Paleoecology and ecosystem restoration: case studies from Chesapeake Bay and the Florida Everglades

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Climate extremes that cause droughts, floods, or large temperature fluctuations can complicate ecosystem restoration efforts focused on local and regional human disturbance. Restoration targets are often based primarily on monitoring data and modeling simulations, which provide information on species' short-term response to disturbance and environmental variables. Consequently, the targets may be unsustainable under the spectrum of natural variability inherent in the system or under future climate change. Increasingly, ecologists and restoration planners recognize the value of the long temporal perspective provided by paleoecological data. Advances in paleoclimatology, including better climate proxy methods and temporal resolution, contribute to our understanding of ecosystem response to anthropogenic and climatic forcing at all time scales. We highlight paleoecological research in the Chesapeake Bay and the Florida Everglades and summarize the resulting contributions to restoration planning. Integration of paleoecological, historic, monitoring, and modeling efforts will lead to the development of sustainable, adaptive management strategies for ecosystem restoration.

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Paleoecology – the study of ecosystem history over various time scales using sedimentary records – provides a unique temporal perspective on patterns, causes, and rates of ecological change due to natural hydrologic and climatic variability, and anthropogenic activity. Traditionally, paleoecological records, coupled with instrument-related records of varying length and quality, have provided firm evidence about the timing and scope of the negative impacts of human activities, such as fertilizer application and nutrient loading (Brush 1984; Cooper and Brush 1991). More recently, paleoecological studies have begun to have a much greater influence than simply documenting trends in ecosystem degradation. First, they provide specific information on pre-anthropogenic baseline levels of variability in biological (eg community structure, diversity), physical (eg salinity, turbidity), and chemical (eg dissolved oxygen) parameters now used to set scientifically rigorous restoration targets for impaired ecosystems (Jackson *et al.* 2001; EPA 2003). Environmental reconstructions use not only fossil assemblage data, but also geochemical proxies for aquatic or atmospheric conditions, allowing direct comparison of biological and physical patterns.

Second, paleoecological research has provided definitive evidence that interannual to multi-decadal temporal variability in both terrestrial and aquatic ecosystems is caused by natural climatic processes, such as the El Niño–Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). Climate variability can be considerable, even in comparison to more regional environmental stressors, and should be incorporated into ecosystem management (Cronin and Walker 2006; Harris *et al.* 2006). The emergence of climate as a driving force for ecosystem management is even more in evidence in the findings of the Intergovernmental Panel on Climate Change (IPCC 2007). The IPCC has concluded that human-induced climate change has already had several impacts: earlier timing of spring events (eg leaf-unfolding, bird migration, and egg-laying), poleward and upward (elevation) shifts in the ranges of plant and animal species, altered ranges of algal, plankton, and fish abundance in high-latitude oceans, and range changes and earlier migrations of fish in rivers. Although much greater uncertainty surrounds future climate change and ecosystem responses, the combined effects of events associated with climate change (eg flooding, drought, wildfire) and anthropogenic drivers of climate change (eg land-use change, pollution, overexploita-

In a nutshell:

- Paleoclimate records show that decadal and longer-term climate variability had major impacts on terrestrial and coastal ecosystems over the past few thousand years
- This variability continues to influence anthropogenically impaired ecosystems
- Natural extremes in precipitation and temperature may override management strategies designed to improve estuarine and wetland water quality and quantity
- Paleoecological records providing baseline data on the predisturbance response of ecosystems to climate variability should be integrated into ecosystem modeling efforts to maximize the likelihood of sustainable ecosystem restoration

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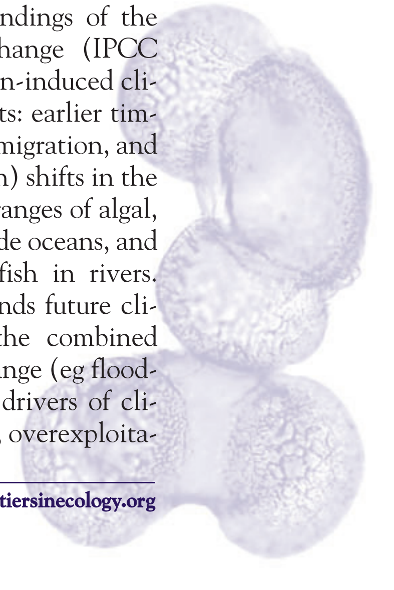

Figure 1. *The Chesapeake Bay watershed, outlined in white, covers 166 000 km^2 and currently hosts a population of > 16 million people. As the nation's largest estuary, the watershed encompasses urban, agricultural, and forested areas in the Atlantic Coastal Plain, Piedmont, and Valley and Ridge Provinces. Restoration efforts to improve water quality and protect living resources are anticipated to cost more than $18 billion by the year 2010 (Chesapeake Bay Commission 2003).*

tion of resources) are likely to overwhelm the resilience of many ecosystems in the next century (IPCC 2007).

Third, many ecosystem restoration and management programs rely heavily on modeling to forecast ecosystem responses to various management options. Paleoecological data, in conjunction with model development, are now used to calibrate climate models analyzing the dynamics of human activity and regional climate, and to establish baseline targets for water quality and quantity (EPA 2003; Marshall *et al.* 2004, 2006). This paper summarizes the contributions of paleoecological and paleoclimatic reconstructions to restoration planning for two premier ecosystems in the eastern US: the Chesapeake Bay, the largest estuary in the nation, and the Florida Everglades, the largest freshwater wetland in the nation.

■ Impacts of climate variability on ecosystems

Patterns of ecosystem responses to natural climate variability during the late Holocene provide relevant information on the impacts of a range of climate conditions on extant species and communities. Changes in global climate over tens to hundreds of thousands of years are caused by changes in Earth's orbital shape (eccentricity), tilt (obliquity), and precession (change in direction of Earth's axis), which all influence the seasonal and geographic distribution of incoming solar radiation. This is the well-known Milankovitch theory of climate change, which strongly influences glacial-interglacial oscillations in global temperature, sea level, ice sheets, and other aspects of the climate system. In contrast, climate changes of the past 2000 years are particularly suited to the purpose of examining short-term climate variability, because they encompass a time when orbital influences are minimal. Climate variability over the past two millennia is dominated by climate processes such as interannual and decadal patterns in ENSO (various indices including the Southern Oscillation Index [SOI]), the NAO (Hurrell *et al.* 2003), AMO (Enfield *et al.* 2001), and the PDO (Barnett *et al.* 1999), as well as volcanic and solar processes. These processes are known as climate forcing agents. Late Holocene climate variability influenced temperature, precipitation, and atmospheric–oceanic interactions on interannual and decadal time scales to varying degrees in different regions. Interactions among these patterns serve to amplify or dampen climate response in complex, partially understood ways. For example, positive AMO periods are consistently associated with greater-than-normal drought frequency in the US, but the PDO phase during a positive AMO phase influences the location of the most severe droughts (McCabe *et al.* 2004). Likewise, NAO variability has a large impact on mid-Atlantic Chesapeake Bay-region winter temperature and precipitation, whereas ENSO strongly influences south Florida winter precipitation.

Although the complexities and interactions of these climate drivers are partially understood, the superposition of anthropogenic atmospheric greenhouse forcing on already complex processes makes the study of climate–ecosystem linkages especially difficult (Jones and Mann 2004). The ecological community has begun to recognize the critical importance of climate variability in driving terrestrial, shallow marine, open-ocean, and tropical-reef ecosystems. Here, we discuss reconstructed climate variability in the Chesapeake Bay and south Florida regions and the implications for future ecosystem management.

■ Environmental degradation and restoration in Chesapeake Bay

In the Chesapeake Bay watershed, extensive agriculture, urbanization, and a rapidly growing population have put major stresses on water quality in rivers, tributaries, and the Bay itself (Figure 1). Before European colonization of North America, large populations of Native Americans occupied the watershed, subsisting primarily on food obtained through foraging, hunting, and (after ~ 1000 years ago) maize agriculture (Smith 1989). These lifestyles had minimal impact on land cover, in contrast to the substantial changes made by European colonists. The clear-

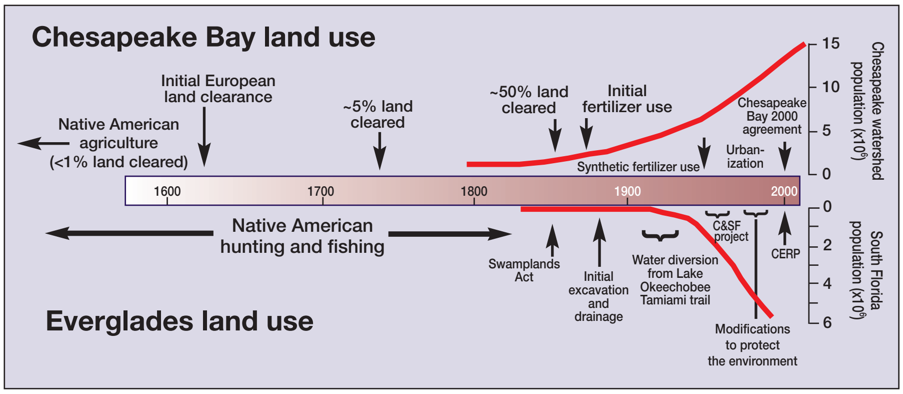

Figure 2. *Timeline of land-use activities in Chesapeake Bay watershed and Florida Everglades. Although Europeans colonized the Chesapeake Bay watershed in the early 17th century, their largest impacts began in the late 19th century, when > 50% of land was cleared. In the Everglades, two phases of water management (~ 1900–1930 and post-1950) and a rapidly growing population greatly altered the ecosystem during the 20th century. Populations in Chesapeake Bay watershed and south Florida were calculated using census data available at the University of Virginia Historical Census Browser (http://fisher.lib.virginia.edu/collections/stats/histcensus/).*

ance of up to 80% of forests, peaking in the late 19th century (Figure 2), increased erosion and downstream sedimentation and decreased water clarity in the Bay. Even as some agricultural land became reforested, increased fertilizer use and urbanization in the late 20th century exacerbated water quality concerns (Willard *et al.* 2003).

Chesapeake Bay became the target of restoration efforts in 1983, when the Chesapeake Bay Program (CBP) was formed and agreements were reached to reduce the excess nutrient influxes that cause algal blooms and decrease dissolved oxygen in the estuary. More recently, the Chesapeake 2000 agreement was signed by government representatives from Washington, DC, and each state in the watershed, as a commitment to restore and sustain Chesapeake Bay and its resources. This plan aimed to define water-quality criteria to protect aquatic living resources and to develop targets for total maximum daily loads (TMDLs) for nitrogen, phosphorus, and sediment.

Baseline variability: dissolved oxygen and sturgeon in Chesapeake Bay

One of the most severe environmental problems in Chesapeake Bay is seasonal development of hypoxia and anoxia in the deep channel, which often extends to shallower waters as a result of winds and tides (Boynton *et al.* 1995). Hypoxia/anoxia has long been attributed to enhanced nutrient fluxes from the watershed, and paleoecological evidence from multiple proxies substantiate the hypothesis that this phenomenon did not exist during the colonial and pre-colonial periods (Brush 1984; Cooper and Brush 1991; Cornwell *et al.* 1996; Karlsen *et al.* 2000; Adelson *et al.* 2001; Zimmerman and Canuel 2002; Bratton *et al.* 2003; Colman and Bratton 2003).

The process of defining acceptable target levels of dissolved oxygen (DO) highlights the challenges facing environmental managers and the advantage of paleoecological data to support resource management decisions. In 2003, the Chesapeake Bay Program convened a group of experts, including ecologists, hydrologists, and paleoecologists, to define TMDLs for DO levels in designated-use areas of the estuary. The group focused particularly on the deep channel of the estuary, because seasonal hypoxia first develops there, and because it was considered an important potential habitat for the anadromous short-nosed sturgeon (*Acipenser brevirostrum*, an endangered species) and the Atlantic sturgeon (*Acipenser oxyrhynchus*). Both species are native to Chesapeake Bay and were commercially valuable until populations declined in the 20th century. At issue was whether anoxia (or hypoxia) was a "natural" phenomenon in the deep channel of the Bay and the appropriate restoration targets for DO in light of concerns about sturgeon, which had recently been reported in the deep channel.

With input from researchers who had reconstructed long-term DO proxy records from sediment cores (Figure 3), the panel reached the consensus that Chesapeake Bay had probably been seasonally anoxic during some years between 1900 and 1960, before major fertilizer application in the watershed, especially in the deep channel where hypoxic/anoxic conditions may have persisted for several months. Anoxia during this period was probably geographically less extensive and less frequent than after the 1960s. These conclusions were supported by very limited observational data from the early 20th century. Seasonally anoxic conditions (lasting weeks to months) probably occurred periodically in the deep channel between 1600–1900 AD. Before European colonization (~ 1600 AD), the deep channel of the Bay may have been briefly hypoxic (< 2 mg l^{-1}) during relatively wet periods (which were common, according to the paleoclimate record; Figure 4) and anoxic only during exceptionally wet conditions. Because the late 16th and much of the 17th century were characterized by extremely dry climate, conditions were not conducive to oxygen depletion.

Based on understanding of nutrient influx, oxygen depletion, and hydrodynamics of the Bay, it was deemed unlikely that the deep channel could be restored to mid-20th century conditions under reasonable nutrient reduction targets. Additional factors making restoration difficult were remnant nutrients locked in sediments in the Bay and behind dams, expected increases in precipitation due to climate change, and rapid local and regional population growth. Most researchers believed that restoring the Bay to conditions prior to 1900 was not realistic, because the tem-

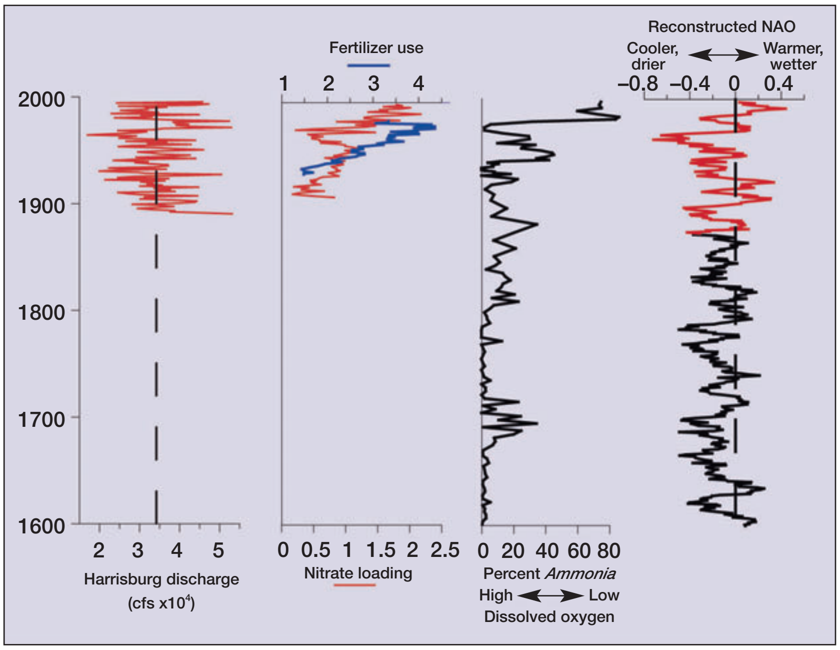

Figure 3. *Natural extremes in precipitation influence the effectiveness of management efforts to improve estuarine water quality. Instrumental (red and blue lines) and proxy-based (black lines) records of: (a) fluvial discharge at Harrisburg, Pennsylvania; (b) fertilizer use in the Chesapeake Bay watershed (blue line) and nitrate loading to Chesapeake Bay (red line); (c) dissolved oxygen based on abundance of* Ammonia, *a hypoxia-tolerant benthic foraminifer; (d) North Atlantic Oscillation Index reconstructed from tree-rings. Although fertilizer use increased steadily throughout the late 20th century, nitrate loading decreased during low-discharge years of the 1970s. (a–c) adapted from Karlsen* et al. *(2000); (d) adapted from Cook* et al. *(2002).*

poral variability (year-to-year and decadal) in "naturally occurring" hypoxia, the irreversible effects of land use, nutrient cycling, and sedimentary processes all rendered a single-target DO level impossible to define.

These results have obvious implications for whether, or when, the deep channel had been suitable habitat, particularly for sturgeon, and for the baseline period to be chosen for DO restoration targets in general. Because of such complexities, and because paleoecological proxies are not yet precise enough to specify the duration of annual anoxic/hypoxic events, an intermediate target value was selected (EPA 2003). These issues illustrate just some of the challenges, uncertainties, and assumptions of ecosystem restoration and the value of retrospective paleoecological data.

Chesapeake Bay water quality and climate variability

As a partially mixed estuary, density-driven circulation in Chesapeake Bay is influenced primarily by variability in regional rainfall and freshwater river inflow over seasonal, interannual, and longer time scales, and secondarily by tides, winds, and bathymetry (Boicourt *et al.* 1999). The Susquehanna River contributes more than 50% of river discharge into the Bay, and discharge is positively correlated with regional rainfall (Najjar 1999) and salinity in the Bay (Gibson and Najjar 2000). Therefore, precipitation is a primary driver of salinity gradients, turbidity (due to sediment influx), in situ biological production, dissolved nutrient loadings, primary productivity, dissolved oxygen, and the distribution of salinity-sensitive species. Intervals of extreme drought or high precipitation therefore have major impacts on estuarine water quality, and sustainable restoration goals must incorporate the variability inherent in the system.

In the same way, periods characterized by unusually warm or cool temperatures influence the distribution of phytoplankton, fish, and other living resources in the Bay and watershed. The late Holocene records of Chesapeake paleotemperature, based on magnesium/calcium ratios in ostracode shells, and precipitation, based on oxygen isotope ratios ($\delta^{18}O$) in benthic foraminiferal shells from sediment cores, are shown in Figure 4. It should be emphasized that geochemical proxies from Chesapeake calcareous microfossils (and most proxy methods used in paleoclimate research) undergo careful, quantitative calibration using modern environments and verification through comparison with the instrument records. Oxygen isotopes are widely used in estuarine and marginal marine sediments to estimate past salinity.

Microfaunal analyses from Chesapeake Bay show large fluctuations in spring water temperatures throughout the past 2000 years, with especially cool temperatures during parts of the Little Ice Age (LIA; 1500–1900 AD), and warmer temperatures during the early Medieval Warm Period (MWP; 800–1200 AD) and the 20th century. In fact, short-term temperature extremes over the past 150 years are among the warmest of the past two millenia (Figure 4). Precipitation also varies greatly at multi-decadal time scales, and the 20th century has undergone periods of extremely wet climate (Cronin *et al.*, 2000, 2005). Extended droughts, reconstructed from sediment cores, confirm the evidence for regional droughts based on tree-ring records (Stahle *et al.* 1998). One important conclusion from paleoclimate studies is that Holocene precipitation patterns in the mid-Atlantic region are clearly linked to hemispheric climate patterns, particularly atmospheric changes in tropical regions (Cronin *et al.* 2005; Willard *et al.* 2005). Climate model simulations of future greenhouse gas-induced changes in ocean and atmospheric circulation therefore have a bearing on the potential range of regional climate changes that can be expected in the eastern US.

These developments are relevant to several management issues. Collectively, the proxy data indicate that, in addition to the overriding influence of human activities during the past 200 years, as seen in diatoms (Cooper and Brush

1991), dinoflagellates (Willard *et al.* 2003), biogenic silica (Bratton *et al.* 2003), molybdenum (Zheng *et al.* 2003), benthic foraminifera (Karlsen *et al.* 2000), and ostracodes (Cronin and Vann 2003), climate variability continues to exert a major influence on Bay ecosystems, even in their current, degraded state. The high flow rates of the 1970s and 1980s exacerbated the impact of increasing fertilizer usage and nutrient input (Figure 3), leading to unprecedented levels of hypoxia and anoxia in the main channel and increased sediment fluxes. It is therefore important to realize that extreme climate events or decadal-scale shifts in precipitation have the potential to override management actions designed to improve water quality and other environmental parameters. Likewise, as discussed below, land-use changes may alter regional patterns of precipitation and temperature variability. Consideration of the potential interactions of land-use and climate change should be an important component of ecosystem-management decisions.

Taken together, the paleo- and instrumental records greatly improve our understanding of multiple causes of temporal patterns of Chesapeake anoxia and other environmental parameters and demonstrate the value of long-term records. They settle a contentious, decades-long debate on whether the Bay had previously experienced long-term increases in hypoxia (reviewed in Hagy *et al.* [2004]). The data are also directly relevant to current management efforts to restore the Bay. In 2003, the Chesapeake Bay Program was criticized for lack of progress in Bay restoration in two popular books (Ernst 2003; Horton 2003). The criticisms focused mainly on political and societal aspects of restoration efforts, which did not attain desired goals, as measured by indicators such as seagrass coverage and volume of hypoxic water in the bay. However, if restoration goals and timetables do not incorporate decadal extremes in climate, it is unrealistic to expect improvements in a climate–precipitation-driven system when wet conditions persist, even if nutrient reduction is accomplished. The notion that there are "normal" or average years is inconsistent with evidence about climate variability. Today, the CBP forecasting effort recognizes that summer winds, excessive precipitation, or extreme storm events can lead to inaccurate forecasts. The relative impacts of land-management actions and uncontrollable climatic processes on restoration progress must continually be evaluated in light of past and future changes.

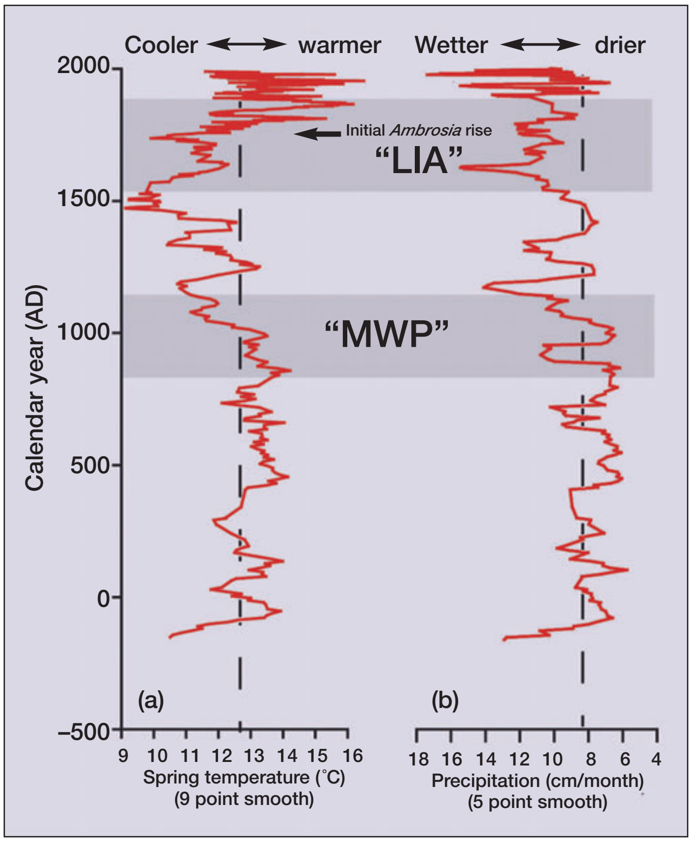

Figure 4. *Large, multidecadal-scale fluctuations in temperature and precipitation are an integral part of the eastern US climate system, as demonstrated by proxy-based reconstructions of: spring temperature (˚C) and precipitation (cm month^{-1}) for the past 2200 years in Chesapeake Bay. Temperature reconstructions are based on Mg Ca^{-1} analyses of ostracode shells (*Loxoconcha*; from Cronin* et al. *[2005]), and precipitation reconstructions are based on δ^{18}O values from benthic foraminifers (from Saenger* et al. *[2006]). The initial* Ambrosia *rise at this site occurred ~ 1750 AD.*

■ Florida Everglades: hydrologic changes and environmental degradation

In the Florida Everglades and Florida and Biscayne Bays, land-use and water management practices dating as far back as the late 19th century have changed the distribution and composition of plant and animal communities throughout the system. The "pre-drainage" (pre-1900) Everglades were influenced primarily by seasonal rainfall and underlying topography. Overflow of water from Lake Okeechobee during the wet season produced seasonal sheet flow across the Everglades, draining into Florida Bay and Biscayne Bay. Wetland hydroperiods and water depths and estuarine salinity were primarily a function of precipitation. Human alteration of the natural hydrologic patterns of the Everglades began in the early 20th century, with construction of canals and the Hoover Dike around Lake Okeechobee (Light and Dineen 1994; Figure 2). A second wave of canal and levee construction in the 1950s and 1960s substantially changed the quantity and seasonality of freshwater flow through the wetland and fragmented the ecosystem. By the early 21st century, the spatial extent of the Everglades wetland had been reduced by approximately one half (Lodge 2005; Figure 5).

These land-use changes also affected water delivery from the Everglades to adjacent marine ecosystems in the Florida and Biscayne Bays. Hypersalinity and the resulting seagrass die-offs in Florida Bay were of particular concern and were attributed to decreased runoff of freshwater from canal building and water management (Robblee *et al.* 1991). In addition, increased nutrient loading from

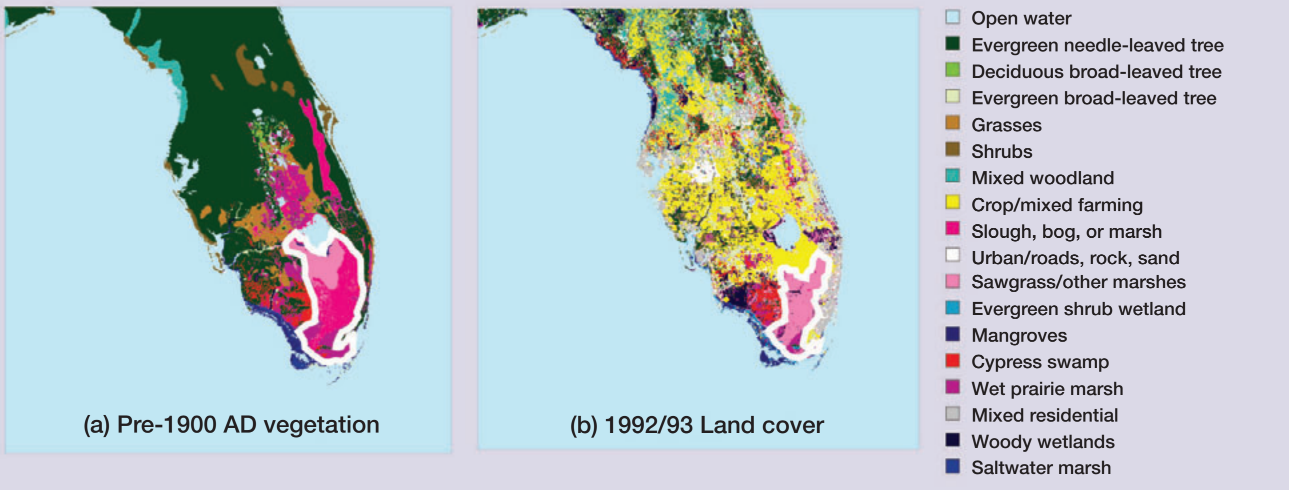

Figure 5. *The Florida Everglades occupy ~ 10 000 km^2 on the southern tip of Florida. Extensive land-cover changes since the early 20th century substantially changed wetland hydrology, plant community distribution, and substrate characteristics. The white line indicates the extent of the freshwater Everglades wetland (modified from Lodge 2005; Marshall* et al. *2004). (a) Reconstruction of pre-1900 AD vegetation is based on a combination of paleoecological proxies and historical references. (b) 1992–1993 land cover was derived from satellite images and modern vegetation maps. Modeling simulations indicate that land-cover changes alone were sufficient to increase diurnal temperature variability and decrease summer rainfall (Marshall* et al. *2004).*

agricultural land use may have changed estuarine ecosystems from clear-water systems with abundant benthic primary production to systems with high turbidity and increased frequency of algal blooms (Rudnick *et al.* 2005).

The degradation of wetlands and associated loss of wildlife resulted in the passage of the Everglades Forever Act in 1994, which aimed to restore healthy ecosystem function to the Everglades. More recently, recognition that the health of the greater Everglades ecosystem and the quality and availability of water affected the economy and culture of south Florida prompted the Comprehensive Everglades Restoration Plan (CERP) to restore natural hydroperiods, seasonality, and connectivity of the ecosystem through modification of existing water-control structures.

Everglades climate variability and relevance for ecosystem model development

One of the tenets of Everglades restoration planning is to "get the water right" (Sklar *et al.* 2005), based on the assumption that restoration of historic water flow and quality will result in restoration of pre-drainage vegetation and landscape structure. Pollen-based reconstruction of Everglades hydrologic variability over the past 2000 years indicates that the system fluctuates between severe droughts and wet conditions. During these droughts, deep-water slough vegetation was replaced by drought-tolerant species and moderate hydroperiod marshes (such as during the MWP; Figure 6). In some cases, the system was resilient enough to recover to pre-drainage states within a few decades, but in others, droughts triggered long-term development of different communities, such as tree islands and sawgrass ridges (Bernhardt *et al.* 2004; Chmura *et al.* 2006; Willard *et al.* 2006).

Everglades pollen assemblages from the past 2000 years generally indicate that pre-drainage hydroperiods were longer and water depths greater than in the modern wetland. This translated into greater delivery of freshwater and lower salinities in the estuaries before the onset of water management, which is confirmed by molluskan and benthic foraminiferal assemblages from Florida Bay (Brewster-Wingard and Ishman 1999) and molluskan assemblages from the freshwater–saltwater ecotone near Biscayne Bay (Gaiser *et al.* 2006). Comparison of proxy-based estimates of pre-drainage salinity and hydroperiod with ecosystem model-based predictions indicates that the models consistently predict higher salinity and shorter hydroperiod than the paleoecological data (Pitts 2006). Thus, proxy evidence is increasingly used to validate and modify existing models and plays an important role in establishing hydrologic targets for the entire ecosystem (Sklar *et al.* 2005). One example is the Natural Systems Model, which is designed to simulate the hydrologic behavior of the pre-drainage Everglades based on recent records of precipitation and other climate parameters (Marshall *et al.* 2006).

Paleoecological evidence has also been critical in understanding the feedbacks between land-cover change and regional climate. To determine whether reported 20th-century increases in temperature and decreases in precipitation could have resulted, at least in part, from the extensive hydrologic changes, a series of climate modeling experiments were undertaken. Pollen data and historic records were used to reconstruct pre-1900 land-cover characteristics (hydroperiod, water depth, substrate) for the entire Florida peninsula. Using the Regional Atmospheric Modeling System (RAMS), a coupled mesoscale atmospheric–ecosystem dynamics model, the pre-drainage dataset was compared with the equivalent dataset from

1993 (Marshall *et al.* 2004; Figure 5). Results of the experiments indicate that land-cover changes alone were sufficient to decrease summer precipitation by 10–12%, with an accompanying increase in diurnal temperature variability (Marshall *et al.* 2004). These results imply that successful restoration of the pre-drainage hydrology and vegetation will further alter diurnal temperature variability and annual precipitation totals, affecting wetland hydrology and estuarine salinity. Acknowledgement of the potential interactions between land-cover change and climate is an integral part of adaptive management aimed at optimizing chances for a sustainable restoration strategy.

■ The role of time in restoration planning

Increasingly, ecologists and resource managers recognize that restoration targets based on monitoring data and modeling simulations alone may not be sustainable under the natural spectrum of climate variability. There are many uncertainties in restoration science, from the future human population and its utilization of the watershed, to the location and frequency of monitoring compliance with TMDLs, to our technological ability to implement engineering strategies (Sklar *et al.* 2005). Paleoecological analyses offer a way to minimize uncertainty in the timing, rate, and magnitude of ecosystem response to a variety of anthropogenic and climate forcings by greatly extending the period of record for environmental observations (Jackson *et al.* 2001). Specifically, by documenting the baseline levels of variability inherent in an ecosystem, one can maximize the likelihood that restoration targets are sustainable. The natural variability of a system reflects the impacts of climate processes operating on a variety (sub-annual to multidecadal and longer) time scales. Modulation of precipitation, which has a fundamental role in controlling water quality and quantity, on these kinds of time scales makes it critical to continually evaluate ecosystem responses to land-management actions. In sum, paleoecological records, used to evaluate, calibrate, and modify ecosystem and climate models, are essential to reduce uncertainties and risks inherent in adaptive-management strategies. The temporal perspective of paleoecology forces environmental managers and engineers to adopt their approach to land-use management by anticipating the longer-term and less predictable climatic and sea-level changes from climate variability and human-induced climate changes.

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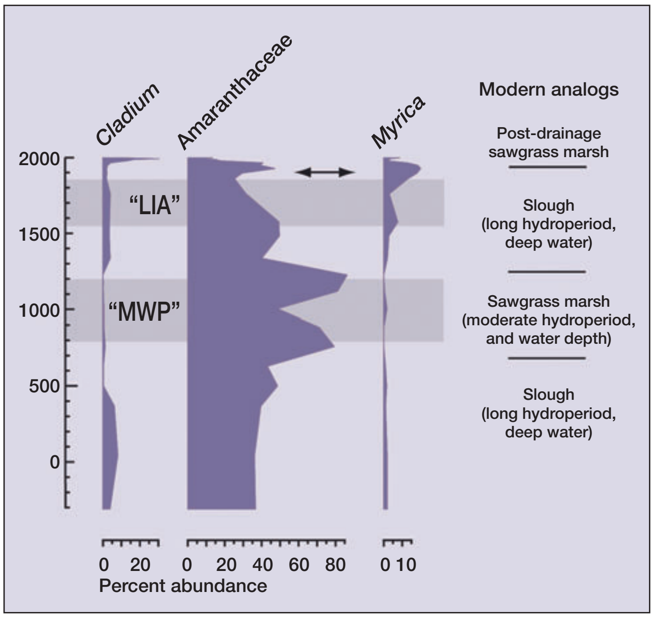

Figure 6. *Pollen evidence for vegetation change in Florida Everglades. Percent abundance of* Cladium *(sawgrass),* Amaranthaceae *(water hemp), and* Myrica *(wax myrtle) pollen, site 3A15, Water Conservation Area 3A, Florida. Double-headed arrows indicate timing of initial 20th-century water diversion. The peak abundance of Amaranthaceae between ~ 800 and 1200 AD indicates lower water levels and shorter hydroperiods during a sustained interval of drought. The shifts between long and moderate hydroperiod wetlands highlight the resilience of slough vegetation to natural fluctuations in climate. Modern analogs and estimated hydroperiod are based on comparison with a surface sample database (modified from Willard* et al. *2001).*

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