CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE AT LONG-TERM ECOLOGICAL RESEARCH SITES

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Climate Variability and Ecosystem Response at the H. J. Andrews Long-Term Ecological Research Site

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Introduction

The H. J. Andrews (AND) Long-Term Ecological Research (LTER) site represe the temperate coniferous forest of the Pacific Northwest (PNW) of the Unit States. The general climate of the area is highly dynamic, displaying variability a variety of timescales ranging from daily to millennial. AND, and its surroundi region, is therefore an ideal site for examining some of the guiding questions of mate variability and ecosystem response addressed by this volume (see chapter A legacy of more than 50 years of research at the site and its surrounding area sures that several of the questions can be investigated in some depth. Here we ganize our discussion within a timescale framework that is consistent with structure of this volume. Thus, following a brief description of the general clim of the site, we discuss climate variability and ecosystem response at the daily, m tidecadal, and century to millennial scale. This discussion for the PNW is supp mented in chapters 6 and 13 by a consideration of the quasi-quintennial scale an additional ecosystem response at the decadal scale.

Having described some of the climate variability and ecosystem response at selected timescales, we will consider what this information can tell us regardi some of the guiding questions of this book. The questions that we specifically dress include the following: What preexisting conditions affect the impact of

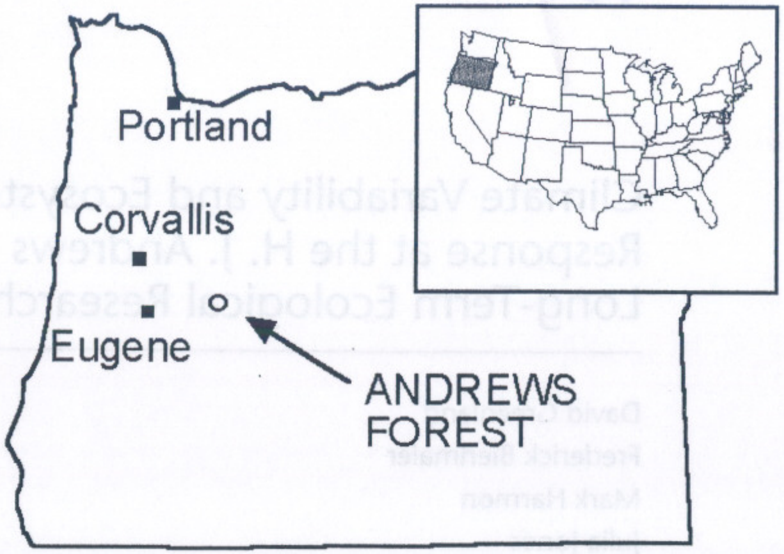


Figure 19.1 Location map of the H. J. Andrews Experimental Forest LTER site.

climatic event or episode? Is the climatic effect on the ecosystems direct or cascading? Does the system return to its original state? We also consider potential future climate change and its possible ecosystem effects.

The Climate of the H. J. Andrews Experimental Forest

Located at latitude 44.2° N and longitude 122.2° W, the Andrews Forest is situated in the western Cascade Range of Oregon in the 6400-ha (15,800-acre) drainage basin of Lookout Creek, a tributary of the Blue River and the McKenzie River (figure 19.1). Elevation ranges from 410 m (1350 feet) to 1630 m (5340 feet). Broadly representative of the rugged mountainous landscape of the Pacific Northwest (PNW), the Andrews Forest contains excellent examples of the region's conifer forests and associated wildlife and stream ecosystems. Lower elevation forests are dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). Upper elevation forests contain noble fir (*Abies procera*), Pacific silver fir (*Abies amabilis*), Douglas-fir, and western hemlock. Low- and midelevation forests in this area are among the tallest and most productive in the world. As elevation increases, Douglas-fir and western red cedar decline in importance and western hemlock is gradually replaced by Pacific silver fir.

The climate is controlled by its close midlatitude proximity to the Pacific Ocean and by the perpendicular orientation of the Coast and Cascade mountain ranges to the prevailing westerly flow. The Andrews Forest is located near the border between temperate maritime and temperate continental climates as a result of these mountain barriers to passage of air masses from the west. Temperatures are moderated at almost all times of the year by maritime air, particularly in winter.

Winter precipitation is high, averaging 287 mm (11.3 in.) per month between January and March. Low-pressure areas and associated storms are steered into the area by the polar jet stream. Long-duration but generally low-intensity storms result from the passage of strongly occluded fronts that are slowed by the mountains. Daily precipitation is significantly autocorrelated up to 14 days (Post and Jones 2001). Temperatures associated with these storms are often mild enough that rain falls at lower elevations of the Andrews Forest while snow falls at higher elevations. This usually results in deep (2 to 4 m), long-lasting, snowpacks above approximately 1000 m. Occasional strong storms can have severe ecological consequences such as windthrow—the toppling of trees by the force of the wind. Late summer and early fall wind from the central Oregon desert may also drive large forest fires. Summertime precipitation is usually low to nonexistent, averaging 38 mm (1.5 in.) per month between June and August. The North Pacific anticyclone intensifies and expands to the northeast along the coast. This blocks the passage of cyclonic storms and stabilizes the air.

Summer drought, mild wet winters, a heavy snowpack above 1000 m, and light to nonexistent snowpack below 800 m are factors affecting the flora and fauna. Late summer moisture stress of the forest has an important part in determining the composition and structure of various forest communities. This moisture stress also helps to give rise to the coniferous nature of the Pacific Northwest forest (Waring and Franklin 1979). Snow and lower temperatures at upper elevations play an important role in the formation of a distinctly different forest zone—the Pacific silver fir (*Abies amabilis* Dougl. ex Forbes)—through mechanical force and modification of temperature and moisture regimes. Large animals, such as elk and deer, are fórced to lower elevations by the heavy upper elevation snowpack, whereas smaller animals use it for shelter and cover. At lower elevations, the mildness and wetness of the winters, combined with little snow, produces a nearly stress-free environment for plants and animals. The mild climate also results in a long growing season. Water use by evapotranspiration in the old growth forests is greatest during the spring and fall and is limited by the low precipitation of the summer months.

Superimposed on this general picture is considerable temporal variability in the climate. At a daily scale there can be severe storms. The El Niño–Southern Oscillation (ENSO) operates at a 2–7 year (quasi-quintennial) scale and provides a context for warmer and drier (El Niño) or cooler and wetter (La Niña) conditions. The Pacific Decadal Oscillation (PDO) functions at a multidecadal timescale that is also characterized by warmer and drier or cooler and wetter periods. Evidence exists for similar climate variability at century, subcentury, and millennial timescales, and these signals have varied in strength over time. There is also the possibility of climatic trends at century and longer timescales. Change is one of the few certainties in the dynamic environment of the Pacific Northwest.

Daily to Annual Scale: Severe Storms and Floods, Insect Outbreaks, and NPP

The most dramatic climatic events at the daily timescale are those concerning severe storms that are accompanied by floods and in some cases windthrow events. Daily precipitation and streamflow values vary by more than two orders of magnitude within each year. Fifteen-minute precipitation and streamflow values can vary by the same amount within a few days. Climatic/meteorologic events related to the ignition and spread of forest fire might also be considered in this category, although these events also incorporate effects of preceding droughts and associated drying of fuels. At the Andrews Forest, a small number of daily timescale events can have a large impact. Snyder (2000), for example, found that in the 50 years of records, most flood-related action and landslides occurred during only three major storm events. Similarly, most windthrow events in the northern Cascade Range, Oregon, since 1890 are associated with just three major individual storms (Sinton et al. 2000).

A very large 50-year-return period flood in 1996 led to a large direct response from the ecosystem. This February flood resulted from 290 mm of precipitation over 4 days that melted a large amount of already accumulated snow. Swanson et al. (1998) and Nakamura et al. (2000) list and document landslides and channel erosion and related disturbance of aquatic and riparian organisms and their habitats as responses to this flood. The hydrographic response varied with altitude because of the varying snowpack dynamics. At least 35 debris flows severely disturbed stream and riparian environments. There was a large amount of fluvial erosion. In some areas riparian vegetation was entirely removed in larger channels, and boulder and coarse woody debris movement was common (Johnson et al. 2000). Scouring in places uncovered objects that had long been buried. Wood samples exposed along the northeast side of Watershed 3 turned out to be over 46,000 years old (http://www.fsl.orst.edu/lter/pubs/spclrpfr.htm). Many stream restoration project structures were washed away. Some biotic responses were very fast. Benthic algae recovered from the event within weeks. Again, this web page on the 1996 flood provides details on these effects: http://www.fsl.orst.edu/lter/pubs/spclrpfr.htm.

At the Andrews LTER site, windthrow events result mainly from southeasterly winds associated with storms arriving from the Pacific (Gratkowski 1956). Windthrow events in winter in the northern Cascade Range of Oregon were found, in some cases, to highlight the importance of preexisting conditions. Sinton et al. (2000) found such events occurred particularly when winds were from the north or east with a preceding period of dry weather. High-pressure conditions in winter gave rise to icing on the branches of trees prior to some windthrow events (D. S. Sinton, pers. comm., 1996). As is well known, windthrow events cause forest gaps that subsequently undergo a cascade of successional events leading to the reestablishment of the forest. However, canopy gaps, especially those with fresh, clear-cut edges, are particularly prone to additional windthrow (Gratkowski 1956; Sinton et al. 2000).

In some cases ecosystems respond to the coincidence of two climatic events. One such example is the occurrence of Douglas-fir bark beetle outbreaks (Powers et al. 1999). In western Oregon and Washington, these insects are usually saprophytic, reproducing in freshly downed Douglas-fir trees. In rare instances, however, this species can kill live trees, and for a 2- to 3-year period can increase overall mortality in forests by a factor of 3 to 10. The coincidence of two climatic events is necessary for this to happen. First, a major windstorm or incidence of ice damage is necessary to create a large amount of breeding habitat. This allows the population to expand to sufficient numbers to attack living trees and kill them. Curiously, at least for this species of beetle (and spruce bark beetle as well), fire-killed timber is not a suitable enough habitat to increase the population. Second, the trees must be under stress during the growing season. This stress is usually caused by drought and reduces the trees' ability to respond to the beetle attack. Even in large numbers, the Douglas-fir bark beetle has little ability to overwhelm trees. Although the beetles can reproduce in live trees, they are unable to increase numbers in this habitat; therefore, outbreaks in live trees rarely last for more than 3 years despite the length of the drought. The rare coincidence of these two sets of climatic conditions means that Douglas-fir bark beetle outbreaks are rare events for western Oregon and Washington forests. Although the historical record of outbreaks is not long, outbreaks appear to occur at an average frequency of 50 years. These outbreaks do have important impacts: They alter forest composition (ironically by removing a more drought-resistant species), speed the rate shade-tolerant species dominate stands, temporarily increase the amount of detritus, and reduce the Net Primary Productivity (NPP) of the forest, with the end result of creating a temporary source of CO_2 to the atmosphere.

Year-to-year oscillations in precipitation are responsible for variations in NPP, decomposition, and Net Ecosystem Productivity (NEP). By examining tree cores and litter fall records, Fraser (2001) found that tree growth and litter fall varied ±30% from year to year. Given lag of 4 to 5 years between leaf production and litter fall, the amount of combined variation is not clear; however, it is likely to be in a similar range. Year-to-year variation in decomposition rates has not been studied extensively, but fortuitous studies carried out during extremely dry and wet years indicate a range of ±30% (Valachovic 1998; Harmon, unpubl. data, 1992). This response is not likely to be mirrored in other forms of detritus, however, because their rates of drying, and response to moisture, differ substantially. Fine litter, for example, dries quickly and, because of its high ratio of surface area to volume, is rarely limited by excessive moisture. In contrast, large wood dries slowly (Harmon and Sexton 1995) and has a low enough surface-area-to-volume ratio that diffusion of oxygen can become limiting for decomposition when moisture content is high (Harmon et al. 1986). This means that summers with high precipitation can lead to fast decomposition of fine litter, but slow decomposition of large wood. Conversely, in summers that are dry, fine litter decomposition can be slow and that of large wood fast. As a result, the year-to-year variation in overall decomposition is likely to be dampened as the detritus pools are "decoupled" temporally from each other. By combining these sources of variation in NPP and decomposition, preliminary estimates are that NEP (the net exchange of carbon with the atmosphere) could vary as much as 2 Mg ha^{-1} $year^{-1}$ in Douglas-fir/western hemlock old-growth forests (Harmon et al., in press). This is a substantial level of variation. Although these forests are thought to have an NEP close to zero over the long term, this variation means that in some years they are uptaking as much carbon as a forest in the peak carbon accumulation phase (Janisch and Harmon in press). Clearly, a more thorough examination of the cause of this year-to-year variation is necessary, but the key lessons that ecosystem processes are not responding to the same climatic variable in the same way and that the sign of the response could differ, even within a process, are likely to hold.

Quasi-Quintennial Scale: ENSO

The atmospheric manifestation of El Niños and La Niñas in the PNW is well documented. El Niños are correlated with warmer winter temperatures, reduced precipitation (Redmond and Koch 1991), and reduced snowpack and streamflow (Cayan and Webb 1992) in the region. The reverse tends to be true for La Niña years. Heavy-rain-bearing storms tend to be a feature of La Niña years. The large flood of February 1996 is a case in point. January, February, and March 1996 were marked by La Niña conditions. An earlier major flood in 1964 also occurred when El Niño conditions were changing over to La Niña conditions.

Recent forest fire history at the Andrews LTER site is probably, at least in part, a response to climate variability. El Niño years tend to lead to drier and warmer winter conditions in the PNW. The strong El Niño year of 1987 was accompanied by numerous large forest fires in the PNW in 1987 and 1988. The El Niño years of the early 1990s were also accompanied by large fires in 1992 and 1994.

Multidecadal Timescale

Multidecadal changes for the Pacific Northwest (PNW) are related to the PDO. Taylor and Southards (1997) (http://www.ocs.orst.edu/reports/climate_fish.html) noted a cool, wet period from 1896 to 1914, a warm and dry period from 1915 to 1946, a cool and wet period from 1947 to 1975, and a warm and dry period from 1976 to 1994. Mantua et al. (1997) have shown these periods to be related to changes in the synoptic-scale climate indices that have reversal times during the period 1900–1996 in 1925, 1947, and 1977. The climate regime shifts related to the PDO were first noticed after the 1976 shift because of the correspondence in numerous ecosystem and environmental responses in the PNW (Ebbesmeyer et al. 1991). These responses include variables such as the numbers of goose nests, crab production, mollusk abundance, and the path of returning salmon and salmon catch (see chapter 13). There are suggestions that another climate regime shift may have occurred in the mid-1990s (JISAO CIG 1999).

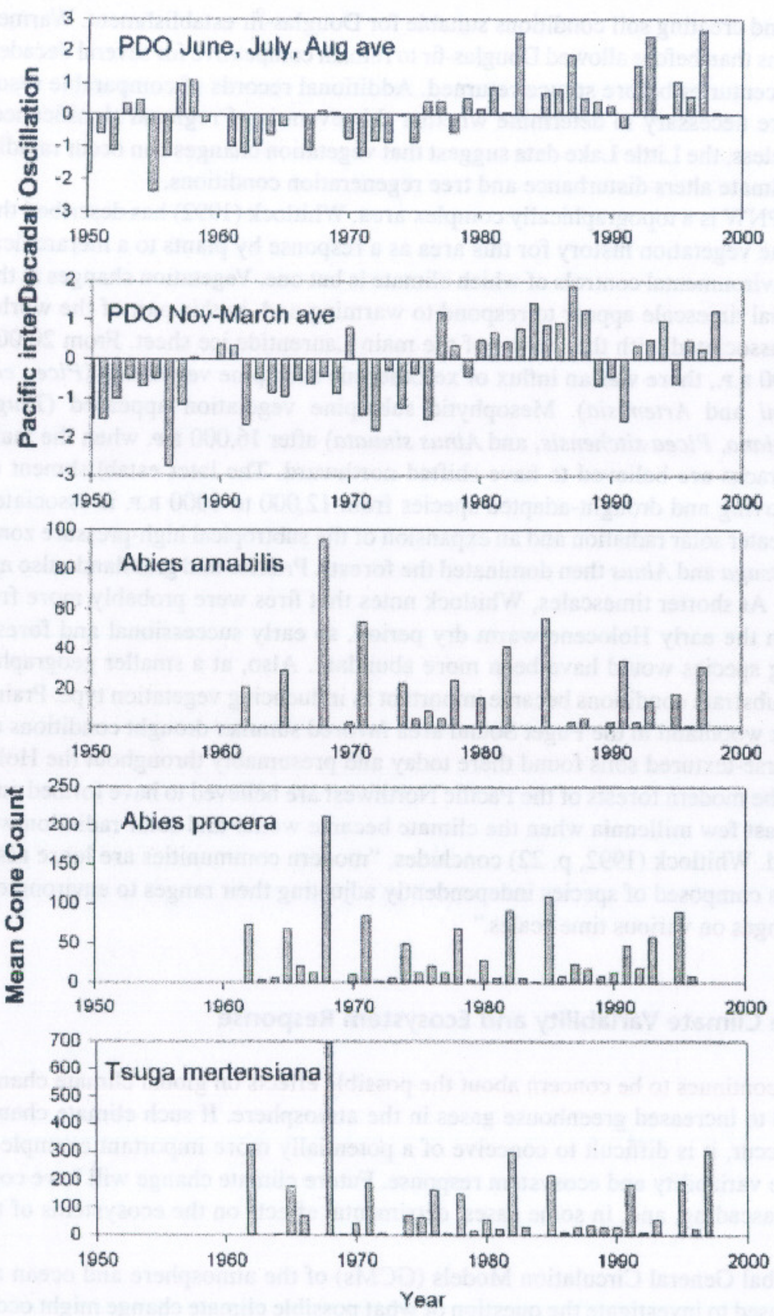
Given these regional changes, one might expect clear evidence of such climate variability and ecosystem responses in the Andrews ecosystems. However, an unequivocal variability before and after 1976 is not immediately apparent in the values of some variables where it might be expected, such as winter water year precipitation, stream discharge, or in the percentage change of water yield relative to that in the 12 years before 1976. There are, however, suggestions of some interesting multidecadal changes in "cyclic" behavior of parts of the system. As described subsequently, such changes in cone production, the number of peak streamflows per year, and possibly in debris flow frequency need about another 100 years of records to establish the reality or absence of cyclic behavior, but these changes do raise some interesting research questions.

Cone production records from high elevations above about 1000 m for noble fir, silver fir, and mountain hemlock at the AND and in other parts of the Cascade Range commence in 1962. There is some evidence to suggest that temporal patterns of cone production by upper slope noble fir, silver fir, and mountain hemlock in the Oregon and Washington Cascades may be associated with variability in the PDO (figure 19.2). Cones counted on canopy trees on 14 plots in the Cascades show a marked 3-year periodicity from 1962 to 1974, as exemplified by Pacific silver fir (*Abies amabilis*) in figure 19.2. This was during a period of lower than average PDO (cool phase). For at least the next two decades, this periodicity ends with the 1971–1974 cone production period for Pacific silver fir, noble fir, and mountain hemlock when the north Pacific sea surface temperature rises above normal (PDO positive, warm phase). This loss of this 3-year periodicity may be caused by loss of a trigger, common to these species, needed for cone production. Preliminary analyses indicate that, until the mid-1970s, warmer than average summer temperatures in the Cascades preceded by one year the large cone crops seen in figure 19.2. No warming or cooling can be seen, however, in average summer (June, July, August) temperatures after 1976. After 1976, another change in cone production pattern occurred: There was less synchronicity both among and within species (figure 19.2). If a PDO regime shift in the late 1990s does prove true, a return to the 3-year cyclic cone production will be one test of the PDO/cone productivity relationship. More research is needed to explore potential links between PDO change and cone production response.

Cone production also displays the importance of preexisting conditions at a monthly timescale. In the case of Douglas-fir, a warm sunny dry June 15 months before cone maturation, cool moist March and April 17 and 18 months before cone maturation, and cool moist summer months 25 to 27 months before cone maturation are all associated with increased cone production.

Although no clear evidence of a 1976 climate regime shift is seen in precipitation and stream discharge records at the Andrews Forest, peak streamflows show an interesting pattern. Five-year running means of the number of peak streamflows per year in unharvested, high-elevation basins at the Andrews site between 1952 and 1996, as counted by storm matching techniques, show two complete and similar "cycles" with a period of about 10 years (Jones and Grant 1996). The "cyclic" nature of these data stops at approximately 1976 and is not seen in the later part of the time series.

Another geomorphologic and ecosystem response to PDO climate fluctuations may involve the occurrence of debris flows, rapid mass movements of 100 to greater than 1000 m^3 of soil and organic debris down steep headwater stream channels. Snyder (2000) examined the inventory of 91 debris flows occurring between 1946 and 2000 in a 125-km^2 study area including the Andrews Forest. Debris flows



igure 19.2 Relationship between Pacific Decadal Oscillation and cone production of three pper slope conifer species in the Cascades of Oregon and Washington. (Courtesy of Joseph eans)

initiated in unharvested forested areas occurred at a rate of 0.38 events per year in the wet phases of the PDO (before 1976 and after 1994) and only 0.05 events per year in the intervening dry phase. The majority (81%) of events in forested areas occurred in just three storms during this greater-than-50-year period, which raises the issue of whether these records represent the vagaries of storm history or a true PDO signal.

Once again, many future years of data and fairly precise methods of identifying and dating debris flows of the past 150–200 years are necessary to see whether the PDO/debris flow relationship may be established. Preexisting conditions may be important in this possible relationship. No matter what meteorological and climatological circumstances occur, debris flows can take place only if the potential debris material has already been rendered into a potentially movable condition.

Some interesting research questions are raised by these data. First, what kind of changes in system subvariables manifest themselves as a result of a multidecadal climate-driving cycle in a system? Can there be changes in system subvariables that show themselves as cyclic but with higher frequencies? Can changes in system subvariables be represented by the absence of a "response cycle" altogether in one phase of the driver cycle? More interesting, what are the complex steps in the system cascade that could give rise to this state of affairs, assuming the answers to these questions are positive. At least three other possibilities exist besides climatic cause and effect. First, there may be some other nonclimatic drivers at work such as land management and road construction. Second, nonclimatic drivers interact with climatic drivers. Third, the ecosystem events are random and there is no cause and effect.

Century to Millennial Scale

The absence of direct meteorological observations for most time periods and geographic areas at the century to millennial scale forces investigators to use proxy evidence from which to infer information concerning the variability of climate. At this scale, therefore, the ecological response is being used to provide information concerning the climate. We thus admit, in this section, to engaging to a certain degree in circular argument while discussing the "inferred" climate variability (as a "cause") and ecosystem response (as a "result"). The fields for which we have the most information at this timescale are those related to tree-ring thickness variability (Graumlich and Brubaker 1986; Graumlich 1987; Holmes et al. 1986; Buckley et al. 1992; Wiles et al. 1995; Garfin and Hughes 1996) and tree-ring–based (Weisberg and Swanson 2003) and lake-charcoal–based forest fire histories (Long et al. 1998), as well as vegetation change noted from pollen analysis (Warona and Whitlock 1995; Sea et al.1995; Grigg and Whitlock 1998).

Warm periods from 1400 to about 1575 and from 1800 to about 1925 were associated with widespread forest fires at the Andrews site and in the western Cascades (Weisberg and Swanson 2003). During the cool period from 1700 to about 1775, there was a marked decrease in the extent of forest fires. Forest fire histories based on tree rings at the Andrews site and in other study areas in western Oregon indicate widespread forest fires during the periods of 1475–1550 and 1850–1900. The most recent period of widespread fire is associated, among other factors, with a warmer, drier climate beginning about 1840, as noted in the tree-ring record (Weisberg and Swanson 2003). They point to anthropogenic factors acting synchronously with climate variability to produce the overall fire history.

The Weisberg and Swanson study suggests that as for crown fire-driven landscapes in general, the PNW may have exhibited high, spatiotemporal variability at any spatial scale. Climate variability at the century to millennial scale operating through the provision of periods for variable forest fire frequency leads to a highly dynamic ecosystem. Swanson has noted that forest establishment after fire may take place in periods of unusually stressful climate. He speculates that this may have affected succession and ultimately the development of present-day old growth forests in ways unlike the potential consequences of forests established by natural processes or management actions in areas with other climate conditions.

Forest fire histories based on lake charcoal for a site about 140 km west of the Andrews Forest complied by Long et al. (1998) extend our information on the interaction of climate and forest fire back even further. Climate models and known changes in the timing of the perihelion and the tilt of Earth's axis (Kutzbach et al. 1993) indicate that, between about 9000 and 6850 years before present (B.P.), the climate was warmer and drier than it is today. During this time fire intervals in the Oregon Coast Range averaged 110 ± 20 years. From about 6850 to 2750 B.P., there was an onset of cool, humid conditions, and, although there was an increase in the abundance of fire-sensitive species, the fire interval lengthened to 160 ± 20 years. From 2750 B.P. to the present, cool, humid conditions resulted in mesophytic taxa, and the mean fire interval increased to 230 ± 30 years. Although the actual fire intervals may be different in the Cascades and near the Andrews site, the overall pattern of changing climate and the ecological response in terms of relative fire intervals might have been similar.

The same overall climate changes that affected fire regime led to pronounced vegetation changes in the PNW. The long-term record shows that the composition of the forests has not been static, but instead has changed continuously with climate changes. Records from Little Lake (central Oregon Coast Range), Indian Prairie (Oregon Western Cascades), and Gold Lake Bog (central Oregon Cascades), for example, show changes in forest composition in the past that were most likely a response to shifts in summer drought and winter precipitation (Worona and Whitlock 1995; Sea et al. 1995). These, in turn, were driven by changes in the seasonal amplitude of insolation, the position of winter storm tracks, and the strength of the northeast Pacific subtropical high-pressure area.

The paleoecological record also suggests that forest communities in this region can change fairly rapidly with climate change. One episode of rapid vegetation change occurred at Little Lake around 14,850 years ago (Grigg and Whitlock 1998) when the pollen record shows that spruce forest was replaced by forest dominated by Douglas-fir in less than a century. A douglas-fir forest then persisted for about 350 years, when it reverted back to spruce forest. The increase in Douglas-fir at Little Lake was preceded by a prominent charcoal peak, which suggests that one fire or several closely spaced fires helped trigger the vegetation change by killing spruce and creating soil conditions suitable for Douglas-fir establishment. Warmer conditions than before allowed Douglas-fir to remain competitive for several decades or even centuries before spruce returned. Additional records of comparable resolution are necessary to determine whether this event is of regional significance. Nonetheless, the Little Lake data suggest that vegetation changes can occur rapidly when climate alters disturbance and tree regeneration conditions.

The PNW is a topographically complex area. Whitlock (1992) has described the Holocene vegetation history for this area as a response by plants to a hierarchical set of environmental controls of which climate is but one. Vegetation changes at the millennial timescale appear to respond to warming and, in this part of the world, drying associated with the retreat of the main Laurentide ice sheet. From 20,000 to 16,000 B.P., there was an influx of xerothermic subalpine vegetation (*Picea engelmanni* and *Artemisia*). Mesophytic subalpine vegetation appeared (*Tsuga mertensiana, Picea sitchensis*, and *Alnus sinuata*) after 16,000 B.P. when the main storm tracks are believed to have shifted northward. The later establishment of warm-loving and drought-adapted species from 12,000 to 6000 B.P. is associated with greater solar radiation and an expansion of the subtropical high-pressure zone. *Pseudotsuga* and *Alnus* then dominated the forests. Prairies and grasslands also appeared. At shorter timescales, Whitlock notes that fires were probably more frequent in the early Holocene warm dry period, so early successional and forest-opening species would have been more abundant. Also, at a smaller geographic scale, substrate conditions became important in influencing vegetation type. Prairie and oak woodland in the Puget Sound area favored summer drought conditions on the coarse-textured soils found there today and presumably throughout the Holocene. The modern forests of the Pacific Northwest are believed to have formed only in the last few millennia when the climate became wetter and solar radiation was reduced. Whitlock (1992, p. 22) concludes, "modern communities are loose associations composed of species independently adjusting their ranges to environmental changes on various time scales."

Future Climate Variability and Ecosystem Response

There continues to be concern about the possible effects on global climate change related to increased greenhouse gases in the atmosphere. If such climate change does occur, it is difficult to conceive of a potentially more important example of climate variability and ecosystem response. Future climate change will have complex, cascading, and, in some cases, detrimental effects on the ecosystems of the PNW.

Global General Circulation Models (GCMs) of the atmosphere and ocean are being used to investigate the question of what possible climate change might occur. Many caveats accompany the use of these models to estimate the potential changes of climate that might occur in a particular region. Apart from model deficiency, one of the most important caveats relates to the uncertainty in the rate of greenhouse gas emissions over the next 100 years. Also the range of temperature and precipitation projected by different models is quite large. For example, projected monthly temperatures vary by about 4°C (7°F) for different models. However, the models have been able to reproduce the increase of global temperatures in the twentieth century and the possibly anthropogenic part of that increase since 1970 (JISAO CIG 1999).

Output from the Canadian Centre for Climate Modeling and Analysis (CCC) GCM was employed by the JISAO group to suggest possible changes of climate in the PNW in the twenty-first century. This model suggests an increase in the cool season (Oct.–Mar.) temperature of about 5.5°C (10°F) and about 4°C (7°F) in the warm season (Apr.–Sept.) by the year 2100. A decrease of cool season temperature of about 5.5°C might eliminate subfreezing temperatures in some parts of the PNW. This might greatly decrease the snowpack and lead to a nonlinear response. The CCC model also suggested an increase in precipitation of about 330 mm (13 in.) in the cool season and 25 mm (1 in.) in the warm season. Despite the projected increase in precipitation, the rise may not be beneficial to forest environments because the large addition in the cool season will increasingly fall as rain, as opposed to snow, because of the higher temperatures. Much of this precipitation will run off and not add to the winter snowpack, if it still exists, for later release as snowmelt. The consensus of opinion of the University of Washington Climate Impacts Group, based on the output of seven GCMs, was that "the models are generally in agreement that winters will be warmer and wetter, but are divided about whether summers will be wetter or drier" (JISAO CIG 1999, p. 20). If some of these scenarios come to pass, the effect on PNW forests might not be favorable. The higher temperatures and possibly decreased amount of warm season soil moisture might increase the possibility of forest fires. Directly, these changes will lead to changes in the rates of growth, seed production, and seedling mortality. Indirectly, they will influence the disturbance regimes of fire, insect infestation, landslides, and disease (Franklin et al. 1992). The fossil record suggests that climate change coupled with disturbance will lead to disequilibrium between vegetation and climate as species adjust to new conditions and competitive interactions change.

Modeling studies (Urban et al. 1993), using an increase in temperature of 2.0–5.0°C, showed some altitudinal zonal and plant composition changes in Cascade ecosystems, but these studies used models that were set to run for 1000 years. Other model studies of biome and hydrologic response currently take an equilibrium approach, so they do not provide information on how, when, or even whether the vegetation/hydrosphere can respond to climate changes of a 2.0–5.0°C magnitude in the next century. Nonetheless, the equilibrium changes in hydrology and vegetation in the West are dramatic. An assessment by Thompson et al. (1998) suggests that it is unlikely that biotic adjustments can be accomplished in the next century for several reasons. First, vegetation responds more slowly than the projected climate change, especially long-lived species such as those in the PNW. The best paleoecological estimates for plant migration rates in the past are 40 times slower than those needed to keep pace with a doubled CO_2-related climate change in the twenty-first century. The plant species that predate humans did not have to contend with human land-use alteration that set up impediments to migration and dispersal. Second, species may not be able to migrate without assistance across a landscape fragmented by past land use. Third, the models only describe what potential, as opposed to actual, vegetation could occupy the climate space. Nonclimatic factors, including competition, will slow the migration process. Disturbance will probably be the catalyst of vegetation change, and the increase in severe fires during the last decade may already be the harbinger of effects of climate conditions to come.

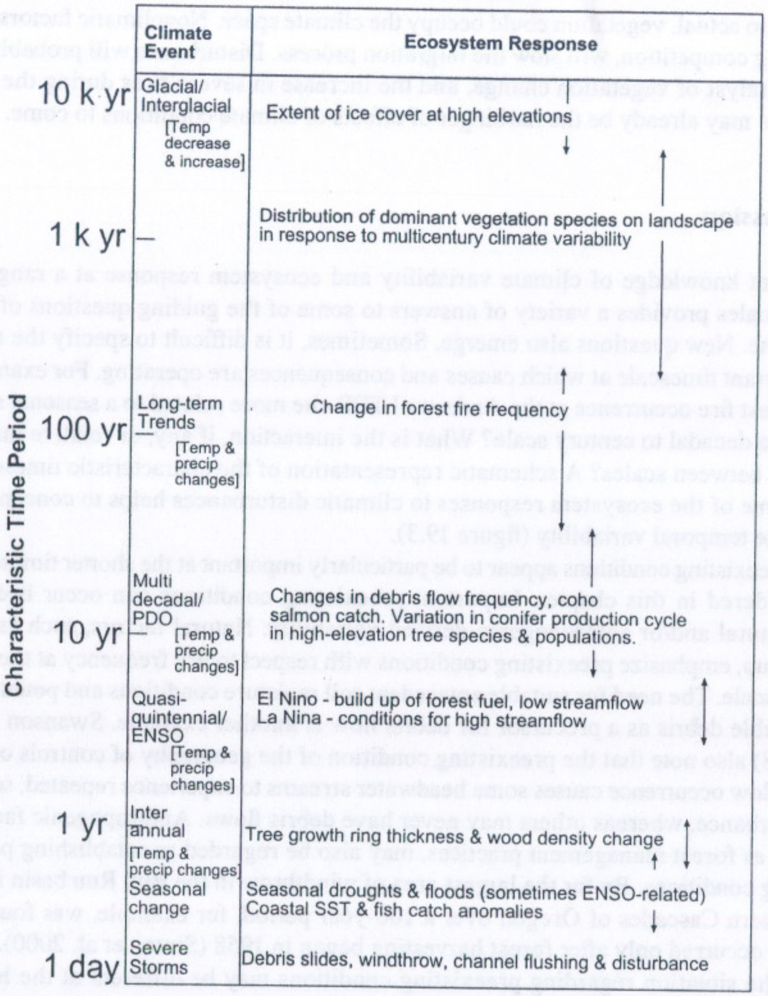
Discussion

Present knowledge of climate variability and ecosystem response at a range of timescales provides a variety of answers to some of the guiding questions of this volume. New questions also emerge. Sometimes, it is difficult to specify the most important timescale at which causes and consequences are operating. For example, is forest fire occurrence at the Andrews LTER site more related to a seasonal scale or to a decadal to century scale? What is the interaction, if any, or relative importance between scales? A schematic representation of the characteristic timescales of some of the ecosystem responses to climatic disturbances helps to conceptualize the temporal variability (figure 19.3).

Preexisting conditions appear to be particularly important at the shorter timescales considered in this chapter. Important preexisting conditions can occur because of natural and/or anthropogenic-derived variability. Natural factors, such as fuel buildup, emphasize preexisting conditions with respect to fire frequency at the century scale. The need for suitable antecedent soil moisture conditions and potentially movable debris as a precursor for debris flow is another example. Swanson et al. (1998) also note that the preexisting condition of the geography of controls on debris flow occurrence causes some headwater streams to experience repeated, severe disturbance, whereas others may never have debris flows. Anthropogenic factors, such as forest management practices, may also be regarded as establishing preexisting conditions. By far the largest area of windthrow in the Bull Run basin in the northern Cascades of Oregon over a 100-year period, for example, was found to have occurred only after forest harvesting began in 1958 (Sinton et al. 2000).

The situation regarding preexisting conditions may be different at the longer timescales. The speed with which plant communities can be altered at the millennial scale in the PNW region, as represented by vegetation changes at Little Lake, implies that the exact nature of the preexisting communities is less important at this scale. The vegetation history in the PNW suggests that the nature of the vegetation existing previous to a climate change plays a minor role in determining the type of ecosystem response in terms of the new vegetation community that takes over a given location. For example, the Little Lake pollen record near 14,500 years B.P., which shows relatively rapid changes from spruce to Douglas-fir and back again (Grigg and Whitlock 1998), gives little evidence, except possibly that related to seed availability, that the later vegetation affected the type of the newer vegetation.

A consideration of longer timescales leads investigators to examine the timing of ecosystem response. Neglecting, for the moment, disturbance- and succession-related vegetation change, as far as the forests of the PNW are concerned, evidence suggests that climate-induced vegetation change can show response to climatic episodes at timescales of as little as 500 to 1000 years (Whitlock 1992). Paleoeco-



igure 19.3 Characteristic timescales of some of the ecosystem responses to climatic dis-urbances.

ogic records reveal the relatively ephemeral nature of modern communities. Modrn forests represent an association that has existed for less than 3–6 millennia, nd in the Cascade Range only a few generations of the forest dominants have been resent in some sites at this timescale (Sea and Whitlock 1995). Species apparently ave responded individualistically to Holocene environmental changes rather than s whole communities, and in the process, plant associations have been dismantled nd reformed at a millennial pace.

There is no doubt that climate change and variability in the ecosystems of this egion go far beyond an individual cause and result. There is almost always a casade of resulting effects. Nakamura et al. (2000) explicitly employed the cascade oncept for short-term events. They have established common sequences of events

related to a cascade of hydrological and geomorphological events associated with the floods at the Andrews Forest. A biotic example of a cascade of events acting through time is evident in the effect of a windstorm, which may topple small trees or patches of trees. In some cases, at the edge of clear-cuts, the toppling event may be followed by drought that favors local eruptions of bark beetles, who emerge from the fallen trees to attack nearby live trees (Powers et al. 1999). At a longer timescale, Long et al. (1998) suggest that throughout the Holocene, changes in both vegetation and fire frequency were controlled by climate in finally determining the species composition and distribution of Coast Range forests. Studies from this region also show that besides cascading effects, extra factors can act as additional forcing functions alongside climate forcing. Factors such as soil texture and humans both causing, and suppressing, fires are examples. This is not a surprising conclusion, but it does emphasize the continued need to establish the importance of climate relative to other kinds of ecosystem forcing.

In this region we find examples at the quasi-quintennial and the multidecadal scales where the event, such as climate stage of ENSO, and the response, such as stream discharge, return to their "original" state by the time of the next event. This might not be true if vegetation or other environmental conditions have changed in the meantime. For example, since stream discharge is affected by water use by the vegetation, a lagged response in vegetation to specific climate variability may produce a lagged response in stream discharge. Furthermore, the concept of vegetation communities being "loose associations composed of species independently adjusting their ranges to environmental changes on various timescales" (Whitlock 1992, p. 22) suggests that at the century and millennial timescales there are likely to be no identical past analogs to the ecosystem at any point in time. It is unlikely that an ecosystem will return to its "original" state at this longer timescale, and the concept of "original" state itself has little meaning.

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20

Climate Variability in Tallgrass Prairie at Multiple Timescales: Konza Prairie Biological Station

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Climate is a fundamental driver of ecosystem structure and function (Prentice et al. 1992). Historically, North American grassland and forest biomes have fluctuated across the landscape in step with century- to millennial-scale climate variability (Axelrod 1985; Ritchie 1986). Climate variability of at decadal scale, such as the severe drought of the 1930s in the Central Plains of North America, caused major shifts in grassland plant community composition (Weaver 1954, 1968). However, on a year-to-year basis, climate variability is more likely to affect net primary productivity (NPP; Briggs and Knapp 1995; Knapp et al. 1998; Briggs and Knapp 2001). This is especially true for grasslands, which have recently been shown to display greater variability in net primary production in response to climate variability than forest, desert, or arctic/alpine systems (Knapp and Smith 2001).

Although the basic relationships among interannual variability in rainfall, temperature, and grassland NPP have been well studied (Sala et al. 1988; Knapp et al. 1998; Alward et al. 1999), the linkages to major causes of climate variability at quasi-quintennial (~5 years) or interdecadal (~10 year) timescales in the North American continental interior, such as solar activity cycles, the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the North Pacific Index (NP), are less well understood.

In this chapter, we will examine how interannual, quasi-quintennial, and interdecadal variation in annual precipitation and mean annual temperature at a tallgrass prairie site (Konza Prairie Biological Station) may be related to indexes of solar activity, ENSO, NAO, and NP, and in turn how these indexes may be related to aboveground net primary productivity (ANPP). Specifically, we present (1) period-spectrum analyses to characterize the predominant timescales of temperature and precipitation variability at Konza Prairie, (2) correlation analyses of quan-