## Chapter 4

# HISTORICAL ECOLOGY, CLIMATE CHANGE, AND RESOURCE MANAGEMENT: CAN THE PAST STILL INFORM THE FUTURE?

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The future ain't what it used to be.
Yogi Berra

## 4.1 INTRODUCTION

Global mean annual air temperatures at the earth's surface are predicted to rise by as much as 6.4°C in the next century, creating climatic conditions unprecedented in at least the last 2 million years (IPCC 2007a; Fig. 4.1). Levels of $CO_2$ in the atmosphere are at their highest in at least 650 000 years, and the long residence time of $CO_2$ in the atmosphere means that the earth is locked into global warming and its results for decades or centuries to come even if international efforts to drastically reduce greenhouse gas (GHG) emissions succeed (IPCC 2007a). At the same time as climates warm, rapid expansion of human populations and economies has dramatically reduced the extent of the earth's natural and seminatural habitats. Land-use change has reduced the availability of suitable habitat for native plants and wildlife, and in many places, fragmentation of habitat has led to landscapes characterized by terrestrial archipelagos of seminatural ecosystems that are only weakly connected via dispersal and migration. These changes decrease the ability of biota to respond to increasing levels of ecological stress that are resulting from a combination of anthropogenic trends, including altered disturbance regimes, air and water pollution, atmospheric deposition, and biotic invasion (Noss 2001; Sanderson et al. 2002).

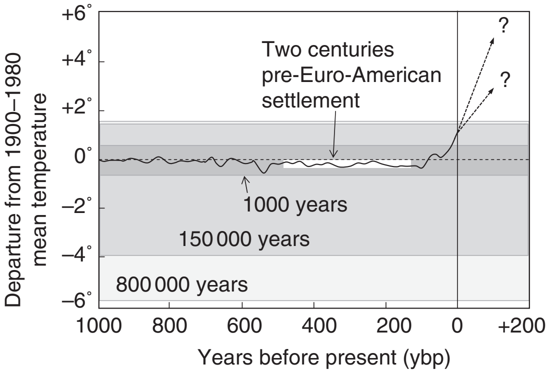

**Fig. 4.1** Historical ranges of variation for global mean annual temperature, compared with the temperature record for the last 1000 years (Bradley 2000) and moderate and extreme warming projections over the next century as modeled by IPCC (2007a). Light gray area is reconstructed range of variation for last 800 000 years; medium gray area is reconstructed range of variation for last 150 000 years (both from Tausch et al. 1993). Dark gray area is reconstructed range of variation for the 1000 years before 1980; the dashed horizontal line is the mean temperature for the twentieth century before 1980 (both from Bradley 2000). The thin white area is the range of variation for the two centuries preceding Euro-American settlement in North America, the most typical reference period for HRV assessment in the United States. The "Little Ice Age" stretched from c. 600 to 100 ybp; the "Medieval Warm Period" stretched from c. 1100 to 650 ybp.

Worldwide, traditional practices of ecosystem management are largely dependent on the characterization of "reference states," which may constitute targets or desired conditions for management activities. Because human alterations to ecosystems have been so pervasive, fully functional contemporary reference ecosystems are rare, and reference states must often be defined based on historical conditions. There is much knowledge to be won by understanding the past histories of natural systems. For example, information gained through historical ecological studies (from pollen sedimentation, packrat middens, tree rings, photographs, historical survey maps, etc.) has been used to, among other things, document and analyze ecological trends, build and validate models of ecological processes, and provide targets for preservation, restoration, and resource extraction activities (Landres et al. 1999; Swetnam et al. 1999; Egan & Howell 2001). Understanding a location's history also provides a philosophical grounding, a "sense of place," that some argue is fundamental to the establishment of a sustainable relationship between people and the earth (Stegner 1992).

One of the time-honored fundaments of restoration ecology and resource management has been the implicit assumption that the historical range of variation (HRV [Box 4.1]; also referred to as the range of natural variation) represents a reasonable set of bounds within which contemporary ecosystems should be managed. The underlying premise is that the ecological conditions most likely to preserve native species or conserve natural resources are those that sustained them in the past, when ecosystems were presumably less affected by people (Manley et al. 1995; Egan & Howell 2001; Wiens et al. 2002). However, rapid and profound changes in climates and land use, as well as other anthropogenic stressors, may threaten the validity of some of the ways in which humans use historical information in resource management (Box 4.1). In the

### Box 4.1 Definitions and background for restoration and climate change related terms used in the text.

| Term | Definition (sources) | Examples of use in resource management | Implications of global change |
|---|---|---|---|
| Historical ecology | The study of the ecological past. Includes paleoecology, archival research (natural and documentary), long-term experiments, instrumental records, and so on. Historical ecology is often focused on describing past processes or patterns before the onset of some form of degradation, human or otherwise (Swetnam et al. 1999; Egan & Howell 2001). | Innumerable. See chapters in this book, and references therein. Historical ecology forms the basis for our understanding of ecosystem change through time, and biological and physical components of this change. | Dynamic and uncertain future requires better understanding of mechanisms driving ecological processes and patterns and their direct and indirect links to climate. Historical ecology is the principal source of this knowledge. |
| Historical range of variation (HRV) | The variation of ecological characteristics and processes over scales of space and time that are appropriate for a given management application. HRV analysis is a segment of the field of historical ecology focused on statistical description of the variability in composition, structure, and function of an ecosystem during some (ecologically relevant) time period in the past (Morgan et al. 1994; Manley et al. 1995; Landres et al. 1999). | There are hundreds. See chapters in this book and references therein. Use of HRV by land and resource managers has tended to focus on HRV-derived reference conditions under assumptions of stationarity (see below), but HRV analyses do not genetically depend on stationarity assumptions, nor do they need to generate static reference condition outputs. HRV is a tool, and limitations to its use are largely products of decisions made by its users (related to, for example, the spatiotemporal scale studied, the variables considered, the management questions or biases involved). | Uses of HRV data assuming stationarity are becoming less tenable. Global change requires assessment of HRV on broader scales of space and time, in order to better identify past conditions that resemble likely future conditions in terms of climate or other drivers. HRV assessments and their users must clearly identify the limitations of HRV outputs (as designed in a given case) under global change scenarios. Use of HRV to study mechanisms of ecological change will become more important; use of HRV to identify specific historic reference conditions will become less important. |

| Term | Definition (sources) | Examples of use in resource management | Implications of global change |
|---|---|---|---|
| Stationarity | The concept that ecosystems fluctuate within an unchanging envelope of variability. A stationary time series is one whose statistical properties (mean, variance, patterns of autocorrelation, etc.) are constant over time, that is, it is free of trends, periodicity, or thresholds (see below). True stationarity rarely, if ever, occurs in nature, although temporal segments of a time series may approximate stationarity (Koutsoyiannis 2006; Milly et al. 2008). | Stationarity assumptions often underlie the use of reference conditions in restoration and management (see below). For example, stationarity assumptions form the basis for hydrologic management (e.g. reservoir management, seasonal streamflow assumptions, 100-year floodplain mapping) and related things like flood insurance rates and property values. | Ecological time series which may have usefully approximated stationarity in the past may not do so in the future, due to changes in climate or other environmental drivers. This may occur because of, for example, a temporal trend in the mean (or variance, etc.), and/or a change in the bounds of statistical variance which characterizes the time series. |
| Historical reference conditions | Derived from the stationarity assumption, where desired future conditions for an ecosystem are simply those which characterized the target ecosystem in the past, before degradation. In US federal land management, historical reference conditions (HRCs) are usually derived from the centuries immediately before Euro-American arrival, or some other time period that represents quasi-stationary behavior in the variable(s) of interest (Morgan et al. 1994; Landres et al. 1999; Egan & Howell 2001). | HRCs are a fundament of traditional ecological restoration. HRCs may be based on high and low bounds in the variability of the ecological variable of interest, or, less advisably, on the mean. Assuming relative continuity of ecological conditions (climate, human impacts, etc.) between the reference period and the current period, HRCs are a powerful management tool, especially where they explicitly recognize the range of statistical variability in ecosystem patterns and processes. | Using HRCs as an endpoint target for management falls victim to the problems identified above for stationarity. If future environmental conditions are not similar to past environmental conditions, then returning an ecosystem to the reference condition may be impossible, unsustainable, or even detrimental. HRCs based on mean values will be less tenable under global change than those incorporating variability. In some cases, HRCs may serve as useful “waypoint” targets for restoration of ecosystems (e.g. “preparing” degraded ecosystems for the effects of global change). |

*Continued*

| Term | Definition (sources) | Examples of use in resource management | Implications of global change |
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| Ecological integrity | Generally defined as the degree to which all ecosystem components and their interactions are represented and functioning. Determined based on "properly functioning" reference sites, which are often derived from historical data and HRV. Functional integrity is usually given more weight than compositional integrity, as individual (non-keystone) species can enter or leave most ecosystems without significantly affecting overall ecosystem function. Characterization and measurement of ecological integrity is dependent on subjective human judgments (Woodley et al. 1993; Karr 1996). | As applied in management, ecological integrity is very dependent on notions of HRV or range of natural variation. The US Forest Service Watershed Condition Classification program ranks river watersheds nationally with respect to their "geomorphic, hydrologic and biotic integrity" relative to their "potential natural condition." The US National Park Service Ecological Integrity Assessment Framework and The Nature Conservancy's Measures of Success framework are other examples. | "Integrity" is difficult to define without allusion to reference conditions; as such, it has same issues as HRV (above). Changes in environmental conditions may make attainment of "integrity" difficult or impossible, since the model for integrity is derived from past conditions. |
| Ecological resilience | The amount of disturbance an ecosystem can absorb without shifting to a different "stable state" (a domain in which a specific set of mutually reinforcing ecological processes and structures maintain the ecosystem within a definable range of variation). Exceeding the resilience of an ecosystem will theoretically lead over a "threshold" to a new stable state, where a different set of ecological processes and structures will be engaged (resulting in a new range of variation) (Peterson et al. 1998; Gunderson 2000). | Maintenance of the capacity of an ecosystem to "snap back" to a desired, or at least well-known, state. Many forest thinning projects in the western United States are designed to keep severe fires from leading to threshold conditions. Invasive species control work in both terrestrial and aquatic ecosystems is focused on resilience as well. | "Resilience" has become a major buzzword in the new managing-for-climate-change parlance. Management for climate change adaptation (see below) is focused to a great extent on maintaining or creating "resilience." Resilience management focused on ecosystem function and structure will be more successful than management focused on species composition. |

| **Term** | **Definition (sources)** | **Examples of use in resource management** | **Implications of global change** |
|---|---|---|---|
| Ecosystem services | The conditions and processes through which ecosystems (and their components) sustain and fulfill human life. Ecosystem services include provisioning services (food, water, fuel), regulating services (water purification, carbon sequestration, etc.), supporting services (seed dispersal, nutrient cycling, etc.), and cultural services (spiritual inspiration, recreation, etc.) (Daily et al. 1997, MEA 2005). | New York City purchase and eco-management of Catskills watershed area to preserve clean drinking water. Protection or planting of riparian forest buffers to filter agricultural runoff from urban water sources around the Chesapeake Bay. In Australia, national science agency (CSIRO) is leading nationwide Ecosystem Services Project to valuate and sustainably manage ecosystem services underpinning key agricultural industries and other benefits like recreation and tourism. | In management, some shift in focus from single species conservation to ecosystem processes and products may prove necessary. Certain ecosystem services or their levels of supply may change significantly under global change. |
| Climate change adaptation | Beneficial adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects. Actions that reduce the vulnerability of an ecosystem to climate change and increase ecosystem resistance or resilience to climate-driven changes in ecological conditions (IPCC 2007b). | In reforestation efforts, use of seeds from climate zones better aligned with future predicted climates. In road management, increasing culvert size to allow passage of higher streamflows. Designation of habitat corridors to permit species migration in response to climate change. | Because climate change mitigation is unlikely to stop global warming soon, climate change adaptation is becoming a central focus area for resource management. |

last decade, as the scale and pace of climate change have become more apparent, a rising chorus of authors has called into question the value and legitimacy of uncritical applications of historical reference conditions to contemporary and, especially, future land and resource management (e.g. White & Walker 1997; Harris et al. 2006; Millar et al. 2007; Craig 2010; Stephenson et al. 2010). At the same time, many of these authors explicitly recognize the fundamental, and even growing, value of historical ecological data to ecosystem management in the twenty-first century and beyond. Many land and resource managers are therefore confused: should we use historical data or not? In what ways? To what ends? In this chapter, we attempt (1) to clarify the nature of the problem, and (2) to provide clearer guidance to managers about promising uses of historical ecology and HRV analyses in land and resource management in the face of climate change.

## 4.2 CLIMATE CHANGE AND THE APPLICATION OF HISTORICAL ECOLOGY: WHAT IS THE PROBLEM?

For as long as the concept of HRV has been a central management tenet, there has been debate about its application. One focus of criticism is the relevance of applying HRV targets in environments that are different from what they were in the past. Landres et al. (1999) and others (e.g. White & Walker 1997; Swetnam et al. 1999; Harris et al. 2006; Millar et al. 2007) have subdivided this criticism into three basic problems:

**1** Every point in space and time is unique, and climates are continually changing. Hence, descriptions of past patterns and processes provide insufficient or even erroneous reference for future management.

**2** Management goals based on HRV often focus on recreating past environments and maintaining them in a static condition. This is a recipe for failure in a rapidly changing world.

**3** Humans have changed natural ecosystems to such an extent that there are no truly pristine areas left on the planet. As a result, information derived from the past is difficult to interpret and apply.

These criticisms rest on the common notion that the past is an imperfect guide to the future, especially when we have good information about a future characterized by strong directional change (e.g. warming temperatures, drying trends, increased $CO_2$). These concerns relate to a more fundamental question in ecology about whether it is ever reasonable to assume equilibrium states for ecological communities (Connell & Sousa 1983; Levin 1992). Although the idea that ecosystems function under permanent stable equilibria was refuted decades ago, many widespread management applications are nonetheless based on assumptions of environmental stationarity – the idea that the long-term mean is more or less invariant and the range of past conditions encompasses current and future conditions as well (Box 4.1; "A" in Fig. 4.2). The reasoning is that, although true environmental stationarity

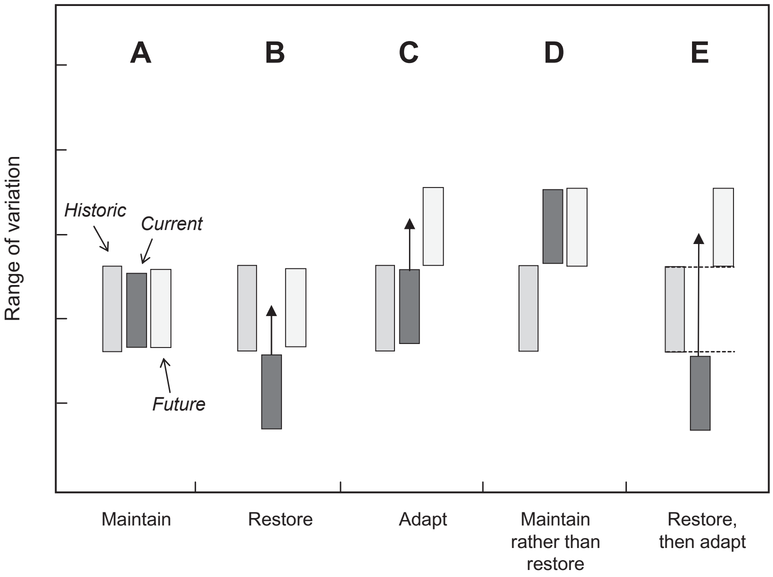

**Fig. 4.2** Comparison of historic (medium gray), current (dark gray), and projected future (light gray) ranges of variation for a given ecological variable. The vertical length of the bars represents the range of variation. Possible management responses for each case are given along the *x*-axis. The assumption is made that the presumed future range of variation is the desired future management condition, but this may not always be the case. For example, under "C," rather than adapting, society could decide to (try to) maintain conditions within HRV; under "D," society could decide to return the system to HRV. In all cases, society could decide to leave the current condition as is. "E" is a common situation in many ecosystems, where human management has diminished some ecological component, pattern, or process, and the current departure from HRV is expected to increase in the future (forest fire frequency in dry-summer parts of the western United States is a good example). In our view, the use of reference condition-based targets as restoration "waypoints" is warranted in these conditions, but the long-term ("endpoint") focus should be on further adaptation to changing conditions. These are extreme cases and most real-world examples will include partial overlap among past, current, and future ranges of variation. Inspiration for this figure comes from Fig. 1 in Landres et al. (1999).

may not exist over the long term, the periodicity or rate of change may be slow enough compared to human experience to permit the useful assumption of stationarity. The best-known example of this assumption being put to use is probably "hydrologic stationarity", which posits that hydrologic variables like streamflow and maximum flood vary about a time-invariant mean and can be reasonably estimated from the instrumental record. In essence, hydrologic stationarity assumes that the future will be statistically indistinguishable from the past (Box 4.1; "A" in Fig. 4.2). Relatively stable hydrologic dynamics over much of the twentieth century facilitated the successful application of this statistical assumption to managing water systems. However, strong directional changes in surface and groundwater hydrology over the last two to three decades have led to a general realization that "stationarity is dead" and that hydrologic prediction must adapt to rapidly changing baselines (Milly et al. 2008; see "C" and "D" in Fig. 4.2). The challenge now is to redesign management strategies for a future that is both dynamic and uncertain.

The same concerns are raised with respect to stationarity in applications of historical ecology to terrestrial resource management (Harris et al. 2006; Millar et al. 2007; Stephenson et al. 2010). For example, in its simplest form, HRV is characterized as the range of some condition or process (e.g. fire-return interval, stand structure, patch size, diversity) that has occurred in the past. Although HRV does not inherently require an assumption of stationarity, many applications of HRV do (Box 4.1). In doing an HRV analysis, one must explicitly define the temporal extent of the historical period over which to characterize natural variability (Wiens et al., Chapter 5, this book). In the United States, the reference period for HRV assessment has often been restricted to the one or two centuries immediately prior to European settlement (Fig. 4.1). Accordingly, many proposed land-management actions have treated the period immediately prior to Euro-American settlement as an explicit target, and have sought to recreate ecological patterns – and sometimes, but much more rarely, processes – thought to be characteristic of this period.

Given the tendency to assume stationarity, a fundamental tension occurs as resource managers look to apply historical ecology in a world of rapid climate change. In many places, site conditions by the end of the twenty-first century may occupy climatic niches that do not exist today (so-called "no-analogue" conditions; "C" and "E" in Fig. 4.2). For example, Saxon et al. (2005) and Williams et al. (2007) project that by 2100, between 25% and 50% of the United States will support climatic domains with no contemporary analogue. Hobbs et al. (2006), Williams and Jackson (2007), and others argue convincingly that widespread novel ecosystems are inevitable outcomes of future climatic shifts. In the face of such dramatic ecosystem change, the pervasive idea that sustainable land and resource management is best undertaken by maintaining the environment within the range of pre-European conditions is difficult to defend. As Stephenson et al. (2010) put it:

> Our world has entered an era in which keystone environmental drivers – those that define the possible range of characteristics of a protected area – simply have no analog in the past, no matter how distantly we look.... Although the range of past ecosystem conditions remains a valuable source of information about the forces that shape ecosystems, it no longer automatically serves as a sensible target for restoration and maintenance of ecosystems.

## 4.3 LESSONS FROM HISTORY

At its foundation, the current dispute about the value and proper use of historical reference conditions is a reprise of the 2500-year-old debate about the value and proper use of human history. As far back as the fifth and fourth centuries BC, Greek historians had fundamentally different approaches to the study of history and different perceptions of history's value to society. For example, Herodotus's focus was on the preservation of great events of individual heroism, while Thucydides and Aristotle stressed the importance of the study of history to understanding the development of both contemporary and future events (Kelley 1991). Questions regarding the relevance of the past – whether history really ever repeats itself or whether each contemporary (and future) event is fundamentally unique – have featured in debates among historians (and practitioners of most professions, for that matter) for millennia. As in almost all such debates, the only reasonable answer is that strict adherence to either position is unjustifiable. Every event is unique, but every incident is also born from the roots of antecedent events (Sprugel 1991; Tausch et al. 1993). Questions related to topics as disparate as low voter turnout in the United States, rates of anorexia among teenagers, the Jewish–Muslim conflict in the Middle East, persistent accelerator failure in Toyota cars, the spread of an invasive aquatic plant, and the causes of spousal conflict are all fundamentally unapproachable without a thorough appreciation for the role of past events and trends. As P.N. Stearns (1998) put it, "How can we evaluate war if the nation is at peace, unless we use historical materials?" In an essay written for the American Historical Society in 1985, W.H. McNeill noted that,

> . . . the study of history does not lead to exact prediction of future events. Though it fosters practical wisdom, knowledge of the past does not permit anyone to know exactly what is going to happen. Looking at some selected segment from the past in order to find out what will occur "next time" can mislead the unwary, simply because the complex setting within which human beings act is never twice the same. Consequently, the lessons of history, though supremely valuable when wisely formulated, become grossly misleading when oversimplifiers try to transfer them mechanically from one age to another, or from one place to another. Anyone who claims to perform such a feat is sadly self-deceived. Practical wisdom requires us instead to expect differences as well as similarities, changes as well as continuities – always and everywhere.

The lesson for resource management is obvious: resource managers should no longer uncritically treat ecological patterns documented by historical studies as default management targets. In a rapidly changing world, management policies and practices that rely heavily on assumptions of ecological stationarity must be suspect. Management plans that seek to recreate past conditions and to artificially maintain a management area in that state over the long term will require increasing investments in energy, time, and money, and may well fail in the end. Historical ecology and HRV analyses will always be keystones of our understanding of environmental change, but under rapid global change, HRV can no longer be uncritically treated as equivalent to "desired condition." There are situations and ecosystems where historical reference conditions continue to provide useful management guidance and even interim targets (Fig. 4.2), but in most places, the use of historical information to substantiate *stationary* land and resource-management practices is truly a thing of the past.

## 4.4 APPLYING HISTORICAL ECOLOGY IN A CHANGING WORLD: BACK TO THE FUTURE

Although specific historical reference conditions are becoming less useful as management targets, we agree with many recent authors (e.g. Harris et al. 2006; Jackson & Hobbs 2009; Keane et al. 2009; Stephenson et al. 2010; Cole et al. 2010a) that the fundamental value of historical ecological information to resource management is unchanged, and indeed its value increases as we sail farther into uncharted climatic and environmental waters. In this section, we highlight three areas and examples where historical data provide fundamental insights unavailable to managers "mired in the present." In this era of rapid global change, we believe that a historical frame of reference remains elemental for (1) comprehending the temporal dynamics of ecosystem processes and patterns (as opposed to specifying static targets for management goals); (2) recognizing and understanding human interactions with ecosystems (as opposed to defining the essential "natural" state of ecosystems); and (3) refocusing our management efforts on critical ecosystem processes (rather than conserving specific biological players).

### Comprehending the temporal dynamics of ecosystems

As species distributions change in response to shifting climate, resulting ecosystems will ultimately consist of novel species combinations and possibly fundamentally altered ecosystem processes (Williams & Jackson 2007). Shifts in ecological processes are likely to render efforts to restore ecosystems to prior conditions difficult or impossible. In this era of rapid environmental change, historical ecology is less likely to provide a target for management conditions but more likely to provide understanding of ecological dynamics through time, and thus some level of predictability of ecological response to changing climates in the future (Swetnam et al. 1999; Keane et al. 2009; Stephenson et al. 2010).

Climate–wildfire relations in western North America provide a classic example of how historical ecology can supply a template for understanding temporal changes in ecological processes. Over the last few decades, wildland fires in western North America have become progressively more frequent, larger, and more destructive of human property, and federal and state governments now spend billions of dollars annually in wildfire control and prevention (Westerling et al. 2006; Miller et al. 2009). Many researchers are engaged in the search for mechanisms that drive fire occurrence and behavior in order to provide some predictability under changing climates. Historical ecological data show that climate strongly controlled fire regimes before Euro-American settlement of the West (Swetnam & Betancourt 1998; Taylor & Skinner 2003). In general, presettlement fire histories show that years of widespread fire tended to follow years of low precipitation, which would result in lower soil and fuel moistures and higher probabilities of successful ignition in the subsequent fire season. More recent data from the mid- to late-twentieth century have shown similar patterns, with different climate–fire correlations characterizing different geographic regions (Westerling et al. 2003; Littell et al. 2009). Now researchers have closed the temporal loop and linked the historical record with twentieth- and twenty-first-century data, allowing the development of region-specific predictive models for fire area based on three centuries or more of climate–fire relations (e.g. Westerling & Swetnam 2003). In this case, the historical data played a major role in developing and calibrating the fire–climate models. More importantly, the historical data extended the data record to the period preceding Euro-American settlement, thus allowing analysis of "natural" fire–climate relations before the introduction of widespread human alterations of the landscape (e.g. agriculture, grazing, and logging), fire regime (e.g. fire suppression and human ignition), and climate (e.g. warmer temperatures, early spring melting). This research reveals that fire area and frequency are still substantially controlled by interannual climate variability, even within the highly modified human landscape. At the same time, the long data record illustrates the regional- and ecosystem-based differences in fire response to climate, and helps managers and scientists to better understand where direct human influences on fire and forest fuels are most likely to influence fire occurrence and behavior (Schoennagel et al. 2004; Littell et al. 2009).

In another example, Swetnam et al. (1999) studied the temporal dynamics of *Pinus edulis* and *Pinus remota* (piñon pine) populations in the southwestern United States. Swetnam et al. (1999) overlaid demographic trends in piñon pine populations on regional reconstructions of climate from tree rings. Their historical analysis suggested that tree mortality during extreme drought periods opened recruitment niches and released younger age-classes from resource competition; strong recruitment pulses tended to occur in the first wet period after a drought and mortality event. The profound drought of the 1950s, thought to be the worst in the last millennium, killed thousands of square kilometers of piñon, leading to high seedling survivorship and a massive pulse in piñon recruitment in the 1970s and 1980s. Since that time, establishment of piñon has been sustained by a long spate of warm wet springs associated with tropical Pacific warming (Swetnam & Betancourt 1998). By the middle of the twenty-first century, this surge in recruitment will greatly change contemporary forest structure. Swetnam et al. (1999) predict that without the comprehensive knowledge of demographics and historical climate in the region, the tendency would be to ascribe patterns of forest change to direct anthropogenic causes (such as grazing or fire suppression), leading possibly to misguided management responses.

## Recognizing and understanding human interactions with ecosystems

Some applications of the HRV concept focus on historical periods in which the impacts of humans were presumed to be weak. Indeed, historical or natural variation is sometimes described as the condition of being apart from humans (Kaufmann et al. 1994; Manley et al. 1995; Romme et al., Chapter 1, this book; Box 1.1). This is ironic, as the use of the term "historic" in HRV was originally meant to differentiate it from "natural" variability, so as to permit the inclusion of past human influences on the environment (Morgan et al. 1994; Egan & Howell 2001). Any emphasis on the pristine as the target condition is problematic for the management of modern ecosystems, as few, if any, contemporary ecosystems are pristine or have been for centuries or millennia (Sprugel 1991; Tausch et al. 1993; Sanderson et al. 2002; Hobbs et al. 2006; Willis

& Birks 2006). Ecosystems can be placed along a gradient from intensively managed to passively managed to "natural," but their location on this gradient is spatially and temporally dynamic. Human activities have altered ecosystems for millennia, for example by simplification, degradation, disturbance, or species introduction. The pace and scope of anthropogenic change have increased dramatically over the last 50 years (Vitousek et al. 1997; Sanderson et al. 2002), and GHG-driven changes in the global climate clearly signal the death knell for the notion that any ecosystems on Earth exist outside the sphere of human influence. Humans and nonhuman species simply cannot be disentangled from each other, so most managed ecosystems are best understood as complex socio-ecological systems (Zavaleta & Chapin 2010). As Hobbs et al. (2010) write, "if nature evolved with human input, the absence of all human influence may not be desirable in some cases." For instance, current resource managers in the United States set fires to create habitat mosaics, similar to the methods of historic populations of Native Americans. However, recognition of this shared tradition to manage the land is relatively new, as the notion of a nature without human influence has guided management practices in the New World for much of the last century, reflecting the inaccurate belief that indigenous people had very little "meaningful" impact on the landscape (Nowacki et al., Chapter 6; Jackson, Chapter 7, this book). On the contrary, in Europe, Asia, and Africa, where human history stretches back tens to hundreds of thousands of years, management for ecological restoration has never really been about restoring a prehuman past (Bakker et al. 2000; Jackson & Hobbs 2009).

The management of modern ecosystems requires different references for sustainability than the historical conditions of a past that did not include pervasive human global change, including rapid GHG-driven changes in climate and atmospheric and oceanic chemistry. Harris et al. (2006) warns that "valuing the past when the past is not an accurate indicator for the future may fulfill a nostalgic need but may ultimately be counterproductive in achieving realistic and lasting restoration outcomes." Historical ecology can help to discriminate between "natural" and "cultural" causes of environmental change (Swetnam et al. 1999), and it can help identify locations and situations where human impacts have deeply and possibly irreversibly altered ecosystems. No-analogue species assemblages by themselves will not necessarily involve an upheaval of ecosystem processes and biotic relationships, but where they do, systems may cross a threshold into a domain of qualitatively different dynamics (Box 4.1; Romme et al., Chapter 1; Wiens et al., Chapter 5, this book). Historical evidence can potentially help to determine whether a sustainable return to some previous state may be possible and well-advised (e.g. "B" in Fig. 4.2), possible but ill-advised ("D" in Fig. 4.2), or simply impossible.

As an example, monitoring data on nitrogen deposition over the last century and a half show that human activities have greatly increased nitrogen availability in terrestrial and aquatic ecosystems in many parts of the industrialized world (Holland et al. 2005). These inputs profoundly change the outcomes of many ecological processes and interactions and constrain our ability to restore and manage ecosystems. Aber et al. (1989) described the various ecosystem effects of "nitrogen saturation," ranging from reduced water quality, to disruptions of physiological function in forests, to increased acidity and cation leaching from soils, to altered competitive relationships. Nitrogen deposition is a major impediment to persistence and restoration of herbaceous vegetation in many places, as fast-growing weedy annual (and often exotic) species invade previously nutrient-poor sites and outcompete native species that had previously dominated (Choi et al. 2008). Atmospheric N inputs have also contributed to eutrophication of lakes and estuaries, reduced fishery productivity, abetted invasive species, and provoked other fundamental changes in the ecology of aquatic ecosystems (Rabalais 2002). In both terrestrial and aquatic ecosystems, apparently irrevocable changes in the physical and biotic environments can make the setting and attainment of historically based management targets an exercise in futility.

Other illustrations of the value of using historical data to recognize human impacts abound. For example, dendrochronology, fire scars, historical photographs, early land surveys, and other historical records were used to ascertain that mid-nineteenth-century grazing practices in the southwestern United States greatly reduced forest-surface fuel loads in *Pinus ponderosa* forests and contributed to a dramatic decrease in the frequency of fire, a change that had previously been ascribed purely to fire-exclusion policies (Savage 1991; Moore et al. 1999; Swetnam et al. 1999). The detection of this important grazing–fire interaction led to a restoration framework that includes recommendations for grazing practices that allow the recuperation of herbaceous fuels at the forest surface (Moore et al. 1999). In another example, Jackson et al. (2001) created a well-dated time series of ecosystem structure based on biological, biogeochemical, physical, and historical proxies to help clarify the underlying causes and rates of ecological change in a variety of coastal aquatic communities, ranging from kelp forests and coral reefs to offshore benthic communities. The historical records reveal long-term disturbance from the overfishing of large vertebrates and shellfish. The major changes provoked by overfishing occurred before the advent of ecological science and thus could only be documented through historical analysis. Jackson et al. (2001) concluded that the historical evidence suggested that large-scale restoration of ecologically important but currently rare ocean species was possible in some ecosystems, but not without a major reduction in other human perturbations.

Given the pervasiveness of human influences on ecosystems, it is wise to use contemporary ecosystems as reference systems whenever possible. We use historical data principally to understand ecological events and processes that we cannot observe firsthand, but directional changes in the baseline state (climate, air, water, soil, etc.) mean that historical conditions may make poor templates for the future. To compensate, contemporary reference ecosystems that are functioning as we desire should form part of the package of information that underlies restoration and resource management. Given the scale of habitat transformation in many regions, however, managers may need to exercise creativity in finding appropriate reference ecosystems.

## Refocusing management efforts on critical ecosystem processes

Biologists are beginning to recognize that resource-management objectives are better defined as "motion pictures" rather than "snapshots" (Dunwiddie 1992) and that "saving all of the parts" (Leopold 1949) is not necessarily more important than understanding how the parts interact and interrelate (Falk et al. 2006). The HRV concept was developed to ensure that ecosystem functions, especially disturbance processes, were incorporated into management (Morgan et al. 1994; Landres et al. 1999). However, as currently practiced, conservation management often focuses on preservation of specific species, species assemblages, or some relatively static notion of the habitat required to maintain populations. In light of rapid climate change, a different perspective is developing, one that is more focused on management of ecosystem structure and function rather than specific species or their habitat (Hunter et al. 1988; Harris et al. 2006; Hobbs et al. 2006; Stephenson et al. 2010). This perspective emphasizes the ecological function or ecological integrity of a site (Box 4.1), and is less concerned with the identities, numbers, or arrangements of biota.

One version of this perspective focuses exclusively on the physical habitat and the long-term maintenance of landscape features and physical processes as "ecological arenas." This approach concentrates on hydrological, pedological, geological, and pyrological processes, rather than on the temporary biological occupants (species) that are affected by these processes, because history shows that (1) "during periods when climate changes are large, communities are too ephemeral to be considered important biological entities in their own right" (Hunter et al. 1988), and (2) biotic responses to climate change usually occur on a more rapid timeline than those of the physical habitat. In the "ecological arena" approach, the focus of management is maintenance of an ecosystem's "dynamic capacity to respond adaptively" to exogenous influences (Costanza et al. 1993), that is, on its resilience to change (Box 4.1). An important feature of the ecosystem-process perspective is an enhanced emphasis on the provision and maintenance of basic ecosystem services, including those that directly benefit mankind. These include not only essential goods such as food, fuel, and water, but other less tangible benefits such as climate regulation, air and water purification, and soil creation (Box 4.1; Daily et al. 1997). Historical ecology forms a basis for this perspective (e.g. expected levels of ecosystem services are based on historical levels, and "properly functioning" ecosystem processes are only definable with an eye to the past), and a foundation of understanding that will sustain long-term management for ecosystem sustainability as climates and environments continue to change (Hunter et al. 1988; Millar & Woolfenden 1999).

Although the focus of resource management and restoration is per force shifting from the past to the future (Egan & Howell 2001; Harris et al. 2006; Choi et al. 2008), the value of historical information is not reduced; rather, the nature of its value is changed. In North America, management has often sought to recreate patterns characteristic of historic (predegradation) reference conditions, and historical information helped provide a blueprint for the desired outcome. In the future, the management emphasis in many ecosystems will shift from one of historical fidelity to one of ecological integrity, resilience, and delivery of services (Box 4.1; Millar et al. 2007; Stephenson et al. 2010; Cole et al. 2010b). In this changed management environment, the role of historical ecology becomes one of informing a management response to global change rather than resisting global change. Historical ecology can, among other things, identify important broadscale and long-term processes that influence local ecological outcomes under different climate conditions or disturbance regimes; provide clues to mechanisms underlying ecosystem dynamics and resilience (i.e. why have some systems persisted through climatic changes in the past?); guide the development and validation of predictive models; suggest appropriate future trajectories; and inform us if current conditions are anomalous and worthy of management intervention (Tausch et al. 1993; Landres et al. 1999; Millar & Woolfenden 1999; Swetnam et al. 1999; Cole et al. 2010a). In the end, historical ecology represents our clearest window into ecological patterns and processes that occur at temporal scales beyond the scope of human observation.

## 4.5 IS TRADITIONAL REFERENCE CONDITION-BASED MANAGEMENT DEAD?

Although the focus of conservation, restoration, and resource management is understandably shifting from the past to the future, from composition to function, and from equilibrium to dynamism, we believe that management targets based on past, predegradation conditions continue to be worthy goals in some places and contexts. In all cases, however, management targets must be thoughtfully articulated to be robust to uncertainty and compatible with trajectories of global change.

Any projection of future conditions is by definition uncertain. Although calibrated models of climate change agree on a range of plausible future mean temperatures, temperature extremes are impossible to predict with any certainty, and the extremes are often the primary drivers of ecological responses to climate (Easterling et al. 2000). Precipitation predictions vary widely, and for some places, models projecting increased precipitation are balanced by other models predicting decreased precipitation. As many authors have noted, uncertainties in future projections of climate change and its impacts are almost certainly higher than uncertainties in the spatial and temporal accuracy of historical ecological data (Willis & Birks 2006; IPCC 2007a; Keane et al. 2009; Lawler et al. 2010). Thus, the argument has been made that because our understanding of historical ecosystems is usually much greater than that for most novel or emerging ecosystems, setting short-term targets based on known, historic ecosystems may minimize the risk of making things worse (Jackson & Hobbs 2009; Romme et al., Chapter 1, this book). Nevertheless, the key is to understand that projected trajectories for many places will lead beyond the HRV in climate – measured over thousands of years – in the next century (Fig. 4.1; "C" through "E" in Fig. 4.2). Reference condition-based management targets may be better seen as "waypoints" rather than "endpoints" ("E" in Fig. 4.2), where the short-term goal is simply pointing the ecosystem in the right direction via restoration work, but the long-term management goal is ecosystem adaptation to changing conditions.

One of the most frequent climate-adaptation recommendations in the literature (rank 3 of 113 in Heller & Zavaleta 2009) is to focus on the mitigation of ecosystem threats *other* than climate. As Noss (2001) notes, "climate change is not currently the greatest threat to (ecosystems) but adds another layer of stress to species and ecosystems already suffering from poor land-use practices." HRV analysis can help to identify salient departures from past variations in ecosystem composition, and structures and/or functions that are not sustainable under contemporary or projected future climates. Mitigating more proximate ecosystem stressors (disturbance frequencies and severities, fragmentation, invasive species, pollution, habitat degradation) identified in such an analysis may be the preferred course of "least regret" for many ecosystem managers beset by the uncertainty of future trajectories of climate, ecosystems, human populations, budgets, staffing, and politics (Noss 2001; Hannah et al. 2002; Lawler et al. 2010).

Under a changing global climate, a major issue is determining when and where historic ecosystems continue to provide reasonable management targets. A case in point might be relatively stable, "pseudo-equilibrial" ecosystems (e.g. ecosystems driven largely by local, biological interactions) where climate change and land-use change are not projected to greatly alter conditions. Such places do exist, although they may be rare and spatially discontinuous. Examples include "refugial" areas in tropical and temperate rainforest, which are hypothesized to have served as colonization sources for surrounding areas affected by cold or drought during Pleistocene climate changes (Prance 1982; Eeley et al. 1999), or wetland ecosystems in temperate mountains in locations that persisted through earlier dry and/or warm climate periods. High-resolution climate modeling in mountain watersheds suggests that features such as cold-air drainage may act to greatly reduce warming in deep valleys (Dobrowski et al. 2009), and such places may serve as biotic refugia in the future as well.

Another way to extend the value of traditional HRV applications may be to adjust the temporal or spatial theaters of their application to reflect changing conditions. Various authors argue that clinging to static goals based on historical conditions narrowly defined may actually undermine ecosystem resilience and adaptability (Harris et al. 2006; Aplet & Cole 2010). The new challenge is to find historical (or contemporary) information that can provide references for conditions that are relevant to the directional changes underway. For example, Millar and Woolfenden (1999) discuss how the period preceding major Euro-American settlement, a common reference period for restoration, coincided with the so-called Little Ice Age, a relatively cold period from 1400 to 1900 AD (Fig. 4.1). Using historical information on conditions during an anomalously cold period as the reference for restoration and management as we go into a warm period certainly does not make sense. Millar and Woolfenden (1999) suggest the Medieval Warm Period, 900–1350 AD, may provide more relevant information for appropriate management goals in the twenty-first century (see Fig. 4.1). Other authors suggest simply using much longer time spans (e.g. millennia instead of centuries) as reference periods for estimated historical natural variation than are used in current practice (Fig. 4.1; Jackson, Chapter 7, this book).

In some cases, we may also be able to extend the life of certain HRV assessments by redefining the spatial domain to which they apply. For example, Fulé (2008), working in semiarid fire-prone conifer forests in the southwestern United States, suggested that restoration treatments based on historical reference conditions for drier, lower elevation sites could be applied to wetter, higher elevation sites that are predicted to become drier and warmer in the future. This would help facilitate projected changes in vegetation composition and structure and reduce the probability of severe ecosystem disturbance. This "assisted migration" of the restoration target is an application of the "waypoint" rather than "endpoint" point of view ("E" in Fig. 4.2), where the object is to realign the target ecosystem with projected future changes by focusing on a historic reference condition for a different place or different time period that qualitatively coincides with the projected future condition of the target.

## 4.6 CONCLUSION

As the old adage states, "change is constant." In many places, however, land and resource management over the last century has ignored this adage and proceeded as if ecosystems were permanent and historic patterns and processes could simply be recreated or preserved ad infinitum. Although current climate trends are largely a human artifice, and although they portend many negative ecological, social, economic, and political consequences, they also serve to remind us of the dynamism of ecosystems. The assumption of stationarity in most ecological systems is unlikely to get us where we want to be. As climates and ecosystems change, we are likely to have more management success focusing on function rather than form, process rather than pattern, and ecological resilience and integrity rather than on historical fidelity. The use of historical ecology will not and should not diminish, but the use of past reference conditions as static targets, explicit or implicit, will become less and less justifiable as the rapidity of ecological change increases.

To conclude, one thing seems clear: even with a thorough understanding of historical cause and effect, we cannot predict the future with sufficient certainty to avoid mistakes in our management of land and resources. Most human learning is experiential (Kolb 1984) and progresses through trial and error. This militates for the adoption of more experimental management procedures, where different and credible hypotheses of change are translated into different management responses carried out on different parts of the landscape, and responses to these management experiments are thoroughly measured and evaluated. Humans are also tuned more to learn from unexpected than expected outcomes (Zaghloul et al. 2009). One of the lessons of history is that unexpected change and unpredictable outcomes have been driving ecological and evolutionary variability since the beginning of time. Species with the broadest capacity for adaptive response to unexpected change are most often the winners on the evolutionary roulette wheel. As climates and other conditions change, the sustainability of ecosystem patterns and processes will depend on a similar human capacity for adaptive response.

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## REFERENCES

Aber, J.D., Nadelhoffer, K.J., Steudler, P., & Melillo, J.M. (1989). Nitrogen saturation in northern forest ecosystems. *Bioscience*, **39**, 378–386.

Aplet, G.H. & Cole, D.N. (2010). The trouble with naturalness: rethinking park and wilderness goals. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 12–33. Island Press, Washington, DC, USA.

Bakker, J.P., Grootjans, A.P., Hermy, M., & Poschlod, P. (eds.). (2000). How to define targets for ecological restoration? *Journal of Applied Science*, **3**, 1–72.

Bradley, R.S. (2000). Past global changes and their significance for the future. *Quaternary Science Reviews*, **19**, 391–402.

Choi, Y.D., Temperton, V.M., Allen, E.B., et al. (2008). Ecological restoration for future sustainability in a changing environment. *Ecoscience*, **15**, 53–64.

Cole, D.N., Higgs, E.S., & White, P.S. (2010a). Historical fidelity: maintaining legacy and connection to heritage. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 125–141. Island Press, Washington, DC, USA.

Cole, D.N., Millar, C.I., & Stephenson, N.L. (2010b). Responding to climate change: a toolbox of management strategies. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 179–198. Island Press, Washington, DC, USA.

Connell, J.H. & Sousa, W. (1983). On the evidence needed to judge ecological stability or persistence. *American Naturalist*, **121**, 789–824.

Costanza, R., Wainger, L., Folke, C., & Maler, K. (1993). Modeling complex ecological economic systems. *BioScience*, **43**, 545–555.

Craig, R.K. (2010). Stationarity is dead–long live transformation: five principles for climate change adaptation law. *Harvard Environmental Law Review*, **34**, 9–75.

Daily, G.C., Alexander, S., Ehrlich, P.R., et al. (1997). Ecosystem services: benefits supplied to human societies by natural ecosystems. *Issues in Ecology*, **2**, 1–18.

Dobrowski, S.Z., Abatzoglou, J., Greenberg, J., & Schladow, G. (2009). How much influence does landscape-scale physiography have on air temperature in a mountain environment? *Agricultural and Forest Meteorology*, **149**, 1751–1758.

Dunwiddie, P.W. (1992). On setting goals: from snapshots to movies and beyond. *Restoration Management Notes*, **10**(2), 116–119.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., & Mearns, L.O. (2000). Climate extremes: observations, modeling and impacts. *Science*, **289**, 2068–2074.

Eeley, H.A.C., Lawes, M.J., & Piper, S.E. (1999). The influence of climate change on the distribution of indigenous forest in Kwazulu-Natal, South Africa. *Journal of Biogeography*, **26**, 595–617.

Egan, D. & Howell, E.A. (eds.). (2001). *The Historical Ecology Handbook: A Restorationist's Guide to Reference Ecosystems*. Island Press, Washington, DC, USA.

Falk, M.A., Palmer, D.A., & Zedler, J.B. (2006). Integrating restoration ecology and ecological theory: a synthesis. In *Foundations of Restoration Ecology* (ed. M.A. Falk, D.A. Palmer, and J.B. Zedler), pp. 341–345. Island Press, Washington, DC, USA.

Fulé, P.Z. (2008). Does it make sense to restore wildland fire in changing climate? *Restoration Ecology*, **16**, 526–531.

Gunderson, L.H. (2000). Ecological resilience – in theory and application. *Annual Review of Ecology and Systematics*, **31**, 425–439.

Hannah, L., Midgely, G.F., & Millar, D. (2002). Climate change-integrated conservation strategies. *Global Ecology and Biogeography*, **11**, 485–495.

Harris, J.A., Hobbs, R.J., Higgs, E., & Aronson, J. (2006). Ecological restoration and global climate change. *Restoration Ecology*, **14**, 170–176.

Heller, N.E. & Zavaleta, E.S. (2009). Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, **142**, 14–32.

Hobbs, R.J., Arico, S., Aronson, J., et al. (2006). Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography*, **15**, 1–7.

Hobbs, R.J., Zavaleta, E.S., Cole, D.N., & White, P.S. (2010). Evolving ecological understandings: the implications of ecosystem dynamics. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 34–49. Island Press, Washington, DC, USA.

Holland, E.A., Braswell, B.H., Sulzman, J., & Lamarque, J.-F. (2005). Nitrogen deposition onto the United States and Western Europe: synthesis of observations and models. *Ecological Applications*, **15**, 38–57.

Hunter, M.L. Jr., Jacobson, G.L. Jr., & Webb, T. III. (1988). Paleoecology and the coarse-filter approach to maintaining biological diversity. *Conservation Biology*, **2**, 375–385.

Intergovernmental Panel on Climate Change (IPCC). (2007a). *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). (2007b). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, UK.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., et al. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science*, **293**, 629–638.

Jackson, S.T. & Hobbs, R.J. (2009). Ecological restoration in the light of ecological history. *Science*, **325**, 567–568.

Karr, J.R. (1996). Ecological integrity and ecological health are not the same. In *Engineering within Ecological Constraints* (ed. P.C. Schulze), pp. 97–109. National Academy of Engineering, Washington, DC, USA.

Kaufmann, M.R., Graham, R.T., Boyce, D.A., et al. (1994). An ecological basis for ecosystem management. General Technical Report RM-GTR-246. USDA Forest Service, Fort Collins, CO, USA.

Keane, R.E., Hessburg, P.F., Landres, P.B., & Swanson, F.J. (2009). The use of historical range and variability (HRV) in landscape management. *Forest Ecology and Management*, **258**, 1025–1037.

Kelley, D.R. (ed.). (1991). *Versions of History from Antiquity to the Enlightenment*. Yale University Press, New Haven, CT, USA.

Kolb, D.A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Prentice Hall, Englewood Cliffs, NJ, USA.

Koutsoyiannis, D. (2006). Nonstationarity versus scaling in hydrology. *Journal of Hydrology*, **324**, 239–254.

Landres, P.B., Morgan, P., & Swanson, F.J. (1999). Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications*, **9**, 1179–1188.

Lawler, J.J., Tear, T.H., Pyke, C., et al. (2010). Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment*, **8**, 35–43.

Leopold, A. (1949). *A Sand County Almanac – with Essays on Conservation from Round River*. Ballantine Books, New York, USA.

Levin, S.A. (1992). The problem of pattern and scale in ecology. *Ecology*, **73**, 1943–1967.

Littell, J.S., McKenzie, D., Peterson, D.L., & Westerling, A.L. (2009). Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications*, **19**, 1003–1021.

Manley, P.N., Brogan, G.E., Cook, C., et al. (1995). Sustaining ecosystems: a conceptual framework. Publication R5-EM-TP-001. USDA Forest Service, Vallejo, CA, USA.

McNeil, W.H. (1985). Why study history? American Historical Society webpage. http://www.historians.org/pubs/archives/whmcneillwhystudyhistory.htm.

Millar, C.I. & Woolfenden, W.B. (1999). The role of climate change in interpreting historical variability. *Ecological Applications*, **9**, 1207–1216.

Millar, C.I., Stephenson, N.L., & Stephens, S.L. (2007). Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, **17**, 2145–2151.

Millennium Ecosystem Assessment (MEA). (2005). *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, DC, USA.

Miller, J.D., Safford, H.D., Crimmins, M., & Thode, A.E. (2009). Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. *Ecosystems*, **12**, 16–32.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D., & Stouffer, R.J. (2008). Stationarity is dead: whither water management? *Science*, **319**, 573–574.

Moore, M.M., Covington, W.W., & Fulé, P.Z. (1999). Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. *Ecological Applications*, **9**, 1266–1277.

Morgan, P., Aplet, G.H., Haufler, J.B., Humphries, H.C., Moore, M.M., & Wilson, W.D. (1994). Historical range of variability: a useful tool for evaluating ecosystem change. *Journal of Sustainable Forestry*, **2**, 87–111.

Noss, R.F. (2001). Beyond Kyoto: forest management in a time of rapid climate change. *Conservation Biology*, **15**, 578–590.

Peterson, G., Allen, C., & Holling, C.S. (1998). Ecological resilience, biodiversity, and scale. *Ecosystems*, **1**, 6–18.

Prance, G.T. (1982). *The Biological Model of Diversification in the Tropics*. Columbia University Press, New York, USA.

Rabalais, N.N. (2002). Nitrogen in aquatic ecosystems. *Ambio*, **31**, 102–112.

Sanderson, E.W., Jaiteh, M., Levy, M.A., Redford, K.H., Wannebo, A.V., & Woolmer, G. (2002). The human footprint and the last of the wild. *BioScience*, **52**, 891–904.

Savage, M. (1991). Structural dynamics of a southwestern pine forest under chronic human influence. *Annals of the Association of American Geographers*, **81**, 271–289.

Saxon, E., Baker, B., Hargrove, W., Hoffman, F., & Zganjar, C. (2005). Mapping environments at risk under different global climate change scenarios. *Ecology Letters*, **8**, 53–60.

Schoennagel, T., Veblen, T.T., & Romme, W.H. (2004). The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience*, **54**, 661–676.

Sprugel, D.G. (1991). Disturbance, equilibria, and environmental variability: what is “natural” vegetation in a changing environment? *Biological Conservation*, **58**, 1–18.

Stearns, P.N. (1998). Why study history? American Historical Society webpage. http://www.historians.org/pubs/free/whystudyhistory.htm.

Stegner, W. (1992). *A Sense of Place*. Random House, New York, USA.

Stephenson, N.L., Millar, C.I., & Cole, D.N. (2010). Shifting environmental foundations: the unprecedented and unpredictable future. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 50–66. Island Press, Washington, DC, USA.

Swetnam, T.W., Allen, C.D., & Betancourt, J.L. (1999). Applied historical ecology: using the past to manage for the future. *Ecological Applications*, **9**, 1189–1206.

Swetnam, T.W. & Betancourt, J.L. (1998). Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, **11**, 3128–3147.

Tausch, R.J., Wigand, P.E., & Burkhardt, J.W. (1993). Plant community thresholds, multiple steady states, and multiple successional pathways: legacy of the quaternary? *Journal of Range Management*, **46**, 439–447.

Taylor, A.H. & Skinner, C.N. (2003). Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications*, **13**, 704–719.

Vitousek, P.M., D'Antonio, C.M., Loope, L.L., Rejmánek, M., & Westbrooks, R. (1997). Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology*, **21**, 1–16.

Westerling, A.L. & Swetnam, T.W. (2003). Interannual to decadal drought and wildfire in the western United States. *EOS*, **84**, 545–560.

Westerling, A.L., Brown, T.J., Gershunov, A., Cayan, D.R., & Dettinger, M.D. (2003). Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society*, **84**, 595–604.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., & Swetnam, T.W. (2006). Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313**, 940–943.

White, P.S. & Walker, J.L. (1997). Approximating nature's variation: selecting and using reference information in restoration ecology. *Restoration Ecology*, **5**, 338–349.

Wiens, J.A., van Horne, B., & Noon, B.R. (2002). Integrating landscape structure and scale into natural resource management. In *Integrating Landscape Ecology into Natural Resource Management* (ed. J. Liu and W.W. Taylor), pp. 23–67. Cambridge University Press, Cambridge, UK.

Williams, J.W. & Jackson, S.T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, **5**, 475–482.

Williams, J.W., Jackson, S.T., & Kutzbacht, J.E. (2007). Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences*, **104**, 5738–5742.

Willis, K.J. & Birks, H.J.B. (2006). What is natural? The need for a long-term perspective in biodiversity conservation. *Science*, **314**, 1261–1265.

Woodley, S.J., Key, J., & Francis, G. (eds.). (1993). *Ecological Integrity and the Management of Ecosystems*. St. Lucie Press, Delray Beach, FL, USA.

Zaghloul, K.A., Blanco, J.A., Weidemann, C.T., McGill, K., Jaggi, J.L., Baltuch, G.H., & Kahana, M.J. (2009). Human substantia nigra neurons encode unexpected financial rewards. *Science*, **323**, 1496–1499.

Zavaleta, E.S. & Chapin, F.S. III. (2010). Resilience frameworks: enhancing the capacity to adapt to change. In *Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change* (ed. D.N. Cole and L. Yung), pp. 142–158. Island Press, Washington, DC, USA.