Chapter 4: Ecosystems, Climate and Fuels

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

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

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

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

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

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

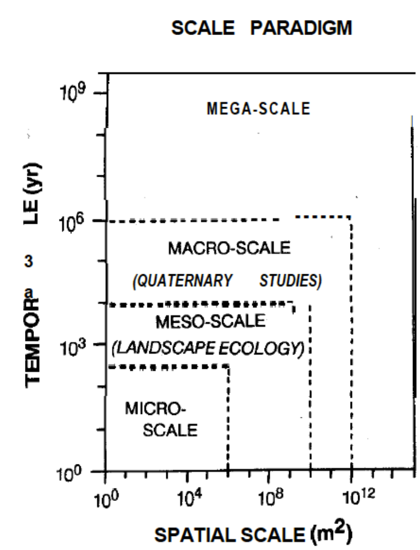

Figure 4.1: Spatial-temporal domains for a hierarchical characterization of environmental forcing functions, biological responses and vegetation patterns. Source: (Delcourt and Delcourt 1988)

Ecological Classification Use in Holocene Paleoecology Studies

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

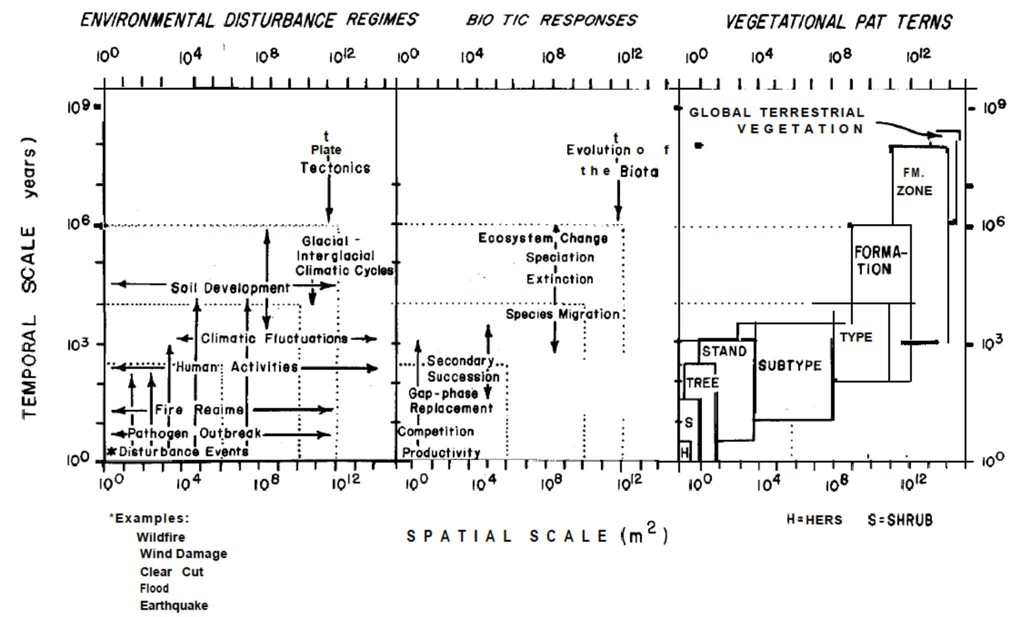

Figure 4.2: Environmental disturbance regimes, biotic responses, and vegetational patterns viewed in the context of four space-time domains. Source: (Delcourt and Delcourt 1988)

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

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

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

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

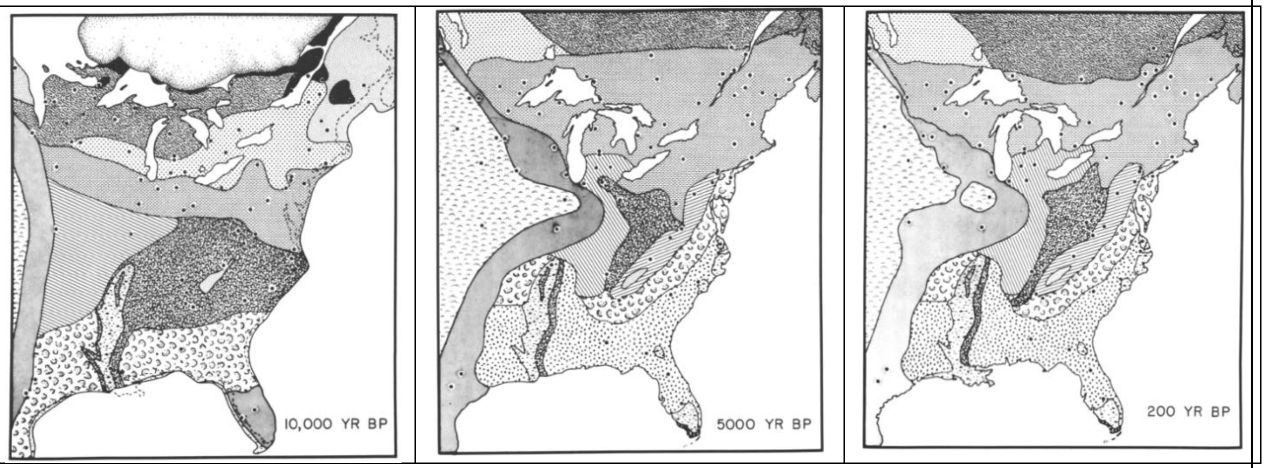

Figure 4.4: Paleovegetation maps for 10,000 BP, 5,000 BP, and 200 BP. The black dots represent locations of sites from which pollen data were used to reconstruct the past vegetation. Source: (Delcourt, Delcourt, and Webb III 1982)

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

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

Bailey's Ecosystem Classification

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

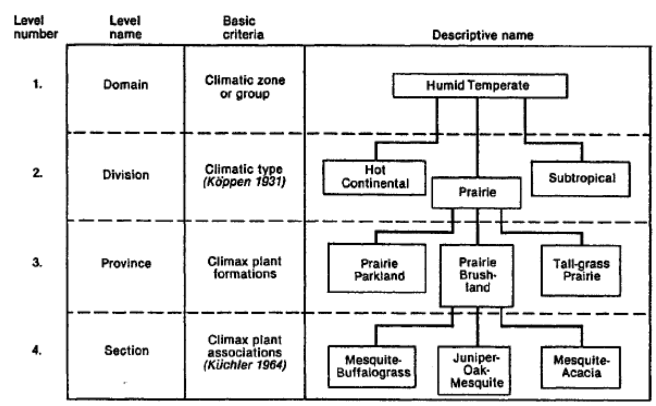

Figure 4.6: A hierarchy to the 4th level for ecosystem regions within the Humid Temperate Domain. Source: (Bailey 1983)

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

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

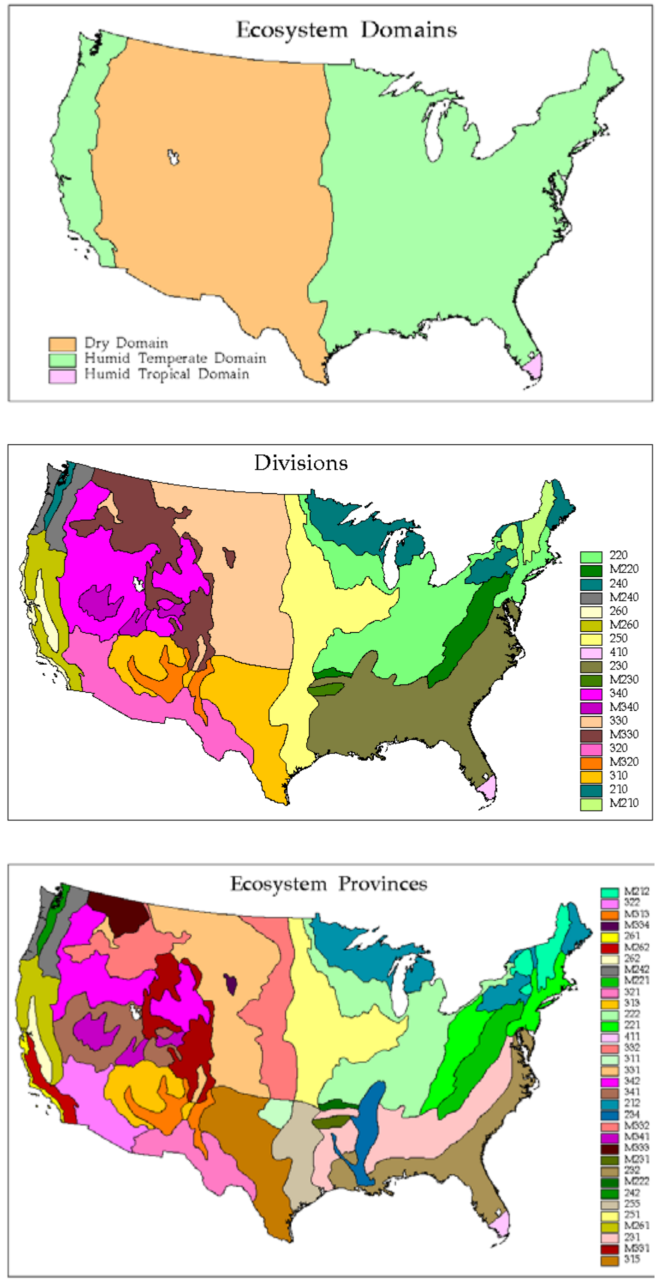

Figure 4.5 a,b,c: Bailey Ecoregion System: Domains, Divisions, and Provinces. Source: http://www.fs.fed.us/land/ecosysmgmt/ Downloaded June 1, 2011

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

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

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

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

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

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

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

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

Topographic variation (e.g. aspect, slope position, and elevation) influences precipitation, runoff, temperature, wind, and solar radiation, which in turn affect flammability through fuel production and moisture (Daly, Neilson, and Phillips 1994; Dague 1930). Climate and topography are two important controls on spatial patterns of fire disturbance in forests globally, via their influence on fuel moisture and fuel production. Climate and topography have been demonstrated as key drivers of fire disturbance patterns (Swetnam and Betancourt 1998), (Taylor and Skinner 1998). However, fire does not necessarily respond consistently to these controls across space and time. Climatic and topographic controls on fire may interact with each other adding further complexity to the processes that drive fire patterns (Rollins, Morgan, and Swetnam 2002). Furthermore, the majority of research on spatial patterns of fire has been carried out in the western U.S. in dry ponderosa pine forests or in wet subalpine and boreal forests. Flatley examined influence of topography in the southern and central Appalachian Mountains and concluded moisture appears to influence topographic patterns of fire, with drier elevations, slope positions and aspects burning most frequently (Flatley, Lafon, and Grissino-Mayer 2011).

Ecosystems, Fire Regimes, Fuels, Ignition and Climate

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

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

Many aspects of fire will be affected by changes in climate, as has been evidenced in the past, with fire regime response to climate change varying over time and space (Malamud, Millington, and Perry 2005; Bailey 2010; Morgan et al. 2001). Fire will be a catalyst for change in vegetation, perhaps prompting more rapid change than would be expected based on plant response to the changes in temperature and moisture availability. Thus fire may be more important than the direct effects of climate change on species fitness and migration (Flannigan et al. 2009). Fires may be more frequent where climate warms; and fires may become more severe and more extensive as predicted for boreal forests (Overpeck et al. 2011; Kasischke, Williams, and Barry 2002; IPCC WG II 2007; Goldammer and Price 1998; Weber and Flannigan 1997). Changes in regional and local fire regimes will be affected by changes in ignition (lightning), vegetation change and land use patterns and land management practices. Climate change appears likely to affect lightning and its capacity for fire ignition. Lightning producing convective storms are expected to become more frequent and intense with 21st Century warming. One study suggests a 30% increase in global lightning activity for the warmer climate and a 24% decrease in global lightning activity for the colder climate. This implies an approximate 5–6% change in global lightning frequencies for every 1°C global warming/cooling (Price and Rind 1994; Christian et al. 2003; Keeley 1982; Macias Fauria and Johnson 2006; Reeve and Toumi 1999).

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

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

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

Source: (Hessl 2011)

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

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

Table 4.1 - Conceptual Scales

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

Bailey's ecosystem classification system provides a standardized hierarchical method of describing ecosystems that enables the application and interpretation of interaction of climate and ecological processes. At the smallest scale (sections) ecosystems are described within the context of larger systems (provinces, divisions, domains). This perspective enables assessing the geographic patterns and connection between actions at one scale and effects at another scale. Standardized classifications are important for ecosystem planning nationally and globally (Bailey 2008; Grossman et al. 1998), and for relating ecosystem characteristics to fire regimes (Bailey 2010; Littell et al. 2009) and fire planning (Rollins, Keane, and Parsons 2004; Rollins 2009). Ecosystem classification systems facilitate understanding of ecosystem evolution, i.e. where ecosystems were located in the past (Delcourt and Delcourt 1988) and how ecosystems may change under future climate conditions. It is important to note that although ecosystem classification systems are contemporary descriptions of ecosystems fixed in time, multiscale classification systems provide the standardized foundation of geographic patterns upon which future changes in ecosystems can be projected, analyzed and characterized. Future ecosystem species assemblages may not have an antecedent legacy, which adds additional complexity to future projections.

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