Century to Millennial Timescale—Synthesis

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At longer timescales, the interaction among climate, ecosystems, and the abiotic components of the environment become increasingly important. These relationships are apparent in the three chapters in part IV. Fountain and Lyons (chapter 16), examining the McMurdo Dry Valleys (MCM) ecosystem in Antarctic, provide an excellent example of a case where past climatic variations truly dictate current ecosystem status. The relatively large climate variations at MCM have concentrated nutrients that could not have been attained without this climate variability. Fountain and Lyons infer climate change from geomorphic evidence of past glacier positions and lake level heights as well as more recent isotopic results from ice cores and temperature measurements from boreholes. They focus on evidence from the most recent 60,000 years. Monger (chapter 17) provides an analysis of millennial-scale climate and ecosystem variability at the Jornada LTER site in southern New Mexico. Monger notes the difficulty of untangling prehistoric climate/ecosystem interactions, where researchers must rely on indirect proxy indicators in lieu of measured data. Monger analyzes a number of proxy data sources, including paleolake levels, plant remnants preserved in packrat middens, fossil pollens, carbon isotope ratios in paleosols, and erosion rates. Although noting the danger of circular reasoning in using proxy data (i.e., ecosystem response used to infer information about climatic change, which is in turn inferred from ecosystem response) Monger uses these data to construct a cogent picture of climate change at the Jornada site (JRN) since the Last Glacial Maximum (LGM) about 18,000–20,000 years B.P. Using remains of beetles, Elias (chapter 18) constructs a temperature history of the Colorado Alpine since the LGM. These late Holocene insect records show a progression from warmer-than-modern to cooler-than-modern summers, and back to warm again. All the authors in this section provide examples to show that it is at century to millennial timescales that ecosystems form, are broken apart and imprinted by the past, and reformed in new configurations.

The McMurdo Dry Valleys is the most poleward-terrestrial ecosystem where streams, lakes, and soil are interconnected. In this polar desert, the biotic system must adopt a strategy to survive the winter in isolation, and the disturbance and formation of the landscape has been primarily dictated by climate and associated abiotic processes. During the last glacial period, the Ross Ice shelf entered Taylor Valley, damming the valley and forming a 200-m-deep lake (23.8 kyrs). Rapid warming occurred about 15 kyrs ago at the termination of the glacial period, and the lake remained until about 8.3 kyrs ago when the ice shelf retreated and the lake drained, leaving smaller lakes in low spots along the valley floor. The former large lake provided nutrients to the soils, and the drawdown of the smaller lakes 1000 years ago concentrated nutrients into pools on which the current ecosystem depends. It is because of the nutrient-poor and energy-limited environment of this polar desert that the past concentrations of nutrients play such a dominant role in the current structure and function of the ecosystem. In addition, the sensitivity of this system to the presence or absence of liquid water and the nonlinear response to changes in temperature near the melting point of water create a system where small changes in climate produce large variations in ecosystem response.

Based on paleoclimatic reconstruction, Monger identifies 9 intervals of climate variability at the Jornada LTER site over the past 20,000 years. His inferences are couched in terms of relative abundance of vegetation by life-form type (i.e., C_4 grassland, C_3 woodland, C_3 shrubland). In general, his reconstruction shows a trend toward increased abundance of C_3 shrubs, displacing C_4 grasses and C_3 woodlands. This trend represents a general increase in aridity consistent with regional changes in climate from the close of the Pleistocene. Although the trend is toward increased aridity, the changes are not monotonic. Particularly evident is the hot, dry Altithermal period (see figure 17.7). This climatic period, culminating about 6000 years B.P., was characterized by an expansion of grasslands in North America well east of their current ranges. Causes for the Altithermal warming are not entirely clear, but probably represent the additive effects of return to preglacial atmospheric CO_2 levels and solar radiation fluxes higher than their modern values (Kutzbach et al. 1996). Forcing by Milankovitch mechanisms has also been suggested as a cause for Altithermal warming (Kutzbach and Street-Perrott 1985; Gillespie et al. 1983). These changes probably weakened the North American monsoon circulation, causing reduction in precipitation and a shift toward predominant zonal westerly flows. Decreased precipitation and increased temperature signals show clearly in the Monger's reconstruction as a decline in lake level (or lake disappearance) and a marked increase in shrubland. Climate intervals 8 and 9 show a recovery of conditions from their mid-Holocene state, but they are still periods of aridity. Historical records for period 9 (since 1850) show a progressive increase of shrubland and a loss of grassland, consistent with continued postglacial aridity. This interval is strongly influenced by human activities, thus complicating the determination of cause and effect.

Using fossil insect records, Elias (table 18.1) provides a temperature reconstruction and vegetation history since the LGM. During the Holocene the Colorado

Front Range (NWT) has experienced a series of climatic fluctuations that have shifted glacial margins and biotic communities. Elias's predictions based on fossil beetle data agree well with a reconstruction of solar radiation based on Milankovitch insolation models (Berger 1978) at millennial scales. However, conflicting interpretations of insect, pollen, and archaeological data during the mid-Holocene suggest the need for additional regional studies. Elias notes that glacial ice has been the dominant force in shaping alpine landscapes, with postglacial communities limited to those able to survive and become reestablished after deglaciation. Elias (chapter 18, p. 466) suggests that "the current group of species in the alpine ecosystem may not be the best fit for the environment, they are simply the best fit among those species able to persist regionally through the last glacial cycle." Elias also notes that the response of major components of vegetation in high-altitude ecosystems may lag behind major climatic changes.

Relationship to Framework Questions

The results discussed in this section clearly show the presence of climate variability at millennial timescales, although (as pointed out previously) they must be interpreted cautiously to avoid circular reasoning. Monger's results coincide with those of other paleoclimate analyses both in the U.S. Southwest (e.g., Hall and Scurlock 1991) and elsewhere (Gillespie et al. 1983). Elias's temperature reconstruction is consistent with Milankovitch forcing, but it differs in details from some other reconstructions. This may be, in part, because of the regional specificity of the Colorado Front Range. Evaluation of some of the other framework questions is complicated by both the nature and timescale of the changes considered here. Use of proxy data always involves inferences about the relationship between the proxies and the climate data they represent; the certainty of these relationships decreases as the inferences extend further into prehistoric time. Nevertheless, results in this section do fit into some of the framework questions. At the millennial timescale, the LGM is an important defining preexisting condition.

Fountain and Lyons show the dominant influence of preexisting conditions, in this case a paleolake and its subsequent contribution of nutrients and organic carbon to the structure and function of the current ecosystem. There are cascades at shorter timescales through the aquatic part of this polar desert ecosystem (Welsh et al., chapter 10) that are driven by factors influencing the presence of liquid water, but the legacy effects in this environment are on the order of thousands of years. Superimposed on this legacy is the nonlinear response at the melting point of ice, which is "at the heart of all observed changes." This melting transition point is critical to discussion of the flow of material and energy through, and the direction of evolution of, this system. A consideration of cycles within this context must take note of this critical transition point.

Monger's results showing changes in vegetation life-form accompanying climate change represents a cascade effect. Monger notes that climate changes can result in vertical reallocation of water by runoff, resulting in the increased availability of moisture downslope. Another cascade can be inferred in the activities of rock glaciers during the late Pleistocene that form new geomorphic surfaces on which new ecosystems develop. These results may be cyclical, but if so the cycle occurs over very long time periods, extending even beyond the millennial timescales considered in this section. The climate events in this case show little evidence of reversal, at least at the timescales considered here. Monger's analysis also hints at the importance of preexisting conditions in the dynamics of the arid ecosystem. Much of his analysis is presented in terms of effects relative to the local topography (i.e., piedmont vs. basin floor, see figure 17.5), suggesting that the "lie of the land" is a crucial influence in this climate/ecosystem. Similar climate change might result in a different outcome given some other geomorphic surface.

Elias draws particular attention to the possible lags between climate variability and the response of trees growing near tree line to changing temperature regimes. This is an important observation, particularly in light of the current rate of climate variability and efforts to understand and predict the response of forests to this relatively rapid change. He notes that the current group of species in the alpine zone consist of those able to survive glaciation and become reestablished in the alpine zone. These species are not necessarily the best "fit" among all possibilities; instead, they are the best fit among those species persisting through the last glacial cycle. Elias further states that present-day ecotones in alpine and subalpine ecosystems are not in equilibrium with the current climate, but are instead a relict of an earlier warm period. Both of these facts point to an important role for legacy effects in alpine climate/ecosystem interaction. If glaciation is viewed as a climate "disturbance," then Elias's findings also suggest that the climate/vegetation interaction does not return to its previous state (i.e., a hysteresis effect) when a climatic disturbance event is completed. The lag effect between climate variation, which often occurs abruptly, and ecosystem response, which lags in response, results in a system where feedback mechanisms associated with previous climate cycles might often overlap. Thus, simple correspondence between climate "event" and ecosystem response is not a suitable framework for analysis of this ecosystem at millennial timescales.

Martinson and coauthors (1998), in presenting a science plan for decade to century-scale climate variability and change, note that the paradigm used for the study of climate variability at seasonal to decadal timescales may not be applicable to decadal and longer timescales. Paleoclimate and historical records are often too short to apply the process of generating hypotheses and quickly evaluating them. Martinson et al. (1988) argue that making progress at these longer timescales will require improved and faster climate models, and expanded paleoclimate data bases. Understanding processes at these longer timescales is essential because it is at these timescales that, as Elias (p. 387) notes, "ecosystems form, break apart, and reform in new configurations." Also, Martinson et al. (1998) note that it is over these time periods that the life prospects of future generations are defined by climatic variability. They argue that informed stewardship of Earth's resources requires a sustained effort to understand processes on these longer timescales.

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

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