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.

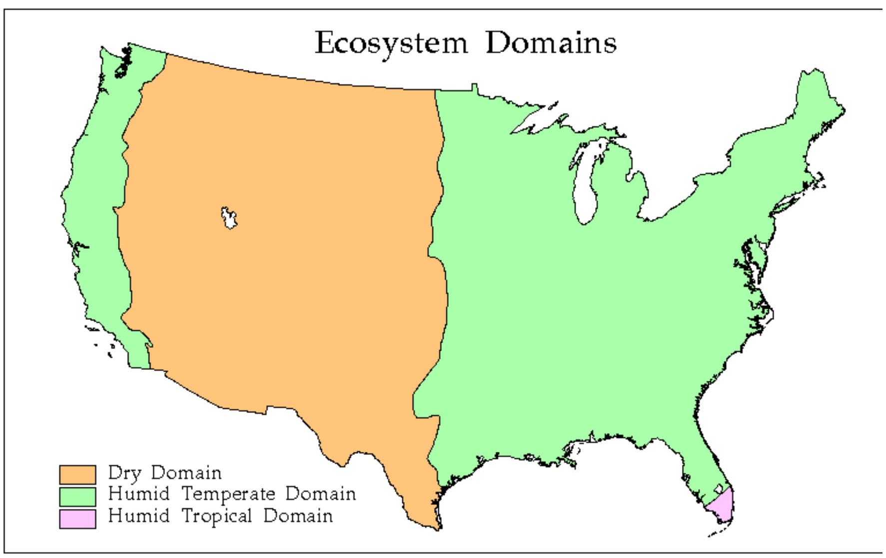


Figure 6.1: Bailey Ecosystem Domains, General Dilineation of Eastern and Western US Fire History

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

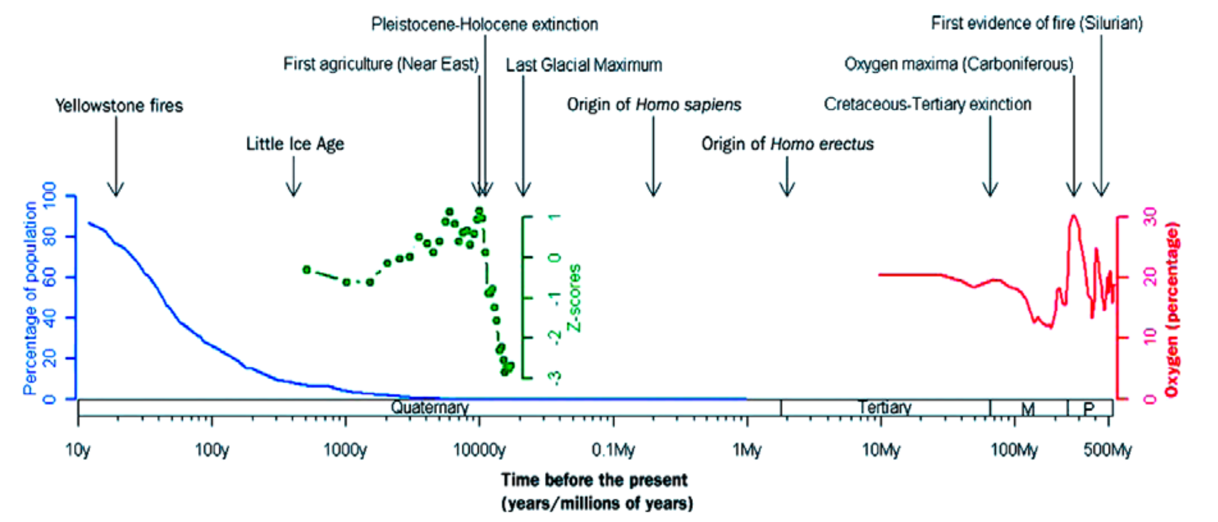


Figure 6.2: Temporal position of key moments in the history of life (time in logarithmic scale). The blue line denotes the proportion of the human world population relative to 2006 (left y-axis). The red line is the atmospheric oxygen concentration (percentage; right y-axis) from 10 million to 550 million 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.

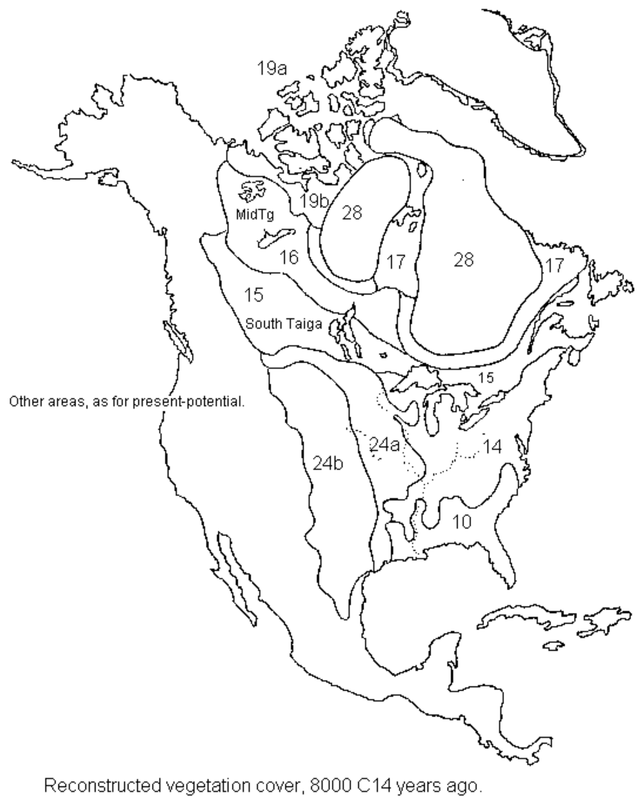
Between 12,000 and 9,000 years BP there was a significant change in fire regimes. 12,000 years BP fire increased from glacial times at sites in northeastern and western North America. By 9,000 years BP, regional charcoal record summaries show greater than-present fire throughout eastern North America 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.

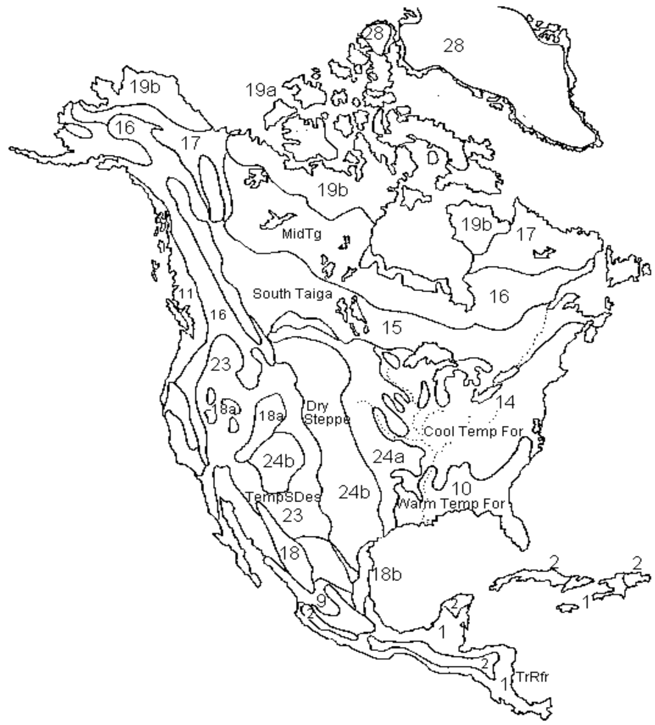
adapted from Adams and Faure, 1997

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).



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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.

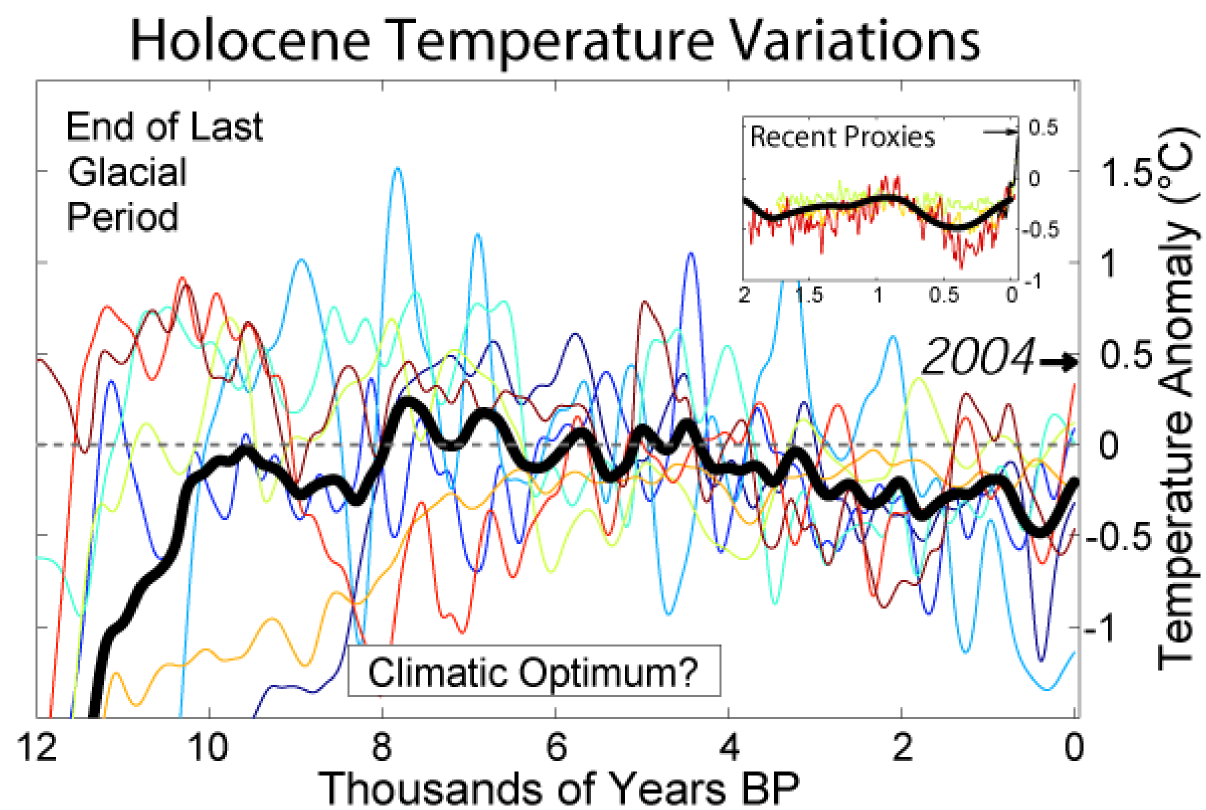

Figure 6.5: Holocene Temperature Variation. Source: (NOAA Paleoclimatology data sets, compiled by R. A. Rhode)

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).

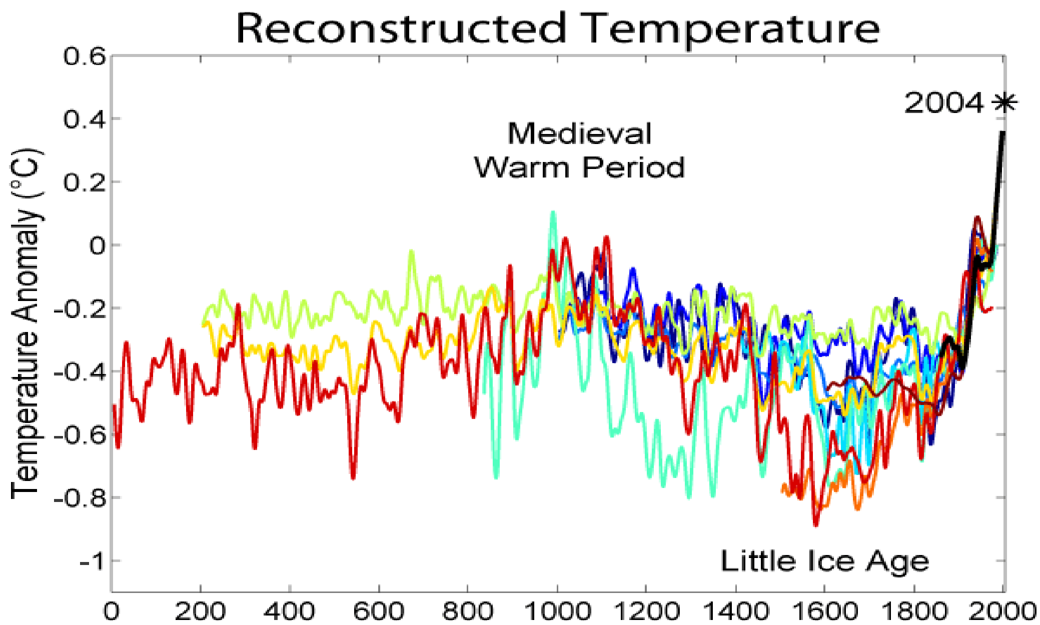

Figure 6.6: Little Ice Age – The cold period between 1550 AD and 1850 AD. Source: (NOAA Paleoclimatology data sets, compiled by R. A. Rhode; http://www.ncdc.gov/paleo)

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 16^{th} and 17^{th}centuries.

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).

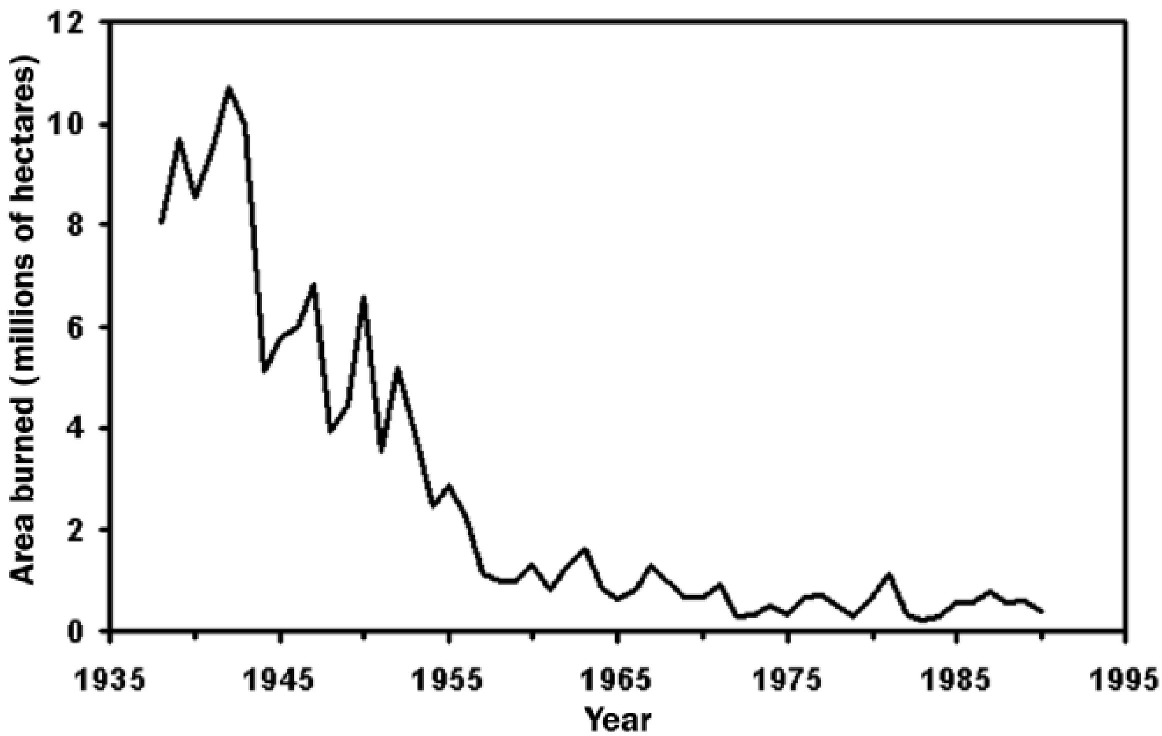

Figure 6.8: Area burned in the eastern United States (1938–1990) based on historic fire records Area includes Minnesota, Iowa, Missouri, Arkansas, Louisiana, and all states eastward. Source: (Nowacki and Abrams 2008)

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).

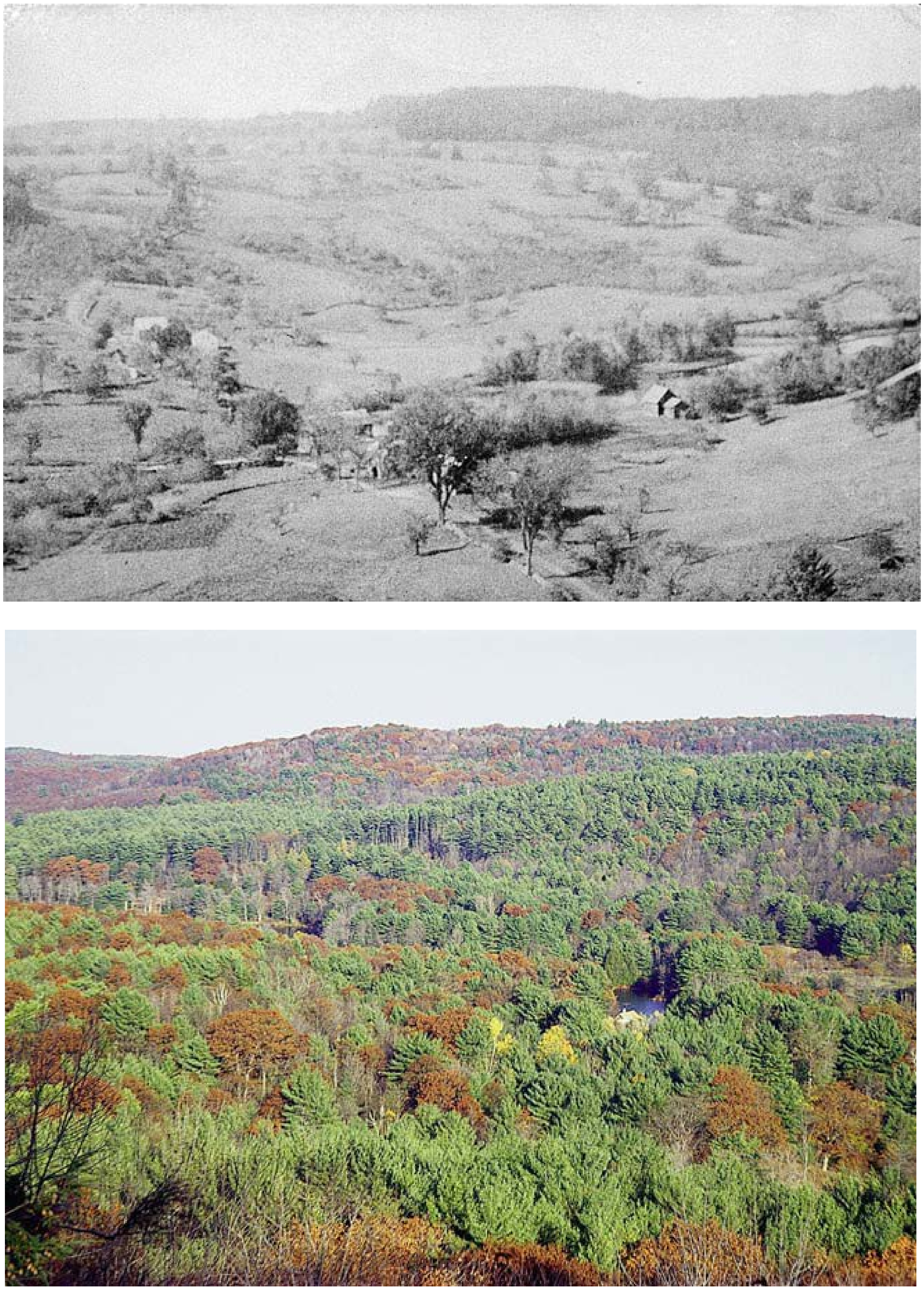

Figure 6.9: Progressively over time and space, agricultural uses replaced forests in much of the Eastern United States. By the 1850s this trend began to give way in some places to natural succession and reversion to forestland in areas less suited to mechanized farming. Central Massachusetts images,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

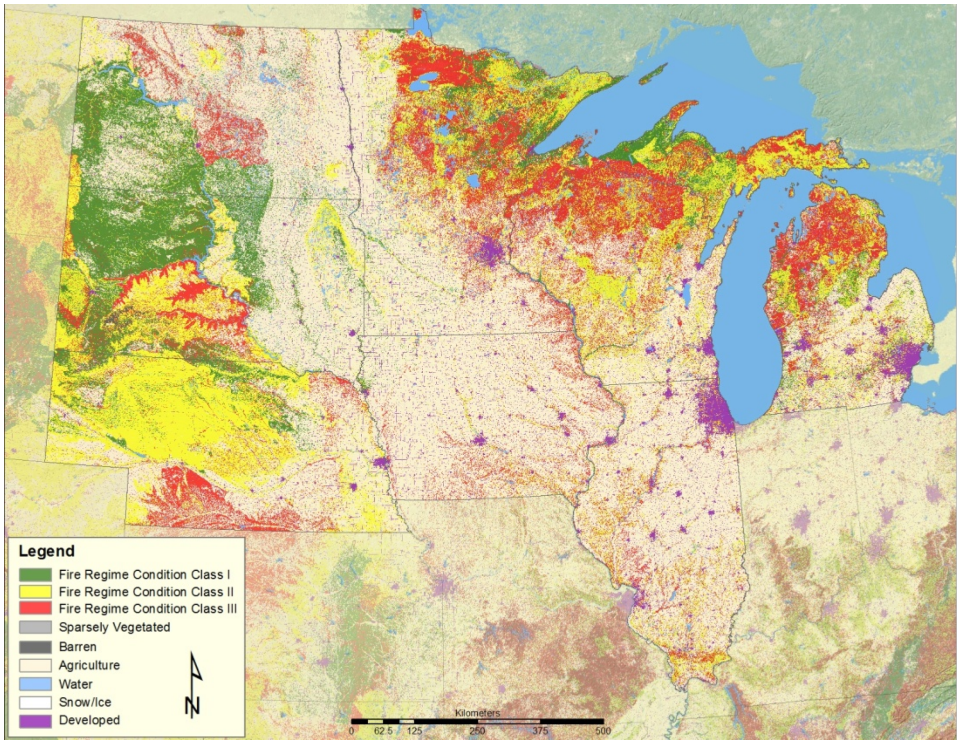

Figure 6.11: North Central US LANDFIRE Fire Regime Condition Class June 2011

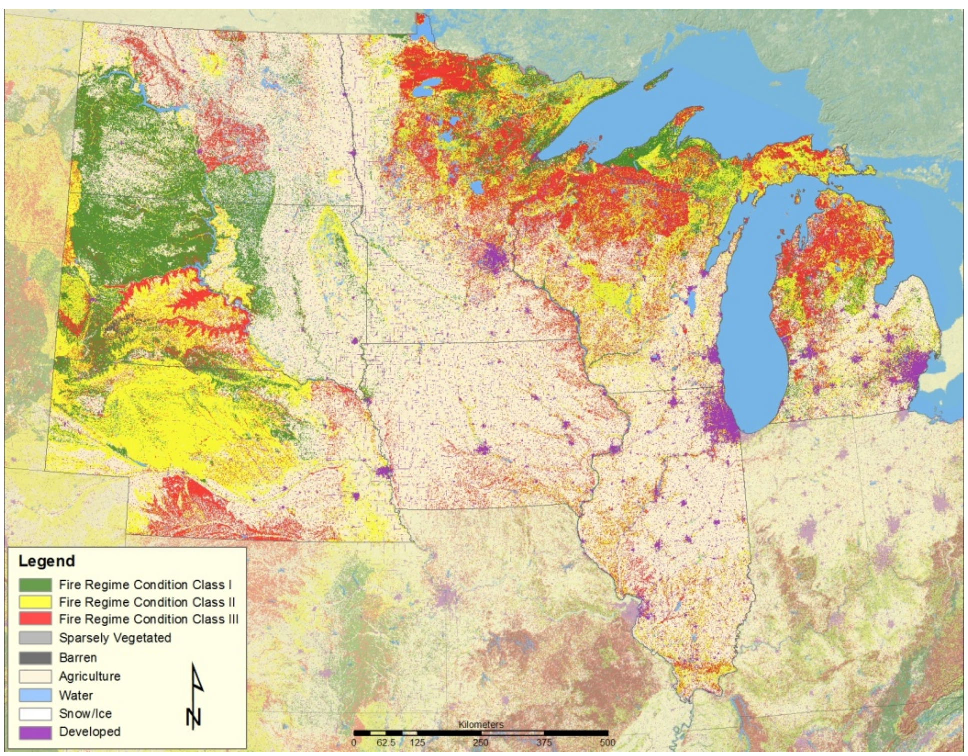

Figure 6.12: North Eastern US LANDFIRE Fire Regime Condition Class June 2011

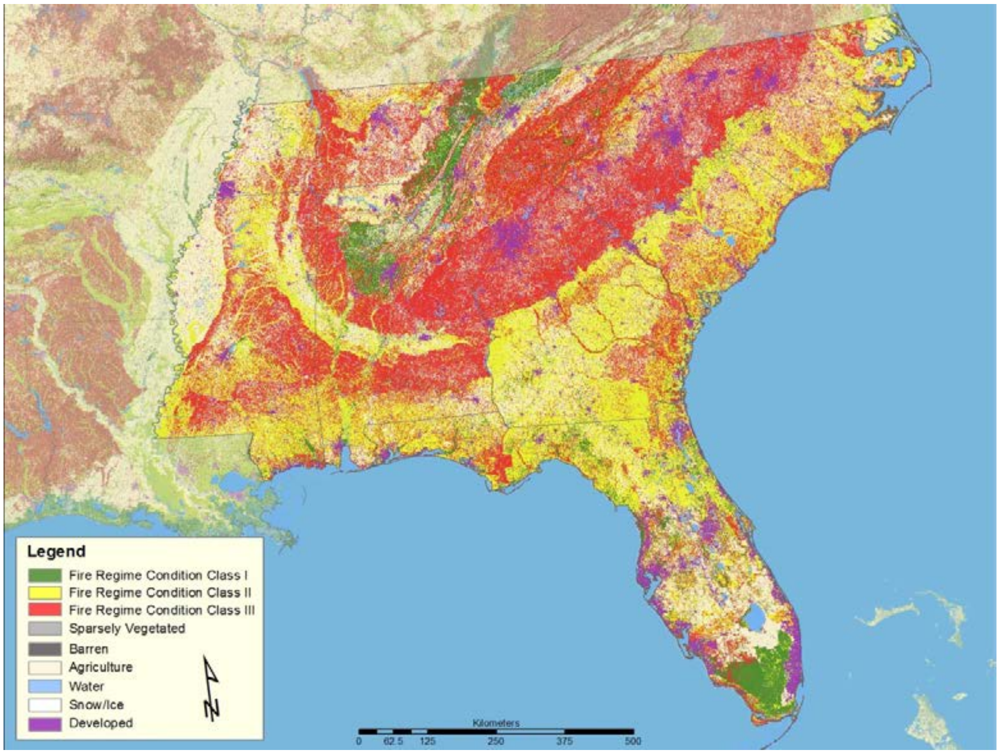

Figure 6.13: South Eastern US LANDFIRE Fire Regime Condition Class June 2011

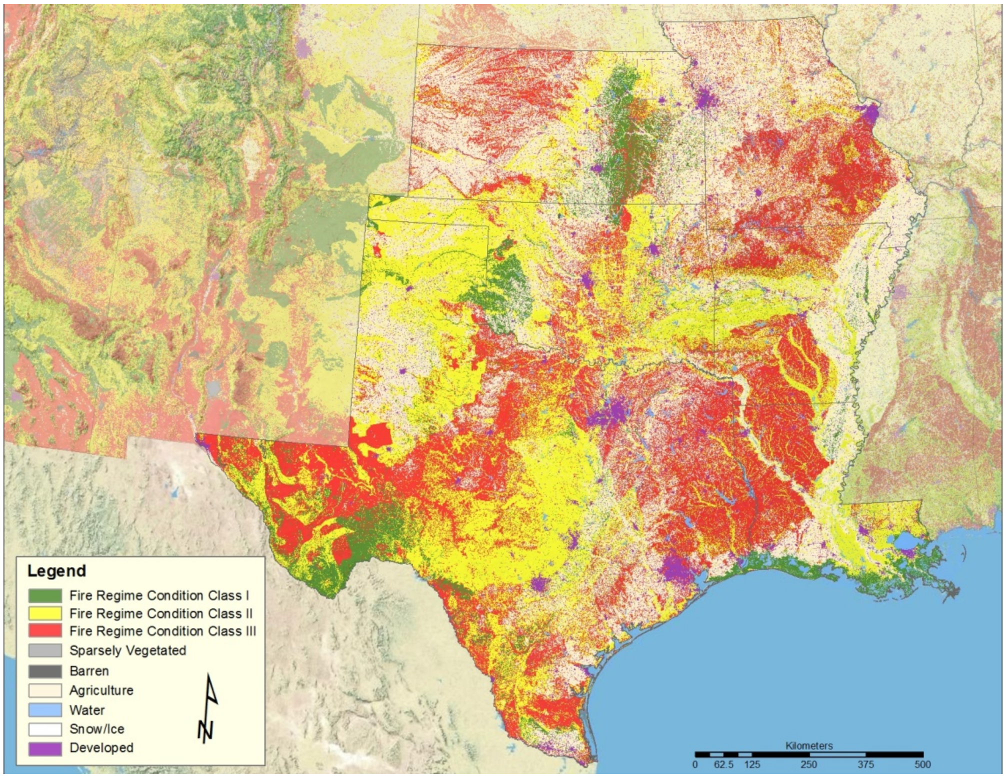

Figure 6.14: South Central US LANDFIRE Fire Regime Condition Class June 2011

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

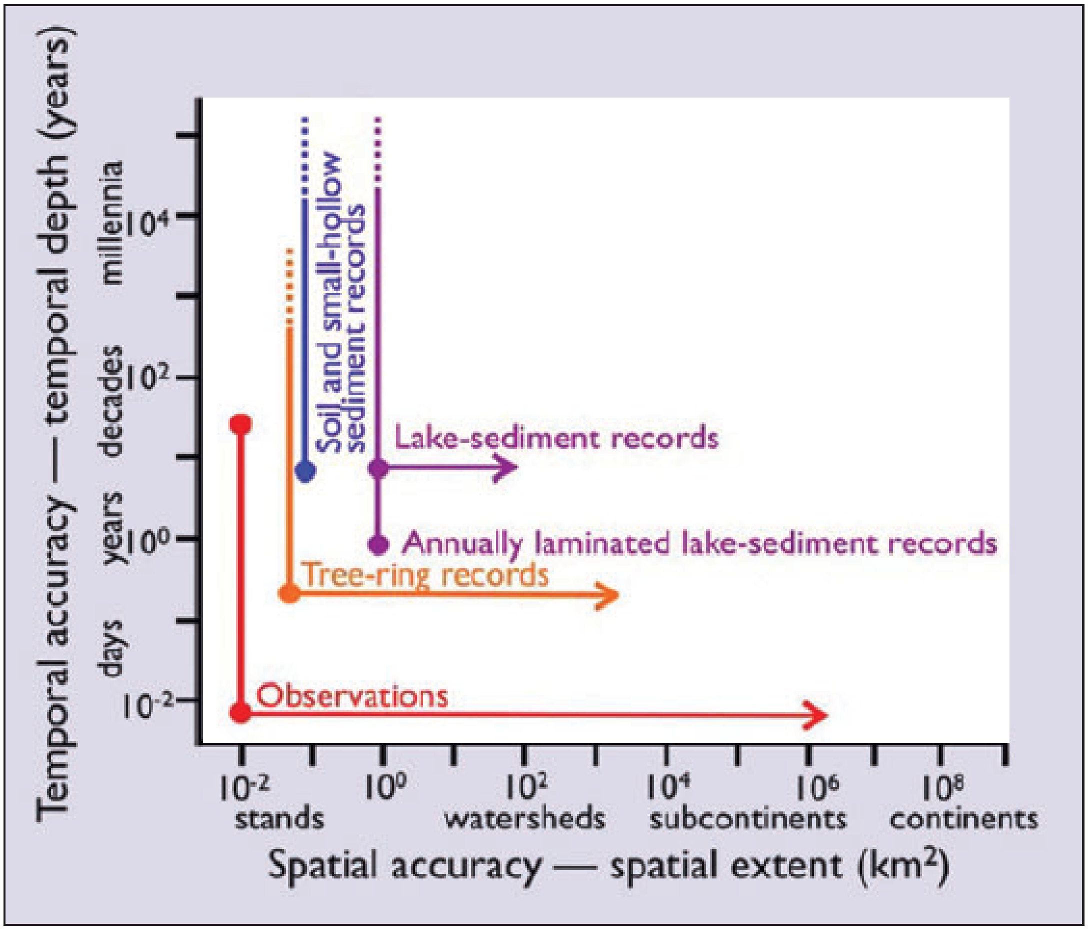

Figure 6.15: The spatial and temporal domains of fire history methods span several orders of magnitude. Vertical lines extend from the finest temporal accuracy to the maximum temporal depth of a particular method. Horizontal lines extend from estimates of the finest spatial accuracy of individual records 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.

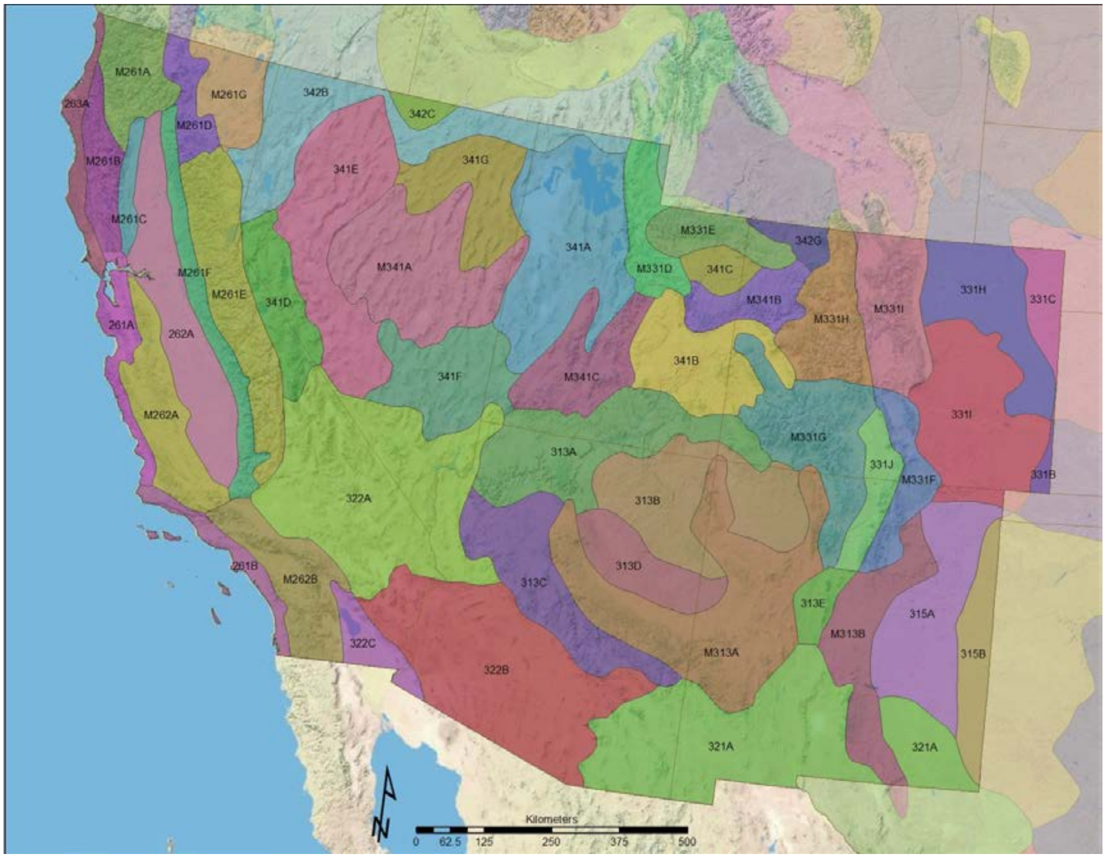

Figure 6.16: Bailey Provinces and Sections for the Southwest region. Section Descriptions, with information on current vegetation, are in Appendix F

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

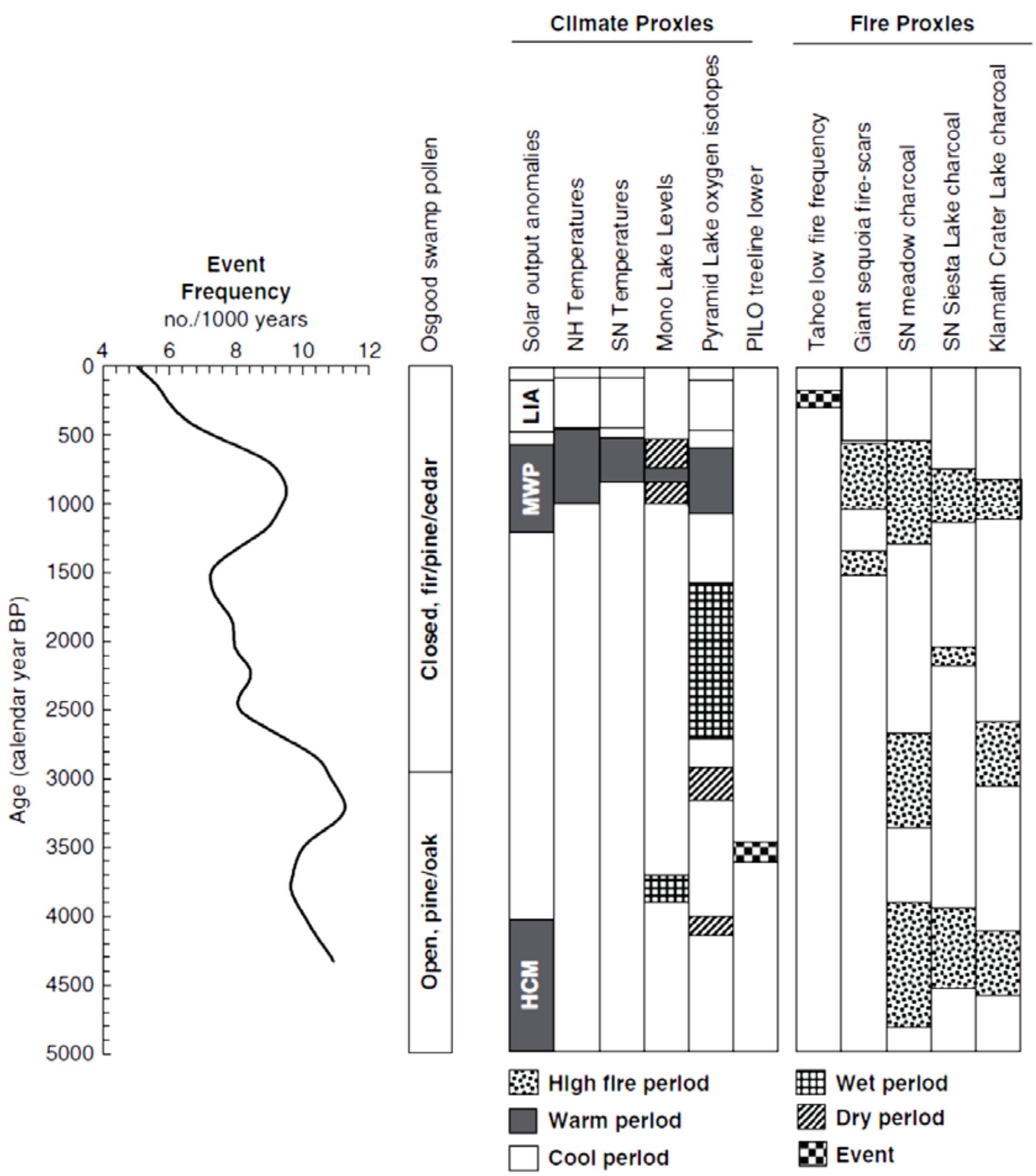

Figure 6.17: This is Figure 8 from (Beaty and Taylor 2009)**)** which compares the charcoal record for the last 4500 years at Lily Pond to other vegetation, climate and fire proxies results in the Sierra Nevada region. Peaks column indicates when influx values exceed background values. Areas of high 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.

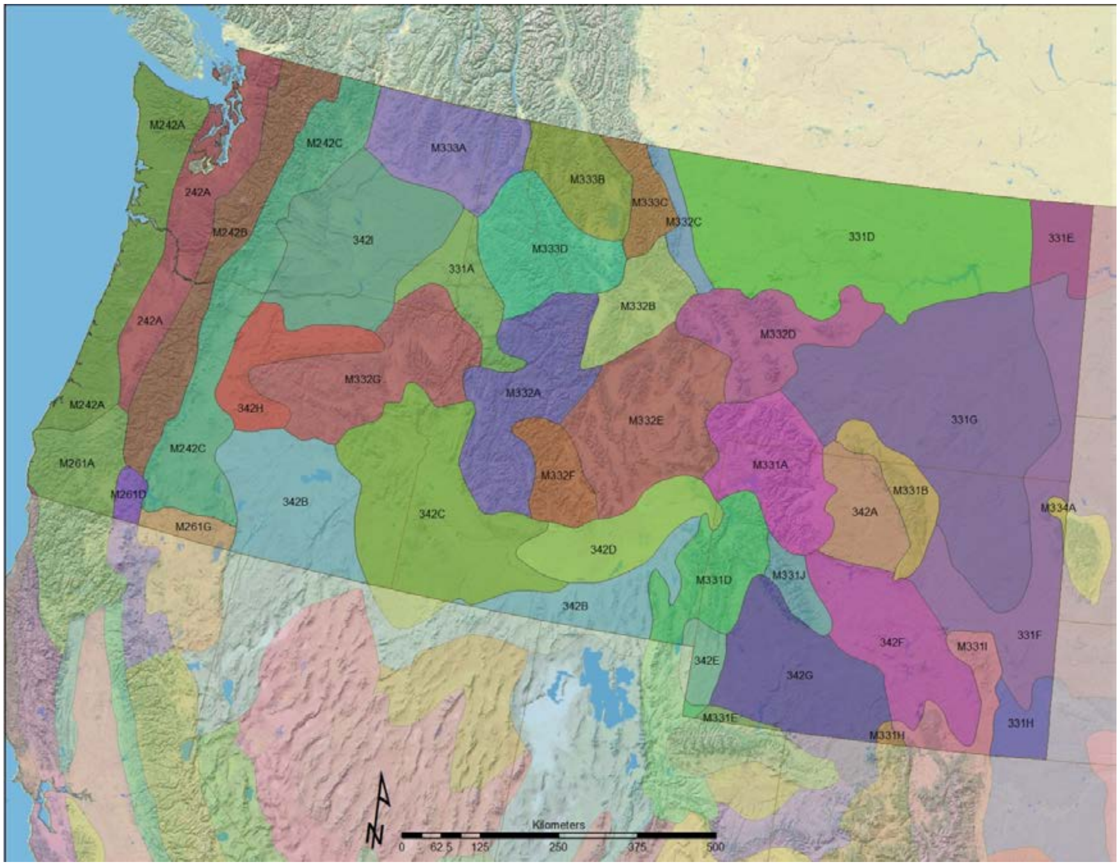

Figure 6.18: Bailey Provinces and Sections for the Northwestern region. Section Descriptions, with information on current vegetation, are in Appendix F

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

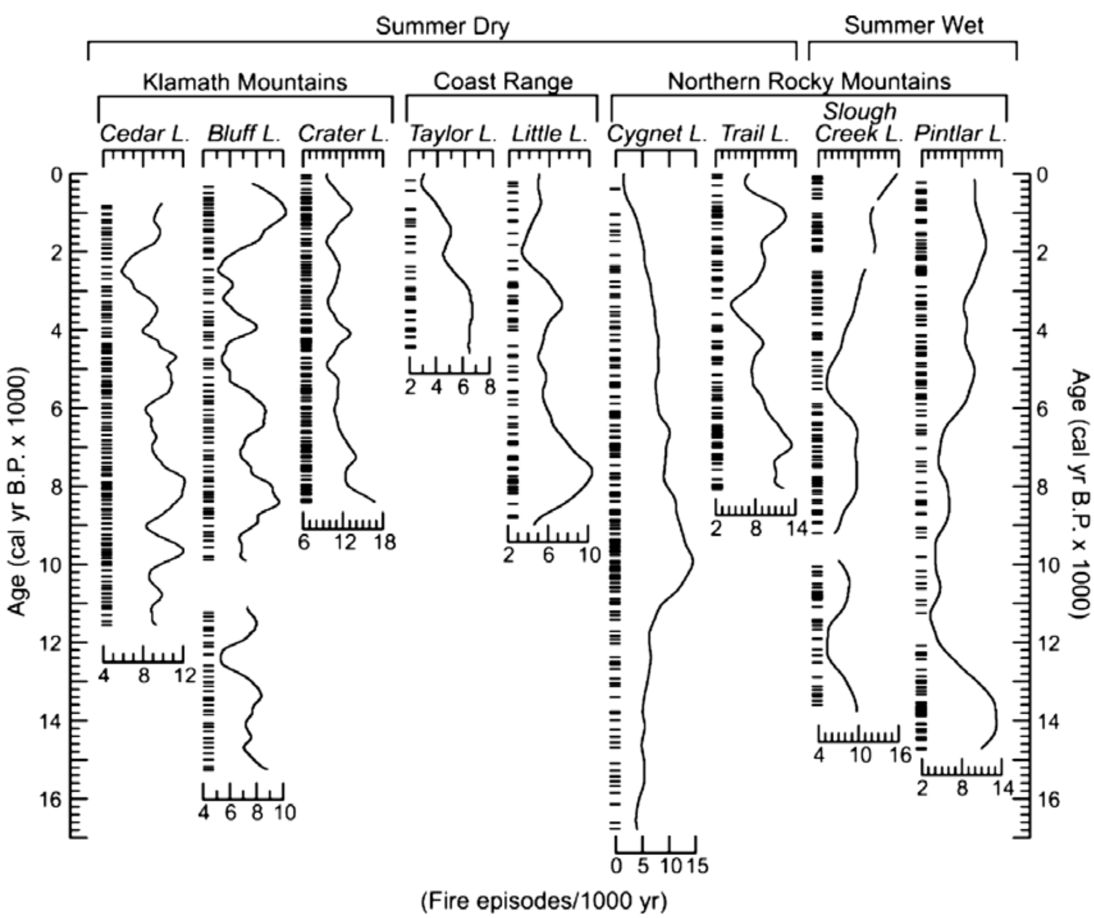

Figure 6.19: Fig. 2 (from Whitlock et al. 2003). Comparison of Holocene fire reconstructions from sites in different geographic and climatic locations in the western US. The horizontal lines at each site represent past fire episodes, i.e., based on the age of peaks in the charcoal record obtained from 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

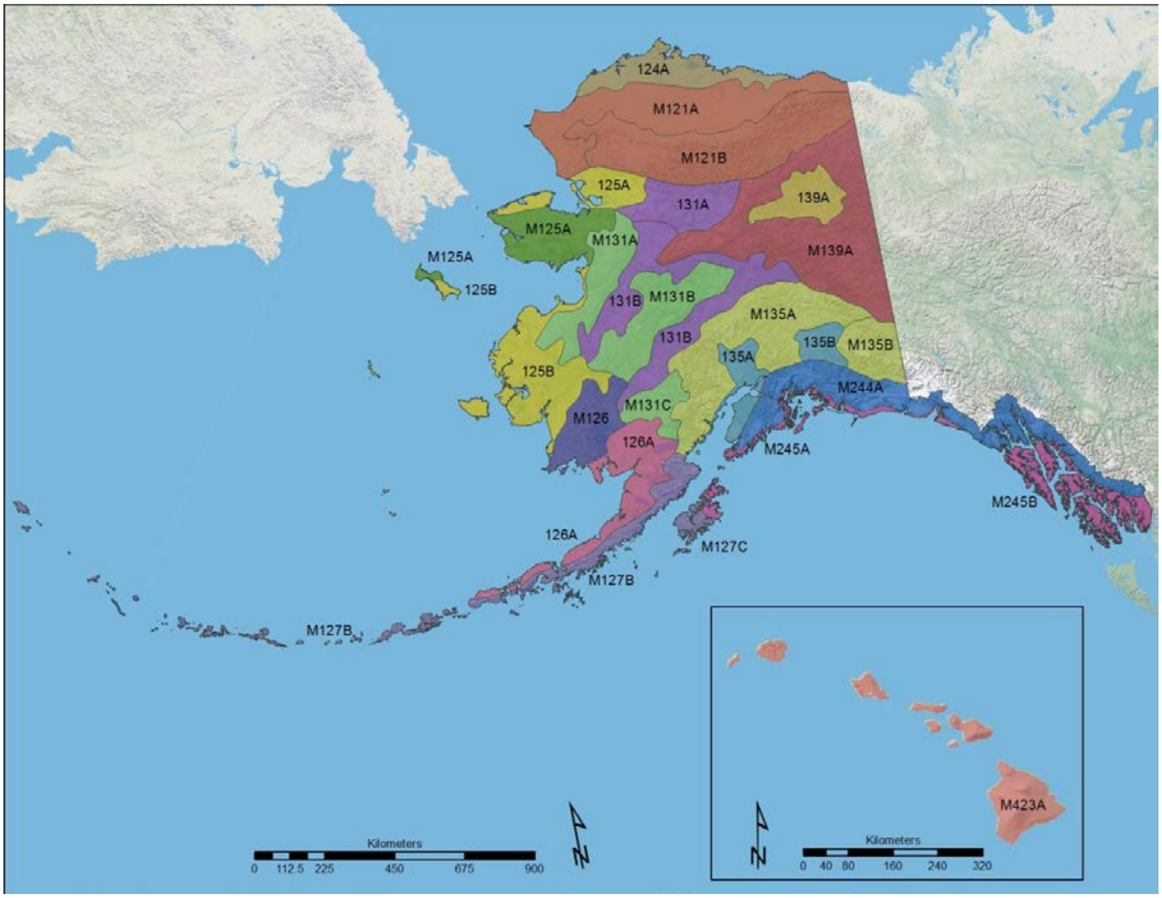

Figure 6.20: Bailey Provinces and Sections for Alaska. Section Descriptions, with information on current vegetation, are in Appendix F

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.

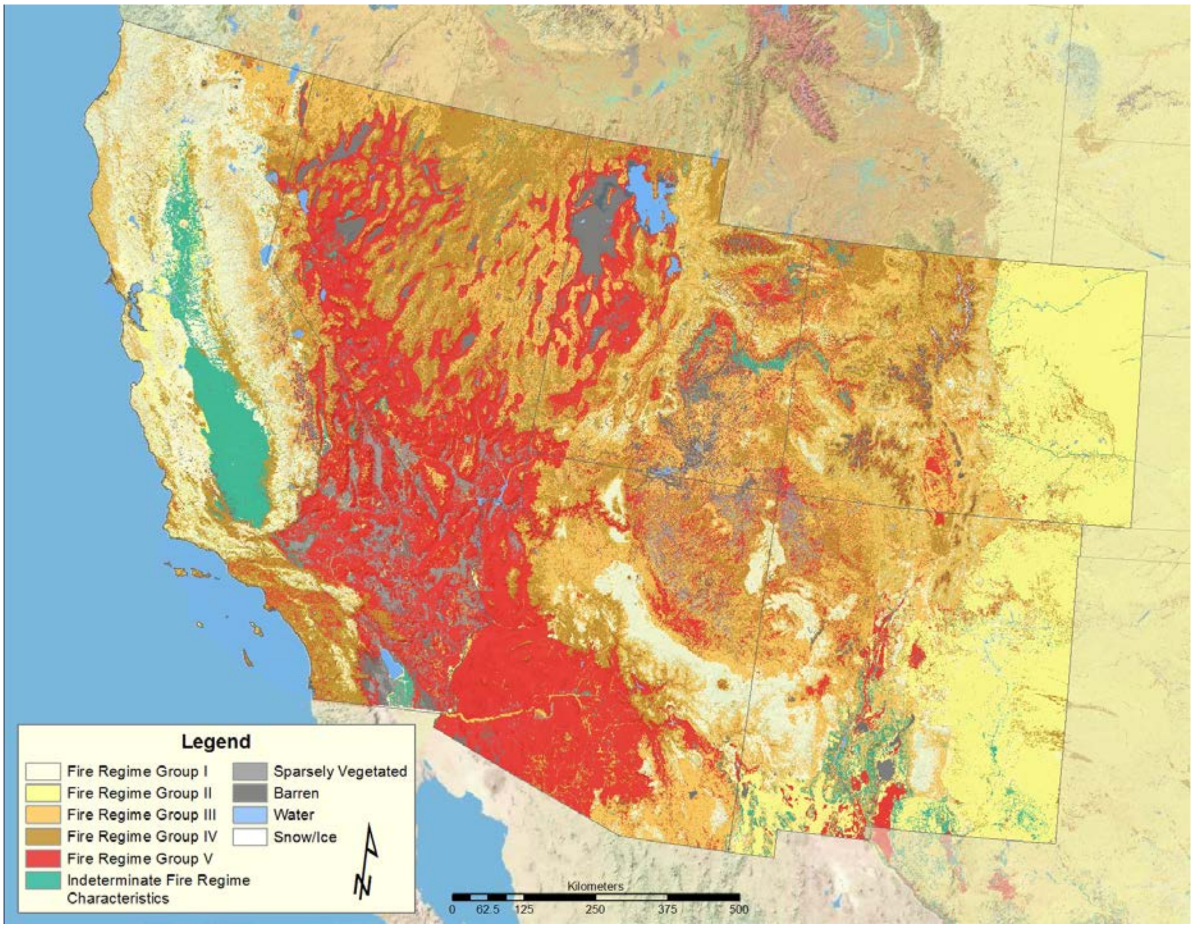

Figure 6.21a: Historic fire regime groups (FRG) in the southwestern US. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG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

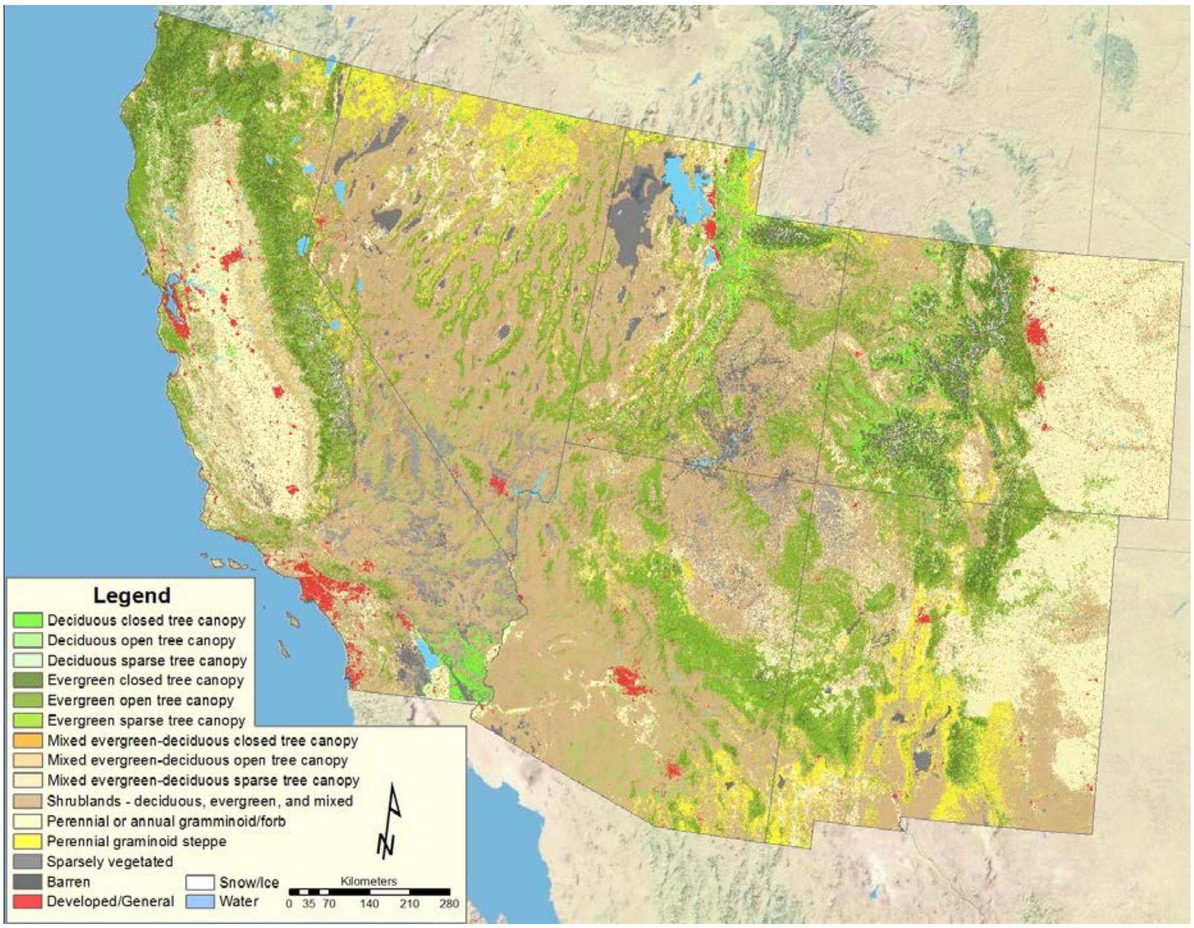

Figure 6.21b: Existing vegetation for the southwestern US. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

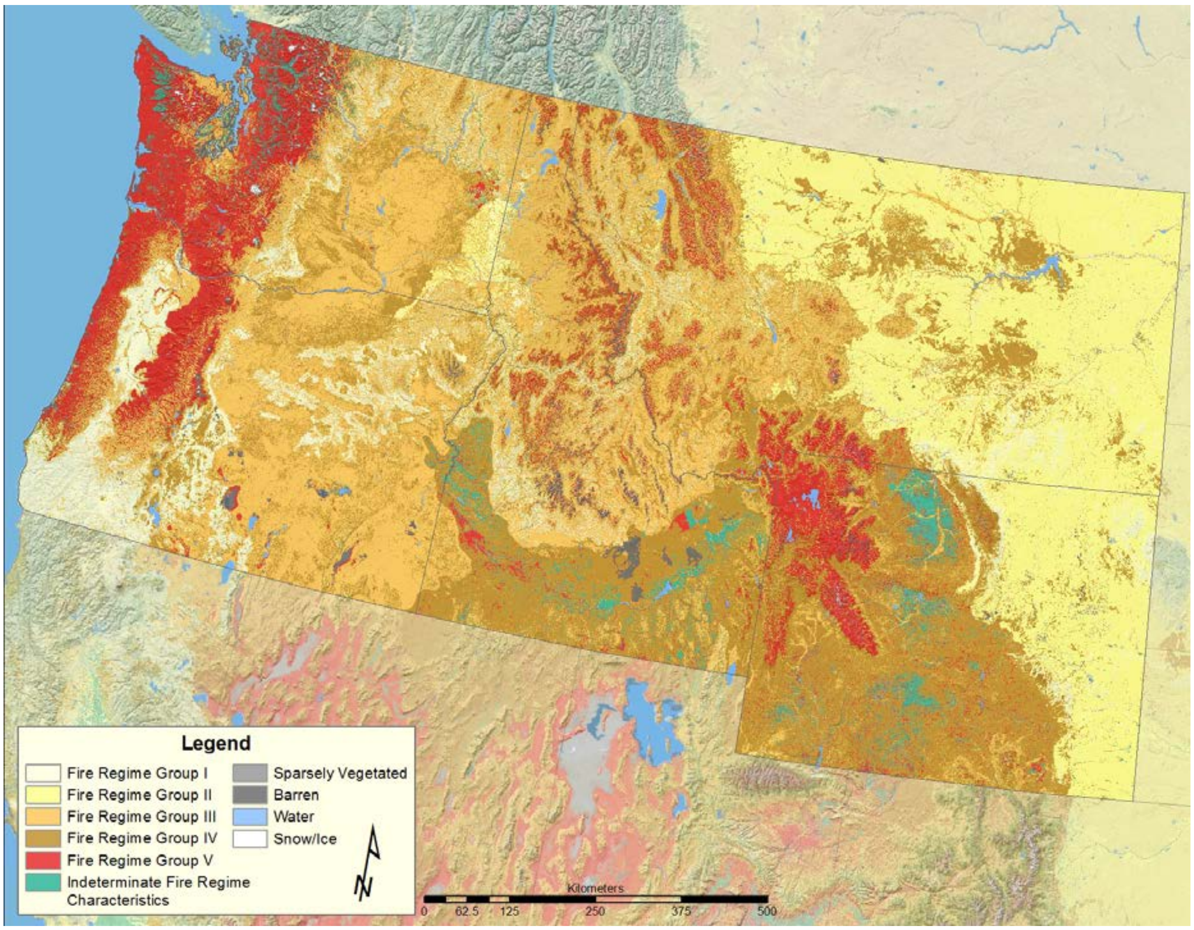

Figure 6.21c: Historic fire regime groups (FRG) in the northwestern US. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG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

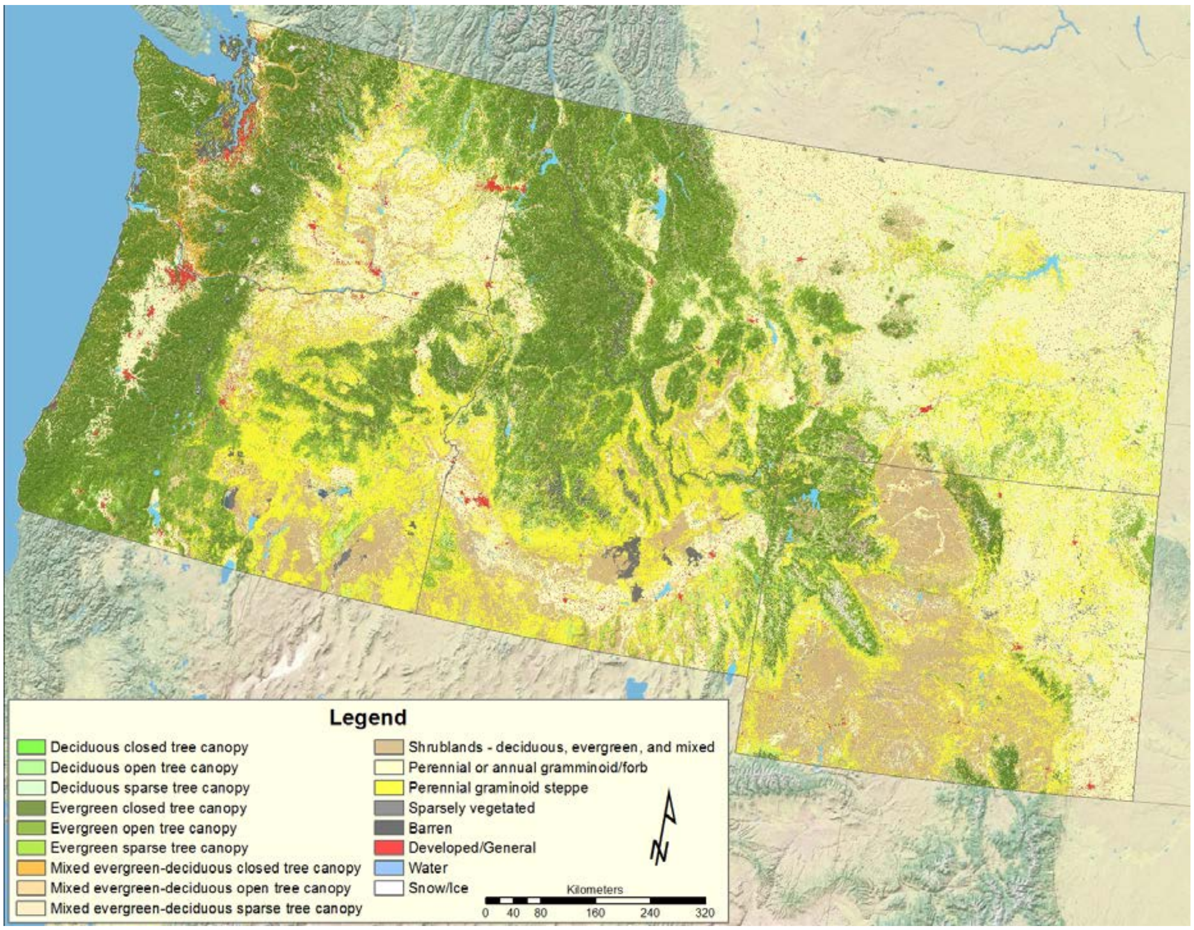

Figure 6.21d: Existing vegetation for the northwestern US. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

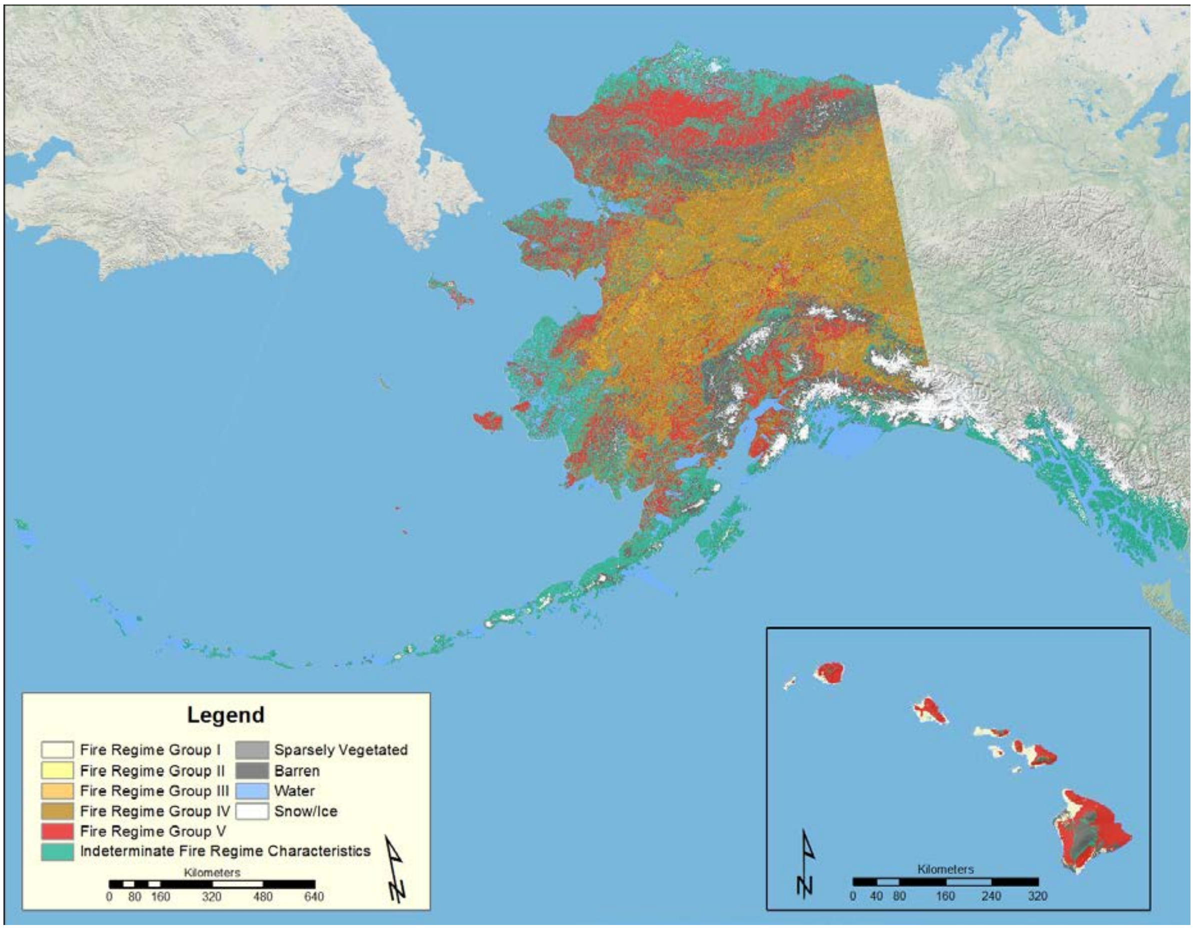

Figure 6.21e: Historic fire regime groups (FRG) in Alaska. FRG I (0 to 35 year frequency, low to mixed severity); FRG II (0 to 35 year frequency, replacement severity); FRG III (35 to 200 year frequency, low to mixed severity); FRG IV (35 to 200 year frequency, replacement severity); FRG V (200+ year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

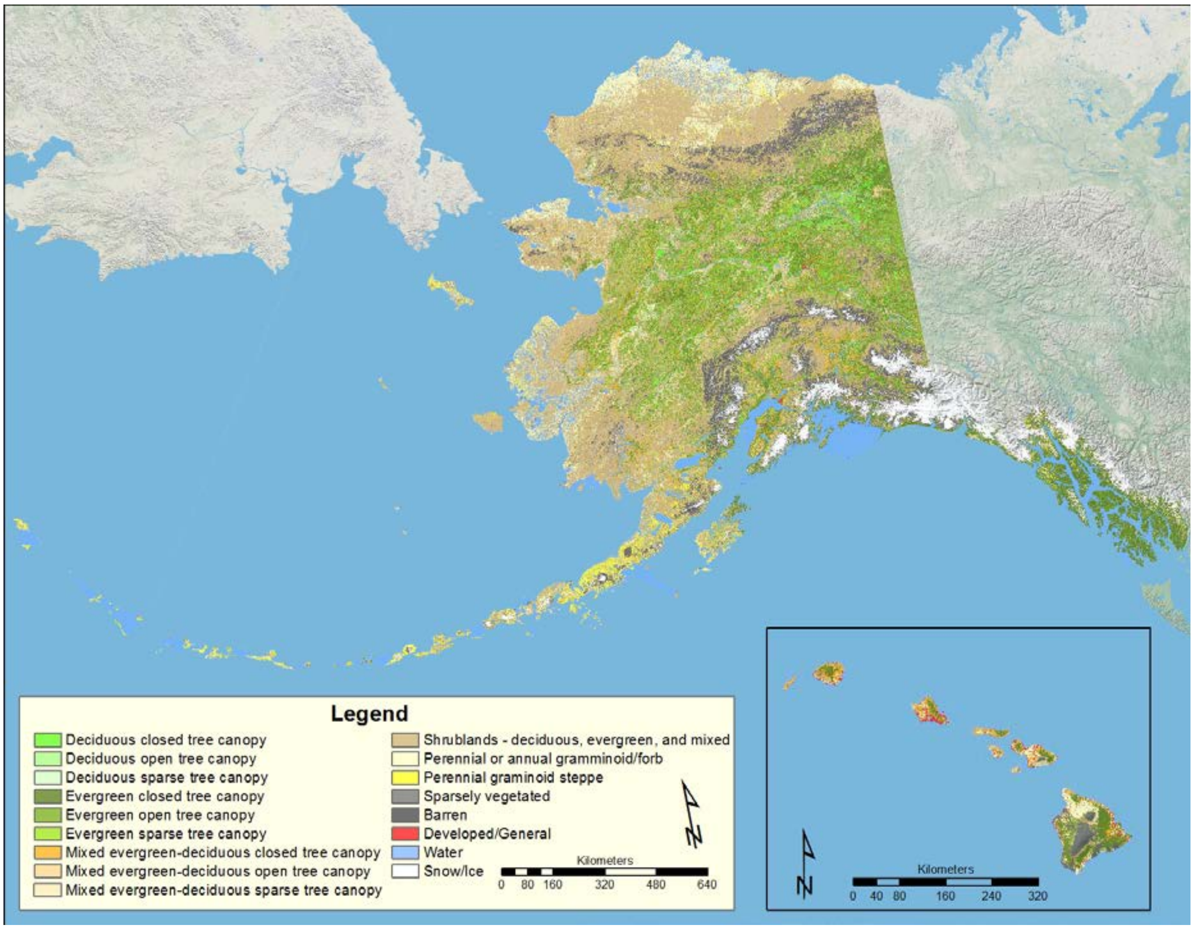

Figure 6.21f: Existing vegetation for Alaska. LANDFIRE vegetation classes have been grouped to simplify representation. Groupings were based on similarity in vegetation structure and life form.

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.

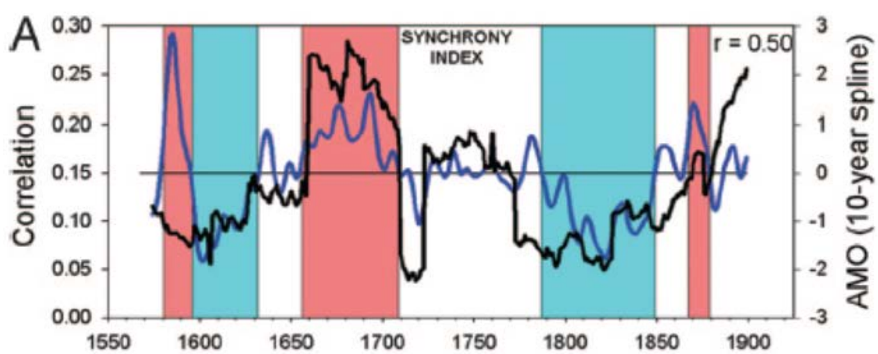

Figure 6.22: Index of fire synchrony (50-year moving correlations between selected regions, black line) compared with a 10-year spline of reconstructed AMO (blue line). Light blue and light red shaded areas indicate periods of low and high AMO, respectively. Synchrony index was computed as the mean of 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

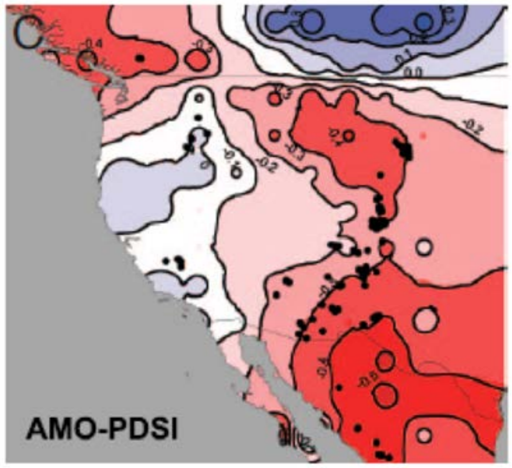

Figure 6.23: Correlations between the 49-year running mean AMO with a time-smoothed version of gridded PDSI (from tree ring data) for the period 1574–1899. . Source: (Kitzberger et al. 2007).

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

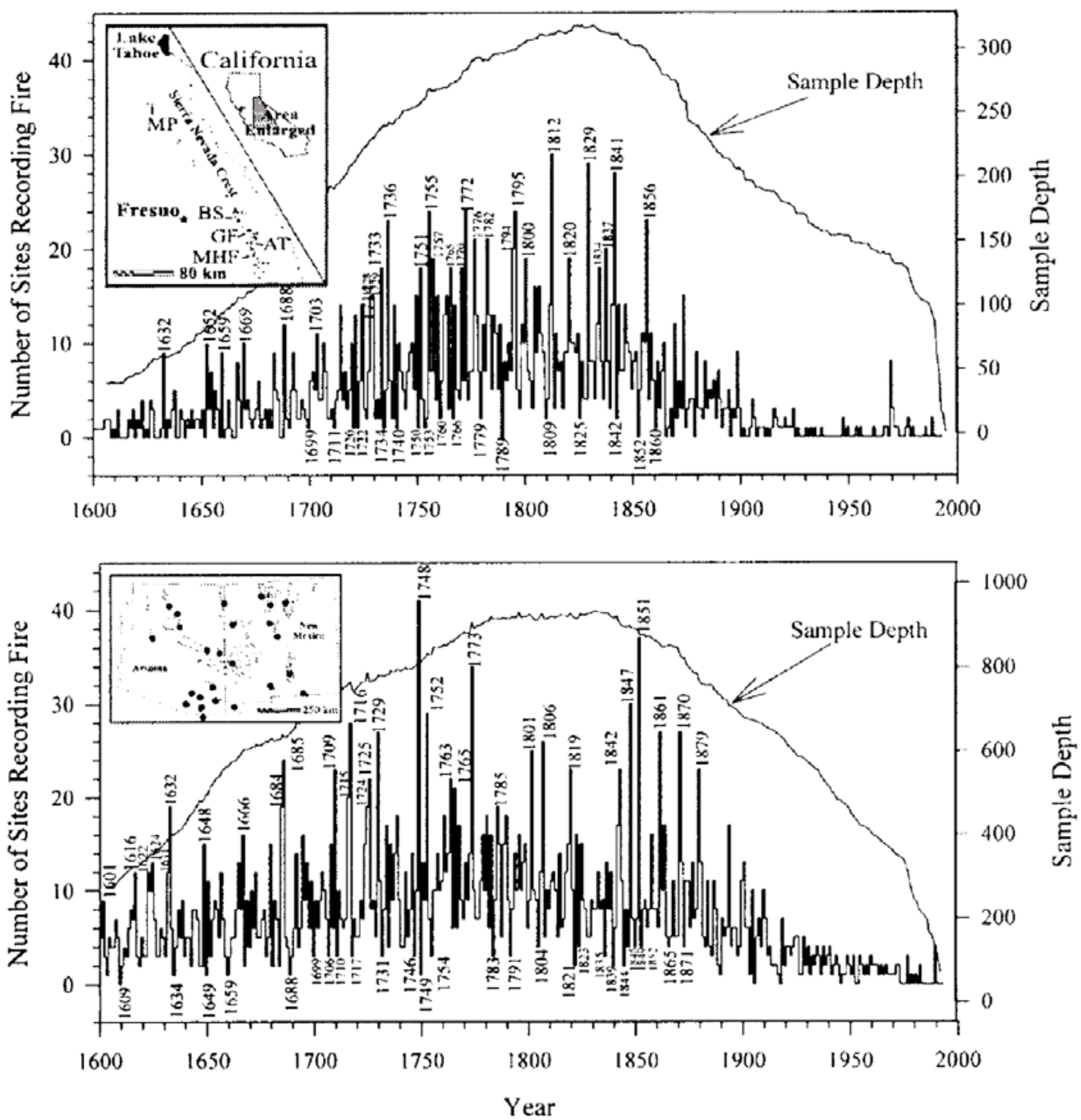

Figure 6.24: Composite time series of fire events in the Sierra Nevada (upper graph) and interior Southwest (lower graph) from regional networks of fire-scar chronologies. Number of sites recording fire each year are shown (AD 1600–1995). Sample depth is the number of fire-scarred trees included in the 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).

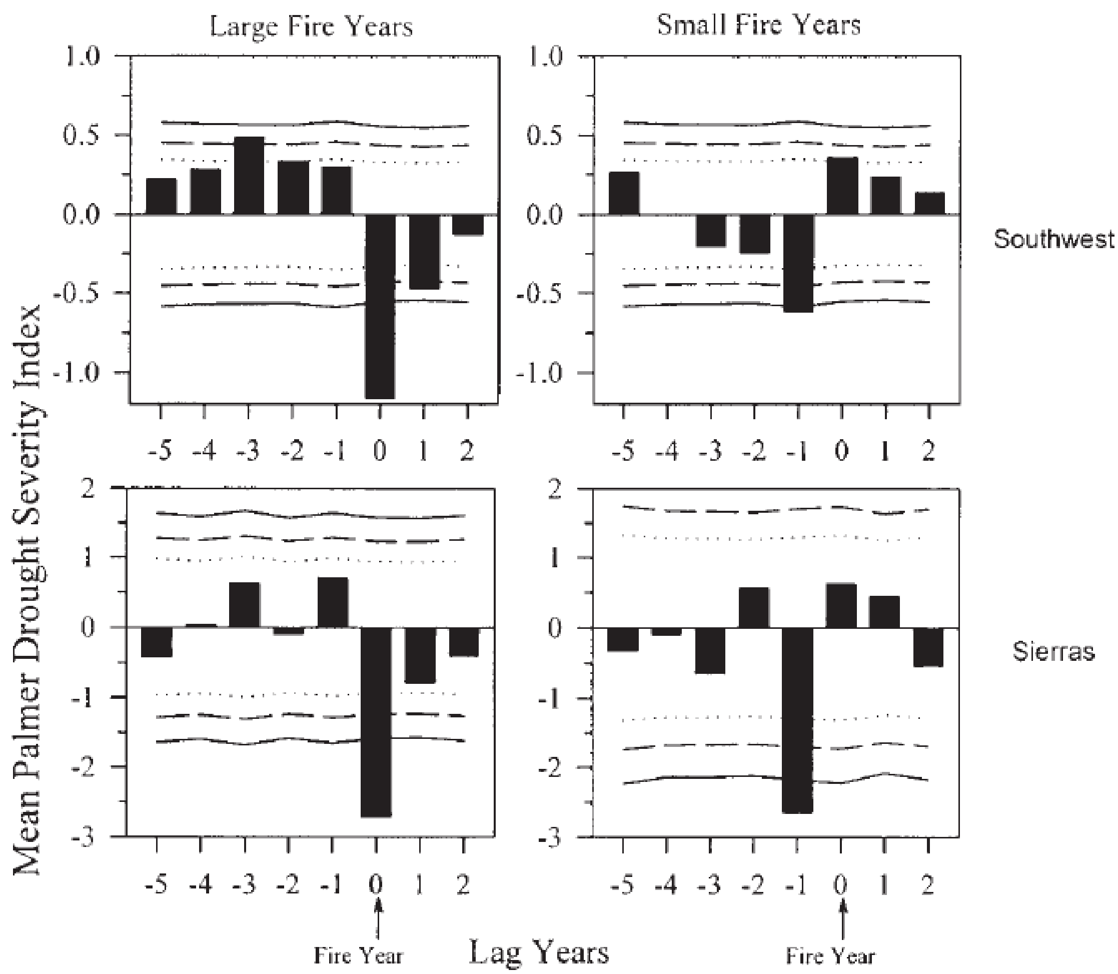

Figure 6.25: Results of superposed epoch analysis (SEA) comparing summer Palmer Drought Severity Indexes (PDSI) during relatively large (extensive) and small (less extensive) fire years in the Southwest (*top row*) and Sierras (*bottom row*). Source: (Swetnam and Baisan 2003).

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*

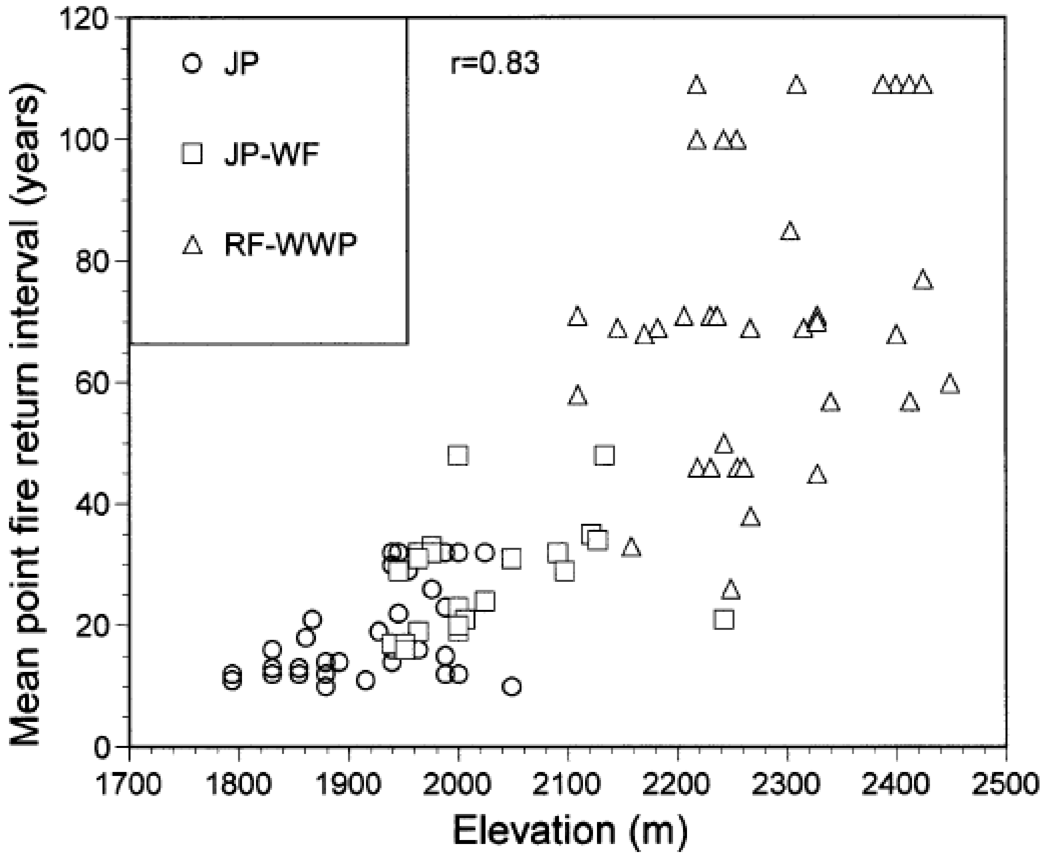

Figure 6.26: Plot of mean point fire return interval and elevation for the three main forest types on Prospect Peak, Lassen National Park. JP: Jeffrey pine forest; JP-WF: Jeffrey pine/white fir forest; RF-WWP: red fire/western white pine forest. *r* = Pearson product–moment correlation coefficient. Source: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

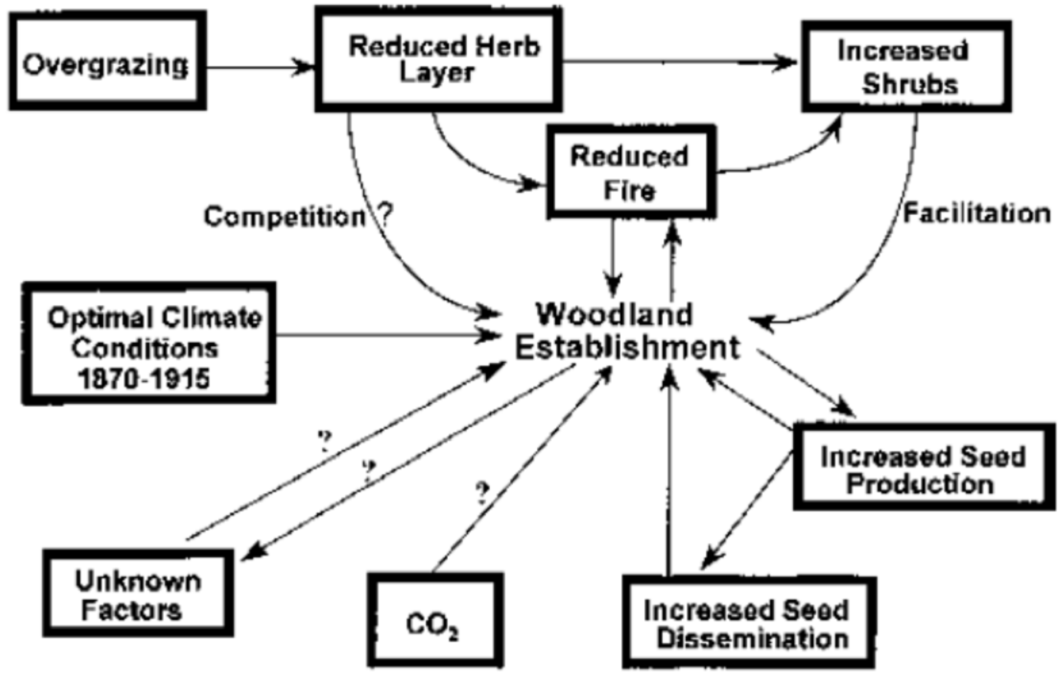

Figure 6.27: This conceptual model illustrates the complex interacting factors hypothesized to have been potentially influencing juniper and pinyon woodland expansion since the late 1800s. From Figure 7 in Miller and Tausch (2000).

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

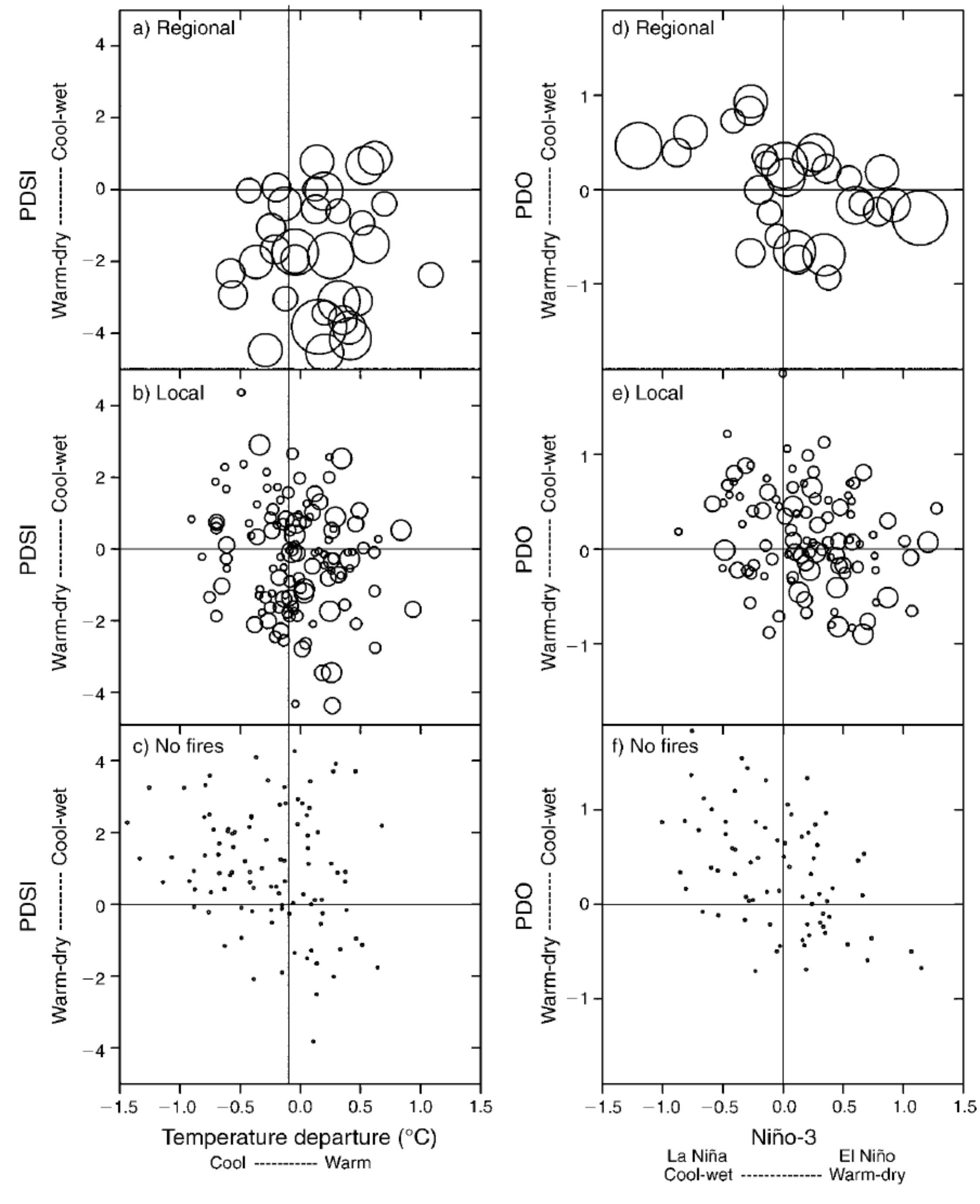

Figure 6.28: Influence of combined phases of tree-ring reconstructed spring-summer temperature (a–c, 1650–1900) and indices of large-scale climate patterns (d–f, 1700–1900) during regional-fire, local-fire, and no-fire years. The temperature time series shows departure from the mean temperature from 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

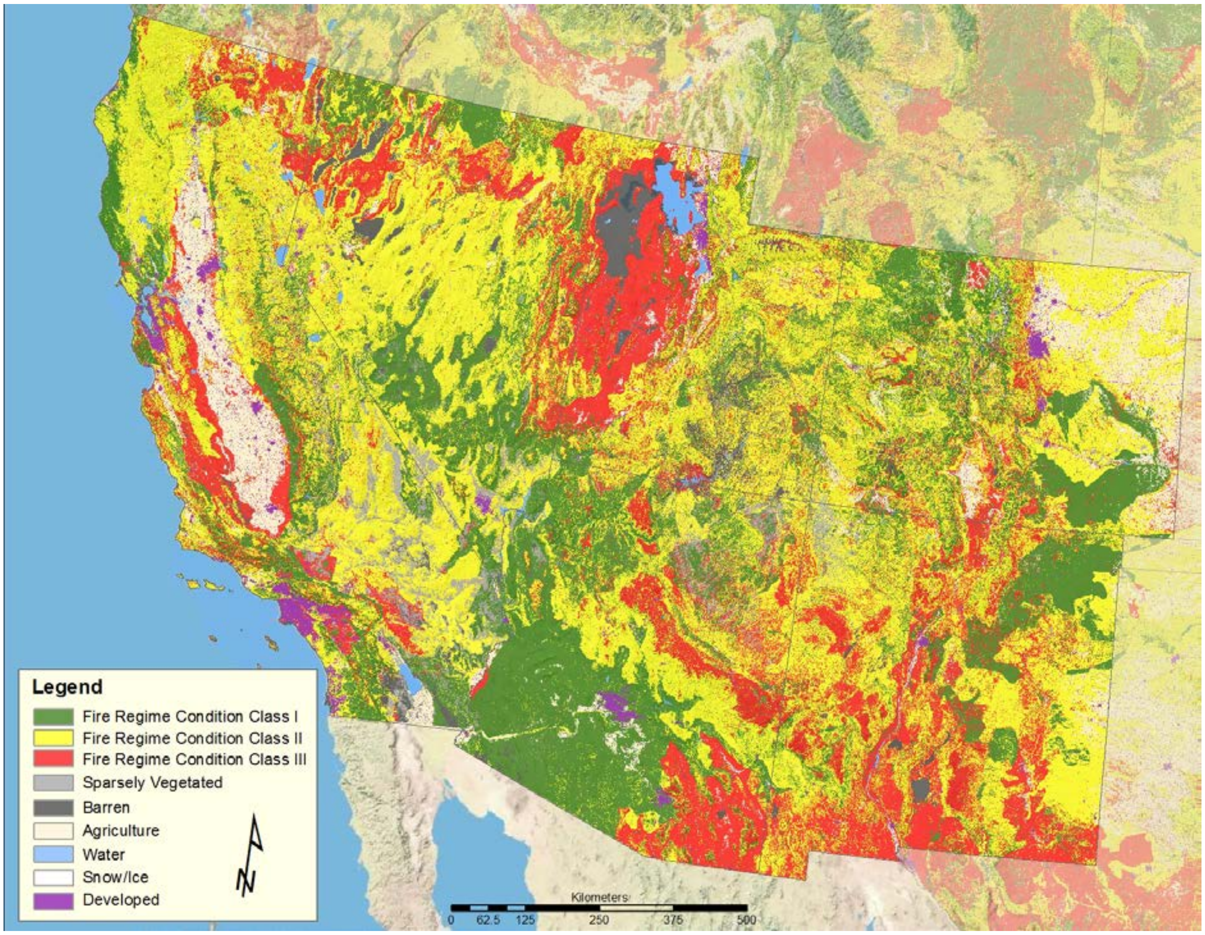

Figure 6.29a: Fire Regime Condition Class (FRCC) for the conterminous United States as used in LANDFIRE national database. FRCC is a metric of the degree of departure of current vegetation from the historical vegetation reference conditions simulated in LANDFIRE (Hann and Bunnell 2001; Hardy 2001; Barrett 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.

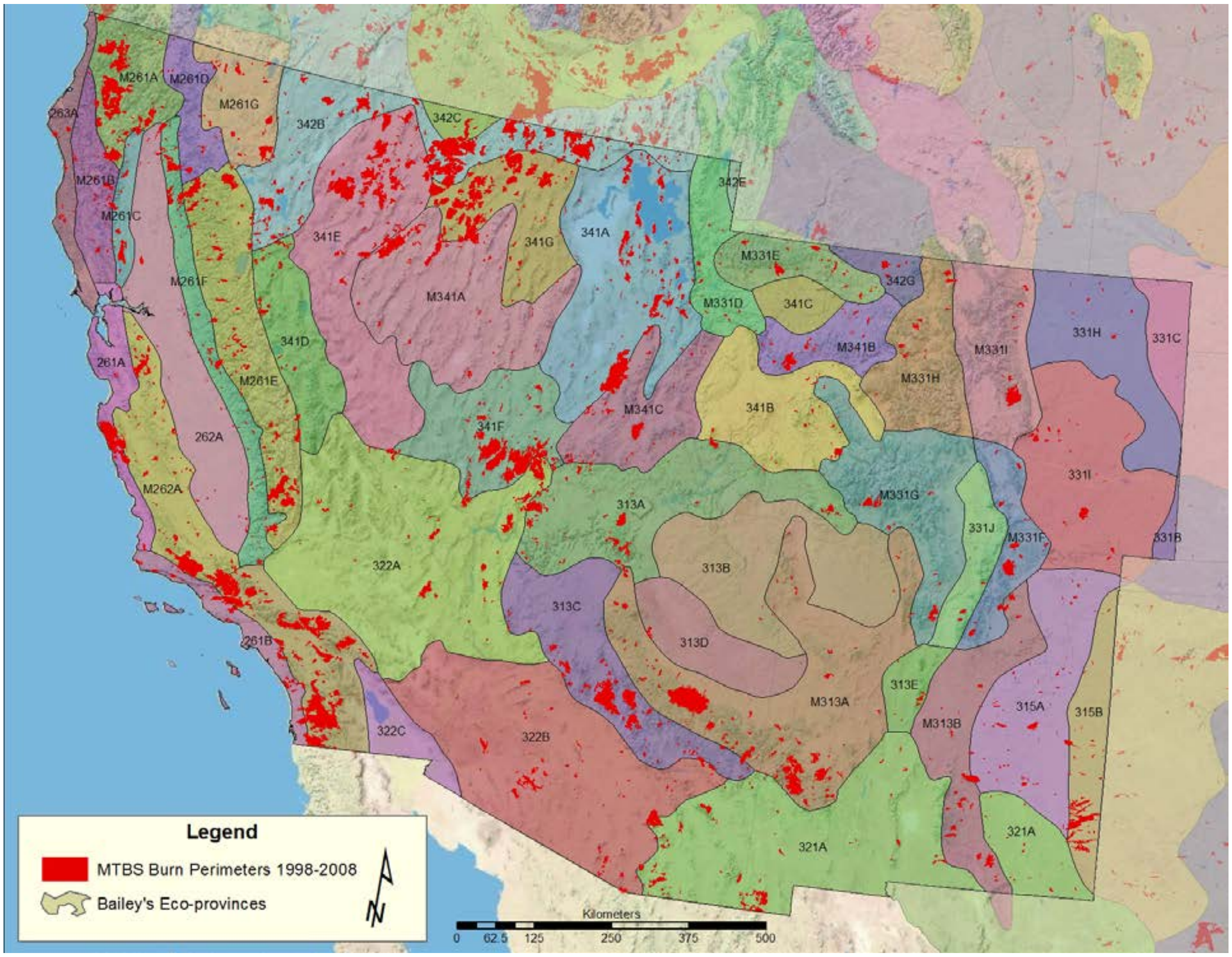

Figure 6.29b: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

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

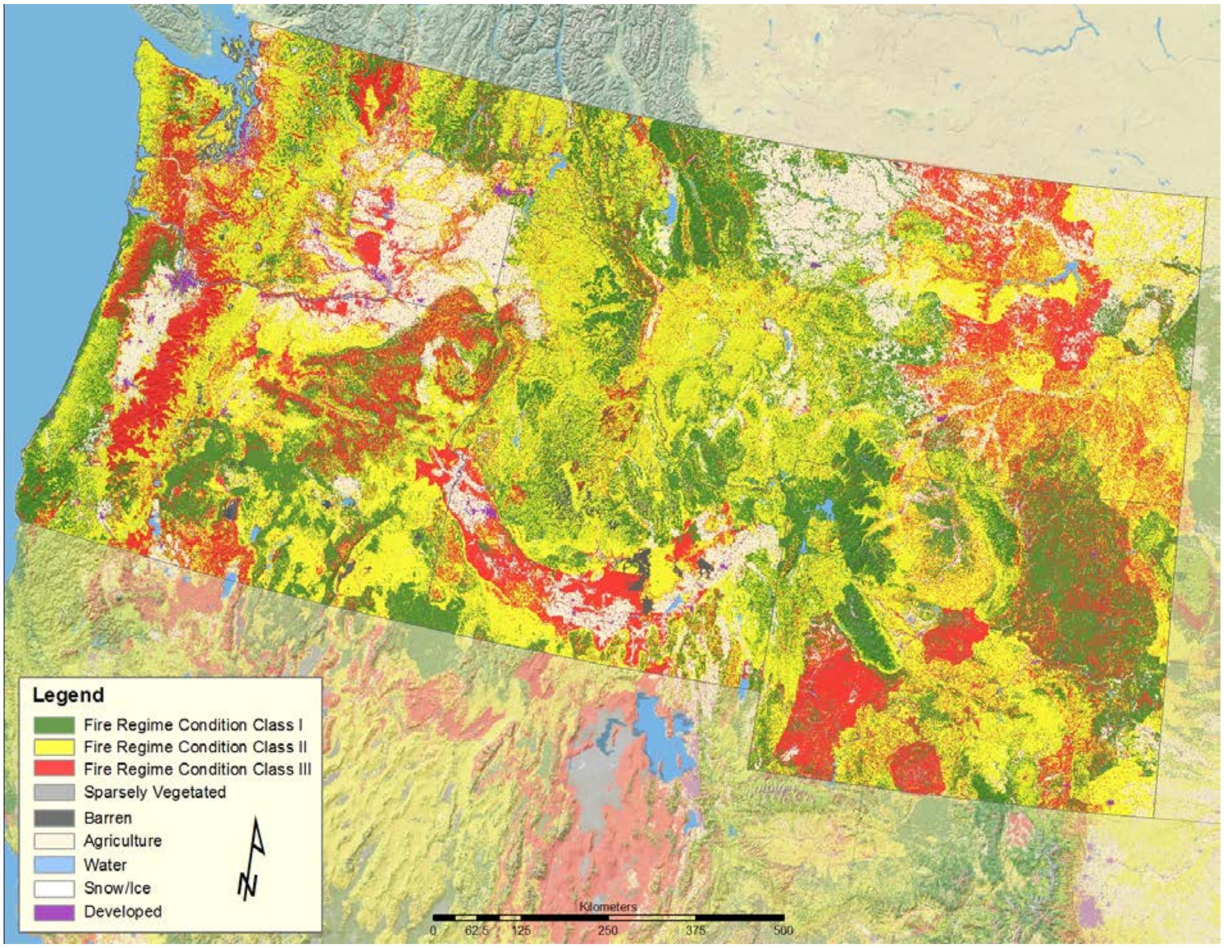

Figure 6.29c: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

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

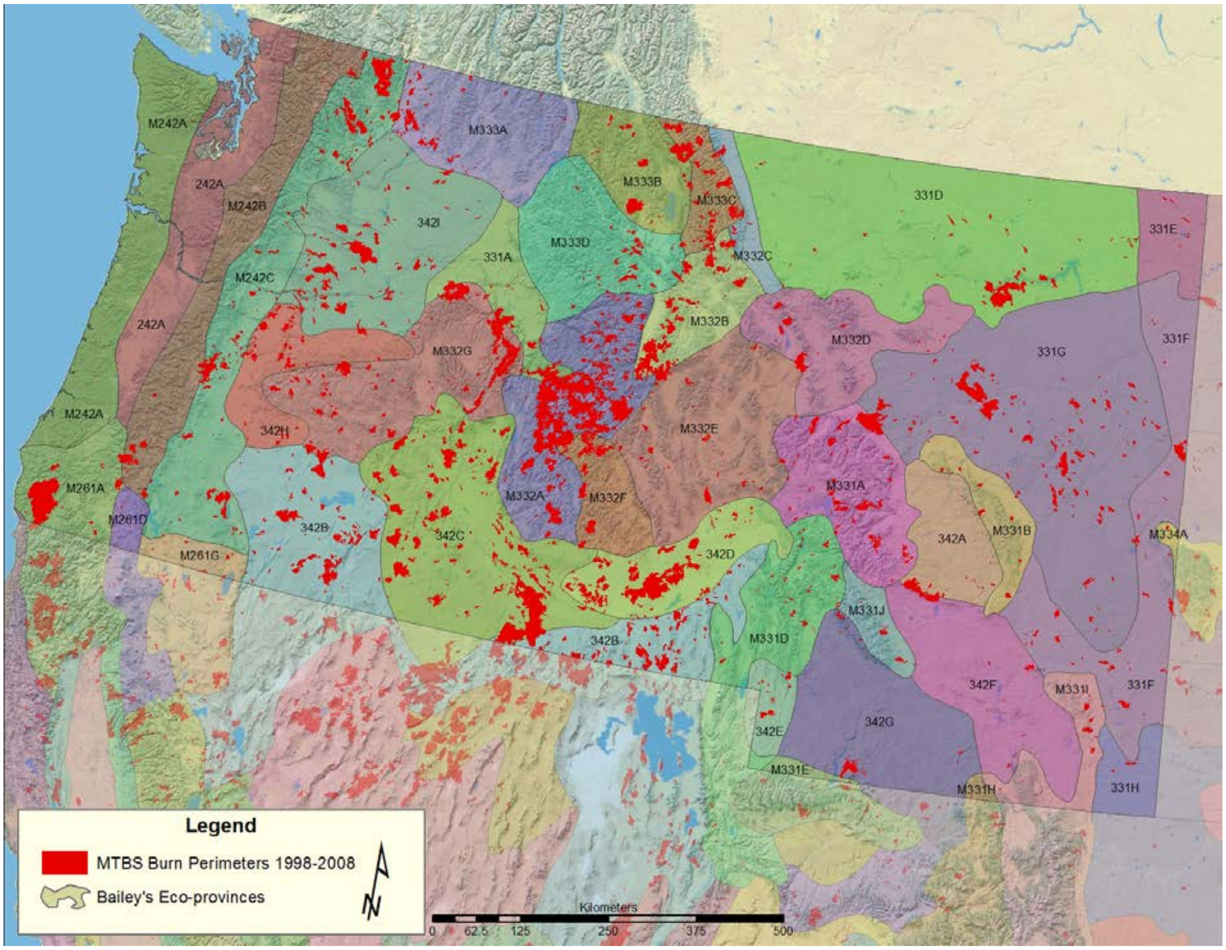

Figure 6.29d: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

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

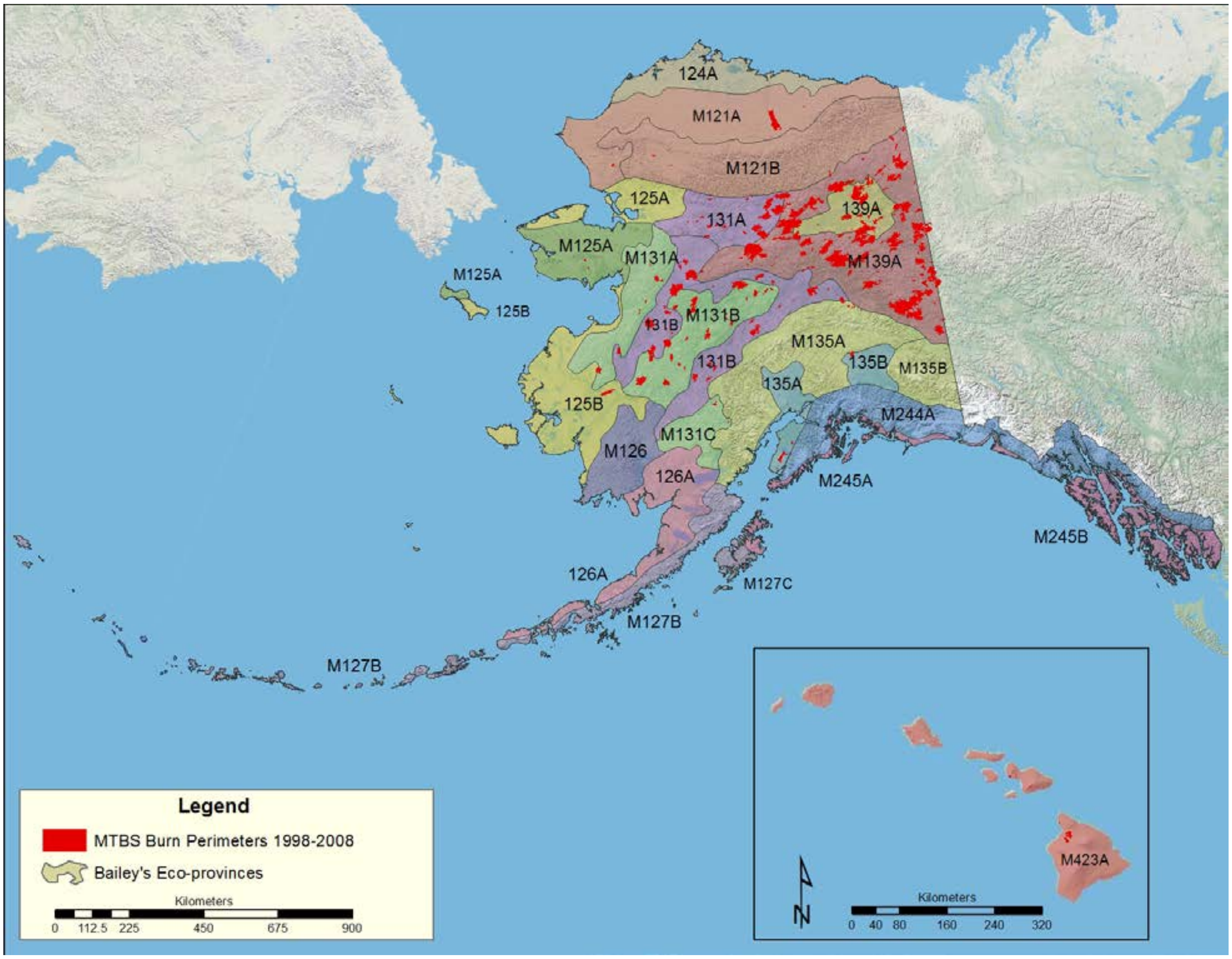

Figure 6.29e: Cumulative burned areas in the southwestern US from 1998 through 2008, overlaid on Bailey's ecoprovinces and sections. Burn perimeter data from the Monitoring Trends in Burn Severity database.

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

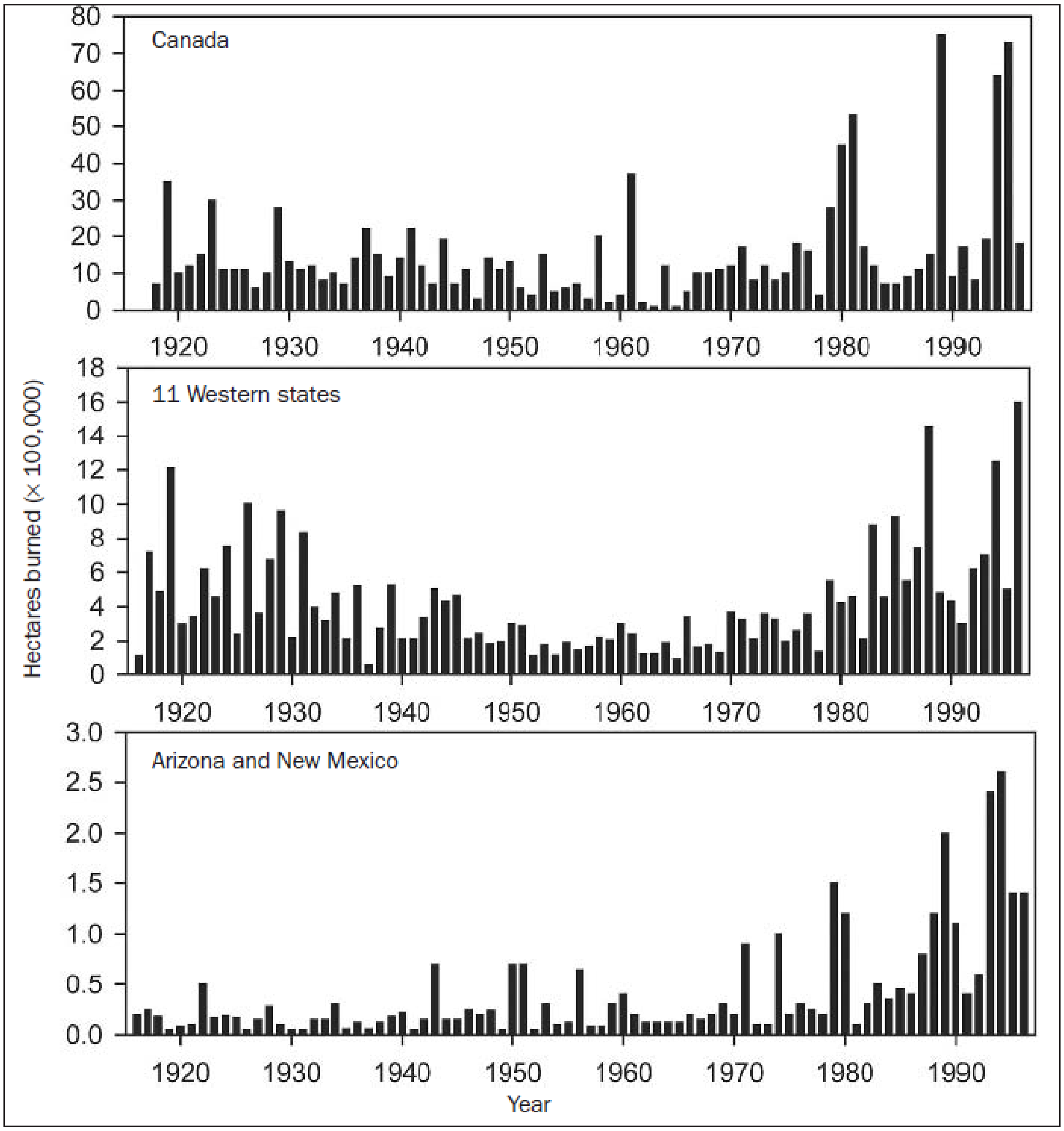

Figure 6.30: Area burned by wildfires in different regions under federal protection across North America. Note apparent increases in burned area starting in the mid to late 1980's, although it is not yet clear whether these represent long-term or cyclic patterns, or how much of the response in each area 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*

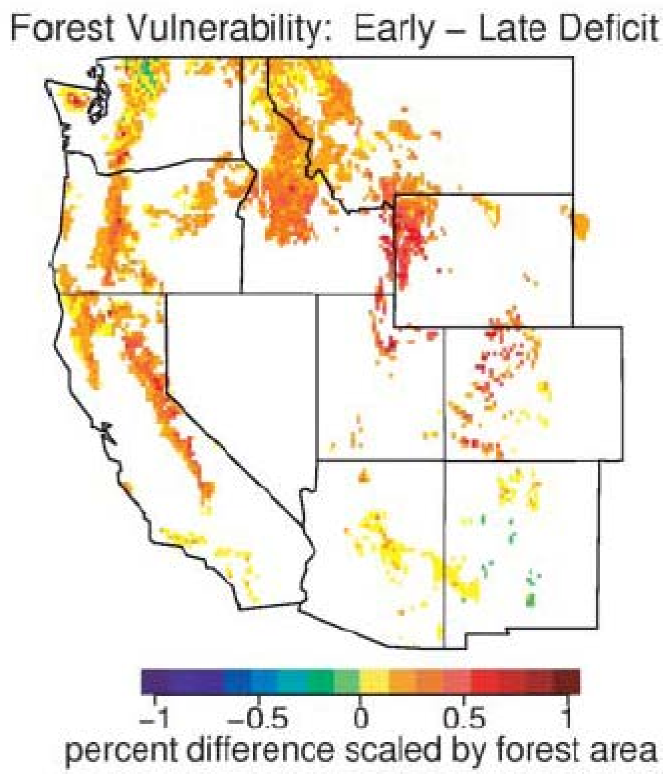

Figure 6.31: Index of forest vulnerability to changes in the timing of spring: the percentage difference in cumulative moisture deficit from October to August at each grid point in early versus late snowmelt years, scaled by the forest-type vegetation fraction at each grid point, for 1970 to 1999. Source: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

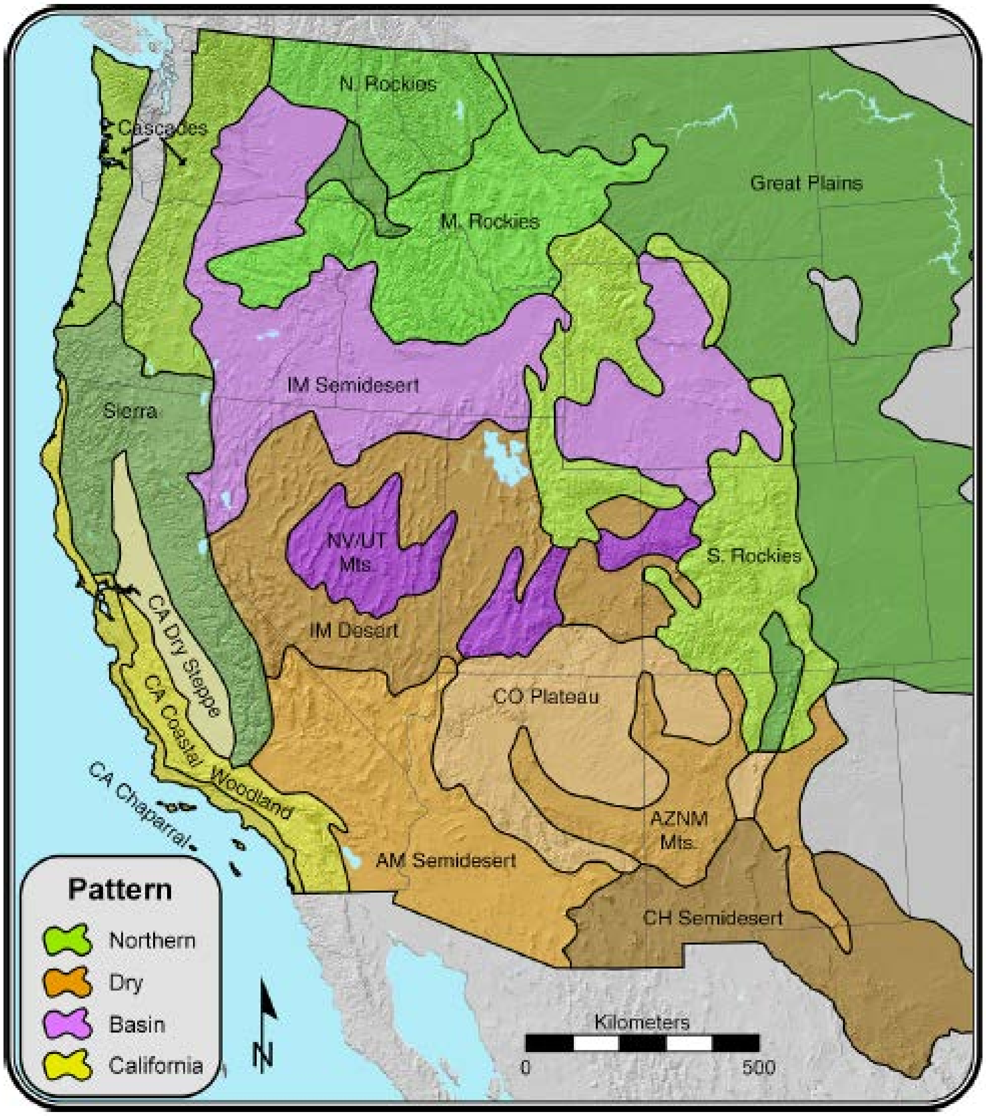

Figure 6.32: Ecoprovinces of the western United States and common patterns of climate–fire associations from correlation and diagnostic regression models. The 16 ecoprovinces for which we provide fire or fire/climate models are labeled. The similar colors group ecoprovinces with similar patterns of climate 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

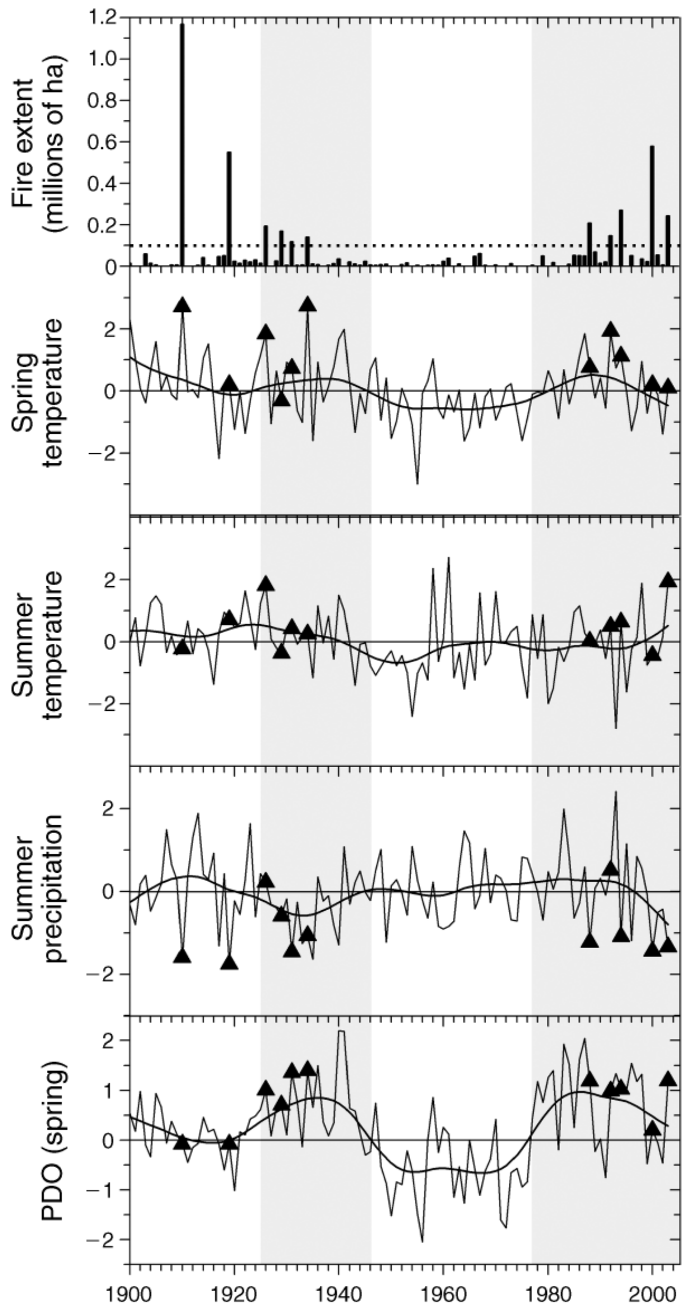

Figure 6.33: Annual fire extent and 20th-century climate in the northern Rockies. The 11 years exceeding the 90th percentile in annual fire extent (102 314 ha, horizontal dotted line) were identified as regional-fire years (top) and indicated with triangles in the other plots. Normalized spring temperature (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).

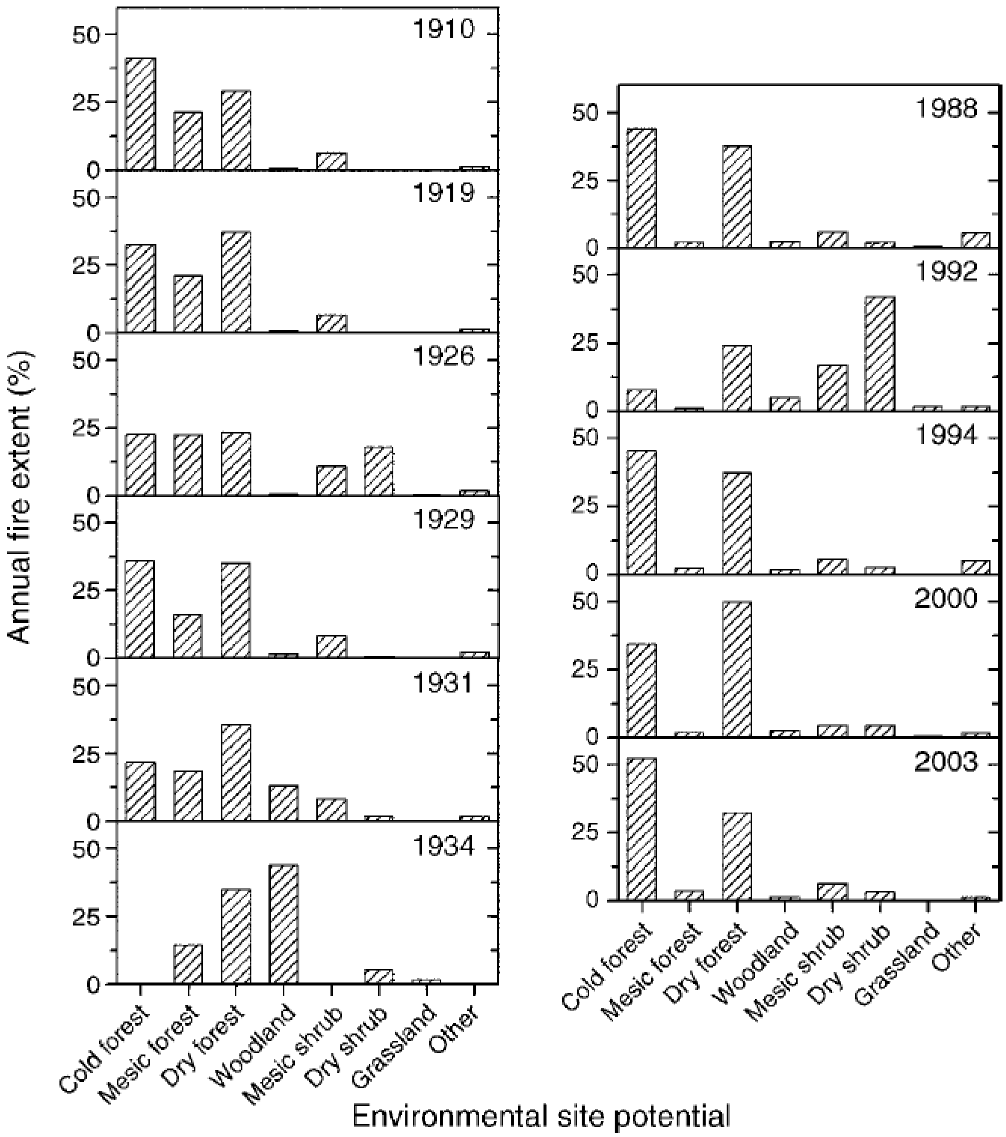

Figure 6.34: Distribution of fire extent by potential vegetation (Environmental Site Potential) during each of the 11 regional-fire years (from 1900 to 2003). Regional-fire years in the left column occurred early in the 20th century, while those in the right column occurred late in the 20th century. 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.

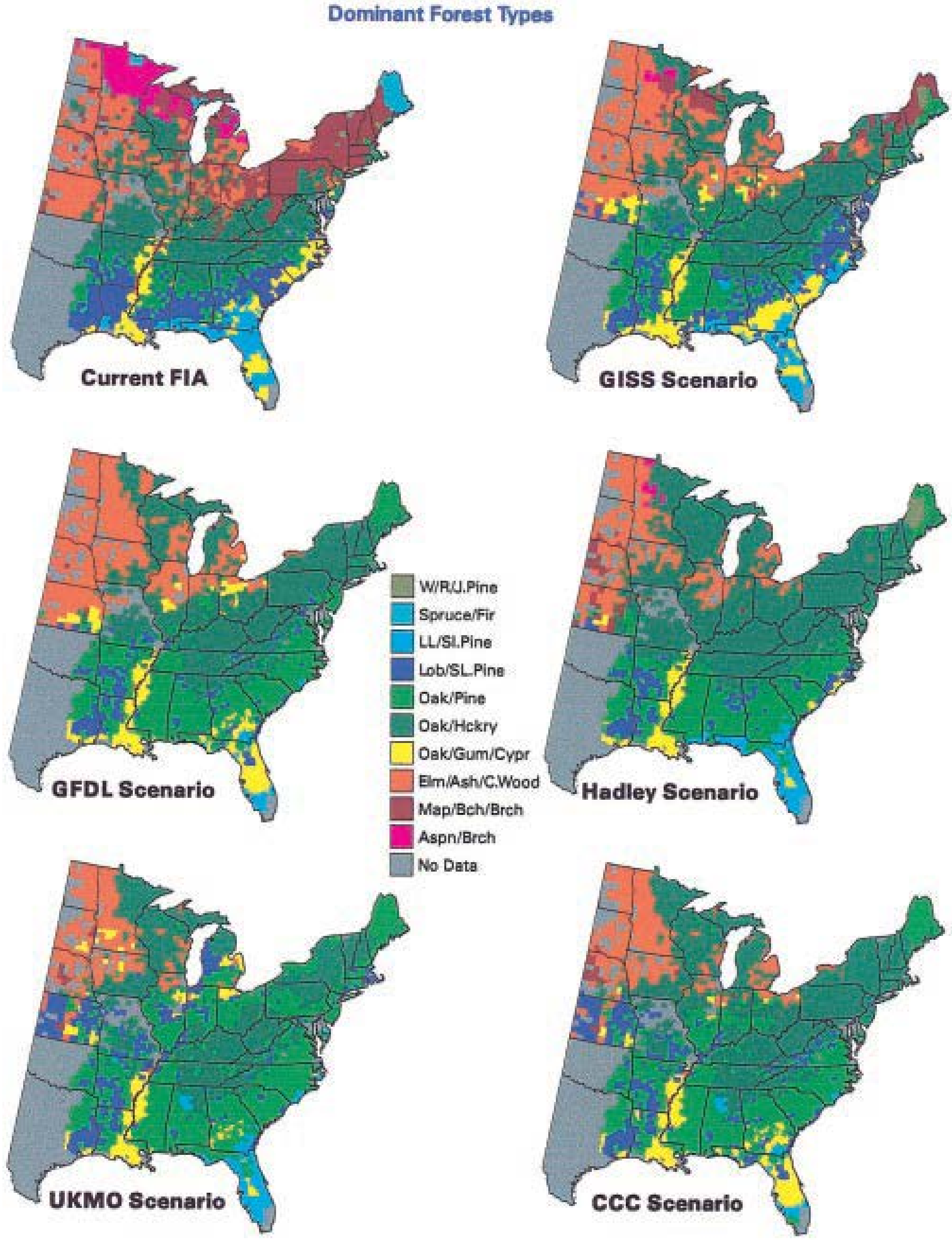

Figure 6.35: Current forest types in the Eastern US as determined from forest inventory data (top left) and potential future forest types with five scenarios of climate change at 2xCO_2 , which some IPCC scenarios project may be reached as early as 2100. From Figure 2 in Iverson and Prasad 2001.

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.

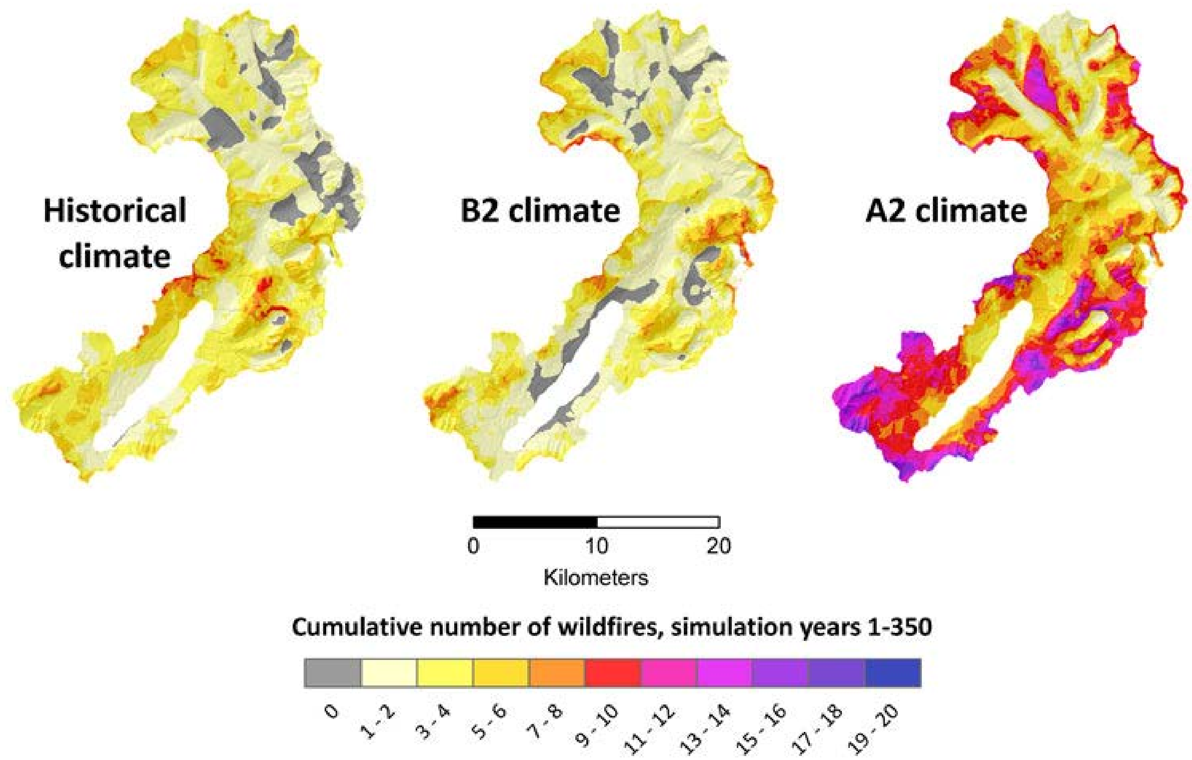

Figure 6.36: Cumulative number of wildfires, based on simulation modeling for on the McDonald drainage of Glacier simulation landscape for historical, B2, and A2 climate scenarios over a 350-year simulation period. Projections for this study region under the B2 scenario are for warmer, wetter summer 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.