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Climate change and biological indicators: detection, attribution, and management implications for aquatic ecosystems

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Climate change is a complex phenomenon that affects the physical, chemical, and biological factors that constitute the intricate ecosystems of the world. Aquatic ecosystems will change in response to climate-induced changes in hydrological regimes, precipitation, and temperature, and these responses are likely to be confounded with responses to changes in land use. Water-resource managers must sort out these impacts for effective decision-making. This challenge may be overwhelming for environmental managers, who already are assessing causes of degradation caused by multiple other stressors. Effective policy and management decisions require use of relevant science (Scarlett 2010), but the interacting effects on aquatic ecosystems of climate change and physical alterations, such as dams, water diversions, land development, and other human infrastructure, have not been explored at global scales (Palmer et al. 2008), nor have the interacting effects of climate change, physical alterations, and pollutants been addressed. Assessments of ecosystem and species trends and their links with climate trends in the context of multiple stressors are needed (Karl et al. 2009). Nevertheless, environmental managers must make decisions. Thus, the challenge is to inform this decision-making process with the best-available science that accounts for complex ecosystem responses to climate change.

Regulatory agencies promulgate protective standards for many chemicals, native biological communities, and physical-habitat structure to protect the environment and human health. Climate change can affect these standards and the baseline conditions used to determine them. Thus, climate change has become an important consideration in environmental management (Hamilton et al. 2010a). Environmental standards for chemicals generally are derived at a national (e.g., US Environmental Protection Agency [EPA] or Environment Canada) or supranational (e.g., Environmental Council for all European Union [EU] Member States or the World Health Organization) level. Ambient and discharge standards for water-quality protection typically are developed at the local, state, or provincial level, as are the protocols for assessing aquatic ecosystem conditions and uses. The range of climate factors to be considered when setting these standards is broad. Climate change could influence chemical standards for environmental and human health at 2 points: during derivation of the standard or during monitoring for compliance with that standard (Crane et al. 2005). Similar points of influence exist for biological standards. Climate change could affect biological indicators, interpretation of metrics and site condition, and monitoring. The papers in this special issue address these points of influence and highlight some of the challenges and paths forward.

Use of biological indicators is becoming more prevalent throughout the world as negative effects from multiple and cumulative stressors are considered more frequently (Dolédec and Statzner 2010). Biological responses to climate change probably will influence water-quality standards and biological criteria through shifts in baseline conditions. Climate change can affect these conditions directly by causing

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shifts in the biological communities at reference locations, thereby altering the characterization of expected levels of ecological integrity. The cascading effects of climate-change-related trends in temperature and precipitation on watershed conditions, water quality, and aquatic biological communities will lead to shifting, most often degrading, baseline conditions (Hamilton et al. 2010b). As a result, standards based on conditions at reference sites might become too low to protect aquatic resources adequately. The challenge to scientists is to determine how bioindicators will be affected by climate change in the presence of multiple stressors and to communicate this information effectively to decision-makers to improve environmental outcomes.

Incorporating Results of Climate-Change Research into Decision-Making

Effective use of results of climate-change research when formulating policies and making decisions is a global challenge. The EU has developed research projects addressing climate change (http://ec.europa.eu/environment/water/adaptation/) and has fostered international collaboration to pursue research questions that will provide a sound scientific foundation for decision-making. Outside of the EU, other countries are establishing their own research agendas. These programs include the Department of Climate Change and Energy Efficiency in Australia (http://www.climatechange.gov.au/) and the US Global Change Research Program (http://www.globalchange.gov/).

The EU has launched several research programs to support policy-making at all levels and to put their sophisticated impact-assessment and monitoring tools at the disposal of all European stakeholders (http://ec.europa.eu/environment/climat/studies/). A small subset of this research is included in the series of papers in this issue. The EU depends upon reliable research to inform international treaty negotiation, such as occurred with the Kyoto Protocol, and to provide an authoritative scientific basis for community policy in fields as diverse as tourism, industry, health, and transport. Thus, having the proper communication network is crucial to transferring knowledge from these research studies to a diverse set of stakeholders. The ultimate goal of the EU is to find a sustainable balance between the environment and the day-to-day decisions made by industry, commerce, and Europe's citizens through coordinated and integrated research. This balance requires good communication and effort to promote awareness. More than 19 countries are involved in coordinated scientific research and implementation of adaptation and mitigation strategies in the EU, and the EU has made substantial efforts to communicate its research results from teams of scientists to policy makers across the EU consortium of nations.

The US has increased its focus on decision-relevant research (at local, state, and national levels) on effects of climate change (Karl et al. 2009). New programs and initiatives from across federal agencies exemplify this focus. For example, the Department of Interior (DOI) is establishing 8 Climate Change Response Centers across the US and is coordinating the creation of Landscape Conservation Cooperatives (LCCs). These LCCs will strive to integrate climate-change-related activities among all US federal agencies, state and local partners, and the general public, and will promote development of landscape-level strategies to address effects of climate change. Promoting awareness of climate change and its effects on the land and water of the US will be facilitated by coordination among the LCCs. Another example is the National Water Program of the US Environmental Protection Agency (EPA), which has developed a strategic plan for incorporating consideration of and response to effects of climate change in its decision-making, research, and regulatory activities (USEPA 2008).

Evaluating the Link between Climate Change and Biological Indicators of Aquatic Systems

The series of papers in this special issue contributes to our knowledge of the responses of aquatic ecosystems to climate change. The papers cover responses at different biological levels and spatial scales from several continents. They illustrate the scientific challenges associated with attributing the effects of climate change on ecosystems, interactions of climate change and other stressors, and adjustments to baseline conditions. The series has 3 themes: 1) changes and prediction of shifts in community composition in response to climate change, 2) shifts in functional responses (traits composition) of taxa to climate change, and 3) biological responses to the interactive effects of climate change and other stressors and their implications for ecosystem management.

Authors of papers addressing the 1st theme focused on biological communities and emphasized benthic macroinvertebrates in streams and rivers in the US, England, and Portugal. Herbst and Cooper (2010) described the effects on benthic invertebrate assemblages of snowmelt flooding of small streams in the Sierra Nevada Mountains of eastern California. Intense flooding caused by rain-on-snow events severely affected assemblages in streams damaged by livestock grazing but not assemblages in reference streams. Assemblages in small, high-mountain streams were resilient to the large rain-on-snow events that are predicted from climate change in this region, although collectors and other mobile species may increase in response to sediment flushing and commensurate increases in organic matter in degraded streams. Thus, headwater streams might be refugia from climate change and sources for recolonization for downstream reaches, where such flooding can be more disruptive to the biological community.

Durance and Ormerod (2010) investigated the effects of climate change on small populations of sympatric planarians in upland Welsh streams, where interspecific competition and prolonged climatic events interacted to favor one species over the other. Interactions among species and between climate and ecological processes are key to understanding observed changes in biodiversity over time. Changes in biodiversity might influence metrics used to define ecological status of streams. Hamilton et al. (2010b) used several regionally distributed state bioassessment data sets to demonstrate that many metrics used for site-condition assessments have demonstrable sensitivities to temperature, as well as to the conventional pollutants they are used to detect. They described a way to address the potential for confounding of temperature and pollutant effects and to identify impairment caused by changing climate conditions. Climatic events and human disturbance also can interact to affect macroinvertebrate assemblages. Feio et al. (2010) evaluated the benthic macroinvertebrate assemblage along a condition gradient in a Mediterranean temporary stream to determine the relative influence of these 2 stressors. The structure of assemblages was more stable in the more-diverse, reference-condition sections and in the less-diverse, poorest-condition sections of the stream than in mildly disturbed sections, which were most responsive to climatic patterns. Feio et al. (2010) suggested that a shift in community equitability precedes species elimination and that this shift in equitability could be used as an early warning for loss of biodiversity because of disturbance or climatic change.

Authors of papers addressing the 2nd theme focused on use of taxon traits as indicators of climate change. Traits-based analyses can be used diagnostically to distinguish changes caused by climate from changes caused by other stressors. Stamp et al. (2010) found that thermal-preference traits could be used to establish expectations for future responses to climate change. Their results suggest that thermal-preference metrics might be used in biomonitoring to distinguish responses to climate change from responses to other stressors. Traits other than thermal preference also might be affected by climate change. Lawrence et al. (2010) used a long-term data set to examine macroinvertebrate responses to climate change in mediterranean-climate streams. They detected differences in distributions of 2 biological trait states common among relatively large, long-lived organisms (semivoltine life cycle, maximum body size >40 mm) between cool and warm years and between wet and dry years. These traits were more useful than conventional indices for detecting and monitoring climate effects on macroinvertebrate assemblages. Long-term changes in temperature and runoff will alter conditions in reference streams, particularly in the western US. Poff et al. (2010) showed that environmental variables explained a large proportion of total trait variation across the western US and that catchment-scale climatic and hydrologic variables explained 19% of total trait variation in their study system. Thus, sites that support a high proportion of temperature- or flow-sensitive taxa will be most vulnerable to predicted climate changes.

Authors of papers addressing the 3rd theme focused on the implications of climate change for management of aquatic resources. Nichols et al. (2010) analyzed a 15-y data set from reference (high ecological condition) and test (lower ecological condition) sites in the Australian Alps to evaluate whether current biological metrics could distinguish sites in reference condition from lower-quality sites in the presence of a small but significant trend in temperature and humidity. Reference condition in this region of Australia has not changed despite a small, progressive change in climate, and the bioindicators chosen to detect ecological impairment were unaffected by the changes in climate.

Evidence of recovery of ecosystems from past stressors also might be confounded by responses to climate change. Johnson and Angeler (2010) analyzed data from a long-term study of phytoplankton and littoral macroinvertebrate assemblages in boreal lakes recovering from acidification and lakes that were minimally disturbed. Their goal was to compare pathways and trajectories of lake communities as climate changed. Phytoplankton assemblages responded strongly to interannual variability in climate (e.g., North Atlantic Oscillation, water temperature). Changes in both assemblages were more strongly correlated with interannual variability in climate than with variability in water chemistry, a result suggesting that the influence of climatic variability on communities is poorly understood.

Verdonschot and van den Hoorn (2010) showed that discharge dynamics and attributes of the macroinvertebrate assemblage, such as rheophily and saprobity, were significantly correlated. They then used projected effects of temperature and precipitation change on discharge dynamics to predict the effects of climate change, changes in land use, and stream restoration on macroinvertebrates in lowland streams in northwestern Europe. They found that restoration of streams impaired by different land uses can reduce effects of climate change on lowland stream ecosystems. Pearlstine et al. (2010) reviewed ecological and management consequences to the Everglades (USA) from climate change and considered the ecological implications for different assemblages critical to the Everglades ecosystem. They described management strategies for adapting to climate change.

The papers in this series further our understanding of the influence of climate change on the ecology of aquatic ecosystems and highlight key issues and areas of concern. One key implication is that efforts already under way to protect aquatic resources or restore water bodies already exposed to multiple stressors might be confounded by alterations in climate. We hope that benefits from this series of papers will be realized in the following ways: 1) our understanding of effects of climate change on aquatic ecology will be enhanced, 2) these studies will serve as a foundation for additional research to refine our understanding of climate change and its ecological effects, and 3) environmental managers will see applications to their water-resource programs.

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