwoods, northern and southern pine forests, and boreal spruce-fir forests (Wright and Bailey 1982).

Native Americans were the primary ignition source in many locations prior to European settlement, given the moist and humid conditions of the East (Whitney 1996). Historical documents indicate that Native American ignitions far outnumbered natural causes (principally lightning) in most locations (Gleason 1922; DeVivo 1991). In this respect, humans were a "keystone species," actively managing the environment with fire over millennia (Guyette, Spetich, and Stambaugh 2006).

Major Periods of Human-Caused Fire Regimes in the South					
Fire Regime	Native American pre-settlement	Early European Settlers	Agriculture Industrialization	Fire Suppression	Fire Management
Time Period	12,500 BP to 1500s AD	1500s AD to 1700s AD	1800s to 1900s	1920s to 1940/80s	1940s/80s to Present
Typical Burns	Low intensity brush(surface) fires	Low intensity brush (surface) fires mainly for agricultural purposes	Stand replacing fires set by loggers and farmers	Federal lands protected from fire	Prescribed fires of mixed intensity and frequency

Table 6.3: Major Periods of Human-Caused Fire Regimes adapted from (Fowler and Konopik 2007)

Prior to European settlement the eastern deciduous biome (Bailey's Humid Temperate Domain) was dominated by fire-adapted ecosystems, notably tall grass prairies and oak-pine savannas, woodlands, and forests. Although surface burns were prevalent, pre-settlement fire regimes varied according to climate, topography, and Native American populations (primary igniters),

creating a mosaic of vegetation types within each of the major plant communities (Nowacki and Abrams 2008). Temporal scales also alter the relative importance of human versus climatic effects on fire regimes. For example, population density and fire were related in pre-Columbian American societies. The role of humans emerges when examined over decades and centuries (Veblen, Kitzberger, and Donnegan 2000).

Abrams and Nowacki (Abrams and Nowacki 2008) describe Native Americans as having a wide spread and substantial influence on eastern North American forest composition prior to the arrival of Europeans. Forest clearance and maintenance by fire appear to be the two most wide spread land management activities pursued by Native Americans (Delcourt and Delcourt 2004; Abrams and Nowacki 2008). Nuts were an important part of Native American diets (Delcourt and Delcourt 2004); providing an incentive to foster the growth of mast trees that produce fruit or nuts at the expense of other species. Native peoples of the Great Eastern Woodlands of North America used fire to preferentially select for fire-tolerant, mast (nut-bearing) trees such as hickory, chestnut and oak (Delcourt and Delcourt 1998). Forest composition correlates with presence of Native American settlements throughout eastern North America including northwestern Pennsylvania where the relative abundances of mast trees was greatest (34%) in areas of high Native American activity and least (<2%) in areas with low Native American activity (Delcourt and Delcourt 1998).

Around 3000-1000 years BP the majority of Eastern Woodland fires were set by Native Americans to not only suppress non-mast trees, but also curb shade-generating undergrowth and promote growth of game attracting sprouts (Delcourt and Delcourt 2004). Native Americans in the Late Archaic period, ~ 3000 years BP, nurtured the development of low-diversity oak-hickory-chestnut forests in New England, the Allegheny Plateau and Appalachian Mountains (Delcourt and Delcourt 2004). Fire scars on pre-European mast trees record fire return intervals of 4–20 years (Signell et al. 2005). The widespread use of fire is documented in the historical record (Ison 2000; Pyne, Andrews, and Laven 1996).

It is clear that humans have affected fire regimes for millennia, and changes in human societies (e.g., from Native Americans to Europeans, from preindustrial to postindustrial) also cause changes in fire regimes. For example, in temperate ecosystems, there were clear and consistent fire-regime changes as hunting and gathering societies moved to agricultural-grazing societies and then to industrial societies, although these changes may have occurred at different times in different parts of the world (Covington and Moore 1994; Guyette, Muzika, and Dey 2002; Pausas and Keeley 2009).

Early European Settlement (1500s-1700s)

In the early settlement period, European burning practices were similar to Native American fire. Native Americans and early European settlers typically used low-intensity brush fires and other methods such as girdling to kill trees to aid land clearance. Like Native American fires, European settlers' fires and their effects on landscapes varied from place to place. Settlers, trappers and woodsmen used fire for many of the same reasons as Native Americans: to facilitate travel, promote and collect wild foods, to hunt, to produce forage for wild game and grazing animals, to clear land for agriculture, defense against predators and protective burning against other fires. Settlers often occupied the sites of abandoned fields of their Native American

predecessors and used the same slash and burn practices to grow maize and maintain open areas. In Europe, the use of fire to clear land and maintain pastures and open areas was well established, and these practices were continued in the "New World" (Fowler and Konopik 2007; Pyne 1982; Whitney 1996).

When Europeans arrived, the landscape of the Southeast was a mosaic of open pine and hardwood woodlands, prairies, meadows, and oak or pine savannas in a variety of successional stages. Oaks, southern pines, and hickories were dominant tree species almost everywhere. Pine barrens or savannas with scattered oaks dominated large areas of the Coastal Plain (Carroll et al. 2002). The dense understory of unburned forests of the South was a key factor prompting Native Americans to manage their land with fire. In the absence of fire, any means of travel was extremely difficult, as small hardwoods combined with shrubs to create dense, impassable thickets (Carroll et al. 2002).

In many parts of the South, European settlers practiced a combination of "Old World" methods and burning methods learned from Native Americans as well as experimenting with fire in new plant communities. In the Southern Appalachians an important difference between European farmers and Native Americans was that Europeans mostly practiced permanent-field agriculture while Native Americans temporarily cleared by cutting and burning previous growth (Fowler and Konopik 2007)**.**

Early settlers used mostly low intensity fires, to clear space for their houses and other buildings. They burned bottomlands, woodlands, and hilltops—annually in some cases—to prepare them for growing corn and other row crops. (G. W. Williams 2002). They also used fire to encourage the growth of early successional plants such as blueberries and to control woody undergrowth (Carroll et al. 2002). In the Florida sandhill region, frequent low-intensity burns helped to create and maintain the longleaf pine and wiregrass communities, where Spanish settlers introduced cattle grazing in the St. Johns River basin in the 16th and 17thcenturies.

The decline of Native American populations and the decrease in Indian fires had significant effects on vegetation. European exploration and settlement caused a decline of 90-95% in Indian populations between the mid-1500s and the 1800s (due to diseases introduced by Europeans, conflict, migration, change in land ownership, and forced removal). In the absence of Native American land managers, many of the places where they had previously used fire to clear vegetation became densely overgrown. Over time, the ways European settlers used fire for land management became very different from those of Native Americans (Carroll et al. 2002; Fowler and Konopik 2007).

European Settlement (1700s-1800s)

With the onset of European settlement, fire regimes changed in various ways. As areas were settled, forests were cut and burned and fire frequency and severity increased due to agricultural land clearing, logging and accidental ignition by various sources such as wood and coal-burning steam engines (Pyne 1982; Nowacki and Abrams 2008).

Nowacki and Abrams (Nowacki and Abrams 2008) describe how changes in fire regimes with European settlement led to major shifts in vegetation composition and structure in the eastern

US. Grasslands, savannas, and woodlands began to convert to closed-canopy forests. Shade-tolerant fire sensitive vegetation began to replace fire dependent vegetation and in the northeast hardwood systems that seldom burned in pre-settlement times were especially impacted (White and Mladenoff 1994). Following heavy logging in northern hardwood forests, major fires in the upper Great Lakes led to major changes in vegetation from hardwood to aspen-birch or oak in vegetation (White and Mladenoff 1994; D. A. Haines and Sando 1969).

In southern Maine, widespread severe fires in 1761-1762 temporarily halted the logging industry. "As the source of timber migrated so did fire" (Pyne 1982). With frequent cutting and burning, a

Figure 6.7: Cutover and abandoned forestland in northern Michigan at the beginning of the 20th century. Source: (MacCleery 1992)

large proportion of northern hardwoods converted to aspen-birch or oak (Schulte et al. 2007). Where settlers used Native American burning practices fire frequency was maintained or increased in the central hardwood region (Cole and Taylor 1995). Frequent understory burning helped maintain the dominance of oak and other fire-adapted vegetations, notably grasses for pasturage (Nowacki and Abrams 2008).

Much of the eastern United States has experienced a substantial decline in oak forests from pre-settlement to present day primarily due to fire exclusion and abandoned farm land (Glitzenstein

et al. 1990; Whitney 1996; Abrams and Ruffner 1995). The fire history of the Ozark-Ouachita highlands also demonstrates effects of migration on fire regimes. Native American migration into the region during the 1700s and European migration in the 1800s caused initial increases and subsequent decreases in fire frequencies. During the late 1700s, Cherokee Indians migrated into the Ozarks after European settlers displaced them from their homelands in the Southern Appalachians. Between 1760 and 1820, the number of sites that were burned in the Current River watershed in Missouri increased by 21%. The number of annually burned sites in the Current River watershed almost doubled as population density increased between 1810 and 1850. By 1803 there were about 6,000 Cherokee living in southeast Missouri and northeast Arkansas (Guyette and Dey 2000; Fowler and Konopik 2007).

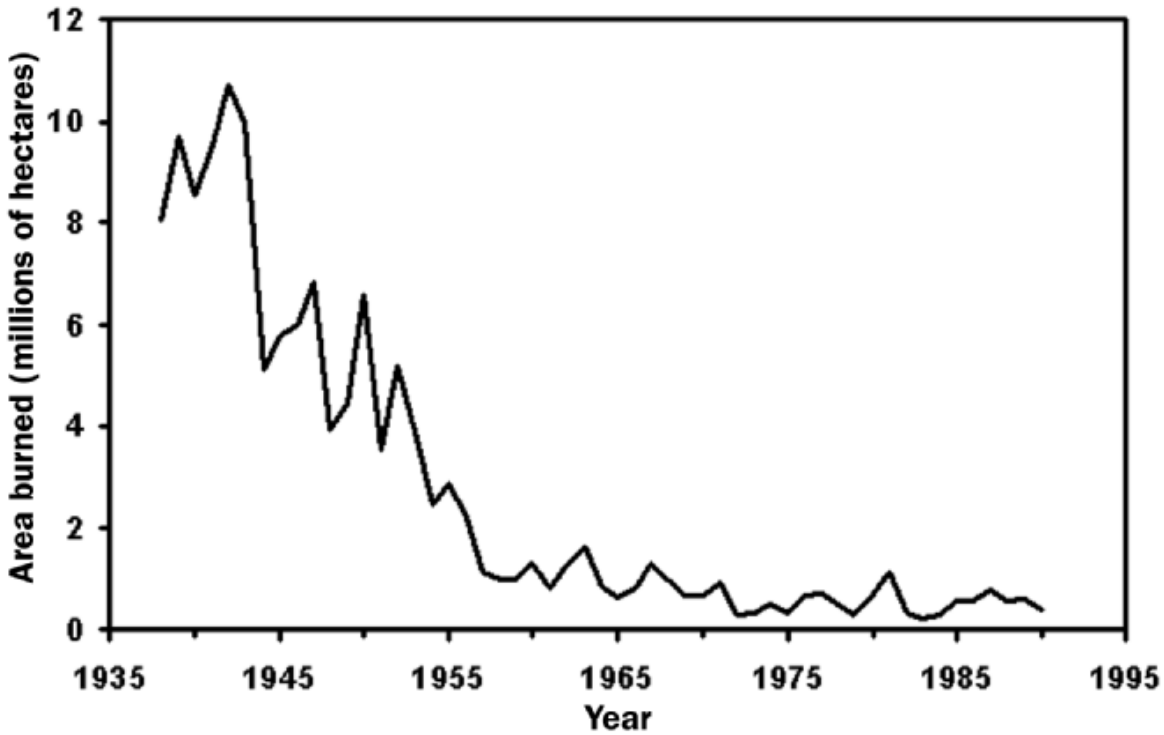

Figure 6.8: Area burned in the eastern United States (1938–1990) based on historic fire records Area includes Minnesota, Iowa, Missouri, Arkansas, Louisiana, and all states eastward. Source: (Nowacki and Abrams 2008)

The midwestern grasslands were the most flammable landscapes and presented the greatest fire danger to settlers and their homes, buildings and other structures. Fire ignitions declined in the absence of Native American burning, and fires that did start were actively suppressed . Native vegetation was rapidly converted to croplands and pastures, and roads and railroads led to landscape fragmentation. In areas not dedicated to agriculture, the release of fire-suppressed sprouts (from centuries-old oak root systems turned native grasslands and oak savannas into closed-canopy forests at astonishing rates (Anderson and Bowles 1999; Abrams 1992; Wolf 2004).

Industrialization- Agricultural Expansion (1800s-1900s)

Fowler and Konopik (Fowler and Konopik 2007) describe the dramatic change in fire regimes in the South in the 1880's as settler population increased and industrial development expanded rapidly. With increased population in the late 1800's and early 1900's came increased demand for agricultural land, timber for homes, railroads, roads, mining and other related commercial activities (van Lear and Waldrop 1989). During pre-settlement and in the early settlement period fires were typically low severity surface fires. Logging era fire regimes were by contrast characterized by high severity, stand replacing fires. Intense, widespread fires occurred in the Southern Appalachians as a consequence of the timber boom that lasted from the 1890s through the1920s (Brose et al. 2001). Willard Ashe, an early forester in the North Carolina mountains, denounced farmers for not understanding that by slashing and burning the woods for farming and grazing, they robbed themselves of future timber resources (Ashe 1895). During the 1880s timber and coal mining companies gained control of large parts of the region and relentlessly exploited the newly acquired properties. Between 1880 and1895 the lumber output in North Carolina alone had more than tripled (Ashe 1895). The slash was often burned and the land used for grazing livestock, which inhibited the re-establishment of woody vegetation (Van Lear and Waldrop 1989). If the slash was not burned intentionally, it dried on site and was easily ignited by sparks from passing locomotives. This resulted in intense burns that could be detrimental for soils or adjacent uncut forests, especially during dry periods (Brose et al. 2001a). However, three-fourths of Southern Appalachia was still forested in 1911 even though farmers had been using slash-and-burn methods in the Southern Appalachians for up to 200 years (Otto 1983). Similar patterns of logging exploitation and severe fire were experienced in the northeast and upper Great Lakes region (see Figure 6.8). *"Fires in 1761-1762 temporarily destroyed the logging industry in southern Maine and led directly to settlement of northern coastal lands. Maine surrendered its timber supremacy between 1840 and 1860 to New York, and New York gave its place in turn to Pennsylvania between 1860 and the 1870's. By the late 1870's the Lake States replaced the Northeast as a national timber region."* (Pyne 1982). The volume of timber used for the single purpose of powering railroad locomotives exceeded the annual growth of timber on Forest Service lands in Michigan, Minnesota, Wisconsin and the Dakotas combined (Huffman 1977)

Although European settlement significantly altered eastern vegetation through land clearing, extensive timber harvesting, severe fires, and the introduction of nonnative pathogens (e.g., chestnut blight) and invasive plants, for the most part, fire-adapted species were sustained during European settlement either directly through fire or indirectly through cutting and thinning. However, later in this period, with the wide-ranging and rapid expansion of agriculture, commercial timber harvesting and related industrial development of the era, changes in fire regimes began to emerge which adversely impacted fire-adapted species. Fire occurrence increased in the fire resistant northern hardwoods, and decreased in the fire adapted tall grass prairies. In other regions, with decline of frequent low intensity fire, the competitive balance began to shift to shade-tolerant species (Nowacki and Abrams 2008).

Figure 6.9: Progressively over time and space, agricultural uses replaced forests in much of the Eastern United States. By the 1850s this trend began to give way in some places to natural succession and reversion to forestland in areas less suited to mechanized farming. Central Massachusetts images, 1880s (top) and the same scene in 2000 (bottom). Source: (MacCleery 1992)

Fire Suppression Era (1900s-1980s)

In the wake of major forest fires in the late 1890's Gifford Pinchot, first chief of the Forest Service, and many foresters as well as timber, pulp, and paper companies forcefully advocated the position that forest fires had to be eliminated in order for forests to grow and thrive. In their view, forest fires not only destroyed standing trees but burned the seedlings and young trees of the next generation of forest. Fire was the moral and mortal enemy of the forests (Saveland 1995; Williams 2002). Chief Forester Henry Graves declared in 1913 that *"the necessity of preventing losses from forest fires requires no discussion. It is the fundamental obligation of the Forest Service and takes precedence over all other duties and activities."* (Saveland 1995).

Industrial logging slash and burn practices facilitated major destructive fires that in turn fostered the concept of fire prevention. The Peshtigo, Michigan, Hinckley, Yacoult and Maine fires burned hundreds of thousands of hectares and killed more than 2000 people between 1871 and 1947. On the same day, October 8, 1871 that fire wiped out the town of Peshtigo, Wisconsin the Chicago fire occurred. The Peshtigo fire covered 518,016 hectares and killed 1150 people, whereas 860 hectares burned and 300 lives were lost in the Chicago fire. In most instances, these major fires were preceded by a prolonged drought (Flesch 2009; Haines and Sando 1969).

Pyne makes the point of the remarkable similarity among the great fires. *"For 50 years, the fires were virtually interchangeable: the names, dates, and locations varied, but otherwise the account of one fire could substitute for another."* The 1903 and 1908 fires in the northeast were the equivalent of the 1910 fire in the west in that they crystallized fire protection efforts at the state and regional level. In addition, there was concern about a possible timber famine (Pyne 1982).

The capability to suppress fire was aided by the Weeks Act of 1911 and led to the creation of 52 national forests in 26 Eastern states and facilitated cooperation among the states for forest and water conservation and provided matching funds for forest fire protection (Huffman 1977).

Forest Service Chief Henry Graves, adopted fire control as a principle duty of the agency (Williams 2002). Fire suppression became the doctrine and leading policy of federal agencies. For instance, when the Great Smoky Mountains National Park was established in 1931, fire suppression was a central objective of forest managers (Harmon 1982). Government officials who wanted to restore southern forests encouraged the prevention and suppression of all forest fires and the restoration of desirable plant and animal species (Power et al. 2008; Williams 1998; Fowler and Konopik 2007).

Fire suppression capabilities advanced with the Clark-McNary Act in 1924 whereby the federal government allocated funding for states to develop their capacity to fight forest fires. In 1926 the U.S. Forest Service developed a policy of controlling wildfires before they reached the size of 10 acres. In 1935 the "10:00 a.m. policy" was born following two severe fires in the Pacific Northwest that killed several firefighters and burned over 500,000 acres. The policy required fires exceeding 10 acres to be controlled before the next high danger period began at 10:00 a.m. (Gorte 2000). Efforts to reduce the number of human-ignited fires focused on educating the public about fires and how to prevent them. These efforts included the well known Disney's

"Bambi" and "Smokey the Bear" along with many other effective anti-fire messages particularly during WW II.

Prescribed burning was banned on most public lands in the South for more than 50 years. Where accidental, lightning, or arson fires occurred they were quickly controlled and extinguished. In the South there were advocates for "light burning" or "Indian fires" opposing the fire control and prevention policies of federal and state agencies. After several decades of fire suppression, land managers, scientists, and policy makers began noticing the forests and fields changing in undesirable ways. Problematic levels of forest fuels were accumulating in some of the places where prescribed burning had been discontinued, ecosystem integrity was declining, and the threat of catastrophic wildfires was increasing (Fowler and Konopik 2007). Even though suppression of fire was nearly the sole fire management policy, prescribed burning continued to be practiced on private lands by the farming, grazing and logging industries and fire helped sustain these economies (Pyne 1982).

In the 1930s, Herbert Stoddard and other advocates of fire management encouraged the use of prescribed fire to create healthy, productive environments (Stoddard 1935). Scientific studies by Greene (1931) and Chapman (1932) strongly advocated the application of prescribed fire to manage the land. Herbert Stoddard published several articles describing the benefits of prescribed burning to longleaf pine forests and upland game management (Stoddard 1935). However, by the end of the 1930's the momentum for fire control was well established and resulted in a substantial reduction in wildland fire. Between 1930 and 1960 the area consumed by fire nationwide had decreased from over 50 million acres annually to about 2-5 million acres (Williams 1998; MacCleery 1992). Thus, "light burning" and "Indian fire" practices were limited even though scientific evidence in favor of controlled burning was increasing

The fire suppression era brought a major shift in fire regimes in most eastern ecosystems that was marked by significantly longer fire return intervals. The fire return interval in the Great Smoky Mountains National Park increased from 10-40 years during the European settlement period (1856-1940) to a projected 2000 year fire return interval in the fire suppression era (1940-1979) (Harmon 1982).

With the onset of fire suppression in the Ozark highlands in the 1930's, fire began to change dramatically. The fire return interval in Hot Springs National park in 1700 was 41 years and by 1980 it had increased to an estimated 1200 years. The McCurtain County Wilderness Area saw the fire return interval change from 30 years in 1700 to 547 years by 1980 (Foti and Bukenhofer 1999).

Fire Regime Conversion

The fire suppression era continued, and probably accelerated, a significant fire regime conversion process throughout most of the Eastern US that began during the European settlement era. With the onset of the fire suppression era in the 1900's, fire steadily declined across the Eastern US. This extensive shift and conversion in fire regimes had unanticipated ecological consequences. "*A cascade of compositional and structural changes took place whereby open lands (grasslands, savannas, and woodlands) succeeded to closed-canopy forests, followed by*

the eventual replacement of fire-dependent plants by shade-tolerant, fire-sensitive vegetation. This trend continues today with ongoing fire suppression." (Nowacki and Abrams 2008).

Nowacki and Abrams (2008) work provides a broad scale and fundamental understanding of the ecology of this conversion process and the extent and magnitude of fire regime change throughout the East. In the absence of fire open landscapes previously maintained by frequent fire transformed to closed canopy forests (Figures 6.9-10). Shady conditions favored shade tolerant fire sensitive plants and began to replace the fire-adapted plants. Cool, damp, shady microclimates created less flammable fuel beds that in turn continued to improve conditions favoring mesophytic vegetation and less favorable conditions for sun loving fire adapted vegetation. Nowacki and Abrams term this process "mesophication" (Nowacki and Abrams 2008). This process is advanced by micro-environmental conditions that continually improve for shade-tolerant mesophytic species and decline further for shade-intolerant, fire-adapted species. This process is not restricted to the Eastern US but is evident worldwide as a result of fire exclusion (Bond, Woodward, and Midgley 2005).

Their research describes the shift from oak and pine dominated forests to highly competitive mesophytic hardwoods (including red maple, sugar maple, beech, birch, cherry, tulip poplar and black gum) resulting from the fire suppression era. Throughout much of the East forest floors became less flammable and thus more resistant to fire. Over the past 50-plus years oak and pine forests declined significantly on most sites dating back to the 1940s and 1950s when broadcast burning was significantly curtailed.

Nowacki and Abrams depict the geographic variation and magnitude of change between past and current fire regimes across the East in figure 6.10. The Midwest shows the largest reductions in fire (shaded in blue) where the fire prone grasslands, savannas, and woodlands were replaced by actively farmed landscapes that rarely burn (Iverson and Risser 1987; Anderson and Bowles 1999). With increased land use and continued fire suppression Midwestern tall grass prairies and oak savannas are now some of the rarest ecosystems in the world (Nuzzo 1986).

The green shaded areas extending eastward and south from the former Midwest grasslands covering the southern two-thirds of the eastern US represent wide-ranging reduction in fire. The southern two-thirds of the eastern US, shaded in green, show extensive reduction in fire associated with the conversion of previously fire dependent ecosystems to agricultural landscapes and remnant forests to increasingly fire-sensitive species…from oaks to mixed mesophytic species in the central hardwoods…from pine to hardwoods in the South. The sub-boreal landscapes of Northern Minnesota also reflect the results of continuing fire suppression (Heinselman 1973; Clark 1990). Landscapes with moist to wet conditions that seldom burned still do not burn. Nowacki and Abrams conclude: "*Vegetation changes associated with fire suppression and mesophication are swifter and more enduring on mesic than on xeric sites. The trend toward mesophytic hardwoods will continue on landscapes where fire is actively suppressed, rendering them less combustible and creating further difficulties for land managers and conservationists who wish to restore past fires regimes and fire-based communities*." (Nowacki and Abrams 2008).

Figure 6.10: Past-to-current fire regime change map based on spatial analysis of past and current fire regime maps. Negative values represent temporal shifts toward less fire, whereas positive values represent shifts toward more fire. The departure from zero relates to the extent of fire regime change. Source: (Nowacki and Abrams 2008)

Recent LANDFIRE fire regime maps of the North Central, North East, South East and South Central regions of the Eastern US (figures 6.11-6.14) were prepared by the LANDFIRE project office (http://www.landfire.gov). Comparison of the Past-to-current fire regime change map by Nowacki and Abrams (figure 6.10) with the LANDFIRE fire regime condition class maps shows

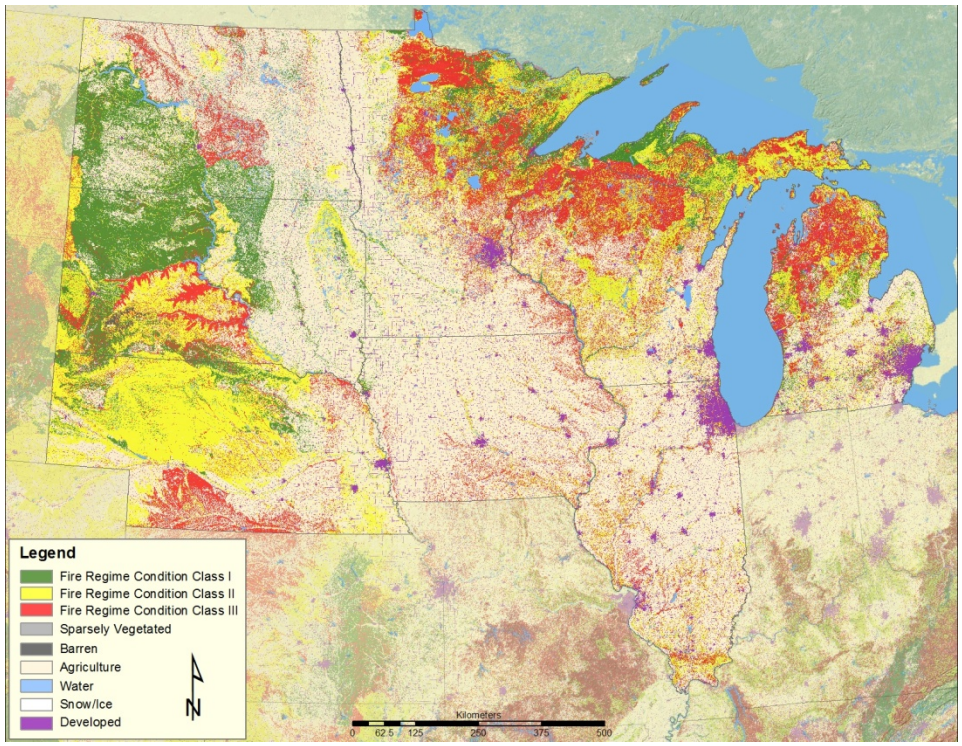

Figure 6.11: North Central US LANDFIRE Fire Regime Condition Class June 2011

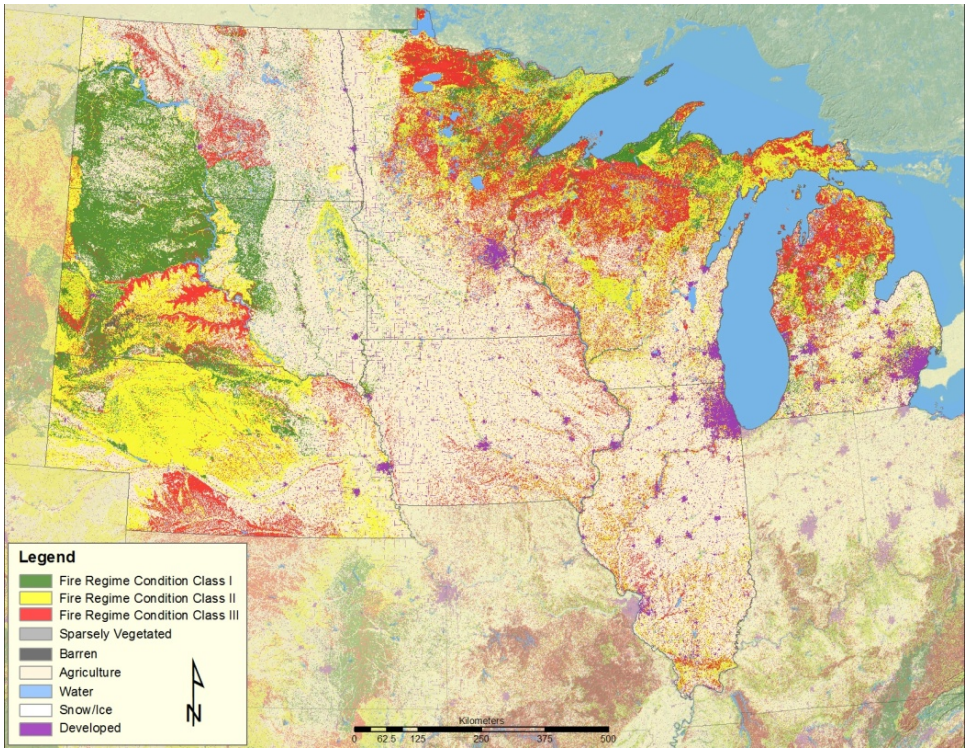

Figure 6.12: North Eastern US LANDFIRE Fire Regime Condition Class June 2011

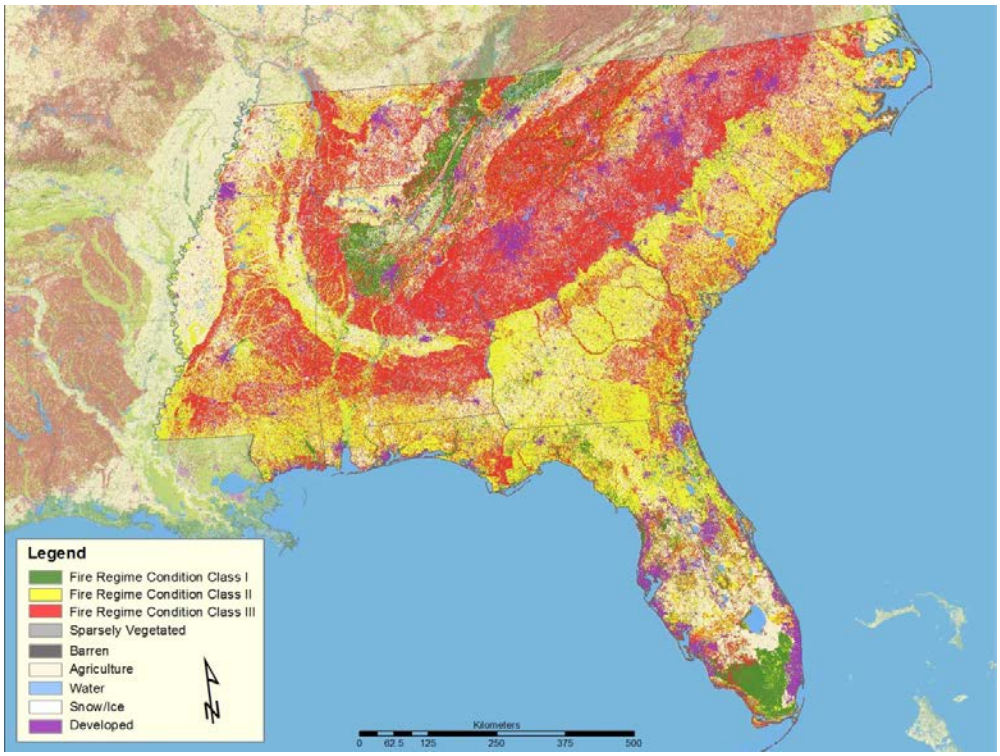

Figure 6.13: South Eastern US LANDFIRE Fire Regime Condition Class June 2011

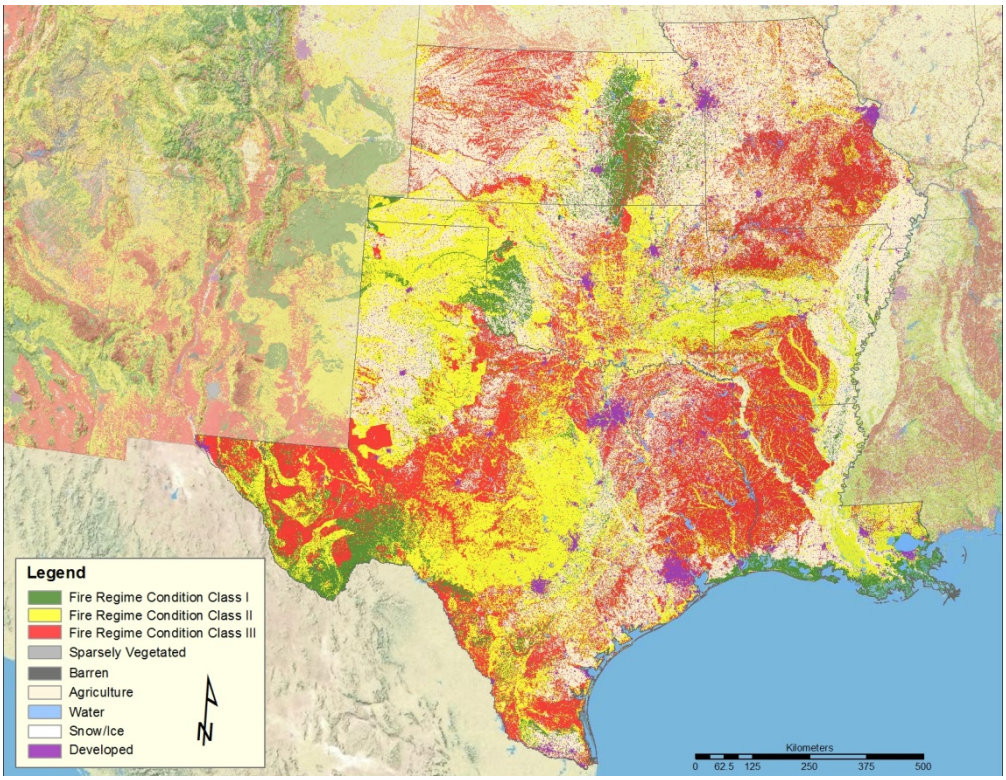

Figure 6.14: South Central US LANDFIRE Fire Regime Condition Class June 2011

a positive correlation with the LANDFIRE fire regime condition class (FRCC) maps. The LANDFIRE maps reflect the changes in both vegetation and fire occurrence that have been taking place in most Eastern ecosystems over many decades of fire exclusion and changes in land use. The period of record appears not yet long enough to detect a climate change signal however, with increasing climatic variability the climate signal is likely to be more apparent. "*The influence of climate on fire occurrence is more strongly expressed when climatic variability is relatively great; and multiple records from a region are essential if climate–fire relations are to be reliably described*" (Gavin, Brubaker, and Lertzman 2003).

Fire Management Era (1980's to present)

The Fire Management era ushered in, with starts and stops, the return of controlled burning in the Eastern US. As time progressed, the beneficial burning practices of Native Americans and early settlers were recognized and reintroduced as essential to maintain or restore landscapes which had deteriorated and those which presented an increasing fire hazard (Stoddard 1935). The Fire Management era is generally characterized by a major shift from fire suppression to a period of increasing knowledge and understanding of fire ecology and the response of varied ecosystems to altered fire regimes (Knapp, Estes, and Skinner 2009; Brose et al. 2001; Wade et al. 2000; Waldrop, White, and Jones 1992; van Lear and Waldrop 1989). Fire management policies were developed to correct deteriorated landscapes and increased fire risk resulting from prior fire control practices and in response to contemporary social, economic, and political needs. Fire managers, resource managers, government officials at all levels, and the public, also began to understand and accept, to various degrees, the importance of the "natural role" of fire and how to better accommodate and "live" with fire (Haines, Busby, and Cleaves 2001). How to "live" with fire entails a complexity of issues that include wildland-urban interface public safety and protection of property, forest health and restoration, wildlife habitat improvement, air quality and health impacts of smoke, acceptance of fire use by a diverse public, need for better scientific information and, now, the impacts of climate change.

In the East, the fire management era, particularly in the South, replaced the fire suppression era with the gradual acceptance of prescribed burning as an ecological and economically effective management tool. Fire protection remains the primary fire management goal.

Although prescribed burning was practiced on private lands during the fire suppression era it was not until 1943 that an official prescribed burn was conducted on federal land in the Osceola National Forest in Florida (Stanturf et al. 2003). The use of prescribed fire for fuels management was enhanced in large part due to the economic incentive of lowering suppression costs. Prescribed fire was practiced more frequently after World War II, however, with continued controversy; it was curtailed in many parts of the south. Fire was excluded from the Okefenokee Swamp and the Florida sandhills in the 1930s and in parts of the Piedmont in the 1940s. Fire was restored to parts of the Piedmont region and the Okefenokee Swamp in the 1970s. In the 1980s, prescribed fire was restored in the Southern Appalachians using low intensity surface fires. In Table Mountain Pine-Pitch forests high intensity crown fires appropriate for this assemblage were employed. More recently, periodic low intensity fires are being used in the Piedmont to restore pine stands similar to those that existed under Native American stewardship (Fowler and Konopik 2007).

Fire management activities involving prescribed burning have varied throughout the Eastern US. In the Northeast, the New Jersey Pine Barrens, with a growing wildland urban interface, continue to be a significant fire management issue. Fire return intervals within the vegetation assemblages range from 5-15 years for dwarf pine plains to 100-200 years for oak-hickory forests and present a complex mix of fire protection and habitat management and restoration issues (Knapp, Estes, and Skinner 2009). The crown fires that are typical in this vegetation are driven by strong winds, which derive from two large-scale atmospheric circulations with strong seasonal variation. In winter, a high-pressure area over central Canada and the Northern Great Plains brings very cold air masses with strong surges of cold NW winds that push southeastward across the eastern half of the US promoting drying conditions. By summer a dominant high-pressure area near Bermuda brings clockwise circulation and southwesterly winds with high moisture, warm temperatures and frequent thunderstorms. Drought is relatively frequent and sets the stage for severe wildfires (Knapp, Estes, and Skinner 2009). Given the strong seasonal variation in the climate of this region, no significant effects due to future climate are expected (Forman 1998).

The Central, Great Lakes and North Atlantic States lie in Bailey's Warm Continental and Warm Continental Mountain Divisions. Fire climate in these Divisions is generally driven by air masses that bring moist humid tropical air in the spring and summer and polar continental air in the late fall and winter. Precipitation is fairly evenly distributed throughout the year ranging from 20-45 inches in the Central States, and about 50 inches in the Great Lake States. There is some prescribed burning in Eastern hardwood forests that is similar to the historical fire burning period used by Native Americans. Most wildfires and prescribed burns occur during the dormant season in the early spring before leaf emergence or in the fall after leaf drop (Knapp, Estes, and Skinner 2009; Wade et al. 2000).

In the North Central region, the essential role of fire in maintaining grasslands led to increased attempts to use prescribed fire, initially to promote livestock forage and later for restoration goals such as reduction of woody vegetation. Climatic influence on these grasslands is predominately in the form of precipitation that ranges annually from 10-20 inches in the north and west and from 20-40 in the south and east. Gulf and Pacific air masses bring most of the moisture however, the Pacific air mass is usually dryer. Gulf air masses bring greater precipitation and limit drought periods. The season for wildfire and prescribed burning varies depending upon the dry fuel component, however, for operational ease, the majority of prescribed burns are typically conducted when vegetation is dormant in the early spring or late fall (Knapp, Estes, and Skinner 2009).

The Fire Management era also brought increased interest in the influence of climate and weather on fire and fire regimes. Many studies examined historical climatic information to gain better understanding of the interaction and teleconnections of fire activity and large-scale climate patterns, particularly El Nino Southern Oscillation (ENSO).

The influence of El Nino/La Nina Southern Oscillation (ENSO) has been documented throughout Florida. Brenner (1991) examined relationships between the EI Nino/ Southern Oscillation (ENSO) and wildfire in Florida over the period 1950-1989. January through May

average central Pacific sea surface temperature (SST) anomalies were compared to acres burned. Florida experienced a “mild” fire season (January through May) when the SST were above mean (El Nino phase). When SST dropped below mean (La Nina phase) Florida experienced greater than average acres burned. There appears to be some lag in the effects of the positive SST (El Nino) anomaly periods, which might help explain years where there were negative anomalies in the SST and sea surface pressure, with no corresponding significant increase in acres burned. The increased rainfall associated with El Nino periods may be capable of sustaining the system for up to a year after occurrence. This is most likely due in large part to a rise in the level of the aquifer. Lakes, ponds, and swamps fill and remain full for many months after prolonged wet periods. These wet areas act as natural barriers to the movement of wildfires. La Nina periods do not seem to have as prolonged an effect on the system as do the positive "El Nino" periods. Florida's fire season can be directly correlated with the amount of precipitation received during the period January through May (Brenner 1991).

Beckage et al. (Beckage et al. 2003) examined climatic and fire data from 1948 to 1999 within the Everglades National Park and found the La Niña phase of the El Niño Southern Oscillation (ENSO) brought decreased dry season rainfall, lower surface water levels, increased lightning strikes, more fires, and larger areas burned. In contrast, the El Niño phase brought increased dry-season rainfall, raised surface water levels, decreased lightning strikes, fewer fires, and smaller areas burned. Shifts between ENSO phases every few years have likely influenced vegetation through periodic large-scale fires, resulting in a prevalence of fire-influenced communities in the Everglades landscape (Beckage et al. 2003).

The 1982–1983 El Nino, described as “perhaps the strongest of the century” (Cane 1983) resulted in climatic anomalies on a global scale. In 1982 and 1983, the USDA Forest Service reported the lowest wildland fire occurrence and area burned since record-keeping began in 1906, while in Indonesia, on the opposite side of the world, one of the greatest wildfires ever known burned 7.6 million acres of tropical rain forest between March and May 1983 (Leighton 1984). Following the 1982-83 El Nino, Simard et al. (Simard, Haines, and Main 1985) conducted an exploratory study correlating El Nino events, annual fire occurrence and area burned in the US over a 53-year period. They found a strong relationship between El Nino events and decreased fire activity in the South. Correlation of El Nino events and fire activity in the Eastern and North-Central states was weak or inconsistent. The study did not attempt to match El Nino criteria with environmental factors that control fire activity or with varying regional fire seasons. The regional analysis was coarse, with state boundaries not necessarily related to the phenomenon being studied (Simard, Haines, and Main 1985).

A broad generalization about fire climatology is that ecosystems with moderately wet climates are the most fire prone (Sauer 1952, Meyn et.al 2007, van der Werf et.al. 2008). These are ecosystems with enough precipitation for heavy biomass/fuel production but with periodic dry spells that permit burning such as temperate forests, tropical savannas, shrublands, and temperate grasslands. High fuel moisture usually precludes fire in extremely wet locations, e.g. tropical rainforests, while arid lands, lacking sufficient fuel build up are much less likely to burn. The humid temperate domain of the South provides the precipitation gradient where fuel moisture restricts fire. Within the humid South, spatial patterns in burning reflect precipitation gradients. The relatively warm, dry environments of Florida are more flammable than cool, moist areas of

the Appalachian Highlands (Lafon 2010). Previously mentioned work by Beckage (2003) and Brenner (1991) suggests that global ocean–atmosphere teleconnections, El Niño-Southern Oscillation, contribute to fire activity by influencing interannual precipitation variability. Most of the South has bimodal fire seasonality, with burning peaks in spring and fall when low relative humidity, high winds, and warm temperatures dry surface fuels (Schroeder and Buck 1970; Lafon 2010).

Flatley et al. (Flatley et al. 2011) examined the influence of climate and topography on the burned area of fires that occurred during the period 1930-2003 in Shenandoah National Park (SNP) and Great Smokey Mountains National Park (GSMNP) and determined drier climatic conditions likely contributed to lower fuel moisture and consequently to greater burned area. In addition, the seasonality of precipitation appears to influence the effect of precipitation on fire activity. The results demonstrate that climate is a strong driver of both spatial and temporal patterns of wildfire. Fire was most prevalent in the drier SNP than the wetter GSMNP, and during drought years in both parks. Topography also influenced fire occurrence, with relatively dry south-facing aspects, ridges, and lower elevations burning most frequently (Flatley et al. 2011).

Eastern Fire History – Some Concluding Thoughts

Fire is an important ecosystem process at large and small scales and thus it is essential for fire and resource managers to understand the response of fire to past, present, and future climatic change. Fire history can be interpreted in climatic terms and used as an indicator of how particular ecosystems respond to past climate changes

Paleo fire history has provided significant insight and perspective on the relationship between climate, vegetation and fire. In recent years, paleoclimate and paleoecology research has undergone a renaissance that has significantly expanded fire history information. Many terrestrial records derived from charcoal sediments, tree rings, ice cores, speleothems, and some marine environments have provided a significant increase in resolution and enabled better understanding of past, present and future influence of climate change on ecosystems.

Climate is recognized as the primary controller of vegetation and species distributions, which have varied in the past as climate changed. Further, plant species are expected to continue to shift in range and abundance as the climate continues to change (Woodward and Williams 1987) Paleoclimatology studies of plants during the Holocene warming provide the strong evidence that plant ranges do indeed shift with climate (Delcourt and Delcourt 1988; Clark et al.1996; Overpeck et al. 1992; Willard 2006). Climate changed from arid-cool (18,000 years BP) to arid-hot (7500 to 5000 years BP) to the current humid temperate domain. Native Americans were well established in the eastern US around 12,000 years BP and actively used fire as a tool to control and adapt their environment. Prior to European settlement, fire adapted ecosystems composed of tall grass prairies and oak-pine savannas, woodlands, and forests covered most of the Eastern US.

Presettlement fire regimes featured frequent, low to mixed intensity surface fire ignited primarily by Native Americans and varied according to climate, vegetation type and topography. European settlement dramatically altered eastern disturbance regimes through land clearing,

extensive timber harvesting, severe fires, and the introduction of nonnative pathogens (e.g. chestnut blight) and invasive plants. In most cases, fire-dependent species maintained themselves during this period either directly through fire or indirectly through other surrogate disturbance agents (e.g. cutting).

Besides climate, fire was the single most important influence that shaped pre-European ecosystems. Initially, European settlers, practicing fire use similar to that of the Native Americans, brought little change to fire regimes in the Eastern US. However, in short time European diseases had devastating impact on Native Americans, causing a population collapse of 90 to 95 percent by 1700. The associated decline in fire activity began a change in composition, structure, and pattern of forest vegetation and associated change in fire regimes particularly in the southeast. European culture and economic systems brought expansion of agriculture and use of fire to clear and maintain land followed closely by timber exploitation and the rise of unprecedented catastrophic fires in the late 1800s.

Vigorous fire exclusion coupled with land use changes reduced fire frequency and enabled a shift to mesophytic forests ('mesophication') with less combustible leaf litter, more shade, and cooler, moister conditions. These changes in disturbance regimes worked in opposition to fire-adapted species. Absent fire or fire surrogates plant communities shifted from fire-adapted species to shade-tolerant fire resistant species. Where fire is actively suppressed, the trend toward mesophytic hardwoods is likely to continue make these plant communities less flammable. In the West however, fire suppression had nearly the opposite effect. Changes in species composition, increased stand density, and increased live and dead fuel load made forests more susceptible to fire. In part, this explains why there is more than twice the acreage burned annually in the West than in the East (Parsons and DeBenedetti 1979; Brown et al. 2000; Nowacki and Abrams 2008).

The Warmer and Drier Future

Increases in the duration, frequency, and severity of past droughts have lead to increased frequency and extent of wildfire and fire in some regions has been related to atmospheric-ocean circulation such as ENSO (Beckage et al. 2003; Kitzberger et al. 2001; Kitzberger et al. 2007; Heyerdahl et al. 2008). As has been evidenced in the past, a vegetation shift is expected with climate change and it is further expected that fire regimes will change and the association between fire and climate will also change. Increased temperatures are expected to indirectly affect fire regimes by controlling the volume of fuel available to burn or by controlling the condition of fuels (Hessl 2011). With a warmer and drier future climate, fuel build-up associated with mesophytic vegetation conversion may provide the setting for severe fires in the eastern US.

Fire History – Western United States

Fire History and Climate Change in the Western US, including Alaska

Changing Fire Regimes and Climate in the Holocene

There have been a large number of studies of interactions between vegetation, fire, and climate over the past 10,000 years at specific locations across the Western US. These studies generally rely on sediment cores from lakes, bogs, or even the ocean to assess changes in rates of charcoal deposition, and frequency of large fire events. Many of these studies have featured west coast locations, with a few in the Rocky Mountains, because the conditions necessary for development of deep sediment deposits tend to be more prevalent in moister areas. Gavin et al. (Gavin et al. 2007) reviewed several studies of charcoal in sediments and soils across western North America (NA) and concluded that they demonstrated effects of climate on fire regimes in different regions, as well as interactions of fire and vegetation with changing climate. Patterns were not, however, synchronous across the West, illustrating that regional factors have influenced changes in fire regimes, vegetation and climate over thousands of years, as they do today. Gavin et al. also compared the spatial and temporal domains of different fire history methods (Figure 6.15). Long-term historical data from sediment charcoal and pollen records are particularly important for understanding fire regime patterns in regions such as the Pacific Northwest and Alaska's south coast, where the modern fire return intervals are very long (sometimes on the order of hundreds of years) and many fires are stand replacement fires. For these conditions, other types of fire history information, such as dendrochronology fire scar data or stand ages do not provide a sufficient record for understanding past fire interactions with climate and vegetation. Marlon et al. (2009) analyzed 35 charcoal records, primarily in the western United States, and concluded that over the glacial–interglacial transition period (~ 15,000 - 10,000 BP) local charcoal peaks at individual sites were associated with changing climate. However, synchronous peaks in soil/sediment charcoal occurred across nearly all sites during three periods of abrupt climate change -- ~13,200 years BP, during a period of very rapid climate warming, and ~ 12,900 and 11,700 years BP at the beginning and end of the Younger Dryas period. Essentially all western NA sites (except those in Alaska) showed evidence of increased charcoal influx between 15,000 and 10,000 BP, and on many sites these changes were also associated with changes in the proportion of tree pollen. Tree pollen generally decreased in British Columbia and the Pacific NW and some sites in California, but increased in the Interior West and the Southwest. A number of authors attribute this increase in charcoal influx to an increase in fuel loads as vegetation continued to develop after the retreat of the glaciers. Marlon's synthesis supports the conclusion that specific vegetation changes differed according to regional climate and regional vegetation patterns.

A study in the northern Rocky Mountains of British Columbia (Gavin et al. 2006) that compared 5,000 years of fire history based on sediment charcoal records from two lakes that were 11 km apart, illustrates the need for caution in extrapolating fire climate relationships from individual sites, and emphasizes that analysis of data from multiple sites is required to move beyond stand scale-data to understanding of regional synchronies. In the Gavin et al. study, the fire histories of two lakes with similar modern environment and vegetation showed no synchrony in fire patterns from 5,000 to 2,500 years BP, but became more synchronous after 2,500 BP. Likewise the

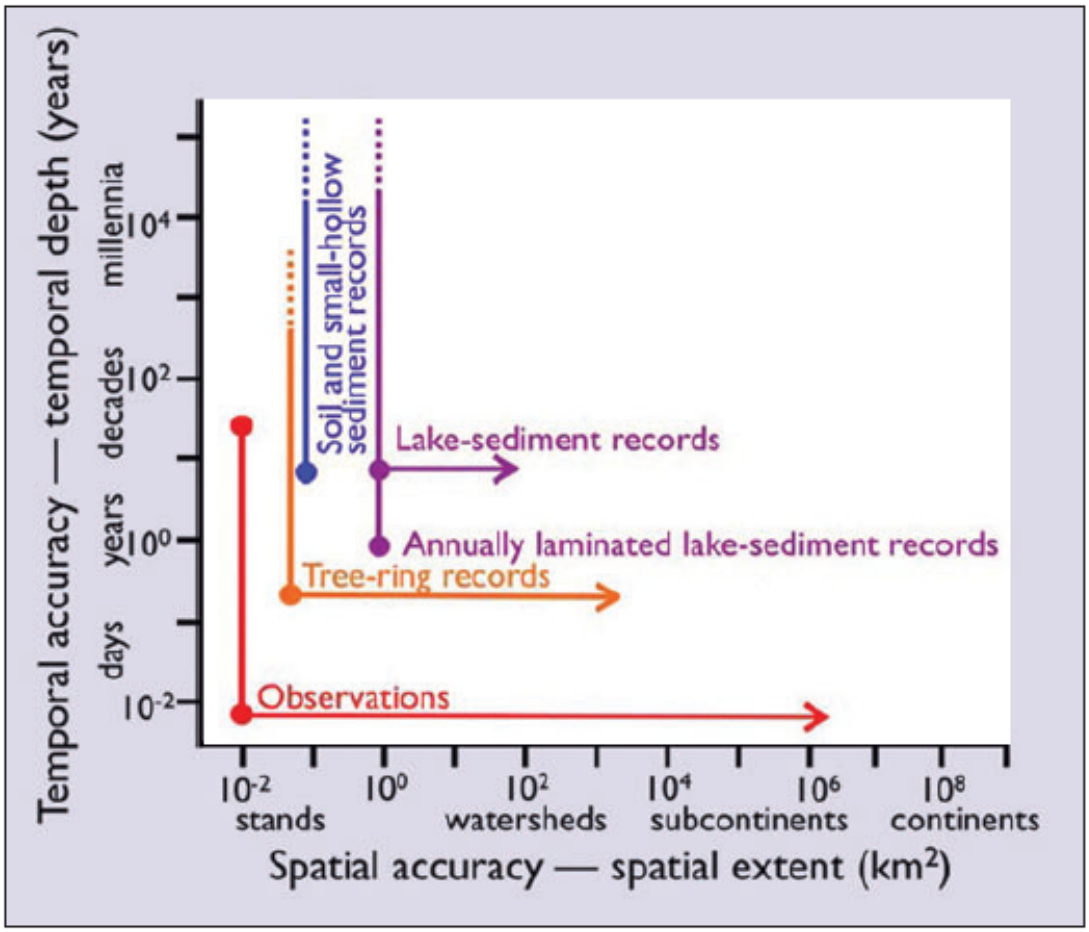

Figure 6.15: The spatial and temporal domains of fire history methods span several orders of magnitude. Vertical lines extend from the finest temporal accuracy to the maximum temporal depth of a particular method. Horizontal lines extend from estimates of the finest spatial accuracy of individual records to the combined spatial extent of all existing North American records. A terminal circle represents an insurmountable constraint on a particular method. Dashed lines represent the potential to extend fire history further back in time, although this is contingent upon discovering such records. Arrows represent the potential for more spatial coverage with future work. While tree-ring and sediment paleo-fire records may be compared from sites separated by hundreds of kilometers, the aggregated area represented by these records is quite small. From Figure 2, Gavin et al (2007). Modified from Swetnam et al. (1999).

frequency distributions of fire intervals of the two lakes were quite different before 2,500 BP, but became similar in the later period. Gavin concludes that, especially in areas of long fire intervals and stand-replacing fires, local controls over occurrence of individual fires (stochastic nature of ignitions, terrain, vegetation patterns, etc.) may override climatic controls.

The next several sections will summarize Holocene records of interactions between fire, climate and vegetation for the Southwest, Northwest, Alaska, and West Central regions of the US.

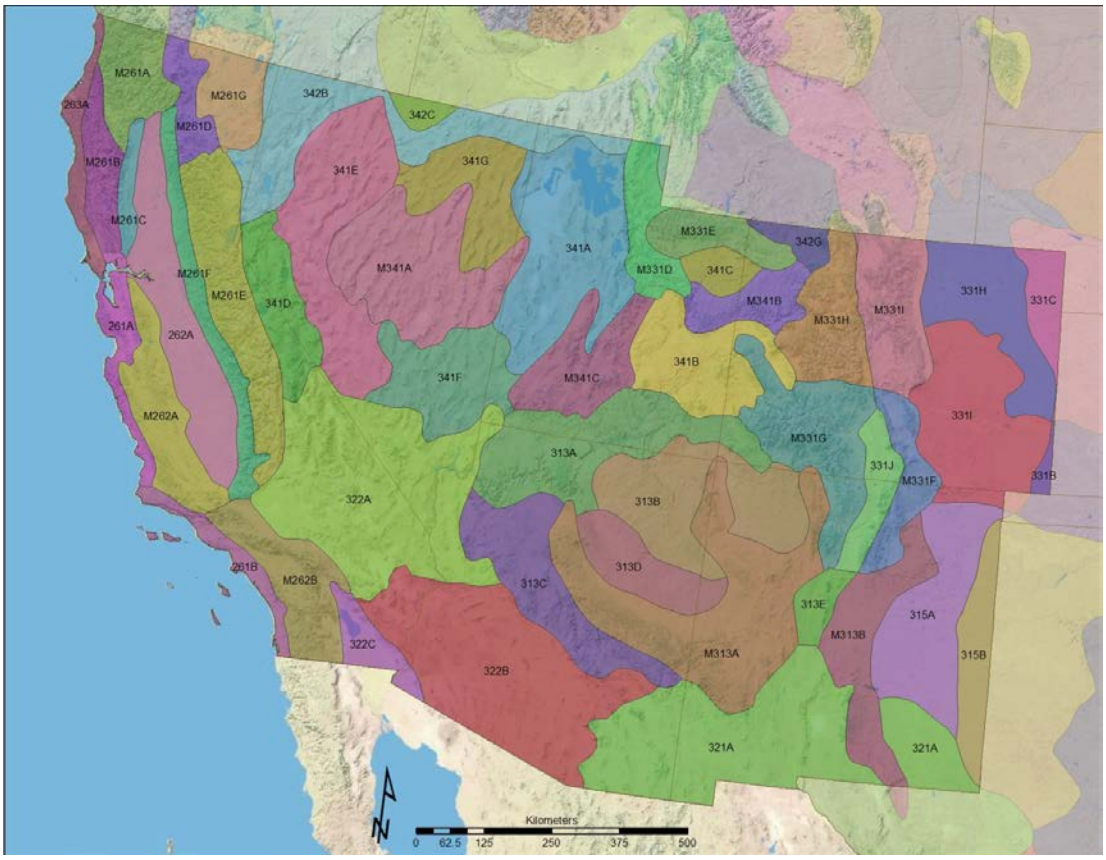

Figure 6.16: Bailey Provinces and Sections for the Southwest region. Section Descriptions, with information on current vegetation, are in Appendix F

200 HUMID TEMPERATE DOMAIN
- 260 Mediterranean Division
  - 261 California Coastal Chaparral Forest and Shrub Province
  - 262 California Dry Steppe Province
  - 263 California Coastal Steppe, Mixed Forest, and Redwood Forest Province
- M260 Mediterranean Division - Mountain Provinces
  - M261 Sierran Steppe--Mixed Forest--Coniferous Forest--Alpine Meadow Province
  - M262 California Coastal Range Open Woodland-Shrub-Coniferous Forest--Meadow Province

300 DRY DOMAIN
- 310 Tropical/Subtropical Steppe Division
  - 313 Colorado Plateau Semidesert Province
  - 315 Southwest Plateau and Plains Dry Steppe and Shrub Province
- M310 Tropical/Subtropical Steppe Division - Mountain Provinces
  - M313 Arizona-New Mexico Mountains Semidesert-Open Woodland--Coniferous Forest--Alpine Meadow Province
- 320 Tropical/Subtropical Desert Division
  - 321 Chihuahuan Semidesert Province
  - 322 American Semidesert and Desert Province
- 330 Temperate Steppe Division
  - 331 Great Plains-Palouse Dry Steppe Province
  - 332 Great Plains Steppe Province
- M330 Temperate Steppe Division - Mountain Provinces
  - M331 Southern Rocky Mountain Steppe—Open Woodland--Coniferous Forest--Alpine Meadow Province
  - M332 Middle Rocky Mountain Steppe--Coniferous Forest--Alpine Meadow Province
  - M333 Northern Rocky Mountain Forest-Steppe--Coniferous Forest--Alpine Meadow Province
- 340 Temperate Desert Division
  - 341 Intermountain Semidesert and Desert Province
  - 342 Intermountain Semidesert Province
- M340 Temperate Desert Division - Mountain Provinces
  - M341 Nevada-Utah Mountains Semidesert--Coniferous Forest--Alpine Meadow Province

Southwest

Northern California Mountains (Bailey Province M261 A, D, G: Sierran Steppe--Mixed Forest--Coniferous Forest--Alpine Meadow Province**;** Figure 6.16)

Several studies in the northern California mountains detail patterns of changes in vegetation, climate, and fire occurrence over the past 10,000 to 12,000 years. Daniels et al. (2005) studied plant macrofossils, pollen, and charcoal in a lake sediment core from the Trinity Mountains of northwestern California. As moisture increased and deeper soils developed between 12,100 and 9800 BP, three pine species were increasingly common, and the area may have supported woodland vegetation. Fire frequencies were low. Between c. 9800 and 7200 BP, oak and other chaparral species expanded as the climate became drier and warmer. Fire frequencies increased during this period, but charcoal accumulation rates were low, indicating a fire regime of frequent low-severity fires. As the climate became cooler and moister from 7200 to 3800 BP, the vegetation contained a mix of conifer species and chaparral species. There was a strong increase in both fire frequency and charcoal accumulation rates during this period. From c. 3800 BP to present the climate became cooler and wetter, a similar result to that in many other studies in California and further north. During this period, there was a transition from white fir (*Abies concolor*) to red fir (*Abies magnifica*), and mountain hemlock (*Tsuga mertensiana*) appeared, along with increasing numbers of mesic pine species and a decrease in (more xeric) evergreen oak species. Although there appears to have been a peak in fire frequency at around 2000 BP, fire frequencies decreased substantially over the rest of the period up to modern times.

Because of the unusually high biodiversity in current-day forests in the Siskiyou Mountains, Briles et al. (Briles et al. 2008) conducted a study to *"evaluate how past climate variability has influenced the composition, structure and fire regime of the Siskiyou forests"*. They used pollen, charcoal, and other evidence to reconstruct vegetation, climate and fire history at two lakes with different moisture regimes. Vegetation at both lakes during the beginning of the Holocene consisted of *Pinus*, *Cupressaceae*, *Abies* and *Pseudotsuga*. During this period the coastal site experienced more frequent fires than the more typically drier inland site. In the Early Holocene, *Pinus*, and *Cupressaceae* were less abundant and fire less frequent at the coastal site, indicating a return to moister conditions near the coast. The authors attribute these changes to differences in coastal upwelling and associated coastal fog between the two periods. As climate cooled in the Late Holocene, *Abies*, *Pseudotsuga*, *Pinus*, and *Quercus vaccinifolia* increased in the forest at both sites. Brewer's spruce (*Picea breweriana*) has become more common at the wetter site within the last 1000 years, perhaps due to decreased fire frequency. Nonetheless both sites experienced their peak fire activities about 9000 BP, when solar input was at its height, and both sites have seen increases in *Pseudotsuga* and high fire frequency over the past 2500 years, along with an indication of overall warming of regional climate. While regional changes in climate since 14,000 BP were reflected in changing vegetation and fire regime, the more local effect of changes in the driver (upwelling) that controls the amount of coastal fog led to asynchronous ecosystem responses at the two sites because of the differing effect of fog on moisture regimes and on the local climate gradients between the coastal and more inland site. This lack of synchrony provides further support for the idea that local controls on climate can greatly influence both vegetation and fire history in ways that may not correlate well with broader regional climate changes.

A study at two additional lakes in northern California (Mohr, Whitlock, and Skinner 2000) found similar changes in vegetation, climate and fire regimes at the two lakes over the past 15,000 years. By 13,000 BP, during a period of cool, wet climate, the sites supported forests of montane pines (western white pine--*P. monticola* and lodgepole pine--*P. contorta*) and fir species, and fires were infrequent. During the early Holocene (about 8300 BP), when conditions were warmer and drier, pines and evergreen oak chaparral (scrub oak--*Quercus vaccinifolia*) dominated at both sites, and fire frequency increased. Under the cooler, wetter climate of the later Holocene (7400 to c. 4500 BP), the vegetation was dominated by fir species at both sites (associated with mountain hemlock—*Tsuga mertensiana* at the moister site). Fires were frequent at both sites *c*.8300 and 4000 BP and during the Medieval Warm Period (c. 1,000 BP). Since 1000 BP, fire frequencies have again decreased to the level they are today (about 7-9 fires/1000yr (kyr)). One interesting aspect of this study was that the Crater Lake site, which has a northwest exposure and generally cooler, wetter conditions, recorded more frequent fire events than the Bluff Lake site. However, because the sedimentation rates were relatively low at these lakes, each event (charcoal peak) most likely represents multiple fire events, and the authors hypothesize that this is a reflection of fire severity rather than fire frequency, such that each event at Bluff Lake may represent more, less severe fires than those at Crater Lake.

Sierra Nevada (Bailey Province M261 E,F: Sierran Steppe--Mixed Forest--Coniferous Forest--Alpine Meadow Province**;** Figure 6.16)

Several of the studies that have reconstructed Holocene fire regimes for sites in the Sierra Nevada Mountains are discussed briefly below.

An 11,000-yr pollen and charcoal record from Balsam Meadow at about 2,000 m. elevation on the west slope of the southern Sierra Nevada showed three distinct vegetation groupings (Davis et al. 1985). From 11,000-7,000 BP the pollen assemblage included high levels of sagebrush (*Artemesia*) pollen, and vegetation was probably similar to that on the east slope of the Sierra Nevada today, indicating a dryer climate than that in the 20th century. Interestingly, other pollen studies have typically not found sagebrush pollen on the west slope of the Sierra even during this early Holocene dry period. From 7,000-3,000 BP pine pollen dominated the site, and sagebrush and other dry site species decreased greatly, indicating a moister climate than during the earlier period. After 3,000 BP the vegetation indicated increasingly cooler and moister conditions as *Abies* (fir), *Quercus* (oak) and other species became more common. By about 1200 BP needles of red fir and lodgepole pine increased and fire frequency decreased, as evidenced by decreases in macroscopic charcoal.

Based on sediment cores from two lakes in Yosemite National Park, Smith and Anderson (1992) concluded that mixed conifer forest had established in the lake basin (at 1550m, elevation) by around 12,000 BP. They suggest that this reflected a cool, wet environment at that time. Because these forests apparently contained a diverse mixture of current high elevation and mid-elevation conifers that does not occur in the region today, they concluded that the cooler, wetter climate of this period may not have any modern-day analogs. By around 10,400 BP forest similar to the current montane forests in the region had established. At this time, low levels of fir (*Abies*) pollen, and high charcoal concentrations indicated a drier climate. From about 6500 BP to 3700 BP fir pollen increased and charcoal concentrations decreased indicating a cooler, wetter climate. After about 3700 BP the climate and vegetation

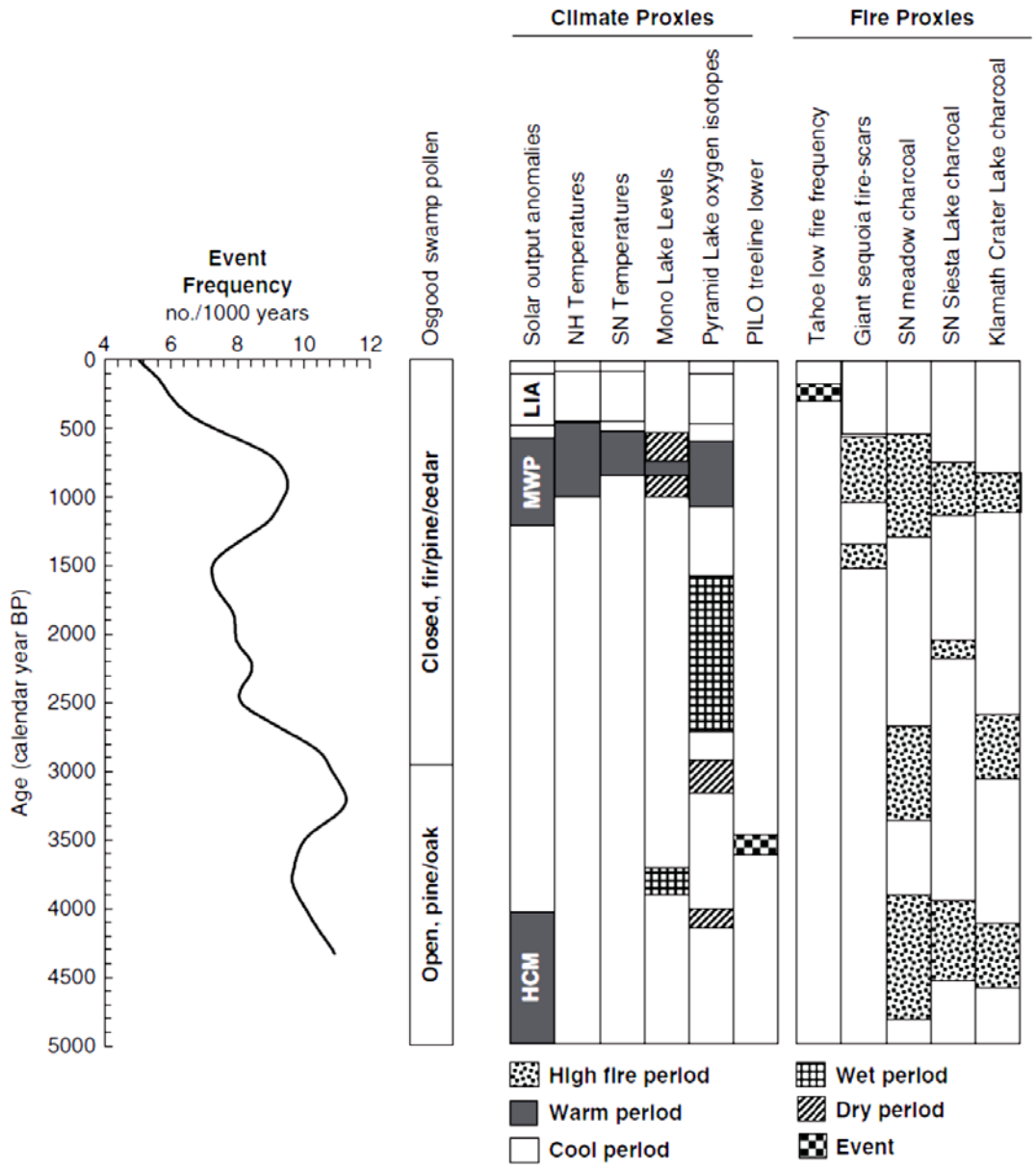

Figure 6.17: This is Figure 8 from (Beaty and Taylor 2009)**)** which compares the charcoal record for the last 4500 years at Lily Pond to other vegetation, climate and fire proxies results in the Sierra Nevada region. Peaks column indicates when influx values exceed background values. Areas of high fire frequency are shaded. The Climate Proxies section shows warm-dry and cold-wet periods based on a variety data (solar output anomolies, COHMAP Members, 1988; Northern Hemisphere temperatures, Mann *et al*., 1999; Sierra Nevada Temperatures, Graumlich, 1993; Mono Lake levels, Stine, 1994; Pyramid Lake oxygen isotopes, Benson *et al.*, 2002; *Pinus longaeva* treeline, LaMarche, 1973). The Fire Proxies section shows periods of high fire frequency from fire history reconstructions at various sites in the Sierra Nevada and Klamath Mountains (Lake Tahoe Basin, Taylor, 2004; Giant Sequoia, Swetnam, 1993; Sierra Nevada meadows, Anderson and Smith, 1997; Sierra Nevada Siesta Lake, Brunelle and Anderson, 2003; Klamath Crater Lake, Mohr *et al*., 2000).

appear similar to those in the 20th century. Charcoal concentrations decreased after about 2,000BP. The current vegetation at the site is a lower montane forest of white fir (*Abies concolor*), ponderosa pine (*P. ponderosa*), sugar pine (*P. lambertiana*), black oak (*Quercus kelloggii*) and incense cedar (*Calocedrus decurrens*).

Beaty and Taylor (Beaty and Taylor 2009) studied a 14,000-yr sediment core record from Lily Pond on the west side of Lake Tahoe. They combined this with dendrochronology data for more recent time periods to reconstruct fire history. Fire frequency increased in the early Holocene until about 6,500 BP and was generally low during the later Holocene, except for peaks at around 3,000 and 1,000-800BP. Current fire frequency in the west Tahoe Basin is at or near its lowest level over the past 14,000 years. They related changes in fire patterns to decadal, centennial and millennial changes in climate, vegetation, and other factors and speculated that climate warming in the future might increase to levels that occurred during periods of drier climate earlier in the Holocene. Beaty and Taylor also compared regional climate changes and drivers to fire records derived from several other studies (Fig. 6.17). This figure clearly illustrates the overall regional influences of changing climate and climate forcing factors on fire occurrence patterns in the Sierra Nevada throughout the Holocene. Across sites, higher fire occurrence was recorded during the Holocene Climate Maximum (about 5,000-4,000BP), the warm period about 3,000 BP and the Mdieval Warm Period about 1000-800BP.

It is important to note that a number of studies in the California mountains reported vegetation complexes in the early Holocene that have no modern-day analogs in those areas (Davis et al. 1985; Smith and Anderson 1992). Such results support the idea that future vegetation complexes under a changing climate may not have exact analogs in present vegetation.

More recent studies in the Sierra Nevada have integrated data from dendrochronological fire history, sediment charcoal, and various records of past climate to better assess long-term interactions of climate and fire regime.

As part of their study reconstructing Holocene fire regimes from lake sediments in Yosemite National Park (Sierra Nevada Mountains), Brunelle and Anderson (2003) compared data from the sedimentary record with fire regimes and climate over the last 1000 years determined from dendrochronological and hydrologic studies. They concluded that the records of climate and fire derived from the sedimentary record corresponded well with results of the tree-ring and hydrological studies, which indicates that sedimentary charcoal and pollen can be reliably used for characterizing changes in fire frequency, vegetation, and climate during the Holocene. Based on these correlations they concluded that fire frequencies during the dry "Medieval Warm Period" were only half as high as those recorded when solar insolation was at a maximum during the early Holocene. They also suggest that the early Holocene temperature maximum, as well as the high fire frequencies, is "*a good analogue for those expected with global warming*". If this is true then future drought may be considerably more severe than any of recent experience.

Swetnam et al. (2009), working with the extremely long-lived giant sequoia (*Sequoiadendron giganteum*), developed a 3000-yr chronology of fire events and changing climate in the Giant Forest, on the west slope of the Sierra Nevada, from dated fire scars, sediment charcoal and independent climate reconstructions. They concluded that mean fire intervals for stand level fires of 70 to 350 ha ranged from about 6 to 35 yr. They then compared variations in Giant Forest fire intervals at annual, multi-decadal and centennial time scales with those documented in tree-

ring and charcoal-based fire chronologies from four other giant sequoia groves in the Sierra Nevada (Swetnam 1993). In this previous study fire patterns were synchronous among the four sites. Variations in fire intervals were related to annual changes in precipitation and longer-term (decades to centuries) variations in temperature. Fire histories of the Giant Forest were well correlated with those at the other four sites, suggesting a broad regional effect of climate on fire regimes in giant sequoia. For all sites the maximum fire frequency over the past 2000 to 3000 years occurred during the Medieval Warm Period from about 1100 to 700 BP, which was the driest period of the past 2000 years.

Central California (Bailey Province 262A: California Dry Steppe Province; Figure 6.16)

There is little information on fire regime changes during the Holocene in what is now the great Central Valley of California. In recent history, this valley, much of which is now agricultural, supported perennial (later annual) grasslands, oak savannas, and extensive riparian and wetland vegetation. Davis (1999) analyzed a sediment core from historically drained Tulare Lake, which is in the southern part of the Central Valley (San Joaquin Valley) in south-central California. Before 7000 BP, the vegetation was similar to that in the Great Basin today, including species such as greasewood (*Sarcobatus*), which currently occurs only east of the Sierra Nevada. The pollen assemblage in the early-Holocene suggests that pinyon–juniper–oak woodland occupied upland areas, with greasewood nearer the lake. The disappearance of greasewood pollen after 7000 BP coincides with increased fire frequency, as indicated by sediment charcoal. The charcoal record indicates variable but frequent fire after this point. The pollen assemblage from 7000–4000 BP includes high levels of pollen from herbaceous species and decreases in oak and pine pollen that suggest expansion of grassland/savanna vegetation as evergreen woodlands decreased. A cold, wet period in the late Holocene (3500–2500 BP) was followed by progressive drying of the lake as climate became warmer and drier.

Interior Southwest: Kaibab Plateau (Bailey Province M313 Arizona-New Mexico Mountains Semidesert-Open Woodland--Coniferous Forest--Alpine Meadow; Figure 6.16)

Plant macrofossils and pollen in sediment cores from two lakes on the Kaibab Plateau in northern Arizona (Weng and Jackson 1999) indicate that by about 12,900 BP Engelmann spruce (*Picea Engelmannii*) and subalpine fir (*Abies lasiocarpa*) forests grew on the top of the plateau (around 2,500-3,000m) during the cold, wet late Glacial. By 11,000 to 10,000 BP (early Holocene) climate was warmer and drier, although still colder that today. During this period ponderosa pine became dominant at lower elevations on the plateau (around Fracas Lake). Several 100 years after the appearance of ponderosa pine, charcoal deposition rates increased greatly, which would be consistent with the modern-day frequent fire regime associated with this species. During this same period higher elevations near Bear Lake were occupied by mixed forests of spruce, fir, ponderosa pine, and Douglas-fir through the rest of the Holocene. After about 4,000 BP, as climate became cooler and wetter after the drier mid-Holocene, Engelmann spruce became more common around Bear Lake. Based on charcoal records, and records of burned spruce needles, localized ponderosa pine establishment near Bear Lake may have occurred after stand replacement fires in spruce forests.

Intermountain West: Great Basin (Bailey Provinces 341 and 342 Intermountain Semidesert; Figure 6.16)

Pinyon and juniper woodlands are widespread in the intermountain west (Great Basin), where they occupy about 20 million acres. Evidence from sediment charcoal and packrat middens Miller and Wigand (1994) indicates that after the last glacial period western juniper first appeared within its current range in northeastern California and eastern Oregon between 7000 and 4000 BP. As climate became moister starting around 4500 BP juniper moved into the lower elevation, drier shrub steppe communities. During this period grass pollen and fire occurrence increased as well. In contrast, the more recent expansion of western juniper has occurred during a period of increasing aridity and fire frequency, primarily within the more mesic sagebrush steppe communities, where exotic annual grasses are affecting fire regimes and vegetation composition. Based on pollen records, western juniper appears to be more abundant in the twentieth century than during the past 5000 years.

Southern Rocky Mountains (Bailey Province M331 Southern Rocky Mountain Steppe—Open Woodland--Coniferous Forest--Alpine Meadow Province; Figure 6.16)

Fall (1997) took an interesting approach to reconstructing Holocene vegetation and fire history in a study of a peat bog at 2900m elevation in the western Rocky Mountains, combining pollen data from peat cores with current pollen rain and current forest structures to reconstruct potential basal areas of dominant tree species from 8000 BP to present. (Table. 6.4)

Table 6.4: Estimates of mean basal area covered by each forest species (m^2 $ha^{-1'}$) (Adapted from Table 5 in Fall (1997).

Taxon	Years BP			
	8000-6400	6400-4400	4400-2600	2600-0
Pinus	12.7	5.7	7.7	23.9
Abies	16.2	5.7	10.2	8.1
Picea	26.5	7.7	13.2	9.5
Populus	9.3	1.5	3.2	2.5
TOTAL	64.7	20.6	34.3	44.0

Up until the last 2500 years, subalpine forests that grew around the Keystone Iron Bog were dominated by Engelmann spruce and subalpine fir. From 8,000 to 6,400 BP the forests were even higher in basal area to those in the region today, with a higher relative dominance in spruce and a lower relative dominance of pine than there is today. All of these factors suggest that the early Holocene climate was cooler and wetter than at the current time. At least three stand-replacement fires occurred during this period, and it took about 200 years for the subalpine forest to regenerate after these events. It appears that between about 6,400 and 4,400 BP the bog was surrounded by a subalpine meadow, and the forest was either low density or farther from the bog.

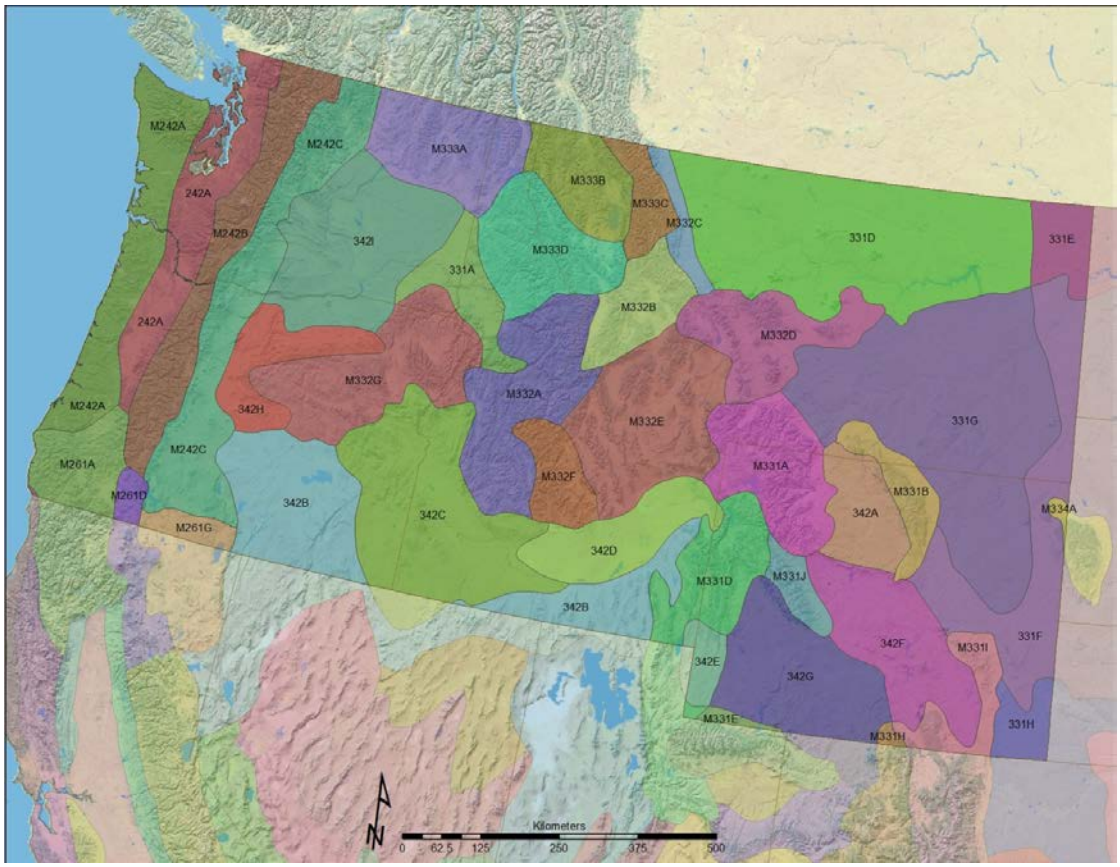

Figure 6.18: Bailey Provinces and Sections for the Northwestern region. Section Descriptions, with information on current vegetation, are in Appendix F

200 HUMID TEMPERATE DOMAIN
- 240 Marine Division
  - 242 Pacific Lowland Mixed Forest Province
- M240 Marine Division - Mountain Provinces
  - M242 Cascade Mixed Forest--Coniferous Forest--Alpine Meadow Province
  - M244 Pacific Coastal Mountains Forest--Meadow Province
  - M245 Pacific Gulf Coastal Forest--Meadow Province
- 260 Mediterranean Division
  - 261 California Coastal Chaparral Forest and Shrub Province

300 DRY DOMAIN
- 330 Temperate Steppe Division
  - 331 Great Plains-Palouse Dry Steppe Province
  - 332 Great Plains Steppe Province
- M330 Temperate Steppe Division - Mountain Provinces
  - M331 Southern Rocky Mountain Steppe--OpenWoodland--Coniferous Forest--Alpine Meadow Province
  - M332 Middle Rocky Mountain Steppe--Coniferous Forest--Alpine Meadow Province
  - M333 Northern Rocky Mountain Forest-Steppe--Coniferous Forest--Alpine Meadow Province
- 340 Temperate Desert Division
  - 341 Intermountain Semidesert and Desert Province
  - 342 Intermountain Semidesert Province

From 4,400-2,600 BP forest density again increased, with a similar composition, but somewhat lower density, to that before this (perhaps) drier period in the mid-Holocene. Around 2600 there

was an apparent shift to drier climate, and from 2600 to present, lodgepole pine has dominated the forests at the site. Fall speculates that fires during this latter period were mostly lower-severity surface fires. Due to the warm dry conditions and south-facing aspect, spruce and fir have never reoccupied the site, although they do occur on other sites in nearby areas. This seems to be a different pattern from that many authors observed in the Sierra Nevada and northern California mountains, where the past 1000 years or so have seen increases in species and fire regimes characteristic of cooler and wetter climates relative to the mid-Holocene and Medieval Warm Periods.

Sediment pollen and charcoal from Little Molas Lake at 3370m in Colorado's San Juan Mountains (showed that tundra vegetation was replaced by spruce forest as climate warmed during the postglacial period (Toney and Anderson 2006). Spruce and other conifers remained in the vegetation around the lake throughout the Holocene. The driest period occurred from about 6200 to 5900BP when lake levels were at their lowest. Since 2600 BP a wetter climate has been associated with expansion of pinyon pine (P. edulis) and ponderosa pine. The lowest fire event frequency was observed after around 4100 BP (~5 events/kyr), during a period of cool, moist climate. The highest frequencies occurred about 10,500 BP (~13 events/kyr), 6,000BP (~8/kyr), and 2,000BP (~9/kyr). The highest peak in the early Holocene was probably associated with increasing vegetation density and fuel buildup as climate warmed. The most recent charcoal peak in the sediment core records the AD 1879 Lime Creek Burn.

Northwest

Coastal Mountains (Bailey M244 Pacific Coastal Mountains Forest--Meadow Province; Figure 6.18)

Charcoal data from coastal rain forests in British Columbia may shed some light on historic fire regimes in the similar coastal forests of northwestern Washington and southern Alaska. Research on Vancouver Island found that many sites on terraces and north-facing slopes had not burned in over 6,000 years (Gavin et al. 2003). A study on similar sites using charcoal from lake sediments found that often fire had not occurred for several thousand years (Brown and Hebda 2002). This study found that fire activity was higher 11,700 to 7,000 years BP, during a period when forest were dominated by more fire-adapted species. Lertzman et al (2002) found that fire frequencies in coastal rainforest areas in southern British Columbia over the past 8-10,000 years varied from several centuries to thousands of years, with a number of sites experiencing from 0-2 fires over the study period. The median fire interval on the higher elevation, more inland Fraser Valley sites was 1200 years, about half that on the more coastal Claoquot Valley site. They concluded that types of disturbance other than fire were more important in forest processes in these wet coastal ecosystems. Drier south-facing slopes, and sites further inland in British Columbia experienced considerably greater fire activity than coastal sites (Brown and Hebda 2002). Many of these sites had experienced fire in the past 1000 years, although fire intervals on the order of 400 years were not uncommon (Hallett et al. 2003). In an earlier study carried out in areas currently dominated by mountain hemlock (*Tsuga mertensiana*) forests in the coastal mountains and more interior Cascade Range of southern British Columbia, Hallett et al. (2003) found frequent fire between 11,000 and 8,800 years BP, during a period when *Abies* (fir) species were apparently present in the sample areas. With decreasing fire frequencies up until around 5-6,000 years BP as the climate became cooler, and *Tsuga* became more dominant. They also

found that fire frequency was higher throughout the mid-Holocene at the Cascade sites, in the late mid-Holocene in the coastal mountains. After a short period of glacial advance around 3,500 to 2,500 BP, the fire frequency again increased, and more *Abies* appeared, as the climate warmed, suggesting an increased frequency of summer drought. Fire intervals in the region appear to have gradually decreased since about 1300 years BP, although fire intervals in these forests are irregular and in a number of cores no fires were recorded over the past 1,000 years.

Long et al. (1998) used sediment charcoal to reconstruct 9000 years of fire history at Little Lake in the Oregon Coast Range. During warmer, drier climate from about 9,000 to 6,850 BP, fire intervals averaged 110 years. Fire intervals increased to 160 years during a cooler period from 6850 to 2750 BP, when tree species typical of moist cool sites, such as western red-cedar, western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) increased in dominance. After 2750 BP, as the climate became cooler and moister, the fire interval increased further, to about 230 years. The authors conclude that fire frequency has varied over thousands of years as climate changed, and that the current (as of 1998) fire frequency in the region had been present for no more than 1000 years. A study of sediments from Taylor Lake in moist coastal Oregon had similar results (Long and Whitlock 2002). Here, fire was more frequent between about 4600 to 2700 BP (140 yr. fire interval) than it has been from 2700 BP to present (240 yr. fire interval). This change was associated with a change in vegetation from forests with red alder (which were similar to more interior sites with summer drought in the region today) to forests with the more mesic and less fire-resistant western hemlock and Sitka spruce.

Siskiyou and Cascade Mountains (Bailey Provinces: M261A Sierran Steppe--Mixed Forest--Coniferous Forest--Alpine Meadow Province; M242B Cascade Mixed Forest--Coniferous Forest--Alpine Meadow Province; Figure 6.18)

Briles et al. (2005) evaluated charcoal and pollen records from sediment cores of Bolan Lake in the drier Siskiyou Mountains (near the Oregon-California border) and compared their results with several other studies on nearby sites in California and Oregon. They concluded that fire frequency (# fires/1000 yr.(kyr)) on these more interior sites varied over a range from about 4/kyr (250 yr. fire interval) around 11,500 BP to a high of about 10/kyr (100 yr. fire interval) around 7000 BP. They concluded that the current fire regimes, climate and vegetation patterns have been in place for about the past 1500-2000 years, with fire frequency ranging from about 8 to 9/kyr (~110-130 yr. fire interval). Their summary of past climates in the region suggests that changes in vegetation across the region have responded to similar changes in climate, with somewhat cooler conditions prevailing from about 6,000 to 2,000 BP, when vegetation dominance of *Tsuga* (hemlock) and other species characteristic of cool, moist climate increased in importance, than at present.

Cwynar (1987) looked at changes in tree pollen and macrofossil assemblages and sediment charcoal in the Cascade Mountains of Washington. He identified five main vegetation complexes: a *Pinus-Populus* zone of open forests that included mountain hemlock, fir species, lodgepole pine (*P. contorta*), and poplar before 12,000 BP, a *Picea-Alnus sinuata* zone, characterized by Sitka spruce, red alder, and *A. sinuata* from > 12,000 to 11,000 BP, an *Alnus rubra-Pteridium* zone, with red alder, Douglas-fir, western hemlock, and bracken fern, indicating a drier climate, along with an increase in charcoal deposits, from 11,030 to 6830 BP. A

Cupressaceae zone beginning at 6830 BP was characterized by an increase in western red cedar and western hemlock during a period of decreased fire, when the climate may have been similar to the climate in the region today. In the late Holocene lodgepole pine and red alder increased in dominance from 2400 to 900 BP, indicating again warming and drying of climate.

Northwest regional

Whitlock et al. (2003) summarized results of studies at 9 sites where lake sediment charcoal and pollen had been investigated across the northwestern US and integrated it with climate data and models. Based on studies from the Pacific Northwest and summer-dry areas of the northern Rocky Mountains (Figure 6.19), they concluded that the highest fire activity in these areas was during two periods when climate was dryer than it is currently, from 11,000-7,000 BP and during

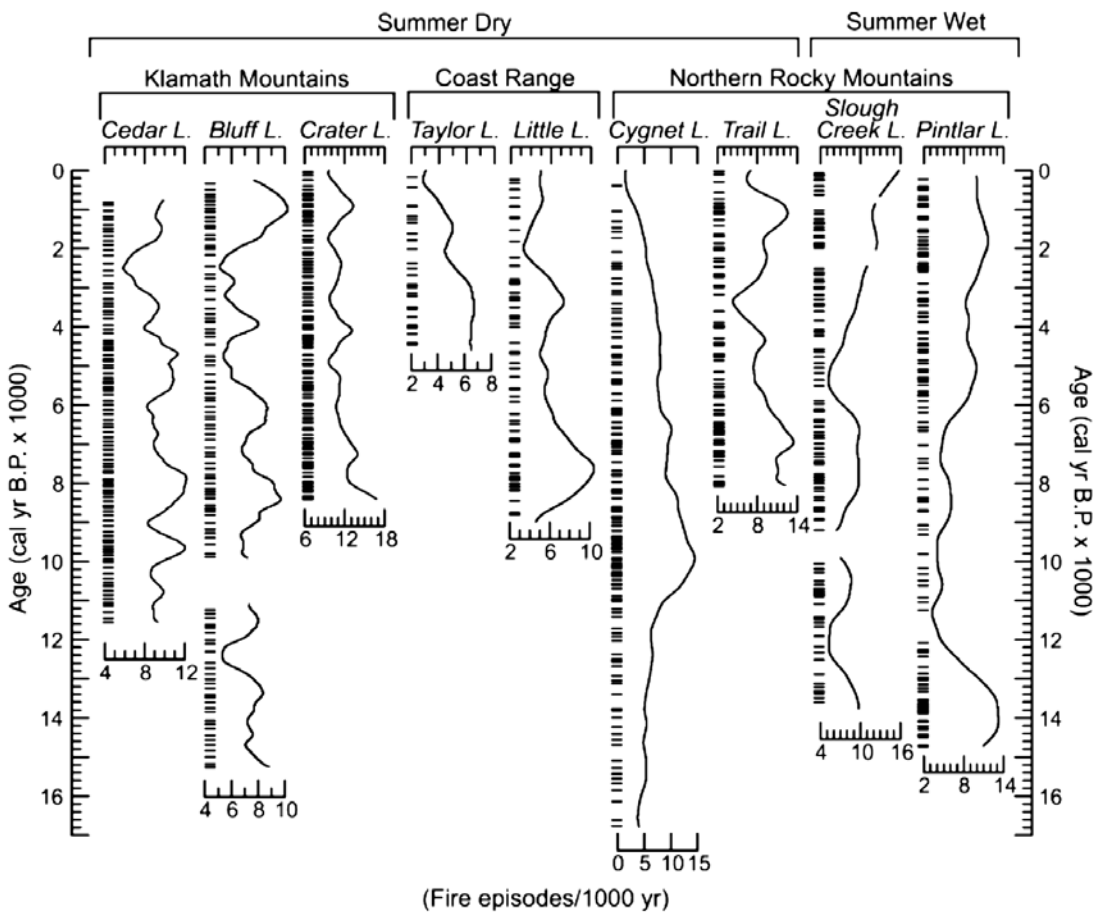

Figure 6.19: Fig. 2 (from Whitlock et al. 2003). Comparison of Holocene fire reconstructions from sites in different geographic and climatic locations in the western US. The horizontal lines at each site represent past fire episodes, i.e., based on the age of peaks in the charcoal record obtained from radiocarbon-dated sediment cores. These peaks represent one or more fires occurring in a decade. The curves depict fire frequency, which is the number of fire episodes per 1000 years averaged over a moving window. Summer dry and summer wet refer to two different precipitation regimes evident in the western US (see text for discussion).

the Medieval Warm Period around 1000 BP. In areas of the northern Rockies that currently experience wet summers, on the other hand, the greatest fire activity has occurred over the past 7,000 years, a period during which dry woodland vegetation developed in the area.

Whitlock et al. (2008) synthesized information from 15 sites across the Northwest, in northern CA, and in the Rocky Mountains. In general charcoal levels in sediment were low as the glaciers retreated, but as vegetation has gradually fully reoccupied sites, fuel biomass has increased over time. As a result charcoal levels have increased throughout the last 11,000 years. In comparing across sites, it is evident that patterns of climate change and fire regime change during the Holocene have varied among regions, and that local site conditions, such as vegetation structure and composition, terrain, and local weather and climate can have a major influence. They noted several regional patterns in Holocene fire frequency. For example, there were relatively few fires in the coastal ranges compared to the interior northern California mountains (e.g. Klamath region). In the Rocky Mountains, areas that currently have dry summers experienced a long period of high fire activity in the early Holocene, whereas those in areas with summer monsoonal patterns had lower fire activity during the same period. Many sites showed higher fire frequency during the Medieval Warm Period (about 700-1000 BP) and most sites in the summer-dry regions of the northwestern US apparently had higher fire frequencies around 6000 BP than they do today. These results support the occurrence of persistent circulation features similar to those observed today that link dry climate and high forest fire activity (e.g. Williams et al. (2009)). Further, it is evident from these Holocene records that large, stand-replacement fires have occurred in many northwestern US ecosystems for thousands of years. Whitlock et al. (2008) conclude that while climate has been the major driver of fire regimes at a regional scale: *"The association between drought, increased fire occurrence, and available fuels evident on several time scales suggests that long-term fire history patterns should be considered in current assessments of historical fire regimes and fuel conditions"* and *"Long-term records of fire history add a unique dimension to our understanding of fire–climate–vegetation linkages and should help discourage oversimplistic assumptions about current fire regimes and their stability."* While some sites have shown increasing fire frequency over time, on others fire activity has decreased since the early Holocene. Reconstructions of Holocene climate and fire patterns provide important background information and context on modern fire regimes and the interactions between historic fire regimes and the development of modern plant communities. Such information can provide an important basis for projecting potential future influences of changing climate on fire regimes and fire/vegetation interactions.

Alaska (Bailey Alaska, Figure 6.20)

There are relatively few studies of Holocene fire regimes in Alaska, but the ones that exist provide interesting insights. Lynch et al. (2004) obtained sediment cores from two lakes in south-central Alaska that were about 20 km apart. The current vegetation in the region is fairlytypical for this part of Alaska, with white spruce (Picea glauca), quaking aspen (Populus tremuloides) and paper birch on well-drained upland sites, and black spruce (Picea mariana) in boggy lowland sites. Their goal was to study relationships among moisture conditions, species composition, and fire intervals. They concluded that moisture availability since 7000 BP has varied over time and that the climate has become wetter over the past 3800 years. Boreal forests similar to those of today existed in the region throughout the study period, although black spruce

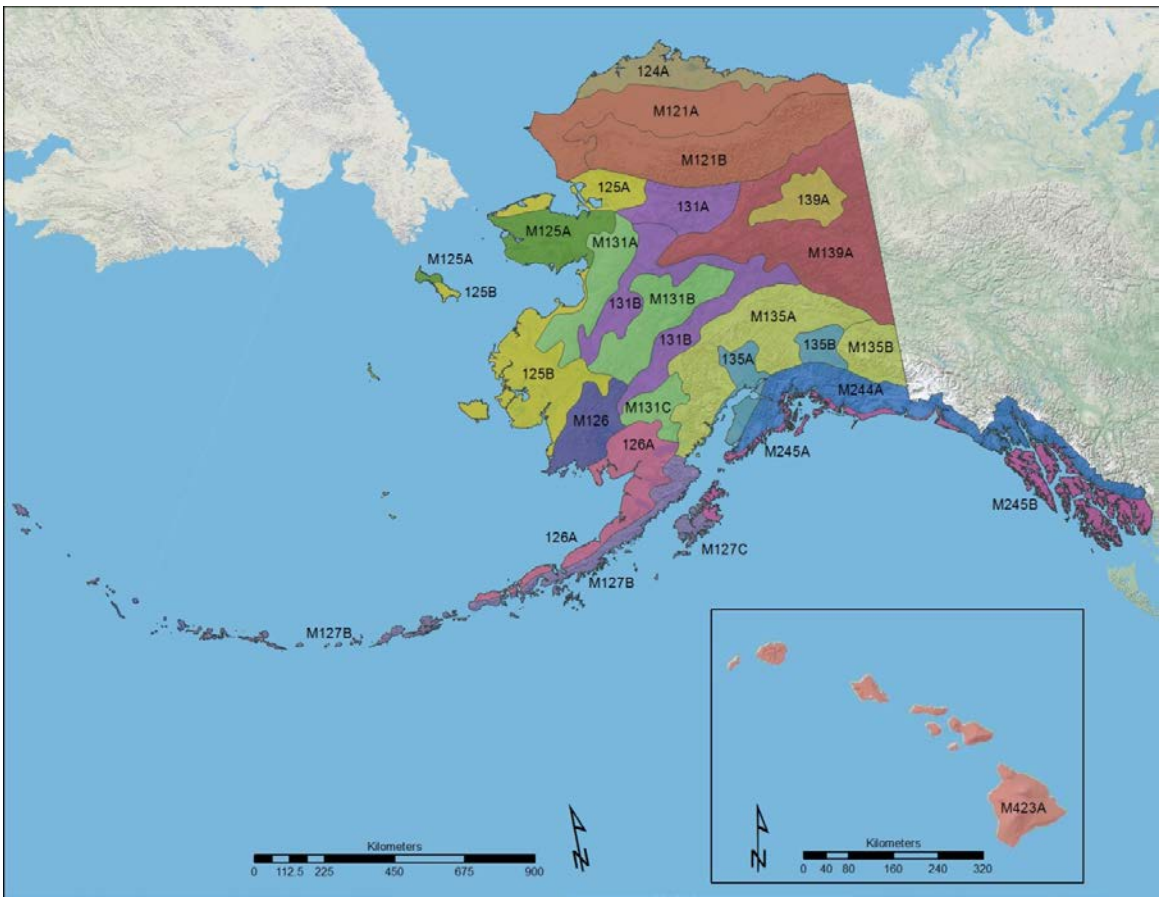

Figure 6.20: Bailey Provinces and Sections for Alaska. Section Descriptions, with information on current vegetation, are in Appendix F

100 POLAR DOMAIN
- 120 Tundra Division
  - 124 Arctic Tundra Province
  - 125 Bering Tundra (Northern) Province
  - 126 Bering Tundra (Southern) Province
- M120 Tundra Division - Mountain Provinces
  - M121 Brooks Range Tundra--Polar Desert Province
  - M125 Seward Peninsula Tundra--Meadow Province
  - M126 Ahklun Mountains Tundra--Meadow Province
  - M127 Aleutian Oceanic Meadow--Heath Province
- 130 Subarctic Division
  - 131 Yukon Intermontane Plateaus Taiga Forest
  - 135 Coastal Trough Humid Taiga Province
  - 139 Upper Yukon Taiga Province
- M130 Subarctic Division - Mountain Provinces
  - M131 Yukon Intermontane Plateaus Taiga--Meadow Province
  - M135 Alaska Range Humid Taiga--Tundra--Meadow
  - M139 Upper Yukon Taiga--Meadow Province

increased in dominance at one of the lakes starting around 2000 BP. Except for a period of about 800 years around 5000 BP when MFI was around 200 years, the mean fire interval was greater than 500 years until it began to decrease after 3800 BP (MFI of 200 yrs. from 3800-2000 BP at

both sites; 150 yrs. after 2000 BP at the more poorly drained Choksana Lake site. Fires at the two study sites occurred more frequently under wetter a climatic condition, which differs from the more typical association of drier climate with increased fire frequency in other ecosystems. The authors suggest that increased fire frequency under wetter conditions may have been due to changes in seasonal soil moisture availability combined with increases in lightning ignitions. A number of other studies in Alaska have shown similar results, with increases in black spruce generally associated with wetter climate and increased fire frequency. In addition to the reasons suggested above, Hu et al. (2006) suggest that higher flammability of black spruce may also be a factor.

Hu et al. (Hu et al. 2006) synthesized results from several recent lake-sediment charcoal and pollen studies of interactions among fire, vegetation, and climate in Alaskan boreal ecosystems during the Holocene. A common result of studies in interior Alaska was that fire occurrence increased as forests became dominated by black spruce (*Picea mariana*). Regardless of when in the Holocene black spruce dominance was established, mean fire-return intervals decreased from ≥300 yrs to as low as 80 yrs. Black spruce expansion was generally associate with regional trends toward cooler, wetter climate. Hu et al. concluded that the increase in fire frequency with black spruce establishment was most likely due to higher flammability and easier fire spread in these forests than in the *Populus* or white spruce forests and woodlands or the tundra vegetation that were there prior to black spruce. Fire frequency also increased at some sites at around 4,000 BP, without evidence of increases in black spruce. On these sites increased lightning frequency may have been a factor. They concluded that Holocene fire histories in areas of similar modern fire regimes differed among sites, that the reasons for these differences are not clear, and that a more extensive network of sediment charcoal data will be necessary, along with more detailed paleoclimate reconstructions, and a better understanding of how to interpret temporal and spatial distribution of fire from charcoal records.

Anderson et al. (2006) used sediment cores from two lowland lakes on the Kenai Peninsula to evaluate the relationships among disturbance, climate and vegetation during the Holocene. By ~ 10,000 BP the postglacial herb tundra had been replaced by shrubby species of willow, alder, and birch, and by 8500 BP white spruce had established in the area. Black spruce and alder became established around 4600 BP. Mean Fire Intervals were longest (~140yr) during the tundra phase and decreased to ~80 years during the shrub and white spruce phases (10,000-4600 BP), in a period of when summers were longer and drier than they are today. As climate became cooler and wetter in the mid-Holocene, black spruce became established, and the fire intervals increased back up to ~130 yr.). These results differ from those of other studies discussed above which found increased fire frequency with the arrival of black spruce. Possible explanations are that the long, dry summers in the early Holocene led to a higher flammability; that lightning may have been more common in the earlier period, and that black spruce is not widespread in the Paradise Lake drainage, but occurs primarily in a narrow band near the lake, so likely had little influence on the overall fire regime of the drainage area.

Brubaker et al. (2009) parameterized the ALFRESCO (Alaskan Frame-based Ecosystem Code) ecosystem model to compare simulated fire regimes with those determined from Holocene charcoal-sediment records in the south-central Brooks Range. They estimated fire intervals over the past 7000 years from short-term variations in sediment charcoal at three lakes and changes in

burned area from long-term deposition rates. Their results support the hypothesis of Hu et al. (2006) that increased dominance of black spruce in the mid-Holocene increased landscape flammability and led to increased fire frequencies even under cooler wetter climates. This somewhat counter-intuitive result is further evidence that fire regimes in boreal systems may be more affected by climate-induced vegetation changes than by direct effects of climate. Species-specific traits of black spruce that lead to increased flammability and fire spread include flammable foliage, ladder fuels, semi-serotinous cones and rapid regeneration after fire.

Higuera et al. (2009) analyzed sediment cores from four lakes in the south-central Brooks Range, Alaska, to detect statistical differences between fire regimes. Vegetation zones were identified by fossil pollen and stomata. From about 15,000–9000 BP as climate warmed, vegetation changed from herb tundra to shrub tundra to deciduous woodlands. None of the observed species assemblages had analogues in current vegetation. Fire intervals decreased from as climate warmed but remained cooler than present. In addition to changing climate, the higher flammability and more continuous fuels of the shrub tundra are hypothesized as a factor in the increased fire incidence. As vegetation shifted to less flammable *Populus* woodlands from 10,300 – 8250 BP, fire intervals decreased (mean FRI ~250 yr) despite warm, dry climate. As climate became cooler and wetter in the mid-late Holocene, white spruce forest-tundra and black spruce forests established (8000 and 5500 BP, respectively). FRIs in forest–tundra were similar to or shorter than those in the deciduous woodlands. When black spruce became established the resulting higher landscape flammability led to lower FRIs (~145 yr) despite continued cooling and wetter climate. As with other studies in the Alaska boreal, shifts in fire regimes were strongly linked to changes in vegetation, as vegetation responded to millennial-scale climate change. These results illustrate how much *"shifts in vegetation can amplify or override the direct influence of climate change on fire regimes, when vegetation shifts significantly modify landscape flammability"*.

This study and others reported above emphasize that it is the feedbacks between climate, vegetation, and fire that have been key determinant of the responses of fire regimes and vegetation dynamics to climate in the past. There is every reason to believe that similar processes will be important in determining responses to climate change in the future, although the rates of anticipated future change in climate may far exceed those of the recent several millennia.

The impact of Native Americans on Fire Regimes

Native Americans in the West used fire for many purposes—to improve habitat for game animals, to drive or trap game so it could be more easily harvested, to favor mast trees such as oaks that provided edible nuts, for defense around settlements, to open up trails, to maintain grasslands and prairies, and to stimulate production of sprouting vegetation such as willows (used for basketry) or browse species favored by large game animals. Little is known about how extensive these practices were across broad landscapes, and the intensity of the effects of Native American use of fire must have varied considerably with the level of the populations and with the region and vegetation types they were living in.

Southwest

Anderson and Moratto (1996) provide an excellent overview of the impact of Native Americans on vegetation and fire regimes in the Sierra Nevada range. They estimate that just before the time of European settlement in the region in the mid-1800's there were approximately 90,000-100,000 Native Americans, belonging to about 13 different tribes, living in the Sierra Nevada. These diverse cultures had adopted somewhat different land-use practices in various areas. In general, however, these native populations used fire extensively, and also practiced localized agriculture. Populations were highest at mid to low elevations (1000-1250 m; 3300-4100 ft), with higher mountain areas used primarily during the summer. Between 1800 and 1850 these aboriginal populations were reduced by some 75% due to a combination of diseases brought by European settlers, starvation, warfare, and outright massacres.

The native people of the Sierra Nevada subsisted on a diverse diet of acorns, seeds of herbaceous plants, and a variety of greens, fruits, roots, and mushrooms, as well as hunting and trapping animals such as deer, fish, small game, and even insects. In addition to use of plants for food, they gathered firewood and plant materials used in making baskets, rope, and shelters. To meet these needs they used a variety of approaches to manipulating vegetation. The foremost of these was fire, which was used to clear understory vegetation, to maintain grassland and meadow areas, prepare areas for planting, stimulate browse species, acorn production, and production of sprouts and grasses used for making baskets and cordage, and reduce fuel accumulation to decrease the likelihood of severe fires in the areas where they lived. Many of these objectives required a frequent burning regime. They also practiced agricultural techniques such as irrigation, planting, pruning, selective harvesting, tilling, transplanting, and weeding. Extensive firewood was needed for cooking, heat, sweat houses, and light; the native Americans in the Sierra Nevada also used fire for felling and "cutting" trees, and (in some tribes) to fire pottery. Anderson and Moratto make a rough estimate that if each Native American household had burned only 10 ha (25 ac) per year, this would have resulted in about 140,000 ha (350,000 ac) being burned every year in the Sierra Nevada. If we assume a five-year rotation, then they may have managed as much as 700,000 ha (1.7×10^6 ac) with fire. Although additional research is needed to improve these estimates, it is clear that the extent of burning by native people in the Sierra Nevada was sufficient to effect significant vegetation change over wide areas.

Native American populations were also high in the California coastal ranges. Keeley (Keeley 2002a) has used a combination of approaches to evaluate the potential impacts of Native American burning on fire regimes and vegetation in the southern coastal ranges. This area is particularly interesting because it has a very low incidence of lightning fires, so a frequent fire regime is a strong indicator of human influence. He notes that charcoal sediment data for a 560-year period suggest that fire frequency in the coastal mountains of Santa Barbara County was similar prior to European settlement to that today (Mensing, Michaelsen, and Byrne 1999). Because the majority of contemporary ignitions in this area are of human origin (Keeley 1982), it seems likely that the Native Americans burned (intentionally or not) extensive areas. Based on ethnographic, archeological, and anecdotal data, it appears likely that most valleys and watersheds with at least seasonal water were inhabited at least some of the year. Keeley (Keeley 2002b) argues that the native chaparral, which is a relatively poor source for food and can be nearly impenetrable, would not have provided sufficient resources or access to those resources to support the high native American populations in the area. Fire in chaparral can greatly increase

biodiversity, and encourages many herbaceous species that were highly desirable food sources. Further, chaparral stands harbor poisonous snakes and other hazards and provided potential cover for both grizzly bears and human enemies. And continuous stands of chaparral support large, dangerous, high intensity fires in fall and winter under Santa Ana wind conditions. Keeley notes that there are extensive areas in this region that now support grassland or scattered shrubs and trees, and concludes that this pattern most likely resulted from extensive and intentional use of fire by Native Americans. The similarity in soils under these different vegetation types provides additional supporting evidence.

Northwest

Williams[29] (2002) states that: "*There is evidence that not all tribes used fire extensively….Indian tribes along the northwest Pacific Coast rarely used fires in the ecosystems they were living, as their subsistence food came from the ocean and rivers. However, a few miles inland, fire was used by different tribes to a much greater extent because they used the forest and prairie or savanna portions of ecosystems to survive.*" The seasonality and frequency of fire use by Native Americans varied with the ecosystem, and with the desired outcome. Williams also presents overviews of Native American burning in the Willamette Valley of Oregon and the western mountains. In the Willamette Valley many areas were burned every couple of years to suppress brush and conifer invasion; to facilitate harvesting of tarweed, which produced highly desired seeds; to provide open grazing grounds for deer herds, and facilitate hunting; to make it easier to collect insects such as grasshoppers for food, etc. An estimated 2 million acres were maintained as prairie by these practices. By the 1850's the Native American populations in the area had been essentially eliminated by disease, warfare, and removal to reservations. After this time, the vegetation in the Valley gradually changed as the invasion of Douglas-fir and shrubs led to decline of the Oregon white oak (*Quercus garryana*), which had been an important food resource both for the Native Americans and for game. Much of this former prairie-savanna is now either agricultural land or is occupied by towns and cities. Similarly, Storm and Shebitz (2006) concluded that historic burning by Native Americans was central to maintenance of prairie vegetation and production of desirable plant species in areas of southwest Washington. In reviewing previous literature on indigenous burning in the region, they concluded that "*Western Washington ecosystems that were indigenously maintained by frequent burning include open bunchgrass prairies, associated oak woodlands, oak/ash (*Quercus garryana/Fraxinus latifolia*) riparian corridors, beargrass…, savannas and low…to mid-elevation…patches of open grasslands and berry grounds.*"

In western North America, Native Americans typically lived in high-elevation mountain areas only during the summer and fall seasons, when there was no snow, and lived in foothills or valleys during the winter. There is some evidence that they set fires in the Cascade Mountains to "improve game range and berry picking" (Minto 908:153); cited in Williams (2002)). In western Montana, Native Americans are reported to have burned primarily in valley grasslands, and low-elevation ponderosa pine, Douglas-fir, and larch (*Larix occidentalis*) forests during the fall and

[29] Willams provides an extensive bibliography related to Native American use of fire, which is worth looking at for those who wish to dig deeper into what information is available for specific localities. Many of the papers he cites are reports of early explorers or settlers, and they often have only scant reference to fire.

spring (Barrett 1980:18, cited in Williams (2002)). Native Americans also set fires in the Blue Mountains of northeastern Oregon to improve hunting and grazing until the mid-1800's (Langston 1995 and Robbins and Wolf 1994; cited in Williams (2002)).

Barrett and Arno (1982) report that burning by Native Americans was apparently widespread in the Northern Rocky Mountains of Montana. Purposes for burning included: maintaining open stands for hunting, travel, and protection from enemies; improving habitat and forage for game and livestock, stimulating production of food and medicinal plants; clearing campsite areas to reduce fire hazard and clean up refuse; and communication. They also compared mean fire interval of stands that had been heavy use areas for Native Americans with more remote stands and concluded that MFI before the 1860's was significantly shorter in the heavy use stands, indicating that the effects of Native American burning on local fire regimes maintained open stands of ponderosa pine in areas that in modern times have been invaded by shrubs and shade-tolerant trees.

Alaska

Lutz (1959) wrote extensively on "aboriginal" use of fire in the boreal forests of North America, with a focus on Alaska. He discussed several uses of fire in this region, including campfires, which were apparently often left unattended and were rarely extinguished—thus often leading to small local fires, and sometimes to larger wildfires. These campfires were used for cooking, protection from insects, warmth, and for softening the pine pitch used to seal canoes. He also noted that the Native American use of signaling fires was widespread; interestingly Knik Indians, who lived near Cook Inlet, were known as the "fire-signaling people". As in other areas of the West, fires in Alaska were also used for driving game, for clearing out underbrush to facilitate hunting, and to stimulate forage production. Native Americans in many areas of Alaska have been reported to burn smudge fires to discourage insects. These were often carried with them as they traveled, whether by canoe or by land, and have been reported to be a potential source of many forest fires. Along the Yukon and Tanana Rivers and across Interior Alaska large areas were also sometimes burned purposefully to drive away insects. Because the stone axes used by Alaskan natives were not very effective at dealing with large trees, fire was also used as a means of downing trees and breaking them up into manageable sections (Lutz 1959).

Williams (2002) points out that while there is considerable anecdotal evidence of Native American use of fire in the western US, there is insufficient information to determine how extensive this fire use was in many areas or what the overall impact was on vegetation composition and dynamics at a landscape or regional scale. As alluded to above, shortly after the arrival of Europeans into the western US, many of the Native American populations were decimated by warfare and disease, or moved from their original locations onto reservations. As a result, their influence on fire regimes was essentially eliminated by the mid-1850's in most areas.

Defining Historic Fire Regimes

When researchers and managers talk about "historic" fire regimes, they are generally referring to fire regimes during the period before extensive European settlement. Because Native American populations were widespread in much of the western US for over 10,000 years, on a broad scale it is generally impossible to separate the effect that they had on vegetation and fire regimes from the effects of fire ignited by lightning and other sources. The LANDFIRE classification of fire regimes has taken this approach and provides useful insights for understanding the spatial distribution of "historic" fire regimes and how much they have changed over time. But it cannot tell us the causes of these changes. Regional fire regimes and vegetation for the Southwestern and Northwestern US and Alaska are shown in Figures 6.21a-f. These figures illustrate both the wide diversity in fire regimes across the western US and the strong regional differences in major vegetation types both geographically, and due to the strong topographic influences in the mountainous west. The areas with the longest fire intervals tend to be on two ends of the environmental spectrum. In forest ecosystems the longest fire intervals (FRG V) are found in mesic coastal forests of the Pacific Northwest and Alaska, and in higher elevation mesic conifer forests of interior mountains. On the other hand, very dry and very cold sites such as interior west deserts and desert margins and shrub tundra on Alaska's North Slope are also characterized by as FRG V, with long fire intervals. Historic fire regimes where fire intervals were typically over 200 years occurred in sites that were either very wet (low probability of ignition), very dry (low fuel loads), or very cold (low fuels and short snow-free period, often with high moisture). Areas that were characterized by intermediate frequency stand replacement fires (FRG IV) include evergreen chaparral and other shrub-dominated ecosystems and some conifer systems, such as the forests of interior Alaska. Low to mixed severity intermediate frequency fires (FRG III) may occur in a wide range of vegetation types (see Tables 6.5 to 6.7). Short interval stand replacement fires (FRG II) were typical in annual and perennial grasslands and some shrublands (such as the primarily drought-deciduous coastal sage scrub in southern California). Low to mixed severity, relatively high frequency fires (FRG 1) were characteristic of more open forest and woodland systems on relatively drier sites or at lower elevations, such as ponderosa pine forest and oak woodlands. One important aspect of fire regimes that the Landfire classification does not address is whether a "stand replacement" fire is lethal to existing vegetation, or merely kills above ground parts of vegetation that has the capability of regenerating vegetatively. In this classification, any fire in which the above-ground parts of vegetation are killed is considered a stand-replacement fire. For example, perennial grasslands and marshlands usually have the potential to regenerate vegetatively after fire, as do many shrublands, deciduous forests, and tundra that are dominated by sprouting shrub species, whereas annual grasslands, some shrublands (and individual shrub species), and most conifers are completely killed in a stand replacement fire, and regenerate only from seed following fire. As Brown and Smith (2000) point out, it is important to understand the responses of local species and systems to stand replacement fire because recovery is much more rapid in areas where perennating parts of vegetation survive. As mentioned in Chapter 3, another important aspect of fire regimes in some regions where peat or deep organic soil layers are present is the frequent occurrence of ground fires, which may persist as long periods as smoldering fires that can burn deeply into the soil or peat deposits and kill overstory vegetation in the absence of canopy fire.

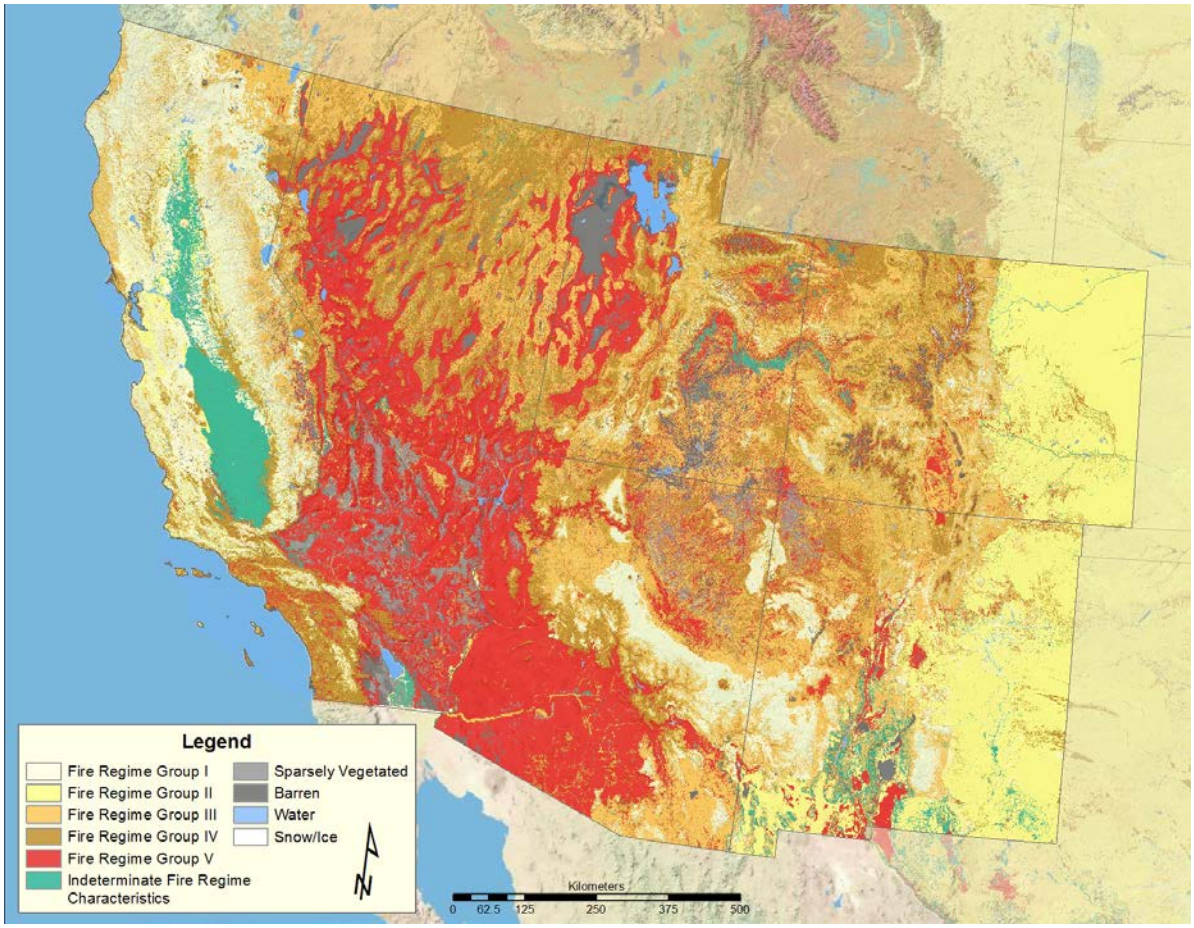

Figure 6.21a: Historic fire regime groups (FRG) in the southwestern US. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG V (200+ year frequency, any severity). Detailed Descriptions of fire regime groups are in Chapter 3, Table 3.2.

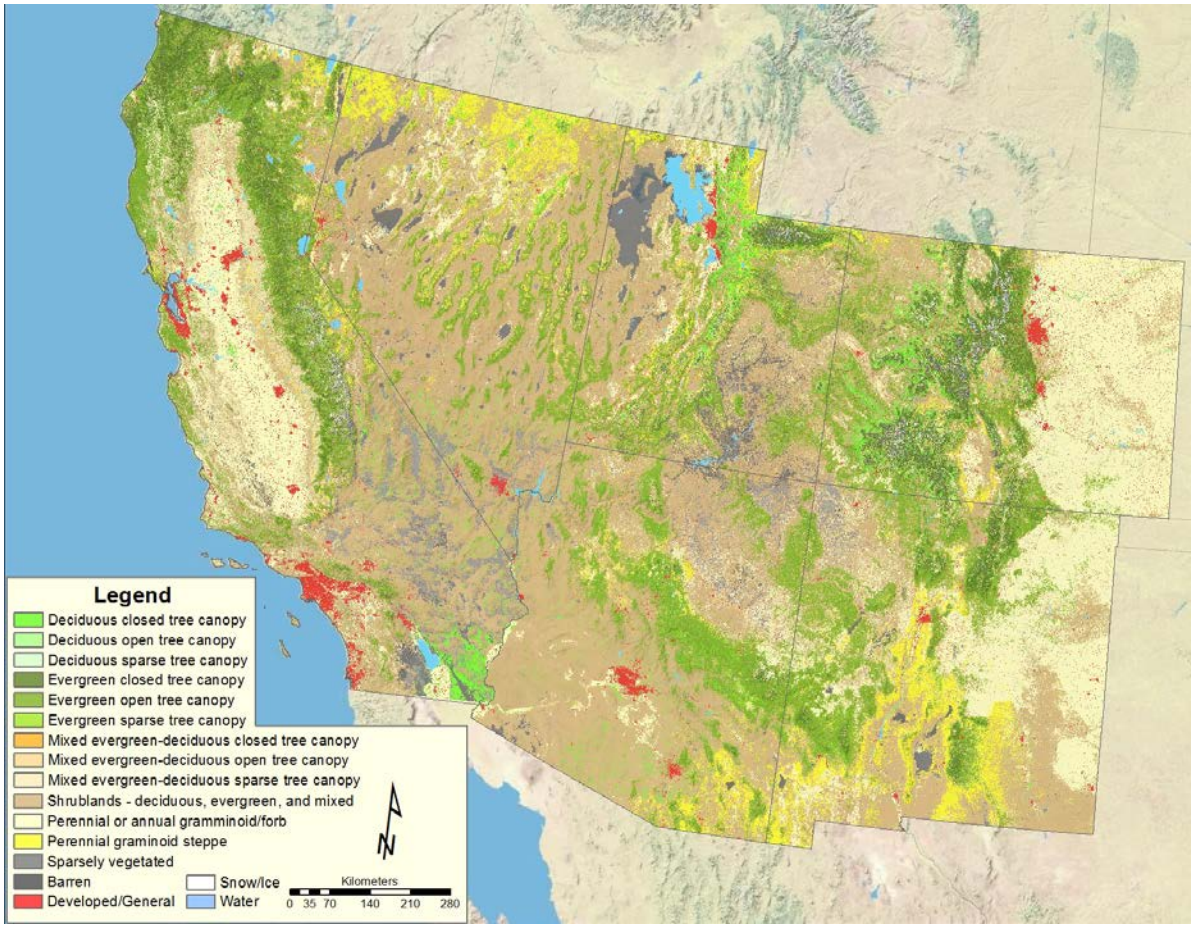

Figure 6.21b: Existing vegetation for the southwestern US. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

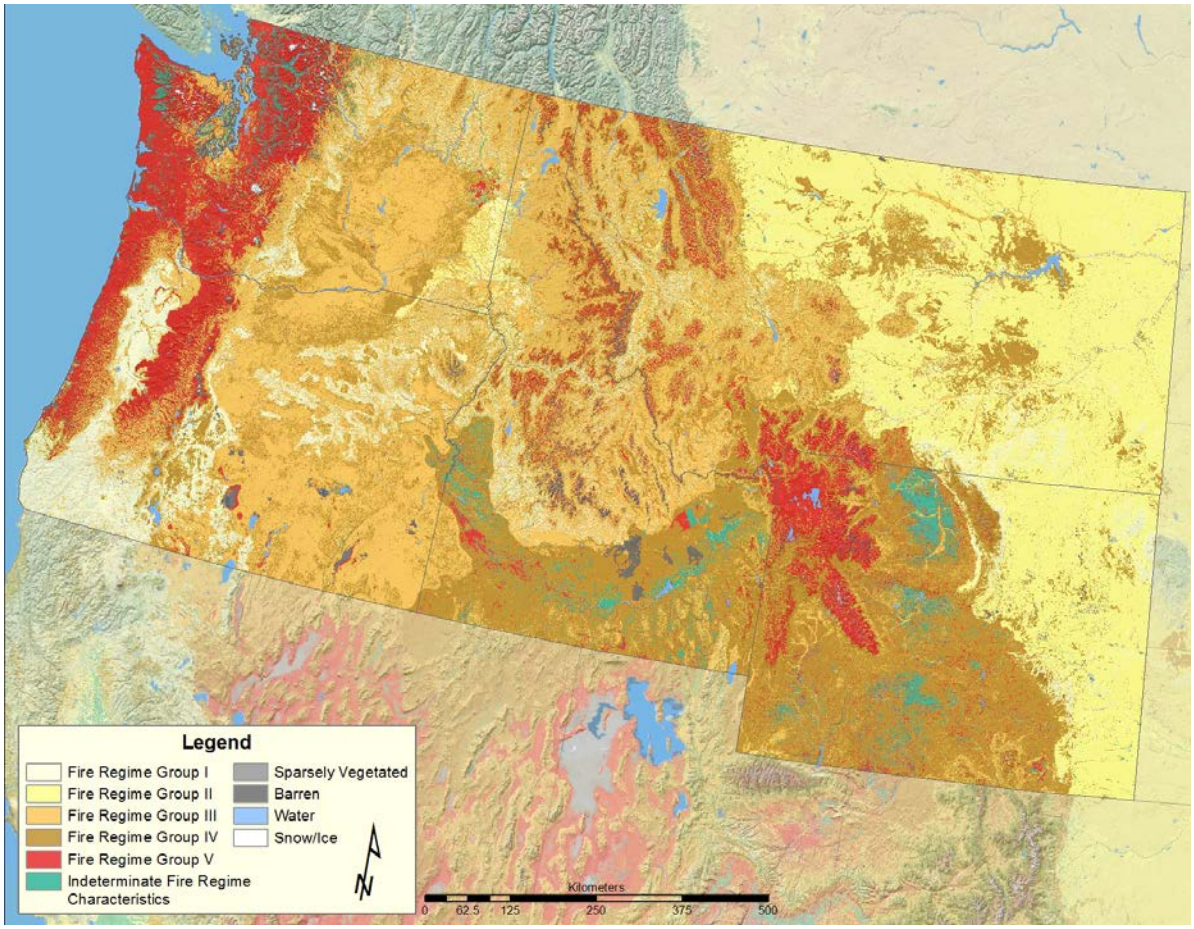

Figure 6.21c: Historic fire regime groups (FRG) in the northwestern US. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG V (200+ year frequency, any severity). Detailed Descriptions of fire regime groups are in Chapter 3, Table 3.2.

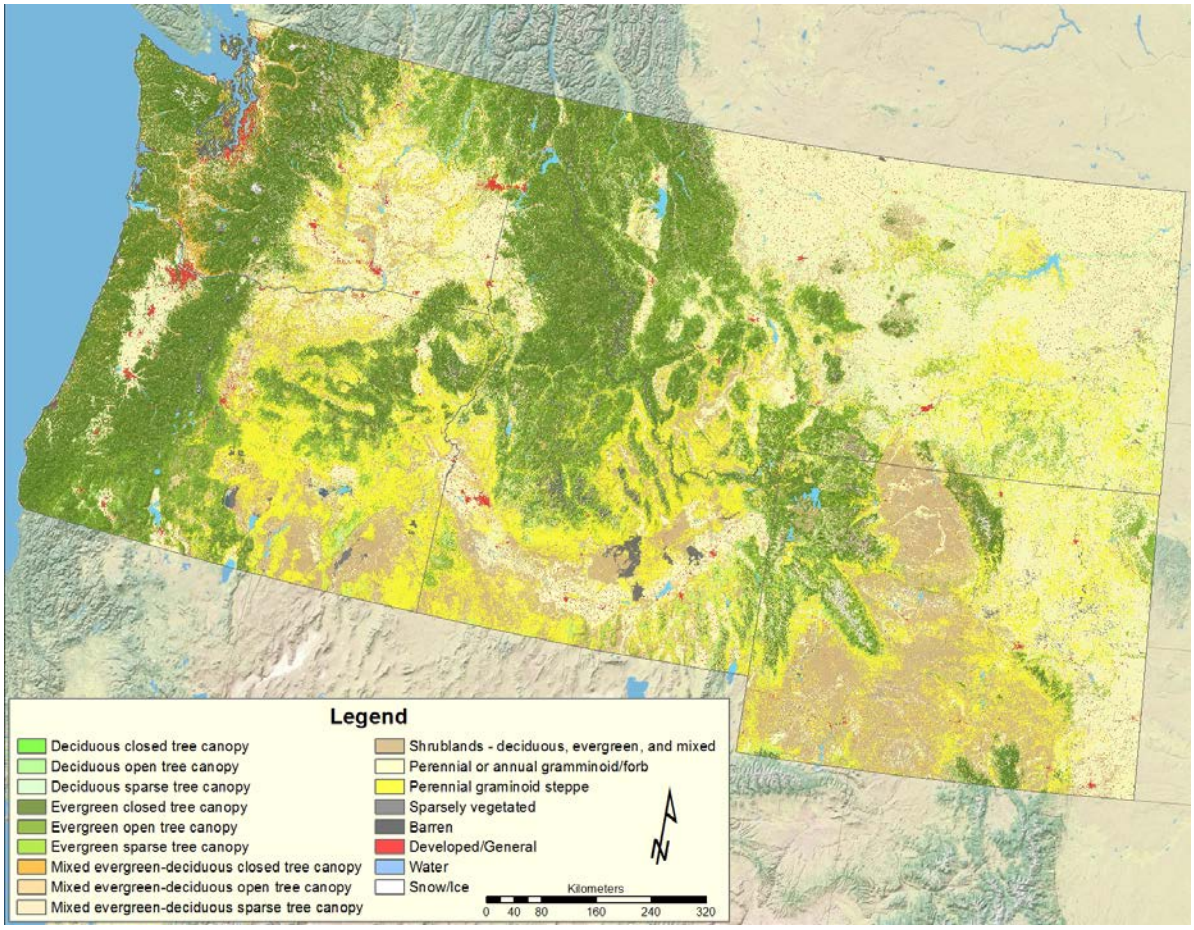

Figure 6.21d: Existing vegetation for the northwestern US. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

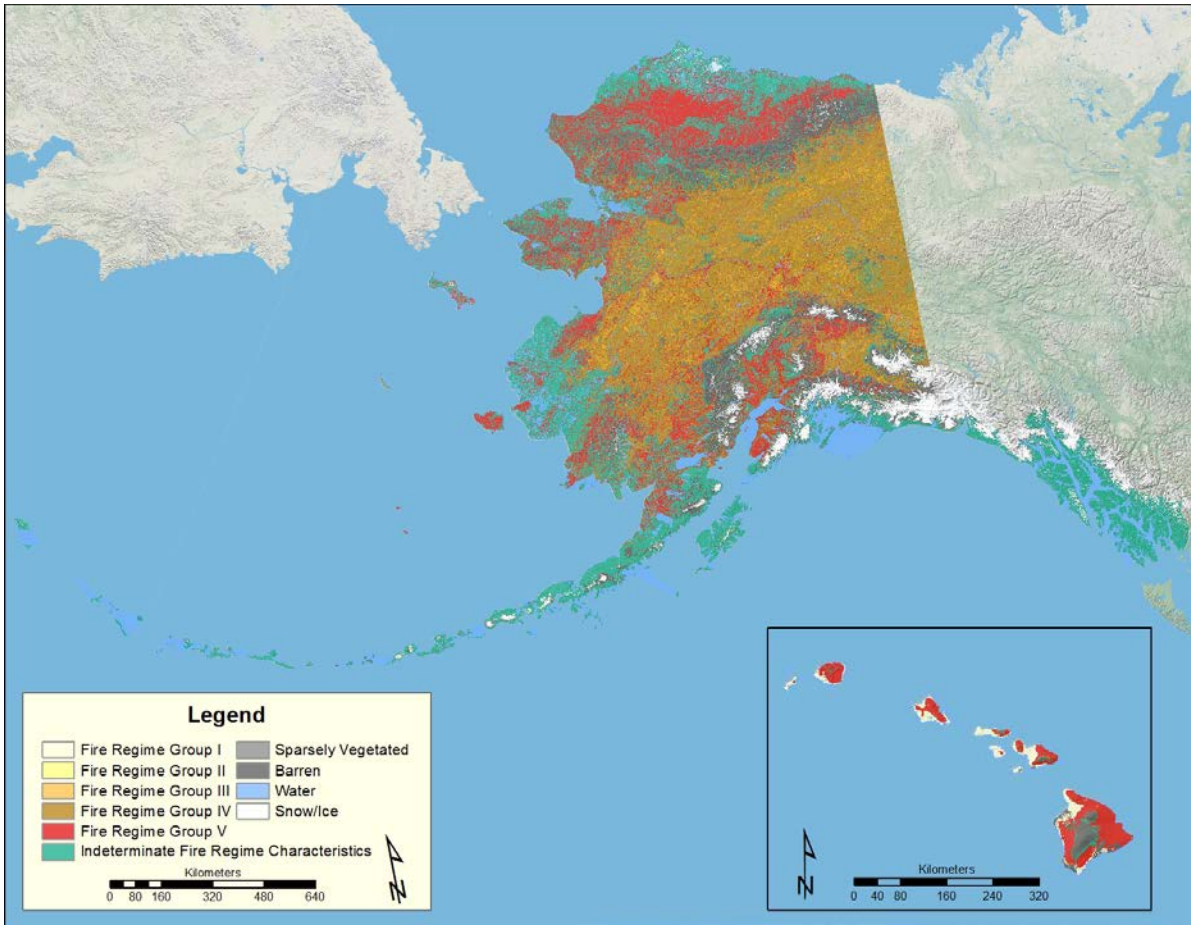

Figure 6.21e: Historic fire regime groups (FRG) in Alaska. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG V (200+ year frequency, any severity). Detailed Descriptions of fire regime groups are in Chapter 3, Table 3.2

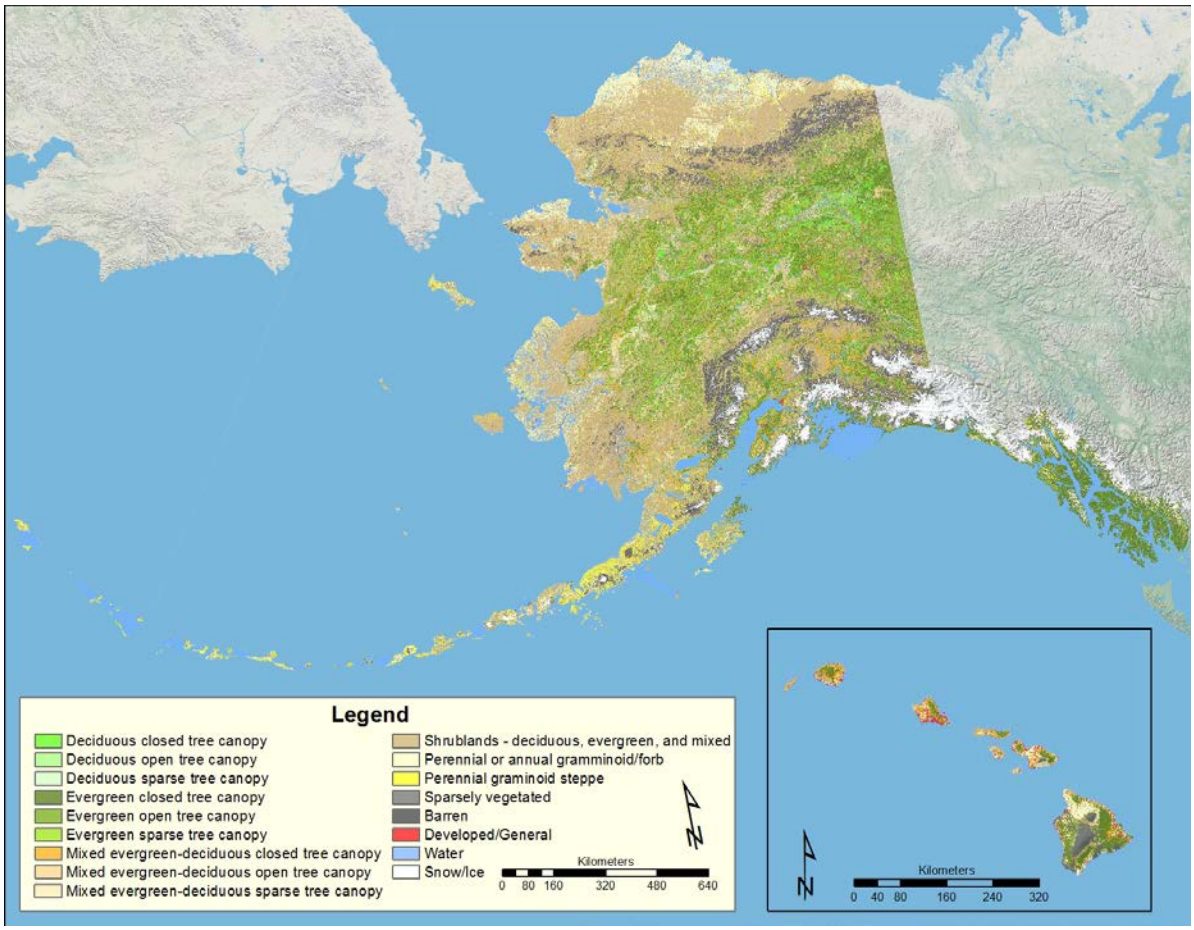

Figure 6.21f: Existing vegetation for Alaska. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

Brown and Smith provide an excellent discussion of fire regimes in major ecosystems across the west, which provides detailed information both on fire regimes and on postfire succession. This is summarized in Tables 6.5, 6.6, and 6.7.

Table 6.5: Occurrence and frequency of presettlement fire regime types by Forest and Range Environmental Study (FRES) ecosystems, Kuchler potential natural vegetation classes (1975 map codes), and Society of American Foresters (SAF) cover types. Occurrence is an approximation of the proportion of a vegetation class represented by a fire regime type. Frequency is shown as fire interval classes defined by Hardy and others (1998) followed by a range in fire intervals where data are sufficient. The range is based on study data with extreme values disregarded. The vegetation classifications are aligned to show equivalents; however, some corresponding Kuchler and SAF types may not be shown**.** (Table 3-1 from Brown and Smith 2000).

			Fire regime types						
			Understory		Mixed		Stand-replacement		
FRES	Kuchler	SAF	Occur[a]	Freq[b]	Occur	Freq	Occur	Freq	Nonfire
Aspen-birch 19	Aspen Parklands [c]	Aspen 16			M	2	M	2	
		Paper birch 252, 18					M	2	
W. aspen [d]	W. spruce-fir K015	Aspen 217			m	1,2	M	1,2	
White-red-jack pine 10	Great Lakes pine K095	Red pine 15			M	2			
		White pine 21			M	2			
		White pine-hemlock			M	2			
		White pine-red oak-red maple 20					M	1,2	
		Jack pine 1			m	1	M	2	
Spruce-fir 11	Great Lakes Spruce-fir K093	Balsam fir 5					M	2,3	
	Northeastern spruce-fir K096	White spruce 107					M	2	
		Red spruce 32					M	3	
		Red spruce-balsam fir 33					M	2	
		Paper birch-red spruce-balsam fir 35					M	2	
—	Black spruce [c]	Black spruce 12					M	2	
—	Conifer bog K094	Black spruce-tamarack 13					M	2	
		Tamarack 38					M	2	
—	Tundra [c]						M	2	

[a]M: major, occupies >25% of vegetation class; m: minor, occupies <25% of vegetation class.
[b]Classes are 1: <35 year, 2: 35 to 200 years, 3: >200 years.
[c]This type occurs primarily in Canada and was not defined by Kuchler.
[d]Added subdivision of FRES.

Table 6.6: (Table 5-1 from Brown and Smith 2002). Occurrence and frequency of presettlement fire regime types by Forest and Range Environmental Study (FRES) ecosystems, Kuchler potential natural vegetation classes (1975 map codes), and Society of American Foresters (SAF) cover types. Occurrence is an approximation of the proportion of a vegetation class represented by a fire regime type. Frequency is shown as fire interval classes defined by Hardy and others (1998) followed by a range in fire intervals where data are sufficient. The range is based on study data with extreme values disregarded. The vegetation classifications are aligned to show equivalents; however, some corresponding Kuchler and SAF types may not be shown.

			Fire regime types						
			Understory		Mixed		Stand-replacement		
FRES	Kuchler	SAF	Occur[a]	Freq[b]	Occur	Freq	Occur	Freq	Nonfire
Coastal[c] Douglas-fir 20	Cedar-hemlock-Douglas-fir K022	Douglas-fir-w. hemlock 230			M	2: 40-150	M	3	
	Mosaic of above and Oregon oak woods K028	Pacific Douglas-fir 229			M	2: 40-150	M	3: 200-500	
		Red alder 221							
	Calif. Mixed evergreen K029	Douglas-fir-tanoak-Pacific madrone 234			M	1			
Redwood 27	Redwood K006	Redwood 23	M	1: 5-25	m	2			
Hemlock-Sitka spruce 24	Spruce-cedar-hemlock K001	Sitka spruce 223			m	2	M	3	m
		W. hemlock 224					M	3	
		W. hemlock-Sitka spruce 225					M	3	
		W. redcedar-w. hemlock 228					M	3	
W. hardwoods 28	Oregon oakwoods K026	Oregon white oak 233	M	1					
	California oakwoods K030	Blue oak-digger pine 250	M	1					
		Canyon live oak 249			M	1,2			
		California coast live oak 255			M	1,2			
Coastal[c] fir-spruce 23	Silver fir-Douglas-fir K003	True fir-hemlock 226					M	3	m
	Fir-hemlock K004	Mountain hemlock 205					M	2,3	m
Inland forests									
Ponderosa pine 21	W. ponderosa pine K011	Pacific ponderosa pine 245	M	1: 5-30	m	2			
	Pine-Douglas-fir K018	Pacific ponderosa-Douglas-fir 244	M	1: 5-30	m	2			
	Mixed conifer K005	Sierra Nevada mixed conifer 243	M	1: 5-30	m	2			
		Jeffrey pine 247	M	1: 5-30	m	2			
		California black oak 246	M	1: 5-30	m	2			
	Arizona pine K019	Interior ponderosa pine 237	M	1: 1-25	m	2			
	E. ponderosa K016	Interior ponderosa pine 237			M	2			
	Black Hills pine K017	Interior ponderosa pine 237	m	1	M	2	M	2	
Interior[c] Douglas-fir 20	Douglas-fir K012	Interior Douglas-fir 210	m	1,2	M	2: 25-100			
Larch 25	Grand fir-Douglas-fir K014	W. larch 212			M	2: 25-200	M	2,3	
		Grand fir 213			m	2	M	2,3	
W. white pine 22	Cedar-hemlock-pine K013	W. white pine 215			M	2: 50-200	M	3: 130-300	
Lodgepole pine 26	Lodgepole pine-subalpine K008	California mixed subalpine 256			M	2			
Rocky Mountain lodgepole pine[c] 26	W. spruce-fir K015	Lodgepole pine 218			M	2: 25-75	M	2,3: 100-300	
	W. spruce-fir K015	Whitebark pine 208			M	2: 50-200	M	3: 150-300	
Interior[c] fir-spruce 23	W. spruce-fir K015	Engelmann spruce-subalpine fir 206					M	2,3: 100-400	m
	Spruce-fir-Douglas-fir K020	White fir 211			M	2	M	2,3	
		Blue spruce 216			M	2	M	2,3	
W. aspen[c] 28	W. spruce-fir K015	Aspen 217			m	2	M	2	

[a]M: major, occupies >25% of vegetation class; m: minor, occupies <25% of vegetation class.
[b]Classes are 1: <35 year, 2: 35 to 200 years, 3: >200 years.
[c]Added subdivision of FRES.

Table 6.7: (Table 6-1 from Brown and Smith 2000). Occurrence and frequency of presettlement fire regime types by Forest and Range Environmental Study (FRES) ecosystems, Kuchler potential natural vegetation classes (1975 map codes), and Society of American Foresters (SAF) cover types. Occurrence is an approximation of the proportion of a vegetation class represented by a fire regime type. Frequency is shown as fire interval classes defined by Hardy and others (1998) followed by a range in fire intervals where data are sufficient. The range is based on study data with extreme values disregarded. The vegetation classifications are aligned to show equivalents; however, some corresponding Kuchler and SAF types may not be shown.

			Fire regime types						
			Understory		Mixed		Stand-replacement		
FRES	Kuchler	SAF	Occur[a]	Freq[b]	Occur	Freq	Occur	Freq	Nonfire
Ponderosa pine 21	SW ponderosa pine[c]	Interior ponderosa pine 237	M	1a:2-10	m	1			
	Arizona pine forest K019		M	1a:2-10	m	1			
	Pine-cypress forest K009	Arizona cypress 240			M	1,2	m	1	
Pinyon-juniper 35	Juniper-pinyon K023	Rocky Mountain juniper 220			M	1			
	Juniper-steppe K024	Western juniper 238			M	1			
		Pinyon-juniper 239			M	1			
		Arizona cypress 240			M	1			
Southwestern oaks[d]	California oakwoods K030	Canyon live oak 249			M	1			
		California coast live oak 255			M	1			
		California black oak 246			M	1			
		Blue oak-digger pine 250	M	1	M	1			
	Oak-juniper K031	Interior live oak 241			M	1			
Shinnery 31	Shinnery K071	Mohrs oak 67			M	1			
Texas savanna 32	Ceniza shrub K045				M	1			
	Mesquite savanna K060	Mesquite 68, 242			M	1			
	Mesquite-acacia savanna K061				M	1			
	Mesquite-live oak savanna K062	Western live oak 241			M	1			
	Juniper-oak savanna K086	Ashe juniper 66			M	1			
	Mesquite-oak savanna K087				M	1			
Sagebrush 29	Sagebrush steppe K055						M	2a:20-70	
	Juniper steppe K024	Rocky Mountain juniper 220					M	2a	
	Great basin sagebrush K038	Western juniper 238					M	2a:20-70	
	Wheatgrass-needlegrass shrubsteppe K056						M	2a	
Desert shrub 30	Mesquite bosques K027	Mesquite 68, 242					M	1,2a	
	Blackbrush K039						M	1,2a	
	Saltbrush-greasewood K040						M	1,2a	
	Creosotebush K041						M	1,2a	
	Creosotebush-bursage K042						M	1,2a	
	Paloverde-cactus shrub K043						M	1,2a	
	Cresotebush-tarbush K044						M	1,2a	
SW shrubsteppe 33	Grama-tobosa K058						M	1,2a	
	Trans-pecos shrub savanna K059						M	1,2a	
Chaparral-Mountain shrub 34	Oak-juniper woodland K031						M	1,2a	

Six hundred years of changing fire regimes

Tree ring chronologies and stand structure information

The initial effects of European settlement in many areas of the West were probably similar to those in the East—as land was cleared, railroads were built, and mining activity increased; the settlers purposefully or inadvertently started many fires. By the beginning of the 20th century, there was increasing concern over the damage and loss of life from these fires. In many ways the year 1910 was a turning point in the West. The huge and uncontrollable fires in the northern Interior West that year were a strong impetus for instituting programs to suppress and control fires in some areas. By this time the Native American populations had been effectively eliminated or sequestered onto reservations in most of the West. There are a huge number of studies of fire history throughout the western US based on fire scar chronologies, stand structure, historical records, agency data, etc. Fire history information for specific areas can be found in the

International Multiproxy Paleofire Database (IMPD) at: http://www.ncdc.noaa.gov/paleo/impd/. This database contains information from tree ring fire scar chronologies and sediment charcoal records, as well as links to the International Tree Ring Data Bank and the Global Pollen Database. Because of the large amount of information available, we will focus this discussion on papers that have synthesized or evaluated information from multiple studies, or on papers that have added significant new understanding to knowledge or interpretation of fire/climate relationships.

Kitzberger et al. (2007), used fire records on 238 sites across the western US from the IMPD for a broad regional comparison of interactions between fire and climate in the region since 1550. They found significant relationships between fire occurrence and a number of indices related to climate, including the Palmer Drought Severity Index (PDSI), sea surface temperatures, and several broad-scale ocean circulation patterns (El Nino Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO)). Interestingly, the high (warm) phases of AMO were associated with synchronously high drought and fire occurrence across most of the western US, except for an area from California up into Oregon which is wetter than normal during these periods (Figures 6.22 and 6.23). Kitzberger et al. (2007) also concluded that the drought-fire phases in the Pacific Northwest and the interior Southwest are consistently opposite each other. When AMO is low (cold) the synchrony among regions decreases, but remains high within the Southwest. When AMO is neutral, patterns of synchrony emerge between the Pacific Northwest and the Black Hills, and between the Sierra Nevada and the Rocky Mountains, a result of increased dominance of the PDO and its effect on precipitation. Overall, this paper illustrates the strong and relatively consistent patterns of climate control over fire patterns for the past 500 years over many areas in the West.

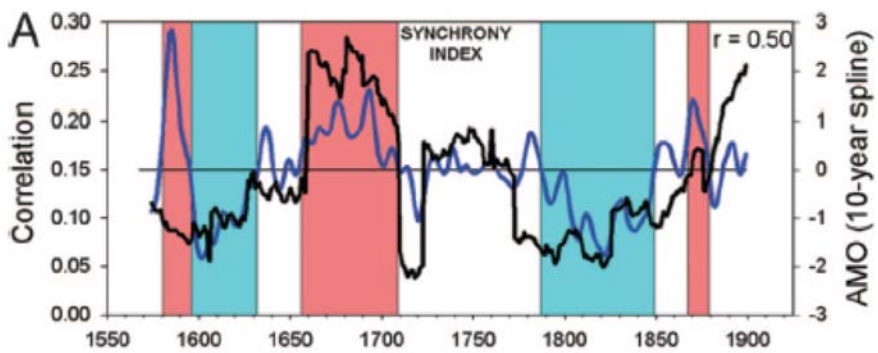

Figure 6.22: Index of fire synchrony (50-year moving correlations between selected regions, black line) compared with a 10-year spline of reconstructed AMO (blue line). Light blue and light red shaded areas indicate periods of low and high AMO, respectively. Synchrony index was computed as the mean of all pairwise 50-year running correlations of percent of sites with fires for all region pairs and reflects overall fire synchrony. Source: (Kitzberger et al. 2007).

Much of the evidence on fire regimes over the past several hundred years in the western US comes from fire scar chronologies. The development of repeated, datable fire scars on tree stems, which is generally the foundation for such chronologies, can only occur in an environment

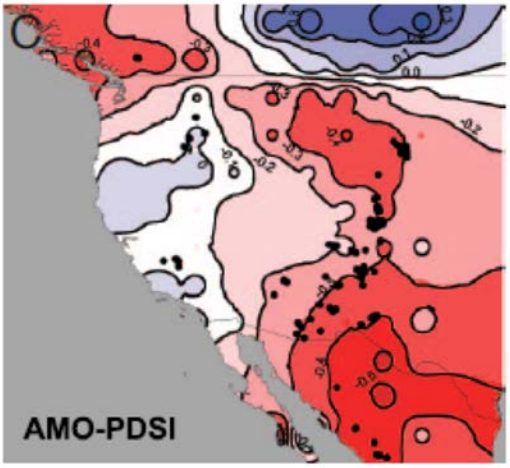

Figure 6.23: Correlations between the 49-year running mean AMO with a time-smoothed version of gridded PDSI (from tree ring data) for the period 1574–1899. . Source: (Kitzberger et al. 2007).

where at least some fire-scarred trees survive multiple fires. And the occurrence of a fire scar on a tree in a given year does not indicate how much area has been burned. As a result care must be taken in the interpretation of fire scar records. While early studies often assumed that any dated fire scar represented a stand-level fire (and therefore reported a composite fire interval for a stand), it has become clear that such assumptions lead to an underestimate of landscape fire intervals. As a result, more recent studies have tended to look more broadly for correlations of fire dates on a number of trees in a sample area, or to impose "filters" requiring that a certain percent or number of trees record a fire before it can be considered a stand-level or landscape-level fire (e.g., (Brown and Sieg 1996; Swetnam and Baisan 1996; Veblen et al. 2000)).

Baker and Ehle (2001) discuss in some detail the types of uncertainties and biases that can occur when fire history data are used to estimate mean fire intervals (MFI) or other fire regime characteristics. One concern is that not all fires are recorded in the fire scar record, in part because for a fire scar to be developed requires a fire that is severe enough to damage the cambium without killing the tree. As this may not occur early in the history of a stand, the time between the origin of a tree and the development of the first fire scar should be considered to be a fire-free interval and included in MFI calculations. Secondly, even in a stand with fire-scarred trees some fires may be of such low intensity that they do not reburn the scars. In addition, they contendthat the tendency to focus on multiple-scarred trees and areas of stands where there are higher densities of scarred trees will lead to a bias toward shorter estimated MFIs. They further point out that the composite FI becomes shorter as the size of the study area or the number of sampled trees increases, either of which results in more fires being recorded. Neither of the two types of data from fire scar records: mean individual tree fire interval, and stand composite fire

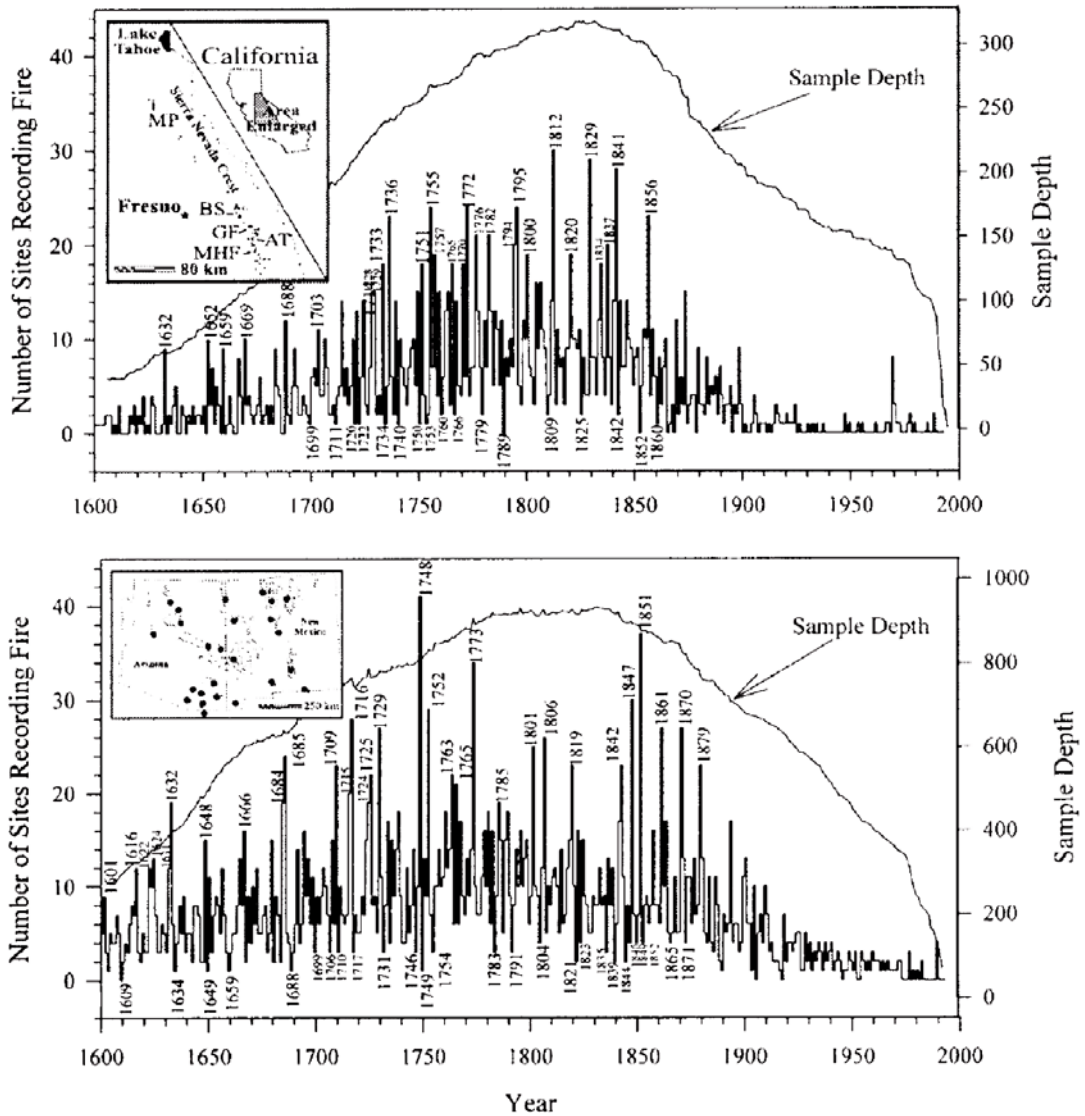

Figure 6.24: Composite time series of fire events in the Sierra Nevada (upper graph) and interior Southwest (lower graph) from regional networks of fire-scar chronologies. Number of sites recording fire each year are shown (AD 1600–1995). Sample depth is the number of fire-scarred trees included in the data sets during each year. The map insert of the Sierras shows locations of the five giant sequoia groves (letter codes) and approximate range of sequoia groves (small irregular dots) . The 49 sites from the Sierras included in the composite are from four elevational transects adjacent to the Mariposa Grove (MP), the Big Stump Grove (BS), Giant Forest (GF), and Mountain Home State Forest (MHF). The map insert of the Southwest shows 26 mountain ranges (as dots) where the 63 sites included in the composite are located. The irregular outline on this map is the approximate range of ponderosa pine in Arizona and New Mexico. Source: Figure 6.5 (Swetnam and Baisan 2003).

interval (all fires recorded) is likely to accurately represent the stand-level fire interval, but Baker and Ehle conclude that they do provide a means of bracketing the potential range of fire intervals. The mean interval from all sampled trees might be seen as a maximum, since it assumes that the average for each tree is the same as the average for the stand. The stand

composite might be seen as a minimum, but it assumes that if any tree is scarred the entire stand burns. And we know that this is not true because of the spatial and temporal variability of fire occurrence. They concluded that some level of filtering (i.e. counting only those fires that are recorded on some percentage of fire-scarred stems) seems reasonable. The detailed analysis of some 35 studies of ponderosa pine fire history presented in this paper illustrates that the mean composite FI's and the mean tree FI's reported in at least some earlier studies for ponderosa pine substantially underestimate the actual mean FI's, which may be on the order of 5 to 10 times longer than those based on composite FI's. They strongly recommend that this uncertainty be explicitly recognized in publications and that researchers strive to better evaluate the methods being used for estimating MFIs and develop improve methods that increase the accuracy of these estimates. This is something that should be considered when comparing results of different studies based on fire scar records. However, recent studies often explicitely discuss these uncertainties, and several studies comparing fire scar data with fire maps or other sources of data have shown very good correlations, especially when filtering is used. Recent studies by Lombardo et al. (2009) and Farris et al. (2010) carried out explicit comparisons of fire scar data with fire perimeter maps for their study areas. These two studies in very different ecosystems (southern California chaparral and southwestern ponderosa pine forests) concluded that estimates of landscape fire intervals were similar for the two approaches, although fire scar data were more likely to miss small fires.

Regional fire history and fire/climate interactions in the Southwest

Swetnam and Baisan (2003) provide an excellent and thoughtful overview of many of the dendrochronology-based fire history studies that have been carried out in the interior Southwest and the Sierra Nevada. Their paper also includes an interesting discussion of both sampling methods and considerations in analysis of fire scar data that addresses many of the issues raised by Baker and Ehle (2001). They show data from 63 sites in 26 mountain ranges in the interior Southwest (New Mexico and Arizona) and from 49 sites sampled along elevational transects in the Sierra Nevada Mountains. In general they have applied 25% filters as a criterion for identifying "widespread" fire events. Elevational transects in the Santa Catalina Mountains (Arizona) and the Mogollon Mountains (New Mexico) looking at the period from the 1600's to present illustrate well the general decrease in frequency of fire events going from low-elevation ponderosa pine through mixed-conifer forests to higher elevation spruce-fir/mixed conifer forests. There are also a number of years with clear fire synchrony across the elevation gradients. In addition, there is a clear decrease in fire occurrence across a wide range of sites in the late 1800's- early 1900's in this region, which is strongly correlated with the beginning of extensive livestock grazing at specific sites. They also conclude that there is little evidence of extensive Native American use of fire in the interior Southwest, other than in localized areas, and usually associated with warfare.

In a comparison of the Sierra Nevada and the interior Southwest mountain ranges, it is clear that there are strong synchronies across sites within these two regions, but the high fire years do not generally correlate between the two regions (Figure 6.24). These graphs also show that the decrease in fire occurrence in the Sierra generally occurred between 1850 and 1870, earlier than in the interior Southwest. This is attributed to a drought in the early 1860's, which caused large sheep herds to be moved out of the Central Valley into the Sierra Nevada—a pattern that persisted for many years. Analyses of patterns of fire in relation to summer drought, based on

dendrochronological reconstructions of historical PDSI (Figure 6.25), showed that large fire years in both the Sierra and the Southwest mountains were correlated with strong summer drought (low PDSI). In the Southwest, however, these droughts were typically preceded by several fairly wet summers, which may be necessary to support adequate fuel buildup. This lag effect only applied to pine-dominated sites. In the Sierra, where sample sites were typically in moister mixed-conifer forests, severe fire seasons do not generally appear to be fuel-limited. In the years where primarily small areas were burned, there was typically a drought in the preceding year, when widespread fires may have occurred, but the small fire years themselves are characterized by fairly high PDSI, representing moister conditions. In addition to the association with PDSI, the years of synchronous regional fire events tended to also be years of La Nina events in the Southwest and in Colorado. In the twentieth century, years of high burned areas in Arizona and New Mexico have been strongly associated with La Nina, and low burned areas with El Nino, a pattern opposite to that observed in the Pacific Northwest (see next section).

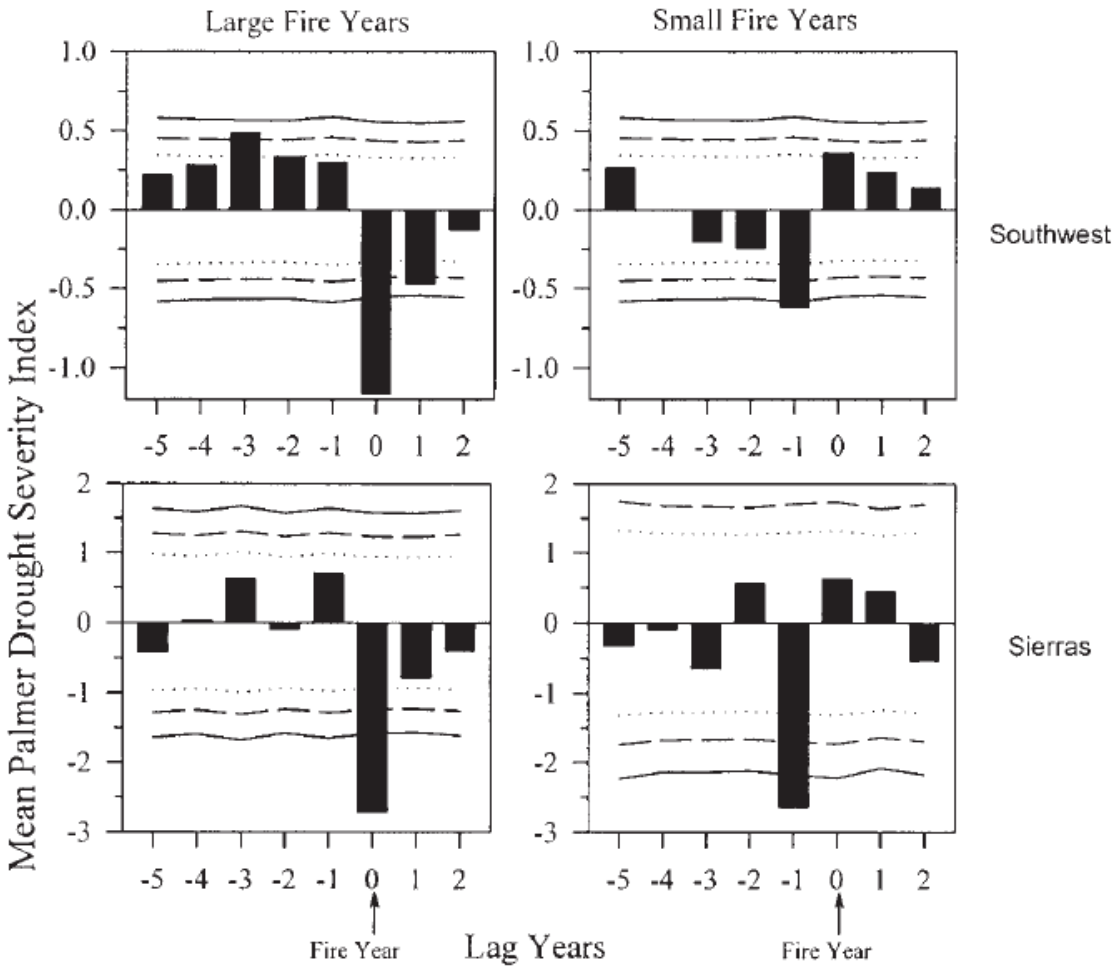

Figure 6.25: Results of superposed epoch analysis (SEA) comparing summer Palmer Drought Severity Indexes (PDSI) during relatively large (extensive) and small (less extensive) fire years in the Southwest (*top row*) and Sierras (*bottom row*). Source: (Swetnam and Baisan 2003).

Grissino-Mayer and Swetnam (2000) evaluated relationships between fire and climate (precipitation patterns) reconstructed from dendrochronological fire scar and tree growth rings from about 1400 AD to the late 20th century in the Southwest. They find both fire patterns that relate to climate changes at multi-century as well as multi-year time scales. During a dry period from about 1400 to 1790, fire frequencies were high. Increases in annual precipitation were associated with decreased fire frequency, as the main rainfall season shifted from midsummer to late spring. Such long-term changes in rainfall patterns appear to reflect changes in atmospheric and ocean circulation patterns, such as ENSO. The pattern seen in other studies of wet years (which presumably drove high accumulations of fine fuels) preceding fire years seemed to hold, although drought during the actual year of fire was a significant factor only during the 1700's. After about 1790 severe drought no longer seemed to be a prerequisite for fire occurrence. Swetnam and Betancourt (1998) also showed a broad regional change in relationships between climate and wildfire in the late 1700's. A regional-scale assessment of drought and fire records from large networks of tree-ring data from the American Southwest also shows a marked change in climate/wildfire relations beginning in the late 1700s (Swetnam and Baisan 2003). Grissino-Mayer and Swetnam (2000) found that between 1800 and 1830 correlations between PDSI and fire occurrence were no longer significant, as a period of long, fire-free intervals began across much of the southwest perhaps "*related to changes in global-scale atmospheric/oceanic circulation patterns that led to changes in ENSO-driven precipitation patterns*" as strength and frequency of El Nino events decreased. These changes in fire regimes occurred across multiple temporal and spatial scales. They conclude that fire climate relationships at longer time scales are not likely to be simple responses of increased fire with increased temperature or stronger summer drought, but also to factors such as seasonality of precipitation. They also hypothesize that unusually high precipitation since about 1976 in the Southwest has led to a dramatic increase in tree growth and increased accumulation of the fine fuels that carry fire in many Southwestern ecosystems. One result is that severe fire years are now more likely when precipitation is close to the long-term average, such as in 1993 and 1994. They state that: "*Furthermore, low fire activity occurred during summers following extreme El Nino events, while exceptionally large fires occurred during subsequent years, especially during the two La Nina events of 1989 and 1995-96.*" Grissino-Mayer and Swetnam then suggest a possible analogue to the shift in climate and fire regimes in the late 1700's that may provide an indication of what could be expected if future climate-induced changes in atmosphere and ocean circulation lead to higher precipitation and stronger influence of La Nina events, although it is difficult to separate out the effects of fire exclusion on these recent fuel buildups and increases in burned area. They conclude that: "*the role of increasing fuel loads in stimulating increased fire activity in western US forests should be reassessed in the light of ongoing climate change*".

Fire in the northern California Mountains

Fry and Stephens (2006) used fire scar dendrochronology to determine fire history from the 1700's to 2005 on six study plots in an area near Whiskeytown Reservoir in the southeastern Klamath Mountains. The several forest vegetation types in the study area ranged from relatively pure ponderosa pine to mesic mixed conifer forests, but ponderosa pine wad the dominant species over much of the area. They analyzed for point MFI, MFI 10 and MFI 25 and found no significant differences in these parameters among plots. In this study area, settlement began in the mid-1800s, so they divided the period into three periods: 1750-1849 (pre-settlement), 1850-

1924 (settlement period); and 1925-2002 (fire suppression era). The pre-settlement mean and median FRI were similar to other studies in ponderosa pine vegetation (median MFI 10: 1.8 yr; MFI 25: 3 yr). During the settlement period, median FRI increased (FRI 10: 7.2 yr and FRI 25: 9.7 yr), largely due to a decrease in smaller fires. After 1924 fires became extremely rare in the study area. In this study of a ponderosa pine-dominated forest, there were no relationships found between the Southern Oscillation Index (SOI) and fire occurrence. As the authors point out, this is not surprising as this region is in the middle of the south-north dipole effect of the ENSO/SOI that has been observed in Northwest and the interior Southwest. However, they did observe an apparent relationship with PDSI, such that a wet year typically occurred three years before a season with widespread fire, but this was statistically significant only in the period after European settlement. This is similar to relationships observed for interior southwest ponderosa pine, and suggests to us that fuel buildup in a wet year may be an important factor in determining fire occurrence in these forests.

Studies of fire history and local influences on fire regimes in the northern California Mountains--Klamath Mountains (Taylor and Skinner 2003) used a combination of dendrochronology and stand structure analysis to describe fire regimes from 1628 to 1995 in ponderosa pine and Douglas fir dominated mixed conifer forests in the Hayfork area of the Klamath Mountains. Median fire return intervals for all vegetation complexes were between 11 and 13 yr, but FRI were longer on north slopes (16 yr). Most fires occurred late in the season (midsummer to fall) after radial growth had essentially stopped. They also found that areas with similar pre-suppression era fire regimes often occurred within discrete topographic units bounded by features such as streams and ridgetops, although in dryer years (based on PDSI) fires were more likely to spread across these boundaries. Taylor and Skinner also found a relationship between the number of sites that burned in a given year and severity of summer drought (as measured by PDSI), such that during the pre-suppression period (1751-1900) five times as many sites burned in the 10 driest years than in the 10 wettest years. After 1900, fire occurrence and estimated burned areas decreased dramatically and regeneration of shade tolerant species such as Douglas-fir and white fir increased.

In a similar study of fire patterns at a site in Lassen National Park in the South Cascade Mountains, Jeffrey pine, Jeffrey pine/white fir, and red fir/western white pine forest had no significant differences in composite mean FRI (range 5 to 15 years) between pre-settlement (before 1850) and post settlement (1850-1904) periods (Taylor 2000). After 1904, however fire essentially disappeared from the study area, with one fire between 1905 and 1994 in Jeffrey pine forest, none in Jeffrey pine/white fir forest, and two in red fir/western white pine forest. Overall, composite MFIs for larger fires (>10% scarred trees) were significantly shorter for the drier, lower elevation Jeffrey pine (6 yr) and Jeffrey pine/white fir (10 yr) forests than for the moister red fir/western white pine forest (27 yr). FRI for both all fires and larger fires (reported here) also were shorter on east (9 yr) and south (11 yr) slopes than on west slopes (28 yr). Fire return intervals were perhaps most strongly influenced by elevation, with a strong and highly significant increase mean point FRI from the lower elevation stands at 1800 m to the highest elevation stands at about 2400 m (Figure 6.26). A combination of age structure analysis and analysis of historic photo pairs demonstrated that forest density and surface fuels have increased in many of the stands over the past 70 years as fires frequency has decreased. In some cases

shrubs have disappeared from the forest floor and white fir is now regenerating in the understory of forests previously dominated by Jeffrey pine.

Beaty and Taylor (2001) conducted a similar study to characterize fire regimes for several types of more mesic mixed conifer forests in the Cub Creek Research Natural Area, Lassen National Forest, in the southern Cascade Mountains. The study area ranged from about 1400 to almost 1900 m elevation, and major forest types were: ponderosa pine/white fir (SW aspects; 1600-1700 m); Douglas-fir/white fir (NE aspects; lower elevations near streams); white fir/sugar pine/incense cedar (W aspects); white fir (N aspects, higher elevations); red fir/white fir (NE aspects; highest elevations). They used a combination of historical fire records (from 1905-1997), fire scar and radial tree growth data from partial sections of trees, and stand age class distribution to characterize They compared composite FRI among three time periods: pre-settlement (1700-1849); settlement (1850-1904); and fire suppression (1905-1997). As with other studies in Northern California, fire activity was similar in the two earlier time periods, but decreased greatly after 1905, with only two fires in the study area from 1905 to 1997. Most fires occurred in the late summer-fall dormant season in all vegetation types. They found that location in the watersheds and slope aspect had a significant impact on median composite FRI, which were longest (34 years) on N aspects dominated by white fir and Douglas/fir forests; 17 yr on southern headwaters (W aspects) dominated by white fir/sugar pine/incense cedar forests; 13.5 yr in northern headwaters (W aspects) dominated by white fir/sugar pine/incense cedar and pure white fir forests, and 9 yr on S aspects dominated by ponderosa pine/white fir forests. Composite FRI for widespread fires (>25% of trees scarred) were generally longer, but showed a similar pattern. Another interesting aspect of this study was that the authors assessed fire severity. They concluded that: Most fires (85.7%) on upper slopes were high severity, most (60%) on lower slopes were low severity and mid-slopes had a mix of moderate severity (46.8%) and low severity (29.9%) fires. Fire severity patterns were similar on N and S aspects with mainly (>60%) low and moderate severity burns, headwater areas were more likely to burn in high severity fires (>60%). As with their study in the Klamath Mountains, the four years between 1750 and 1900 when large fires (>150 ha) occurred in the study area were associated with summer drought based on their classification as dry or very dry years on the PDSI (Taylor and Skinner 2003).

While studies in the Klamath Mountains and the southern Cascade range have consistently found correlations between occurrence of large fire years and either current year or lagged (past years) PDSI, they have generally failed to find consistent correlations between fire patterns and the ENSO Southern Oscillation Index. Taylor and Beaty (2005) studied fire history in an extensive area (about 2,000 ha) of Jeffrey pine forest east of Lake Tahoe in the northern Sierra Nevada to reconstruct fire/climate relationships for the presettlement period (1700-1850). The last recorded fire in the area was in 1871, substantially earlier than for areas further north discussed above. From 1775 to 1850 they found reduced fire frequency, a shift to larger, more synchronous fire events, and strengthening of the correlations between interannual variations in climate and fire frequency and extent. Before 1775, fire activity was associated with climatic variation at decadal time scales, but not at annual scales. They conclude that: *"Overall climatic conditions (i.e. fire season length, fuel moisture, relative humidity, ignitions) before 1775 were apparently more conducive to fire; fires were significantly more frequent before than after 1775. During this high fire frequency period, the relationship between fire extent and moisture were consistent over*

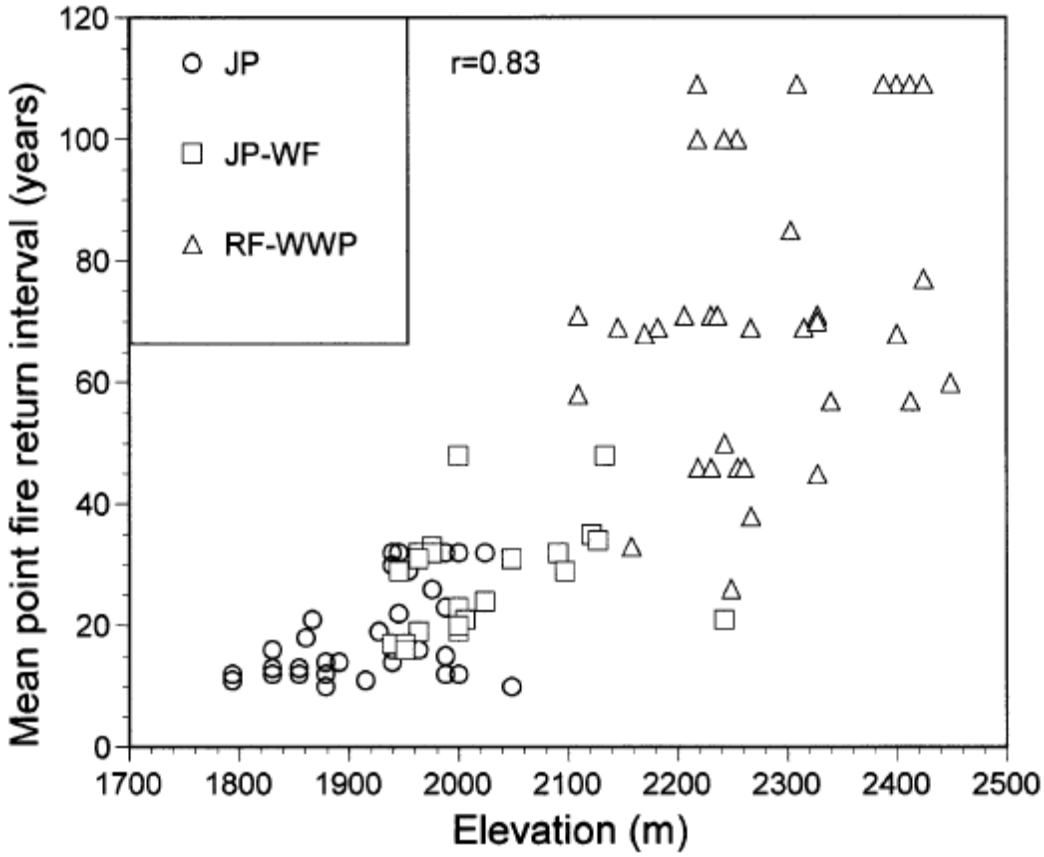

Figure 6.26: Plot of mean point fire return interval and elevation for the three main forest types on Prospect Peak, Lassen National Park. JP: Jeffrey pine forest; JP-WF: Jeffrey pine/white fir forest; RF-WWP: red fire/western white pine forest. *r* = Pearson product–moment correlation coefficient. Source: Figure 3 in Taylor (2000).

decades but annual drought was not a necessary condition for fire as it was after 1775." Fires after 1775 occurred mainly when dry years followed wet years, implying that fuels were more limiting during this period. This pattern appears related to phase changes from a warm to a cool Pacific Decadal Oscillation (PDO). They hypothesize that during this period: "*The strengthening...of interannual fire–climate relationships is probably caused by the weak influence of interannual ENSO variability on fire in the northern Sierra Nevada, and a shift from strong interdecadal to interannual climate influence related to the breakdown of ...relationships between the PDO and ENSO*". Before 1775, the ENSO and PDO phases apparently reinforced each other in ways that did not occur later, resulting in a strong influence of these ocean/atmosphere circulation patterns on fire regimes during this period. After 1775 the influence of ENSO decreased, and wet years followed by drought and phases of the PDO became strongly correlated with fire activity. These findings illustrate the strong effect that shifting modes in interacting ocean/atmosphere circulation patterns can have on fire regimes.

Fire history in the Colorado Rockies and the Great Basin

Fire in the Colorado Rockies

The forests in the Rocky Mountains range from ponderosa pine forests at lower elevations, through mixed conifer forests at mid- elevations and subalpine forests at higher elevations. Schoennagel et al. (2004) provide an excellent overview of the range in fire regimes across these forest types, and the relative influences of fuels and climate on fire occurrence. The pre-settlement fire regimes in Rocky Mountain ponderosa pine forests were similar to those in ponderosa pine forests across the West. These forests were characterized by frequent, low-severity severity fires, which typically occurred after one or more years of above average spring/summer precipitation (such as occurs with an El Nino), which causes high production of surface fuels, is followed by a drier year (as occurs with La Nina) (also see Veblen et al. (2000). Schoennagel et al. point out that in most ponderosa pine systems, there is summer drought every year, so the real limiting factor to when fires occur in these systems is the presence of adequate fuels (Schoennagel et al. 2004). Because of the fuel dependence of fire in these systems, and the generally low energy release of fires that do occur, they are more amenable than higher elevation systems to modification of fire regimes by human activity. Both grazing and fire suppression have been pointed to as causes of reduction in fire frequency and increase in stem density in ponderosa pine forests in the 20th century. Interestingly, in the mid 1800's around the time of European settlement, there was an increase in fire frequency in Rocky Mountain ponderosa pine forests, which Shoennagel et al. (2004) attribute to a combination of increased ignitions from settlement and a period of enhance climate variability that has been noted in other studies in the western US. They contrast this situation in ponderosa pine with fire regimes in subalpine forests in the Rocky Mountains, which are dominated by species such as Engelmann spruce (*Picea Engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine. Closed subalpine forests are characterized by moist conditions, low levels of readily-combustible surface fuels, dense canopies, and high levels of dead (lodgepole pine) or living (spruce and fir) ladder fuels. In these systems, fuels are not limiting, the historic time between fires was long (often several centuries), and the fires are typically crown fires that occur under severe drought conditions associated with persistent atmospheric blocking ridges that prevent low pressure systems and associated rainfall from entering the area. Buechling and Baker (2004) found that fire regimes in subalpine forests in a 9,000 ha study area in Rocky Mountain Park were strongly dominated by high severity crown fires, with an estimated fire rotation of about 350 yr. They found no difference between pre-settlement and settlement periods, but they did observe that differences in the frequency of severe drought (as indicated by PDSI) among the 18th, 19th, and 20th centuries were related to the estimated cumulative areas burned in those time periods. Because long fire intervals are the norm and fires that do occur are typically high intensity (and resistant to control), Buechling and Baker agree with Schoennagel et al. that fire suppression has likely had little effect on fire regimes in closed canopy subalpine forests. The intermediate case is mid-elevation mixed conifer forests, composed of variable densities of ponderosa pine, Douglas fir, grand fir, and western larch (*Larix occidentalis*) (Schoennagel et al. 2004). The age-class structure, canopy density, and surface fuel loads of these forests vary across the landscape, and there may be patches that historically experienced low to moderate severity surface fires, and other areas that have

experienced crown fires. Fires may be both temporally and spatially heterogeneous depending on burning conditions and on local fire and vegetation history. It appears that on some drier, lower elevation sites tree densities have increased during the suppression era, but fire regimes and forest structure on other sites may have been minimally affected by human interference.

Not all subalpine forests in the Rocky Mountains, however, are characterized by stand-replacement fire regimes. Donnegan et al. (2001) investigated fire regimes across an elevation gradient in central Colorado (Pike National Forest), and found little difference in fire return intervals or fire regimes among ponderosa pine, montane mixed conifer, and subalpine forests. They attribute this to the fact that forests in this area are generally more open than at other locations in the Rockies, such that all of the forest types studied have grassy understories. In this situation, apparently all the forests were to some extent fuel limited, and the response to climate across the elevation gradient was similar to that typical for ponderosa pine forests, where fires typically occur in a dry year following wet years. In this study they found three distinct periods of different fire frequency. The pre-settlement period (before 1850) was characterized by moderate fire frequency, and was also a period of relatively low climatic variability. Fire frequency increase during the settlement period (1850-1910), which was a time of both increased human-caused ignitions and increased climate variability, and decreased to below pre-settlement levels by 1910-1920, when climate variability again decreased, grazing increased, intentional fire ignitions may have decreased, and fire suppression began to be implemented. The overall picture is one of complex interactions between climate and human activities that make attribution of the cause of changing fire regimes difficult.

Because fire regimes in closed-canopy subalpine forests appear to be driven more by climate than by fuel conditions, it is easier to clearly isolate fire/climate interactions in these systems. Schoennagel et al. (2007) evaluated interactions between fire occurrence and historical climate patterns for subalpine forests in Colorado between 1600 and 2003. They found that both short-term and multi-decadal patterns of fire occurrence were associated severe droughts during cool phases of ENSO and PDO and with warm phases of AMO. The most severe fire years were those in which the cool phases of ENSO and PDO and warm phase of AMO occurred simultaneously. When the reverse pattern was present, fire synchronicity was not evident.

The effects of livestock grazing on fire regimes in ponderosa pine forests are often hypothesized but rarely carefully investigated. Madany and West (1983) compared vegetation structure and fire regimes on the grazed Horse Pasture Plateau with those on two nearby ungrazed mesas in Zion National Park, Utah. The Plateau had been heavily grazed during the European settlement period (late 1800's and early 1900's). The Plateau and the mesa's are at similar elevations and both are dominated by ponderosa pine and Gambel oak (*Quercus gambelii*). Other common species on all sites include Rocky Mountain juniper (*J. scopulorum*), pinyon pine (*P. edulis*), and bigtooth maple (*Acer grandidentatum*). Large ungulates are present both on the mesas and on the Plateau. The vegetation on the Plateau contains dense forests of ponderosa pine, Gambel oak, and juniper saplings, while the mesas support open ponderosa pine woodlands with a grassy understory. Age class distribution of ponderosa pine on the Plateau shows a peak in reproduction from around 1900-1940, with similar establishment patterns for Gambel oak and juniper, which were plentiful in the pine forest. Ponderosa pine trees over 100 years old were rare, and total tree density was about 600 stems/ha. On the mesas, however, not only were the ponderosa pine

forests considerably less dense, but about 60 percent of the pines were over 100 years old and there were only scattered oaks and junipers, and total tree density was about 120 stems/ha. Herbaceous ground cover in ponderosa pine forest was about 5% on the Plateau and about 50% on the mesa. The fire history of the Plateau recorded a point MFI of every 4-7 years before grazing became established. By 1881, after a decade of grazing, fire had essentially disappeared from the plateau. Over the same time periods, the point MFI on the mesas was 56 to 79 years. Most interestingly, despite these relatively long fire free intervals, an open forest with herbaceous understory has persisted on the mesas, a strong indication that it was the reduction of competition from herbaceous vegetation by heavy grazing, not simply exclusion of fire, that fostered establishment of high densities of pine, juniper, and oak.

Fire history of Great Basin woodlands

There have been a large number of studies on the history of pinyon-juniper forests, woodlands and savannas in the Great Basin. Recent summaries include Miller and Tausch (2000) and Baker and Shinneman (2004). Both of these papers provide a multitude of references, as well as rather different perspectives, for those who want to dig deeper into information about specific locations or site conditions. While there appears to be some general agreement over changes in vegetation patterns from the presettlement period to the 20th century, the relatively small amount of concrete data on fire regimes leaves open the possibility of different interpretations of our understanding of the role of fire in these changes (Baker and Shinneman 2004). Miller and Tausch (2000) provide a good overview and interpretation of what is known about the historic patterns of pinyon and juniper, starting in the Holocene (10,000-8000 BP) when pinyon and juniper ranges expanded gradually northward and up in elevation across the Great Basin and onto the Colorado Plateau. By the warmer mid-Holocene (8000-4000 BP) Great Basin woodlands had reached elevations about 500 m higher than where they are found today, with evidence suggesting that the expansion of grasses and in fire occurrence during this period limited development of high density woodlands. Charcoal and pollen studies suggest that by the beginning of the late Holocene (2500 BP) periods of severe drought and associated fires led to expansion of sagebrush and other desert shrublands to higher elevations, and decreases in juniper, pinyon, and perennial grasses. Woodlands expanded again with increased summer precipitation during the Medieval Climate Anomaly (1500-1100 BP), and abundance of woodland species, but not their ranges, decreased again briefly during a dry period from 900-700 BP. It appears likely that increased moisture during the Little Ice Age (700-150 BP) led to further decreases in dominance and extent of woodlands as herbaceous fuels and, therefore, fire frequency, increased. The climate in the region has generally been warming since the Little Ice Age, and one might expect a large increase in fire activity, such as occurred around 2500 BP In contrast the region-wide decline in fire events that has been observed over the past 130 years is more rapid than any that has occurred over the past 5,000 years.

During the post-settlement period (starting about 1860) there have been rapid expansions and densification of juniper and pinyon woodlands throughout the Great Basin, and this expansion still continues in many areas. Factors associated with this expansion include increased precipitation and milder winters that promoted establishment and growth of junipers (especially

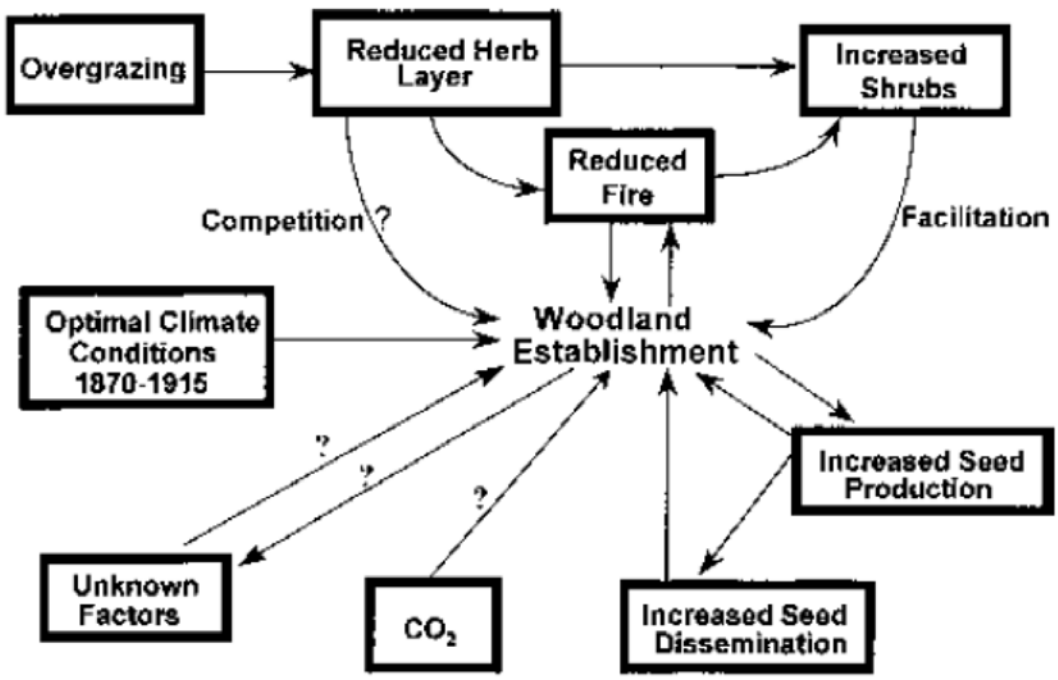

Figure 6.27: This conceptual model illustrates the complex interacting factors hypothesized to have been potentially influencing juniper and pinyon woodland expansion since the late 1800s. From Figure 7 in Miller and Tausch (2000).

between about 1850 and 1916. These conditions normally would be expected to promote fine fuel development, however, this was also a period of extensive livestock grazing, which dramatically reduced the fine fuels available to carry a fire and also led to an increase in density of shrub species that act as nurse plants for tree regeneration. These interactions, and others discussed by Miller and Tausch (2000), are summarized in Figure 6.27. Limited fire history data suggest that woodland expansion, especially on the most fertile sites, was inhibited by frequent fire in the pre-settlement period, although fire return intervals evidently varied considerably from site to site due to the diverse plant communities and soils that can support juniper and pinyon woodlands. The available data suggest MFIs for the presettlement period ranging from 10 to as long as 400 years. As woodlands have expanded and become increasingly dense during late 19th and 20th centuries, they seem to be becoming increasingly vulnerable to crown fires (Miller and Tausch 2000). And as fires do occur, whether in shrublands, woodlands, or desert grasslands, sites in the Great Basin are increasingly vulnerable to invasion by non-native annual grasses, which can greatly increase fire frequency, shift the fire season to earlier in the year, and present reestablishment of native woodlands and shrublands (Brooks and Pyke 2000). As Baker and Shinneman (2004) point out in their review of the primary literature on interactions fire regimes of pinyon-juniper woodlands, the patterns and effects of fire in these woodlands are not fully understood; they clearly vary from site to site; multiple interpretations of data are sometimes possible; and more quantitative research is needed to clarify the details of the general relationships discussed above.

Fire history in chaparral

There has long been a controversy over the impact of Native American burning, European settlement and fire suppression policies on fire patterns in chaparral. Because chaparral species are generally top-killed in fires, and due to the generally dry climate, the region has few sites appropriate for dendrochronological fire scar reconstructions or historical lake sites appropriate for analyzing charcoal and pollen in sediment. To evaluate long-term regional fire patterns in southern California chaparral, Mensing et al. (1999) evaluated data from two sediment cores taken from the Santa Barbara Channel in the Pacific Ocean south of Santa Barbara, CA. These cores covered a 560-year period from 1425 to 1985, and contained charcoal accumulated from fires in the area of the current Los Padres National Forest in the mountains from northwest to northeast of Santa Barbara. Calibration of varved sea-floor sediment cores with data on large 20th century fires (which typically occur during periods of high Santa Ana winds), showed a strong correlation of large fire events in the region with high influxes of large charcoal from both aerial deposition and water-borne sediments. The authors determined that over the 560-year period of their study, the average time between large fires was 21 years from 1425 to 1770 (Chumach Indian period); 29 yr from 1770 to 1900 (European settlement); and 23 years from 1900 to 1985 (modern fire suppression). They concluded that large fire years throughout this period occurred at the beginning of drought periods that followed wet years. They also saw no evidence of changes in the large fire record associated with periods of Native American or European presence in the region, and concluded that 20th century patterns of large fires during the fire suppression era were essentially unchanged from the patterns in previous centuries when climate is taken into account.

Lombardo et al. 2009 (2009) took a somewhat novel dendrochronological approach to evaluate fire history of chaparral on the Los Padres National forest. The highly fire-resistant big-cone Douglas-fir (*Pseudotsuga macrocarpa*) grows both at edges of chaparral stands and as scattered individuals within chaparral stands. Lombardo et al. used a combination of fire scars and tree ring growth rates from trees growing within chaparral stands to determine historical fire patterns from 1600 to 1893. They calibrated their dendrochronology-based records with fire atlas data for the 20th century and found strong correspondence between the two records. Their results for large fires were similar to those obtained by Mensing et al (1999), in that fire scar data, combined with data on tree growth, showed large fires occurring every 24 to 34 years throughout the period. However, the tree-ring record also records small fires, which could not be observed in sediment records. Lombardo et al. found that there were also large numbers of localized fire events (FRI of about 10 years) before 1864, when Euro-American influence was becoming more widespread, and Native Americans had largely be removed from their historic habitats. The number of these smaller fire events decreased from 1864 into the 20th century, and the fire regime after this time was dominated by four widespread fire events (an average of 34 years between events). They also observed an increase in scarring rates in these large fires, perhaps evidence of increased fire severity during this later period. The reasons for these changes are not obvious, as they occurred long before the beginnings of effective fire suppression (around 1950). Possibilities might include climatic shifts or a decrease in the effects of localized prescribed burning by Native Americans (see (Keeley 2002c; Keeley 2002a)). In any event, it is clear based on the results of the studies by Mensing et al. (1999) and Lombardo et al. (2009) that large fires have dominated

the fire regime of chaparral in southern California for many centuries, and that fire suppression has had little, if any, effect on large-fire occurrence.

Regional fire history and fire/climate interactions in the Northwest

Arno (Arno 1980) provided an overview of fire history patterns for sites representative of the major vegetation series in the Northern Rocky Mountains based largely on dendrochronological studies. He found that mean fire intervals ranged from 6-12 year in ponderosa pine, to 13-26 (140) years in Douglas-fir, 20-50 (300) years in lodgepole pine, and 70-120 years in grand fir (*Abies grandis*) and western red-cedar/western hemlock series. Series were defined not by current vegetation, but by the most shade-tolerant (climax) species on the sites. He emphasized that the variability in mean fire intervals is at least in part a function of patchiness of the vegetation on the landscape, local terrain conditions, surrounding vegetation, and other factors. All of the fire histories used in this study started before 1750, so they included both the pre-European period and the period after European occupation. For the ponderosa pine series, it appears that fires were more frequent before the advent of fire suppression (1910-1930), but that many areas had since become occupied by dense young stands that might be more susceptible high-severity fire. The Douglas-fir series, which includes forests of lodgepole pine, ponderosa pine, larch, and Douglas-fir, occurs on more mesic or higher elevation sites than the ponderosa pine series, and appears to have had a mixed severity fire regime of relatively frequent low to moderate severity surface fires interspersed with higher severity crown fires. On some sites these forests had been maintained in a relatively open condition by frequent surface fires for several centuries; on others, when longer fire intervals led to increased fuel loads, severe crown fires had occurred. This transition became more common after fire suppression began, as illustrated by photoseries taken over this period. At still higher elevations, mostly on drier sites, extensive stands of nearly pure lodgepole pine occur.

As in other mountainous areas of the West, fire regimes in the Northwest are affected by climate on a broad regional basis, but local controls such as aspect, elevation, the occurrence of barriers to fire spread and other factors have more site-specific influences on fire regimes. Heyerdahl et al. (2001) evaluated some of these effects on four watersheds in the Blue Mountains of eastern Oregon and Washington. They determined fire frequency based on a combination of fire scars and ages of regeneration (the latter on sites with mixed-severity or stand-replacement fire). They concluded that fire frequency (before 1900) in different areas within watersheds was affected by aspect and elevation, with higher frequency on southwest slopes (2 watersheds), at lower elevation (in dry forests, but not in mesic forests). Higher severity fire regimes tended to occur on north and east aspects and in mesic forest types, while lower-severity was typical for forests on south and west aspects or at lower elevations and in dry forest types. After 1900 fires became extremely rare, indicating a change in controlling factors as livestock grazing and fire suppression became more prevalent.

Heyerdahl et al. (2008a) developed fire chronologies from 21 ponderosa pine sites in the Northern Rocky Mountains of Idaho and Montana and related them to regional climate patterns as indicated by temperature, PDSI, ENSO, and PDO for the period from 1650-1900. They did not look at later periods because after 1900 fire frequency was greatly affected by human influence. They classified fire patterns into regional fire years (5 or more sites with fire), local fire years (fires at 1-4 sites) and no-fire years (fires at no sites). Regional fire years occurred 32

times over the period of study, with fires recorded on up to 10 sites (in 1748) per year. The fire locations in these years were generally widespread across the region. They recorded 99 no-fire years, and the rest had fires at only a few sites. Regional fire years had significantly higher summer temperatures and more drought (based on PDSI). The no-fire years were significantly cooler and wetter and tended to occur in years with La Nina, which is typically associated with high snowpacks, late snowmelt, and short fire seasons. Neither ENSO nor PDO had significant relationships to the occurrence of regional fire years. These relationships are illustrated in Figure 6.28. They observed no time-lag between wet years and fire occurrence, as has been reported for fuel limited systems in the Southwest. They concluded that "*Spring–summer temperature and moisture are the primary drivers of fire in our study area and while ENSO and PDO are responsible for some variation in spring climate in the northern Rockies ... the climate conditions that are conducive to regionally synchronous fires can occur here regardless of the phases of ENSO and PDO*".

Heyerdahl et al. (2008b) did a similar study of fire/climate interactions (from 1651-1900) on 15 sites in interior Oregon, Washington, and British Columbia. They categorized years by the degree of fire synchrony among sites: low synchrony—fires at 1 to 3 sites (96 years); moderate synchrony—fires at 4 to 6 sites (101 years); high synchrony—fires at more than 6 sites (35 years). There were also 18 years when no fires were recorded. Before 1725 the frequency of high synchrony fire years was every 14 to 35 years; over half of the no-fire years also occurred during this period. Between 1725 and 1800, high synchrony fire years were more frequent (every 2 to 16 years), and from 1800 to 1900, there was a short period of high synchrony fire years every 10 to 19 years. In this study, the high fire years were also associated with high drought severity (low PDSI) and the low or no-fire years were wetter (high PDSI). There was also a weak association of ENSO and PDO with fire synchrony, but only when they were considered in combination. Of the 35 high synchrony fire years, 23 fit the dipole pattern described by Kitzberger et al. (Kitzberger et al. 2007) with warm, dry summers in the northwest and cool, wet summers in the southwest.

These studies illustrate the importance of the broad regional, climate-driven, synchrony and the importance of local controls on fire regimes in mountainous regions across the Northwest.

Interactions between Fire and Climate in the 20th Century

Over the past 150 years or so, fire regimes across the west were affected by European settlement as well as by changes in climate. As European settlers moved into the West, they brought livestock, which affected the fuels available to burn, especially across large areas of the Southwest. They eliminated Native American populations, which had often used fire to manage the vegetation in areas where they lived, and they began, in many areas, extensive logging and land-clearing activities, which often resulted in high fuel loads and made areas more susceptible to large, severe fires, such as those of 1910. In addition, as populations grew, there were often more frequent unintentional ignitions, that could cause extensive fires out of the normal Indian-burning or lightning fire seasons during periods of high fire hazard. And, especially in the 20th

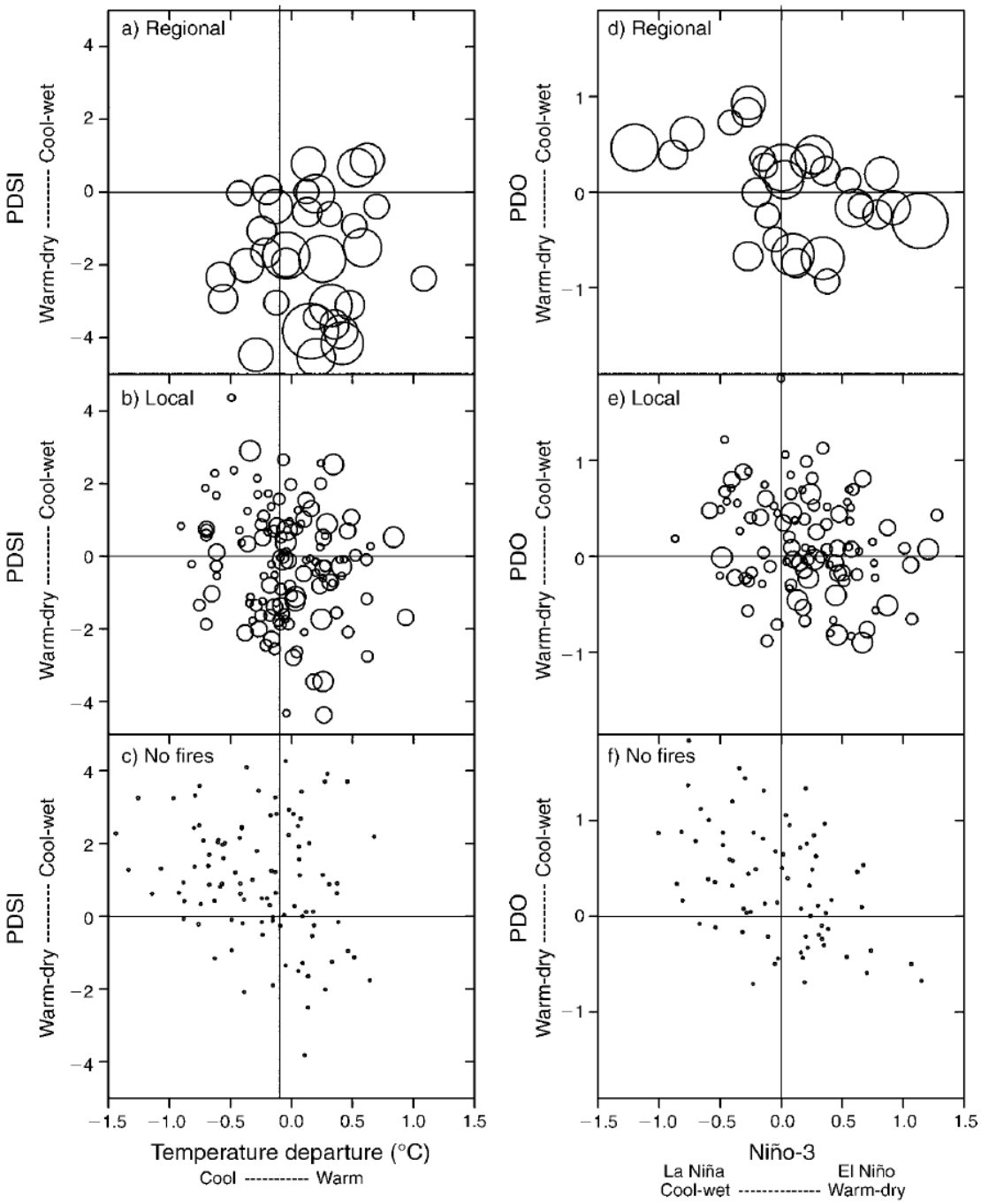

Figure 6.28: Influence of combined phases of tree-ring reconstructed spring-summer temperature (a–c, 1650–1900) and indices of large-scale climate patterns (d–f, 1700–1900) during regional-fire, local-fire, and no-fire years. The temperature time series shows departure from the mean temperature from 1951 to 1970. The diameter of the circles is proportional to the number of sites with fire, from no sites for the smallest diameter to 12 sites for the largest. Warm-dry conditions lie in the lower right quadrant in all panels. Source: Figure 4 (Heyerdahl et al. 2008)

century, policies of fire suppression were instituted across the country. The net effect of these activities has, of course, varied greatly across the West. One of the most widely documented effects has been a reduction in fire frequency, and concomitant increase in fire hazard, on forests with historic low severity high frequency fires, such as the ponderosa pine forests of the southwest and interior west. The great variety in the degree of departure from historic fire regimes across the West is well illustrated for different regions of the West by data from the LANDFIRE databases for the Southwest (Figure 6.29a) and the Northwest (Figure 6.29c). Burn perimeters from the Monitoring Trends in Burn Severity database for the Southwest (Figure 6.29b), the Northwest (Figure 6.29d) and Alaska (Figure 6.29e) overlain on Bailey Divisions illustrate the occurrence of fire over the past 10 years and its relationship in some areas to historical changes in fire regimes.

While previous sections have looked at fire and interactions among fire regimes, vegetation, and climate from the early Holocene up to the early 20th century. The records over much of this time are necessarily spotty, as studies depend on relatively scattered sediment charcoal and pollen data; on dendrochronological data based on fire scars and tree ring growth chronologies; and, for some systems dominated by crown fire or mixed severity fires, on reconstruction of stand age structures across limited landscape areas. This is a rich record that produces a sound foundation for understanding and interpreting fire/climate interactions, but it still leaves many questions unanswered. For example, while we may have information on seasonality of fires, or on relationship of fires to seasonal drought, such studies are often unable to tell us the length of summer drought periods, the timing of snowmelt, the fire size, or spatial patterns of fire. It is only in the 20th century that agencies in the US began to maintain consistent records on locations and sizes of fires within their purview, and these records, too, have improved and become more complete over time. Such data provide yet another rich resource for better exploring the details of interactions between fire and climate over the past 50 to 100 years, and illustrate well (but do not explain) the increase of fire activity that has occurred across the western US and in Canada starting in around the 1980's (Figure 6.30). More recent development of the Monitoring Trends in Burn Severity database and the Landfire databases will provide a much stronger foundation for monitoring fire and vegetation patterns as they relate to changing future environments.

Several recent studies have used 20th century fire data across large areas of the west to better evaluate the drivers of interactions between fire and climate and how they relate to the effects of past management actions (fire suppression, etc.) on changing fire regimes. Westerling has been started investigating and modeling fire climate interactions in California in the early 2000's, but garnered considerable attention in the press and the scientific community with publication of a seminal paper in Science (Westerling et al. 2006) that used agency fire records for the western US to evaluate changes in wildfire activity and fire/climate interactions between 1970 and 2003. They documented significant increases in the frequency of large wildfires (>400 ha) starting in the mid-1980s. From 1987 to 2003, the annual average number of large wildfires was almost four times that for the 1970 to 1986 period, and the annual area burned had increased more than six times. Spring and summer temperatures, length of the fire season, and timing of snow melt were all highly correlated with frequency of large fires throughout this period. The increase in fire frequency was greatest in the northern Rocky Mountains, but was also high in the Sierra Nevada, the California Coast Range and the southern Oregon mountains. They found that the areas with greatest increases in fire frequency were also those where the summer moisture deficit also had the greatest sensitivity to timing of spring snowmelt (Figure 6.31). They concluded

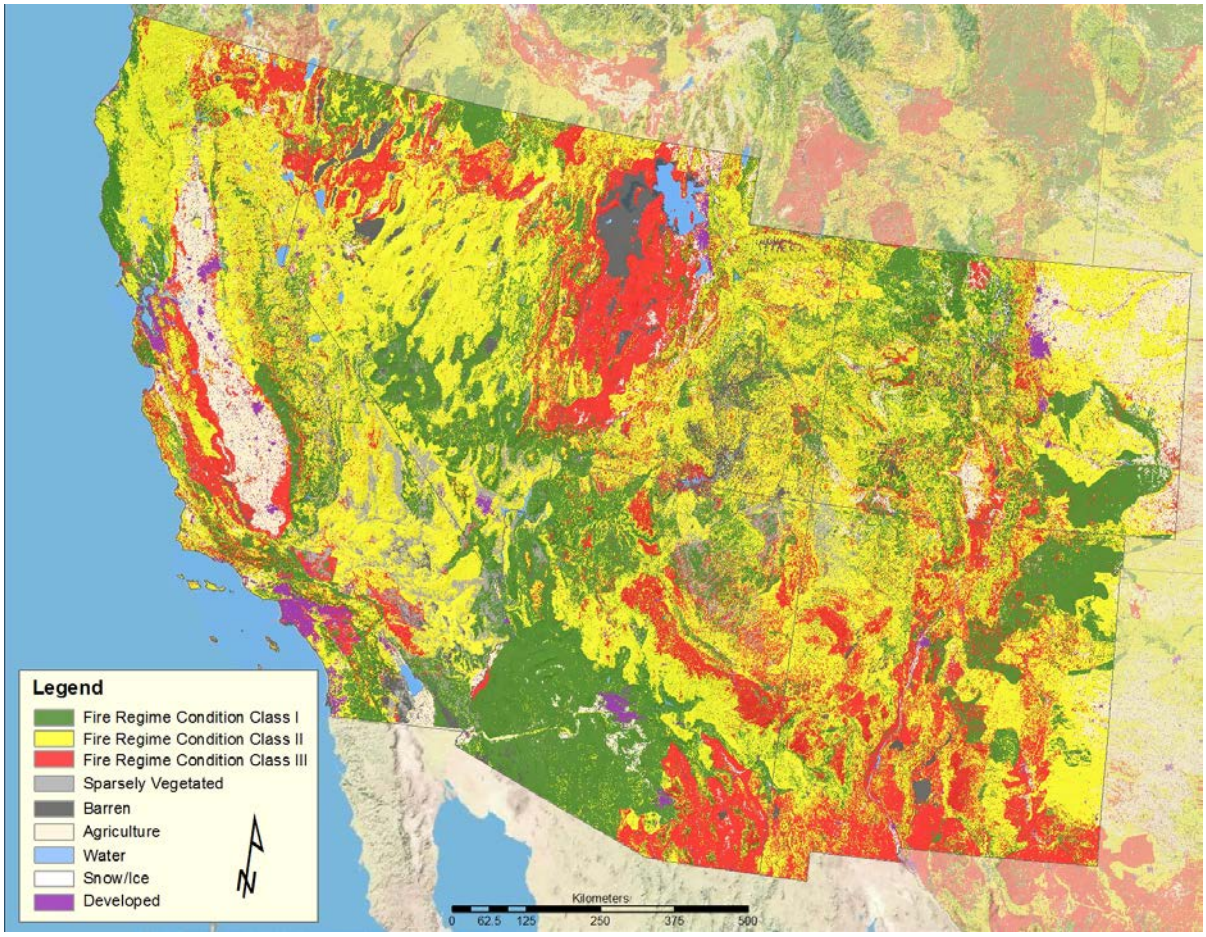

Figure 6.29a: Fire Regime Condition Class (FRCC) for the conterminous United States as used in LANDFIRE national database. FRCC is a metric of the degree of departure of current vegetation from the historical vegetation reference conditions simulated in LANDFIRE (Hann and Bunnell 2001; Hardy 2001; Barrett 2010; Holsinger and others 2006). The three condition classes describe low departure (FRCC 1), moderate departure (FRCC 2), and high departure (FRCC 3). See Fig. 3.4 and text for additional information.

that: "...although land-use history is an important factor for wildfire risks in specific forest types (such as some ponderosa pine and mixed conifer forests), the broad-scale increase in wildfire frequency across the western United States has been driven primarily by sensitivity of fire regimes to recent changes in climate over a relatively large area". They also cautioned that these changes are an indication of the substantial impacts that future climate change may have on fire regimes across the west.

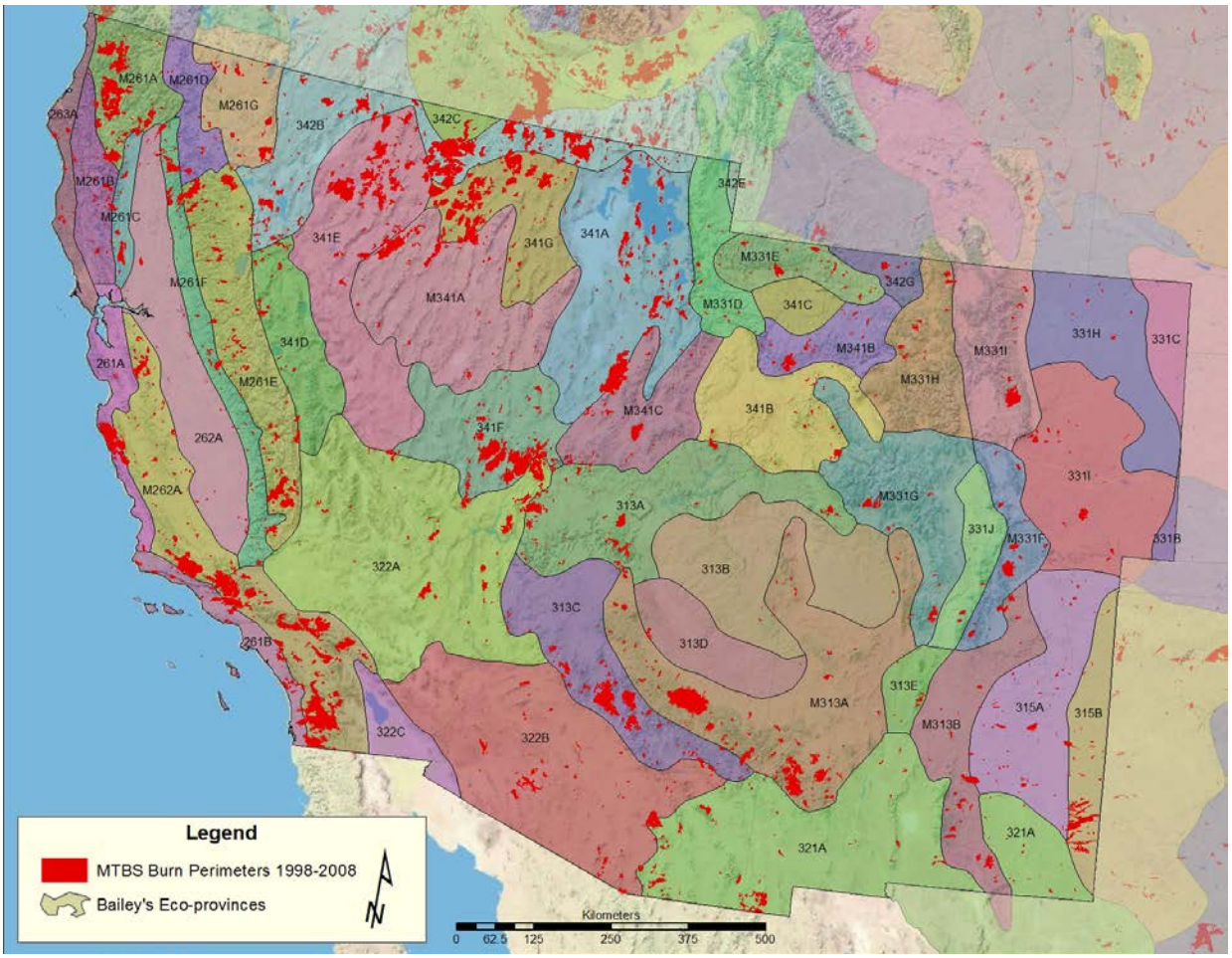

Figure 6.29b: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

Littell et al. (2009) expanded on the work of Westerling et al. (Westerling et al. 2003; Westerling et al. 2006), by reconstructing burned areas for the 11 western states from 1916 to 2003, and comparing these data to various climate parameters for 16 Bailey ecoprovinces in the West (see Figures 6.16, 6.18, 6.20 and 6.32). For the 1977-2003 period, regression relationships with climate variables (T, PDSI, and lagged, seasonal, or current year precipitation) as independent variables explained between 33 and 87 percent of the variation in annual burned area for all ecoregions evaluated. Patterns were similar for the entire period of record, but regression relationships were not as strong. They hypothesize that this may be due to a major shift in the PDO around 1970, which led to a change in the basic fire/climate relationship patterns. The most important points from this work are, first, that it confirms that for the more northern and montane ecosystems (generally crown fire systems) fire regimes as reflected in burned area are driven primarily by weather (fuel condition) in the year of the fire, while fire regimes in the more southern and drier ecosystems (which tend to have more frequent surface fires) are driven by either wet years prior to the year of the burn, or by a combination of antecedent wet periods and

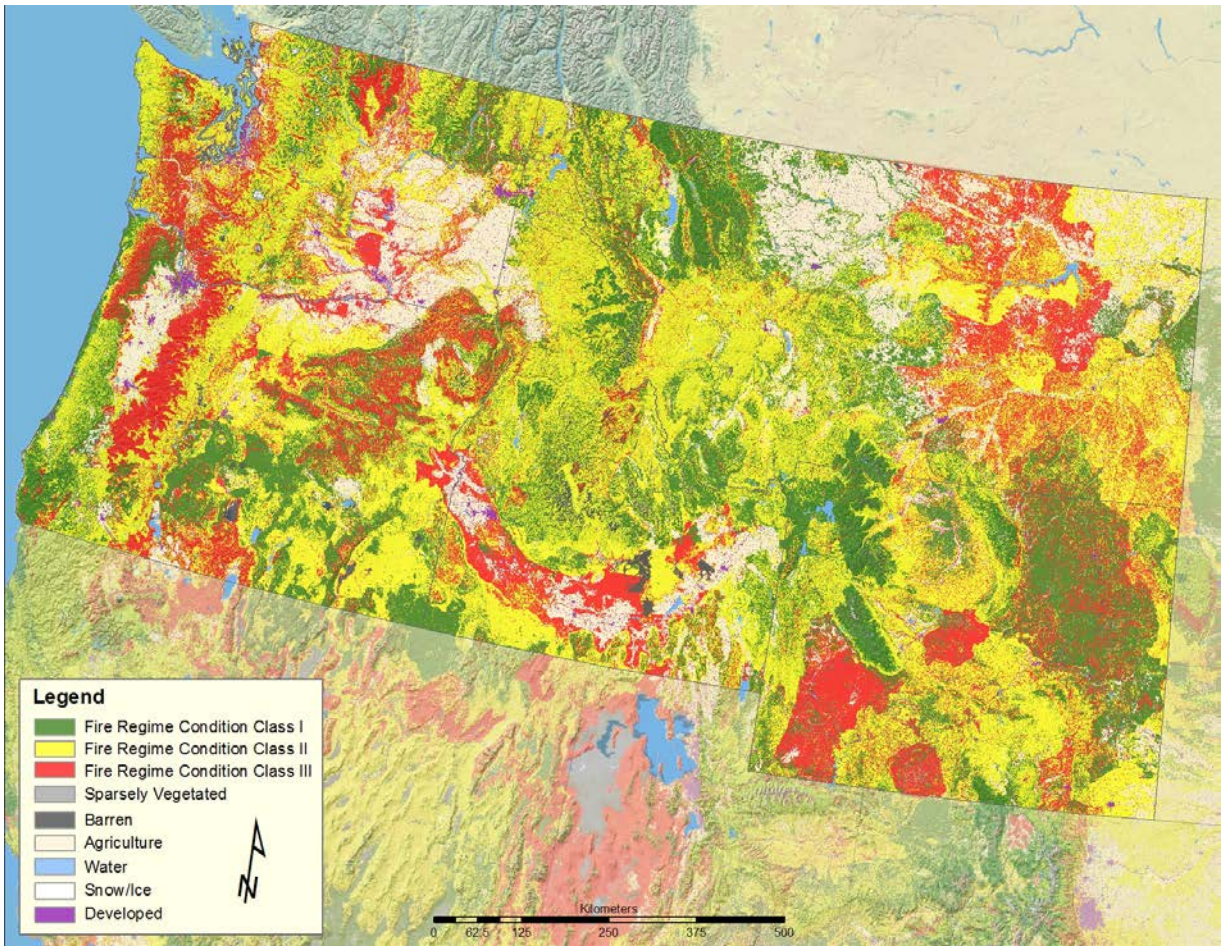

Figure 6.29c: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

dry conditions the year of the burn. For example, in the Rocky Mountains, Sierra Nevada, and Cascade Ranges, low rainfall, high temperature, and drought (as indicated by negative PDSI) immediately before and during the year of the fire were associated with increased burned areas. In the Great Basin mountains and deserts, on the other hand, antecedent warm, wet winter conditions, which drive fuel production and availability in the dry season, were the only factors associated with area burned. Their results make it clear that any projections of the potential future effects of climate on fire regimes must consider specific ecosystem characteristics such as vegetation composition and structure, fuel dynamics, and seasonality of climate. Further, they conclude that fuel modification is more likely to be a viable management option in ecosystems that are more strongly fuel-limited than climate-limited.

There have been a number of studies relating PDSI and various ocean atmosphere circulation patterns to historic fire data. Collins et al. (2006) evaluated these relationships for the 20th century over a broad region of the Interior West from Montana and Idaho in the north to Arizona and New Mexico in the South, and in Colorado. In the Interior West summer PDSI generally showed the strongest relationships with annual area burned, with weaker relationships for winter

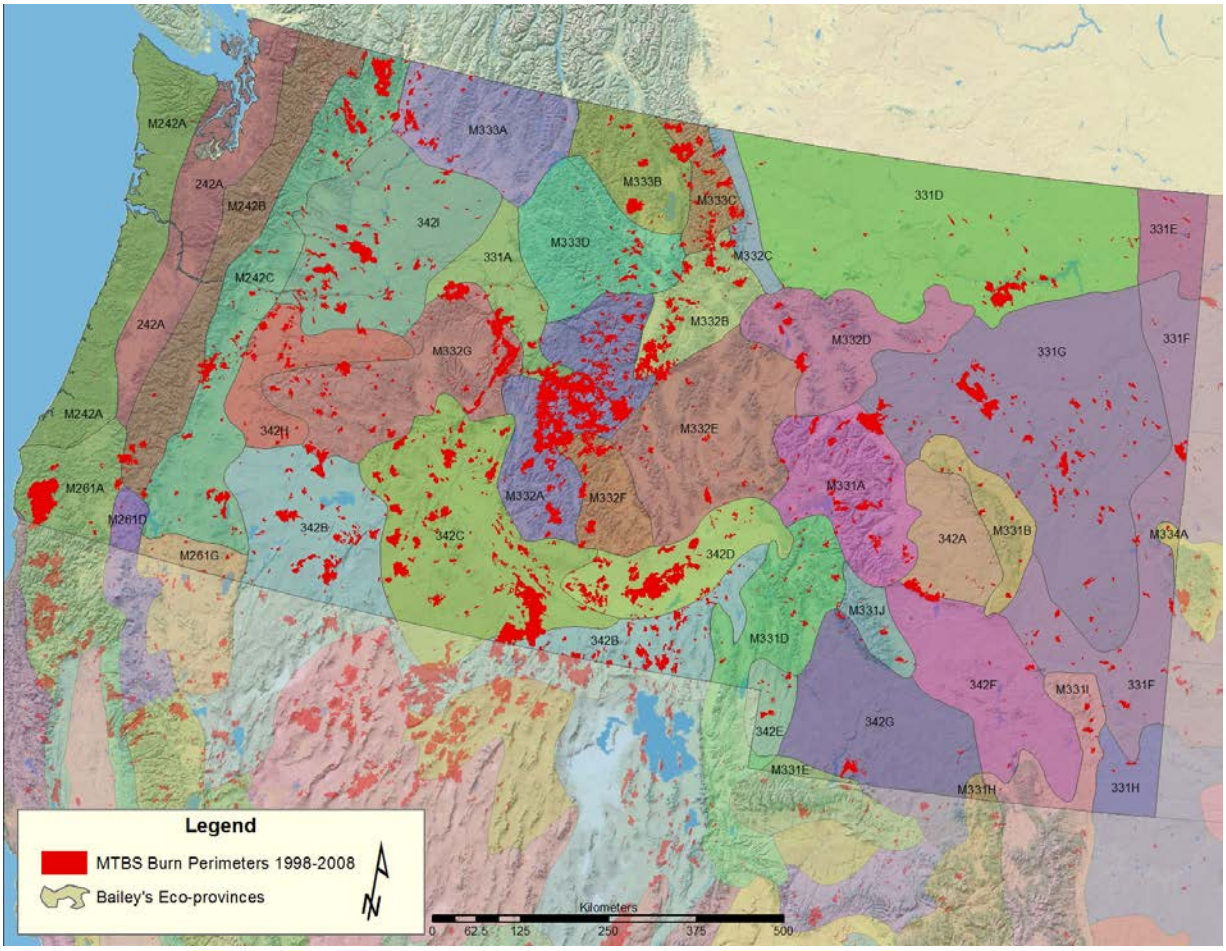

Figure 6.29d: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

SOI, and PDO, and no significant relationships with AMO. Throughout the Interior West and in most of Colorado, burned areas were positively correlated with 1-year time lagged PDSI (wet summers), and negatively correlated with current-year PDSI (dry summers). This pattern was consistent during warm phases of both PDO and AMO, except in the central region (Nevada and Utah). The strength of the relationship with PDSI varied over time, among regions (north, central, and south) and with the phases of both AMO and PDO. In the southern region (new Mexico and Arizona) PDSI was not significantly related to burned area when AMO was in its cool phase (1926-46). In the northern region (Idaho, Montana, Wyoming), there was no significant relationship with PDSI during the cool phase of PDO (1947-1976); it is notable that this was a period of relatively low fire activity throughout much of the West. The strongest relationships found between climate and burned area in this study were with PDSI, at both the regional and subregional scale. And the relationships with lagged PDSI throughout the area indicate the importance of fine fuel buildup in prior years for fire occurrence throughout this mostly dry region. Positive relationships between antecedent moisture and burned area were

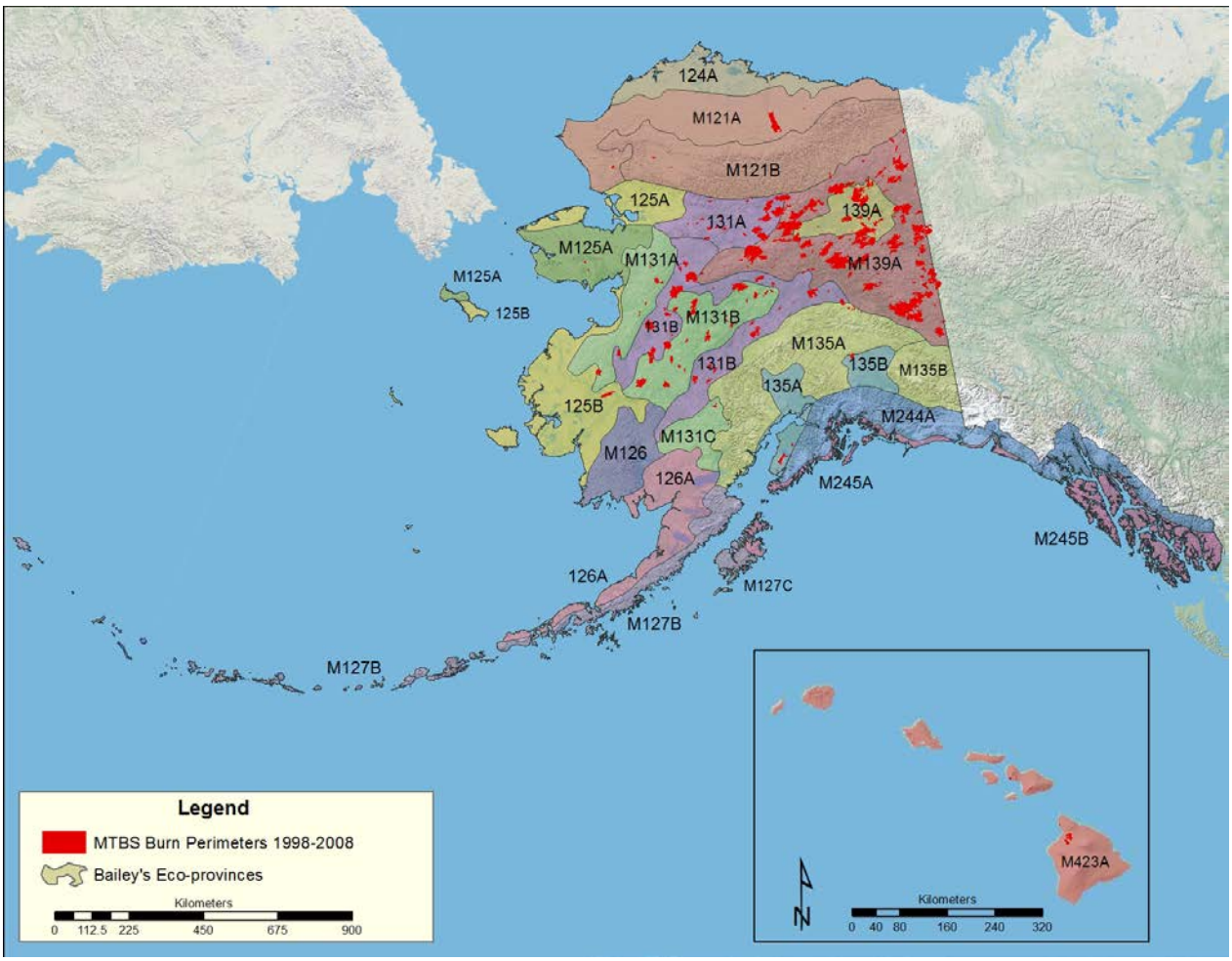

Figure 6.29e: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

strongest during warm phases of AMO in the south and during both cool phases of AMO (1926-46) and warm phases of PDO (1926-46; 1977-98) in the central and northern parts of the region. Clearly these are highly complex and regionally specific relationships, but they do appear similar to relationships derived previously from fire frequency studies in the same region.

Gedalof et al. (2005) investigated relationships between atmospheric and climatic variability and annual burned area on National Forests in Washington, Oregon, and Idaho. They identified four patterns of annual burned area that were associated with different climatic processes. Antecedent drought (PDSI) and the presence of summertime blocking ridges immediately before, during, and after the fire season were associated with extreme fire years, and the total length of the fire season is an important variable. The response differed among forest types. While these conditions are necessary for fire to occur in the more mesic forest types, they are not sufficient, as ignition incidents are rare. Further, on very dry sites, blocking ridges can produce severe enough drought for fires to occur even in the absence of antecedent drought. Summertime

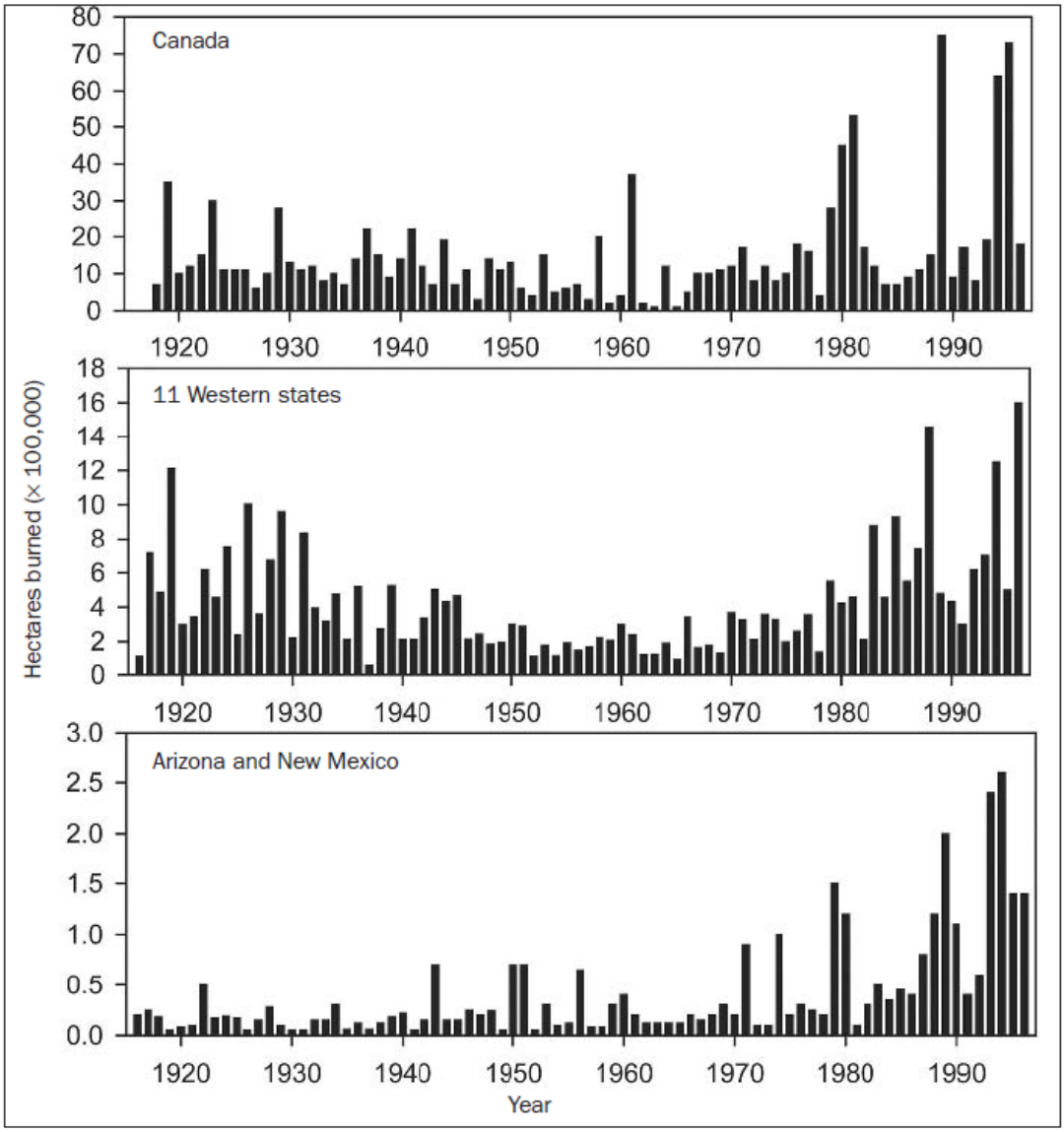

Figure 6.30: Area burned by wildfires in different regions under federal protection across North America. Note apparent increases in burned area starting in the mid to late 1980's, although it is not yet clear whether these represent long-term or cyclic patterns, or how much of the response in each area may be due to climate. Source: Grissino-Mayer and Swetnam (Grissino Mayer and Swetnam 2000)

cyclonic patterns can also lead to increased area burned, probably due to dry lightning storms with high winds. While this study found a strong interannual influence of The PDO on wildfire activity, with weaker impacts on inter-decadal variability, although the mechanism for these influences was unclear, as it may have resulted either from influences on winter drought or effects on summer atmospheric circulation patterns. They found no significant relationships between ENSO and area burned. They conclude that: "*Although fuel treatments are undoubtedly a necessary component of effective fire management, they cannot realistically be expected to*

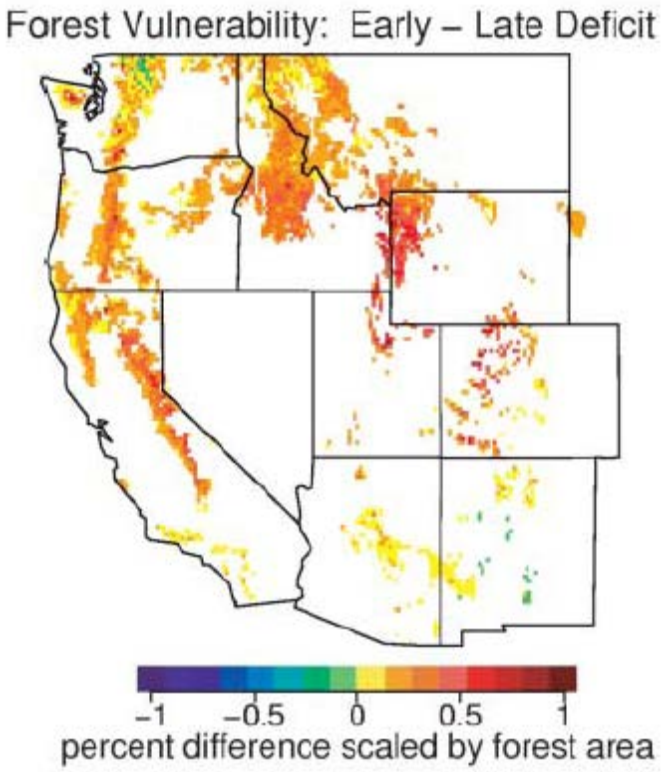

Figure 6.31: Index of forest vulnerability to changes in the timing of spring: the percentage difference in cumulative moisture deficit from October to August at each grid point in early versus late snowmelt years, scaled by the forest-type vegetation fraction at each grid point, for 1970 to 1999. Source: Figure 4 from Westerling et al. (2006)

eliminate large area burned in severe fire weather years. Additionally, the potential consequences of impending climate change on fire severity needs greater consideration" as increased drought stress is predicted in the Pacific Northwest for the future as climate continues to warm.

Trouet et al. (2006) focused on 20th century interactions (from 1929-2004) between fire and climate along the Pacific Coast (National Forests of Washington, Oregon, and California). Their results were remarkably similar to those of Gedalof et al. (2005) in that they found large fire years were associated with drought and with presence of a blocking ridge over the West Coast. This was associated with a positive phase of the PDO, while small fire years were associated with a negative PDO. This climate signal is strong, despite the extensive fire suppression efforts over the period of study. The authors point out, however, that this relationship has not been stable over long time periods, as the PDO teleconnection has a dipole characteristic between the northwest and the interior southwest, and this region is the pivot point. Therefore, variations in the location of this dipole may cause shifts in this relationship in the future as they have in the past.

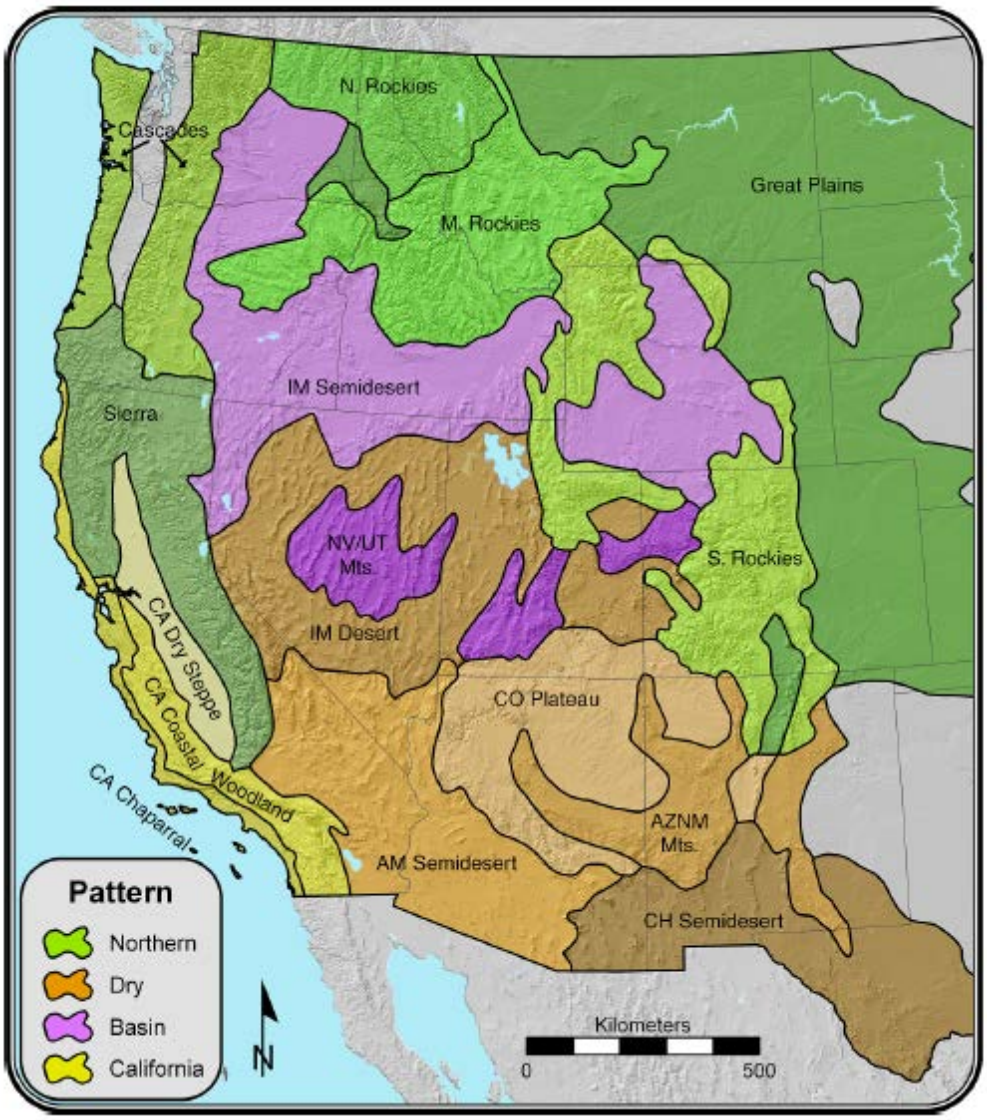

Figure 6.32: Ecoprovinces of the western United States and common patterns of climate–fire associations from correlation and diagnostic regression models. The 16 ecoprovinces for which we provide fire or fire/climate models are labeled. The similar colors group ecoprovinces with similar patterns of climate relationships (northern/mountain ecoprovinces, dry/lower-elevation ecoprovinces, Great Basin and Columbia Basin ecoprovinces, and California ecoprovinces). Source: Figure 2 in Littell et al. (Littell et al. 2009).

Morgan et al. (2008) used fire atlas data on mapped fires from 1900-2003 in the northern Rocky Mountains west of the continental divide (Idaho and Montana) to study patterns of fire and climate synchronicity in the 20th century. They found 11 regional fire years when area burned exceeded the 90th percentile. Six of these were before 1935 and five were between 1988 and 2003 (Figure 6.33). No large fire years were observed in the intervening period (1935-1987). Both of these periods had similar relationships between fire occurrence and climate. Regional fire years were characterized by warm springs (early snow melt; likely longer fire seasons) and

warm, dry summers, as well as by the positive phase of PDO. The only large fire years that do not fit these patterns are 1910 and 1919. These were both years of extreme drought (and very high winds in 1910) during a period of active logging, large numbers of ignitions associated with railroads and other factors, and less efficient suppression than would occur in future years. Large fire years were not related to ENSO phases, or to climate in previous years. During regional fire years, fires consistently burned across a variety of vegetation types (Figure 6.34). The period in mid-century when large fire years did not occur was characterized by a negative PDO, cool wet springs, and a lack of severe summer drought. Although the climate signal is clear, the lack of fire during this period may have been accentuated by relative ease of fire suppression. And burn patterns throughout the period of study were undoubtedly influenced to some extent by fire suppression and other land management and land use changes. Because of the strength of the climate signal, the authors believe that climate, rather than effects of fire suppression, has been dominant factor in increases in burned area in this region since 1988. Considering the projections of climate models for warmer springs and warm, dry summers, this region is likely to continue to experience severe regional fire years of large, synchronous fires in the future.

Alaska is one of the few areas of the US with a good database of fire perimeters on all lands for much of the 20th century (1960-present). This has enabled researchers analyze 20th century changes in fire regimes as well as interactions among fire regimes, climate, and weather with a high degree of accuracy (Kasischke et al. 2010; Duffy et al. 2005; Macias Fauria and Johnson 2008; Abatzoglou and Kolden 2011).

Kasischke et al. (2010) did a synthesis of changing fire regimes in Alaska from the 1940s through the beginning of the 2000s. Burned areas (Figure 6.35) have generally been increasing over time, and during the 2000s, 50% more area burned perimeter (767,000 ha/yr) than since the burned area data base began in the 1940's, although similar burned areas were estimated during the late 1800's. While the number of lightning ignitions has decreased over the past 60 years, large lightning-ignited fire events have increased. This change in lightning ignitions, and their relationship to climate patterns, has been described in some detail by Macias-Fauria and Johnson (2006). While human-caused ignitions have increased over time, the area burned in these fires has decreased due to improved fire suppression near settlements. The amount of the area burned during late-season fires has also increased over the past two decades. This has led to higher fire severity, in particular deeper burning of surface organic layers in black spruce (*Picea mariana*). These changes suggest increasing vulnerability of black spruce forest on all but the most poorly drained sites.

Duffy et al. (2005) related fire patterns in Alaska to weather and climate variables to assess interactive patterns of fire season severity from 1950-2003. The y found that independent variables such as spring and summer temperatures winter PDO, June precipitation, and an interaction term, collectively explained 79% of the variability in annual area burned by lightning-caused fires. Average June temperature was the most important of these variables, explaining about a third of the variation. The spring and summer weather that is conducive to fire activity was related to patterns of the winter Pacific Decadal Oscillation and the East Pacific teleconnection indices, which have the potential to be useful in predicting upcoming fire season activity. Strong positive phases of the EP lead to summertime blocking ridges and consequent summer drought, which is

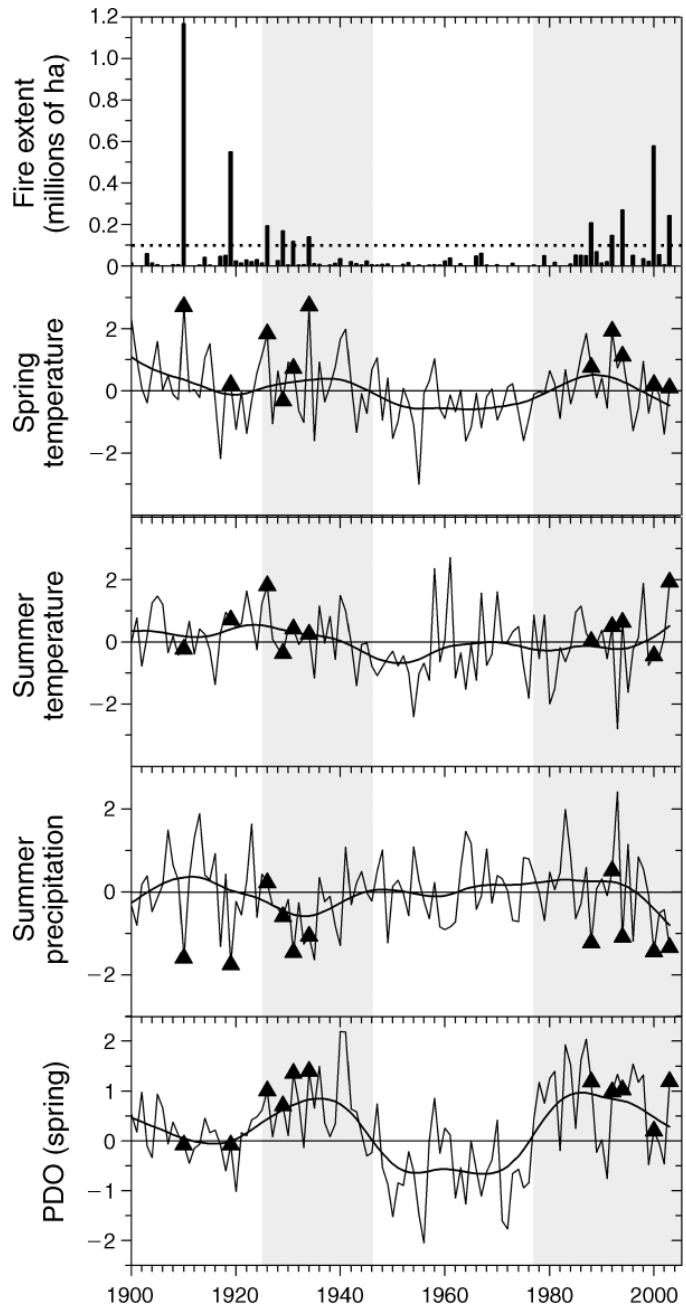

Figure 6.33: Annual fire extent and 20th-century climate in the northern Rockies. The 11 years exceeding the 90th percentile in annual fire extent (102 314 ha, horizontal dotted line) were identified as regional-fire years (top) and indicated with triangles in the other plots. Normalized spring temperature (March–May), summer temperature (June–August), and summer precipitation were averaged over the five climate divisions covered by this study. Heavy lines are smoothed climate data that retain 50% of the variance at periods of 25 years. Positive phases of the Pacific Decadal Oscillation (PDO) are shaded (Mantua et al. 1997). Source: Figure 3, Morgan et al. (2008).

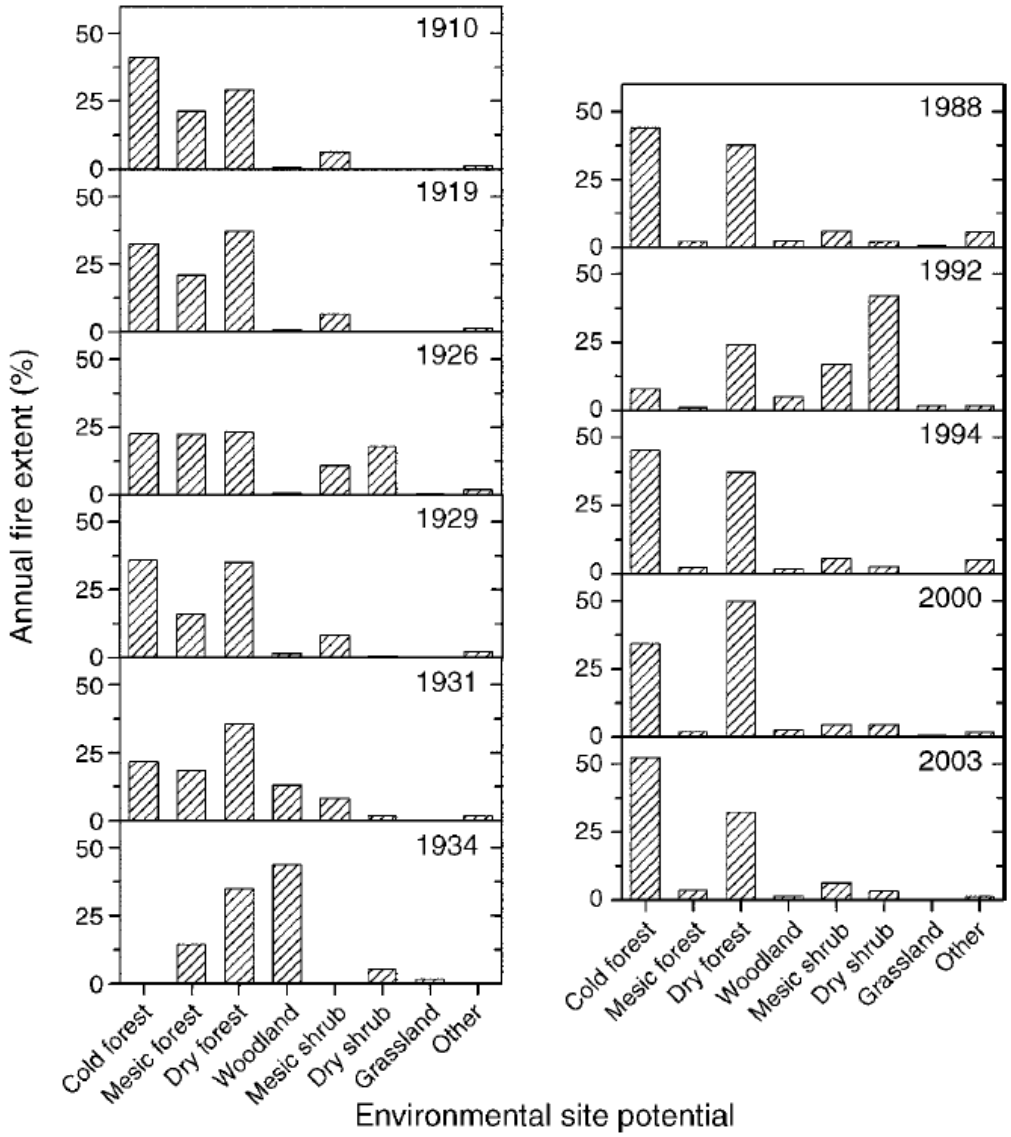

Figure 6.34: Distribution of fire extent by potential vegetation (Environmental Site Potential) during each of the 11 regional-fire years (from 1900 to 2003). Regional-fire years in the left column occurred early in the 20th century, while those in the right column occurred late in the 20th century. No regional-fire years occurred between 1935 and 1987. Source: Figure 6 in Morgan et al. (2008).

associated with high fire activity. There was a high correlation between area burned and cool phases of the PDO, which is related to wet winter temperatures. The reasons for this interaction are not yet entirely clear. Abatzoglou and Kolden (2011) point out, however, that in Interior Alaska fire growth and ultimate fire size cannot be predicted well by antecedent climate, but is highly dependent on weather patterns during the burn.

Understanding seasonal factors related to the temporal and spatial distribution of fires is also important. Bartlein et al. (2008) analyzed patterns in daily locations of wildfire ignitions in the

western US from 1986 through 1996. They concluded that patterns of both lightning ignitions and human caused fires show consistent relationships to ecosystem distribution, terrain, and other factors. Both lightning and human-caused fires also showed clear seasonality, but the human-caused fires generally tended to increase the length of the fire season, and also were strongly affected by population levels and human activities (there is a very distinct peak in human-caused fires on the Fourth of July every year). The inter- and intra-annual variability in lightning-caused fires was higher than that for human-caused fires because of the dependence on specific weather patterns that vary over time. In addition, lightning fire outbreaks generally progress from west to east as major weather systems move across the country.

As yet, there is little information on potential effects of changing climate on health of forest stands, although there is a growing body of evidence associating warming climate in the Rocky Mountains, Alaska, Canada and other areas with increasingly severe insect outbreaks in conifer stands, as well as evidence of expansion of insects such as mountain pine beetle far outside their historic ranges. Van Mantgem et al. (van Mantgem et al. 2009) evaluated changes in background mortality rates in undisturbed old forests across the West, and their results are a strong indication that increased drought and warming climate appear to be already having a substantial and widespread effect on forest health. They found steep increases in mortality rates across a range of elevations, tree size and age, and dominant species, with doubling rates of 17 to 29 years. There was no pattern of increased mortality for areas where fire exclusion has had an impact on stand structure; fire history did not have a significant effect on this west wide pattern. Although they did not look at relationships of mortality to fire occurrence, one might speculate that the same factors that are driving mortality will increase fuel hazard and the risk of fire in many of these systems, perhaps especially those where burned area has historically been climate driven.

There have been numerous studies of 20th century relationships between fire and climate for local regions of the western US. These will not be specifically discussed here, but many are listed in our supplemental bibliography.

Western Fire History – Some Concluding Thoughts

There is a rich literature on interactions among climate, vegetation, and fire across the West from the early Holocene (after retreat of glaciers in the north) up until the present. The early record is one of millennial to century time scales, and is comprised of local examples based largely on sediment records of charcoal and pollen, but it does make clear that relationships between fire and climate vary over time, and further, that they vary with vegetation type. One example of this is the somewhat counterintuitive increase in fire in Alaska during a cool wet period in the mid-Holocene. This appears to be a result of increases in black spruce, which has a canopy structure that makes it more flammable and more amenable to stand replacement fires.

As we move forward in time, the tree ring record enables us to look at fire patterns over centuries and decades, and often to not only precisely date years in which fires occurred, but also to determine seasonality. These records are of necessity local, and depend on accurate cross-dating and on vegetation where fire history has been recorded through fire scars on living trees. In vegetation dominated by stand-replacement fires, historical reconstructions of stand age and structure have been useful in determining past fire regimes. It was not until the 20th century that

increasingly-consistent agency fire records began to be developed, enabling more comprehensive analyses of local and regional patterns of fire/climate interactions for the 20th century.

Throughout this long period, it is evident that climate and vegetation have worked together as drivers of fire regimes. It is also evident that the specific relationships between fire and climate vary regionally and over time. The influences of the various ocean-atmosphere circulation patterns (PDO, AMO, ENSO, etc.) on fire are strong but differ regionally, and their strength and variability change over time, as do their interactions with each other. The PDSI index appears to fairly consistently relate to the occurrence of severe fire seasons on both local and regional scales, but the strength if this relationship also varies over time, probably largely due to the effects of changing and interacting circulation patterns. Another fairly consistent pattern that seems associated with fire occurrence is the presence of blocking ridge systems that can cause local or regional drought. These may be caused by phases of different circulation patterns depending on the location. Another critical factor, particularly in dry, fuel-limited systems, is the apparent dependence of large fire events on periods of high rainfall one to three years before a dry summer. This stimulates the growth of fine fuels that are needed to carry a fire.

We agree with the authors who have concluded that fuel management is most likely to be effective, and fire suppression more likely to have an influence on fire regimes in ecosystems (e.g. ponderosa pine) where fire occurrence is fuel-driven, which are typically characterized by relatively low-severity surface fire. More purely climate-driven fire regimes are typified by high or mixed severity fires which often burn with an intensity that does not make them amenable to control.

Another important conclusion from many of these studies is that the climate signal is a strong driver of the occurrence of severe fire seasons throughout the western region, although local human influences on fire exclusion (e.g. through grazing or fire suppression), changes in land use such as logging, changes in human-caused ignitions, or expansion of invasive species may dampen or enhance the amplitude of the climate effect.

Based on projections of generally warmer climate in many regions of the West, we can expect the frequency of large fires and severe fire seasons to continue to increase, but the strength of this effect will depend to a large extent on how changing climate affects the intensity, variability, and dominant phases of key ocean-atmosphere circulation patterns.

Using fire history and other ecosystem information to model the future

Fire history from an ecosystem perspective aids our understanding of how fire and climate have interacted in the past, and how they have interacted with other factors such as management systems and non-fire disturbances like insects and disease and invasive species. It is also useful useful to aid development of models to enable managers to explore different scenarios of future conditions and how they might be affected by management actions. While climate models continue to improve in resolution, modelers in the natural resource research community are working to incorporate understanding of how climate interacts with vegetation and fire at various scales into products that can be useful to managers or policy-makers in evaluating the potential impacts of various climate projections or scenarios.

Several studies that use past information on fire/climate/vegetation interactions to project the potential effects of climate on future vegetation and fire regimes in the US, often using downscaled climate projections, have been reported. Approaches to this problem include looking at current or past distributions of individual species or ecosystems/biomes as they relate to current or past climate as well as integration of biophysical vegetation, fire, and climate models to project vegetation into the future. GCMs outputs often need to be downscaled to scales appropriate to landscape management. Approaches for downscaling include development or application of finer scale gridded atmosphere/climate interaction models, or assuming that relationships between elevation, terrain, and regional climate will be similar under future climates to what they are today.

Table 6.8: Predicted area occupied by the climate profiles of major biotic community types in the West under the present climate and the change in area of these climate profiles expected from global warming by 2030, 2060, and 2090. The extramural percentage reflects the percent of the total area of the current distribution of each climate profile that is projected to be outside the current range by 2100. The percentage remaining in place represents the percent of the area where the climate profile is not projected to change from 2000 to 2100. The Group Composition codes represent the specific biotic communities included within each grouping. For example, Montane forests include Rocky Mountain montane conifer forests (6) and Sierra-Cascade montane conifer forests (7). Adapted from Table 5 in Rehfeldt et al. 2006.

Grouping	Group composition[a]	Total area in 2000 (%)	Δarea (%)			Extramural by 2100 (%)	Remaining in place through 2100[c] (%)
			2030	2060	2090[b]		
Great Plains	5	24.4	2.2	−3.6	6.6 (1.6)	61	89 (33)
Grasslands[d]	10, 18, 20	18.4	−13.0	−0.8	17.9 (3.3)	53	33 (13)
Desertscrub	14, 19, 22, 24	17.3	31.2	22.9	3.0 (0.5)	53	25 (4)
Montane forests	6, 7	15.2	15.4	14.9	11.7 (1.8)	12	51 (45)
Great Basin woodlands	13, 15	8.2	−26.0	−9.6	−28.7 (−2.2)	3	17 (17)
Subalpine tundra	3, 4, 9, 11	7.7	−32.0	−71.8	−84.7 (−6.5)	19	10 (9)
Evergreen forest-chaparral	12, 16, 17, 21, 23	4.1	23.8	42.1	53.2 (2.3)	88	45 (5)
Coastal forests	2,8	3.6	4.1	4.8	0.1 (0.0)	62	60 (29)
Madrean	25, 26	0.3	−76.1	−20.3	10.2 (0.1)	86	0 (0)

[a] Codes are defined in table 2.
[b] Value in parentheses is percentage relative to total landscape.
[c] Value in parentheses is percentage remaining in place and within the climatic profile.
[d] Other than Great Plains.

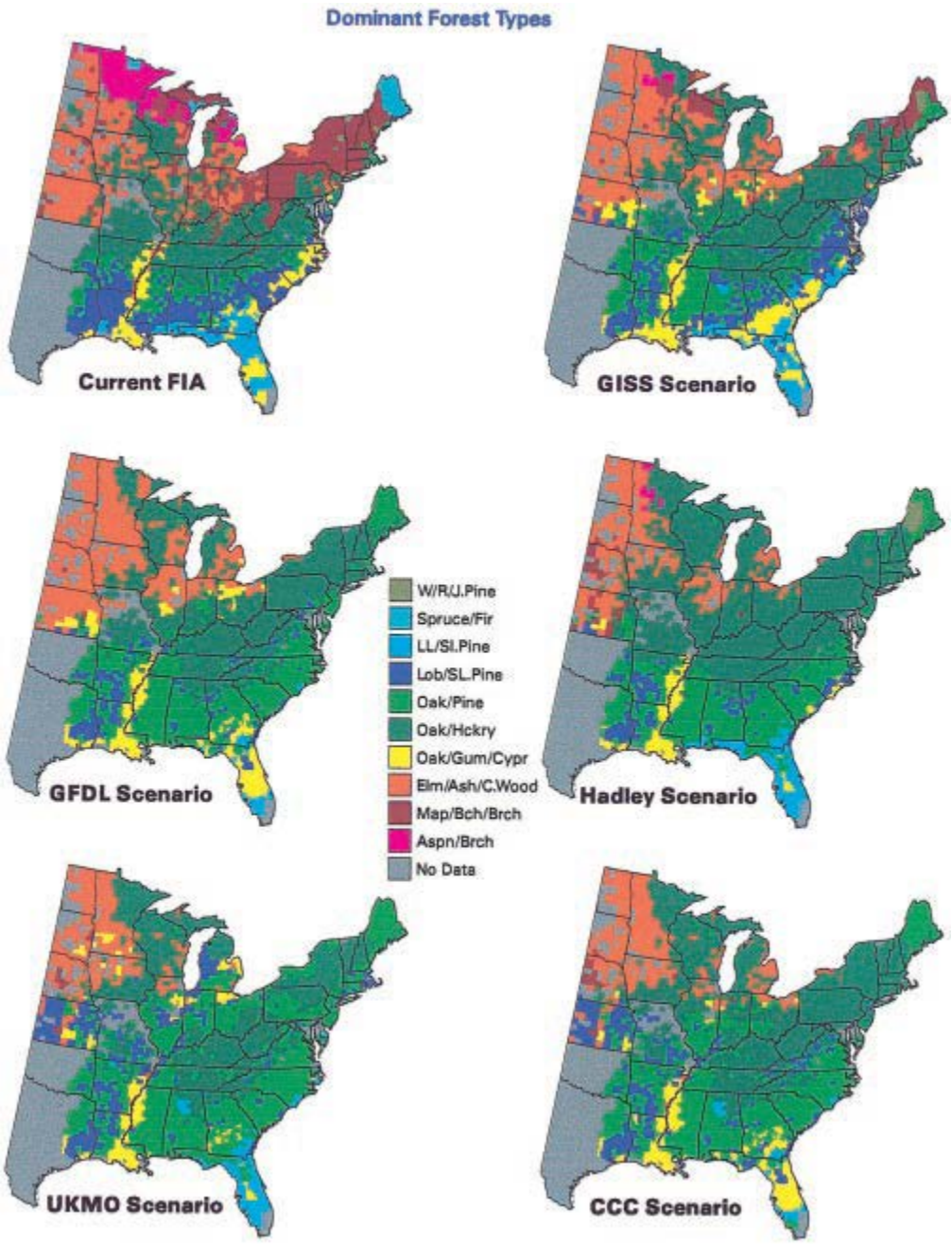

Figure 6.35: Current forest types in the Eastern US as determined from forest inventory data (top left) and potential future forest types with five scenarios of climate change at $2xCO_2$, which some IPCC scenarios project may be reached as early as 2100. From Figure 2 in Iverson and Prasad 2001.

The climate envelope approach has formed the basis for projecting potential changes in distribution of major tree species distribution in the West (Rehfeldt et al. 2006) and for projecting potential changes in both species and vegetation types in the East (Iverson and Prasad 2001; Iverson and Prasad 2002; Iverson and Prasad 1998) under various climate-change scenarios. Rehfeldt at al. (2006) projected that by 2100, the climates over about 55% of the

landscape in the western US would be incompatible with current vegetation. They provided estimates of spatial changes in compatible climates over time for both major tree species and major vegetation types (Table 6.8) of the West, and illustrate that by 2100 we can expect major changes in distribution of suitable habitat both for most vegetation complexes and for individual species in the West. Iverson and Prasad and their colleagues have developed an on-line tool that enables users to map the effects of various climate scenarios on the distribution of appropriate biophysical conditions for both tree species and vegetation in the eastern US[30] (Figure 6.35). As can be seen from the figure, the models yield somewhat different projections, but all models project large decreases in the area of suitable habitat for Loblolly/shortleaf pine in the Southeast and for the maple/beech/birch forests of the Northeast. While climate envelope approaches to determining suitable habitat as a basis for projections such as these do not provide information on actual mechanisms of vegetation survival or migration, they are quite instructive as to potential changes in locations of suitable habitat for various species or vegetation complexes over time as climate changes.

There have also been a number of efforts to incorporate fire and climate into existing land management, tree growth, ecosystem, and biome models, which may incorporate the results of climate envelope models, information on physiological responses of different species to environment, or alternative approaches. Among spatial simulation models of fire and vegetation dynamics (landscape fire succession models or LFSMs), some have the potential to be adapted to use for studies of fire-climate interactions. Keane et al. (2004) briefly described and classified 44 of these models, all of which incorporated the key parameters of fire ignition, fire spread, fire effects, and vegetation succession, with the aim of helping managers to decide which models might be most appropriate for particular purposes. They determined that over a dozen of these models had the potential to be used for simulating interactions among climate, vegetation and fire—although it is interesting that a number of other models they looked at have since had climate components incorporated (e.g. LANDIS and ALFRESCO). Weinstein and Woodbury (2010) discuss the types of models that are available and focus primarily on the usefulness for risk assessment of four of the most widely used succession models that contain processes that link vegetation change to fire prediction: SIMPPLLE, MAGIS, VDDT, and TELSA. They provide a good summary of various modeling systems, including MAPPS-CENTURY (discussed briefly below). Additional discussion of LANDSUM, SIMPPLLE, and VDDT can be found in (Barrett 2001). (Cary et al. 2006) carried out a model comparison exercise to evaluate the feasibility of incorporating climate information into existing landscape-level postfire succession models. They compared effects of terrain, fuel type and climate on burned area and concluded that the models were generally more sensitive to weather and climate than to the other factors. Cary et al. (2009) considered the relative influence of fuel management, fire management, and weather in determining variations in burned area for five landscape models and determined that annual variations in weather and in the success of fire management were more influential than fuel management effects on burned area.

There are ongoing efforts to incorporate climate change parameters into the Forest Vegetation Simulator (FVS), which is the stand growth projection model used by the US Forest Service and

[30] http://www.nrs.fs.fed.us/atlas/

some other agencies. Crookston et al. (2010) summarize this effort to develop a management tool (Climate-FVS) that can be used by managers to make projections for forest planning, using three pilot test areas. Climate is being incorporated into the model by linking tree mortality, regeneration, growth, and potential population-level genetic responses to climate variables in order to project the potential changes in tree growth and species composition that might accompany changing climate. Changes in modeled stand dynamics were most sensitive to climate-induced changes in mortality.

LANDIS is a landscape dynamics model originally developed in the Great Lakes region for projecting effects of different management activities and disturbance on forest growth, structure, and composition. This model has been used to assess impacts of climate on species composition, fire regimes, and forest dynamics in several areas of the United States (He et al. 1999; Yang et al. 2004). LANDIS-II has also been parameterized for an area of central Siberia, where it was used to project interacting effects of climate change, logging, and insect outbreaks on forest composition, fire regime, carbon stocks, and landscape pattern (Gustafson et al. 2010).

In Alaska, historical fire/climate relationships based on sediment charcoal have been used to parameterize the ALFRESCO model to project effects of changing climate and vegetation on fire regimes (Brubaker et al. 2009; Rupp et al. 2002).

The MAPPS group has been working with broad-scale Dynamic Global Vegetation Models to investigate potential interactions between climate change and biome-level vegetation dynamics for many years, and has put a good deal of effort into developing methods for incorporating fire into their models on regional and global levels. In general these models are driven by broad scale atmospheric processes, such as prolonged drought, and model fire regimes (burned area) at a rather coarse scale useful for broad projections of potential climate effects (e.g. (Lenihan et al. 1998). More recently, the vegetation change and fire models are being adapted for use at a finer scale (Lenihan et al. 2003; Rogers et al. 2011), although they still incorporate only broad vegetation categories that are useful more at the policy level than the operational management level.

The BIOME-BGC model, which is a mechanistic ecosystem model, has been used for several regional studies of potential interactions between climate and fire regimes, including simulations of effects of climate on vegetation structure and distribution in Glacier National Park, and the effects of these changes on potential fire patterns over time (Figure 6.36), as well as simulations of the potential effect of climate change on whitebark pine (Loehman et al. 2011). As is evident from Figure 6.36, the projected magnitude of future warming resulting from the emissions scenario used has a tremendous impact on the results. As mentioned in other chapters, the largest error in most GCM projections of future climate (and therefore of future vegetation and fire regimes) results from the difficulty of deriving appropriate emission scenarios due to uncertainty of future international climate change mitigation policy responses. At present, emissions are exceeding the projections of even the A2 scenario.

There is a growing array of models and approaches that have potential usefulness—and more are being modified to incorporate fire/climate/vegetation interactions—as well as interactions with insects, management, and other disturbances. We have not attempted to cover all of them here.

Most of the models discussed above have been parameterized only for certain locations or vegetation types, but researchers continue to broaden the geographic scope and improve the scale of their applications. This is a very fast-moving area of research and application, which holds great promise for availability of improved tools for managers as we move forward.

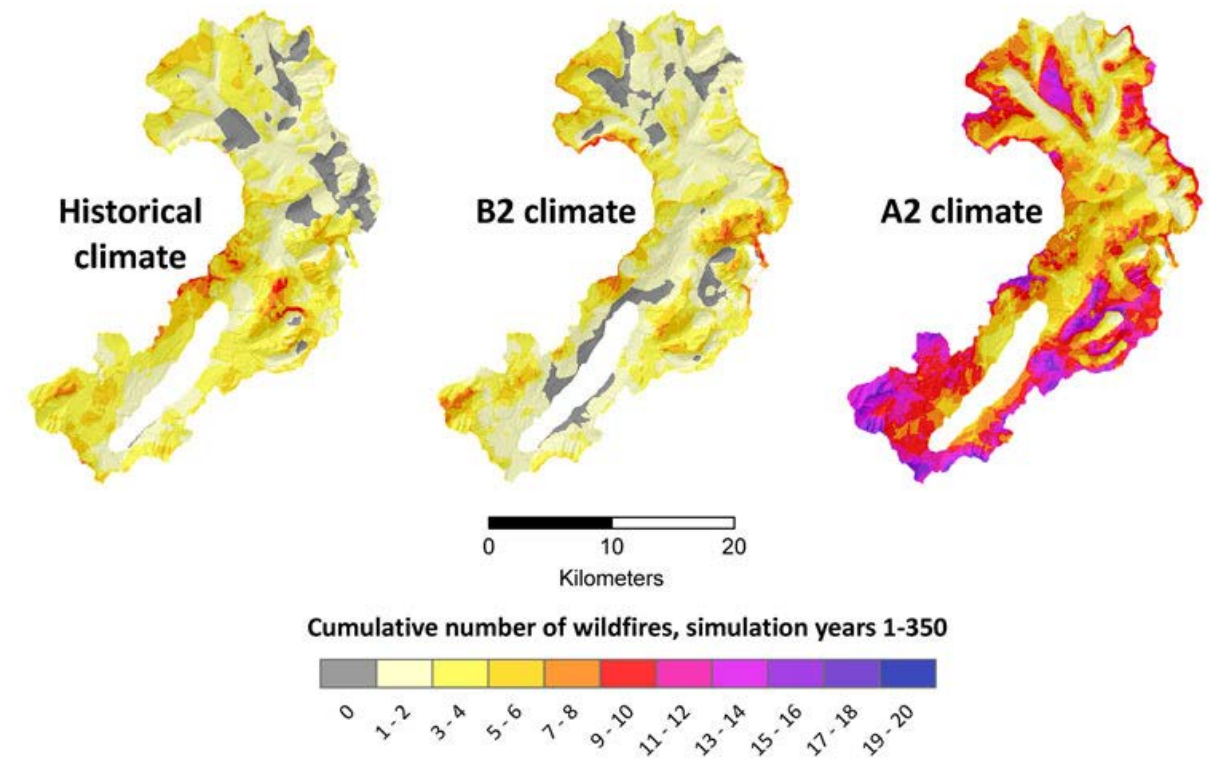

Figure 6.36: Cumulative number of wildfires, based on simulation modeling for on the McDonald drainage of Glacier simulation landscape for historical, B2, and A2 climate scenarios over a 350-year simulation period. Projections for this study region under the B2 scenario are for warmer, wetter summer conditions (+2.1 °C, +24 percent precipitation) and warmer but slightly drier winters (+1.8 °C, -1.0 percent precipitation). The A2 scenario projects hotter, drier summers (+6.7 °C, -34 percent precipitation) and warmer, wetter winters (+2.5 °C, -11 percent precipitation) than at present. From Figure 9 in Loehman et al. 2011.

Chapter 7: Scientific Progress Expected over the Next Decade

Substantial progress has been made in climate change science during the two decades since the Intergovernmental Panel on Climate Change (IPCC) issued its first assessment report in 1990. That IPCC First Assessment Report (FAR) included 10 pages on effects of climate change on ecosystems, none of which included fire (Melillo et al. 1990; Houghton, Callander, and Varney 1992). By the 2007 release of the fourth (AR4) IPCC assessment report (IPCC WG I 2007), much of the overall uncertainty concerning climate change had been resolved, most Earth system components were being included in ever more exacting numerical models, and impacts of climate change were receiving greater attention (IPCC WG II 2007). In the 4 years since the AR4 release, scientific progress in areas of more immediate applicability to fire management has been substantial. More than 40% of the ~ 1000 papers[31] refernced in this synthesis have been published since the release of AR4. With strong consensus answers to most of the scientific questions regarding the basic drivers of global climate change, and models that are continually improving in terms of both process inclusion and spatial-temporal resolution, a greater portion of scientific effort is being directed to ecosystem (including fire) impacts and the climate processes that affect them. We see particular opportunity for scientific advancement in the decade ahead in the areas of: paleo fire history; quantification of burned areas, fire severity, fire emissions, smoke transport and deposition; climate effects on fire regimes; feedbacks of changing fire regimes to climate, carbon and ecosystem processes; climate change forcing of ecoregion change at longer time scales; climate change effects of other ecosystem disturbances, forest health, and invasive species; improved forecasts of annual to interannual climate variability associated with various coupled atmosphere-ocean circulation oscillations such as ENSO (El Nino-Southern Oscillation); and enhancement of ecosystem monitoring capabilities to record climate change impacts (Lowman et al. 2009). These and other areas of scientific progress will combine in different ways to aid managers at the Short (synoptic to seasonal), Intermediate (annual to interannual) and Long (decadal to centennial) time scales discussed in Chapter 5 (McKenzie et al. 2011). These time scales are roughly equivalent to those used for Land Management Planning (LMP), Seasonal to interannual fire planning and incident management and recovery (Simard 1991; Christensen 1989; Lessard 1998; Neary et al. 2000; Hann and Bunnell 2001; Roads et al. 2005).

Expected Scientific Progress for use at Long (decadal to centennial) time scales

Continuing incremental progress is expected in General Circulation Models (GCMs) used for climate change projections, especially in connection with release of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) expected in 2014 (Hulme et al. 2010). In addition to improvement in resolution, inter-model comparability and multiple Earth system processes, a scheduled upgrade of emission factor scenario inputs will be included (Moss et al. 2010; Thomson et al. 2011). Since there appears little likelihood of new international agreements aimed at mitigating climate change, business as usual emissions projections are

[31] The online Fire History and Climate Change bibliographic data base may be accessed at: https://www.zotero.org/groups/jfsp_fire_history_and_climate_change/items/order/creator

increasingly likely to be accurate and of greater utility for long term planning (Schmittner et al. 2008). Increasing accuracy of long-term climate projections will result in better input for ecosystem change projections of what species and distributions future climate is likely to support, including for reanalysis of Bailey ecosystem classifications to adjust them to future climate conditions (Monserud and Leemans 1992; Sala 2000; Iverson and Prasad 2002; Saxon et al. 2005). These projections of future ecosystem composition at the Bailey Division/Province/Sector levels will afford fire managers the opportunity to respond to fire with knowledge of likely post-fire ecosystem response given future climate (Hannah et al. 2002; Fulé 2008; Stephens et al. 2010; Sandel and Dangremond 2011). Higher resolution and broader scale data gained from an increasing array of paleo-fire information sources and information management advances is improving the utility of fire history knowledge. Combining improved long-term climate projections with this improved fire history knowledge of fire-ecosystem changes during similar past climate will greatly help fire managers plan for climate change in areas where paleo-fire information is available (Swetnam 1993; Swetnam et al. 1998; Grissino Mayer and Swetnam 2000; Whitlock et al. 2003; Hessl et al. 2004; Schoennagel et al. 2004). For areas of the country where fire history is either not plentiful or where future fire regimes have no historic analogue, managers will gain some advantage by matching future ecosystems in their locale with analogous ecosystems and their historic fire regimes from other regions (Emanuel et al. 1985; Dale et al. 2001; Mouillot et al. 2002; Mouillot and Field 2005).

Expected Scientific Progress for use at Intermediate (annual to interannual) time scales

We expect significant scientific progress at the Intermediate time scale because of improved observation and understanding of the atmosphere-ocean circulation patterns forcing interannual atmospheric variability; prospects of significantly improved climate forecasts at these scales; and major advancements in the understanding of how atmospheric variability at this scale does and does not impact regional scale fire and fire regimes. Scientists have demonstrated teleconnections between variability in fire regimes and oscillating atmosphere-ocean circulation patterns, such as El Nino Southern Oscillation (ENSO) (Simard et al. 1985; Biondi et al. 2001; Hessl et al. 2004; Taylor and Beaty 2005; Kitzberger et al. 2007; Trouet et al. 2006; Le Goff et al. 2007). The observation, understanding and predictability of ENSO and related oscillatory patterns have shown remarkable advancement for a wide variety of climate ecosystem linked processes (Brenner 1991; Trenberth and Hoar 1997; Beckage et al. 2003; Alencar et al. 2006; Benson et al. 2008; Carmona-Moreno et al. 2005; Collins et al. 2010; Goodrick and Hanley 2009; Greenville et al. 2009; Galeotti et al. 2010; Trouet and Taylor 2010; Kasischke et al. 2010; Williams et al. 2010; Yocom et al. 2010; Lean and Rind 2009; Lanning et al. 2010; Dai 2011). The combination of improvements in climate forecasts and quantification of effects of annual to interannual climate variability on fire should yield significant advances for fire planning in the decade ahead.

Expected Scientific Progress for use at Short (synoptic to seasonal) time scales

Advances in climate prediction at Long time scales are not as likely as for the Intermediate scales over the next decade, although decadal prediction is receiving attention (Keenlyside and Ba 2010). At long time scales uncertainty with projections of future GHG emissions resulting from

inability to determine sociopolitical drivers in the advance of international climate change governance outweighs uncertainty associated with the GCMs themselves. However, improvements in our understanding of how ecosystems will respond to future climate change under business as usual emission scenarios are likely to take place. Both ecosystem and satellite based observing systems are building databases to help monitor and describe how ecosystems are responding to ongoing climate change. The potential exists to employ ongoing LANDFIRE updates to focus this ecosystem information on fire regime changes. To achieve this, the fire community needs to assure that LANDFIRE and other nationally consistent efforts developed over the last decade or so are maintained and updated. It would also be beneficial to have a nationally consistent fire regime classification system with agreed to criteria and measurable indicators available for applying more general ecosystem/climate change observation to fire business.

Chapter 8: Recommendations for Managers

Wildland fires will accelerate ecosystem change in many areas of the United States, both in areas where fire has been common and in areas where fire has been largely absent, as fire regimes respond to 21st Century climate change (Flannigan et al. 2009; Krawchuk et al. 2009; Swetnam and Anderson 2008; Mack et al. 2011). As a result fire managers need to plan for increased fire activity (longer fire seasons, more large fires, and increased fire severity) in many areas of the country. The potential for these changes also means that other resource managers, whose focus may be on ecosystem restoration or carbon sequestration, consistently need to incorporate the potential of increased fire activity in their planning efforts. Fire is an important component of both climate change mitigation and adaptation planning (Pan et al. 2011; Littell et al. 2011; National Research Council 2010a; National Research Council 2010b; National Research Council 2010c). 21st Century fuels management includes managing fuels to increase carbon sequestration or reduce carbon losses (mitigation) and to increase ecosystem health and resiliency in a changing environment (adaptation). Because increases in extent and severity of fire events and other disturbances, such as insect-induced mortality and expansion of invasive species, are some of the first impacts of changing climate on ecosystems, they can be viewed as opportunities to accelerate ecosystem adjustments to climate change. For example, by planning for post-fire replanting with climate adapted species managers can foster more rapid adjustment of ecosystems to future climate (Millar et al. 2007). Planning success is more likely when informed by both knowledge of place based fire history and monitoring of climate-driven fire regime change in the context of ecosystem structure and dynamics. Acquisition and maintenance of place-based fire history is best done at the operating unit level, but monitoring is best supported by standardized, nationally agreed to indicators (variables that can be measured) of change that are mapped over time at regional through smaller scales (Bailey Division through Province and Sector). Time and space scale considerations should always be present when applying climate-related information (see discussion in Chapter 5 of this synthesis), particularly for climate model projections. Following Gedalof (2011), we suggest categorization of scale dependent fire applications of climate/weather information at short (synoptic to seasonal), intermediate (annual to interannual) and long (decadal to centennial) time scales.

Progress has been made in the five years since Federal agencies were criticized for slow response to climate change concerns although concerns remain that agency funding and priorities are not aligned (US Government Accountability Office 2007; Littell et al. 2011; US Government Accountability Office 2011). Millar et al. (2007) note in their conclusion *"Although general principles will emerge, the best preparation is for managers and planners to remain informed both about emerging climate science as well as land-use changes in their region, and to use that knowledge to shape effective local solutions."* We fully agree and suggest the foundation for this preparation consists of 1) maintaining an accessible knowledge base of developing climate science information applicable to fire and natural resource management issues; 2) consistently applying fire regime concepts as a bridge between climate change and fire business; 3) monitoring fire regime indicators to quantify change at the Bailey Division and Province level; 4) using and/or developing information relationships based on Bailey's classification to foster sharing of fire related climate information of interest to fire and other natural resource managers; 5) adhering to short, intermediate and long time scale categories to align information about climate/weather change, variability, and patterns with fire information needs; 6) developing

(where absent) and/or updating (where available) fire history information at the local operating unit level as a knowledge base benchmarking future change and 7) continuing to improve the capability of land management planning models to incorporate fire/climate interactions.

Climate Science

- Federal agencies with climate and fire science responsibilities should provide an annually updated review of climate science progress for use by managers
- Managers and scientists should actively incorporate expected progress in climate/weather forecasts associated with ENSO, and other coupled atmosphere-ocean patterns, that drive intermediate scale fire variability into their planning efforts
- Progress in forecasting how climate change will influence future statistical distributions of short scale weather that drives actual fire events, for example Santa Ana winds and lightning activity, is less clear, but managers should actively press scientists for improvement in this arena
- Fire scientists should actively collaborate with scientists working on projected ecosystem vegetation responses to climate change in order to have disturbance fully incorporated in those efforts and to have fuel relevant outputs become available to better inform long time scale fuel management planning
- Fire managers and scientists should become more aware of the growing importance of carbon sequestration as a natural resource management issue and actively develop ways to quantify fire management options for enhancing sequestration and diminishing emissions of carbon by fire

Fire Regimes and Fuel Management

- Scientists should work with managers to agree to a standardized set of measurable fire regime indicators that can be monitored for change and be offered as endpoints for coupling to regional GCM outputs, and to coordinate the development of these indicators with international partners
- Paleofire history knowledge, particularly from tree ring/fire scar studies, is making rapid and significant progress in many geographic areas where fire has been historically important. Managers should actively utilize information advances that help to explain fire regime variability over time and space
- The Monitoring Trends in Burn Severity project and LANDFIRE should be fully supported, both to maintain and update data bases, and for ongoing research for validation and for evaluating and improving methods as appropriate
- Satellite-based fire monitoring data used for global and regional models needs to be developed to include consistent assessment of fire severity and modeling of emissions that takes into account fuel structure, fuel condition (eg. moisture) and fire weather
- Understanding basic concepts of fuels and how to manage them for landscape resilience, and having a way to evaluate effectiveness of fuel treatments, is a good combination for sustainable management at large spatial scales

- Managers should keep in mind the four principles for a fire-safe forest introduced by Agee and Skinner (2005): (1) reduce surface fuels, (2) increase height to live crown, (3) decrease crown bulk density, and (4) retain large trees
- Managers should anticipate and plan for changes in species composition and plant assemblages borne of climate change and other disturbance processes that can affect future fire activity and fire management response. Citations to consider include: Iverson and Prasad (2002); Lenihan et al. (2003); Mouillot et al. (2002); Pausas (1999)

Ecosystem Classification

- The fire community should seek to use and incorporate the Bailey (or similar biophysically based vegetation classification) system, whenever feasible in order to gain access to a broad array of existing and future information and to build information bridges with the larger natural resources community that is increasingly interested in fire
- While climate information at the Province level remains desirable, managers should plan to use Division level climate change information for the immediate future at most locations. Where Province level information is available, the usefulness of the finer scale information should be quantified to justify funding in support of its expanded production
- Fire researchers should work closely with the remote sensing community to ensure that satellite-based vegetation classification systems used for global and regional models include sufficient categorization of vegetation for distinguishing vegetation types (e.g. conifers with dominant crown fire vs. conifers with dominant surface fire regimes)
- Bailey's ecosystem classification system provides a standardized hierarchical method of describing ecosystems which enables the application and interpretation of interaction of climate and ecological processes. This perspective enables assessing the geographic patterns and connection between actions at one scale and effects at another scale
- Ecosystem classification systems are recognized as a valuable tool for translating climate change projections into ecological impacts.

Scale dependent variability and change

- Fire occurs at the nexus of atmosphere-ecosystem interactions and displays variability over a broad range of scales. Managers should work with fire scientists to identify the information they need for short, intermediate, and long time scale planning based on changing fire variability
- Because climate change projections are inherently future statistical distributions of weather, managers should utilize risk assessment methodologies when applying those projections to fire planning
- Planning at scales that are too fine will fail to account for disturbances that arise outside small management units; planning at scales that are too coarse, such as regional scales, will not account for local patterns of spatial and temporal variability and are in danger of applying one-size-fits-all solutions (Heyerdahl 2001)

- Increasing the size of management units to hundreds or thousands of hectares across logical biogeographic entities such as watersheds will improve the likelihood of accomplishing objectives (Smith and Lenhart 1996). For example, large strategically located blocks of forest land subjected to fuel treatments will reduce fire spread more effectively than smaller dispersed units (Finney 2001)

Fire History

- Managers should be familiar with both paleo and contemporary fire history. Fire history reinforces our understanding of the interaction and dependencies of climate, vegetation and fire. Also, the absence of fire can enable changes in plant communities that may or may not be desireable. Further, the absence of fire of may set the stage for more destructive fires by enabling the build-up of fuels

- Managers and planners should consider Native American traditional use of fire in future programs for ecosystem management. This traditional knowledge was based on adaptive practices maintain ecosystems which evolved over millennia

- Because of fire's importance as an ecosystem process at large and small scales, Managers should understand: (1) the response of fires to past, present, and future climate change for global change assessments; and (2) the role of fire in maintaining forest health and promoting ecosystem change for better forest management. Like many types of paleoenvironmental data, information on past fires can be interpreted in climatic terms as well as used as an indicator of how particular ecosystems respond to known climate changes. The benefit of the knowledge of fire history is to both…understand the cause and ecological consequences of climate change

- Managers and planners should seek to understand differences in fire history not only between the east and the west (Domains) but also differences in fire history between Bailey's Divisions and perhaps Provinces

Chapter 9: Conclusions

The over whelming preponderance of scientific evidence is that anthropogenic driven climate change will be significant, inevitable and increasing during the remaining years of the 21st Century and beyond. There is no indication that international actions will produce sufficient reductions of global GHG emissions (particularly CO_2 emissions from fossil fuel consumption) to mitigate projected climate change. There is no credible evidence available to countervail these conclusions.

Fire has been an important component of Earth history for over 420 million years, with historic fire variability well correlated with past climate change and variability. Fire regimes and ecosystem classifications are proven useful means for consolidating fire and ecosystem characteristics and relating them to climate change and variability. Fire regimes and ecosystem pattern and structure will undergo substantial change in response to ongoing 21st Century climate change. The rate of climate change will likely accelerate, resulting in significantly greater change after mid-century. Fire regime change is also likely to accelerate in response to climate, with fire activity increasing for those ecosystems where vegetative growth continues to produce sufficient fuel and where current fuel limited regimes respond to climate change with added fuel accumulation.

Climate is, by definition, the long-term (commonly 30 years) statistical compilation of weather events (commonly observed hourly and reported daily) that helps to shape ecosystems and ecosystem functions, including disturbances such as fire. Ecosystem classification systems are dominated by climatic factors at larger to mid-range scales. Managers should incorporate concepts of change, variability, pattern and scale in their planning to maximize utility of information about atmosphere-ecosystem-fire relationships and how they are changing with climate.

Climate change scaling considerations can be described from a fire perspective as follows. Basic fire event components and processes will not be altered by climate change, but their frequency, amplitude, and duration will. In differing ways at differing locations the type and condition of fuels, frequency of ignition, length of fire season, period of high fire danger rating and other traditional fire business metrics will change the short term (seasonal) probability characteristics of fire regimes, including the behavior and ecosystem impacts of fires. There is also growing evidence that a likely consequence of climate change will be changes in occurrence patterns of daily (synoptic scale) weather systems, such as Santa Ana winds, that are a predominant factor in certain fire regimes and the basis for synoptic weather pattern classifications that inform modern fire weather forecasting. Managers can expect significant increases of climate variability information needed to better inform seasonal fire probability projections and can expect to begin to receive projections of future changes in Santa Ana and similar dominant fire weather patterns resulting from climate change.

Fire history and other fire science studies are providing increasing evidence of the importance of natural climate variability, as personified by the El Nino Southern Oscillation (ENSO) coupled atmosphere-ocean circulation pattern, to fire at Intermediate (annual to interannual) time scales. Climate scientists are in turn developing strong evidence that climate change is altering the frequency, amplitude and persistence of these naturally occurring examples of climate variability. As a result we are experiencing more frequent, higher amplitude and longer lasting

episodes of heat waves and drought. Anyone who has had to deal with seasonal and longer term assessments of fire risk is familiar with Palmer Drought Severity Index (PDSI) patterns of fuel desiccation and heightened fire danger that have been an increasing feature of seasonal and longer fire potential outlooks. Managers should actively engage in rapid utilization of improvements in both prediction of ENSO and other patterns of climate variability and knowledge of how they impact fire regime variability.

At long (decadal to centennial) time scales, fire should be viewed more as an ecosystem function that, along with other disturbances, is likely to accelerate ecosystem adjustment to climate change, abruptly alter ecosystem function trajectories (such as carbon sequestration) and ultimately help to determine transitions to future ecosystems for given locations. Holocene fire history is extremely useful for understanding how ecosystems have evolved during past climate change and how ecosystems will evolve in response to ongoing and future climate change, but it is important to recognize that the rates of change may be considerably more rapid than during most perios in the Holocene. Fire managers should have an important role in planning for long-term ecosystem based approaches for adapting to climate change by assuring that the increasing role of fire is included in such planning and in helping to describe how fire management can seek to increase the resilience of existing and future ecosystems in the face of climate change.

Fire management has been on a converging pathway with climate change for more than a Century. One hundred years ago, the seminal events shaping modern fire management and our understanding of how humans are altering our climate began parallel paths that now intertwine and will continue to do so for the rest of this Century and beyond. We now realize that climate change considerations will be prominent for all aspects of fire management as well as for many other aspects of natural resources management impacted by fire. Our understanding of climate change and variability and how they historically relate to fire has grown substantially in recent years. When coupled with advances in climate change science, that understanding provides knowledge to help inform fire management about changes in historic fire activity resulting from longer, hotter, dryer fire seasons with increased ignitions for different ecosystems and fire regimes. For those fire regimes affected by seasonal to multi-year drought, advances in seasonal to interannual prediction of climate variability provide unprecedented opportunities for effective seasonal to multi-year fire planning. Managers will be challenged to adopt this new intermediate scale information in their planning structures. Finally, all managers will be challenged to fully incorporate fire in planning long-term adaptive responses to climate change. The option of restoring future ecosystems to what they once were will simply not exist in the 21st Century. Instead, adapting ecosystems to be fully functional within the bounds of future climate, and getting them there with likely increased fire accelerating the transition, is the challenge to be addressed. Fire and fuel management will be critical components for climate change adaptation, for both traditional fire management objectives and for new climate related emphases such as carbon sequestration. We believe the literature reported in this synthesis supports these conclusions and offers managers a foundation for building their ecosystem specific plans.

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Appendix A – February 2010 Workshop Highlights

We held a Fire History and Climate Change (FHCC) Project Workshop in collaboration with The Wildland Fire Lessons Learned Center and the JFSP Fire and Climate Science (FACS) Project February 9–11, 2010 at NAFRI/Wildland Fire Lessons Learned Center in Tucson, Arizona. A full Workshop Report is on file with the JFSP. Copies can be obtained on request from the authors.

The FHCC Land Manager Workshop sought to engage land managers to help ensure that the proposed syntheses would meet the needs of fire and resource managers and other relevant managers and planners by:

- Ascertaining and evaluating user needs.
- Evaluating approaches to the synthesis projects and draft deliverables.
- Stimulating discussion on how to deal with future climate change and future fire regimes.

We structured the Workshop around 12 Questions. We highlight Workshop outcomes as summarized responses to those 12 Questions, as follows:

Q1. Should we structure this synthesis to meet the needs of managers who have a solid fire management knowledge base–or to meet the needs of a more diverse group of managers who need to consider fire as part of a broader climate change context?

1. Synthesis should include natural resource managers as well as fire managers at different levels and that managers at different levels require different types (complexity) of information.
2. 1-page summaries for policy makers along the lines of the IPCC (Intergovernmental Panel on climate Change) reports.

Q2. Should the synthesis include an overview of the fundamental concepts of climate change science?

1. Include fundamentals of climate change to provide managers basic concepts and terminology and facilitate internal and external discussions relative to land management decisions
2. Fact sheets, brief and to the point, presenting climate change fundamentals with strong graphical descriptions.
    a. Avoid defending climate change science…present basic science.
    b. Address uncertainties–areas where researchers are confident in the science, and areas where they are not

Q3. Considering that General Circulation Models (GCM) and Emissions Scenarios are the basis for climate change predictions–how much effort should be devoted to describing them?

1. Discuss GCM's, depict graphically, and discuss variation in agreement of model results, and refinement in predictive accuracy.
2. More detailed discussion of GCM's and climate modeling could be included in appendix.

Q4. The synthesis will address both "fire history" and "historical fire regimes". What do those concepts mean to you?

1. Clarify and distinguish between the terms "fire history" and "historical fire regimes"
2. fire history is the record of the fire events that have occurred on a specific piece of land, and fire regimes are the ecological processes that have developed over time–the fire cycles in specific vegetation types that are usually measured according to return intervals, seasonality, extent and severity
3. Weather vs. Climate analogy
4. Expand discussion (examples) on fire history and fire regimes
5. Fire history 'what we know', fire regimes as 'what we understand.'
6. Fire regime classification – indicative of what a stand/landscape would look like with a given frequency and severity of fire
7. Historical fire regimes may help characterize areas absent fire records (history).
8. Fires now beyond threshold values, "normal" is changing veg. types.
9. Focusing solely on general patterns may miss unique (significant) events that substantially influence change in veg. and fire regimes.

(This was one of the most intensely discussed topics….there is clearly and wide range of views and understanding on fire history, fire regimes and historical fire regimes. Great care must be made to clearly define these terms and further explain with examples)

Q5. How will improved historical information relating climate to fire regimes help you shape fire and fuel management decisions under climate change?

1. Triage – The synthesis should provide managers a basis upon which to prioritize management actions and treatments to most effectively use the available funding…i.e. won't be able to "fix" everything…what actions will bring the greatest benefit.
2. The synthesis should help in understanding how plastic and adaptable ecosystems were in the past and how they might respond as we move into the future…i.e. how to build future ecosystem resilience…and what is unlikely to succeed.
3. Vegetation model links to climate change…i.e. veg. changes accelerated in changing climate
4. Historically, what were the rates of change in a certain ecosystem, and what will be the probable change rates projected into the future.
5. Investigators were encouraged to provide support/evidence for managers who are going to be explaining to a skeptical public why they are changing management strategy based on climate change.
6. There were concerns that there needs to be recognition of the limitations of using historical information.
7. What is the likely range of variability in future fire regimes…what are the applicable locales?
8. Uncertainty about future conditions may overshadow the role of historical information about a particular system.
9. The synthesis should help to 'daylight' (emphasize) the need for better predictive systems.
10. Systems are highly altered from historical patterns, so big changes in the future are going to result in unknown changes in density and distribution–the mechanisms and processes might be outside of our understanding.

    a. Unprecedented climate conditions suggest our view of "normal" is changing. i.e. Black Saturday Fire of Australia- 2009.

11. Related Topics – Suggest the influence of future climate change and future fire regimes on these topics be addressed in some fashion.
    a. Carbon sequestration and mitigating fire risk
    b. T&E Species
    c. Sensitive Habitats
    d. Biomass (fuels mgmt.) co-generation
    e. Vegetation type conversion thresholds
    f. Lightening regime(locale and frequency) changes
    g. Water/watershed management.

Q6. We have proposed a few structural approaches for use in our synthesis. One involves describing information in terms of "What we know", "What we understand", and "What we expect". Do you consider this useful?

1. Need to clearly define/describe the key terms "what we know" , "what we understand", and "what we expect" …and by extension "what we don't know" or "What we need to know"
2. The Synthesis could include discussion of ecoregions at greatest risk, ecoregions "expected" to experience the greatest ecological change in successional processes.
3. Anecdotal examples (case studies, lessons learned, after action reviews, etc.) of manager experiences describing actions that conducted…what made a difference…and what did not work. (This may be applied in several of the Synthesis chapters).

Q7. We also are proposing to discuss climate/weather and fuels/fire linkages at 3 scales to explain atmosphere–vegetation interaction under climate change. These conceptual scales are "Ecosystem Fuels, Seasonal and Incident". Do you consider this useful? *[This was the most challenging topic for the both Work Groups…and the comments reflect disparate views on how this topic should be handled in the Synthesis….a good deal more discussion is needed to determine how to appropriately incorporate and link (tag) fire history references to the 3 scales…*

1. Short term(incident or event- local fire forecast (subprovince , province)
2. Seasonal-interannual – El Nino, La Nina, PDO (division, province)
3. Climate/climate change - fire regime (domain, division)
4. Clarify distinction between the 3 scales to be used in the Synthesis. Use climate/fire examples to demonstrate and explain the 3 scales…both spatially and temporally.
5. Use of the term 'incident' would be confusing to users who would assume that the synthesis was providing climate information that would be relevant on an individual fire.
6. There was a great deal of discussion of how these scales split spatially and temporally. For example, Santa Ana winds could be described at the incident or seasonal scale. Attendees were not sure how the synthesis would get down to the incident level, or how useful that information would be. Does "event" correspond to "incident"?
7. Most felt that these were categories, not scales. In addition, most attendees felt that the ('event' scale might be better but problems remain there as well). Most agreed that the scales should be clearly defined and perhaps represented visually (showing how a fire can span scales)

8. It was also proposed that the investigators consult with predictive services to coordinate approaches and terms that might be compatible.

Q8. We have proposed synthesizing 'fire history' information for the entire US at the Bailey ecodivision level. Is that a reasonable scale to present information?

1. Synthesis of fire history at the ecodivision level useful as an overarching organizational framework where tied to vegetation classification (plant association groups)
2. Use as fine a level (ecoprovince) as the data permits and scale up to the level (ecodivision) the historical data will allow.
3. Recognize synthesis of fire history at the ecodivision level or even province level may not be useful at the Park or unit level...probably too coarse for practical use by field managers.
4. Include a description of the relationship to LANDFIRE/BEHAVE models, and then let manager's crosswalk the information to fuel type.
5. Several attendees felt the Southeast region should get strong coverage in the synthesis– that is where the most acres are treated

Q9. The amount and type of published fire history information will vary greatly among ecodivisions, such that for some locations (e.g. Arizona) a relatively rich trove of biophysical based knowledge will be available while at other locations (e.g. Maine) we will need to rely more on cultural history sources. For ecodivisions where no specific published literature exists, we will need to rely on interpretation of larger scale information. Is this a reasonable approach?

1. The synthesis is going to be driven by the data and analysis available.
2. OK to use information such as historical journals, naturalist descriptions, anthropological reports etc. absent dendrochronology records, provided a clear description and explanation of the limitations, scales, and uncertainty associated with different sources.
3. Scale down in the southwest (AZ) where fire history data is abundant….scale up in New England (ME) where fire history data is sparse.
4. Supplement data sources with current understanding of prescribed fire processes areas without fire scars as well as information on life histories and plant strategies.

Q10. The synthesis will include extensive review of current literature. How important is it for you to be able to access the original documents we cite in the synthesis? If it is important, do you have the tools needed to access journal and other publications thru bibliographic links?

1. Access to the abstract will be sufficient in most cases.
2. Synthesis needs to provide a basic link to original documents.
3. Hyperlinks change, so there needed to be full references of some type.
4. The Rainbow Series provides an example of a balance between synthesis and references.

Q11. We believe that LANDFIRE data and models can provide useful tools for understanding the relationship between fire and climate change.
1) Is this a reasonable belief?
2) How important would a LANDFIRE link be to you?
3) How should we approach LANDFIRE information in this synthesis?

1. OK to use LANDFIRE data and models for large scale fuel modeling and predictive applications…i.e. ecodivision level and perhaps ecoprovince level in some cases. (Note- some users view underlying vegetation data is incorrect.)
2. LANDFIRE had proved its usefulness in allowing people to work across agency boundaries–at the watershed level for example.
3. LANDFIRE has come under criticism because of its coarseness…some might dismiss this Synthesis as not being valid.
4. Be specific about what LANDFIRE data they were using and why…identify uncertainties in use of data.

Q12. Several questions could be posed that will reveal gaps in knowledge. For example the following questions were recently posed (D. Petersen):
Scientific Questions
a. Are fire area and fire severity changing as a result of a warmer climate?
b. Will fire regimes change in response to a warmer climate?
c. What will be the relative roles of climate and fuels as limiting factors?
d. How will spatial and temporal patterns of wildfire be affected by warmer climate?
Management Questions
e. How will a warmer climate affect fuel treatments and silviculture?
f. Are different fire management strategies needed in a warmer climate?
g.Would it be of value for this synthesis to include a knowledge needs section highlighting questions/issues of importance that are only partially addressed or unaddressed by existing literature?

1. These are important questions that should be addressed in the synthesis, and these brought out a number of important points for the investigators to keep in mind while building the synthesis. Using these questions would help to broaden research by spurring more comprehensive questions about changes in vegetation distribution and patterns, successional trends and vegetation types.
    a. How you propose your confidence intervals around your answers to these questions will be important – that is where the important information lies.
    b. Show managers how to understand the questions, synthesize, and develop answers for themselves in relation to their own unit would be key (e.g. you are seeing changes in the fuels, how does that affect planning?)
    c. "If you can answer these questions, great–you know where you are going."
2. Need to discuss social aspects of climate change and how it relates to land management. Look at the LTER projects for ideas on how to incorporate the social dimensions.
3. These questions emphasize global warming…and that not all places will be warming. Also, some felt that question c needed to be reworded. Investigators were again cautioned to be clear about what was not known in relation to these questions as well and to not shy away from the 'we have no idea' answer.

Workshop attendees provided very valuable insight and guidance that strongly shaped the direction of this synthesis. We gratefully acknowledge their help by listing the attendees of the Workshop and their affiliations at that time:

- Erica Bigio – University of Arizona
- Time Brown – Desert Research Institute (DRI)
- Peter Brown – Rocky Mountain Tree Ring Research (RMTRR)
- Ed Brunson – Bureau of Indian Affairs
- Tony Caprio – National Park Service
- Stan Coloff – George Mason University
- Susan Conard – George Mason University
- Donald Falk – University of Arizona
- Calvin Farris – National Park Service
- Anne Fege – San Diego county Museum
- Gregg Garfin – University of Arizona
- Mark Kaib – US Fish and Wildlife Service
- Mary Lata – US Forest Service
- Josh McDaniel – Wildland Fire Lessons Learned Center
- Donald McKenzie – US Forest Service
- Ted Milesneck – Bureau of Land Management
- Jan Passek – US Fish and Wildlife Service
- Matt Rollins – US Geological Survey
- Leslie Sekavic – US Forest Service
- Randall Smith – US Forest Service
- Bill Sommers – George Mason University
- Cathy Stewart – US Forest Service
- Elaine Kennedy Sutherland – US Forest Service
- Tom Swetnam – University of Arizona
- Michael Van Dyck – US Forest Service
- Amy Waltz – The Nature Conservancy
- Craig Wilcox – US Forest Service
- Tom Zimmerman – US Forest Service

Appendix B – Glossary of Terms

This Glossary of Terms provided below is a limited selection of terms accessed from:

- Glossary of Terms used in the IPCC Fourth Assessment Report, Intergovernmental Panel on Climate Change (**IPCC**) 2007 (http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf)
- Glossary of Wildland Fire Terminology, PMS 205, National Wildfire Coordinating Group (**NWCG**) 2011 (http://www.nwcg.gov/pms/pubs/glossary/index.htm)
- Glossary of Meteorology, Second Edition, American Meteorological Society (**AMS**) 2000 (http://www.ametsoc.org/memb/onlinemembservices/online_glossary.cfm)

We recommend that readers access those original sources for terms not included below or for more in depth descriptions of terminology.

Aerosols A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 µm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds (see Indirect aerosol effect).

Albedo The fraction of *solar radiation* reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Atlantic Multi-decadal Oscillation (AMO) A multi-decadal (65 to 75 year) fluctuation in the North Atlantic, in which *sea surface temperatures* showed warm phases during roughly 1860 to 1880 and 1930 to 1960 and cool phases during 1905 to 1925 and 1970 to 1990 with a range of order 0.4°C.

Anthropogenic Emissions Emissions (see **Emissions** below) to the atmosphere of gases *(and aerosols)* as a result of human activity.

Atmosphere The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% *volume mixing ratio*) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active *greenhouse gases* such as *carbon dioxide* (0.035% volume mixing ratio) and *ozone*. In addition, the atmosphere contains the greenhouse gas water vapor, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and *aerosols*.

Available Fuel That portion of the total fuel that would actually burn under various environmental conditions.

Biomass The total mass of living organisms in a given area or volume; dead plant material can be included as dead biomass.

Biome A biome is a major and distinct regional element of the *biosphere*, typically consisting of several *ecosystems* (e.g. *forests*, rivers, ponds, swamps within a *region*). Biomes are characterized by typical communities of plants and animals.

Black carbon (BC) Operationally defined *aerosol* species based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of *soot*, *charcoal* and/or possible light absorbing refractory organic matter

Burn Severity A qualitative assessment of the heat pulse directed toward the ground during a fire. Burn severity relates to soil heating, large fuel and duff consumption, consumption of the litter and organic layer beneath trees and isolated shrubs, and mortality of buried plant parts.

Carbon cycle The term used to describe the fl ow of carbon (in various forms, e.g., as *carbon dioxide*) through the *atmosphere*, ocean, terrestrial *biosphere* and *lithosphere*.

Carbon dioxide (CO_2) A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning *biomass* and of *land use* changes and other industrial processes. It is the principal *anthropogenic greenhouse gas* that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a *Global Warming Potential* of 1.

Carbon Dioxide (CO_2) A colorless, odorless, nonpoisonous gas, which results from fuel combustion and is normally a part of the ambient air.

Charcoal Material resulting from charring of *biomass*, usually retaining some of the microscopic texture typical of plant tissues; chemically it consists mainly of carbon with a disturbed graphitic structure, with lesser amounts of oxygen and hydrogen (Charlson and Heintzenberg, 1995, p. 402). See *Black carbon*; *Soot*.

Climate Climate in a narrow sense is usually defi ned as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defi ned by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*. In various chapters in this report different averaging periods, such as a period of 20 years, are also used.

Climate The prevalent or characteristic meteorological conditions of any place or region, and their extremes.

Climate The slowly varying aspects of the atmosphere–hydrosphere–land surface system.
It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities. Climatic classifications include the spatial variation of these time-averaged variables. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate has broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability. *See also* climate system, climatology, climate change, climatic classification.

Climate Class In NFDRS, one of four classifications of general climate of an area.

Climate change Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or *external forcings*, or to persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*. Note that the *Framework Convention on Climate Change* (UNFCCC), in its Article 1, defines *climate change* as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and *climate variability* attributable to natural causes. See also *Climate variability; Detection and Attribution*.

Climate change Any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer. Climate change may be due to natural external forcings, such as changes in solar emission or slow changes in the earth's orbital elements; natural internal processes of the climate system; or anthropogenic forcing.

Climate model (spectrum or hierarchy) A numerical representation of the *climate system* based on the physical, chemical and biological properties of its components, their interactions and *feedback* processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a *spectrum* or *hierarchy* of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical *parametrizations* are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology (see Chapter 8). Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual *climate predictions*.

Climate prediction A climate prediction or *climate forecast* is the result of an attempt to produce an estimate of the actual evolution of the *climate* in the future, for example, at seasonal, interannual or long-term time scales. Since the future evolution of the *climate system* may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also *Climate projection*; *Climate scenario*; *Predictability*.

Climate projection A *projection* of the response of the *climate system* to *emission or concentration scenarios* of *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, often based upon simulations by *climate models*. Climate projections are distinguished from *climate predictions* in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial *uncertainty*.

Climate scenario A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of *anthropogenic climate change*, often serving as input to impact models. *Climate projections* often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A *climate change scenario* is the difference between a climate scenario and the current climate.

Climate shift or climate regime shift An abrupt shift or jumpin mean values signalling a change in *regime*. Most widely used in conjunction with the 1976/1977 climate shift that seems to correspond to a change in *El Niño-Southern Oscillation* behavior.

Climate system The climate system is the highly complex system consisting of fi ve major components: the *atmosphere*, the *hydrosphere*, the *cryosphere*, the land surface and the *biosphere*, and the interactions between them. The climate system evolves in time under the infl uence of its own internal dynamics and because of *external forcings* such as volcanic eruptions, solar variations and *anthropogenic* forcings such as the changing composition of the atmosphere and *land use change*.

Climate system The system, consisting of the atmosphere, hydrosphere, lithosphere, and biosphere, determining the earth's climate as the result of mutual interactions and responses to external influences (forcing). Physical, chemical, and biological processes are involved in the interactions among the components of the climate system.

Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all *spatial and temporal scales* beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (*internal variability*), or to variations in natural or *anthropogenic external forcing* (*external variability*). See also *Climate change*.

Climate variability The temporal variations of the atmosphere– ocean system around a mean state. Typically, this term is used for timescales longer than those associated with synoptic weather events (i.e., months to millennia and longer). The term "natural climate variability" is further used to identify climate variations that are not attributable to or influenced by any activity related to humans.

Combustion The rapid oxidation of fuel in which heat and usually flame are produced. Combustion can be divided into four phases: preignition, flaming, smoldering, and glowing.

Combustion Efficiency The relative amount of time a fire burns in the flaming phase of combustion, as compared to smoldering combustion. A ratio of the amount of fuel that is consumed in flaming combustion compared to the amount of fuel consumed during the smoldering phase, in which more of the fuel material is emitted as smoke particles because it is not turned into carbon dioxide and water.

Combustion Period Total time required for a specified fuel component to be completely consumed.

Combustion Rate Rate of heat release per unit of burning area per unit of time. *see also:* Reaction Intensity

Condition Class Depiction of the degree of departure from historical fire regimes, possibly resulting in alternations of key ecosystem components. These classes categorize and describe vegetation composition and structure conditions that currently exist inside the Fire Regime Groups. Based on the coarse-scale national data, they serve as generalized wildfire rankings. The risk of loss of key ecosystem components from wildfires increases from Condition Class 1 (lowest risk) to Condition Class 3 (highest risk). *synonym:* Fire Regime Current Condition Class

Condition of Vegetation Stage of growth or degree of flammability of vegetation that forms part of a fuel complex. Herbaceous stage is at times used when referring to herbaceous vegetation alone. In grass areas minimum qualitative distinctions for stages of annual growth are usually green, curing, and dry or cured.

Consumption The amount of a specified fuel type or strata that is removed through the fire process, often expressed as a percentage of the preburn weight.

Continental Climate Climate that is characteristic of the interior of a land mass of continental size, marked by large annual diurnal and day-to-day ranges of temperature, low relative humidity and irregular precipitation.

Crown Cover The ground area covered by the crown of a tree as delimited by the vertical projection of its outermost perimeter.

Crown Fire A fire that advances from top to top of trees or shrubs more or less independent of a surface fire. Crown fires are sometimes classed as running or dependent to distinguish the degree of independence from the surface fire.

Drought In general terms, drought is a 'prolonged absence or marked deficiency of precipitation, a deficiency that results in water shortage for some activity or for some group', or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance' (Heim, 2002). Drought has been defined in a number of ways. *Agricultural drought* relates to moisture deficits in the topmost 1 meter or so of soil (the root zone) that affect crops, *meteorological drought* is mainly a prolonged deficit of precipitation, and *hydrologic drought* is related to below-normal streamflow, lake and groundwater levels. A *megadrought* is a long drawn out and pervasive drought, lasting much longer than normal, usually a decade or more.

Ecosystem An interacting natural system including all the component organisms together with the abiotic environment and processes affecting them.

El Niño-Southern Oscillation (ENSO) The term *El Niño* was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled *atmosphere*-ocean phenomenon, with preferred time scales of two to about seven years, is collectively known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the *sea surface temperatures* in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific *region* and in many other parts of the world, through global *teleconnections*. The cold phase of ENSO is called *La Niña*.

Emission A release of combustion gases and aerosols into the atmosphere.

Emission Factor (EFp) The mass of particulate matter produced per unit mass of fuel consumed (pounds per ton, grams per kilogram).

Emission scenario A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., *greenhouse gases*, *aerosols*), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. *Concentration scenarios*, derived from emission scenarios, are used as input to a *climate model* to compute *climate projections*. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) new emission scenarios, the so-called SRES scenarios, were published, some of which were used, among others, as a basis for the climate projection. For the meaning of some terms related to these scenarios, see *SRES scenarios*.

Emission Rate The amount, or mass of smoke produced per unit of time. For example: Emission Rate = Available Fuel x Burning Rate x Emission Factor.

Ensemble A group of parallel model simulations used for *climate projections*. Variation of the results across the ensemble members gives an estimate of *uncertainty*. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal *climate variability*, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty than is possible with traditional multi-model ensembles.

Energy Release Component (ERC) The computed total heat release per unit area (British thermal units per square foot) within the flaming front at the head of a moving fire.

External forcing External forcing refers to a forcing agent outside the *climate system* causing a change in the climate system. Volcanic eruptions, solar variations and *anthropogenic* changes in the composition of the *atmosphere* and *land use change* are external forcings.

Fine Fuels Fast-drying dead or live fuels, generally characterized by a comparatively high surface area-tovolume ratio, which are less than 1/4-inch in diameter and have a timelag of one hour or less. These fuels (grass, leaves, needles, etc.) ignite readily and are consumed rapidly by fire when dry. *see also:* Flash Fuels

Fire Rapid oxidation, usually with the evolution of heat and light; heat fuel, oxygen and interaction of the three.

Fire Behavior The manner in which a fire reacts to the influences of fuel, weather, and topography.

Fire Business The characterization of fire occurrence in an area, described in terms of total number of fires and acres per year; and number of fires by time, size, cause, fire-day, large fire-day, and multiple fire-day.

Fire Climate Composite pattern of weather elements over time that affect fire behavior in a given region.

Fire Climax Plant community maintained by periodic fires.

Fire Concentration (Complex) Generally, a situation in which numerous fires are burning in a locality. 2 More specifically, the number of fires per unit area or locality for a given period, generally a year.

Fire Danger Sum of constant danger and variable danger factors affecting the inception, spread, and resistance to control, and subsequent fire damage; often expressed as an index.

Fire Danger Index A relative number indicating the severity of wildland fire danger as determined from burning conditions and other variable factors of fire danger.

Fire Danger Rating A fire management system that integrates the effects of selected fire danger factors into one or more qualitative or numerical indices of current protection needs.

Fire Danger Rating System The complete program necessary to produce and apply fire danger ratings, including data collection, data processing, fire danger modeling, communications, and data storage. *see also:* National Fire Danger Rating System

Fire Dependent Plants and vegetation communities which have evolved adaptations such as a reliance on fire as a disturbance agent, protection as a species against the effects of wildland fire, or even a strengthening or enhancement by it.

Fire Ecology The study of the effects of fire on living organisms and their environment.

Fire Effects **T**he physical, biological, and ecological impacts of fire on the environment.

Fire Environment The surrounding conditions, influences, and modifying forces of topography, fuel, and weather that determine fire behavior.

Fire Frequency A general term referring to the recurrence of fire in a given area over time.

Fire Interval The number of years between two successive fire events for a given area; also referred to as fire-free interval or fire-return interval.

Fire Management Activities required for the protection of burnable wildland values from fire and the use of prescribed fire to meet land management objectives.

Fire Planning Systematic technological and administrative management process of designing organization, facilities, and procedures, including fire use, to protect wildland from fire.

Fire Potential The likelihood of a wildland fire event measured in terms of anticipated occurrence of fire(s) and management's capabiltiy to respond. Fire potential is influenced by a sum of factors that includes fuel conditions (fuel dryness and/or other inputs), ignition triggers, significant weather triggers, and resource capability.

Fire Regime Description of the patterns of fire occurrences, frequency, size, severity, and sometimes vegetation and fire effects as well, in a given area or ecosystem. A fire regime is a generalization based on fire histories at individual sites. Fire regimes can often be described as cycles because some parts of the histories usually get repeated, and the repetitions can be counted and measured, such as fire return interval. *see also:* Fire Regime Groups

Fire Regime Current Condition Class A qualitative measure classified into three classes describing the relative degree of departure from historical fire regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings. *see also:* Condition Class

Fire Regime Groups A classification of fire regimes into a discrete number of categories based on frequency and severity. The national, coarse-scale classification of fire regime groups commonly used includes five groups: I - frequent (0-35 years), low severity; II - frequent (0-35 years), stand replacement severity; III - 35-100+ years, mixed severity; IV - 35-100+ years, stand replacement severity; and V - 200+ years, stand replacement severity. *see also:* Fire Regime

Fire Risk 1. The chance of fire starting, as determined by the presence and activity of causative agents. 2 A causative agent. 3 A number related to the potential number of firebrands to which a given area will be exposed during the rating day (National Fire Danger Rating System).

Fire Scar 1. A healing or healed injury or wound to woody vegetation, caused or accentuated by a fire. 2 The mark left on a landscape by fire.

Fire Scar Analysis Analysis of one or more fire scars to determine individual tree fire frequency or mean fire intervals for specified areas.

Fire Season 1. Period(s) of the year during which wildland fires are likely to occur, spread, and affect resources values sufficient to warrant organized fire management activities. 2 A legally enacted time during which burning activities are regulated by federal, state or local authority.

Fire Severity Degree to which a site has been altered or disrupted by fire; loosely, a product of fire intensity and residence time. *see also:* Burn Severity

Fire Triangle Instructional aid in which the sides of a triangle are used to represent the three factors (oxygen, heat, fuel) necessary for combustion and flame production; removal of any of the three factors causes flame production to cease.

Fire Weather Weather conditions which influence fire ignition, behavior, and suppression.

Fire Weather Weather variables, especially wind, temperature, relative humidity, and precipitation, that influence fire starts, fire behavior, or fire suppression.

Fire Weather Forecast A weather prediction specially prepared for use in wildland fire operations and prescribed fire.

Fire Weather Index (FWI) A numerical rating in the Canadian fire danger rating system, based on meteorological measurements of fire intensity in a standard fuel type. (The standard fuel type is representative of jack pine and lodgepole pine.) The FWI is comprised of three fuel moisture codes, covering classes of forest fuel of different drying rates, and two indices that represent rate of spread and the amount of available fuel.

Fireline Intensity 1 The product of the available heat of combustion per unit of ground and the rate of spread of the fire, interpreted as the heat released per unit of time for each unit length of fire edge. The primary unit is Btu

per second per foot (Btu/sec/ft) of fire front. 2 The rate of heat release per unit time per unit length of fire front. Numerically, it is the product of the heat yield, the quantity of fuel consumed in the fire front, and the rate of spread.

Foehn Wind A warm, dry and strong general wind that flows down into the valleys when stable, high pressure air is forced across and then down the lee slopes of a mountain range. The descending air is warmed and dried due to adiabatic compression producing critical fire weather conditions. Locally called by various names such as Santa Ana winds, Devil winds, North winds, Mono winds, etc.

Forest Fire Variously defined for legal purposes (e.g., the State of California Public Resources Code: uncontrolled fire on lands covered wholly or in part by timber, brush, grass, grain, or other flammable vegetation). Types of fires are ground, surface, and crown.

Fuel Any combustible material, especially petroleum-based products and wildland fuels.

Fuel Condition Relative flammability of fuel as determined by fuel type and environmental conditions.

Fuel Management Act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives.

General Circulation Model (GCM) See *Climate model*.

Geologic Time Time as considered in terms of the history of the earth. It is divided into geologic eras, periods, and epochs. Depending on the part of the geologic time scale, increments are as long as tens of millions of years or as short as hundreds of years. In general, geologic time is more finely divided closer to the present.

Greenhouse Effect the heating of the earth's surface by both atmospheric infrared radiation and incoming solar radiation.

Greenhouse effect *Greenhouse gases* effectively absorb *thermal infrared radiation*, emitted by the Earth's surface, by the *atmosphere* itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-*troposphere* system. This is called the *greenhouse effect*. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming *solar radiation*, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a *radiative forcing* that leads to an enhancement of the greenhouse effect, the so-called *enhanced greenhouse effect*.

Greenhouse gas (GHG) Greenhouse gases are those gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specifi c wavelengths within the spectrum of *thermal infrared radiation* emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the *greenhouse effect.* Water vapour (H_2O), *carbon dioxide* (CO_2), nitrous oxide (N2O), methane (CH4) and *ozone* (O3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human made greenhouse gases in the atmosphere, such as the *halocarbons* and other chlorine- and bromine-containing substances, dealt with under the *Montreal Protocol.* Beside CO2, N2O and CH4, the *Kyoto Protocol* deals with the greenhouse gases sulphur hexafl uoride (SF_6), hydrofl uorocarbons (HFCs) and perfl uorocarbons (PFCs).

Greenhouse gases Those gases, such as water vapor, carbon dioxide, ozone, methane, nitrous oxide, and chlorofluorocarbons, that are fairly transparent to the short wavelengths of solar radiation but efficient at absorbing the longer wavelengths of the infrared radiation emitted by the earth and atmosphere. The trapping of

heat by these gases controls the earth's surface temperature despite their presence in only trace concentrations in the atmosphere. Anthropogenic emissions are important additional sources for all except water vapor. Water vapor, the most important greenhouse gas, is thought to increase in concentration in response to increased concentrations of the other greenhouse gases as a result of feedbacks in the climate system.

Haines Index An atmospheric index used to indicate the potential for wildfire growth by measuring the stability and dryness of the air over a fire.

Holocene The Holocene geological epoch is the latter of two *Quaternary* epochs, extending from about 11.6 ka to and including the present.

Incident An occurrence either human-caused or natural phenomenon, that requires action or support by emergency service personnel to prevent or minimize loss of life or damage to property and/or natural resources.

Industrial revolution A period of rapid industrial growth with far reaching social and economic consequences, beginning in Britain during the second half of the eighteenth century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil *carbon dioxide*. In this report the terms *pre-industrial* and *industrial* refer, somewhat arbitrarily, to the periods before and after 1750, respectively.

Keetch-Byram Drought Index (KBDI) An estimate (0-800) of the amount of precipitation (in 100ths of inches) needed to bring the top 8 inches of soil back to saturation. A value of 0 is complete saturation of the soil, a value of 800 means 8.00 inches of precipitation would be needed for saturation. In the 1988 version of NFDRS, outputs of KBDI are used to adjust live and dead fuel loadings.

Land Use Plan A set of decisions that establish management direction for land within an administrative area; an assimilation of land-use-plan-level decisions developed through the planning process regardless of the scale at which the decisions were developed.

Land/Resource Management Plan (L/RMP) A document prepared with public participation and approved by an agency administrator that provides general guidance and direction for land and resource management activities for an administrative area. The L/RMP identifies the need for fire's role in a particular area and for a specific benefit. The objectives in the L/RMP provide the basis for the development of fire management objective and the fire management program in the designated area.

Large Fire For statistical purposes, a fire burning more than a specified area of land e.g., 300 acres. 2 A fire burning with a size and intensity such that its behavior is determined by interaction between its own convection column and weather conditions above the surface.

Lightning Fire Wildfire caused directly or indirectly by lightning.

Long-Range Forecast Fire weather forecast for a period greater than five days in advance.

Long-Term Fire Danger The results of those factors in fire danger affecting long-term planning; involves consideration of past records and conditions and probable future trends.

Long wave (also called planetary wave) With regard to atmospheric circulation, a wave in the major belt of westerlies that is characterized by large length and significant amplitude. The wave length is typically longer than that of the rapidly moving individual cyclonic and anticyclonic disturbances of the lower troposphere. The angular wave number of long waves is generally taken to be from 1 to 5. Compare short wave; see Rossby wave

Macroclimate General large-scale climate of a large area or country as distinguished from smaller scale mesoclimate and microclimate.

Mathematical Model A model that is a quantitative and mathematical representation or simulation which attempts to describe the characteristics or relationship of physical events.

Model A simplified or generalized representation of reality; a description, analogy, picture, or hypothesis to help visualize something that cannot be directly observed.

Medieval Warm Period (MWP) An interval between AD 1000 and 1300 in which some Northern Hemisphere *regions* were warmer than during the *Little Ice Age* that followed.

Modes of climate variability Natural variability of the *climate system*, in particular on seasonal and longer time scales, predominantly occurs with preferred spatial patterns and time scales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called *regimes*, *modes* or *teleconnections*. Examples are the *North Atlantic Oscillation* (NAO), the *Pacifi c-North American pattern* (PNA), the *El Niño-Southern Oscillation* (ENSO), the *Northern Annular Mode* (NAM; previously called Arctic Oscillation, AO) and the *Southern Annular Mode* (SAM; previously called the Antarctic Oscillation, AAO). Many of the prominent modes of climate variability are discussed in section 3.6. See also *Patterns of climate variability*.

National Fire Danger Rating System (NFDRS) A uniform fire danger rating system that focuses on the environmental factors that control the moisture content of fuels. *see also:* Fire Danger Rating System

Normal Fire Season **1** A season when weather, fire danger, and number and distribution of fires are about average. 2 Period of the year that normally comprises the fire season based on historical fire occurrence.

Normalized Difference Vegetation Index (NDVI) A satellite observation-derived value that is sensitive to vegetative growth, measured at 1.1 km (0.6 mile) spatial and 1 week temporal scales.

North Atlantic Oscillation (NAO) The North Atlantic Oscillation consists of opposing variations of barometric pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems

Organic Matter That fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

Organic Soil Any soil or soil horizon containing at least 30% organic matter (e.g., muck, peat).

Orographic Pertaining to, or caused by mountains.

Pacific decadal variability Coupled decadal-to-inter-decadal variability of the atmospheric circulation and underlying ocean in the Pacifi c Basin. It is most prominent in the North Pacific, where fluctuations in the strength of the winter Aleutian Low pressure system co-vary with North Pacific *sea surface temperatures*, and are linked to decadal variations in atmospheric circulation, sea surface temperatures and ocean circulation throughout the whole Pacific Basin. Such fluctuations have the effect of modulating the *El Niño-Southern Oscillation* cycle. Key measures of Pacific decadal variability are the *North Pacific Index (NPI)*, the *Pacific Decadal Oscillation (PDO)* index and the *Inter-decadal Pacific Oscillation (IPO)* index

Palaeoclimate *Climate* during periods prior to the development of measuring instruments, including historic and geologic time, for which only *proxy* climate records are available.

Paleoclimate (Or geological climate) Climate for periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

Palmer Drought Severity Index (PDSI) An index formulated by Palmer (1965) that compares the actual amount of precipitation received in an area during a specified period with the normal or average amount expected during that same period. The PDSI is based on a procedure of hydrologic or water balance accounting by which excesses or deficiencies in moisture are determined in relation to average climatic values. Values taken into account in the calculation of the index include precipitation, potential and actual evapotranspiration, infiltration of water into a given soil zone, and runoff. This index builds on Thornthwaite's work (1931, 1948), adding 1) soil depth zones to better represent regional change in soil water-holding capacity; and 2) movement between soil zones and, hence, plant moisture stress, that is, too wet or too dry.

Permafrost A short term for "permanently frozen ground"; any part of the earth's crust, bedrock, or soil mantle that remains below 32° F (0° C) continuously for a number of years.

Projection A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from *predictions* in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial *uncertainty*.

Radiative forcing Radiative forcing is the change in the net, downward minus upward, irradiance (expressed in W m^{-2}) at the *tropopause* due to a change in an external driver of *climate change*, such as, for example, a change in the concentration of *carbon dioxide* or the output of the Sun. Radiative forcing is computed with all tropospheric properties held fi xed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called *instantaneous* if no change in stratospheric temperature is accounted for. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with *cloud radiative forcing*, a similar terminology for describing an unrelated measure of the impact of clouds on the irradiance at the top of the *atmosphere*.

Rate of Spread The relative activity of a fire in extending its horizontal dimensions. It is expressed as rate of increase of the total perimeter of the fire, as rate of forward spread of the fire front, or as rate of increase in area, depending on the intended use of the information. Usually it is expressed in chains or acres per hour for a specific period in the fire's history.

Red Flag Warning Term used by fire weather forecasters to alert forecast users to an ongoing or imminent critical fire weather pattern.

Regime A regime is preferred states of the *climate system*, often representing one phase of dominant patterns or *modes of climate variability*.

Risk 1 The chance of fire starting as determined by the presence and activity of causative agents. 2 A chance of suffering harm or loss. 3 A causative agent. 4 (NFDRS) A number related to the potential of firebrands to which a given area will be exposed during the rating day.

Risk Management (RM) A continuous, five-step process that provides a systematic method for identifying and managing the risks associated with any operation.

Rossby wave (Also called planetary wave) A wave on a uniform current in a two-dimensional nondivergent fluid system, rotating with varying angular speed about the local vertical (beta plane). A stationary Rossby wave is thus of the order of the distance between the large-scale semipermanent troughs and ridges in the middle troposphere. The Rossby wave moves westward relative to the current, in effect slowing the eastward movement of long-wave components relative to the short-wave components in a barotropic flow. See long wave.

Scenario A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from *projections*, but are often based on additional information from other sources, sometimes combined with a *narrative storyline*. See also *SRES scenarios*; *Climate scenario*; *Emission scenario*.

Significant Fire Event An event measured by the occurrence of fire(s) that requires mobilization of additional resources from outside the fire event area.

Significant Fire Potential **T**he likelihood a wildland fire event will require mobilization of additional resources from outside the area in which the fire situation originates.

SRES scenarios SRES scenarios are *emission scenarios* developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the *climate projections*.

Solar radiation Electromagnetic radiation emitted by the Sun. It is also referred to as *shortwave radiation*. Solar radiation has a distinctive range of wavelengths (spectrum) determined by the temperature of the Sun, peaking in visible wavelengths. See also: *Thermal infrared radiation*, *Insolation*.

Stand Replacing Fire Fire which kills all or most of the living overstory trees in a forest and initiates forest succession or regrowth. Also explicitly describes the nature of fire in grasslands and some shrublands.

Synoptic Literally, at one time. Thus, in meteorological usage, the weather conditions over a large area at a given point in time.

Synoptic 1. In general, pertaining to or affording an overall view. In meteorology, this term has become somewhat specialized in referring to the use of meteorological data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and nearly instantaneous picture of the state of the atmosphere. Thus, to a meteorologist, "synoptic" takes on the additional connotation of simultaneity. 2. A specific scale of atmospheric motion with a typical range of many hundreds of kilometers, including such phenomena as cyclones and tropical cyclones.

Synoptic Chart In meteorology, any chart or map on which data and analyses are presented that describe the state of the atmosphere over a large area at a given moment in time.

Teleconnection 1. A linkage between weather changes occurring in widely separated regions of the globe. 2. A significant positive or negative correlation in the fluctuations of a field at widely separated points. Most commonly applied to variability on monthly and longer timescales, the name refers to the fact that such correlations suggest that information is propagating between the distant points through the atmosphere.

Total solar irradiance (TSI) The amount of *solar radiation* received outside the Earth's *atmosphere* on a surface normal to the incident radiation, and at the Earth's mean distance from the Sun. Reliable measurements of solar radiation can only be made from space and the precise record extends back only to 1978. The generally accepted value is 1,368 W m−2 with an accuracy of about 0.2%. Variations of a few tenths of a percent are common, usually associated with the passage of *sunspots* across the solar disk. The *solar cycle* variation of TSI is of the order of 0.1% (AMS, 2000). See also *Insolation*.

Uncertainty An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifi able errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative

statements, for example, reflecting the judgment of a team of experts (see Moss and Schneider, 2000; Manning et al., 2004).

United Nations Framework Convention on Climate Change (UNFCCC) The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return *greenhouse gas* emissions not controlled by the *Montreal Protocol* to 1990 levels by the year 2000. The convention entered in force in March 1994.

Variable Any changing characteristic; in statistics, a measurable characteristic of an experimental unit.

Wave A disturbance that transfers energy from one point to another point and may take the form of a deformation of pressure or temperature. In the atmosphere such disturbances may result in major storms or merely result in changes in cloud, wind and temperature conditions. Development of a wave on a front usually slows the advance of the front due to transfer of energy to the wave development and movement.

Wildfire An unplanned, unwanted wildland fire including unauthorized human-caused fires, escaped wildland fire use events, escaped prescribed fire projects, and all other wildland fires where the objective is to put the fire out. *see also:* Uncontrolled Fire Wildland Fire

Wildland An area in which development is essentially non-existent, except for roads, railroads, powerlines, and similar transportation facilities. Structures, if any, are widely scattered.

Wildland Fire Any non-structure fire that occurs in the wildland. Three distinct types of wildland fire have been defined and include wildfire, wildland fire use, and prescribed fire. *see also:* Prescribed Fire Wildfire Wildland Fire Use

Wildland Urban Interface (WUI) The line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels.

Younger Dryas A period 12.9 to 11.6 kya, during the deglaciation, characterized by a temporary return to colder conditions in many locations, especially around the North Atlantic.

Appendix C – Unit Conversion and other Tables

Below are a few Unit Conversion and other Tables, listed under general areas of applicability.

Source: http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=477

SI (Système International) Units

Physical Quantity	Name of Unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
thermodynamic temperature	kelvin	K
amount of substance	mole	mol

SI (Système International) Units *(continued)*

Fraction	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	µ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
			10^{18}	eta	E
			10^{21}	zeta	Z

Special Names and Symbols for Certain SI-Derived Units

Physical Quantity	Name of SI Unit	Symbol for SI Unit	Definition of Unit
force	newton	N	kg m s^{-2}
pressure	pascal	Pa	kg m^{-1} s^{-2} (= N m^{-2})
energy	joule	J	kg m^{2} s^{-2}
power	watt	W	kg m^{2} s^{-3} (= J s^{-1})
frequency	hertz	Hz	s^{-1} (cycles per second)

Non-SI Units

°C degree Celsius (0 °C = 273 K approximately)
ppmv parts per million (10^{6}) by volume
ppbv parts per billion (10^{9}) by volume
pptv parts per trillion (10^{12}) by volume
yr year

Units of mass which have come into common usage

kt kilotonnes (10^{3} tonnes)
GtC gigatonnes of carbon (1 GtC = (10^{9} tonnes C = 3.67 Gt carbon dioxide)
PgC petagrams of carbon (1 PgC = 1 GtC)
MtC megatonnes (10^{6} tonnes) of carbon
TgC teragrams of carbon (1 TgC = 1 MtC)

Decimal Fractions and Multiples of SI Units Having Special Names

Physical Quantity	Name of SI Unit	Symbol for SI Unit	Definition of Unit
length	ångstrom	Å	10^{-10} m = 10^{-8} cm
length	micron	µm	10^{-6} m
area	hectare	ha	10^{4} m^2
force	dyne	dyn	10^{-5} N
pressure	bar	bar	10^{5} N m^{-2} = 10^{5} Pa
pressure	millibar	mb	10^{2} N m^{-2} = 1 hPa
mass	tonne	t	10^{3} kg
mass	gram	g	10^{-3} kg

Conversion Factors for Mass

To:	kg	t	lt	st	lb
From:	*multiple by:*				
kilogram (kg)	1	0.001	9.84×10^{-4}	1.102×10^{-3}	2.2046
tonne (t)	1000	1	0.984	1.1023	2204.6
long ton (lt)	1016	1.016	1	1.120	2240.0
short ton (st)	907.2	0.9072	0.893	1	2000.0
Pound (lb)	0.454	4.54×10^{-4}	4.46×10^{-4}	5.0×10^{-4}	1

Conversion Factors for Volume

To:	**gal US**	**gal UK**	**bbl**	**ft^3**	**l**	**m^3**
From:	*Multiple by:*					
US Gallon (gal)	1	0.8327	0.02381	0.1337	3.785	0.0038
UK Gallon (gal)	1.201	1	0.02859	0.1605	4.546	0.0045
Barrel (bbl)	42.0	34.97	1	5.615	159.0	0.159
Cubic foot (ft^3)	7.48	6.229	0.1781	1	28.3	0.0283
Litre (l)	0.2642	0.220	0.0063	0.0353	1	0.001
Cubic metre (m^3)	264.2	220.0	6.289	35.3147	1000.0	1

Hectare is a metric system area unit which equals to 107639.1 sq feet.
Acre is an imperial area unit which equals to 43560 square feet.
1 Hectare (ha) = 2.47105381 Acres
1 Square Kilometer (km^2) = 1,000,000 m^2 = 100 ha (hectare) = 0.386302 square miles = 247.1 acres

Appendix D – **ZOTERO Bibliographic Data Base**

ZOTERO reference management software is an important feature used throughout this Fire History and Climate Change synthesis project. ZOTERO is used to manage bibliographic information and generate bibliographic (author/title) and bibliographic (with abstract) databases available online and that accompany CD versions of this report.

Zotero Summary

Zotero [zoh-TAIR-oh] is a free, easy-to-use tool to help collect, organize, cite, and share research sources. It lives in the web browser itself.[32] Zotero is an extension for the Firefox web-browser. It runs in its own pane within Firefox, separately from web pages. Zotero is, at the most basic level, a citation manager. It is designed to store, manage, and cite bibliographic references, such as books and articles. In Zotero, each of these references constitutes an item. Every item contains different metadata, depending on what type it is. Items can be everything from books, articles, and documents to web pages, artwork, films, sound recordings, bills, cases, or statutes, among many others. Items appear in the center column. The metadata for that item is in the right column. This includes titles, creators, publishers, dates, and any other data needed to cite the item. The left column includes My Library, which contains all items. Clicking the button above the left column creates a new collection, a folder into which items relating to a specific project or topic can be placed. Collections can also contain sub-collections. Zotero has many other important features that are fully described at the Zotero website (see footnote).

> *"Zotero (pronounced /zoʊˈtɛroʊ/) is free, open source reference management software to manage bibliographic data and related research materials (such as PDFs). Notable features include web browser integration, online syncing, generation of in-text citations, footnotes and bibliographies, as well as integration with the word processors Microsoft Word, LibreOffice and OpenOffice.org Writer. It is produced by the Center for History and New Media of George Mason University (GMU)."*
>
> http://en.wikipedia.org/wiki/Zotero

JFSP Fire History and Climate Change Bibliographic Database – Public Access

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Relative importance of weather and climate on wildfire growth in interior Alaska	
Item Type	Journal Article
Title	Relative importance of weather and climate on wildfire growth in interior Alaska
Author	Abatzoglou, John T.
Author	Kolden, Crystal A.
Abstract	Efforts to quantify relationships between climate and wildfire in Alaska have not yet explored the role of higher-frequency meteorological conditions on individual wildfire ignition and growth. To address this gap, meteorological data for 665 large fires that burned across the Alaskan interior between 1980 and 2007 were assessed to determine the respective influence of higher-frequency weather and lower-frequency climate, in terms of both antecedent and post-ignition conditions on fire growth. Antecedent climate exhibited no discernable influence on eventual fire size. In contrast, fire size was sensitive to weather in the days to weeks following ignition, particularly the post-ignition timing of precipitation. Prolonged periods of warm and dry conditions coincident with blocking that persists for several weeks after ignition enabled growth of large wildfires, whereas the return of wetting precipitation generally within a week after ignition inhibited growth of smaller wildfires. These results suggest that daily weather data are a critical predictor of fire growth and large fire potential and encourage their use in fire management and modeling.
Publication	International Journal of Wildland Fire
Volume	20
Issue	4
Pages	479

Clicking on this link will give you searchable access to nearly 1,000 items compiled for this JFSP Fire History and Climate Project. Here is an example of the information you would obtain by clicking on a typical reference item:

We plan to maintain and periodically update the Fire History and Climate Change ZOTERO bibliographic database for at least one year after project completion. We will maintain future public access through the George Mason University EastFIRE Laboratory website: http://eastfire.gmu.edu

Appendix E - **PATTERNS AND INDICES OF CLIMATE VARIABILITY— Adapted from A. Kaplan**

Source: (Blunden, Arndt, and Baringer 2011) Pages S20 – S25

Climate variability is not uniform in space; it can be described as a combination of some "preferred" spatial patterns. The most prominent of these are known as modes of climate variability, which affect weather and climate on many spatial and temporal scales. The best known and truly periodic climate variability mode is the seasonal cycle. Others are quasi-periodic or of wide spectrum temporal variability. Climate modes themselves and their influence on regional climates are often identified through spatial teleconnections, i.e., relationships between climate variations in places far removed from each other.

For example, Walker (1924) named the Southern Oscillation (SO) and associated its negative phase with Indian monsoon failure. Later, Bjerknes connected negative SO phases with El Niño occurrences episodes of amplified seasonal ocean surface warming in the eastern equatorial Pacific and coastal Peru (Fig. 1.3a). Subsequently, the El Niño—Southern Oscillation (ENSO) was observed to be a powerful, demonstrably coupled tropical ocean-atmosphere variability with a global set of climate impacts. In recent years, ENSO events were separated into canonical (Eastern Pacific) and Central Pacific ENSO events (a.k.a. "Modoki", Fig. 1.3b).

Walker (1924) also noticed a smaller-scale (compared to the SO) seesawing surface pressure between the Azores and Iceland (Fig. 1.3c) and named it the North Atlantic Oscillation (NAO). A positive phase of the NAO strengthens the Atlantic storm track and moves it northward, resulting in warm and wet European winters, and cold and dry winters in Greenland and northeastern Canada. In the negative phase the storm track is weaker and more eastward in direction, resulting in wetter winters in southern Europe and the Mediterranean and a colder northern Europe.

Traditionally, indices of climate variability were defined as linear combinations of seasonally-averaged anomalies from meteorological stations chosen in the proximity of maxima and minima of the target pattern. Since gridded fields of climate variables are now available, appropriate regional averages often replace station data. The strongest teleconnections in a climate field are also identified by pairs of grid points with the strongest anti-correlation. Table 1.1 defines the most prominent modes of large-scale climate variability and the various indices used to define them; changes in these indices are associated with large-scale changes in climate fields. With some exceptions, indices included in Table 1.1 generally have been (1) used by a variety of authors and (2) defined relatively simply from raw or statistically analyzed observations of a single surface climate variable, so that observational datasets longer than a century exist.

Climate variability modes sometimes force other modes of climate variability. For example, a principal component analysis of the North Pacific sea surface temperature (SST) anomaly field (20°N–70°N), relative to the global mean, gives a pattern and index of the Pacific Decadal

Oscillation (PDO), illustrated in Fig. 1.3d. It is different from ENSO but thought to be connected to it through atmospheric bridges and/or internal oceanic wave propagation. Despite being defined with Northern Hemisphere data only and being similar to the simple mean sea level pressure-based North Pacific Index (NPI), the PDO index captures well variability in both hemispheres and is similar to the Interdecadal Pacific Oscillation (IPO).

Principal component analysis of the entire Northern Hemisphere extratropical sea level pressure field identifies a leading mode known as the Northern Annular Mode (NAM) or Arctic Oscillation (AO), which turns out to be very similar to the NAO. The Pacific North American pattern (PNA; Fig. 1.3e) also appears as one of the leading variability patterns in the Northern Hemisphere. A Southern Hemisphere analogue of the NAM is the Southern Annular Mode (SAM, Fig. 1.3f), also referred to as the Antarctic Oscillation (AAO), calculated using mean sea level pressure, 850 hPa, or 750 hPa geopotential height in the extratropical Southern Hemisphere.

Atlantic Ocean meridional circulation is affected by the Atlantic Meridional Oscillation (AMO; Fig. 1.3g), which is indexed by the average Atlantic Ocean SST from which the long-term trend is removed. Regional modes of tropical climate variability were identified in Atlantic and Indian Oceans: Atlantic Niño mode and tropical Atlantic meridional mode, Indian Ocean Basin Mode, and Indian Ocean Dipole mode (Fig. 1.3h-k). These modes dominate SST variability in these regions. The “Cold Ocean-Warm Land” (COWL, Fig. 1.3l) variability is not thought to represent a “true” climate variability mode but has proved very useful for interpreting variations in the hemispheric-scale surface temperature means.

The multiplicity of indices defining the same climate phenomenon arises because no index can achieve a perfect separation of a target phenomenon from all other effects in the real climate system. As a result, each index is affected by many climate phenomena whose relative contributions change with time periods and data used. Limited length and quality of observational record compounds this problem. Thus the choice of indices is always application specific.

Table 1.1: Established indices of climate variability with global or regional influence.

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
El Niño – Southern Oscillation (ENSO) - canonical, Eastern Pacific ENSO	NINO3	SST anomaly averaged over (5°S–5°N, 150°W–90°W)	Cane et al. (1986); Rasmusson and Wallace (1983)	Traditional SST-based ENSO index
	NINO3.4	SST anomaly averaged over (5°S–5°N, 170°W–120°W)	Trenberth (1997)	Used by NOAA to define El Niño/La Niña events. Detrended form is close to the 1st PC of linearly detrended global field of monthly SST anomalies (Deser et al. 2010)
	Cold Tongue Index (CTI)	SSTA (6°N–6°S, 180°–90°W) minus global mean SSTA	Deser and Wallace (1990)	Matches "cold tongue" area, subtracts effect of the global average change
	Troup SOI	Standardized for each calendar month MSLP difference: Tahiti minus Darwin, x10	Troup (1965)	Used by Australian Bureau of Meteorology
	SOI	Standardized difference of standardized MSLP anomalies: Tahiti minus Darwin	Trenberth (1984)	Maximizes signal to noise ratio of linear combinations of Darwin/Tahiti records
	Darwin SOI	Standardized Darwin MSLP anomaly	Trenberth and Hoar (1996)	Introduced to avoid use of the Tahiti record, considered suspicious before 1935.
	Equatorial SOI (EQSOI)	Standard difference of standard MSLP anomalies over equatorial (5°S–5°N) Pacific Ocean; east (130°W–80°W) minus west (90°E–140°E)	Bell and Halpert (1998)	
Central Pacific El Niño (Modoki)	El Niño Modoki Index (EMI)	SSTA: [165°E–140°W, 10°S–10°N] minus ½[110°W–70°W, 15°S–5°N] minus ½[125°E–145°E, 10°S-20°N]	Ashok et al. (2007)	A recently identified ENSO variant: Modoki or Central Pacific El Niño (non-canonical)

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific Decadal and Interdecadal Variability	Pacific Decadal Oscillation (PDO)	1st PC of the N. Pacific SST anomaly field (20°N–70°N) with subtracted global mean	Mantua et al. (1997); Zhang et al. (1997)	
	Intedecadal Pacific Oscillation (IPO)	The 3rd EOF3 of the 13-year low-pass filtered global SST, projected onto annual data	Folland et al. (1999); Power et al. (1999)	
	North Pacific Index (NPI)	SLP (30°N–65°N, 160°E–140°W)	Trenberth and Hurrell (1994)	
North Atlantic Oscillation	Lisbon/Ponta Delgada-Stykkisholmur/ Reykjavik North Atlantic Oscillation (NAO) Index	Lisbon/Ponta Delgada minus Stykkisholmur/ Reykjavik standardized MSLP anomalies	Hurrell (1995)	A primary NH teleconnection both in MSLP and Z500 anomalies (Wallace and Gutzler 1981); one of rotated EOFs of NH Z500 (Barnston and Livezey 1987) . MSLP anomalies can be monthly, seasonal or annual averages. Each choice carries to the temporal resolution of the NAO index produced that way.
	Gibraltar - Reykjavik NAO Index	Gibraltar minus Reykjavik standardized MSLP anomalies	Jones et al. (1997)	
	PC-based NAO Index	Leading PC of MSLP anomalies over the Atlantic sector (20°N–80°N, 90°W–40°E)	Hurrell (1995)	
Annular modes: Arctic Oscillation (AO), a.k.a. Northern Annular Mode (NAM) Index and Antarctic Oscillation (AAO), a.k.a. Southern Annular Mode (SAM) Index	PC-based AO index	1st PC of the monthly mean MSLP anomalies poleward of 20°N	Thompson and Wallace (1998, 2000)	Closely related to the NAO
	PC-based AAO index	1st PC of 850hPa or 700hPa height anomalies south of 20°S	Thompson and Wallace (2000)	
	Grid-based AAO index: 40°S–65°S difference	Difference between normalized zonal mean MSLP at 40°S and 65°S, using gridded SLP analysis	Gong and Wang (1999)	
	Grid-based AAO index: 40°S–70°S difference	Same as above but uses latitudes 40°S and 70°S	Nan and Li (2003)	
	Station-based AAO index: 40°S–65°S	Difference in normalized zonal mean MSLP at 40°S and 65°S, using station data	Marshall (2003)	

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific/North America (PNA) atmospheric teleconnection	PNA pattern index	¼ [Z(20°N, 160°W) - Z(45°N, 165°W) + Z(55°N, 115°W) - Z(30°N, 85°W)], Z is the location's standardized 500 hPa geopotential height anomaly	Wallace and Gutzler (1981)	A primary NH teleconnection both in MSLP and Z500 anomalies
Atlantic Ocean Thermohaline circulation	Atlantic Multidecadal Oscillation (AMO) index	10-yr running mean of de-trended Atlantic mean SST anomalies (0°–70°N)	Enfield et al. (2001)	Called "virtually identical" to the smoothed first rotated N. Atlantic EOF mode
	Revised AMO index	As above, but subtracts global mean anomaly instead of de-trending	Trenberth and Shea (2006)	
Tropical Atlantic Ocean non-ENSO variability	Atlantic Niño Index, ATL3	SSTA (3°S–3°N, 20°W–0°)	Zebiak (1993)	Identified as the two leading PCs of detrended tropical Atlantic monthly SSTA (20°S–20°N): 38% and 25% variance respectively for HadISST1, 1900–2008 (Deser et al. 2010)
	Atlantic Niño Index, PC-based	1st PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)	Deser et al. (2010)	
	Tropical Atlantic Meridional Mode (AMM)	2nd PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)		
Tropical Indian Ocean non-ENSO variability	Indian Ocean Basin Mode (IOBM) Index	The 1st PC of the IO detrended SST anomalies (40°E–110°E, 20°S–20°N)	Deser et al. (2010)	Identified as the two leading PCs of detrended tropical Indian Ocean monthly SSTA (20°S–20°N): 39% and 12% of the variance, respectively, for HadISST1, 1900–2008 (Deser et al. 2010)
	Indian Ocean Dipole mode (IODM), PC-based index	The 2nd PC of the IO detrended SST anomalies (40°E–110° E, 20°S–20°N)		
	Indian Ocean Dipole Mode Index (DMI)	SST anomalies: 50°E–70°E, 10°S–10°N)-(90°E–110°E, 10°S–0°)	Saji et al. (1999)	
Cold Ocean – Warm Land (COWL) Variability	COWL Index	Linear best fit to the field of deviations of NH temperature anomalies from their spatial mean; the COWL pattern itself is proportional to the covariance pattern of the NH spatial mean with these deviations.	Wallace et al. (1995); Thompson et al. (2008)	Useful for removing some effects of natural climate variability from spatially averaged temperature records.

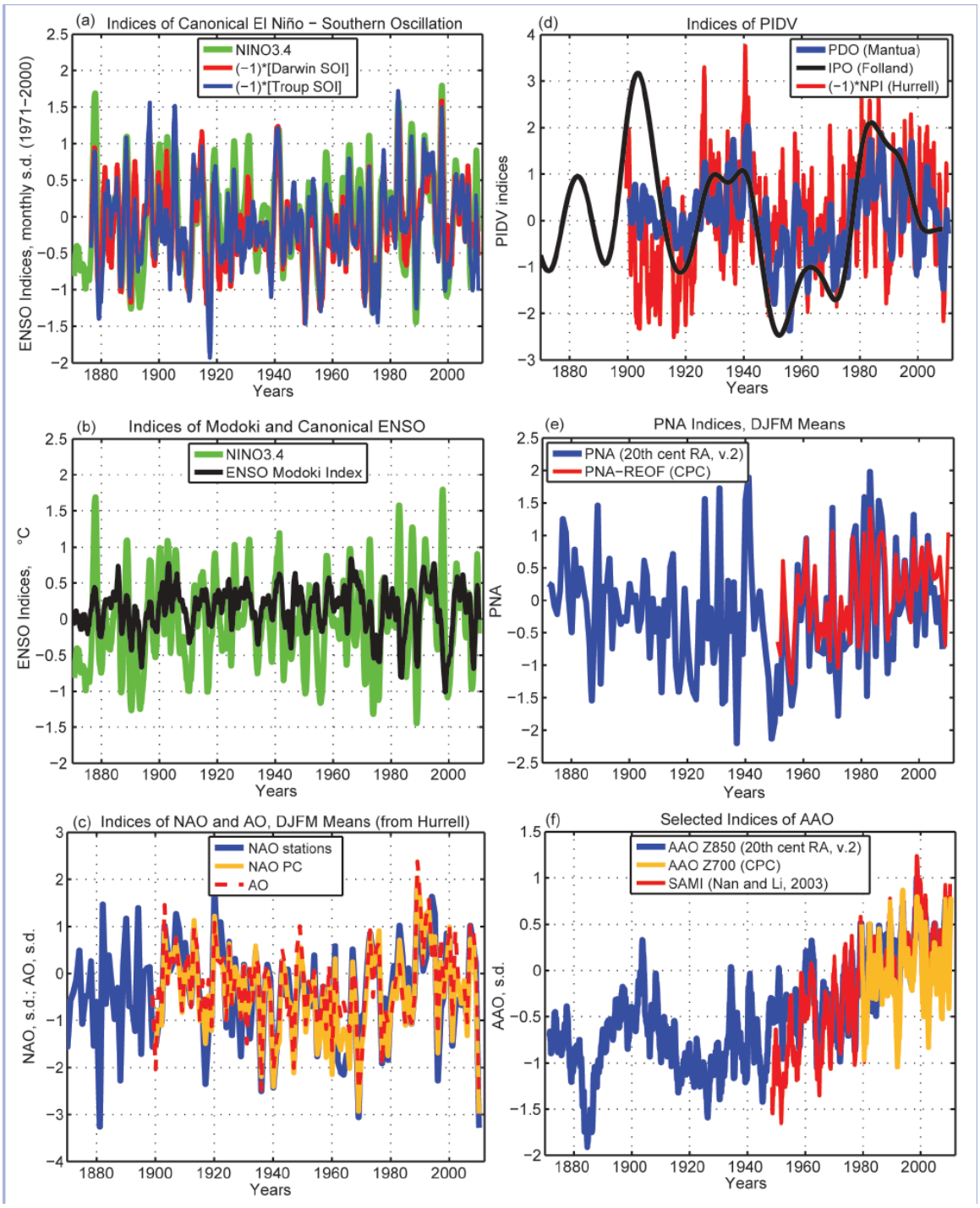
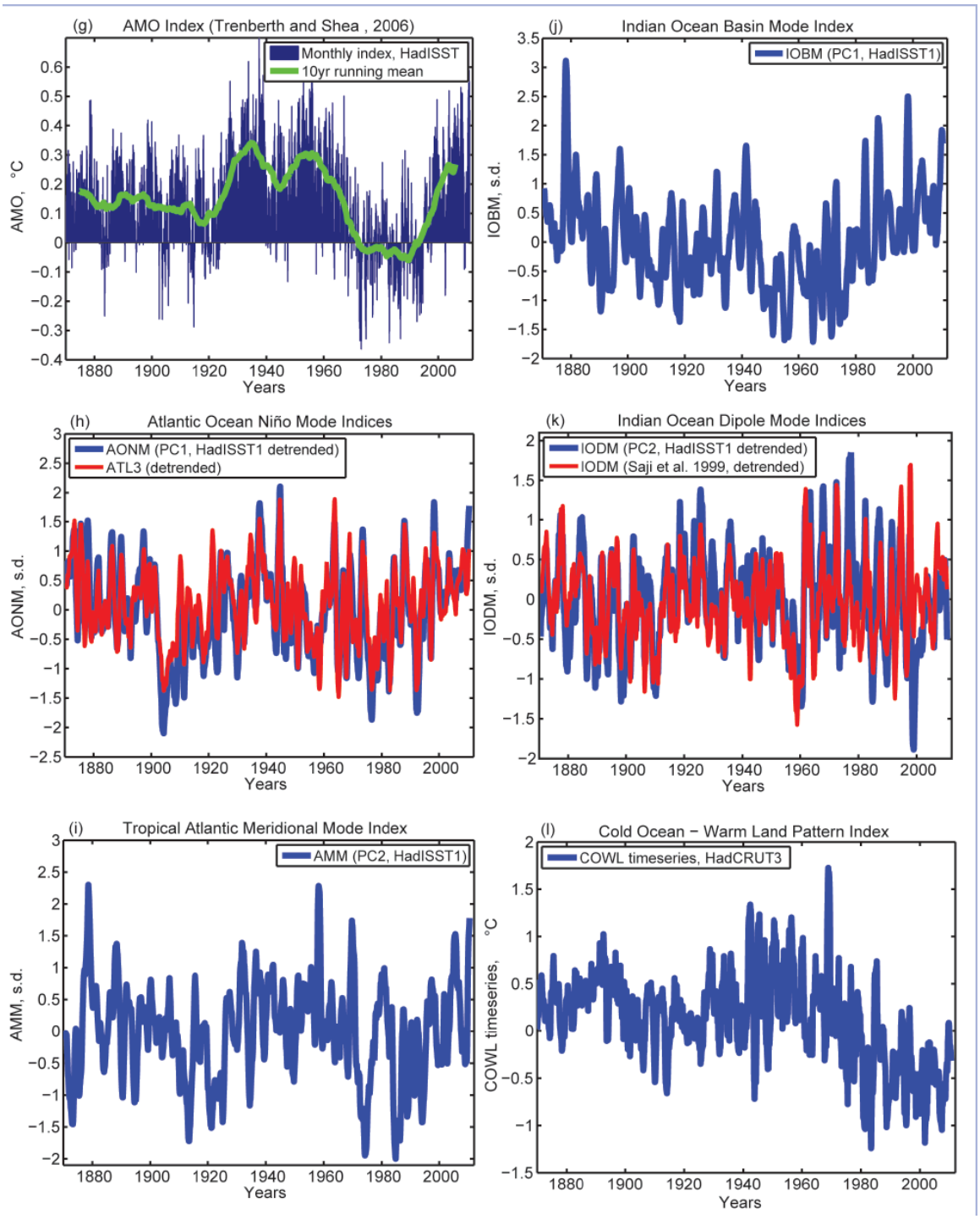


Figure 1. Selected indices of climate variability, as specified in Table 2.3, for the period 1880–2010, grouped into categories: (a) Canonical El Nino -Southern Oscillation (ENSO); (b) the Modoki variant of ENSO; (c) Northern Hemisphere oscillations (NAO, AO, NAM) for the boreal cold season; (d) indices of Pacific Inter-decadal Variability; (e) Pacific-North American indices for the boreal cold season; (f) Southern Hemisphere oscillations (SAM, AAO) for the austral cold season;



(g) Atlantic Meridional Oscillation index; (h) Atlantic Niño Mode indices; (i) Tropical Atlantic Meridional Mode Index; (j) Indian Ocean Basin Mode Index; (k) Indian Ocean Dipole indices; and (l) Cold Ocean— Warm Land pattern. Unless otherwise noted in their panel, 13-month running means of monthly data are shown.

Appendix F – Bailey Descriptions

Geomorphic characteristics and potential natural vegetation for Bailey Ecoprovince Sections in the United States

Adapted and condensed from information at: http://www.fs.fed.us/land/pubs/ecoregions/toc.html (accessed 110919)

This site also includes information for each section on geology, soils, climate, hydrology, fauna, land use, and cultural ecology, as well as appendices with information on species nomenclature, compilers, a glossary, etc.

Additional information, including data, maps, and areas of different vegetation in each section and subsection available at: http://svinetfc4.fs.fed.us/clearinghouse/other_resources/ecosubregions.html

A more general description of sections and how they were delineated is in: GTR_WO-76B (2007) *Description of "Ecological Subregions: Sections of the Conterminous United States": First Approximation*, Compiled by W. H. McNab, et al., which is available for download at the website above.

Arctic Tundra

The area of this Section, located in northern Alaska, is about 19,100 mi2 (49,500 km2).

Section 124A--Coastal Plain

Geomorphology. A relatively smooth plain that gradually ascends from the Arctic Ocean to the adjacent Brooks Range foothills. The area is mantled with Quaternary deposits of alluvial, glacial, and aeolian origin. Permafrost-related terrain features mark local surfaces (e.g., pingos, ice-wedge polygons, frost boils). Small sand dunes irregularly occur along the coast. Essentially, the area is a gently rolling to level, treeless plain with many lakes and rivers. Elevation is less than 660 ft (200 m).

Potential Natural Vegetation. Wet tundra communities dominated by sedges, rushes, mosses, lichens, and willows.

Disturbance Regimes. Disturbance from wildfire is low.

Bering Tundra (Northern)

These Sections, located in western Alaska bordering the Bering Sea, include the islands of St. Lawrence, St. Matthew, and Nuviak. The area of these Sections is about 46,900 mi2 (121,500 km2).

Section 125A--Kotzebue Sound Lowlands

Geomorphology. Flat, poorly drained coastal plains dominated by terraces, low hills, stabilized and active dune fields. The many thaw lakes and sinks are connected by a maze of waterways. Pingos are abundant in the lowland around the Selawik River. Elevation is less than 330 ft (100 m).

Potential Natural Vegetation. Since standing water is almost always present, wet tundra communities consisting of sedge mats predominate. Peat ridges, drainage ways, and polygonal features provide better drainage upon which woody plants like white spruce, willows, alder, and paper birch occur. Black spruce forests are abundant along the Kobuk River, whereas grasses grow on the dunes along the coast.

Section 125B--Yukon-Kuskokwim Delta

Geomorphology. The area is a lake-dotted marshy plain with many low hills of basalt and volcanic cinder cones and craters. Elevation is less than 400 ft (120 m).

Potential Natural Vegetation. Wet tundra communities consisting primarily of sedge mats, moss, and low growing shrubs predominate. Alder, willows, and scattered, stunted spruce and birch grow along the major streams.

Section 126A--Bristol Bay Lowlands

Geomorphology. This Section is a flat-to-rolling moraine and outwash-mantled lowland. The source of the material is from surrounding glaciated mountains. Elevation is generally less than 500 ft (150 m).

Potential Natural Vegetation. Moist and wet tundra meadows are the dominant vegetation. Mosses, sedges, and low-growing shrubs cover most of the area. Alder and willows and, in scattered places, stunted spruce and birch grow along the major rivers and streams.

Brooks Range Tundra - Polar Desert

These sections are in northern Alaska, north of the Arctic Circle. The area of these Sections is about 101,600 mi2 (263,100 km2).

Section M121A--Foothills

Geomorphology. In the northern portion, rock folding and unequal erosion have produced a linear-ridge topography. The sedimentary rocks of the southern portion are tightly folded and form irregular buttes, mesas, and long linear ridges. Hummocky morainal ridges border most north-south valleys. Ice-related features are common (e.g., pingos, solifluction lobes, ice-wedge polygons, stone stripes). The area consists of maturely dissected low hills and ridges that have never been glaciated. Elevation is mainly less than 1,970 ft (600 m).

Potential Natural Vegetation. Moist tundra-cottongrass tussocks are interspersed with willow-dominated communities along river corridors. **Fauna.** Moist tundra communities provide nesting

habitat for several species of sandpiper (e.g., Baird's, stilt, and buff-breasted) and small mammals such as the insular vole. Willow ptarmigan and Alaskan hare inhabit the scattered patches of birch, alder, and willow. Predators include rough-legged hawks, peregrine falcons, gyrfalcons, snowy owls, and Arctic foxes. Wood frogs have been reported north of the Brooks Range. Arctic char and Arctic grayling are found in most rivers and some of the shallow tundra lakes.

Section M121B--Mountains

Geomorphology. Rugged, deeply dissected, east-west trending mountains having rounded-to-sharp summits. Abrupt mountain fronts frequently face northward. Small cirque glaciers occur only on the highest peaks of the Brooks Range. Elevation ranges from 1,640 to 8,530 ft (500 to 2,600 m).

Potential Natural Vegetation. Many of the highest ridges are barren or ice-covered. Alpine tundra heath communities occur on upper and intermediate slopes, whereas moist tundra sedge-tussock meadows with occasional trees prevail on lower slopes. Shrub thickets occur along river corridors.

Seward Peninsula Tundra - Meadow

Located in northwestern Alaska along the Bering Sea, it includes much of the Seward Peninsula and part of St. Lawrence Island. The area of this Section is about 20,600 mi2 (53,400 km2).

Section M125A--Seward Mountains

Geomorphology. The area consists mainly of extensive uplands of broad convex hills and flat divides indented by sharp V-shaped valleys. Isolated groups of glaciated mountains and peaks cover the higher elevation areas. Elevation ranges from sea level to 4,600 ft (1,400 m).

Potential Natural Vegetation. Vegetation patterns consist of moist tundra sedge-tussock meadows at lower elevations, interspersed with scattered willows, birch, and isolated spruce-hardwood forests, particularly along rivers. Alpine tundra heath meadows and barrens dominate the high mountains.

Ahklun Mountains Tundra - Meadow

It is located in southwestern Alaska, bordering the Bering Sea. The area of this Section is about 16,700 mi2 (43,300 km2).

Section M126A---Ahklun Mountains

Geomorphology. A group of rugged steep-walled mountains having sharp summits separated by broad, flat valleys and lowlands. This Section includes the Pribilof Islands. Elevation ranges from sea level to greater than 4,920 ft (1,500 m).

Potential Natural Vegetation. Alpine tundra heath meadows and barrens predominate in the mountains, whereas moist tundra sedge-tussock meadows occur in valley bottoms. Black spruce forest vegetation dominates some hills and ridges. Forests of white spruce, paper birch, and alder cover the low hills along the major rivers.

Aleutian Oceanic Meadow - Heath

These Sections are located in southwestern Alaska, and, as their names describe, include the Alaska Peninsula, Aleutian Islands, and part of Kodiak Island. The area of these Sections is about 22,200 mi2 (57,500 km2).

Section M127A--Alaska Peninsula

Geomorphology. The Aleutian Range consists of rounded east-trending ridges surmounted at intervals by rugged volcanoes. The mountains were heavily glaciated during the Pliestocene epoch. This Section is bordered to the north by the Bristol Bay Lowlands where the Aleutian Mountains become increasingly submerged southwestwardly, forming the Aleutian Islands. Elevation ranges from sea level to 8,530 ft (2,600 m).

Potential Natural Vegetation. The vegetation is primarily alpine tundra heath meadows and barrens, with willow and alder occurring at lower elevations and along drainages.

Section M127B--Aleutian Islands

Geomorphology. The Aleutian Islands are made up of a chain of volcanic islands perched atop the crest of a submarine ridge. Topography varies from wave-beaten level platforms near sea level, to intensely glaciated mountains indented with fjords and bordered by cliffs. The islands gradually emerge above sea level to the northeast forming the Alaska Peninsula. Elevation rises from sea level to greater than 6,230 ft (1,900 m).
Potential Natural Vegetation. Vegetation consists of alpine tundra heath meadows. Lichen communities prevail on windswept ridges. Moist tundra meadows occur at lower elevations and are dominated by grass, sedge, and scattered willows and birch.

Section M127C--West Kodiak Island

Geomorphology. The Kodiak Mountains are mostly glaciated, with broad, smooth ridges that extend northwestward. The coastline is extremely irregular, having many fjords and islands. The western part of the island has many broad U-shaped valleys. Elevation ranges from sea level to 4,270 ft (1,300 m).

Potential Natural Vegetation. The vegetation is primarily alpine tundra heath meadows and barrens with moist and wet sedge meadows occuring at lower elevations. Shrub thickets occur along some drainages.

Province 131--Yukon Intermontane Plateaus Tayga

These Sections are located in central Alaska; their area is about 56,100 mi2 (145,300 km2)

Section 131A--Upper Kobuk Valley

Geomorphology. Diverse topography which includes scattered groups of hills and low mountains surrounded by irregular lowlands and broad flat divides. Elevation ranges from 1,300 to 3,940 ft (400 to 1,200 m).

Potential Natural Vegetation. Closed forests of spruce, birch, and aspen occur on moderately drained to well drained sites. In wetlands, open black spruce forests are often interspersed with willow thickets and treeless bogs.

Section 131B--Yukon-Kuskokwim Bottomlands

Geomorphology. This Section represents a collection of flat bottomlands along the larger rivers of interior Alaska. Although nearly level, broad valleys and basins are typical, some low rolling hills and piedmont slopes do occur. Riparian features, such as meandering streams and side sloughs, are prevalent. Oxbow, thaw, and morainal lakes are abundant. Elevation generally ranges from 400 ft (120 m) in the west to 1,640 ft (500 m) in the east.
Potential Natural Vegetation. Dominant vegetation communities span a moisture gradient from mesic to hydric and include spruce-poplar forests, open black spruce forests, floodplain thickets of willow and alder, and graminoid marsh.

Coastal Trough Humid Tayga

The area of these Sections, which are located in south-central Alaska, is about 15,700 mi2 (40,700 km2).

Section 135A--Cook Inlet Lowlands

Geomorphology. A level-to-rolling surface derived mainly through glacial events (ground moraine, drumlin fields, eskers, and outwash plains). Elevation ranges from sea level to 500 ft (150 m).

Potential Natural Vegetation. Lowland black spruce forests are abundant. Bottomland spruce-poplar forests are adjacent to larger river drainages, along with thickets of alder and willow. Some wet tundra communities exist along the Cook Inlet coastline.

Section 135B--Copper River Basin

Geomorphology. The area is a broad basin of rolling-to-hilly moraines and nearly level alluvial plains that occupy the site of a Pleistocene glacial lake. Most rivers originate from glaciers located in the surrounding mountains. Elevation ranges from 1,380 to 2,950 ft (420 to 900 m).
Potential Natural Vegetation. Open black spruce forests interspersed with large areas of brushy tundra characterize this Section. White spruce forests occur on south-facing, gravelly moraines, whereas cottonwood-tall bush communities are found on large floodplains.

Upper Yukon Tayga

Located in east-central Alaska, the area of this Section is about 13,000 mi2 (33,700 km2).

Section 139A--Upper Yukon Flats

Geomorphology. The Yukon Flats encompass gently sloping outwash fans and floodplains of the Chandalar, Christian, Sheenjek, and Upper Yukon Rivers. This Section is a relatively flat, marshy basin patterned by braided and meandering streams, numerous thaw and oxbow lakes, and meander scars. Elevation ranges from 300 to 820 ft (90 to 250 m).

Potential Natural Vegetation. Bottomland spruce-aspen-birch grow on the better drained alluvial sites. Alder and willow form thickets on newly exposed alluvial sites, which are subject to periodic flooding. The wettest sites have black spruce, willow, or graminoid marsh cover.

Yukon Intermontane Plateaus Tayga - Meadow

The area of these Sections, located in central Alaska, is about 55,000 mi2 (142,400 km2).

Section M131A--Nulato Hills

Geomorphology. The Nulato Hills generally consist of northeast-trending, even-crested ridges having rounded summits and gentle slopes. Valleys are narrow and flat-bottomed. Elevation ranges from sea level to 4,040 ft (1,230 m).

Potential Natural Vegetation. Most of the area supports alpine tundra vegetation of sedges and prostrate shrubs (e.g., willows). Barren areas are frequent at high elevations. Spruce-aspen-birch forests occur at lower elevations.

Section M131B--Kuskokwim Mountains

Geomorphology. The Koskokwim Mountains are northeast-trending ridges having rounded-to-flat summits and broad, gentle slopes. Deep narrow valleys are prevalent. Elevation ranges from 1,310 to 4,430 (400 to 1,350 m).

Potential Natural Vegetation. Open black spruce forests are abundant. Alpine tundra vegetation of sedges and shrubs (willow and alder) cover most hills and ridges. White spruce-paper birch communities occur on hills bordering the Yukon and Kuskokwim Rivers.

Section M131C--Nushagak-Lime Hills

Geomorphology. This Section comprises largely rounded, flat-topped ridges having broad, gentle slopes and broad, flat, or gently sloping valleys. Elevation ranges from 1,310 to 4,270 ft (400 to 1,300 m).

Potential Natural Vegetation. Spruce-aspen-birch forests prevail at low elevations, whereas alpine tundra heath meadows and barrens dominate at high elevations.

Alaska Range Humid Tayga - Tundra - Meadow

These Sections are located in southern Alaska, partly bordering Canada. The area of these Sections is about 61,000 mi2 (158,000 km2).

Section M135A--Alaska Mountains

Geomorphology. This Section consists of steep, rugged mountain ridges separated by broad valleys. Elevation ranges from 1,640 ft (500 m) in valleys to greater than 13,125 ft (4,000 m) on mountain peaks. Mount McKinley is about 20,320 ft (6,200 m).

Potential Natural Vegetation. A substantial portion of the area is barren of vegetation. Where vegetation exists, alpine and moist tundra communities of prostrate plants predominate. Riparian spruce-hardwood forests occur infrequently at low elevations.

Section M135B--Wrangell Mountains

Geomorphology. This Section, comprised of steep, rugged mountains of volcanic origin, is extensively covered by ice fields and glaciers. Elevation ranges from 1,970 to about 16,400 ft (600 to 5,000 m).

Potential Natural Vegetation. Most areas are barren of vegetation. Where vegetation occurs, alpine tundra communities of prostrate shrubs, forbs, grasses, and lichens predominate.

Upper Yukon Tayga - Meadow

This Section is located in east-central Alaska, bordering Canada. Its area is about 68,400 mi2 (177,200 km2).

Section M139A--Upper Yukon Highlands

Geomorphology. The area mainly consists of rounded, low mountains and hills, interspersed frequently by valleys. Elevation ranges from 985 to 5,900 ft (300 to 1,800 m).

Potential Natural Vegetation. Forests of white spruce, birch, and aspen dominate most lower slopes in the south and south-facing slopes in the north. Black spruce forests typically grow at higher elevations, on all north-facing slopes in the south, and on all but steep south-facing slopes in the north. Black spruce forests also occur at lower elevations where drainage is impeded. Highest elevations are either barren or have tundra vegetation, with sedge and mosses dominating poorly drained sites and low-growing shrubs on drier sites (e.g., scrub birch and willow).

Laurentian Mixed Forest

These Sections are located in the north-central and northeastern conterminous States, including parts of Minnesota, Wisconsin, Michigan, Pennsylvania, New York, Vermont, and Maine. The area of these Sections is about 147,300 mi2 (381,500 km2).

Section 212A--Aroostook Hills and Lowlands

Geomorphology. The Section is part of the New England geomorphic province. It is a glacially scoured and dissected peneplain characterized by gently rolling terrain and pitted outwash plains, with scattered, low, rounded mountains (monadnocks). Mass wasting and fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from 600 to 1,000 ft (180 to 300 m). Local relief ranges from 300 to 500 ft (90 to 150 m). Gentle slopes cover 50 to 80 percent of the landscape, 50 to 75 percent in the lowlands. Subenvelop elevation range is 325 to 650 ft (100 to 200 m).

Potential Natural Vegetation. Kuchler vegetation types are northern hardwood and northern hardwood-spruce. Regional characterizations of important vegetation types include lowland red spruce-balsam fir and northern hardwood-conifer. The western boundary of this region coincides with a vegetation transition zone where species characteristic of more temperate regions are replaced by species of more boreal affinity.

Disturbance Regimes. Disturbance from fire and large scale windthrow is rare. Historical documentation of fire occurrence in this region shows considerable variability through time. Wind disturbance to individual trees and groups of trees may be common. Ice and wet, heavy snow can cause extensive crown damage, particularly in conifer types. Insect and disease disturbances occur, commonly from defoliating insects and particularly from the spruce budworm. Although the distribution of modern and pre-settlement forest types match well regionally, 250 years of land use activity have affected forest structure and composition across the landscape. The land has been both selectively and intensively logged throughout this century and the last. Land has been cleared and farmed since the time of early settlement. Beginning around 1870, land unprofitable for agriculture was abandoned and much was allowed to revert to forest land.

Section 212B--Maine and New Brunswick Foothills and Eastern Lowlands

Geomorphology. The Section is part of the New England geomorphic province. It is a glacially scoured and dissected peneplain dominated by a broad, central, marine plain. The rest of the Section is characterized by gently sloping hills and low, rounded mountains (monadnocks). The Section exhibits some glacial features, primarily kames, eskers, and terraces. Mass wasting and fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from 400 to 1,000 ft (120 to 300 m); local relief ranges from 100 to 500 ft. (30

to 150 m). Gentle slopes cover 50 to 80 percent of the landscape, 50 to 70 percent in the lowlands. Subenvelop elevation ranges from 330 to 980 ft (100 to 300 m).

Potential Natural Vegetation. Kuchler vegetation types are northern hardwood and northern hardwood-spruce. Regional characterizations of important vegetation types include montane red spruce-balsam fir, lowland spruce-fir, northern hardwood-conifer.

Disturbance Regimes. Disturbance from fire and large scale windthrow are rare. Historical documentation of fire occurrence in this region shows considerable variability through time. Individual to few tree group level wind caused disturbance may be common. Ice and heavy snow can cause extensive crown damage, particularly in conifer types. Insect and disease disturbance have resulted from defoliating insects, particularly spruce budworm and hemlock looper; impact from beech bark disease and white pine blister rust have been severe. Significant brown ash dieback has also occurred. Although regionally the distribution of modern and pre-settlement forest types match well, 250 years of land use activity have affected forest structure and composition across the landscape. The land has been both selectively and intensively logged throughout this century and the last. Forest land has been cleared and farmed since the time of early settlement. Beginning around 1870, land unprofitable for agriculture was abandoned and much was allowed to revert to forest.

Section 212C--Fundy Coastal and Interior

Geomorphology. The Section is part of the New England geomorphic province. It is a glacially scoured and dissected peneplain with a few low, rounded mountains (monadnocks). The Section exhibits some glacial features, primarily kames, eskers, and terraces. Topography is gently rolling, sloping toward the coastal zone, which is characterized by low ridges surrounded by poorly drained and relatively flat terrain. Coastal and fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from 100 to 400 ft (30 to 120 m), with local relief from 1,000 to 1,400 ft (300 to 425 m). Gentle slopes cover 50 to 80 percent of the area; 50 to 75 percent are found in the lowlands. Subenvelop elevation range is 0 to 160 ft (0 to 50 m).

Potential Natural Vegetation. Kuchler vegetation types are northeastern spruce-fir, northern hardwood, and northern hardwood-spruce forests. Regionally described important vegetation types include lowland red spruce-balsam fir, coastal spruce-fir, coastal raised peatlands, and coastal plateau peat lands.

Disturbance Regimes. Disturbance from fire is rare, although historical documentation of fire occurrence in this region shows considerable variability through time. Severe wind events can cause considerable blowdown in forested communities near coastal areas. Tidal flooding associated with storms occurs along the coast. Insect and disease disturbances have resulted from hemlock looper, spruce budworm, and European larch canker. Severe impacts have resulted from beech bark disease. Although regionally the distribution of modern and pre-settlement forest types match well, 250 years of land use activity have affected forest structure and composition across the landscape. The land has been both selectively and intensively logged throughout this

century and the last. Land has been cleared and farmed since the time of early settlement. Beginning around 1870, land unprofitable for agriculture was abandoned and much was allowed to revert to forest land.

Section 212D--Central Maine Coastal and Interior

Geomorphology. The Section is part of the New England geomorphic province. It is a glacially scoured and dissected peneplain, sloping toward the coast. It exhibits some glacial features, mainly kames, eskers, and terraces. Flat to gently rolling terrain is characteristic except around Penobscot Bay, where the terrain is dominated by knobby bedrock ridges and high hills that have a linear, southwest to northeast trend. Coastal and fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from sealevel to 400 ft (120 m); Local relief ranges from 100 to 1,000 ft (30 to 305 m). Gentle slopes occupy 50 to 80 percent of the area; 50 to 75 percent are in the lowlands. Subenvelop elevation ranges from 0 to 50 ft (0 to 15 m).

Potential Natural Vegetation. Kuchler vegetation types are northeastern spruce-fir, northern hardwood-spruce, and northern hardwood forests. Regionally this area is described as a transitional zone. From west to east the forest transition ranges from northern Appalachian oak, pine, and mixed hardwoods typical of the southern New England coastal plain to northern coastal spruce-fir and spruce-fir-northern hardwood communities. From south to north, coastal communities grade to more montane spruce-fir and northern hardwood communities. Coastal pitch pine communities are represented on sand dunes and outcrops in the coastal zone.

Disturbance Regimes. Disturbance from fire is uncommon, but historical documentation of fire occurrence in this region indicates this has varied. Severe winds can cause considerable blowdown in forested communities near coastal regions. Tidal flooding associated with storms occurs along the coast. Insect and disease disturbances from beech bark disease and white pine blister rust have been severe. Impacts from European larch canker on coastal larch and dwarf mistletoe on coastal white spruce are ongoing. Although regionally the distribution of modern and pre-settlement forest types match well, 250 years of land use activity have affected forest structure and composition across the landscape. The land has been both selectively and intensively logged throughout this century and the last. Land has been cleared and farmed since early settlement. Beginning around 1870, land unprofitable for agriculture was abandoned and much was allowed to revert to forest land.

Section 212E--St. Lawrence and Champlain Valley

Geomorphology. The Section is part of the St. Lawrence Valley geomorphic province. The eastern half is dominated by Lake Champlain, which is bracketed by wave-cut terraces and low hills. The western prong is characterized by marine plains and rolling, low parallel ridges. Lake shore and fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from 80 to 1,000 ft (25 to 300 m), increasing gradually from the St. Lawrence River southward and from Lake Champlain to the east and west. Local relief ranges

from 500 to 1,000 ft. Gentle slopes cover 50 to 80 percent of the area, 50 to 75 percent in the lowlands. Subenvelop elevation range is 0 to 650 ft (0 to 200 m).

Potential Natural Vegetation. Kuchler vegetation types are northern hardwood and beech-maple forest. Regional characterizations of important vegetation types include transition hardwood-white pine-hemlock, northern hardwood-elm-red maple, northern hardwoods, aspen-gray birch-paper birch, and pitch pine-heath barrens.
Disturbance Regimes. Fire is an important, small scale disturbance on areas characterized by xeric edaphic extremes. Drought can be an important climatic influence. About 75 percent of this area is in agriculture; the remaining area is in forest. As in other areas dominated by agriculture in this region, extensive forest land occurs, generally on very dry or wet sites and is second or even third growth. Insect and disease disturbances have resulted from Dutch elm disease, beech bark disease, gypsy moth, false pine budworm, and butternut canker.

Section 212F--Northern Glaciated Allegheny Plateau

Geomorphology. The Section is part of the Appalachian Plateaus geomorphic province. It is a maturely dissected plateau of moderate relief, over-printed with notable moraine, drumlin, kettle, scour, and other glacial features. The Section is characterized by irregular topography-- broadly rolling with high hills, and steep valleys typified by the north-south trending Finger Lakes. It is demarcated by north-facing escarpments south of and paralleling Lake Ontario, and east-facing escarpments west of and paralleling the Hudson River, the most prominent of which stands up to 2,000 ft (610 m) above the valley. Mass wasting, karst solution, fluvial erosion, and transport and deposition are the primary operating geomorphic processes. Elevation ranges from 650 to 1,970 ft (200 to 600 m); local relief ranges from 400 to 1,000 ft (120 to 300 m). Gentle slopes cover 20 to 50 percent of the landscape; more than 75 percent are in the upland. Subenvelop elevation range is 650 to 1,000 ft (200 to 300 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwoods and Appalachian oak forest. Regionally defined important vegetation types include Appalachian oak-hickory forest, Appalachian oak-pine forest, beech-maple mesic forest, and hemlock-northern hardwood forest.

Disturbance Regimes. Fire was historically of some importance in maintaining oak dominated communities in the central part of the plateau and elsewhere on southern and western slopes of this region. Insect and disease disturbances have resulted from chestnut blight, beech bark disease, sugar maple defoliators, and ongoing ash dieback. Climatic influences include occasional droughts, particularly in the central part of the region.

Section 212G--Northern Unglaciated Allegheny Plateau

Geomorphology. This Section is part of the Appalachian Plateaus Geomorphic Province. It is a maturely dissected plateau characterized by sharper ridge tops and narrower valleys than the glaciated portions of the plateau to the north and west. Drainage is dendritic. Mass wasting,

fluvial erosion, transport and deposition are the primary geomorphic processes currently operating. Broad, low amplitude, northeast-southwest trending folds imperceptibly tilt the horizontal sedimentary layers and lend a subtle grain to the topography. Elevation ranges from 1,000 to 2,000 ft (305 to 610 m). Local relief ranges from 100 to 670 ft (30 to 205). Local relief ranges from 100 to 670 ft (30 to 205 m).

Potential Natural Vegetation. Kuchler vegetation types are Northern hardwoods forest and Appalachian oak forest. Eastern hemlock, and American beech-hemlock forests are abundant on moist sites; American beech-sugar maple forests are common on the better drained sites. Common associates include red maple, sweet birch, black cherry, white ash, yellow birch, eastern white pine, yellow-poplar, and cucumbertree.

Disturbance Regimes. Tornadoes and other windstorms commonly cause catastrophic disturbances on sites tens to thousands of acres in size. Periodic outbreaks of insects (e.g., gypsy moth, elm spanworm, cherry scallop shell moth) and diseases (e.g., chestnut blight, beech bark disease) may cause significant tree defoliation and mortality. Lightning may be an important cause of individual tree mortality. Ice storms have periodically caused large-scale tree crown dieback. Intensive human uses of the land, including logging and oil and gas development, have disturbed this landscape for more than the past one hundred years. Moderate to high deer populations have existed nearly continuously for the past 70 years, causing significant changes in plant composition and structure of the forests.

Section 212H--Northern Great Lakes

Geomorphology. This Section is part of the Central Lowlands geomorphic province. It is a level to gently rolling lowland (glacial ground moraine) and flat outwash or lacustrine plain, with dune fields near the Great Lakes. Cropping out of the lowlands and plains are partially-buried end moraines and mounded ice-contact hills that trend roughly parallel to the Great Lakes shorelines. Drainage is dendritic with pronounced terracing. Geomorphic processes operating in the Section are fluvial erosion, transport, and deposition; lake-shore erosion and deposition; and minor dune construction. Elevation ranges from 580 to 1,725 ft (176 to 523 m). In Upper Michigan, the elevation range is mostly between 580 to 850 ft (176 to 259 m). Local relief is generally less than ten feet except in moraines, where it may range up to 325 feet.

Potential Natural Vegetation. Kuchler vegetation types are northern hardwoods dominating on moraines and stratified ice-contact hills, and northern hardwood-fir forests on similar landforms in the coldest climatic regimes of Upper Michigan. Great Lakes pine forests occurred on outwash and lacustrine sands, with jack pine forests occupying outwash and lacustrine sand plains, and white and red pine forests on more mesic areas and grading into the ice-contact hills. Conifer bogs occupied low-lying areas in Upper Michigan and near the Straits of Mackinac. The elm-ash forest dominated a part of the Saginaw Bay lowlands in the southeastern part of the Section.

Disturbance Regimes. Fire is the dominant natural disturbance in pine forests, with catastrophic fires during pre-European settlement times, occurring in 80 go 250 year intervals. Ground fires occurred more frequently. Gap-phase windthrow is the primary disturbance regime in northern

hardwood forests, with about one percent of the canopy affected annually in patches mostly less than a half acre. Larger blowdowns due to windshear and tornadoes occur infrequently, but can cause extensive localized disturbance.

Section 212J--Southern Superior Uplands

Geomorphology. This Section comprises the eastern two-thirds of the Superior Upland geomorphic province. About half the Section is level to gently rolling lowlands (glacial ground moraines) and flat laustrine plain; the rest is hillier uplands with escarpments. The lowlands and plains are intermittently overlain by low, undulating ridges (glacial end moraines) and by other mounded or hummocky glacial features (e.g., kames and eskers). Kettled glacial outwash plains are common. Most prominent of the uplands are linear "ranges" trending southwest-northeast along the Superior shore. Drainage is dendritic with only minor entrenchment. Geomorphic processes operating in the Section are lake-shore and fluvial erosion, transport and deposition. Elevation ranges from 600 to 1,980 ft (183 to 603 m). Local relief is generally 100 to 600 ft (30 to 183 m).

Potential Natural Vegetation. Kuchler vegetation types are maple-beech-birch, aspen-birch, spruce-fir forests. More recent vegetation classification is more specific. Acer-Tsuga Series and Acer-Series occur on mesic landforms; Tsuga Series occur on dry-mesic landforms; Pinus Series occur on xeric landforms; and Tsuga-Thuja Series occur on wetland landforms.

Disturbance Regimes. Light to medium (10 to 40 percent canopy removal) windfall disturbance dominates in northern hardwoods on mesic landforms. In pine and mixed-pine cover types on xeric and dry mesic landforms, fire is the dominant disturbance, occurring at about 50 to 250 year intervals. Widespread thunderstorm downbursts occur at only about 1,200 to 2,000 year intervals.

Section 212K--Western Superior

Geomorphology. The Section comprises part of the Superior Uplands geomorphic province. It is mostly poorly drained, flat to slightly rolling ground moraine and plain-pitted outwash with kettles intermittantly overlain by low, undulating ridges (glacial end moraines) and drumlins. Poor to unintegrated (chaotic) drainage dominates, except along the St. Croix River where dendritic drainage is established in and adjacent to a glacial channel. Geomorphic processes operating in the Section are fluvial erosion, transport, and deposition. Elevation ranges from 650 to 1,650 ft (200 to 500 m). Local relief is generally less than 100 ft (30 m), but ranges up to 200 ft (60 m) in pitted outwash areas.

Potential Natural Vegetation. Primarily coniferous and deciduous forests dominate. Some jack pine and oak barrens are on the Bayfield peninsula. Kuchler types are mapped as Great Lakes pine forest, Great Lakes spruce-fir forest, and maple-basswood forest.

Disturbance Regimes. Fires were very intensive, frequent, and quite severe on the landscape. This helped to keep a conifer dominated uplands Forest. The Jack pine and oak barrens were also maintained by intensive fires. Logging, grazing, and farming also caused large dramatic disturbances.

Section 212L--Northern Superior Uplands

Geomorphology. The Section is part of the Superior Uplands geomorphic province. It is a glacially scoured peneplain characterized by level-to-rolling uplands and hills. Most prominent of the hills are linear ranges trending southwest to northeast along Lake Superior and parallel ranges farther north (Mesabi, Vermillion). There is a prominent escarpment along Superior's shore. Innumerable small lakes and potholes dominate the northern part of the Section. An east to west trending series of small lakes occurs in the northeasternmost portion of the Section; and an east to west trending series of larger lakes follows a fault zone in the most western part of the Section. Elevation ranges from 600 to 2,280 ft (183 to 695 m). Local relief ranges from 600 (180 m). General relief is 10 to 60 ft (3 to 20 m). Upland areas rise 300 to 600 ft (90 to 180 m) above lowlands, interspersed between lakes or bogs.

Potential Natural Vegetation. Dominant vegetation includes mixed pine with aspen-birch, white pine, red pine, jack pine, black spruce, balsam fir, and white cedar, with less common occurrences of northern hardwoods along the shore of Lake Superior. Kuchler types are Great Lakes spruce-fir forest and Great Lakes pine forest.

Disturbance Regimes. Fire, windstorm, insect infestation, animal browsing, and logging are major disturbances. Fires have burned 80 to 90 percent of the area one to several times during the last three hundred to four hundred years. High intensity crown fires tend to occur once every one hundred fifty to two hundred years. Low intensity fires tend to occur about every twenty to forty years. Atmospheric pollutants of greatest concern are mercury, ozone, and acidifying substances. Of these, only mercury has resulted in a demonstrated effect on resource uses through health-based limits on fish consumption by humans. Ozone impacts on vegetation and mercury impacts on wildlife (other than fish) are suspected, but have not been adequately studied to assess severity.

Section 212M--Northern Minnesota and Ontario

Geomorphology. The Section is part of the Central Lowlands geomorphic province. It is dominated by a flat glacial lake plain. Some low moraines and beach ridges occur, especially in the northwest and east. The Section is poorly drained, with mostly boggy ground. Anoxic accumulation of plant material is the dominant geomorphic process operating; fluvial erosion, transport and deposition occur in the northwest. Elevation ranges from 1,100 to 1,500 ft (330 to 450 m). Local relief is less than 50 ft (15 m).

Potential Natural Vegetation. Kuchler types are (primarily) conifer bog, with lesser extent of Great Lakes spruce-fir and Great Lakes pine. Sedge fen, black spruce-sphagnum bog, and white

cedar-black ash swamp dominates the Section. Some low moraines and beach ridges are dominated by jack pine or trembling aspen-paper birch forests.

Disturbance Regime. Fire occurred on the peat lands. Insect infestations, such as spruce budworm probably lead to fires. Water level fluctuation, caused both by short-term climatic changes and by beaver dams, probably contributed to tree mortality.

Section 212N--Northern Minnesota Drift and Lake Plains

Geomorphology. This Section is part of the Central Lowlands geomorphic province. It is a level to gently rolling lowland characterized by its glacial features. outwash plains, kettles, bogs, lake plains, till plains, narrow outwash channels, morainal ridges, and drumlin fields. Drainage is poorly to moderately integrated and includes the headwaters of the Mississippi River. Fluvial erosion, transport and deposition are the primary operating geomorphic processes. Elevation ranges from 1,100 to 1,850 ft (330 to 560 m). Local relief ranges from 50 to 165 ft (15 to 50 m).

Potential Natural Vegetation. Vegetation includes a mix of conifer and hardwood forest communities. Northern hardwoods grow in the south and around larger lakes. Conifers (Great Lakes pine and Great Lakes spruce-fir) are associated with outwash plains and coarsely textured end moraines. Large areas of lowlands are dominated by potential natural communities of black spruce, tamarack, and sedge meadows. Kuchler types are Great Lakes pine forest, Great Lakes spruce-fir forest, and conifer bog.

Disturbance Regimes. Fire occurred historically on about a 10 to 40 year rotation within much of the Section, accounting for a dominance of upland conifers and trembling aspen-birch forests.

Coniferous Forest - Alpine Meadow

These Sections are located in the northeastern conterminous States, including parts of New York, Vermont, New Hampshire, Massachusetts, and Maine. The area of these Sections is about 43,600 mi2 (112,900 km2).

Section M212A--White Mountains

Geomorphology. The Section is part of the New England geomorphic Province. It is a glacially scoured, maturely dissected, irregular highland characterized by clusters of low, rounded mountains and scattered monadnocks. Highest elevations occur in a wide belt trending southwest to northeast through the Section, ending in central Maine. Glacial features are most evident in the Section's southern half and include cirques carved into the high peaks and U-shaped valleys, as well as kames, eskers, and drumlins. Mass wasting, fluvial erosion, transport and deposition are the primary geomorphic processes. General elevation ranges from 1,000 to 4,000 ft (300 to 1,200 m); isolated peaks are greater than 5,000 ft (1,500 m); local relief ranges from 1,000 to 3,000 ft (300 to 900 m). Gentle slopes cover 20 to 50 percent of the area; 75 percent of gentle slopes occur in the lowland. Subenvelop elevation ranges from 200 to 1,800 (60 to 550 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood, northern hardwood-spruce, and northeastern spruce-fir forest. Regionally-defined important vegetation types include northern hardwood-conifer, montane spruce-fir, lowland spruce-fir, alpine krummholz, and alpine meadow. Robbin's cinquefoil is a Federally listed plant, unique to alpine communities of the Presidential Range in New Hampshire.

Disturbance Regimes. Montane forests in this region lack significant fire regimes and are characterized by large blowdown disturbances resulting from hurricanes or other severe wind events and smaller area, single tree phenomena. Higher elevation forests are often characterized by an even-aged windthrow disturbance phenomenon known as fir-waves. Insect and disease disturbances have resulted from gypsy moth, spruce budworm, spruce beetle, severe beech bark disease, and butternut canker. At higher elevations, spruce decline is related to severe winter injury and soil cation depletion. Forest composition at lower elevations has been influenced by agriculture dating from the colonial period and subsequent farm abandonment since about 1870, as well as by selective logging of certain species, particularly conifers. Although regionally the distribution of modern and pre-settlement forest types matches well, 250 years of land use activity has affected forest structure and composition across the landscape. The land has been both selectively and intensively logged throughout this century and the last. Forest land has been cleared of trees and farmed since the time of early settlement. Beginning around 1870, land unprofitable for agriculture was abandoned and often allowed to revert to forest land.

M212B--New England Piedmont

Geomorphology. The Section is part of the New England geomorphic Province. It is a glacially scoured, maturely dissected peneplain with open, low mountains and mondanocks. Glacial features include kames, eskers, drumlins, and lacustrine plains. Mass wasting, fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 600 to 3,000 ft (180 to 900 m); local relief ranges from 1,000 to 3,000 ft (300 to 900 m). Gently sloping land covers 20 to 50 percent of the area; more than 50 percent is found in lowlands. Subenvelop elevation ranges from 200 to 1,800 (60 to 550 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood and northern hardwood-spruce forest. Regionally-defined important vegetation types include montane spruce-fir, lowland spruce-fir, northern hardwood-conifer, and transition hardwood-conifer.

Disturbance Regimes. This area occupies the lower end of a regional disturbance gradient, ranging from relatively frequent occurrence of fire and hurricane winds in southern New England and New England coastal areas to a very low incidence of disturbance in more northern inland sites. Percent of land in forest continues to increase over time. However, composition of present day forest on a landscape scale is heavily influenced by agriculture dating from the colonial period and subsequent farm abandonment from about 1870, as well as by selective logging of certain species, particularly conifers. Although regionally the distribution of modern and pre-settlement forest types match well, 250 years of land use activity have affected forest structure and composition across the landscape. Insect and disease disturbances have resulted

from chestnut blight, gypsy moth, spruce budworm, severe beech bark disease, butternut canker, and periodic birch and sugar maple defoliators. At higher elevations, spruce decline is related to severe winter damage and soil cation depletion.

Section M212C--Green, Taconic, Berkshire Mountains

Geomorphology. The Section is part of the New England geomorphic Province. North of central Vermont, the Green Mountains are north to south trending, linear ranges. To the south, they and the Berkshires are highlands characterized by dissected, flat-topped plateaus (up-warped peneplains) with scattered monadnocks. The Taconic Mountains are west of and separated from the southern Green and Berkshire Mountains by a broad, nearly continuous valley (the Marble Valley) about 1,500 ft (460 m) lower than the highlands on either side. The Taconic Mountains contrast with the plateaus to the east by being more deeply cut into peaks, sharper ridges and canyons with a linear, north to south topographic trend. Scattered glacial features include kames and eskers; the mountains have been smoothed and rounded by glacial scour. Mass wasting, minor karst solution, fluvial erosion, transport and depositions are the primary geomorphic processes operating. Elevation ranges from 600 to 4,000 ft (180 to 1,200 m) with isolated peaks greater than 4,300 ft (1,300 m). Local relief ranges from 1,000 to 3,000 ft (400 to 900 m). Gentle slopes cover less than 20 to 50 percent of the Section; 75 percent occurs in lowlands. Subenvelop elevation ranges from 200 to 1,800 (60 to 550 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood, northern hardwood-spruce, and northeastern spruce-fir forest. Regionally-defined important vegetation types include montane spruce-fir, lowland spruce-fir, northern hardwood-conifer, and transition hardwood-conifer.

Disturbance Regimes. This area of New England occupies the lower end on a regional disturbance gradient ranging from relatively frequent occurrence of fire and hurricane winds in southern New England and New England coastal areas to a very low incidence of disturbance in more northern inland sites. Percentage of land in forest continues to increase over time. Composition of present day forest on a landscape scale is heavily influenced by agriculture dating from the colonial period and subsequent farm abandonment from about 1870, as well as by selective logging of certain species, particularly conifers. Although regionally, the distributions of modern and pre-settlement forest types match well, 250 years of land use activity has affected forest structure and composition across the landscape. Insect and disease disturbances have resulted from gypsy moth, spruce budworm, periodic birch and sugar maple defoliators, periodic hemlock looper, ash dieback, and butternut canker. At higher elevations, spruce decline is related to severe winter damage and soil cation depletion.

Section M212D--Adirondack Highlands

Geomorphology. The Section is also known as the Adirondack geomorphic Province, but includes a small part of the Appalachian Plateau (Tug Hill Plateau) at the southwest corner. It is a dissected, asymmetrical dome in overall configuration. It is most mountainous, highest, and

steepest in the north and east, with lower, rolling hills farther south and west. Local relief exceeds 3,000 ft (915 m). Glaciers covered the dome, producing cirques and other scour features, moraines, lake plains, and a prominent esker system in the north-central area. Tug Hill is a southwest-tilting plateau separated from the Adirondacks by the Black River Valley 1,200 ft (365 m) below the plateau. Mass wasting, fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation extends from 500 to 5,344 ft (150 to 1,630 m); local relief ranges from 1,000 to 3,000 ft (300 to 900 m). Gentle slopes cover 20 to 50 percent of the area; more than 75 percent occurs in lowlands. Subenvelop elevation ranges from 200 to 1,800 (60 to 550 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood-spruce and northeastern spruce-fir forest. Regionally-defined important vegetation types include montane spruce-fir, lowland spruce-fir, northern hardwood-conifer, alpine krummholz, and alpine meadow.

Disturbance Regimes. Montane spruce-fir and spruce-northern hardwood forests lack significant fire regimes and are characterized by blowdown disturbances from severe wind events and smaller area, single tree phenomenon. Higher elevation forests are often characterized by even-aged windthrow disturbance phenomenon known as fir-waves. Insect and disease disturbances have resulted from gypsy moth, spruce budworm, periodic severe spruce beetle, beech bark disease, and sugar maple defoliators; scleroderis canker on red pine is ongoing. At higher elevations, spruce decline is related to severe winter injury and soil cation depletion. Hardwood-dominated communities are more extensive now than in pre-settlement times due to intensive and selective logging of conifers up to about 1900, followed by fire.

Section M212E--Catskill Mountains

Geomorphology. The Section is an inclusion in the northeast corner of the Appalachian Plateau geomorphic Province. Topographically, it is a maturely dissected plateau with a steep, 2,000 to 3,000 foot (610 to 915 m) scarp on its eastern margin (the Catskill Mural Front). It slopes gently westward, where it merges into the hilly landscape that typifies the rest of the Allegheny Plateau. The Catskills have the highest elevations on the plateau. They are characterized by steeply rolling uplands and ridges interlaced with deep ravines. Glaciation is expressed mostly by rounded hilltops and by cirques and other scour features. Mass wasting, fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 900 to 4,200 ft (275 to 1,260 m), peak elevations range from 3,000 to 4,200 ft (900 to 1,260 m); subenvelop elevation ranges from 900 to 2,500 ft (270 to 910 m). Local relief is from 1,000 to 3,000 ft (300 to 910 m). Less than 20 percent of area is covered by gentle slopes.

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood and northern hardwood-spruce forest. Regionally-defined important vegetation types include central hardwoods, transition hardwoods, northern hardwood-conifer, and montane spruce-fir.

Disturbance Regimes. Significant fire regime is absent. Higher elevation spruce-fir forests are characterized by blowdown disturbances from severe wind events and smaller area, single tree mortality. Insect and disease disturbances have resulted from beech bark disease, Dutch elm disease, hemlock wooly adelgid, and chestnut blight, which have resulted in the reduction of some species. Selective logging through about 1880 impacted forest composition. Hemlock, once an abundant species, was selectively logged and has not come back readily.

Eastern Broadleaf Forest (Oceanic)

These Sections are located in the eastern conterminous States, including parts of Tennessee, Kentucky, West Virginia, Ohio, Pennsylvania, New York, New Jersey, Rhode Island, Massachusetts, New Hampshire, and Maine. The area of these Sections is about 104,500 mi2 (270,650 km2).

Section 221A--Lower New England

Geomorphology. The Section comprises parts of the New England, Piedmont, and Coastal Plain geomorphic provinces. Cape Cod and Long Island are large terminal moraine complexes modified by coastal processes. Glacial features such as small to large delata plains, lacustrine basins, eskers, and extensive drumlin fields are widespread. The Section gradually descends in a series of broad, hilly plateaus to the coastal zone. Central Connecticut and western Massachusetts are characterized by a north to south trending basin, a lowland plain, punctuated with a central linear ridge. Primary geomorphic processes are coastal and fluvial erosion, transport and deposition, and mass wasting. Elevation ranges from sea level to 1,500 ft (450 m). Some high hills (monadnocks) are 2,000 ft (600 m). Local relief ranges from 100 to 1,000 ft (30 to 300 m). Gentle slopes cover less than 20 to 80 percent of the area; 50 to 75 percent are in lowlands. Subenvelop elevation ranges from 0 to 650 ft (0 to 200 m).

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood, Appalachian oak, and northeastern oak-pine forest. Regionally-defined important vegetation types include northern hardwood-hemlock-white pine, central hardwoods, coastal pitch pine, maritime oak, and maritime red cedar.

Disturbance Regimes. Central and coastal New England have intermediate to high occurences of fire and hurricane winds (thirty to fifty years) relative to inland New England sites. Tidal flooding associated with storms occurs along the coast. Regionally, the distribution of modern and pre-settlement forest types match well. At a landscape scale, modern forest characteristics are strongly controlled by land use, particularly agriculture dating from colonial time and subsequent farm abandonment from about 1850. Insect and disease disturbances result from gypsy moth, beech bark disease, chestnut blight, Dutch elm disease, hemlock woolly adelgid, periodic pitch pine and hemlock looper, oak leaf tier damage, and red pine scale and adelgid.

Section 221B--Hudson Valley

Geomorphology. The Section is the northernmost extension of the Ridge and Valley geomorphic province. It is characterized by a linear lowland, a glacial lake plain in part, bounded on either side by high escarpments. The lowland was created by graben-faulting, easily eroded bedrock, and glacial scour. Fluvial erosion, transport and deposition, and mass wasting are the primary geomorphic processes operating. Minimum elevations range from about 200 ft (61 m) in the north to near sea level south of Long Island Sound. Maximum local elevations are generally under 500 ft (152 m) but range to 1,000 ft (305 m). Gentle slopes cover 50 to 80 percent of the area, 50 to 75 percent occurs in uplands.

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood and Appalachian oak forest. Regionally-defined important vegetation types include central hardwoods, transition hardwoods, and northern hardwoods grading from south to north. Albany sand plains support pitch pine-scrub oak communities.

Disturbance Regimes. This region generally lacks large-scale natural disturbance regimes; however, fire is an important small-scale disturbance in the maintanance of pitch pine-scrub oak communities on sand plains and ridges along the middle to lower Hudson River Valley. In general, forest land occurs on edaphic extremes, i.e., steep, shallow, or otherwise unsuitable land for farming or settlement. All forest land is in second or third growth. Insect and disease disturbances have resulted from chestnut blight, dutch elm disease, beech bark disease, butternut canker, and ongoing wooly adelgid infestation.

Section 221C--Upper Atlantic Coastal Plain

Geomorphology. The Section is part of the Coastal Plain geomorphic province. It is characterized by a series of moderately dissected, northeast to southwest trending terraces that get progressivly lower toward the coastline. It has a prominent lowland that forms its northwest border. The coastline is characterized by dune fields, beaches, lagoons, embayments, and barrier islands. Drainage is dendritic; coastal and fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 0 to 300 ft (0 to 100 m). Most of the area is less than 150 ft (50 m).

Potential Natural Vegetation. Kuchler's map shows mostly northeastern oak-pine forest, with some oak-hickory-pine forest adjacent to Delaware Bay, and some fringes of northern cordgrass prairie along the Atlantic coast. Braun's discussions tell of cedar bogs with transition pine forests and deciduous swamps. There are also pine plains and grassy savannas, especially in the pine barrens area.

Disturbance Regimes. Historically, fire was a significant natural disturbance. Most of the vegetative types owe their existance to repeated fires. Other disturbances include bog-iron mining; construction of ore furnaces; utilization of clay deposits and glass sands; and logging. Early sawmills were driven by water power. Cedar bogs were exclusively logged which resulted

in an increase in deciduous swamps. The cranberry industry caused the construction of small dams, sluice gates, and ditches to facilitate drainage. Although peat was low grade, some harvesting did take place.

Section 221D--Northern Appalachian Piedmont

Geomorphology. The Section comprises part of the Piedmont geomorphic province. Most of the Section is a maturely dissected peneplain, sloping gently toward the coast. It is hilly to rolling terrain with a few high ridges, where local relief can be up to 1,200 ft (365 m). The Section is crossed southwest to northeast by a broad, structural basin forming a lowland plain, an extension of the one noted in Section 221A. Drainage is dendritic; fluvial erosion, transport and deposition, and mass wasting are the primary geomorphic processes operating. Elevation ranges from 80 to 1,650 ft (25 to 500 m). The predominant elevation ranges from 300 to 1,000 ft (100 to 300 m).

Potential Natural Vegetation. Prior to Euro-American settlement in the early 17th century, the native vegetation consisted mainly of oak and hickory. Chestnut, yellow-poplar, ash, walnut, and elm were associated species. Maple was dominant on the wet bottomlands of the Piedmont area. Currently Appalachain oak forest (Kuchler) and sugar maple-mixed hardwoods, hemlock-mixed hardwoods, oak-chestnut (Braun) dominate.

Disturbance Regimes. Historically, fire was a significant natural disturbance. Gypsy moth and chestnut blight have had effects on the vegetation.

Section 221E--Southern Unglaciated Allegheny Plateau

Geomorphology. This Section comprises part of the Appalachian Plateaus geomorphic province. It is a maturely dissected plateau characterized by high hills, sharp ridges, and narrow valleys. An exception is the broad Teays Valley, created by a major, preglacial river. The valley was dammed by an ice sheet during the Pleistocene and abandoned by the river after the melt. Local relief in the Section exceeds 2000 ft (610 m) along the New River Gorge, but is generally much less. Drainage is dendritic; mass wasting, karst solution, and fluvial erosion, and transport and deposition are the primary geomorphic processes operating. A notable but very minor landform is anthropogenic. lands that have been strip-mined exhibit hummocky or gouged topography. Elevation ranges from 650 to 1,300 ft (200 to 400 m). Local relief is generally about 160 to 325 ft (50 to 100 m).

Potential Natural Vegetation. Kuchler types are mapped as mixed mesophytic forest and Appalachian oak forest. Other recognized communities include mixed oak forest, oak-hickory-chestnut forest, oak-pine forest, hemlock forest, beech forest, floodplain forest and swamp forest.

Disturbance Regimes. Historically, low-intensity fires probably occurred at a given site at five to 10 year intervals. Fires of higher intensity occurred at intervals of up to 50 years. Dry ridges and slopes facing south to west burned more frequently than moist creek bottoms and slopes facing north to east. Annual spring flooding occured annually to some degree along major rivers. The forests were probably affected locally by insect and tree diseases. Climatic-influenced disturbances included winter ice storms, occasional tornadoes, and periodic flooding along major river floodplains. Natural disturbances to the streams and rivers incude floods and droughts. Man-made disturbances to streams include channelization, construction of locks and dams, and input of industrial waste, sewage, mining wastes, and soil.

Section 221F--Western Glaciated Allegheny Plateau

Geomorphology. The Section comprises part of the Appalachian Plateaus geomorphic province. It is a maturely dissected upland modified by glaciation. It is characterized by rounded hills, ridges, and broad valleys. Glacial features include valley scour, ground moraines, kames, eskers, and kettled outwash plains. Drainage is dendritic; mass wasting and fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 650 to 1,000 ft (200 to 300 m). Local relief ranges from 6 to 50 ft (2 to 15 m).

Potential Natural Vegetation. Kuchler types are mapped as beech-maple forest, Appalachian oak forest, northern hardwood forest, mixed mesophytic forest, and a small extent of oak-hickory forest. Other recognized types include maple-ash-oak swamp forest, wet beech forest, beech-sugar maple forest, oak-maple forest, and mixed oak forest.

Disturbance Regimes. Forests in the more rugged ravines and on dissected slopes were locally affected by insect and tree diseases and windstorms. The terraces and flood plains were also affected to some extent by large animals, insect and tree diseases, windstorms, droughts, and fires, but these impacts were less severe. Beaver also affected the flood plains along streams by building dams that sometimes killed relatively large stands of trees and created temporary ponds. Natural disturbances to the streams and rivers are floods and droughts. Man-made disturbances to streams in this Section include channelization, construction of dams, and input of industrial waste, sewage, and soil.

Section 221H--Northern Cumberland Plateau

Geomorphology. This Section is in the Appalachian Plateaus geomorphic province. Broad uplift of strata gently-dipping strata to a level-bedded plateau, followed by fluvial erosion and mass wasting, has resulted in a moderately dissected region of dendritic drainages. Landforms on about 80 percent of the Section consist of high hills. Other landforms in the southern part of the Section are about equal areas of tablelands and open low mountains. Elevation ranges from 1,270 to 2,000 ft (380 to 600 m). Local relief ranges from 50 to 100 ft (15 to 30 m).

Potential Natural Vegetation. Kuchler classifies vegetation as mixed mesophytic forest and Appalachian oak forest. The predominant vegetation form is cold-deciduous broad-leaved forest with evergreen needle-leaved trees. The shortleaf pine-oak forest cover type dominates much of this Section in Kentucky. The oaks on drier sites include post, southern red, scarlet, and blackjack; on moister sites, white and black oaks predominate. In Tennessee, the same oaks are present, but pines are not a dominant overstory component. Hickories, including pignut, mockernut, shagbark, and bitternut, form a common but minor component.

Disturbance Regimes. Fire has probably been the principal historical source of disturbance, previously burning over moderately sized areas between natural barriers with moderate frequency and low intensity. Climatic influences include occasional summer droughts, winter ice storms, and tornadoes.

Section 221I--Southern Cumberland Mountains

Geomorphology. This Section is in the Appalachian Plateaus geomorphic province and originated when the Cumberland overthrust block was pushed westward as a result of thin-skinned tectonics. Prominent strike ridges are apparent along the thrust plate. Differential rates of erosion have contributed to the strongly dissected landscape. Landforms consist of low mountains and open hills. Elevation ranges from 1,200 to 3,000 ft (360 to 900 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler classifies vegetation as Appalachian oak forest and mixed mesophytic forest. The predominant vegetation form is cold-deciduous broad-leaved forest with evergreen needle-leaved trees. The oak-hickory forest cover type dominates this Section. The oaks on drier sites include post, southern red, scarlet, chestnut, and blackjack; on moister sites, white, southern red, and black oaks predominate. Shortleaf pine is usually present. Hickories, including pignut, mockernut, shagbark, and bitternut, form a common but minor component.

Disturbance Regimes. Fire has probably been the principal historical source of disturbance, previously burning over moderate-size areas between natural barriers with moderate frequency and low intensity. Climatic influences include occasional summer droughts and ice storms.

Section 221J--Central Ridge and Valley

Geomorphology. This Section is in the Ridge and Valley geomorphic province. The Section consists of a folded, faulted, and uplifted belt of parallel valleys and ridges, strongly dissected by differential erosion, mass wasting, fluvial transport, and deposition. Landforms on most of the Section consists of open hills. Elevation ranges from 650 to 2,000 ft (200 to 600 m). Local relief ranges from 300 to 700 ft (90 to 210 m).

Potential Natural Vegetation. Kuchler classifies vegetation as Appalachian oak forest. The predominant vegetation form is cold-deciduous broad-leaved forest with evergreen needle-leaved trees. The oak-pine forest cover type dominates. The oaks on drier sites include post, southern

red, scarlet, chestnut, and blackjack; on moister sites, white, southern red, and black oaks predominate. Shortleaf pine usually forms a major part of the canopy. Hickories, including pignut, mockernut, shagbark, and bitternut, form a common but minor component throughout. The loblolly pine-shortleaf pine cover type is prevalent in the southern part of the Section. In these stands canopy hardwoods on well-drained soils include sweetgum, blackgum, southern red oak, post oak, white oak, mockernut hickory, and pignut hickory.

Disturbance Regimes. Fire has probably been the principal historical source of disturbance, previously burning over small areas between natural barriers with moderate frequency and low intensity. Climatic influences include occasional droughts and ice storms. During the early 1900's, all American chestnut trees were killed by an introduced pathogen; sprouting still occurs from root systems.

Eastern Broadleaf Forest (Continental)

These Sections are located in the central conterminous States, including parts of Arkansas, Missouri, Tennessee, Kentucky, Illinois, Indiana, Ohio, New York, Michigan, Wisconsin, Iowa, and Minnesota. The area of these Sections is about 270,000 mi2 (699,300 km2).

Section 222A--Ozark Highlands

Geomorphology. This Section is part of the Ozark Plateaus geomorphic province. It is a maturely dissected high plateau with dendritic and radial drainage patterns. Most of the Section is equally divided between steep hills with local relief up to 1,000 ft (300 m) and rolling hills with local relief between 200 and 500 ft (60 to 150 m). There are also gently rolling plains with local relief of less than 200 ft; also present is the flat, 6-mile (10-km) wide Mississippi River flood plain, composed of broad bottomlands with associated terraces, ox-bows, and meander scars. Current geomorphic processes are fluvial erosion, transport and deposition, and mass wasting. Widespread karst features include caves, sinkholes, and springs. Elevation ranges from 300 to 1,800 ft (100 to 600 m).

Potential Natural Vegetation. Kuchler vegetation types are mapped as oak-hickory forest, oak-hickory-pine forest, mosaic of bluestem prairie and oak-hickory forest, and cedar glades. Dry upland sites include post oak-blackjack oak-black hickory with lichen-moss ground cover, and shortleaf pine-oak in areas of sandstone bedrock. Mesic slopes sites have white oak-northern red oak-bitternut hickory-flowering dogwood. Riparian sites have river birch-silver maple. Glades have little bluestem-baldgrass; eastern redcedar has invaded these prairie sites as a result of fire suppression. The current trend is to characterize Ozark's landscapes as "woodland" or "savanna" rather than "forest," in recognition of the role of frequent, low-intensity fire.

Disturbance Regimes. Frequent, low intensity, widespread fire occurred prior to European settlement. Fire suppression led to changes in community type and species composition. Closed-canopy forests replaced many woodlands; pastures replaced prairies, glades, and bottomland forests. Climatic influences include occasional summer droughts, winter ice storms, and tornadoes.

222C--Upper Gulf Coastal Plain

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landforms are irregular, shallow to moderately dissected plains of alluvial origin formed by deposition of continental sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. Geomorphic processes currently active include gentle-gradient valley stream erosion, transport and deposition. Elevation ranges from 80 to 330 ft (25 to 100 m). Local relief seldom exceeds 100 ft (30 m).

Potential Natural Vegetation. Kuchler classifies vegetation as oak-hickory forest, blackbelt, and a mosaic of bluestem prairie and oak-hickory forest. The predominant vegetation form is temperate lowland and submontane broad-leaved cold-deciduous forest and cold-deciduous alluvial forest. The oak-hickory forest cover type dominates this Section. The oaks on drier sites include post, southern red, scarlet, chestnut and blackjack; on moister, sites white, southern red, and black oaks predominate. Shortleaf pine is usually present. Hickories, including pignut, mockernut, shagbark, and bitternut, form a common, but minor component. Bottom land hardwoods occupy recent alluvium along major rivers. Many young stands are dominated by eastern cottonwood and black willow. Older stands include a mixture of species, including hackberry, sugarberry, American elm, boxelder, overcup oak, water hickory, and green ash.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include winter ice storms and periodic flooding along major rivers.

222D--Interior Low Plateau, Shawnee Hills

Geomorphology. This Section is part of the Interior Low Plateaus geomorphic province. Extensive sandstone bluffs, cuestas, rise up to 100 ft (30 m) above the terrain in front of them and dip gently down the back slope. Other landforms include steep-sided ridges and hills, gentler hills and broader valleys, karst terrain, gently rolling lowland plains, and bottom lands along major rivers, with associated terraces and meander scars. A notable but very minor landform is anthropogenic. lands that have been strip-mined exhibit humocky or ridge-swale topography. Current geomorphic processes are fluvial erosion, transport and deposition; mass-wasting; and karst solution. Elevation ranges from 325 to 1,060 ft (100 to 325 m). Lowest elevations occur along the Ohio Rive, the highest at Williams Hill in Illinois.

Potential Natural Vegetation. Kuchler vegetational types include oak-hickory forest in the uplands of Illinois and Kentucky, and joined by maple-beech-birch in Indiana; oak-gum-cypress forest occupies the bottom lands throughout the Section. Uplands are dominated by the white oak, black oak, shagbark hickory community; the black jack oak, scarlet oak, pignut hickory community occupies drier sites; the beech, tuliptree, bitternut hickory, sugar maple, white ash community occupies deep, mesic ravines. The southern flood plains along the Ohio and Wabash rivers are dominated by the sycamore, Kentucky cofftree, sugarberry, and honey locust community, with local tupelo and cypress swamp communities.

Disturbance Regimes. The natural communities in this Section were influenced by large herbivores such as elk, by insects and tree diseases, by windstorms, and by drought and fire. Drastic environmental influences on the generally forested hills discouraged trees and maintained openings, glades, on slopes; extensive, bushy grasslands, called barrens, occur on some of the drier sites. Large herbivores, drought, windstorms, insects, and tree diseases kept the forest canopy open and similar to a savanna on ridges. Occasional wildfires helped to maintain the hill-prairies, glades, and barrens. Most communities were affected by mass wasting, due to shale bedrock outcrops, thin soils, and frequent freeze-thaw conditions. Beaver affected timber in narrow flood plains. Anthropogenic disturbances dominate today (see below).

Section 222E--Interior Low Plateau, Highland Rim

Geomorphology. This Section is in the Interior Low Plateau geomorphic province. Landforms were formed by platform deposition of continental sediments into a shallow inland sea, followed by uplifting to form a level-bedded plateau, which has been shaped by differential erosion to form a moderate to deeply dissected surface. Landforms on about 70 percent of the Section consist of about equal areas of open hills and irregular plains. About 20 percent consists of tablelands. Elevation rages from 650 to 990 ft (200 to 300 m). Local relief ranges from 100 to 300 ft (30 to 100 m) on irregular plains and from 300 to 600 ft (100 to 200 m) on tablelands.

Potential Natural Vegetation. Kuchler classifies vegetation as oak-hickory forest, cedar glades, and a mosaic of bluestem prairie and oak-hickory forest. The predominant vegetation form is temperate low land and submontane broad-leaved cold-deciduous forest. The oak-hickory forest cover type dominates this Section. The oaks on drier sites include post, southern red, scarlet, chestnut, and blackjack; on moister sites, white and black oaks predominate. Shortleaf pine is usually present. Hickories, including pignut, mockernut, shagbark, and bitternut, form a common but minor component.

Disturbance Regimes. Fire has probably been the principal historical disturbance, previously burning over moderate-size areas between natural barriers with low frequency and low intensity.

Section 222F--Interior Low Plateau, Bluegrass

Geomorphology. This Section is in the Interior Low Plateaus geomorphic province. Platform deposition of continental sediments into a shallow inland sea was followed by uplifting to form a level-bedded plateau, which has been shaped by differential erosion to form a moderately to deeply dissected surface. Landforms on about 90 percent of the Section consist of about equal amounts of irregular plains and open hills. A small area consists of smooth plains. Elevation ranges from 650 to 1,000 ft (200 to 300 m). Local relief ranges from 100 to 500 ft (30 to 150 m) in the open hills. In the smooth plains, relief is 100 to 300 ft (30 to 100 m).

Potential Natural Vegetation. The predominant vegetation form is temperate lowland and submontane broad-leaved, cold-deciduous forest, while cold-deciduous alluvial forest occurs along the major rivers. Major species in the oak-hickory cover type includes white, black, and northern red oaks. Other important species include sugar maple, beech, black walnut, and

yellow-poplar. Bitternut, pignut, or shagbark hickories may also be present. Sycamore, silver maple, boxelder, willow, and American elm are common species along major river bottom lands.
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Disturbance Regimes. Fire has probably been the principal historical disturbance, previously burning over moderate-size areas between natural barriers with low frequency and low intensity. Climatic influences include occasional summer droughts and tornadoes.

Section 222G--Central Till Plains, Oak-Hickory

Geomorphology. This Section forms part of the Central low lands geomorphic province. The northern half is characterized by relative flatness and shallow entrenchment of drainages due to thick till deposits (50 to 100 ft, 15 to 30 m) that mask the topographic expression of the bedrock. Till is thinner (6 to 50 ft, 2 to 15 m) in the southern half, allowing the topography to be controlled by the relief on the deeply eroded bedrock. The dominant geomorphic process operating in the Section are fluvial erosion, transport and deposition. A notable but very minor landform is anthropogenic. lands that have been strip-mined exhibit humocky or ridge-swale topography. Elevation ranges from 330 to 985 ft (100 to 300 m).

Potential Natural Vegetation. Kuchler indicates that the uplands support oak-hickory forest. bottom lands along the Ohio and lower Wabash support oak-gum-cypress; elm-ash-cottonwood forest grows along the upper Wabash and its major Indiana tributaries. Historically, 40 percent of uplands in the Section were tall-grass prairie, not forest. The dominant forest community is post oak, black oak, shingle oak, mockernut hickory, and shagbark hickory. Forests on the drier southern and western slopes are of the white oak, shingle oak, and black oak community; the white oak, white ash, basswood, sugar maple, and slippery elm community dominates more mesic sites. The flat woods community is post oak, swamp white oak, blackjack oak, and pin oak. Forests in the broad flood plains are dominantly silver maple, willow, sycamore, and American elm nearest the rivers, with pin oak, white oak, hickory, ash, hackberry, and honeylocust on heavier soils farther from the river banks. Pin oak occasionally grows in pure stands.

Disturbance Regimes. Fire, both natural and human-caused, has probably been the principal historical source of disturbance, burning over moderate-size areas between natural barriers with moderate frequency and low intensity. Besides fire, grazing ungulates, insects and tree diseases, windstorms, drought, and ice were the major disturbances during presettlement times. They generally discouraged woody vegetation and encouraged grasslands on the flatter upland divides between forested drainages, and opened the canopy in the ravines and on slopes. Beaver dams occasionally created temporary ponds large enough to kill large stands of timber in the ravines and bottom lands. Over a period of years these ponds became filled with silt and became shallow wooded swamps or, on some sites, wet sedge meadows. Land use since settlement has caused conversion from forest, prairie, and wetland to agriculture on at least 80 percent of the area.

Section 222H--Central Till Plains, Beech-Maple

Geomorphology. This Section is part of the Central Lowlands geomorphic province. It is characterized by its flatness and by shallow entrenchment of its drainages. This is a level to

gently rolling till-plain (glacial ground moraine), with broad bottom lands along the few major river valleys. The plain is overlain by a series of low ridges (glacial end moraines) generally trending west to east in an undulating pattern. Drainage is dendritic with only minor entrenchment. The dominant geomorphic process operating in the Section is fluvial erosion, transport and deposition. Elevation ranges from 650 to 1,000 ft (200 to 300 m). Local relief is mainly a few meters, but in places, hills rise as much as 80 ft (25 m).

Potential Natural Vegetation. Kuchler type is beech-maple forest over most of the Section, with a significant amount of oak-hickory forest mapped in the southeast portion, and a few patches mapped as mosaic of bluestem prairie and oak-hickory forest.

Disturbance Regimes. Disturbance from fire is uncommon, scattered, and small. By far the largest disturbance effect is from land use. Climatic-influenced disturbances include winter ice storms, occasional tornadoes, and periodic flooding along major river flood plains.

Section 222I--Erie and Ontario Lake Plain

Geomorphology. This Section is part of the Central low lands geomorphic province. It is characterized by its flatness and by shallow entrenchment of its drainages. This is a combination of level to gently rolling till-plain (glacial ground moraine), and flat lake plain. There are a few areas with broad, low ridges (glacial end moraines) generally trending parallel to the lakes' shorelines. The eastern end of the Section, in New York State, includes either or both moderately dissected till and drumlin plains on three low but notable "stairstep" escarpments, parallel to and below the northern margin of the Allegheny Plateau. Geomorphic processes operating in the Section include: fluvial erosion, transport and deposition; lakeshore erosion and deposition; and minor dune construction. Elevations range from 245 ft (75 m), which is the mean elevation of the surface of Lake Ontario, and extend up to 1,000 ft (300 m) along the Appalachian Plateau border. Most of the land is under 800 ft (240 m) in elevation. Local relief ranges between 0 to 300 ft (0 to 90 m). Gentle slopes cover 50 to 80 percent of the area, 50 to 75 percent occur on low lands.

Potential Natural Vegetation. Kuchler vegetation types include northern hardwood forest, beech-maple forest, and elm-ash forest. Other, regionally-defined important vegetation types include beech-maple mesic forest in the east, maple-basswood forest, hemlock-northern hardwood forest, oak openings, and pitch pine-heath barrens.

Disturbance Regimes. Climatic-induced disturbances include winter ice storms and occasional tornadoes. Presettlement swamp forests, wet prairies, and marshes, were flooded during several months of the year. Natural disturbance regimes now affecting the streams and rivers are floods and droughts. Anthropogenic disturbance to aquatic systems includes channelization, ditching, and input of industrial waste, sewage, and soil. Insect and disease disturbances have resulted from Dutch elm disease, chestnut blight, and ash dieback among others. Occasional fire disturbances are small and scattered.

Section 222J--South Central Great Lakes

Geomorphology. This Section is part of the Central low lands geomorphic province. It is a combination of a level to gently rolling low land (glacial ground moraine) and flat outwash or lacustrine plains. Dune fields are present along Lake Michigan. Cropping out of the plains are partially buried end moraine ridges and mounded ice-contact hills. Three glacial lobes converged in southern Michigan, and morainal ridges are arranged in roughly parallel arcs along the paths of glacial retreat. Glacial outwash plains and deltas are found along major drainages. Drainage is dendritic with pronounced terracing. Geomorphic processes operating in the Section include: fluvial erosion, transport, and deposition; lakeshore erosion and deposition; and minor dune construction. Elevation ranges from 580 to 1,280 ft (175 to 396 m), mostly below 1,000 ft (300 m). Local relief is primarily 6 to 200 ft (2 to 60 m).

Potential Natural Vegetation. Kuchler vegetation types are oak-hickory forest, dominating sandy sites and beech-maple forest on loamy soils.

Disturbance Regimes. Fire was the dominant natural disturbance in the oak-hickory forest. Tornadoes and windshear events, together with gaps in the overstory, were responsible for regenerating the beech-sugar maple forests.

Section 222K--Southwestern Great Lakes Morainal

Geomorphology. This Section is part of the Central Lowland geomorphic province. It is characterized by flat to undulating topography resulting from glaciation:plains composed of till, outwash, and lacustrine; drumlin fields and morainal ridges; and local occurrences of other features (kames, eskers, kettles, etc.). Drainage is dendritic with only minor entrenchment. Geomorphic processes operating in the Section include: are fluvial erosion, transport and deposition; lakeshore erosion and deposition; and minor dune construction. Elevation ranges from about 570 to 1,650 ft (175 to 500 m). Local relief ranges from a few feet on plains to about 300 ft (90 m) in some places, such as interlobate moraines and a few bedrock escarpments.

Potential Natural Vegetation. Kuchler vegetation types are primarily oak savanna, with a lesser extent of maple-basswood forest, and some small areas of bluestem prairie.

Disturbance Regimes. Fire was apparently important in maintaining the oak Savannas and prairies. Windthrow ocurred in some localized areas.

Section 222L--North-Central U.S. Driftless and Escarpment

Geomorphology. This Section is part of the Central low lands Geomorphic Province. It is bisected by the Mississippi River flood plain. The Section is a maturely dissected, upland plateau where broad, steep-sided bedrock ridges and "mounds" up to 500 ft (150 m) high are separated by wide, flat-bottomed drainages in the southern portion of the Section, and by narrow, V-shaped

valleys farther north. Current geomorphic processes include: fluvial erosion, transport and deposition; masswasting; and karst solution. Elevation ranges from 650 to 1,300 ft (200 to 400 m). Local relief ranges from 100 to 600 ft (30 to 180 m).

Potential Natural Vegetation. Kuchler types are oak savanna and maple-basswood forest, with some northern flood plain forest along some of the major rivers.

Disturbance Regimes. Fire was historically important on the upland prairie and oak dominated ecosystems. Recent records of tornadoes and ice storms indicate that they locally impacted forest vegetation.

Section 222M--Minnesota and Northeastern Iowa Morainal

Geomorphology. This Section is part of the Central Lowland geomorphic province. It is characterized by level plains and low, irregular hills resulting from glaciation: till and outwash plains; drumlin fields and morainal ridges; and local occurrences of other features (e.g., kames, eskers, and kettles). Poor to unintegrated (chaotic) drainage is common in the northern portion of the Section; to the south, drainage is dendritic with only minor entrenchment. Geomorphic processes operating in the Section are fluvial erosion, transport and deposition. Elevation ranges from 1,000 to 1,600 ft (300 to 485 m). Local relief is generally less than 100 ft (30 m).

Potential Natural Vegetation. Kuchler's map shows mostly bluestem prairie with significant maple-basswood forest and lesser amounts of oak savannah, oak-hickory forest, and northern flood plain forest. Other investigators indicate bluestem prairie may be a more minor component, with greater dominance of oak savannah and oak wood lands.

Disturbance Regimes. Fire was historically important in oak savanna development. Windthrow was common in the sugar maple-basswood forests. tornadoes and other high wind events and floods also created natural disturbances. Major anthropogenic disturbances during the past 100 to 150 years have included logging and clearing for agriculture.

Section 222N--Lake Agassiz, Aspen Parklands

Geomorphology. This Section is part of the Central Lowlands geomorphic province. It forms the southeastern margin of a large, level lake plain (created by glacial Lake Agassiz) that extends far to the north and west into Manitoba, Saskatchewan, and Alberta. Low dunes and wet swales mark the Section's western edge; prominent beach and morainal ridges cross the Section in several places. Drainage is dendritic, with only minor entrenchment. Geomorphic processes operating in the Section are fluvial erosion, transport and deposition. Elevation ranges from 900 to 1,250 ft (270 to 380 m). Local relief is low; most areas are nearly level. The western edge has up to 50 to 150 ft (15 to 45 m) of local relief along beach ridges.

Potential Natural Community. Kuchler mapped this area as bluestem prairie and oak savann, with a minor component of maple-basswood forest. Local investigators indicate the pre-

European settlement vegetation was primarily aspen savanna, with significant components of tallgrass prairie, wet prairie, and dry gravel prairie (on gravelly beach ridges.)

Disturbance Regimes. Fire was the most common natural disturbance, followed by floods and tornadoes. Fire frequency and intensity were reduced by the natural barrier of low dunes, beach ridges, and wet swales that mark the western edge of the Section.

Central Appalachian Broadleaf Forest - Coniferous Forest - Meadow

These Sections are located in the eastern conterminous States, including parts of Georgia, North and South Carolina, Virginia, West Virginia, Maryland, and Pennsylvania. The area of these Sections is about 68,100 mi2 (176,400 km2).

Section M221A--Northern Ridge and Valley

Geomorphology. This Section forms part of the Ridge and Valley geomorphic province. It is characterized by a series of parallel, southwest to northeast trending, narrow valleys and mountain ranges (high ridges) created by differential erosion of tightly folded, intensely faulted bedrock. The eastern boundary is the Great Valley low land; the western boundary is a steep, high ridge, the Allegheny Front. Drainage is structurally controlled, dominantly trellis with some dendritic patterns. Mass wasting, karst solution, and fluvial erosion, transport and deposition are the dominant geomorphic processes currently active. A notable but very minor landform is anthropogenic: lands that have been strip-mined exhibit hummocky or gouged topography. Elevation ranges from 300 to 4,000 ft (100 to 1,200 m). Local relief is 500 to 1,500 ft (150 to 450 m).

Potential Natural Vegetation. Because much of this area lies in the rain shadow of the Allegheny Mountains Section, vegetation reflects drier conditions. Kuchler types are mapped as Appalachian oak forest, oak-hickory-pine forest, and some northern hardwoods forest. Braun classified much of the area as oak-chestnut. Before arrival of the blight that decimated the chestnut, this Section was a stronghold of the species. Oaks now dominate. As a broad generalization, red and white oaks occur on more productive, mesic sites. Eastern white pine can occur, with white oak on the lower portions of slopes. Scarlet and black oaks are more common on drier sites. On the driest sites, oaks are mixed with pitch, table mountain, or Virginia pines. The latter can also occur as pure stands.

Disturbance Regimes. Fire was undoubtedly used extensively by Native Americans. Major historical disturbances include grazing from about 1780 onward and extensive logging from 1880 to 1920. Many logging operations were followed by fire. Since the 1930's, many fires have been suppressed through Federal and State agency efforts. Gypsy moth has affected forests in this Section, notably in Virginia.

Section M221B--Allegheny Mountains

Geomorphology. This Section comprises part of the Appalachian Plateaus geomorphic province. It is a maturely dissected plateau characterized by high, sharp ridges, low mountains, and narrow valleys. It has a prominent structural and topographic grain created by broad, northeast to southwest trending folds in the bedrock. Drainage is dendritic to trellis, but primarily the former. Mass wasting, karst solution, and fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 1,000 to 4,500 ft (300 to 1,400 m), with a few peaks higher, notably Spruce Knob (4,861 ft, 1,620 m), the highest point in West Virginia. Local relief generally ranges from 1,000 to 2,500 ft (300 to 600 m).

Potential Natural Vegetation. Kuchler mapped this Section as northeastern spruce-fir, northern hardwoods, mixed mesophytic, and oak-hickory-pine. Strongly influenced by elevation and aspect, the vegetation of the Allegheny Mountains can be placed in four broad groups: red spruce, northern hardwoods, mixed mesophytic, and oaks. Red spruce is characteristic above 3,500 ft (1,060 m) and includes stands of American beech and yellow birch. Beech is more common on northerly aspects, and yellow birch on southerly. The northern hardwood group features sugar maple occurring with beech and black cherry. The mixed mesophytic represents a transition to drier types and presents a wide variety of successional pathways. Characteristic species are red oak, basswood, white ash, and tulip poplar. The productive, diverse cove hardwoods are included in this group. Oak sites occur mostly on foothills, but are much less common in this Section than in the Northern Ridge and Valley Section.

Disturbance Regimes. Erosional processes over eons have been the primary disturbance agents. In the pre-European settlement era, fire was not a significant element of change because of the relatively high precipitation. The current forest was largely shaped by logging and associated fires from about 1880 to 1920. In some areas, notably those in the red spruce zone above 3,500 ft (1,200 m) elevation, some areas burned so severely that soil was removed to the bedrock. These areas are now stunted forests with blueberry understories. Gypsy moth is now entering this Section. Its effect on this Section may be less than on the Northern Ridge and Valley Section, because oak, preferred by the moth, is less extensive here.

Section M221C--Northern Cumberland Mountains

Geomorphology. This section is in the Appalachian Plateaus geomorphic province. Synclinal structure resulting from folding, faulting, and uplift, followed by differential erosion, has resulted in long monoclinal mountains and dissected uplands. Landforms are mainly low mountains where less than 20 percent of the area is gently sloping. Drainage is dendritic to trellis; mass wasting, karst solution, and fluvial erosion, transport and deposition are the primary geomorphic processes operating. Elevation ranges from 2,000 to 2,600 ft (600 to 800 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler classified vegetation as mixed mesophytic forest, Appalachian oak forest, and northern hardwoods. The predominant vegetation form is cold-deciduous broad-leaved forest with a mixture of evergreen needle-leaved trees. Existing forest types consist of oak-hickory. The component consists of white, black, scarlet, and blackjack oaks; common hickories include mockernut and pignut.

Disturbance Regimes. Fire has probably been the principal historical source of disturbance. Climatic influences include occasional summer droughts and ice storms.

Section M221D--Blue Ridge Mountains

Geomorphology. This Section is in the Blue Ridge geomorphic province. The Section was formed by tectonic faulting and uplift of resistant, crystalline bedrock into a relatively narrow band of highly metamorphosed, somewhat parallel mountain ranges. The northern part of this Section (north of Roanoke Gap in Virginia) is characterized by a single, broad (5 to 10 mi, 8 to 16 km) ridge that extends into southern Pennsylvania. The southern half of the Section is broader, higher, more mountainous, and displays little or no structural grain. Though high (46 peaks are over 6,000 ft (1,820 m) in elevation), the mountains are rounded and generally lack prominent angularity. Drainage is structurally controlled, dominantly trellis in the north; dendritic patterns dominate the southern half. Landforms on about 80 percent of the Section are low mountains. The remainder of the Section is open, low mountains. Elevation ranges from 1,000 to over 6,000 ft (300 to 1,800 m). Local relief ranges from 500 to 1,000 ft (150 to 300 m). Mt. Mitchell, the highest point in eastern North America (6,684 ft, 2,025 m), occurs here.

Potential Natural Vegetation. Kuchler classified vegetation in this Section as Appalachian oak forest, southeastern spruce-fir forest, and northern hardwoods. The predominant vegetation form is montane cold-deciduous broad-leaved forest dominated by the genus {\it Quercus}. The oak forest type consists of black, white, and chestnut oaks that dominate dry mountain slopes; pitch pine is often a component along ridge tops. Mesophytic species such as yellow-poplar, red maple, northern red oak, and sweet birch dominate the valleys and moist slopes. Smaller areas of cold-deciduous broad-leaved forest with evergreen needle-leaved trees are present in the intermontane basins, with the hardwood-pine cover type of scarlet, white, blackjack, and post oaks and shortleaf and Virginia pines. Table Mountain pine, a fire-dependent species with serotinous cones, occurs on xeric ridge tops where fire was historically more common. Eastern white pine dominates small areas of coarse-textured soils and parts of the Blue Ridge escarpment joining the Southern Appalachian Piedmont Section. Mesic sites at higher elevations (4,500 ft, 1,360 m) are occupied by northern hardwoods (e.g., sugar maple, basswood, and buckeye); drier sites are dominated by northern red oak. The broad-leaved forest changes to evergreen needle-leaved forest with conical crowns (e.g., red spruce, Fraser fir) above altitudes of about 5,000 to 6,000 ft (1,800 m).

Disturbance Regimes. Fire, wind, ice, and precipitation are the principal causes of natural disturbance. It is believed that native Americans used fire for many purposes, especially at low elevations in intermountain basins, where drier conditions prevail. Fire caused by lightning is more prevalent in some areas, especially in the vicinity of Grandfather Mountain. Tornadoes are

uncommon, but more prevalent are localized "micro-bursts" of intense winds, which cause small patches of trees to be up-rooted, especially on mountain slopes. Winter ice storms are not uncommon at mid-to-high elevations and cause extensive damage to tree crowns. Occasional events of prolonged, intense precipitation cause localized scouring and erosion of drainage channels, followed by siltation, sedimentation, and flooding downstream. An introduced pathogen, the chestnut blight, caused considerable disturbance to composition of most forest stands from 1920 to 1940 by top-killing all American chestnut trees. Gypsy moth has not affected forests in the central and southern subsections, but has the potential to cause a major impact on forest vegetation because of the dominance by oaks.

Ozark Broadleaf Forest - Meadow

Located in parts of Arkansas and Oklahoma, the area of this Section is about 6,400 mi2 (16,600 km2).

Section M222A--Boston Mountains

Geomorphology. This Section is in the Ozark Plateau geomorphic province. Geomorphic characteristics include broad uplift of generally flat-lying marine sediments to a plateau, followed by fluvial erosion, resulting in a strongly dissected region with dendritic drainages. About 80 percent of the Section has landforms of low mountains; 20 percent consists of open hills and plains with hills. Elevation ranges from 650 to 2,600 ft (20 to 80 m). Local relief ranges from 100 to 800 ft (30 to 240 m).

Potential Natural Vegetation. Kuchler mapped this area as oak-hickory forest and oak-hickory-pine forest. Predominant vegetation form is temperate low land and submontane broad-leaved, cold-deciduous forest, with smaller areas of cold-deciduous, broad-leaved forest with evergreen needle-leaved trees. Common oak species in the oak-hickory forest type include white oak, black oak, and northern red oak. Hickories include pignut and mockernut. The shortleaf pine-oak cover type occurs on drier sites where post, scarlet, and blackjack oaks dominate with shortleaf pine.

Southeastern Mixed Forest

These Sections are located in the southeastern conterminous States, including parts of Virginia, North and South Carolina, Georgia, Alabama, Mississippi, Arkansas, Louisiana, and Texas. The area of these Sections is about 193,000 mi2 (499,900 km2).

Section 231A--Southern Appalachian Piedmont

Geomorphology. This Section is in the Appalachian Piedmont geomorphic province. It consists of an intensely metamorphosed, moderately dissected plain consisting of thick saprolite, continental sediments, and accreted terranes. Differential erosion has produced some isolated mountains (monadnocks) which rise above the general land surface. Landforms on about 70 percent of the Section are irregular plains. Landforms on the remaining area are about equally

divided; plains with high hills; open low hills; and tablelands of moderate relief. Elevation ranges from 330 to 1,300 ft (100 to 400 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler mapped this area as oak-hickory-pine forest and southern mixed forest. Predominant vegetation form is evergreen forest with rounded crowns, and about equal areas of cold-deciduous broad-leaved forest with evergreen needle-leaved trees. The oak-hickory forest cover type consists of white, post, and southern red oaks, and hickories of pignut and mockernut. The loblolly-shortleaf pine cover type is common on disturbed areas and usually has an understory component of dogwood and sourwood.

Disturbance Regimes. Fire has probably been the principal historical disturbance, previously burning over small to moderate-size areas between natural barriers with low frequency and low intensity. Climatic influences include occasional summer droughts and winter ice storms, and infrequent tornadoes. Insect-related disturbances are often caused by southern pine beetles.

Section 231B--Coastal Plains, Middle

Geomorphology. This Section is in the Coastal plains geomorphic province. The predominant landform on about 80 percent of the area consists of moderately dissected, irregular plains of marine origin formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Elevation ranges from 80 to 650 ft (25 to 200 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler mapped vegetation as oak-hickory-pine forest, blackbelt, and oak-hickory forest. The predominate vegetation form is evergreen, needle-leaved forest with cold-deciduous, broad-leaved trees. The principal forest cover type consists of loblolly and shortleaf pine with hardwoods, including sweetgum, flowering dogwood, elm, red cedar, southern red oak, and hickories. In central Mississippi and Alabama the hardwood component may be dominant, depending on soil moisture regime and past disturbance. A narrow band of oak-hickory forest type occurs along the extreme western edge of the Section, adjacent to flood plains of the Mississippi River and along major river bottoms.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include occasional summer droughts and winter ice storms, and infrequent tornadoes. Insect disturbances are often caused by southern pine beetles.

Section 231C--Southern Cumberland Plateau

Geomorphology. This Section is in the Appalachian Plateaus geomorphic province. It was formed by the broad uplift of gently-dipping strata to a level-bedded plateau, followed by fluvial erosion and mass wasting. The result of these geomorphic processes is a strongly dissected region of dendritic drainages. About 60 percent of this Section consists of open hills. Other landforms consist of tablelands of considerable relief and open high hills. Elevation ranges from 330 to 1,300 ft (100 to 400 m). Local relief ranges from 300 to 500 ft (90 to 150 m).

Potential Natural Vegetation. Kuchler mapped vegetation as oak-hickory-pine forest and southern mixed forest. The predominant vegetation form consists of needle-leaved, evergreen

trees with cold-deciduous, broad-leaved forest. Principal species include loblolly pine, sweetgum, water oak, red maple, southern red oak, and white oak.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include occasional summer droughts, winter ice storms, and occasional tornadoes.

Section 231D--Southern Ridge and Valley

Geomorphology. This Section is in the Ridge and Valley geomorphic province. The area is a folded, faulted, and uplifted belt of parallel valleys and ridges, strongly dissected by differential erosion, mass wasting, fluvial erosion, and transport and deposition. About 60 percent of this Section consists of plains with hills and 40 percent consists of open high hills. Elevation ranges from 650 to 2,000 ft (200 to 600 m). Local relief ranges from 300 to 500 ft (90 to 150 m) in areas of plains, with elevation ranging from 500 to 1,000 ft (150 to 300 m) in areas of high hills.

Potential Natural Vegetation. Kuchler mapped vegetation as oak-hickory-pine forest and southern mixed forest. The predominant vegetation form is needle-leaved, evergreen trees with cold deciduous, broad-leaved forest. The principal cover type is oak-hickory, which includes southern red oak, white oak, post oak, red maple, winged elm, flowering dogwood, pignut hickory, and loblolly pine. In some areas, loblolly and shortleaf pines are dominant.

Disturbance Regimes. Fire has probably been the principal historical disturbance, previously burning over small areas between natural barriers with moderate frequency and low intensity. Insect related disturbances have resulted from southern pine beetles. Climatic related influences include occasional droughts and ice storms.

Section 231E--Mid Coastal Plains, Western

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform occupying about 80 percent of the Section consists of moderately dissected irregular plains of marine origin. The plains were formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Other landforms consist of plains with hills and smooth plains. Elevations range from 80 to 650 ft (25 to 200 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler mapped this area as oak-hickory-pine forest, southern mixed forest, and southern floodplain forest. The predominant vegetation form consists of needle-leaved evergreen trees. Belts of cold deciduous, broad-leaved hardwoods are prevalent along rivers. The principal forest cover type is loblolly and longleaf pines. Where hardwoods are prevalent, species consist of post, white, blackjack, and southern red oaks. Species of bottom lands are red maple, green ash, Nuttall oak, sweetgum, and swamp hickory.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include occasional summer droughts and winter ice storms, and infrequent hurricanes. Insect disturbances are often caused by southern pine beetles.

Section 231F--Eastern Gulf Prairies and Marshes

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from 10 to 330 ft (3 to 100 m). Local relief ranges from 0 to 100 ft (0 to 30 m).

Potential Natural Vegetation. Kuchler classified vegetation as bluestem-sacahuista prairie and southern cordgrass prairie. Predominant vegetation is mid to tall grass grasslands. Species consist of little bluestem, indiangrass, switchgrass, and big bluestem. Occasional areas of live oak are present. Poorly drained areas along the coast support freshwater and saltwater marsh vegetation of sedges, rushes, saltgrass, and cordgrass.

Disturbance Regimes. Fire and ocean tides have likely been the principal historical disturbance. Climatic influences include occasional hurricanes.

Section 231G--Arkansas Valley

Geomorphology. This Section is in the Ouachita geomorphic province. The area consists of a folded, faulted, and uplifted belt of parallel valleys and ridges, moderately dissected by differential erosion, mass wasting, fluvial erosion and transport and deposition. About 80 percent of this land consists of plains with hills and 20 percent includes open low mountains. Elevation ranges from 330 to 3,000 ft (100 to 900 m). Local relief ranges from 300 to 500 ft (90 to 150 m) in areas with hills. Relief is 500 to 1,000 ft (150 to 300 m) in areas with low mountains.

Potential Natural Vegetation. Kuchler mapped vegetation as oak-hickory forest, oak-hickory-pine forest, cross timbers ({\it Quercus-Andropogon}), and southern floodplains forest. The predominant vegetation form is about equal areas of cold-deciduous, broad-leaved forest and needle-leaved evergreen trees. Principal forest cover types are oak-hickory and loblolly-shortleaf pine. Species include white, black, bur, post, and blackjack oaks; pignut and mockernut hickories; and loblolly and shortleaf pines. Oak-gum-cypress forest type is dominant along major river bottoms and includes cottonwood, sugarberry, river birch, and green ash.

Outer Coastal Plain Mixed Forest

These Sections are located in the southeastern conterminous States, including parts of Delaware, Maryland, Virginia, North and South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas. The area of these Sections is about 173,800 mi2 (450,100 km2).

Section 232A--Middle Atlantic Coastal Plain

Geomorphology. This Section is in the Coastal Plains geomorphic Province. The predominant landform consists of a flat, weakly dissected alluvial plain formed by deposition of continental

sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Landforms on about 50 percent of this Section consist of flat plains. Much of the other landforms are irregular plains. Elevation ranges from 0 to 80 ft (0 to 25 m). Local relief ranges from 10 to 20 ft (3 to 6 m) on flat plains and from 20 to 40 ft (6 to 12 m) on the irregular plains.

Potential Natural Vegetation. Kuchler classified vegetation as oak-hickory-pine forest and southern flood plain forest. The predominant vegetation form is needle-leaved evergreen forest and smaller areas of cold-deciduous broad-leaved forests. The main forest cover type is loblolly pine-hardwood, where hardwood species consist of sweetgum, water oak, white ash, yellow-poplar, red maple, and swamp hickory. On bottomland areas along major rivers, species include green ash, sugarberry, water oak, American sycamore, sweetgum, and American elm.

232B--Coastal Plains and Flatwoods, Lower

Geomorphology. This Section is in the Coastal Plain geomorphic Province. The predominant landform is a flat, weakly dissected alluvial plain was formed by deposition of continental sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. About 90 percent of this Section consists of irregular or smooth plains. Other landforms include open hills. Elevation ranges from 80 to 660 ft (25 to 200 m). Local relief ranges from 10 to 30 ft (3 to 9 m) on smooth plains, and from 30 to 50 ft (9 to 15 m) in areas of hills.

Potential Natural Vegetation. Kuchler mapped this area as southern mixed forest and oak-hickory-pine forest, with smaller areas of southern flood plain forest and pocosin ({\it Pinus-Ilex}). The predominant vegetation form is evergreen needle-leaved trees with scattered areas of cold-deciduous and evergreen broad-leaved forest. Slash and longleaf pines are prevalent throughout the Section, but loblolly pine is common in the northern areas. Sand pine is prevalent in xeric, deep-sand areas of Florida. The oak-gum-cypress forest cover type is common along flood plains of major rivers and includes Nuttall oak, laurel oak, water tupelo, sweetbay, bald cypress, and pond cypress. Localized areas of mostly hardwoods occur, especially in central Florida; types include laurel oak, water oak, sweetbay, sweetgum, live oak, red maple, and spruce pine. An extensive area of grassland vegetation is present in central Florida, north of Lake Okeechobee.

Disturbance Regimes. Fire has been the principal historical disturbance, previously burning over medium to large size areas between natural barriers, generally with moderate frequency and low intensity. Fire occurrence is common in areas dominated by sand pine and is frequent in areas of longleaf pine. Fire intensity can range from moderate to high. Climatic influences include frequent hurricanes. Insect disturbances are often caused by southern pine beetles.

Section 232C--Atlantic Coastal Flatlands

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from 0 to 80 ft (0 to 25 m). Local relief ranges from 0 to 25 ft (0 to 8m).

Potential Natural Vegetation. Kuchler classified vegetation as mainly southern mixed forest and oak-hickory-pine forest, with smaller areas of southern flood plain forest and pocosin ({\it Pinus-Ilex}). The predominant vegetation form is needle-leaved evergreen forest with smaller areas of evergreen broad-leaved forest. Forest cover type is mainly longleaf pine and slash pine in the northern areas. In the southern areas, slash pine replaces loblolly. Pond pine, a fire-maintained species with serotinous cones, is prevalent in coastal North Carolina, where poorly drained organic soils are present and wildfire is common. The oak-gum-cypress forest type is common along flood plains and major rivers; it includes water oak, laurel oak, swamp tupelo, sweetbay, bald cypress, and pond cypress. Localized areas of mostly hardwoods occur and include laurel oak, water oak, sweetbay, sweetgum, live oak, red maple, and spruce pine.

Disturbance Regimes. Fire has probably been the principal historical disturbance, although high intensity fires are relatively common in the pocosin area of eastern North Carolina. Climatic influences include frequent hurricanes. Insect disturbances are often caused by southern pine beetles.

Section 232D--Florida Coastal Lowlands (Western)

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from 0 to 80 ft (0 to 25 m). Local relief ranges from 0 to 100 ft (0 to 30 m).

Potential Natural Vegetation. Kuchler classified vegetation as oak-hickory-pine forest, southern flood plain forest, and live oak-sea oats. The predominant vegetation form is evergreen needle-leaved forest and evergreen broad-leaved forest. The main forest cover type is longleaf pine and slash pine. Large areas of oak-gum-cypress cover type are present in the central part of the Section along major river bottoms, with species of water oak, laurel oak, swamp tupelo, sweetbay, bald cypress, and pond cypress.

Section 232E--Louisiana Coast Prairies and Marshes

Geomorphology. This Section is in the Coastal Plains geomorphic Province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from 0 to 160 ft (0 to 50 m). Local relief ranges from 0 to 50 ft (0 to 15 m).

Potential Natural Vegetation. Kuchler classified vegetation as bluestem-sacahuista prairie and southern cordgrass prairie. Much of the existing vegetation is nonforested grasslands. Prairie grasslands dominate areas inland from the coast and consist of little bluestem, indiangrass, switchgrass, and big bluestem. Occasional areas of live oak are present. Poorly drained areas along the coast support freshwater and saltwater marsh vegetation of sedges, rushes, saltgrass, and cordgrass.

Disturbance Regimes. Fire and ocean tides have probably been the principal historical disturbance. Climatic influences include occasional hurricanes.

Section 232F--Coastal Plains and Flatwoods, Western Gulf

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform consists of weakly to moderately dissected irregular plains of alluvial origin formed by deposition of continental sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. About 80 percent of this Section consists of irregular plains. Other landforms include flat plains and plains with hills. Elevation ranges from 80 to 660 ft (25 to 200 m). Local relief mostly ranges from 100 to 300 ft (30 to 90 m) on irregular plains; however, relief ranges from 0 to 100 ft (0 to 30 m) on flat plains and 300 to 500 ft (90 to 150 m) where plains with hills are present.

Potential Natural Vegetation. Kuchler mapped vegetation as southern mixed forest, oak-hickory-pine forest, and southern flood plain forest. The predominant vegetation form is evergreen needle-leaved forest with a small area of cold-deciduous alluvial forest. The slash pine and longleaf pine cover type dominates most of the Section. The loblolly pine-shortleaf pine cover type is common in the northern parts of the Section. A bottomland type is prevalent along most major rivers and consists of cottonwood, sycamore, sugarberry, hackberry, silver maple, and red maple.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include occasional summer droughts and winter ice storms and infrequent hurricanes. Insect disturbances are often caused by southern pine beetles.

Section 232G--Florida Coastal Lowlands (Eastern)

Geomorphology. This Section is in the Coastal Plains geomorphic Province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation averages 52 to 64 in (1,300 to 1,600 mm). There is little local relief.

Potential Natural Vegetation. Kuchler classified vegetation as oak-hickory-pine forest, southern flood plain forest, and live oak-sea oats. The predominant vegetation form is evergreen needle-leaved forest and evergreen broad-leaved forest. The main forest cover type is longleaf pine and slash pine. Large areas of oak-gum-cypress cover type are present in the central part of the Section along major river flood plains, with species of water oak, laurel oak, swamp tupelo, sweetbay, bald cypress, and pond cypress.

Lower Mississippi Riverine Forest

This Section is located in the south-central conterminous States, including parts of Missouri, Arkansas, Tennessee, Mississippi, and Louisiana. The area of this Section is about 44,300 mi2 (114,700 km2).

Section 234A--Mississippi Alluvial Basin

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform consists of flat, weakly to moderately dissected alluvial plains. The plains were formed by deposition of continental sediments into a submerged, synclinal trough, which was later exposed by sea level subsidence. Elevation ranges from 0 to 660 ft (0 to 200 m). Local relief in most of the Section ranges from 0 to 100 ft (0 to 30 m).

Potential Natural Vegetation. Kuchler classified vegetation as southern floodplain forest and oak-hickory forest. The predominant vegetation form is cold-deciduous, alluvial broadleaf forest, with small areas of cold-deciduous, broad-leaved forest on upland sites. The main cover type is oak-gum-cypress, where main species are Nuttall oak, water oak, laurel oak, cherrybark oak, cottonwood, sycamore, hackberry, red and silver maple, and baldcypress. The oak-hickory cover type consists of post oak, bur oak, northern red oak, black oak, and white oak.

Disturbance Regimes. Periodic flooding has been the principal historical disturbance, but has been reduced by a series of levees and dams built for flood control.

Ouachita Mixed Forest - Meadow

This Section is located in Arkansas and Oklahoma. The area is about 8,800 mi2 (22,800 km2).

Section M231A--Ouachita Mountains

Geomorphology. This section is in the Ouachita geomorphic province. It was formed by tectonic faulting and uplift of resistant bedrock into a narrow band of metamorphosed, parallel (east-west trending) mountain ranges. This was followed by mass wasting and steep and gentle stream valley erosion with fluvial transport. About 75 percent of the area consists of open high hills. Also included are open low mountains. Elevation ranges from 330 to 2,600 ft (100 to 800 m). Local relief in much of the section ranges from 500 to 800 ft, but it can range from 1,000 to 2,000 ft in areas with low mountains.

Potential Natural Vegetation. Kuchler classified vegetation as oak-hickory-pine forest. Existing forest types are mainly loblolly-shortleaf pine. The predominant vegetation form is evergreen needle-leaved forest and a small area of cold deciduous, broad-leaved forest. Loblolly pine and shortleaf pine cover types occur widely. Lesser areas of a shortleaf-oak type (southern red, scarlet, black, post, and blackjack oaks) and oak-hickory (black, scarlet, post, and white oaks and pignut and mockernut hickories) occur in Oklahoma.

Disturbance Regimes. Fire has probably been the principal historical disturbance. Climatic influences include occasional summer droughts, winter ice storms, and infrequent tornados. Insect disturbances are often caused by southern pine beetles.

Pacific Lowland Mixed Forest

The area of this Section, which is located in Washington and Oregon, is about 14,900 mi2 (38,600 km2).

Section 242A--Willamette Valley and Puget Trough

Geomorphology. To the south, there are primarily cyclic flood deposits. To the north, Pleistocene glaciers have deposited and eroded morainal debris. South of the glacial limit, a zone of branching drainages and low divides is sculpted in soft rocks. Throughout the Section, isolated basalt-capped mesas and islands of bedrock occur. Elevation ranges from sea level to 2,000 ft (700 m).

Potential Natural Vegetation. The Willamette Valley portion is a mixture of Douglas-fir and White Oak series with local areas of Western Hemlock and Western Red Cedar series on more moist sites. A similar pattern occurs in the Puget Trough portion, but with a greater abundance of Western Hemlock and Western Red Cedar series and less amount of White Oak and Douglas-fir series. Riparian areas include Cottonwood, Willow, Ash, and Alder series. Bigleaf maple occupies mixed sites. Prairies of Idaho fescue are on droughty, gravelly soils in the Puget Trough; in the Willamette Valley, grasslands of danthonia, bentgrass, orchard grass, needle

grass, fescue, and prairie June grass are on the drier sites. Tufted hairgrass and shrub thickets are dominant in wetlands.

Section M242A--Oregon and Washington Coast Ranges

Geomorphology. These primarily highly dissected low mountains were shaped by debris slide and avalanche erosion processes on slopes of 40 to 120 percent. Incised valleys are distributed throughout the Section. The Olympic Mountains in the north are an anomalously high range, with very deeply incised, fault-controlled drainages which experienced episodes of glaciation. Coastal lowlands formed from active mountain erosion have slopes less than 30 percent and are formed into marine and riverine terraces. Dunes and bogs occur along the coast, with numerous headlands formed of more resistant rock. Elevation range from sea level to 1,800 ft (545 m) is dominant. Most mountain tops are below 4,000 ft (1,212 m). Olympic Mountains peaks extend to 8,000 ft (2,424 m). Local relief is 200 to 800 ft (60 to 242 m).

Potential Natural Vegetation. Lower mountain slopes are dominated by Western Hemlock series. Coastal fog belt areas are dominated by Sitka Spruce and Western Hemlock series. Western Red Cedar series is abundant in the drainages and lower elevations where soil moisture is abundant. Pacific Silver Fir series is dominant on the cryic soils. Shore Pine series occurs on dunes.

Section M242B--Western Cascades

Geomorphology. This is an uplifted sequence of extrusive volcanics and volcanoclastic rocks, interspersed with intrusives, that have been dissected by large order riverine systems. Alpine glaciation has left till and outwash deposits at the higher elevations. The high Cascades to the east of the Section are active volcanoes with evidence of recent, and in some cases, remnant glaciation. The northern part of the Section contains more metasediments than the southerly portion and abounds with classical U-shaped valleys and cirques. Elevation ranges from near sea level at the Columbia River to greater than 14,000 feet (4,516 m) in the peaks of the Cascade Mountains. Most of the Section is between 2,000 and 7,000 feet (645 and 2,258 m). Local relief is more than 1,000 feet (322 m) in most of the Section.

Potential Natural Vegetation. According to Kuchler, the dominant vegetation is silver fir--Douglas--fir forest. The next most abundant is fir-hemlock forest. At the highest elevations, there are dispersed areas of alpine meadow and barrens. In the northernmost portion, there is western spruce-fir forest. Western Hemlock series dominates the frigid and udic regimes. Western red cedar is common in drainages. Cryic regimes are dominated by Pacific Silver Fir, Mountain Hemlock and Subalpine Fir series. Parkland of forbs, grasses, shrubs, lichens, mosses, and krummholz are interspersed at the high elevations above timberline.

Section M242C--Eastern Cascades

Geomorphology. Glaciation of high volcanic peaks has resulted in a relatively steep eastern slope for the Section. High energy streams and flows of debris and mud are common. Glacial forms have not stabilized. Classical U-shaped valleys and cirques abound in the northern part of

the Section. To the south, glaciation was less severe and gradually diminishes towards the southern limit of the Section. Individual volcanic peaks rise above the surrounding incised topography. Many are still active, primarily south of the Olympic-Wallowa lineament. Statistically, an eruption occurs about every 25 years. Small recent volcanic vents are common on the flanks of larger volcanoes. Large areas of fresh lava flows abound in the east of this Section. Volcanic ash from earlier eruptions originally blanketed the east slope. This ash has been concentrated in a southern pumice plateau, blanketing all but the higher hills and ridges. Elevation ranges from near sea level at the Columbia River to more than 10,000 ft (3,300 m) in the high mountain peaks. Most of the Section is between 3,000 and 7,000 ft (968 and 2,258 m). Local relief varies from about 200 ft in the plateau regions to more than 2,000 ft in the deeply dissected mountains.

Potential Natural Vegetation. According to Kuchler, the dominant vegetation is silver fir--Douglas--fir forest. The next most abundant is fir-hemlock forest. At the highest elevations, there are dispersed areas of alpine meadow and barrens. In the northernmost portion, there is western spruce-fir forest. Vegetation series is highly variable and diverse in the Eastern Cascades Section. Ponderosa Pine and Lodgepole Pine series dominate the lower elevations. In the pumice plateau of Oregon they are largely on cryic and xeric soils. Ponderosa Pine series also is in the mesic and frigid and xeric regimes. In the northern part of the Section, Lodgepole Pine series is mostly in cryic regimes. Douglas-fir series occupies frigid and xeric regimes. The higher elevations are dominated by White Fir, Grand Fir, Pacific Silver Fir, and Subalpine Fir series. Local areas of White Bark Pine, and Engelmann Spruce series occur. Quaking aspen occurs adjacent to and in some wet areas. Grass and sedge meadows (dry to wet) are scattered.

Section M244A--Chugach-St. Elias Mountains

Geomorphology. The Kenai, Chugach, and St. Elias Mountains form a rugged, crescent-shaped barrier along the coast of the Gulf of Alaska. High segments of the mountains are dominated by extremely rugged east-trending ridges. The entire range is heavily glaciated, and the topography is characterized by horns, aretes, cirques, and U-shaped valleys. The south coast is deeply indented by fjords and sounds, and the ridges extend southward as chains of islands. Elevation ranges from 330 to greater than 14,750 ft (100 to more than 4,500 m).

Potential Natural Vegetation. Most of the Section is either barren, ice-covered, or mantled with alpine tundra heath meadows. Some spruce-hardwood forests occur along the largest rivers.

Section M244B--Lynn Canal

Geomorphology. The area is dominated by rugged glaciated mountains with deep V-shaped and U-shaped valleys. Many of the bays have narrow borders of hilly moraines, with short flat-bottomed valleys at the head. Most slopes throughout the Section are steep. Elevation ranges from sea level to over 14,750 ft (4,500 m).

Potential Natural Vegetation. Since the Section is partially modified by polar air masses, the prevailing vegetation is quite diverse. Forest vegetation dominated by western hemlock and Sitka

spruce predominate in the low-lying areas up to 300 m in elevation. Mixed conifer, black cottonwood, and lodgepole pine forest types occur on drier inland sites. Low-growing alpine tundra vegetation of sedges and mosses prevails on sites above tree line.

Section M244C--Boundary Range

Geomorphology. The area is dominated by rugged glacier-covered mountains or glaciated mountains with deep V-shaped and U-shaped valleys that straddle the international boundary with Canada. Most slopes throughout the Section are steep. Elevation ranges from sea level to over 9,840 ft (3,000 m).

Potential Natural Vegetation. Most of the area is either barren, ice-covered, or covered by alpine heath meadows. Forest vegetation of hemlock and spruce occurs along river corridors within mountain passes.

Section M245A--Northern Gulf

Geomorphology. This area includes Afognak Island, Prince William Sound, coastal lowlands of Copper River Delta, and Yakutat Forelands. The foreland areas consist of alluvial fans, uplifted estuaries, morainal deposits, dunes, river deltas, and terraces. Crustal uplifting has created terraces or dunes that run parallel to the coastline. Erosion by glacial outburst floods dissect the forelands and dominate landscape patterns. The headlands within Prince William Sound and Afognak Island are erosional bedrock features that end as sea cliffs at the water's edge where little to no deposition occurs except in bays and shallow estuaries. Elevation ranges from sea level to 500 ft (150 m).

Potential Natural Vegetation. Coastal subpolar rainforests of western hemlock and Sitka spruce are characteristic in areas with better soil drainage. Along the coastline, areas with high water tables support sphagnum mosses, sedges, and willows, which foster peatland development.

Disturbance Regimes. Wildfire occurrence is rare.

Section M245B--Northern Alexander Archipelago

Geomorphology. This Section includes Baranof, Chichagof, and Admiralty Islands, and the portion of the mainland below the permanent snowfields in southeast Alaska. These areas have rugged topography with many long and broad U-shaped glaciated valleys, many of which terminate at tidewater. Side slopes are very steep and exposed bedrock is common along the glacially scoured valley walls. The rolling moraine landforms dominate the low hills and valley bottoms. Elevation ranges from sea level to over 3,280 ft (1,000 m).

Potential Natural Vegetation. Perhumid rainforests of Sitka spruce and western hemlock predominate. Water-tolerant plants, such as sphagnum moss, sedges, bog kalmia, and shore pine, occur in peatlands. Alpine tundra heath meadows and barrens occur at higher elevations.

Disturbance Regimes. Wildfire is rare,

Section M245C--Southern Alexander Archipelago

Geomorphology. This Section includes all the islands below Fredrick Sound, as well as the mainland south of the Stikine River corridor below the permanent snowfields in southeast Alaska. Most of the area is rugged mountains with many broad, U-shaped, glaciated valleys which terminate as fjords at tidewater. Tidewater glaciers are infrequent in this Section. Elevation ranges from sea level to over 3,280 ft (1,000 m).

Potential Natural Vegetation. Coastal perhumid rainforests of Sitka spruce and western hemlock predominate. The northern limits of western red cedar and salal correspond to the northern boundary of this Section. Hydric vegetation of sphagnum moss, sedges, and willows predominate on peatlands. Some alpine heath meadows occur on the highest mountains.

Disturbance Regimes. Wildfire occurs only during drought periods.

Prairie Parkland (Temperate)

These Sections are located in the north-central conterminous States, including parts of Oklahoma, Kansas, Nebraska, Missouri, Illinois, Indiana, Iowa, Minnesota, and North and South Dakota. The area of these Section is about 218,200 mi2 (565,100 km2).

Section 251A--Red River Valley

Geomorphology. This Section is part of the Central Lowland geomorphic province. It forms the southern extension of a large, level lacustrine plain (Glacial Lake Agassiz) that extends far to the north and west into Manitoba, Saskatchewan, and Alberta. The plain is bisected by the Red River valley. Prominent alluvial fans formed where the Pembrina and Sheyenne Rivers entered the glacial lake from the west. Beach and morainal ridges border the Section on the east. Other features include kettles, wetlands, and dunes adjacent to the fans. Drainage is a modified trellis pattern; tributaries enter the Red River from uplands to the east and west. Geomorphic processes operating in the Section are fluvial erosion, transport and deposition. Elevation ranges from 825 to 1,150 ft (250 to 350 m). Local relief is 3 to 25 ft (1 to 8 m).

Potential Natural Vegetation. Kuchler types are bluestem prairie and northern flood plain forest, with the latter mapped in a narrow strip along the Red River and its major tributaries.

Disturbance Regimes. Fire, drought, and annual flooding are significant. High wind events are also common. Historically, bison grazing and ant activity caused important faunal modifications of vegetation and soils.

Section 251B--North-Central Glaciated Plains

Geomorphology. This Section is part of the Central Lowland geomorphic province. It is mostly level to rolling till plain. A series of low, sub-parallel, south to north and southeast to northwest trending morainal ridges is featured in the northwestern third of the Section. The Coteau des

Prairies, a moderately dissected, relatively high plateau with a much thinner till cover, is prominent in the northwestern portion. The Minnesota River's broad valley was created by the Pleistocene draining of Glacial Lake Agassiz. There are scattered lacustrine lowlands and outwash channels as well. Elevation ranges from 750 to 2,000 ft (225 to 600 m). Local relief is generally 20 to 100 ft (6 to 30 m); it is higher in a few localized areas, notably the edge of the Coteau des Prairies.

Potential Natural Vegetation. Kuchler type is mapped as almost entirely bluestem prairie, with a narrow corridor of northern flood plain forest along the Minnesota River, and a few fingers of oak-hickory forest along other drainages in the southern part.

Disturbance Regimes. Historically, fire was the most common natural disturbance. Floods and tornadoes also occurred. Fire suppression has allowed woodlands to develop from what was originally oak openings or brush prairies.

Section 251C--Central Dissected Till Plains

Geomorphology. This is part of the Central Lowland geomorphic province. It is characterized by moderately dissected, glaciated, flat to rolling plains that slope gently toward the Missouri and Mississippi River valleys, which bracket the Section on the west-south and east, respectively. Local relief is 20 to 165 ft (6 to 50 m). A minor anthropogenic landform, strip-mined areas, exhibit hummocky or ridge-swale topography. Drainage is dendritic; current geomorphic processes are fluvial erosion, transport and deposition, and minor mass wasting. Elevation ranges from 600 to 1,500 ft (185 to 450 m).

Potential Natural Vegetation. Kuchler vegetation types are mapped as dominantly mosaic of bluestem prairie and oak-hickory forest, with oak-hickory forest along drainageways. An estimated 60 percent of the land surface was bluestem (tall-grass) prairie, with bur oak and white oak savannas interspersed and in transitional areas. Upland forest (white oak-shagbark hickory) occurred on more dissected land, grading into bottomland forests and wet bottomland prairies along rivers.

Disturbance Regimes. Fire and grazing by herds of bison and elk were most important in creation and maintenance of this landscape.

Section 251D--Central Till Plains

Geomorphology. This Section is part of the Central Lowlands geomorphic province. It is a level to gently rolling till-plain (glacial ground moraine), with broad bottomlands and associated terraces and meander scars along major river valleys. The plain is overlain by a series of low, undulating ridges (glacial end moraines). Relief along flood plain margins of major rivers and their larger tributaries can exceed 150 ft (45 m). A notable but minor landform is anthropogenic. lands that have been strip-mined exhibit humocky or ridge-swale topography. The dominant geomorphic processes operating in the Section are fluvial erosion, transport and deposition, with

minor mass wasting. Elevation ranges from 600 to 1,000 ft (180 to 300 m). Local relief is dominantly 3 to 100 ft (1 to 30 m), but ranges up to 165 ft (50 m) along bedrock bluffs along some major streams.

Potential Natural Community. This area is principally tall grass prairie. variations on the big bluestem-indiangrass-prairie dropseed-switchgrass community; cord grass-sedge-blue jointgrass communities on wet sites; and little bluestem-side oats-grama on drier sites. Forest communities occur along stream valleys. white oak-black oak-shagbark hickory community on slopes, with basswood-sugar maple-elm-ash community on wetter, shaded sites. Kuchler mapped the area as oak savanna and oak-hickory forest.

Disturbance Regimes. Historically, major natural disturbances were prairie fires and grazing ungulates. Since settlement, most of the wetlands, marshes, and "prairie potholes" have been drained for agriculture, and virtually all prairie habitats have been replaced with row crops or pasture.

Section 251E--Osage Plains

Geomorphology. This is part of the Central Lowlands geomorphic province. It is characterized by a series of sub parallel, southwestern to northeastern trending, maturely dissected, low cuestas or escarpments separating level to gently rolling plains. Local relief on the cuestas is generally between 100 and 300 ft (30-90 m); on the plains it is less than 100 ft. Elevation ranges from 300 to 1,300 ft (100 to 400 m).

Potential Natural Vegetation. Kuchler vegetation types are mapped as dominantly mosaic of bluestem prairie and oak-hickory forest, with corridors of oak-hickory forest along drainageways. This section was once 70 percent tall-grass prairie, little bluestem and associates, with groves of post and blackjack oaks. Upland prairie graded into wet bottomland prairie, with sloughs, marshes, and mixed bottomland forest. This forest included silver maple, green ash, cottonwood, pecan, pin oak, and bur oak.
Disturbance Regimes. Fire, grazing, drought (occasionally very severe), and tornadoes were the principal prehistoric sources of disturbance. Coal is strip-mined in many places.

Section 251F--Flint Hills

Geomorphology. Relatively old episodes of Paleozoic platform sedimentation were followed by uplift and dissection, characteristic of geomorphic processes historically active in this Section. Present geomorphic processes include gentle and moderate gradient valley stream erosion, transport and deposition. Gentle sloping hills with relief of 300 to 500 ft, found among lowlands, make up most of the area. This Section is within the Central Lowlands geomorphic physical province. Elevation ranges from 985 to 1,970 ft (300 to 600 m).

Potential Natural Vegetation. There is bluestem prairie with northern flood plain forest along major drainages.

Disturbance Regimes. Fire and drought have probably been the principal historical sources of disturbance.

Section 251G--Central Loess Plains

Geomorphology. Dissected loess plains comprise this Section. It has gently rolling smooth, and irregular plains mantled by loess. Drainage pattern cuts into upper loess mantle and exposes older Loveland loess. Stream valleys are narrow, not deeply incised. Local relief ranges from tens to hundreds of ft. This Section is in the Central Lowlands and Great Plains geomorphic provinces. Elevation ranages from 600 to 1,970 ft (183 to 600 m).

Potential Natural Vegetation. There is bluestem prairie with northern flood plain forest along major drainages.

Disturbance Regimes. Drought and fire are probably the principal sources of disturbance.

Prairie Parkland (Subtropical)

These Sections are located in Oklahoma and Texas. The area of these Sections is about 80,100 mi2 (207,500 km2).

Section 255A--Cross Timbers and Prairies

Geomorphology. This Section is in the Central Lowlands geomorphic province. The predominant landform on about 70 percent of the Section consists of irregular plains that originated from uplift of level bedded continental sediments, that had been deposited into a shallow inland sea, followed by a long period of erosion. Other landforms include plains with hills and open high hills. Elevation ranges from 330 to 1,300 ft (100 to 400 m). Local relief ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler classified vegetation as cross timbers ({\it Quercus-Andropogon}), oak-hickory forest, and oak-hickory-pine forest. The predominant vegetation form is cold-deciduous broad-leaved forest and extensive areas of tall grassland with a tree layer. Forest cover consists of post, live, and blackjack oaks, and pignut and mockernut hickories. Grasses consist of big and little bluestems, indiangrass, and sunflower.

Disturbance Regimes. Fire and drought have probably been the principal historical sources of disturbance.

Section 255B--Blackland Prairies

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform is irregular plains. This Section is an elevated sea bottom that has been shaped by marine and shore-zone processes resulting from repeated episodes of submergence and emergence of the land from the ocean. Some geomorphic processes currently active throughout

the area are gentle gradient valley stream erosion, transport and deposition. Elevation ranges from 330 to 660 ft (100 to 200m). Local relief ranges from 100 to 300 ft.

Potential Natural Vegetation. Kuchler mapped vegetation as blackland prairie ({\it Andropogon-Stipa}) and juniper-oak savanna. The predominant vegetation form is tall grassland consisting mainly of bunch grasses, such as indiangrass, big bluestem, switchgrass, and eastern gamagrass. A savanna community occurs along many major rivers, consisting of elm, pecan, cottonwood, and hackberry, with grasses between the trees.

Disturbance Regimes. Fire and drought have probably been the principal historical sources of disturbance.

Section 255C--Oak Woods and Prairies

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform on about 80 percent of the Section consists of irregular plains. Other landforms include plains with hills and smooth plains. This Section is an elevated sea bottom that has been shaped by marine and shore-zone processes resulting from repeated episodes of submergence and emergence of the land from the ocean. Some geomorphic processes currently active throughout the area are gentle gradient valley stream erosion, transport and deposition. Elevation ranges from 650 to 1,310 ft (200 to 400 m). Local relief ranges from 100 to 300 ft.

Potential Natural Vegetation. Kuchler classified vegetation as oak-hickory forest, cross timbers ({\it Quercus-Andropogon}), and juniper-oak savanna. The predominant vegetation type is cold-deciduous, broad-leaved forest. The oak-hickory cover type consists of scarlet, post, and blackjack oaks, and pignut and mockernut hickories. Forests of elm, pecan, and walnut are in bottomlands. Little bluestem is the dominant grass.

Disturbance Regimes. Fire and drought have probably been the principal historical disturbances.

Section 255D--Central Gulf Prairies and Marshes

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform consists of a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore-zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from sea level to 160 ft (0 to 50 m). Local relief ranges from 0 to 100 ft.

Potential Natural Vegetation. Kuchler classified vegetation as bluestem-sacahuista prairie and southern cordgrass prairie. The predominant vegetation form is tall grassland consisting mainly of bunch grasses. Prairie grasslands dominate areas inland from the coast and consist of little bluestem, indiangrass, switchgrass, and big bluestem. Occasional areas of live oak are present.

Poorly drained areas along the coast support freshwater and saltwater marsh vegetation of sedges, rushes, saltgrass, and cordgrass.

Disturbance Regimes. Ocean tides have probably been the principal historical disturbance. Climatic influences include occasional hurricanes.

California Coastal Chaparral Forest and Shrub

These Sections are located along coastal California. The area of these Sections is about 10,300 mi2 (26,700 km2)

Section 261A--Central California Coast

Geomorphology. This area includes parallel ranges and valleys on folded, faulted and metamorphosed strata; there are rounded crests of subequal height. This Section is in the Coast Ranges geomorphic province. Elevation ranges from sea level to 2,400 ft (0 to 730 m).

Potential Natural Vegetation. Kuchler mapped vegetation as mixed hardwood forest, coastal prairie-scrub, coastal sagebrush, mixed hardwood and redwood forest, redwood forest, and southern oak forest. Predominant potential nautral communities are Coastal Sage (Lucian), Coast Live Oak, Coastal Perennial Grassland and Redwood (northern part) series. Fires are of variable frequency, season, and intensity.

Section 261B--Southern California Coast

Geomorphology. This Section comprises narrow ranges and broad fault blocks, as well as alluviated lowlands and coastal terraces. It is in the Transverse and Peninsular Ranges geomorphic province. Elevation ranges from sea level to 3,000 ft (0 to 912 m).

Potential Natural Vegetation. Kuchler mapped vegetation as chaparral, coastal sagebrush, southern oak forest and valley oak savanna. Predominant potential natural communities are Coastal Sage (Venturan) and Coastal Perennial Grassland series. Historic occurrence of fire has changed from variable frequency, season, and intensity to more frequent, larger, and more intense fires.

California Dry Steppe

The area of this Section, which is located in California, is about 19,200 mi2 (49,700 km2).

Section 262A--Great Valley

Geomorphology. This low fluviatile plain is in the Great Valley geomorphic province. Elevation ranges from sea level to 800 ft (0 to 243 m).

Potential Natural Vegetation. Kuchler mapped vegetation as California prairie, riparian forest, tule marsh, San Joaquin saltbush and valley oak savanna. Predominant potential natural communities are Valley Oak, Valley Needlegrass, and Saltbush series. Historic occurrence of

fire has changed from frequent, fast moving, large fires to infrequent small fires, or fire has been mostly excluded because of conversion to irrigated agriculture and urban uses.

California Coastal Steppe, Mixed Forest, and Redwood Forest

This Section is located along coastal California. The area of this Section is about 4,600 mi2 (11,900 km2).

Section 263A--Northern California Coast

Geomorphology. This area has parallel ranges, and folded, faulted, and metamorhosed strata; there are rounded crests of subequal height. This Section is in the Coast Ranges geomorphic province. Elevation ranges from sea level to 3,000 ft (0 to 912 m).

Potential Natural Vegetation. Kuchler mapped vegetation as redwood forest, mixed evergreen forest, coastal prairie-scrub, coastal cypress and pine forest, and mixed hardwood forest. Predominant potential natural communities include Redwood, Douglas-Fir, Tanoak, Coast Live Oak, Coastal Sage (Franciscan) and North Coastal Shrub series. Historic occurrence of fire is changing from frequent, low to high intensity surface fires to infrequent, moderate to high intensity stand-replacing fires.

Sierran Steppe - Mixed Forest - Coniferous Forest

The area of these Sections is about 68,300 mi2 (176,900 km2).

Section M261A--Klamath Mountains

Geomorphology. This is an uplifted and dissected peneplain on strong rocks; there are extensive monadnock ranges. Elevation ranges from 1,500 to 8,000 ft (456 to 2,432 m). This Section is in the Klamath Mountains geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Klamath montane forest, mixed evergreen forest, Oregon oak forest and northern yellow pine forest. Predominant potential natural communities are Douglas-Fir, Ponderosa Pine, Mixed Conifer, Jeffrey Pine, White Fir and Red Fir series. At lower and mid elevations, historic occurrence of fire has changed from frequent, low intensity ground fires to infrequent, high intensity stand-replacing fires. At higher elevations, historic occurrence has changed from infrequent, low and moderate intensity ground fires to infrequent, low, moderate and high intensity surface or stand-replacing fires.

Section M261B--Northern California Coast Ranges

Geomorphology. This area has parallel ranges, and folded, faulted, and metamorhosed strata; there are rounded crests of subequal height. Elevation ranges from 1,000 to 7,500 ft (304 to 2,280 m). This Section is in the Coast Ranges geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Coast Ranges montane forest, mixed evergreen forest, chaparral, blue oak-foothill pine forest, and mixed hardwood forest. Predominant potential natural communities are Douglas-Fir, White Fir, Ponderosa Pine, Tanoak, Interior Live Oak, Coast Live Oak and Mixed Chaparral series. Historic occurrence of fire has changed from frequent, low, moderate, and high intensity surface fires to infrequent, high intensity ground or stand-replacing fires.

Section M261C--Northern California Interior Coast Ranges

Geomorphology. This area has parallel ranges and folded, faulted, and metamorhosed strata; there are rounded crests of subequal height. Elevation ranges from 200 to 2,500 ft (61 to 760 m). This Section is in the Coast Ranges geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as blue oak-foothill pine forest, chaparral and California prairie. Predominant potential natural communities are Blue Oak, Mixed Chaparral and Valley Needlegrass series. Fires are low, moderate, and high intensity surface or stand-replacing fires.

Section M261D--Southern Cascades

Geomorphology. These volcanic mountains are variously eroded; there is no distinct range. Elevation ranges from 1,500 to 14,000 ft (456 to 5,256 m). This Section is in the Cascade Range geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Sierran montane forest, sagebrush steppe, yellow pine-shrub forest and northern yellow pine forest. Predominant potential natural communities are White Fir, Ponderosa Pine, Mixed Conifer, Red Fir, Lodgepole Pine and Oregon Oak series. At lower and mid-elevations, historic occurrence of fire has changed from frequent, low intensity, surface fires to infrequent, high intensity, stand-replacing fires. At higher elevations, historic occurrence has changed from infrequent, low and moderate intensity surface fires to infrequent, low, moderate, and high intensity surface or stand-replacing fires. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities.

Section M261E--Sierra Nevada

Geomorphology. This block mountain range tilts west and has accordant crests. Elevation ranges from 1,000 to 14,495 ft (300 to 4,407 m). Local relief ranges from 500 to 2,000 ft (150 to 600 m). It is in the Sierra Nevada Range geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Sierran montane forest, upper montane-subalpine forest, alpine communities and barren, and northern Jeffrey pine forest. Predominant potential natural communities are Ponderosa Pine, Ponderosa Pine-Mixed Conifer, Douglas Fir-Mixed Conifer, White Fir-Mixed Conifer, Red Fir, Lodgepole Pine, Jeffrey Pine, Big Sagebrush, Canyon Live Oak, White Alder, Mountain Alder, Huckleberry Oak, Carex and Aspen series. At lower and mid-elevations, historic occurrence of fire has changed from

frequent, low intensity ground fires to infrequent, high intensity stand-replacing fires. At higher elevations, historic occurrence has changed from infrequent, low and moderate intensity ground fires to infrequent, low, moderate, and high intensity surface or stand-replacing fires. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities.

Section M261F--Sierra Nevada Foothills

Geomorphology. This block mountain range tilts west and has accordant crests. Elevation ranges from 500 to 3,500 ft (152 to 1,064 m). It is in the Sierra Nevada Range geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as blue oak-foothill pine forest, and chaparral. Predominant potential natural communities are Blue Oak, Interior Live Oak, Valley Needlegrass and Mixed Chaparral series. Fires are low, moderate, and high intensity surface or stand-replacing fires.

Section M261G--Modoc Plateau

Geomorphology. This area comprises northwesterly trending fault-block mountains and ridges, with intervening basin-like grabens commonly interspersed with lake bed deposits, shield volcanoes, cinder cones, or lava flows. Elevation ranges from 3,000 to 9.900 ft (912 to 3,010 m). This in in the Modoc Plateau geomorphic province (part of the Basin and Range Province flooded with volcanics related to those of the Cascade Range Province).

Potential Natural Vegetation. Kuchler mapped vegetation as yellow pine-shrub forest, juniper-shrub savannah, Sierran montane forest, sagebrush steppe, upper montane-alpine forests, and northern Jeffrey pine forest. Predominant potential natural communities are Ponderosa Pine, Mixed Conifer, Western Juniper, White Fir, Big Sagebrush, Low Sagebrush and Carex series. Historic occurrence of fire has changed from frequent, low intensity ground fires to infrequent, high intensity stand-replacing fires.

California Coastal Range Open Woodland - Shrub - Coniferous Forest - Meadow

These Sections are located in California. The area of these Sections is about 24,900 mi2 (64,500 km2).

Section M262A--Central California Coast Ranges

Geomorphology. This area has parallel ranges, and folded, faulted, and metamorphosed strata; the rounded crests are of subequal height. This Section is in the Coast Ranges geomorphic province. Elevation ranges from 500 to 3,500 ft (152 to 1,064 m).

Lithology and Stratigraphy. There are Cenozoic marine and nonmarine sedimentary rocks and alluvial deposits; late Mesozoic shelf, slope, and eugeosynclinal sedimentary rocks; and Mesozoic ultramafic rocks.

Soil Taxa. Soils include Alfisols, Aridisols, Entisols, Inceptisols, Mollisols, and Vertisols, in combination with thermic soil temperature regime and xeric and aridic soil moisture regimes.

Potential Natural Vegetation. Kuchler mapped vegetation as blue oak-foothill pine forest, California prairie, and chaparral. Predominant potential natural communities are Blue Oak, Interior Live Oak, Valley Oak, Mixed Chaparral, Western Juniper-Pinyon Pine (southern part), Bluegrass, and Valley Needlegrass series. Fires are low, moderate, or high intensity ground or stand-replacing fires. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities.

Section M262B--Southern California Mountains and Valleys

Geomorphology. There are narrow ranges and broad fault blocks, alluviated lowlands, and dissected westward sloping granitic uplands. This Section is in both the Transverse and Peninsular Ranges geomorphic provinces. Elevation ranges from 500 to 11,500 ft (153 to 3,496 m).

Lithology and Stratigraphy. There are Cenozoic marine and nonmarine sedimentary rocks and alluvial deposits, and Mesozoic granitic rocks.

Soil Taxa. Soils include Alfisols, Entisols, Inceptisols, and Mollisols, in combination with thermic, mesic, and frigid soil temperature regimes and xeric and aridic soil moisture regimes.

Potential Natural Vegetation. Kuchler mapped vegetation as southern oak forest, coastal sagebrush, chaparral and southern yellow pine forest. Predominant potential natural communities include Chamise, Ceanothus, Mixed Chaparral, Scruboak, Coast Live Oak, Englemann Oak, Needlegrass, Jeffrey Pine, Canyon Oak and Big Cone Douglas-Fir series. There are stand-replacing fires of variable frequency, season, and intensity. Some plant and animal species show effects of air pollution.

Great Plains Steppe and Shrub

Most of this section is located in Oklahoma. The area of this Section is about 17,600 mi2 (45,600 km2).

Section 311A--Redbed Plains

Geomorphology. This Section is in the Central Lowlands geomorphic province, and is mostly in Oklahoma. Platform uplift of continental sediments deposited previously into a shallow inland sea, followed by a long period of erosion; these processes resulted in a moderately to strongly dissected region. About 70 percent of this Section consists of irregular plains. Other landforms include about equal areas of plains with low mountains, smooth plains, and tablelands. Elevation ranges from 1,600 to 3,000 ft (500 to 900 m). Local relief in much of the Section ranges from

100 to 300 ft (30 to 90 m). Smaller areas are present where relief ranges from 30 to 60 ft (10 to 20 m) in tablelands and up to 1,000 ft (300 m) in low mountains.

Potential Natural Vegetation. Kuchler classified vegetation as bluestem-grama prairie, and cross timbers ({\it Quercus-Andropogon}); shinnery ({\it Quercus-Andropogon}); and sandsage-bluestem prairie. The predominant vegetation form is medium-tall grasslands with sparse tree cover. Grasses consist mainly of sand bluestem, little bluestem, and sand saltbrush. Fire and drought have probably been the principal historical disturbances.

Colorado Plateau Semi-Desert

These Sections are located in the southwestern conterminous States, including parts of Arizona, New Mexico, Utah, and Colorado. The area of these Sections is about 75,300 mi2 (195,000 km2

Section 313A--Grand Canyon

Geomorphology. This Section is in the Colorado Plateau physiographic province. Grand Canyon lands are in the south-central part of Utah and the northern portion of Arizona. It extends into the southwestern corner of Colorado. This area is eroded by the Colorado River and its tributaries. Deep sheer-walled canyons, lines of cliffs, elevated plains, low plateaus, mesas, buttes, and badlands dominate landscape. Major landforms are the Grand Canyon and Colorado Plateau. Elevation ranges from 4,200 to 7,800 ft (1,300 to 2,400 m).

Potential Natural Vegetation. This area consists of pinyon-juniper woodland with a small area of Great Basin sagebrush, and blackbrush vegetation. The area has a cold desert shrub and steppe woodland vegetation, with some paleoendemic blackbrush. Fire is cyclical. Grazing for sheep and cattle is the major land use. Hay and pasture lands also occur to a very limited extent along drainage ways. Climate is very dry and hot in the summer and cold and moist in the winter, indicative of a cold, desertic condition.

Section 313B--Navajo Canyonlands

Geomorphology. This Section is in the Colorado Plateaus physiographic province. Navajo Canyonlands are in the northeast part of Arizona and southeast Utah. Geomorphic processes active in this area are deep canyon formations as the result of plateau dissection. Volcanic mountains exist in this Section, but block-fault structural mountain ranges do not. Major landforms are canyonlands, plateaus, plains, and hills. Major landform features are the Painted Desert, Vermillion and Echo Cliffs, Glen Canyon Recreation Area, and Canyonlands National Park. Elevation ranges from 4,000 to 8,000 ft (1,210 to 2,425 m).

Potential Natural Vegetation. Vegetation consists of pinyon-juniper woodlands at higher elevations. Grama and galleta grasses are found at lower elevations; greasewood and saltbrush are found on calcareous and salt affected soils. Fires are variable in frequency and intensity. Flash floods and drought are common. Approximately 90 percent of this area is rangeland. It is grazed by both cattle and sheep.

Section 313C--Tonto Transition

Geomorphology. The Tonto Transistion Section lies between the Basin and Range and Colorado Plateaus physiographic provinces. The Tonto Transition Section is located in central and northwest central Arizona. Precambrian through Mesozoic volcanic activity and sedimentary deposition were major geomorphic processes. Lava flows, plugs, dikes, and relatively flat sedimentary deposits resulted. Major landforms are mountains, hills, scarps, and some plains. Major landform features include the Mazatzal Mountains, Black Hills, Aquarius Mountains, Bradshaw Mountains, and the Superstition Mountains. Elevation ranges from 3,000 to 7,400 ft (915 to 2,255 m).

Potential Natural Vegetation. Vegetation consists of interior chaparral of Turbinella oak on coarse igneous parent materials, steep slopes, and fire disturbed regimes. There are pinyon-juniper on elevations higher than about 4,200 ft (1,280 m); ponderosa pine occurs in frigid and limited mesic soil temperature regimes at higher elevations.

Fire climaxes occur on steep slopes and many coarse igneous rocks in mesic and thermic soil temperature regime areas in the interior chaparral community. Frequency is variable, but may range from 25 to 100 years. Flash floods and droughts are common.

Section 313D--Painted Desert

Geomorphology. This Section is in the Colorado Plateaus physiographic province. Geomorphic processes active in this area are Mesozoic sedimentary deposition followed by tilting and erosion into majestic plateaus. Major landforms are plains, hills, canyonlands, and valley plains. Elevation ranges from 4,000 to 7,000 ft (1,210 to 2,134 m).

Potential Natural Vegetation. Grama and galleta grasses occur at lower elevations and pinyon-juniper woodlands at higher elevations; saltbrush-greasewood type occur in dry, salt affected, and calcareous soils. Fires are variable in frequency and intensity. Flash floods and drought are common. Most of this area is rangeland. It is grazed by both sheep and cattle.

Section 313E--Central Rio Grande Intermontane

Geomorphology. This Section, which is in the Basin and Range physiographic province, is located in central New Mexico. Active geomorphic processes in this Section are basins produced by erosional and depositional action of running water. Major landforms are valleys and lowland and outwash plains, and alluvial fans and terraces. The Rio Grande basin is the major landform feature.

Potential Natural Vegetation. Grama and galleta grasses and four-wing saltbrush occur along with sand sage at lower elevations; pinyon-juniper woodlands are at higher elevations. A few areas have riparian species such as cottonwood and willow. Fires are variable in frequency and intensity, depending on fuel and moisture. Most of this Section is grazed by sheep and cattle.

Southwest Plateau and Plains Dry Steppe and Shrub

These Sections are located in the New Mexico and Texas. The area of these Sections is about 160,900 mi2 (416,700 km2).

Section 315A--Pecos Valley

Geomorphology. This section is in the Great Plains physiographic province. It is located in west-central New Mexico. Major landforms are plains, hills, basins, and fans. Major landform features include the Pecos Plains and the Canadian Valley. Elevation range from 4,000 to 6,900 ft (1,200 to 2,100 m)

Potential Natural Vegetation. Vegetation consists of grama and galleta grass, pinyon-juniper in mesic soil temperature regimes, and ustic soil moisture regimes, and mesquite bush in aridic soil moisture regimes.

Disturbance Regimes. Fires vary in frequency and intensity, depending on fuel load and moisture.

Section 315B--Texas High Plains

Geomorphology. This Section is in the Great Plains geomorphic province. The predominant landform consists of a broad, extensive flat plain formed by fluvial sedimentation of continental erosional products from adjacent mountain ranges, followed by sheet erosion and transport. These processes resulted in a region of moderate dissection. Elevation ranges from 2,600 to 6,500 ft (800 to 2,000 m). Local relief in most of the Section ranges from 100 to 300 ft, however, relief in the tablelands ranges from 300 to 500 ft.

Potential Natural Vegetation. Kuchler classified vegetation as grama-buffalo grass and shinnery ({\it Quercus-Andropogon}). The predominant vegetation form is short grass communities composed of bunch grasses with a sparse shrub layer. Species include short grasses (blue gramma, and buffalograss), sagebrush, mesquite, and yucca.

Disturbance Regimes. Fire and drought have probably been the principal historical disturbances.

Section 315C--Rolling Plains

Geomorphology. This Section is in the Central Lowlands geomorphic province. Landforms originated from platform uplift of continental sediments deposited previously into a shallow inland sea, followed by a long period of erosion. These processes resulted in a moderately dissected landscape. About 80 percent of this Section is equally divided between irregular plains and tablelands. Smaller areas of smooth plains and plains with hills are also present. Elevation

ranges from 1,640 to 2,950 ft (500 to 900 m). Local relief in most of the Section ranges from 100 to 300 ft. Smaller areas are present where local relief ranges from 300 to 500 ft.

Potential Natural Vegetation. Kuchler classified vegeataion as mesquite-buffalo grass. The predominant vegetation form is medium-tall grassland with a sparse shrub cover. The vegetative community consists of sand and little bluestems and sagebrush.

Disturbance Regimes. Fire and drought have probably been the principal historical disturbances.

Section 315D--Edwards Plateau

Geomorphology. This Section is in the Great Plains geomorphic province. The predominant landform consists of a broad, extensive flat plain formed by fluvial sedimentation of continental erosional products from adjacent mountain ranges, followed by sheet erosion and transport; these processes resulted in a region of moderate dissection. About 90 percent of this Section consists of landforms equally divided between smooth plains and tablelands having moderate relief. Also included are smaller areas of open high hills, high hills, and plains with hills. Elevation ranges from 650 to 4,000 ft (200 to 1,200 m). Local relief in most of the Section ranges from 100 to 300 ft (30 to 90 m). In a small area of hills, relief ranges from 300 to 500 ft (90 to 150 m).

Potential Natural Vegetation. Kuchler classified vegetation as juniper-oak savanna and mesquite-acacia-savanna. The predominant vegetation form is mid to short grasslands and evergreen scale-leaved woodlands with a sparse cover of drought-deciduous shrubs. A mixture of species may occur, including blackjack oak, red cedar, mesquite, live oak, and species of mid and short grass grasslands.

Disturbance Regimes. Fire and drought have probably been the principal historical disturbances.

Section 315E--Rio Grande Plain

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform in this Section is a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto submerged, shallow continental shelf, which was later exposed by sea level subsidence. Elevation ranges from 80 to 1,000 ft (25 to 300 m). Local relief in most of the Section ranges from 100 to 300 ft (30 to 90 m).

Potential Natural Vegetation. Kuchler classified vegetation as mesquite-acacia-savanna and ceniza shrub. The predominant vegetation form is short grassland with a sparse cover of drought deciduous shrubs. Species include mesquite, cactus, and tall and mid grasses. Live oaks and cottonwoods may be present along stream banks.

Disturbance Regimes. Drought has probably been the principal historical disturbance.

Section 315F--Southern Gulf Prairies and Marshes

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform consists of a flat, weakly dissected alluvial plain formed by deposition of continental sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore-zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from sea level to 160 ft (0 to 50 m). Local relief ranges from 0 to 50 ft (0 to 18 m).

Potential Natural Vegetation. Kuchler classified vegetation as bluestem-sacahuista prairie and southern cordgrass prairie. The predominant vegetation form is tall grassland with little tree cover. Grasslands dominate areas inland from the coast and consist of little bluestem, indiangrass, switchgrass, and big bluestem. Occasional areas of live oak are present. Poorly drained areas along the coast support freshwater and saltwater marsh vegetation of sedges, rushes, saltgrass, and cordgrass.

Disturbance Regimes. Ocean tides and grazing have probably been the principal historical disturbance. Climatic influences include occasional hurricanes.

Arizona-New Mexico Mountains Semi-Desert - Open Woodland - Coniferous Forest - Alpine Meadow

These Sections are located in Arizona and New Mexico. The area of these Sections is about 50,200 mi2 (130,000 km2).

Section M313A--White Mountain-San Francisco Peaks-Mogollon Rim

Geomorphology. Located in the Colorado Plateau physiographic province, this section is in central and eastern-central Arizona and west-central New Mexico. Geomorphic processes active in this Section include Cenozoic volcanism, including basaltic lava flows, cinder cone eruptions, and volcanic ash. Major landforms include mountains, plains, plateaus, and hills. Major landform features include the San Francisco Mountains, White Mountains, and Jemez and Mogollon Mountains. Elevation ranges from 6,000 to over 12,600 ft (1,820 to 3,860 m).

Potential Natural Vegetation. Predominant vegetation consists of ponderosa pine and gambel oak in frigid soil temperature and ustic soil moisture regimes, and white fir, Douglas-fir in frigid-udic regimes. Engelmann spruce and corkbark fir are in cryic-udic regimes and mountain avens are in pergelic-udic regimes. Natural fires occurred in ponderosa pine about every 3 to 10 years, but have been prevented recently. This has led to a higher canopy cover and increased fuel loads, resulting in a less resilient ecosystem and increased hazard of wildfire. Much of this area is covered with timber, with rangeland and recreation being secondary uses.

Section M313B--Sacramento-Manzano Mountain

Geomorphology. This Section is in the Basin and Range physiographic province; it is located in central and south-central New Mexico. Major landforms are mountains, hills, plains, and scarps. Major landform features are the Sacramento, Manzano and Sandia Mountains and the Canadian Escarpment. Elevation ranges from 6,000 to 11,000 ft (2,130 to 3,690 m).

Potential Natural Vegetation. Vegetation consists of ponderosa pine in frigid soil temperature regimes and ustic and udic soil moisture regimes, Douglas-Fir in frigid-udic regimes, pinyon-juniper in mesic-ustic regimes, and Engelmann spruce, and subalpine fir in cryic-udic regimes. A few areas support grey oak at the lowest elevations. Natural fire regime averages 3 to 10 years of frequency in ponderosa pine forests. Much of this area is covered with timber, with some areas of commercial quality. Another use of land is as range.

Chihuahuan Semi-Desert

These Sections are located in the southwestern conterminous States, including parts of Arizona, New Mexico, and Texas. The area of these Sections is about 85,200 mi2 (220,700 km2).

Section 321A--Basin and Range

Geomorphology. This area, which is in the Basin and Range physiographic province, is located in southeast Arizona and southwest and central New Mexico. Relatively recent episodes of continental rifting, volcanism, erosion, and sedimentation have dominated this Section. Various landforms comprise about equal areas: (1) plains with low mountains consisting of 50 to 80 percent of gently sloping area and local relief of 1,000 to 3,000 ft; (2) plains with high hills where relief is 1,000 to 3,000 ft; (3) open high hills with relief of 500 to 1,000 ft; and (4) tablelands with moderate relief averaging 100 to 300 ft. Elevation ranges from 2,600 to 5,500 ft (800 to 1676 m).

Potential Natural Vegetation. Kuchler mapped vegtation as trans-Pecos shrub savanna ({\it Flourensia-Larrea}); grama-tobosa desert grasslands; oak-juniper woodland; and mesquite-tarbush desert scrub. Drought has probably been the principal historical source of disturbance.

Section 321B--Stockton Plateau

Geomorphology. This Section is in the Great Plains geomorphic province. The predominant landform consists of open high hills with smaller areas of tablelands. These landform were formed by fluvial sedimentation of continental erosional products from adjacent mountain ranges, which was followed by sheet erosion and transport. These processes resulted in a region of shallow dissection. Elevation ranges from 2,600 to 4,500 ft (800 to 1,300 m). Local relief in most of the Section ranges from 500 to 1,000 ft. Relief in a small area of tablelands ranges from 300 to 500 ft.

Potential Natural Vegetation. Kuchler classified vegetation as trans-Pecos shrub savanna ({\it Flourensia-Larrea}); with juniper and redcedar woodlands. The predominant vegetation form is

short to mid height grasslands with sparse cover of drought-deciduous and scale-leaved shrubs and small trees. Species include desert shrubs in association with short to mid height grasses and oak savannas. This section is part of the Chihuahuan Desert and drought has been the principal disturbance.

American Semi-Desert and Desert

These Sections are located in California and Arizona. The area of these Sections is about 87,700 mi2 (227,100 km2).

Section 322A--Mohave Desert

Geomorphology. This area comprises widely separated short ranges in desert plains. It contains isolated mountains, plateaus, alluvial fans, playas, basins, and dunes. Elevation ranges from 300 ft below sea level to 11,000 ft above sea level (-91 to 3,344 m). This Section is in the Basin and Range geomorphic province.

Potential Natural Vegetation. uchler mapped vegetation as Mojave creosote bush, juniper-pinyon woodland, desert saltbush, and Joshua tree scrub. Predominant potential natural communities include creosote bush, blackbush, greasewood and saltbush series on basins, plains, and hills; Joshua Tree series on plains and hills; and basin sagebrush, western juniper and pinyon pine series on mountains. Areas with less than about 8 in (200 mm) of rainfall rarely support enough vegetation to carry a fire. Fire occurrence in areas receiving more than about 8 in (200 mm) has been influenced by introduced grasses. Fires are variable in frequency and intensity. Flash floods are commonly associated with the irregular occurrence of precipitation events.

Section 322B--Sonoran Desert

Geomorphology. This Section is in the Basin and Range physiographic province. There are widely separated short ranges in desert plains. This Section, which is located in southwestern Arizona, has as its major landforms, plains, fans, and terraces. Elevation ranges from 300 to 3,500 ft (91 to 1,064 m).

Potential Natural Vegetation. Potential natural communities include palo verde, creosote bush, saguaro, mesquite series, and bursage. Composition and successional sequence of some communities have changed because of plant and animal species introduced between the late 1800's and early 1900's related to mining and grazing.

Section 322C--Colorado Desert

Geomorphology. There are alluvial slopes, basin, dunes, and delta plain (Gulf of California). Elevation ranges from 230 feet below sea level to 1,000 ft (-70 to 304 m). This Section is in the Basin and Range geomorphic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Sonoran creosote bush, Salton Sea saltbush, and oasis scrub-woodland. Predominant potential natural communities include creosote

bush and mesquite series. Strong winds and drifting sand are common in parts of the area. Flash floods are commonly associated with the irregular occurrence of precipitation events. Precipitation does not occur every year.

Great Plains-Palouse Dry Steppe

These Sections are located in the north-central conterminous States, including parts of Oklahoma, Kansas, Colorado, Nebraska, Wyoming, South and North Dakota, and Montana. The area of these Sections is about 290,700 mi2 (752,900 km2).

Section 331A--Palouse Prairie

Geomorphology. This Section comprises moderately to strongly dissected loess-covered basalt plains, hills with large steptoes, undulating plateaus, and some river breaklands. Mountains occur in the southeast part of the Section. This Section is within the Columbia Plateau physiographic province. Elevation ranges from 1,200 to 6,000 ft (366 to 1,830 m).

Potential Natural Vegetation. Grasslands and meadow-steppe vegetation dominated by grasses are the prototypical vegetation of the Palouse. Woodlands and forests occur in the eastern portion of the Section on hills and low mountains. The relatively arid western portion of the Section is dominated by grassland, where bluebunch wheatgrass and Idaho fescue are the most prominent. Meadow-steppe vegetation characterized by Idaho fescue and common snowberry dominates areas with more precipitation, but still too dry to support forest vegetation on deep loamy soils. Most of this meadow-steppe as well as the grassland to the west, has been converted to crop lands. Ponderosa pine woodlands and forests form the lower timberline in the eastern portion of the Section on hills and low mountains. The transition zone between forest and meados-steppe consists of a complex interfingering between these two vegetation types. Douglas-fir series forests dominate at higher elevations in the mountains. Isolated fragments of the Western Red Cedar series and Grand Fir series occur on sheltered north slopes in the mountains. Wind is the principal source of natural disturbance.

Section 331B--Southern High Plains

Geomorphology. This Section is in the Great Plains geomorphic province. The predominant landform is a broad, extensive flat plain formed by fluvial sedimentation of continental erosional products from adjacent mountain ranges, followed by sheet erosion and transport. These processes resulted in a region of moderate dissection. Landforms consist mostly of smooth plains with smaller areas of tablelands. Elevation ranges from 2,600 to 4,000 ft (800 to 1,200 m). Local relief ranges mainly from 100 to 300 ft (90 m). A small area of tablelands is present where relief ranges from 300 to 500 ft (90 to 150 m).

Potential Natural Vegetation. Kuchler classified vegetation as sandsage-bluestem prairie and bluestem-grama prairie. The predominant vegetation form is short to mid-height grasslands. Species composition includes bluegrama, buffalograss, hairy grama, and little bluestem.

Section 331C--Central High Tablelands

Geomorphology. This Section includes broad intervalley remnants of smooth fluviatile plains. Smooth loess-mantled tablelands with gently rolling slopes and major valleys are bordered by steep slopes. Broad, level flood plains and terraces occur on major rivers and streams. This Section is in Fenneman and Johnson's Great Plains geomorphic physical division. Elevation ranges from 2,625 to 3,950 ft (800 to 1,200 m).

Potential Natural Vegetation. Kuchler mapped vegetation as grama-buffalo grass prairie, bluestem-grama prairie, sandsage-bluestem prairie, and wheatgrass-bluestem-needlegrass prairie. The predominant vegetation is short grass prairie. Fire, insects, and disease are predominant disturbance regimes.

Section 331D--Northwestern Glaciated Plains

Geomorphology. This Section includes level to gently rolling continental glacial till plains and rolling hills on the Missouri Plateau. Steep slopes border some of the larger rivers. Elevation ranges from 2,500 to 5,000 ft (763 to 1,525 m). This Section is within the Great Plains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as grama-needlegrass-wheatgrass. Common species include blue grama, bluebunch wheatgrass, green needlegrass, needleandthread, western wheatgrass, and basin wildrye. Fire and drought are the principal sources of natural disturbance.

Section 331E--Northern Glaciated Plains

Geomorphology. This area includes gently undulating to rolling continental glacial till plains with areas of kettle holes, kames, and moraines. Slopes adjacent to major stream valleys are steep. Elevation ranges from 2,000 to 6,000 ft (610 to 1,830 m). This Section is within the Great Plains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as wheatgrass-needlegrass. The natural prairie vegetation is characterized by western wheatgrass, needleandthread, green needlegrass, and blue grama. Little bluestem occurs on sloping and thin soils. Prairie cordgrass, northern reedgrass, and slim sedge occur on wet soils. Western snowberry and prairie rose are common shrubs. Fire and drought are the principal natural sources of disturbance.

Section 331F--Northwestern Great Plains

Geomorphology. This area includes gently sloping to rolling, moderately dissected shale plains. There are some steep, flat-topped buttes, particularly in eastern Wyoming. Badlands with eroded escarpments are in North Dakota and western South Dakota. Elevation ranges from 1,500 to 3,900 ft (458 to 1,200 m). This Section occurs on the Missouri Plateau and High Plains within the Great Plains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as wheatgrass-needlegrass. Most of the Section has natural prairie vegetation, which includes western wheatgrass, green needlegrass, blue grama, needleandthread, and buffalograss. Bluebunch wheatgrass, little bluestem, and

sideoats grama occur on shallow soils. Common shrubs in draws and along streams include buffaloberry, chokecherry, snowberry, and sagebrush. Ponderosa pine, juniper, and some aspen occur in North Dakota and on the Pine Ridge in South Dakota. Fire and drought are the principal natural sources of disturbance.

Section 331G--Powder River Basin

Geomorphology. This area includes gently rolling to steep dissected plains on the Missouri Plateau. Wide belts of steeply sloping badlands border a few of the larger river valleys. In places, flat-topped, steep-sided buttes rise sharply above the surrounding plains. Elevation ranges from 3,000 to 6,000 ft (915 to 1,830 m). This Section is within the Great Plains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as grama-needlegrass-wheatgrass. About 20 percent of the area supports eastern ponderosa forest. Dominant grassland species include western wheatgrass, blue grama, green needlegrass, bluebunch wheatgrass, and needleandthread. Little bluestem replaces bluebunch wheatgrass in the eastern part of the Section. Basin wild rye and sagebrush occur along streams and on bottomlands. Fire and drought are the principal natural sources of disturbance.

Section 331H--Central High Plains

Geomorphology. This Section includes undulating to rolling plains, moderately dissected by streams. There are steep slopes, large streams, and isolated mesas, with rolling to hilly sand dunes that border some valleys. Local relief ranges up to tens of meters. Elevation ranges from 3,610 to 5,905 ft (1,100 to 1,800 m). This Section is in Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Predominant vegetation is short and mid grass prairie. Kuchler classified potential vegetation as grama-buffalo grass prairie and sandsage-bluestem prairie, with northern floodplain forest along major drainages. Fire, insects, and disease are predominant natural disturbances.

Section 331I--Arkansas Tablelands

Geomorphology. This Section includes undulating to rolling plains composed of shale that are moderately dissected by streams. In many places the shale is mantled by loess, alluvium, and outwash. Large stream valleys and isolated mesas with steep slopes and rolling to hilly dunes border some of the valleys. Local relief ranges from 10 to 300 ft (3 to 90 m). Elevation ranges from 3,610 to 6,235 ft (1,100 to 1,900 m). This Section is in Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Predominant vegetation consists of short and mid grass prairie, and some woodlands. Kuchler classified vegetation as grama-buffalo grass prairie, sandsage-bluestem prairie, and juniper-pinyon woodland.
Fire, drought, insects, and disease have been the principal historical source of disturbance.

Section 331J--Northern Rio Grande Basin

Geomorphology. This area is in the Southern Rocky Mountain Province. This Section is located in north-central New Mexico and south-central Colorado. Landforms include valley, lowland, and elevated plains and hills. Elevation ranges from 6,875 to 8,800 ft (2,100 to 2,680 m). The major landform features are The San Luis Valley and the Rio Grande River.

Potential Natural Vegetation. Grama, galleta and sand dropseed grasses and Great Basin big sagebrush are found in ustic soil moisture regimes and cottonwood and willow along riparian corridors. Fescue-mountain muhly prairie also occurs. Kuchler mapped potential vegetation as saltbush-greasewood and wheatgrass-needlegrass.

Southern Rocky Mountain Steppe - Open Woodland - Coniferous Forest - Alpine Meadow

These Sections are located in the west-central conterminous States, including parts of New Mexico, Colorado, Utah, Wyoming, Idaho, and Montana. The area of these Sections is about 35,000 mi2 (68,000 km2). Section M331C is not delineated.

Section M331A--Yellowstone Highlands

Geomorphology. The Yellowstone Plateau was formed from two volcanic episodes. Other areas include high rugged mountains with ridges and cirques at higher elevations and narrow to broad valleys. Much of this area has been glaciated,and moraines are common. Elevation ranges from 6,000 to 13,000 ft (1,800 to 4,100 m) in the mountains, and 2,500 to 6,500 ft (763 to 1,983 m) in the basins and valleys. This Section is within the Middle Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler mapped potential vegetation as wheatgrass--needlegrass--shrubsteppe on drier, lower elevation valleys (55 percent), and Douglas-fir forest and western spruce-fir forest (45 percent) between 5,500 and 9,500 ft (1,667 and 2,879 m). Lodgepole pine is the common cover type, with an understory of grouse whortleberry, pine grass, heartleaf arnica, or Oregongrape. Alpine vegetation, including whitebark pine and subalpine fir, occurs above 9,500 ft (2,878 m). Sheep fescue, alpine bluegrass, and American bistort are common grass and forb species. Historic fire occurrence has been low intensity, low severity, patchy fires and infrequent, high intensity, high severity, continuous fires. Fire suppression has largely reversed this situation. Insect infestations and outbreaks of disease are also an important natural source of disturbance.

Section M331B--Bighorn Mountains

Geomorphology. There are high mountains with sharp crests, rolling uplands, and dissected hills, with alpine glaciation dominating the upper third of the area. The rugged hills and mountains are cut by many narrow valleys with steep gradients. Elevation ranges from 4,000 to 13,000 ft (1,220 to 3,962 m). This Section is within the Middle Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler mapped potential vegetation as Douglas-fir forest and western spruce--fir forest (50 percent) and wheatgrass--needlegrass--shrubsteppe (50 percent). Common tree species include lodgepole pine, Douglas-fir, subalpine fir, and Engelmann spruce. Idaho fescue, bluebunch wheatgrass, and mountain big sagebrush are common grass and shrub species.

Disturbance Regimes. Fire, insects, and disease are the dominant natural sources of disturbance. Fire has historically been fairly frequent, low intensity, and patchy; however, fire suppression has caused this pattern to change to less frequent, more intense, larger fires.

Section M331D--Overthrust Mountain

Geomorphology. This Section occurs within the Middle Rocky Mountain physiographic province. The Overthrust Mountains Section is part of western Wyoming, southeastern Idaho, and north-central Utah. Mountain ranges include the Teton and Salt River Ranges in Wyoming; Snake River, Caribou, Webster, Aspen, Portneuf, Bannock, and Bear River Ranges in Idaho; and the Wasatch Range in Utah. Anticlinal and synclinal structures and thrust fault zones control development of linear valleys and ridges in the northern part of this Section. Some ranges are bound by thrust faults that dip west. Snake River Mountains are distinct, separate, and subparallel. They are mostly steep, rugged mountains with narrow to broad valleys. The Teton Range is the highest in this Section. The Wasatch Range has very steep topography and an extensive and active fault. Higher portions of this Section have been glaciated, with few active glaciers and snow fields in the Teton Range. Many cirques, moraines, and other glacial features are present and extend into Utah. Alluvial fans and mud flow fans have developed at the mouths of many canyons in Utah. Mass movements are common and helped form the Wyoming Range. Elevation ranges from 5,000 to 13,000 ft (1,524 to 3,962 m). Local relief ranges from 3,000 to 7,000 ft (900 to 2,134 m).

Potential Natural Vegetation. Kuchler vegetation types include lodgepole pine-subalpine forest, and Douglas-fir forest with outer fringes of sagebrush steppe in the northern portion of the Section. Mountain mahogany-oak scrub surrounds a Douglas-fir forest in the Utah portion of the Section. The Soil Conservation Service identifies the potential natural vegetation as mixed conifers and sagebrush-grassland with Douglas-fir, lodgepole pine, and aspen occupying northern aspects. About 50 percent is Douglas-fir forest. Vegetation zones are controlled by a combination of altitude, latitude, slope exposure, and prevailing winds. Areas of alpine tundra exist on highest mountains, subalpine zone has spruce--fir forests, and montane zone has ponderosa pine and Douglas-fir forest. Sagebrush occurs at the lower elevations. After fire, aspen and lodgepole pine replace higher seral species.

Disturbance Regimes. Mass movements are common and water erosion is occurring.

Section M331E--Uinta Mountains

Geomorphology. This Section occurs within the Middle Rocky Mountain province. The Uinta Mountains Section is located in northeastern Utah and the southwest corner of Wyoming. Mountains are an anticlinal uplift with an east-west orientation. Periglacial and glacial processes

have shaped higher elevation landforms with freezing and thawing, an active process. At lower elevations, erosion by water and wind are active landforming processes. Elevations range from approximately 6,000 to 13,000 ft (1,800 to 3,900 m). Slopes range from about 5 percent to vertical in gradient.

Potential Natural Vegetation. Kuchler vegetation types include alpine meadows, Douglas-fir forest, and western spruce-fir forest. It has been noted that some of Kuchler's vegetation types are incorrect for this Section. More accurate information, from higher to lower elevations, is alpine tundra, Engelmann spruce, spruce-fir, lodgepole pine, subalpine meadow, Douglas-fir, ponderosa pine, aspen, mountain big sagebrush, oak and mountain brush, pinyon-juniper, Wyoming big sagebrush, and cold desert shrub. Douglas-fir is limited to limestone and lower elevations in canyons on quartzite. Oak communities are generally limited to the western portion of the Section. The eastern portion is mostly juniper-pinyon woodland with sagebrush steppe.

Disturbance Regimes. From low to high elevation, alpine fire is probably insignificant. Engelmann spruce has low frequency and small fires (frequency of 300 to 400 years or more and mostly less than 100 acres. In mixed conifers there are more frequent and larger fires than in the Engelmann spruce belt. Lodgepole pine has an 80 to 200 year interval and large fires to 20,000 acres or more. Ponderosa pine has 20 to 50 year interval underburns. Mountain big sagebrush and mountain brush have 20 to 80 year intervals and 10 to 1,000 acres or more in size. Pinyon-juniper has a 20 to 200 year interval with small fires up to 100 acres being common and larger fires being rare. These estimates of fire frequency and size are applicable to presettlement times. In modern times, the national forest fire suppression policy has resulted in reduced fire frequency and size in all timber types.

Section M331F--Southern Parks and Rocky Mountain Ranges

Geomorphology. Included in the Southern Rocky Mountain Province, this Section is located in northeast-central New Mexico and south-central Colorado. Landforms are mountains and a few valley plains. The Sangre de Cristo Mountains are this Section's major landform feature. Elevation ranges from 7,500 to 14,000 ft (2,300 to 4,300 m).

Potential Natural Vegetation. Predominant vegetation includes Douglas-fir and ponderosa pine in frigid soil temperature regimes; Engelmann spruce and subalpine fir in cryic soil temperature regimes; and *Kobresia*, *Geum* and *Arenaria* in alpine pergelic zones.

Disturbance Regimes. Fires vary in frequency and intensity in ponderosa pine stands, but may occur when fuel load is high and dry. Fire is rare in areas with cryic temperature regimes and udic soil moisture regimes. The upper mountain slopes are forested, but merchantable timber is scarce.

Section M331G--South-Central Highlands

Geomorphology. Steeply sloping to precipitous mountains are dissected by many narrow stream valleys with steep gradients. Upper mountain slopes and crests may be covered by snowfields and glaciers. High plateaus and steep walled canyons are common, especially in the west. Elevation ranges from 7,545 to 14,110 ft (2,300 to 4,300 m). This Section is within Fenneman

and Johnson's Southern Rocky Mountains (eastern half of the Section) and Colorado Plateaus (western half of the Section) geomorphic physical divisions.

Potential Natural Vegetation. Vegetation ranges from shrub and grasslands, forests, and alpine tundra. Kuchler classified vegetation as southwestern spruce--fir forest; pine--Douglas-fir forest; mountain mahogany--oak scrub; Great Basin sagebrush; juniper-pinyon woodland; and alpine meadows and barren.

Disturbance Regimes. Fire, insects, and disease are principal sources of natural disturbance.

Section M331H--North-Central Highlands and Rocky Mountain

Geomorphology. This area includes steeply sloping to precipitous flat-topped mountains dissected by narrow stream valleys with steep gradients. High plateaus have steep walled canyons. There are gently rolling mountain parks, mountain ridges, and foothills. Elevation ranges from 5,600 to 12,000 ft (1,706 to 3,657 m). This Section is within three geomorphic physical divisions: Fenneman and Johnson's Wyoming Basin (northern part of the Section), Southern Rocky Mountains (central part of the Section), and the Colorado Plateaus (southern part of the Section).

Potential Natural Vegetation. Kuchler mapped vegetation as western spruce--fir forest, pine--Douglas-fir forest, juniper--pinyon woodland, mountain mahogany--oak scrub, and sagebrush steppe. Above timberline, alpine tundra predominates. At higher elevations types include Engelmann spruce, subalpine fir, Douglas-fir, ponderosa pine--Douglas-fir, aspen, and meadows of grass and sedge. At lower elevations, there are pinyon pine, shrubs, grass, and shrub-grass vegetation. **Disturbance Regimes.** Fire, insects, and disease are the principal sources of natural disturbance.

Section M331I--Northern Parks and Ranges

Geomorphology. Steeply sloping to precipitous mountains are dissected by many narrow stream valleys with steep gradients. This area has gently rolling mountain parks and valleys, with some mountain ridges. Rugged hills and low mountains are found in narrow bands along the eastern slopes of the Rocky Mountains. These hills are strongly dissected and in many places are crossed by large streams flowing eastward from the mountains. Elevation ranges from 5,575 to 14,410 ft (1,700 to 4,400 m). This Section is within Fenneman and Johnson's Southern Rocky Mountains geomorphic physical division.

Potential Natural Vegetation. Kuchler mapped vegetation as alpine meadows and barren, fescue--mountain muhly prairie, sagebrush steppe, juniper-pinyon woodland, and Great Basin sagebrush. **Disturbance Regimes.** Fire, insects, and disease are predominate sources of natural disturbance.

Section M331J--Wind River Mountains

Geomorphology. This Section, which occurs within the Middle Rocky Mountain physiographic province, is located in western Wyoming. It has high alpine mountains that have been glaciated.

Glacial troughs, cirque headwalls, and floors are common. The highest areas have glaciers covering the mountain tops. Elevation ranges from 6,000 to 13,000 ft (1,800 to 4,100 m).

Potential Natural Vegetation. Kuchler vegetation types include lodgepole pine and alpine grasses and forbs. Areas of spruce-firs and Douglas-fir forest occur in this Section.

Disturbance Regimes. Mass movements are infrequent, and erosion is occurring from water.

Great Plains Steppe

These Sections are located in the north-central conterminous States, including parts of Oklahoma, Kansas, Nebraska, and South and North Dakota. The area of these Sections is about 134,000 mi2 (347,100 km2).

Section 332A--Northeastern Glaciated Plains

Geomorphology. This is an area of nearly level to undulating continental glacial till and glacial lake plains, with areas of kettle holes, kames, and moraines. Some steep slopes occur adjacent to streams. Elevation ranges from 700 to 2,300 ft (214 to 704 m). This Section is within the Central Lowlands physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as wheatgrass-bluestem-needlegrass. The natural prairie vegetation is dominantly western wheatgrass, needleandthread, green needlegrass, and blue grama. Little bluestem is important on sloping and thin soils. Northern reedgrass, prairie cordgrass, big bluestem, and slim sedge are important species on wet soils.

Disturbance Regimes. Fire and drought are the principal natural sources of disturbance.

Section 332B--Western Glaciated Plains

Geomorphology. Nearly level to undulating continental glacial till plains occur, with areas of kettle holes, kames, moraines, and glacial lake plains. Glacial lake plains and some steep slopes are adjacent to streams. Elevation ranges from 1,000 to 2,000 ft (305 to 610 m). This Section is within the Central Lowland physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as wheatgrass-bluestem-needlegrass. The natural prairie vegetation is mainly western wheatgrass, needleandthread, green needlegrass, and blue grama. Little bluestem is important on sloping and thin soils. Northern reedgrass, prairie cordgrass, big bluestem, and slim sedge are important species on wet soils. Northern flood plain forest occurs along major drainages.

Disturbance Regimes. Fire and drought are the principal natural sources of disturbance.

Section 332C--Nebraska Sandhills

Geomorphology. This area has rolling to steep, irregular sand dunes stabilized by vegetation, with narrow, elongated, gently rolling sloping valleys between dunes. Elevation ranges from 1,970 to 3,950 ft (600 to 1,200 m). This Section is within Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Mid and tall grass plant communities are present including Nebraska sandhills prairie (bluestem, sandreed). Kuchler classified vegetation as sandhills prairie, wheatgrass-bluestem-needlegrass, and, along major drainages, northern flood plain forest.

Disturbance Regimes. Fire, insect and disease are predominant natural disturbances.

Section 332D--North-Central Great Plains

Geomorphology. There are nearly level to gently rolling till plains with potholes and well defined dendritic drainage system. Moderate to steep slopes are adjacent to major valleys. River and creek valleys have smooth floors and steeps walls. Higher parts of tablelands are moderately sloping, but steeper areas occur on ridges and drainage ways. Drainages are well defined except in some undulating areas where eolian materials cover the bedrock. Elevation ranges from 1,310 to 2,950 ft (400 to 900 m). This Section is within Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Kuchler mapped potential vegetation as wheatgrass-needlegrass prairie and wheatgrass-bluestem-needlegrass prairie and wheatgrass-bluestem-needlegrass prairie with northern flood plain forests along the Missouri River lowlands. Other communities consist of mixed and natural prairie.

Disturbance Regimes. Fire, insects, and disease are the primary natural disturbances.

Section 332E--South-Central Great Plains

Geomorphology. Gently sloping loess-mantled narrow ridgetops are separated by steep slopes bordering drainage ways. Some stream valleys with nearly level flood plains and large stream terraces exist. Dissected plains with broad rolling ridgetops and moderately steep valley sides occur. Valleys are usually narrow with broad flood plains and terraces, and hilly dissected plains. There are rivers with wide flood plains and terraces, and small streams with narrow bottomlands. Rolling plains have a deep mantle of windblown sand and sandy outwash. Elevation ranges from 1,310 to 2,950 ft (400 to 900 m). This Section is within Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Predominant vegetation is grass and prairie communities. Kuchler mapped vegetation as bluestem-grama prairie, sandsage-bluestem prairie, northern flood plain forests, and buffalograss.

Disturbance Regimes. Fire, insects, and disease are primary natural disturbances.

Middle Rocky Mountain Steppe - Coniferous Forest - Alpine Meadow

These Sections are located in the northwestern conterminous States, including parts of Oregon, Washington, Idaho, and Montana. The area of these Sections is about 81,800 mi2 (211,900 km2).

Section M332A--Idaho Batholith

Geomorpholgy. These are mountains with alpine ridges and cirques at higher elevations. Large U-shaped valleys with broad bottoms indicate that the area has been strongly glaciated. Mature surfaces are dissected with major drainages deeply incised, resulting in steep breaklands. Elevation ranges from 3,000 to 10,000 ft (900 to 3,000 m). Local relief ranges from 3,000 to 5,000 ft (900 to 1,500 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as grand fir--Douglas-fir forest, western spruce--fir forest, and western ponderosa forest.

Disturbance Regimes. Fire, insects, and disease are the dominant natural sources of disturbance. Fires have been frequent, low intensity, and patchy, and occasionally high intensity and continuous. Mass wasting is also an important source of disturbance in some areas.

Section M332B--Bitterroot Valley

Geomorphology. This area includes high, glaciated mountains with alpine ridges and cirques at higher elevations and glacial and lacustrine basins at lower elevations. Steep slopes, sharp crests, and narrow valleys are characteristic. Elevation ranges from 2,500 to 6,000 ft (763 to 1,830 m) in basin areas; the range is 3,000 to 8,000 ft (915 to 2,440 m) in mountains, with some alpine areas up to 10,000 ft (3,050 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler classified vegetation as Douglas-fir forest and western ponderosa forest (80 percent) and foothills prairie (20 percent), mostly in the lower valleys. The upper timberline occurs at about 8,800 ft (2,667 m). Common tree species include western larch, Douglas-fir, subalpine fir, and ponderosa pine. Grassland species are mainly bluebunch wheatgrass, Idaho fescue, and rough fescue.

Disturbance Regimes. Fire, insects, and disease are the dominant natural sources of disturbance. Fires were generally low intensity, frequent ground fires prior to fire suppression efforts. Fuel accumulations have now set the stage for large, high-intensity fires.

Section M332C--Rocky Mountain Front

Geomorphology. There are glaciated mountains with limestone scarps and ridges interspersed with glacial and lacustrine intermontane basins. Alpine ridges and cirques occur at higher elevations. Elevation ranges from 5,500 to 8,500 ft (1,678 to 2,593 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Douglas-fir forest and western spruce-fir forest (15 percent), occur mostly between 4,500 to 8,000 ft (1,360 to 2,425 m). Extensive aspen groves also occur. Limber pine is also present. Foothills prairie (85 percent) occurs on lower elevation foothills. Common grasses include wheatgrasses, fescues, and needlegrass.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance. Strong chinook winds that cause windthrow are also a source of disturbance.

Section M332D--Belt Mountains

Geomorphology. This Section comprises high mountains, gravel-capped benches, and intermontane valleys bordered by terraces and fans. Plains and rolling hills surround the isolated mountain ranges. Elevation ranges from 4,000 to 8,500 ft (1,220 to 2,593 m) in the mountains; elevation ranges from 2,500 to 5,000 ft (763 to 1,525 m) on the plains. Most of this Section is within the Northern Rocky Mountains physiographic province, but the eastern part extends onto the Missouri Plateau within the Great Plains physiographic province.

Potential Natural Vegetation. Kuchler classified vegetation as foothills prairie (75 percent) and Douglas-fir forest--eastern ponderosa forest (25 percent). Forests are associated with prominent mountain ranges and the Missouri River breaks, and cover all but the highest peaks. Typical prairie species include wheatgrasses, fescues, grama, and needlegrass. Common tree species are Douglas-fir, ponderosa pine, limber pine, and subalpine fir.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance.

Section M332E--Beaverhead Mountains

Geomorphology. This area encompasses complex and high, steep mountains with sharp alpine ridges and cirques at higher elevations, glacial and fluvial valleys, and alluvial terraces and flood plains. Elevation ranges from 2,500 to 6,500 ft (763 to 1,983 m) in valleys; elevation ranges from 4,000 to 10,000 ft (1,220 to 3,050 m) in the mountains. This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Vegetation consists of sagebrush steppe with small areas of alpine vegetation (75 percent) above 9,500 ft (2,880 m), and Douglas-fir forest (25 percent) the latter spans an elevation range of only about 1,000 to 1,500 ft (300 to 450). Typical steppe species include big sagebrush, fescues, wheatgrasses, and needlegrass. Douglas-fir, limber pine, and lodgepole pine are common tree species.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance.

Section M332F--Challis Volcanic

Geomorphology. This Section occurs within the Middle Rocky Mountain physiographic province. The Challis Volcanics Section is in central Idaho. Mountain ranges include White Cloud Peaks, Pioneer Mountains, Smokey Mountains, Boulder Mountains, White Knob Mountains, and portions of the Salmon River Range. Areas of glaciation occur in this Section. Most of the mountain ranges have residual weathering. Elevation ranges from 4,000 to 11,800 ft (1,200 to 3,600 m).

Potential Natural Vegetation. Kuchler vegetation types include a mixture of western spruce-fir forest and sagebrush steppe. Douglas-fir forest occurs also in this Section. The Soil Conservation Service identifies the potential natural vegetation as mixed conifer forest. Also included are areas of Lodgepole Pine series. Whitebark Pine and Subalpine Fir series also occur at the highest elevations. Areas of Big Sagebrush series are on southerly exposure and at lower elevation.

Disturbance Regimes. Common high intensity forest fires occur during summer thunderstorms. Erosion by water is occurring.

Section M332G--Blue Mountains

Geomorphology. This is a moderately dissected wide, uplifted plateau dominated by landslide and fluvial erosion processes in the western portion. Mesas and buttes are common. Moderately dissected mountains dominated by glacial and fluvial erosion processes are in the eastern half. From the low-lying Ochoco Mountains in the southwest, individual ranges, separated by north-south trending valleys, rise to ice-sculpted peaks and deep canyons in the Wallowa Range. Wide, low elevation valleys between ranges are alluvium-filled fault troughs. Elevation ranges from 1,000 to 10,000 ft (300 to 3,300 m). Most of the mountainous part of the Section is between 4,000 and 7,500 ft (1,212 and 2,273 m), and the valleys are less than 4,000 ft (3,030 m). Local relief is 2,000 ft (606 m) or more in the mountains and 100 to 500 ft (30 to 150 m) on the broad valley floors.

Potential Natural Vegetation. The Kuchler vegetation types are dominantly grand fir--Douglas-fir forests, followed by western ponderosa forests. High elevation forests are western spruce-fir. Great basin sagebrush and juniper steppe woodland are interspersed on relatively dry, mesic regime sites. Wheatgrass-bluegrass occurs on mesic-xeric soils in canyons and south slopes. Alpine meadows and barrens occupy the highest elevations. Grand fir and Lodgepole Pine are the dominant series and are at mid elevations on the moderately deep and deep volcanic ash soils with frigid temperature regimes and udic to xeric moisture regimes. Some lodgepole pine is on cryic soils. Ponderosa Pine series dominates at mid to low elevations on mesic and frigid xeric soils. Douglas-Fir series is intermediate between the Lodgepole Pine and Ponderosa Pine series. Subalpine Fir series dominates at the highest elevations on cryic soils. Western Juniper series occurs at low elevations on mesic and xeric soils. Shrub series of Snowberry, Mountain Mahogany, Bitterbrush, Common Snowberry, and Low Sage are interspersed. Grasslands are at the highest and lowest elevations. High elevation, cryic soils are dominated by green and Idaho

fescues, and sedges. At mid and low elevations, Idaho fescue and bluebunch wheatgrass, occur with lesser amounts of Sandbergs bluegrass and prairie junegrass. Wet meadows are dominated by sedges and tufted hairgrass.

Disturbance Regimes. Fire was a major factor in disturbance until the early the advent of fire control in the early 20th century. Periodicities ranged from as few as 10 to 15 years. to as infrequent as several decades on the cooler and wetter sites. A variety of insects, including beetles, tussock moth, spruce budworm, and others, are endemic; periodic epidemics appeared and declined until recently. Epidemic occurrences have had significant effects in the recent decade. A variety of diseases also have had some local effects. Periodic floods and ice jams are important in some watersheds.

Northern Rocky Mountain Forest-Steppe - Coniferous Forest - Alpine Meadow

These Sections are located in the northwestern conterminous States, Including parts of Washington, Idaho, and Montana The area of these Sections is about 38,100 mi2 (98,700 km2).

Section M333A--Okanogan Highlands

Geomorphology. This Section's features range from accretion of continetal shelf material forming the Okanagan Highlands, in response to the uplifting and movement of the oceanic shelf to the east, to the Rocky Mountain facies and volcanic influences from the rise of the Kettle Dome. Extreme metamorphism and deformation have occurred, as well as deposits of glacial till, outwash, and debris that cover most of the modern landscape. The area is inudated with glacial lakes, rivers, and streams, as well as mountains, and both narrow and broad valleys. Elevation ranges from 1,376 to 7,309 ft (444 to 2,358 m). Local relief ranges from 500 to 1,000 ft (161 to 322 m).

Potential Natural Vegetation. Vegetation pattern in this Section is strongly influenced by the strong east-west precipitation gradient. Vegetation in the western third of the Section found west of the Kettle Mountains crest differs significantly from that in the eastern two-thirds. The Big Sagebrush series dominates the lowest elevations on mostly xeric soils. The Ponderosa Pine series occurs at slightly higher elevations, also on xeric soils. This series is replaced by the Douglas-Fir series at higher elevations. Soils with this series have a xeric moisture regime and mesic or frigid temperature regimes. The Subalpine Fir series occupies higher elevations to upper forest line on cryic soils.

Vegetation east of the Columbia River is characterized by the Douglas-Fir series at lowest elevations followed by the Grand Fir series, Western Hemlock and Western Red Cedar series, and the Subalpine Fir series with increasing elevation. The Douglas-Fir and Grand Fir series occur on xeric soils, with the Grand Fir series occupying slightly cooler and more mesic habitats. The Western Hemlock and Western Redcedar series occur on soils with udic regimes. The Subalpine Fir series occurs on cryic soils. The Whitebark Pine series and the Green Fescue series occur at the highest elevations throughout the Section above continuous forest line.

Disturbance Regime. Historic fire events have changed a large portion of the forest. Changes are periodic and range from high intensity, high severity, continuous fires to low severity,

infrequent fires. Composition and successional sequences of some communities has changed because of harvesting practices and the introduction of animal species into the valleys. Wide fluctuations in precipitation and temperatures for periods of years result in significant changes in biological communities. Insects and diseases are frequent disturbance features.

Section M333B--Flathead Valley

Geomorphology. There are glaciated mountains, glacial moraines, large glacial troughs, and glacial and lacustrine basins. Elevation ranges from 2,000 to 7,000 ft (610 to 2,135 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler mapped vegetation as Douglas-fir forest and western ponderosa forest. Principal tree species include Douglas-fir, ponderosa pine, hemlock, cedar, and grand fir.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance.

Section M333C--Northern Rockies

Geomorphology. There are steep glaciated overthrust mountains with sharp alpine ridges and cirques at higher elevations. Some areas of glacial deposition also occur. Elevation generally ranges from 3,000 to 9,500 ft (915 to 2,898 m). Some alpine areas range from 8,000 to 10,000 ft (2,440 to 3,050 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler mapped potential vegetation as Douglas-fir forest. The alpine treeline occurs at about 8,000 ft (2,420 m). Foothills prairie with wheatgrasses, fescues, and needlegrass occurs in the drier valleys. Principal tree species include Douglas-fir, hemlock, cedar, and grand fir.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance.

Section M333D--Bitterroot Mountains

Geomorphology. This area comprises steep dissected mountains, some with sharp crests and narrow valleys. Elevation ranges from 1,200 to 7,000 ft (366 to 2,135 m). This Section is within the Northern Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler classified potential vegetation as cedar-hemlock-pine forest, Douglas-fir forest, and western ponderosa forest. Common species include western redcedar, western hemlock, western white pine, Douglas-fir, and ponderosa pine. Other important tree species include grand fir and mountain hemlock.

Disturbance Regimes. Fire, insects, and disease are the principal natural sources of disturbance. Mass wasting also occurs in some areas. Fires were mostly large, low frequency, high intensity, stand-replacing fires, except for the eastern quarter of the Section, which had mostly low

intensity, frequent ground fires. Fire suppression efforts have altered the fire regime to a large extent.

Black Hills Coniferous Forest

The area of this Section, which is located in Wyoming and South Dakota, is about 3,700 mi2 (9,600 km2).

Section M334A--Black Hills

Geomorphology. Slopes range from moderate on some of the high plateaus to very steep along drainage ways and on peaks and ridges. Narrow valleys are mostly gently sloping to strongly sloping. Elevation ranges from 2,950 to 7,220 ft. (900 to 2,200 m). This Section is within Fenneman and Johnson's Great Plains geomorphic physical division.

Potential Natural Vegetation. Kuchler classified vegetation as dominates open to dense forest vegetation. Black Hills ponderosa pine forest.

Disturbance Regimes. Fire, insects, and disease are principal natural disturbances.

Intermountain Semi-Desert and Desert

These Sections are located in the west-central conterminous States, including parts of Nevada, Utah, and Colorado. The area of these Sections is about 107,100 mi2 (277,400 km2).

Section 341A--Bonneville Basin

Geomorphology. This Section occurs within the Basin and Range physiographic province. Dominant landforms are north-south trending mountains separated by broad, sediment-filled valleys, many of which have internal drainages. Mountains were formed by faulting and were subsequently modified by erosion. Large alluvial fans have developed at the mouths of most canyons. Some fans are coalescing, nearly burying the eroded mountains. Playas are found in some closed basins, and salt flats are common. Elevation ranges from 4,000 to 8,000 ft (1,200 to 2,400 m).

Potential Natural Vegetation. Kuchler vegetation types are saltbush-greasewood and juniper-pinyon woodlands. Areas of sagebrush and wheatgrass-grama-buffalograss also were mapped. The Soil Conservation Service identifies the potential natural vegetation as desert shrub, shrub-grass, and woodland vegetation.

Disturbance Regimes. Common low intensity short duration burns of sagebrush and desert shrubs occur during summer thunderstorms. Often there is insufficient understory to carry fires, or they are suppressed.

Section 341B--Northern Canyon Lands

Geomorphology. This area occurs within the Colorado Plateau physiographic province. Northern Canyon lands Section is located in the eastern portion of Utah. This area is eroded by

the Colorado River and its tributaries. Deep sheer-walled canyons, canyonlands, lines of cliffs, low plateaus, mesas, buttes, and badlands dominate the landscape. Major landforms are the San Rafael Swell, Henry Mountains, Abajo Mountains, La Sal Mountains, and Circle Cliffs. Elevation ranges from 4,200 to 12,700 ft (1,300 to 3,900 m).

Potential Natural Vegetation. Kuchler vegetation types are blackbrush, juniper-pinyon woodlands, saltbush-greasewood, and galleta-three awn shrub steppe. Areas of ponderosa pine series occur on the La Sal and Abajo Mountains. Areas of Arizona pine occur on the Henry Mountains. The Soil Conservation Service identifies the area as desert shrub and woodland vegetation with some big sagebrush. Spruce-fir forests with aspen occur on the higher elevations of the Henry, Abajo, and La Sal Mountains.

Disturbance Regimes. Common, low intensity, short duration burns occur due to thunderstorms. Water and wind erosion is also occurring.

Section 341C--Uinta Basin

Geomorphology. This area occurs within the Colorado Plateau physiographic province. Unita Basin Section lies south of the Unita Mountain Range in northeastern Utah. It is a synclinal and topographical basin, with its east-west axis running near the south flank of the Unita Mountains. The central portion is gently rolling with eroded slopes. Elevation ranges from 6,200 to 7,300 ft (1,900 to 2,200 m). Local relief ranges from 100 to 1,000 ft (30 to 300 m).

Potential Natural Vegetation. Kuchler vegetation types include juniper-pinyon woodlands and saltbush-greasewood. The Soil Conservation Service identifies some of the area as grasslands-shrub vegetation with some big sagebrush. Series include juniper-pinyon and saltbush-greasewood. Areas of big sagebush also occur.

Disturbance Regimes. Few low intensity short duration burns of sagebrush occur due to summer thunderstorms. Most disturbance is from wind and water erosion.

Section 341D--Mono

Geomorphology. Isolated ranges of largely dissected block mountains are separated by aggraded desert plains (alluvial fans and basins). Elevation ranges from 4,000 to 14,200 ft (1,216 to 4,315 m). This Section is in the Basin and Range geomorphic province.

Potential Natural Vegetation. Kuchler classified potential vegetation as sagebrush steppe, juniper-pinyon woodland, northern jeffrey pine forest, Great Basin subalpine forest, and alpine communities and barren. Potential natural communities include western juniper, pinyon pine, Jeffrey pine, basin sagebrush and bristlecone pine series.

Disturbance Regimes. Fires are infrequent, low, moderate, and high intensity surface or stand-replacing fires. This area contains locations with eruptive activity (lava flows and ash fall) within the past 200 years. This is a seismically active area with strong shaking and ground rupture.

Section 341E--Lahontan Basin

Geomorphology. This area occurs within the Great Basin physiographic province. Lahontan Basin Section is located in the western portion of Nevada. Block-faulting created upthrusted north-south trending mountains which are interspersed with interior playas; surface water occurs frequently. Little glaciation is evident. Elevation ranges from 4,000 to 9,800 ft (1,200 to 3,000 m). Star Peak in the Humboldt Range is south of Winnemucca.

Potential Natural Vegetation. Kuchler vegetation types include saltbush-greasewood, big sagebrush, juniper-pinyon, aspen, marshes, and intermittent lakebeds with greasewood or little vegetation. The Soil Conservation Service identifies the vegetation as desert shrub with widespread shadscale. Areas of big sagebrush also occur.

Disturbance Regimes. Fires are historically common due to thunderstorm activity. Large fires (1,000 acres or more) are common and moderately intense in the north end of this Section. Water and wind erosion also is occurring.

Section 341F--Southeastern Great Basin

Geomorphology. This area is within the Basin and Range physiographic province. The Southeastern Great Basin Section is located in southern Nevada. North-south trending mountains are separated by broad sediment-filled valleys. Mountains are formed by faulting and modified by erosion. Large alluvial fans are at the mouths of most canyons. Elevation ranges from 4,700 to 9,400 ft (1,425 to 2,900 m). There are three or four peaks southwest of the Quinn-Canyon Range (in the Ely Ranger District of the Humboldt National Forest), which are at or close to 9,400 ft (2,900 m) elevation (e.g., Kawich Peak in the Kawich Range and Bald Peak in the Groom Range). These peaks are south and east of the southeastern-most end of the Toquima Range of the Toiyabe National Forest.

Potential Natural Vegetation. Kuchler vegetation types include Great Basin sagebrush with some Great Basin pine forest and saltbush-greasewood. The Soil Conservation Service has classified the area as being desert-shrub, shrub-grass, and woodland vegetation. This area is a transitional zone between the mountains of the Toquima--Grant--Quinn Ranges, and the true Mojave (represented by Joshua tree cactus). Site factors (precipitation, soils, and topography) influence distribution of cholla chactus, greasewood and saltbush species, ephedra, sagebrush species, galleta grass, banana yucca, Fremont barberry, little leaf mahogany, Utah juniper, and single leaf pinyon; small amounts of limber pine, ponderosa pine, bristlecone pine, and subalpine fir.

Disturbance Regimes. Infrequent, small to moderate, low intensity fires start due to thunderstorms. Fires remain small due to sparse fuels. Erosion by wind and water occur.

Section 341G--Northeastern Great Basin

Geomorphology. This area occurs within the Basin and Range physiographic province. The Northeastern Great Basin Section is located in northeastern Nevada. There are north-south

trending mountains with broad sediment-filled valleys, formed by thrust-faulting (e.g., south Independence Range). Some glaciation is evident on the highest peaks. Elevation ranges from 4,800 to 10,704 ft (1,500 to 3,250 m).

Potential Natural Vegetation. Kuchler vegetation types include Great Basin sagebrush and juniper-pinyon woodlands. Juniper-mahogany woodlands and aspen are also found.

Disturbance Regimes. Infrequent, moderate to large sized fires occur due to summer thunderstorms. Periodic catastrophic snowmelt in high snow years leads to debris flows down steep mountain valleys.

Intermountain Semi-Desert

These Sections are located in the northwestern conterminous States, including parts of Washington, Oregon, California, Nevada, Idaho, Utah, Wyoming, and Colorado. The area of these Sections is about 159,100 mi2 (412,100 km2).

Section 342A--Bighorn Basin

Geomorphology. There are piedmont plains and mountain footslopes with large stream terraces along the Wind-Bighorn River system. Plains are eroded to clay shale bedrock in some places, forming badlands. Elevation ranges from 3,600 to 5,900 ft (1,100 to 1,800 m). This Section is within the Middle Rocky Mountains physiographic province.

Potential Natural Vegetation. Kuchler classified potential vegetation as saltbush-greasewood, wheatgrass-needlegrass-shrubsteppe, and sagebrush steppe. Common species include big sagebrush, gardner saltbush, indian ricegrass, and needleandthread. Black sage and bluebunch wheatgrass are common on areas with shallow soils.

Disturbance Regimes. Fire and drought are the principal natural sources of disturbance.

Section 342B--Northwestern Basin and Range

Geomorphology. This area occurs within the Basin and Range physiographic province. Northwestern Basin and Range Section is located in the northern portion of Nevada, southeastern Idaho, and south-central Oregon. It extends into northern Utah also. Nearly level basins and valleys are bordered by long, gently sloping alluvial fans. North-south trending mountain ranges and few volcanic plateaus rise sharply above the valleys. Large alluvial fans have developed at the mouths of most canyons. Elevation ranges from 4,000 to 7,200 ft (1,200 to 2,200 m).

Potential Natural Vegetation. Kuchler vegetation types include sagebrush steppe. The Soil Conservation Service identifies the potential natural vegetation as shrub-grass with saltbush-greasewood vegetation.

Disturbance Regimes. Short duration and low intensity brush fires occur due to summer thunderstorms. Water and wind erosion is also occurring.

Section 342C--Owyhee Uplands

Geomorphology. This area occurs within the Columbia Plateau physiographic province, also known as the Columbia Intermontane province. The Owyhee Uplands Section is part of southwest Idaho, southeast Oregon, and northern Nevada. This area is an uplifted region with doming and block-faulting common. It is deeply dissected from erosional processes. Lavas are older than that of the Snake River Plains. The Owyhee Mountains are made of granite; however, most of the uplands are rhyolites and welded tuffs with silicic volcanic flows, ash deposits, and wind-blown loess. Elevation ranges from 4,000 to 8,000 ft (1,200 to 2,500 m).

Potential Natural Vegetation. Kuchler vegetation types are sagebrush steppe with {\it Artemisia} and {\it Agropyron} and small areas of wheatgrass-bluegrass. The Soil Conservation Service identifies the area as having a sagebrush-grass potential natural vegetation.

Disturbance Regimes. After fire, grasses and forbs replace higher seral species. Water and wind erosion is also occurring.

Section 342D--Snake River Basalts

Geomorphology. This area occurs within the Columbia Plateau physiographic province, also known as the Columbia Intermontane province. The Snake River Basalts Section is part of southeast and south-central Idaho. Most of this Section is characterized by nearly horizontal sheets of basalt laid down in the Snake River drainage to form a plain. Lava flows range from less than 100 ft thick to several thousand ft thick. Block-faulted mountains are also included in this Section. The basalts are mainly two ages: the older flows are of the Miocene and Pliocene epoch; the younger lavas are Pliocene through Recent. The Section is about 60 mi wide and is essentially flat; however, the eastern portions of the Section are much higher in elevation. The surface is a youthful lava plateau with a thin wind-blown soil layer covering it. Shield volcanoes, cinder cones, and squeezed-up lava ridges are common. Craters of the Moon National Monument is an example of the recent volcanic features. Elevation ranges from 3,000 to 6,000 ft (900 to 2,000 m). Lava plain and hills are nearly level to steeply sloping.

Potential Natural Vegetation. Kuchler vegetation types include sagebrush steppe with {\it Artemisia} and {\it Agropyron}. The Soil Conservation Service identifies the area as having a sagebrush-grass potential natural vegetation.

Disturbance Regimes. After fire, grasses and forbs replace higher seral species. Water and wind erosion is also occurring.

Section 342E--Bear Lake

Geomorphology. This area occurs within the Middle Rocky Mountain physiographic province. The Bear Lake Section is located in the southeast corner of Idaho, southwest corner of Wyoming, and northern corner of Utah. Steep north-south oriented mountain ranges with broad linear valleys are the major landforms. Few areas have been glaciated and were mostly formed from thrust and faults, landslides, and pluvial action.

Potential Natural Vegetation. Kuchler vegetation types include lodgepole pine and Douglas-fir forests, with outer fringes of sagebrush lands. Oak-pine forests occur in the Utah portion of this Section. The Soil Conservation Service identifies the potential natural vegetation as mixed conifers and sagebrush-grassland with Douglas-fir, lodgepole pine, and aspen occupying northern aspects.

Disturbance Regimes. A few high intensity, short duration burns of shrubs occur in the summer due to thunderstorms. Water and wind erosion occurs.

Section 342F--Central Basins and Hills

Geomorphology. Plains eroded to clay shale bedrock, creating badlands. Mountain ranges include steep slopes that rise sharply from desert basins. There are alluvial fans, piedmont plains, and piedmonts that slope from the mountains to stream terraces of the Wind-Bighorn system, and to broad intermountain basins. Rugged hills and low mountains are cut by narrow valleys with steep gradients. Broad flood plains are associated with some of the major rivers. Elevation ranges from 3,610 to 10,170 ft (1,100 to 3,100 m). This Section is within Fenneman and Johnson's Wyoming Basin geomorphic physical division.

Lithology and Stratigraphy. The northern half of the Section is Tertiary sandstones, siltstones, and shales. The southern half of the Section is Cretaceous through Tertiary sandstones, siltstones, shales, conglomerates, and local coals. The middle part of the Section also includes local Precambrian granite and metamorphosed sedimentary and volcanic rocks and Precambrian granite and Paleozoic carbonates in the Seminole Mountains.

Soil Taxa. There are mesic and frigid temperature regimes. Soils include Mollisols, Inceptisols, Aridisols, and Entisols, including, Argids, Orthents, Borolls, and Fluvents.

Potential Natural Vegetation. Vegetatative communities range from grass to grass-shrub to shrub-grass to forest. Kuchler mapped vegetation as sagebrush steppe (sagebrush-wheatgrass); wheatgrass-needlegrass shrub steppe; grama-needlegrass-wheatgrass prairie; and Douglas-fir forests.

Disturbance Regimes. Fire, insects, and disease are primary sources of disturbance.

Section 342G--Green River Basin

Geomorphology. This Section includes rugged hills and low mountains, with narrow valleys having steep gradients. Broad flood plains and fans are present on major rivers. Alluvial fans, piedmont plains, and piedmont slopes from the surrounding mountains join to form broad intermountain basins. Elevation ranges from 3,610 to 7,875 ft (1,100 to 2,400 m). This Section is within Fenneman and Johnson's Wyoming Basin geomorphic physical division.

Potential Natural Vegetation. Vegetative communities include grasses to grass-shrub to forests. Kuchler classified potential vegetation as sagebrush steppe (sagebrush-wheatgrass), saltbush-greasewood, and wheatgrass-needlegrass shrubsteppe.

Disturbance Regimes. Primary sources of disturbance are fire, insects and disease.

Section 342H--High Lava Plains

Geomorphology. This area includes moderately dissected mountains and broad flat uplands. This Section is dominated by debris slides, rock fall and slow creep erosion processes on slopes of 20 to 120 percent. Some ancient lake terraces occur along the valley sides on slopes less than 30 percent. A multitude of young eruptive events have left volcanic features. During glacial stages numerous large lakes formed, filling to the playas found today. Elevation ranges from 2,000 to 5,000 ft (700 to 1,700 m). Local relief is mostly 300 to 800 ft (90 to 242 m).

Potential Natural Vegetation. Kuchler vegetation is characterized by three principal groups. Sagebrush-steppe (Artemesia-Agropyron}) is considered dominant; followed by the juniper-steppe woodland (Juniperus-Artemesia-Agropyron}) type; least common is wheatgrass-bluegrass (Agropyron-Poa}). More recent classifications reveal a somewhat different characterization. A savanna with ponderosa pine occurs along the extreme western edge of this Section. Proceeding east, western juniper forms a woodland mixed with native sagebrush, bitterbrush and bunchgrasses. This woodland dominates the landscape over much of the western one-third of the Section. The woodland character soon changes as one proceeds east, with sagebrush and bunchgrasses dominating the undulating land; western juniper becomes restricted to rocky outcrops and other areas that have not experienced a recent fire. The eastern portion of the Section maintains a vegetative dominance of sagebrush and bunchgrass, but elements of either the desert or salt desert shrub communities are noticeable. Locally, grasses, sedges, rushes, and forbs occupy wet sites in meadows and along streams.

Disturbance Regimes. Prior to fire protection, fire was a common disturbance factor. Periods were about 15 to 30 years.

Section 342I--Columbia Basin

Geomorphology. The Section is characterized by generally flat-lying basalt flows. It is a large dissected plain high above sea level. Structurally the Plateau is a great basin between the Rockies and the Cascades. Also, it is the best known example of plateau flood basalts. Channeled scablands, the result of mega-floods, range from excavated low points to coulees miles wide and hundreds of ft deep. Deposits of glacial till, glacial moraine, or glacial outwash blanket the plain. Rolling hills of loess cover unglaciated areas to the south and east. Elevation ranges from less than 200 ft near the Columbia River to more than 4,500 ft on high ridges and low mountains (70 to 1,500 m).

Potential Natural Vegetation. According to Kuchler, the sagebrush-steppe is dominant, followed by fescue-wheatgrass and wheatgrass-bluegrass.

Disturbance Regimes. Wind is the principal disturbance feature. Composition and successional sequences of some communities have changed because of agricultural practices and the introduction of animal species into the valleys.

Nevada-Utah Mountains Semi-Desert - Coniferous Forest - Alpine Meadow

These Sections are located in the west-central conterminous States, including parts of Nevada, Utah, and Colorado. The area of these Sections is about 43,600 mi2 (112,900 km2).

Section M341A--Central Great Basin Mountains

Geomorphology. This area occurs within the Central Nevada Basin and Range physiographic province. The Central Great Basin Mountains section is located in central Nevada and a small area of western Utah. The dominant landforms are north-south trending mountains separated by broad, sediment-filled valleys, many of which have internal drainages. Mountains were formed by faulting and were subsequently modified by erosion. Large alluvial fans have developed at the mouths of most canyons. Some fans are coalescing, nearly burying the eroded mountains. Elevation ranges from 5,000 to 13,000 ft (1,500 to 4,000 m).

Potential Natural Vegetation. Kuchler vegetation types include Great Basin sagebrush and areas of saltbush-greasewood and juniper-pinyon woodlands. The Soil Conservation Service identifies the potential natural vegetation as saltbush-greasewood, big sagebrush, and pinyon-juniper woodland vegetation.

Disturbance Regimes. Erosion by wind and water is occurring. Fires also occur.

Section M341B--Tavaputs Plateau

Geomorphology. This area occurs within the Colorado Plateau physiographic province. The Tavaputs Plateau Section is located in eastern Utah and western Colorado. One of Utah's most rugged areas is between the relatively level interior of the Uinta Basin and the valleys cut in the Mancos Shale in Carbon, Emery, and Grand Counties. The structure is relatively simple. Strata of Cretaceous and Tertiary periods rise gradually southward and upward from the center of the Uinta Basin to reach elevations between 8,000 and 10,000 ft where they are abruptly cut off in great erosional cliffs that descend in giant steps to the valleys of the south; there elevations are between 4,000 and 5,500 ft. The great system of linear cliffs is evident. The lower one, most visible and best known, is the Book Cliffs. Elevation ranges from 7,300 to 10,000 ft (2,100 to 3,000 m). Local relief ranges from 5 percent on the broad plateau uplands, to steep vertical canyon sidewalls comprised predominantly of bedrock.

Potential Natural Vegetation. Kuchler vegetation types include juniper-pinyon and big sagebrush. The eastern part of this Section (Book Cliffs-Roan Plateau-East and West Tavaputs Plateau) as delineated by Stokes includes juniper-pinyon, black sagebrush, big sagebrush, mountain brush, Salina wildrye grasslands, ponderosa pine, aspen, Douglas-fir, and spruce-fir.

Disturbance Regimes. Occurrence of fire is common, with large grass and shrub areas burning rapidly. At higher elevations, small fires are common, generally caused by lightening. They are usually confined to aspect and vegetation type. These fires are generally not extensive.

Section M341C--Utah High Plateaus and Mountains

Geomorphology. This area occurs within the Colorado Plateau physiographic province. It includes portions of south-central Utah. This Section is located in the northwest corner of the Colorado Plateau physiographic province. These plateaus are primarily fault-controlled, have relatively high elevations, are aligned in a north-south direction, and are underlain with rocks of Mesozoic and Cenozoic eras. The east flank of the high plateaus is bordered by the Canyonlands. The western boundary is faulted, separating it from the Basin and Range physiographic province. They are a series of high plateaus that are gently rolling on top, but rise steeply from the valley bottoms. They are separated by north-south trending valleys. Landslides have influenced many areas in this Section and several plateaus were sites of local icecaps during at least the Wisconsin age. The tops of the plateaus have been capped with volcanic flows and glacial deposits. Colorful badland topography exists near Bryce Canyon and Cedar Breaks. another fault-controlled depression, and by the Paunsaugunt Fault. The western boundary of the Utah High Plateaus and Mountains Section also follows the northern part of Hurricane Fault.

Potential Natural Vegetation. Kuchler vegetation types include western spruce-fir forest, Arizona pine forest, and spruce-fir--Douglas-fir forest. The Soil Conservation Service identifies potential natural vegetation as conifer, aspen, grasses, mountain shrub, and sagebrush-grass. Areas of big sagebrush also occur.

Disturbance Regimes. The primary disturbance forces are infrequent mass movements and erosion from water. Historically, fire was a major disturbance that modified the vegetation. Fire suppression practices during the past century has altered this process.

Everglades Province

This Section is located in southern Florida and has an area of about 7,800 mi2 (20,200 km2).

Section 411A--Everglades

Geomorphology. This Section is in the Coastal Plains geomorphic province. The predominant landform is a flat, weakly dissected alluvial plain formed by deposition of marine sediments onto a submerged, shallow continental shelf, which was later exposed by sea level subsidence. Along the coast, fluvial deposition and shore-zone processes are active in developing and maintaining beaches, swamps, and mud flats. Elevation ranges from sea level to 80 ft (25 m). Local relief ranges from 0 to 10 ft (3 m).

Potential Natural Vegetation. Kuchler classified five potential communities: Everglades ({\it Mariscus, Magnolia-Persea}); mangrove, cypress savanna, and sub-tropical pine forest. This Section is dominated by two principal potential natural communities adapted to hydric conditions: an extensive treeless savanna (the Everglades) on the eastern side of the Section, and forested woodlands (the Big Cypress Swamp) on the western side. The Everglades is a shallow, broad (60 mi, 95 km) river with freshwater flowing southward from Lake Okeechobee to the Gulf of Mexico. Physiognomy of vegetation varies by duration of inundation and amount of salt

content. Vegetation includes: grasses in permanently submerged freshwater habitats; trees in dry to intermittently flooded fresh water habitats; and shrubs to small trees in saltwater estuary habitats. Predominant vegetation of flooded freshwater habitats includes sawgrass (actually a sedge), swamp lily, and spatterdock; on islands of slightly higher elevation (hammocks), trees include slash pine, royal palm, gumbo limbo, and strangler fig. Epiphytes are common. Big Cypress Swamp, and other adjacent areas to the north, are characterized by intermittently flooded freshwater habitats with very poor drainage that are dominated by cypress; oaks and magnolias occupy better drained areas. Poorly drained soils along the east coast, and farther inland along the west coast, are dominated by south Florida slash pine. Sand pine, with scrub oak and saw palmetto understory, occupies excessively drained, deep sands. Both south Florida slash and sand pine are well adapted to an environment of frequent fire. Coastal areas influenced by saltwater tidal zones are occupied by successive zones of vegetation, from freshwater to saltwater environments, of button mangrove, black mangrove, and red mangrove, respectively. Other species common to this tropical environment include Florida fishpoison-tree, Bahama lysiloma, royal poinciana, tamarind, shortleaf fig, Florida royalpalm, Jamaica thatchpalm, and oxhorn bucida. Key West Cephalocereus, a tree-sized member of the cactus family, occurs in thin, dry soils of the Florida Keys. Exotic species are creating a threat to native species. For example, the cajuput, or bottle-brush tree, a native of Australia has been planted widely as an ornamental and is now invading the Everglades National Park. Also, the water hyacinth, a free-floating Brazilian herb, clogs waterways.

Disturbance Regimes. Hurricanes are probably the most widespread form of natural disturbance, followed by infrequent fires during the winter dry season. Fire consumes irregular areas of organic soils, which fill with water during the wet season to make shallow lakes.

Land Use. Much of the land along the east and west coasts has been cleared of natural vegetation, originally for agriculture, but more recently for urban development. This Section contains the Everglades National Park, the Seminole and Miccosukee Native American reservations, and several national wildlife refuges.