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ABSTRACT

The North Atlantic Landscape Conservation Cooperative LCC (NA LCC) is a public–private partnership that provides information to support conservation decisions that may be affected by global climate change (GCC) and other threats. The NA LCC region extends from southeast Virginia to the Canadian Maritime Provinces. Within this region, the US National Climate Assessment documented increases in air temperature, total precipitation, frequency of heavy precipitation events, and rising sea level, and predicted more drastic changes. Here, we synthesize literature on the effects of GCC interacting with selected contaminant, nutrient, and environmental processes to adversely affect natural resources within this region. Using a case study approach, we focused on 3 stressors with sufficient NA LCC region-specific information for an informed discussion. We describe GCC interactions with a contaminant (Hg) and 2 complex environmental phenomena—freshwater acidification and eutrophication. We also prepared taxa case studies on GCC- and GCC-contaminant/nutrient/process effects on amphibians and freshwater mussels. Several avian species of high conservation concern have blood Hg concentrations that have been associated with reduced nesting success. Freshwater acidification has adversely affected terrestrial and aquatic ecosystems in the Adirondacks and other areas of the region that are slowly recovering due to decreased emissions of N and sulfur oxides. Eutrophication in many estuaries within the region is projected to increase from greater storm runoff and less denitrification in riparian wetlands. Estuarine hypoxia may be exacerbated by increased stratification. Elevated water temperature favors algal species that produce harmful algal blooms (HABs). In several of the region's estuaries, HABs have been associated with bird die-offs. In the NA LCC region, amphibian populations appear to be declining. Some species may be adversely affected by GCC through higher temperatures and more frequent droughts. GCC may affect freshwater mussel populations via altered stream temperatures and increased sediment loading during heavy storms. Freshwater mussels are sensitive to un-ionized ammonia that more toxic at higher temperatures. We recommend studying the interactive effects of GCC on generation and bioavailability of methylmercury and how GCC-driven shifts in bird species distributions will affect avian exposure to methylmercury. Research is needed on how decreases in acid deposition concurrent with GCC will alter the structure and function of sensitive watersheds and surface waters. Studies are needed to determine how GCC will affect HABs and avian disease, and how more severe and extensive hypoxia will affect fish and shellfish populations. Regarding amphibians, we suggest research on 1) thermal tolerance and moisture requirements of species of concern, 2) effects of multiple stressors (temperature, desiccation, contaminants, nutrients), and 3) approaches to mitigate impacts of increased temperature and seasonal drought. We recommend studies to assess which mussel species and populations are vulnerable and which are resilient to rising stream temperatures, hydrological shifts, and ionic pollutants, all of which are influenced by GCC. *Integr Environ Assess Manag* 2015;11:355–369. © 2014 SETAC

Keywords: Algal blooms   Contaminants   Global climate change   Hypoxia   Nutrients

INTRODUCTION

The US National Climate Assessment (Melillo et al. 2014) summarized global climate change (GCC) and its present and potential impacts on the United States. This report and others (IPCC 2007; Lemmen et al. 2008) indicate that the warming of the North American climate is unequivocal and project more

rapid temperature increases, with changing patterns and intensity of precipitation. In addition to direct effects on plants and animals, GCC causes shifts in the home ranges of species with cascading impacts through ecosystems. For example, the area of the Northeast United States climatically suitable for the Eastern hemlock (*Tsuga canadensis*) is projected to contract due to warmer winters that favor the spread of a nonnative pest, the hemlock wooly adelgid (*Adelges tsugae*). Combined effects of climate and pests would not only affect hemlock populations but may result in loss or a geographic shift in associated bird and mammal species. Furthermore, reduced hemlock density may alter soil characteristics enhancing transport of nutrients into streams (Frumhoff et al. 2007).

The release of toxic chemicals and excess nutrients into the environment affects the survival, growth, and reproduction of microorganisms, plants, and animals (Rabelais et al. 2010; Sparling et al. 2010; Coristine and Kerr 2011). The topic of GCC–contaminant interactions was synthesized by Schiedek et al. (2007) and Noyes et al. (2009). A comprehensive investigation of GCC–contaminant interactions was undertaken in 2011 by a Society for Environmental Toxicology and Chemistry (SETAC)-sponsored international workshop (Stahl et al. 2013). A key concept advanced was that GCC, toxicants, and biota interact in 2 primary ways. The first involves changes in chemical distribution and availability to biota that may occur due to GCC. This could result from GCC-induced changes in the physical and/or chemical nature of the contaminant's local environment or from changes in human response to GCC. For example, in response to increased temperature and changes in precipitation, there may be shifts in agriculture and associated pesticide application and changing patterns of power demand and generation (and resulting pollution). The second interaction can occur in biota where toxicity or climate adaptation can be altered. Climate-induced toxicant sensitivities (CITS) are manifested when GCC alters environmental conditions, affecting biochemical and physiological processes and changing responses and sensitivity of organisms to toxicants. Toxicant-induced climate susceptibility (TICS) occurs when a toxicant hinders the ability of an organism to acclimate to environmental conditions altered by GCC (Hooper et al. 2013). Such interactions can potentially affect populations and ecological communities (Moe et al. 2013). Paradigms were suggested for adapting ecological risk assessments (Landis et al. 2013) and natural resource damage assessments (Rohr et al. 2013) to accommodate GCC-contaminant interactions into the environmental regulatory process.

The US Department of the Interior established 22 Landscape Conservation Cooperatives (LCCs) in the United States and adjacent areas of Mexico and Canada as part of a Secretarial Order to address GCC impacts (Salazar 2010). LCCs are geographically based partnerships among federal, regional, and state and/or provincial agencies, Native American tribes, universities, and nongovernmental organizations. LCCs address increasing land use pressures, resource threats, and uncertainties amplified by a rapidly changing climate, enabling the conservation community to enhance and maintain landscapes that sustain natural and cultural resources.

In this article, we discuss GCC interactions with selected contaminants, nutrients, and environmental processes within the North Atlantic LCC (NA LCC) region (Figure 1). This region extends from southeast Virginia north to and including parts of southern Quebec and the Maritime Provinces of Canada (New Brunswick, Prince Edward Island, and Nova Scotia). Fifty million people live within this 50 million-ha area. Ecoregions and habitat types include freshwater, estuarine, and coastal marine waters; wetlands; agricultural lands; urban and developed lands; and piedmont, coastal plains, and mountains. The primary land cover types are forest (56%), agriculture (14%), urban and suburban developed lands (13%), forested wetlands (9%), open water (4%), and emergent marsh (2%). The NA LCC region includes highly urban and suburban landscapes (e.g., Washington, DC, Baltimore, Philadelphia, New York City, Boston), as well as rural and heavily forested areas.

The region's history of agriculture, forestry, industrialization, resource extraction, and urbanization has placed severe demands on natural resources and the environment. Nevertheless, these ecosystems still support diverse fish and wildlife resources, including threatened and endangered species. The NA LCC (USFWS 2009) list of high priority species for conservation includes threatened and endangered species, as well as those that have experienced population declines and may be subjected to habitat alteration from changes in land use and GCC.

The goal of the current assessment is to provide the NA LCC with a series of demonstrations on how to consider potential threats to natural resources posed by GCC interactions with contaminants, nutrients, and environmental processes. We chose to focus on 5 case studies to illustrate the range of effects, using data from the NA LCC region. We 1) describe how 3 stressors (e.g., eutrophication, Hg, and freshwater acidification) may be affected by GCC, 2) summarize the potential effects of GCC and GCC-stressor interactions on 2 key taxa (amphibians and freshwater mussels), and 3) provide research recommendations for these stressors and taxa.

METHODS

The NA LCC leadership identified contaminant–climate interactions as a knowledge gap for the partnership and provided funding to address that need. The lead author organized a workshop in June 2012 with a panel of scientists with varied expertise to develop objectives, strategy, and tasks. This process was not, by design, an expert solicitation, but rather an attempt to bring together scientists with a diverse knowledge of regional issues to consider the potential for climate change to exacerbate contaminant impacts. The USFWS Literature Search Service (approximately 30 relevant databases) was used to identify published and unpublished studies that were provided to workshop participants as background information. Searches used terms related to climate change, regions (e.g., Northeast, Adirondacks, Chesapeake Bay), contaminants, and nutrients. More articles were identified through citation searches with Google Scholar (Google, Mountain View, CA) and Web of Science (Thompson Reuters, New York).

We reviewed GCC reports, literature, and models of observed and predicted changes in temperature, precipitation patterns, and sea level rise in the NA LCC region. We discussed the SETAC workshop findings to provide a framework for examining interactions between GCC and toxicants. Just as GCC models have been geographically downscaled for specific regions, we constrained the approach and findings of the SETAC workshop to the NA LCC region.

The authors used their knowledge of ecotoxicology, nutrient cycling, biogeochemical processes, GCC, and experience in

Figure 1. Map of the US Fish and Wildlife Service Northeast Region (Region 5) showing the North Atlantic Landscape Conservation Cooperative.

the NA LCC region to evaluate the available literature. To narrow the universe of chemicals under consideration as case studies, we started with the contaminant groups in the US Environmental Protection Agency (USEPA)/US Geological Survey/USFWS evaluation (2012) of toxic contaminants in the Chesapeake Bay watershed. These were: polychlorinated biphenyls, dioxins and furans, polycyclic aromatic hydrocarbons, petroleum hydrocarbons, pesticides, pharmaceuticals, household and personal care products, polybrominated diphenyl ether flame retardants, biogenic hormones, metals, and metalloids. The list was amended to include road salts because of concerns of the long-term effects of their application on stream ecosystems (Kaushal et al. 2005). Because our scope includes eutrophication and associated

effects, nutrients, algal toxins, and hypoxia were included. Finally, the topic of freshwater acidification, a major concern within the NA LCC region, was added.

At present, there are no compounds, chemical groupings, or processes that have an extensive literature base on stressor–GCC interactions. For many stressors, the paucity of data would make discussion almost entirely speculative. Thus, we decided to focus on a few stressors for which there was sufficient NA LCC- specific information to prepare examples for an informed discussion. We developed stressor case studies to discuss GCC linkages with: 1) the related and interacting phenomena of eutrophication, hypoxia, and harmful algal blooms (HABs); 2) bioavailability and effects of Hg; and 3) ecosystem responses to freshwater acidification. These issues

were chosen as examples of the diverse types of contaminant/nutrient/environmental processes that interact with GCC. In addition to GCC, loadings and effects may be altered by environmental regulations, economic demand, and sensitivity of already impacted landscapes (Staudt et al. 2013).

These 3 stressors were not selected to be prioritized above other contaminants, nutrients, and environmental processes, some of which may be equally important for investigation for GCC interactions but are less well-studied. For example, polychlorinated biphenyls (PCBs), organochlorine pesticides, and polynuclear aromatic hydrocarbons (PAHs) all bind strongly to sediments. Certainly, any GCC processes that facilitate soil and streambank erosion from contaminated areas will increase the release of such compounds from the watershed to water bodies. A variety of taxa may be affected; however, little NA LCC-specific information on GCC linkages with these contaminants was available.

Based on the NA LCC's goal to conserve priority species, we chose to also investigate GCC– contaminant interactions using specific taxa as a focus. Thus, we developed taxa case studies on direct GCC effects and GCC-contaminant/nutrient/process effects on amphibians and freshwater mussels. Conservationists have documented population declines and extinctions of these taxa in many parts of the world, including North America (amphibians: Stuart et al. 2004; Hoffman et al. 2010; Adams et al. 2013; mussels: Williams et al. 1993; Neves et al. 1997). Although in North America, the greatest biodiversity and number of species are found in the US Southern Appalachians (Chaplin et al. 2000), these taxa are key to the functioning of freshwater ecosystems of the NA LCC region. We recognize that many other taxa are affected by GCC, some of which are discussed in the 3 stressor case studies. The holistic focus on these 2 taxa, allowed us to interpret GCC interactive effects of other stressors (e.g., pesticides, ionic pollutants) in addition to the 3 stressor case studies.

CLIMATE CHANGE IN THE NA LCC REGION

The consequences of GCC in the United States were recently summarized in the National Climate Assessment (Melillo et al. 2014). This report features regional analyses including the Northeast states (WV through ME) (Horton et al. 2014), which overlap the NA LCC region. Other reports have focused on geographic areas relevant to the NA LCC such as Canada (Lemmen et al. 2008; Coristine and Kerr 2011), Chesapeake Bay watershed (Najjar et al. 2010), and Lake Champlain basin (Stager and Thill 2010). Although climate within the Northeast region is diverse and variable, the overall documented changes described by Horton et al. (2014) were

1. Between 1895 and 2011, average annual temperatures increased by almost 1.1 °C;
2. Between 1895 and 2011, average annual precipitation increased by approximately 12.7 cm;
3. Sea level increased by approximately 0.3 meters since 1900, exceeding the global average by 50%, which has increased susceptibility to storm surges and resulted in more coastal flooding.
4. Between 1958 and 2010, the amount of precipitation falling in very heavy events increased by 74%. This change was greater than that in any other US region.

Horton et al. (2014) summarized the following projected changes that would occur in the region under International Panel on Climate Change (IPCC 2007) scenarios (A2 and B1) with varying emission rates of heat–trapping gases as follows: 1) increases in the frequency, intensity, and duration of heat waves; in the southern part of the region there may be a doubling of days per year with maximum temperatures greater than 35 °C by the 2050s; 2) changes in precipitation are less certain but include projections for increasing winter precipitation, frequency of heavy downpours (with river flooding), and seasonal drought; and 3) global sea levels are projected to rise between 0.3 m and 1.2 m by 2100, with the rise in the Northeast exceeding the global average by up to 10 cm; occurrence of coastal flood events could triple by 2100.

We analyze the interactive effects of these documented and projected climatic changes within the NA LCC region with the following stressor and taxa case studies.

STRESSOR CASE STUDIES

Mercury

Mercury (Hg), a contaminant of concern, is distributed worldwide largely as a result of atmospheric emissions and long range transport. Approximately one-third of atmospheric Hg emissions are from direct anthropogenic sources, the largest of which are coal-fired power plants, cement production, and artisanal gold mining. The remaining two-thirds of emissions are from natural sources, such as volcanoes, burning biomass, and remobilization of previously deposited Hg (Driscoll et al. 2013). In the NA LCC region, most Hg is derived from regional (eastern North American) and global sources (Driscoll, Han et al. 2007), but there are local effects from industrial waste site and urban releases (Nobis Engineering 2008). After deposition, Hg may be sequestered in soil, reemitted to the atmosphere or transported from the watershed to surface waters. Bacterial transformation of inorganic Hg into methylmercury (MeHg), which strongly biomagnifies in aquatic and terrestrial food webs, is most active under reducing conditions in sediments of wetlands, riparian zones, intertidal areas, and coastal waters. Human exposure to MeHg occurs largely through fish consumption.

MeHg can threaten the integrity of terrestrial and aquatic ecosystems by adversely affecting the physiology, behavior, and reproductive success of high trophic level species. Residue-effect thresholds (i.e., concentrations associated with adverse effects) have been proposed for fish (Sandheinrich and Wiener 2011; Shore et al. 2011), avian piscivores (Evers et al. 2008; Depew et al. 2012), and avian invertivores (Jackson et al. 2011). The Canada Council of Ministers of the Environment (CCME 2000) issued national water quality criteria for the protection of wildlife from food-chain derived MeHg. As of 2011, all 50 US states had fish consumption advisories due to Hg contamination. There are statewide or lake-specific Hg advisories for freshwater habitats in all NA LCC states, the 4 Canadian provinces, and in coastal waters of Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine (USEPA 2013a; Schmeltz et al. 2011). Many advisories are restricted to top predator species and limits are often more stringent for children and women of childbearing age.

The NA LCC region includes ecosystems that are particularly sensitive to Hg inputs. Forested areas are effective in scavenging Hg from the atmosphere and exhibit limited losses from evasion (land–atmosphere exchange). The production of MeHg in sediments is mediated by sulfate and Fe-reducing bacteria; factors that affect methylation include temperature,

hydrology, hydrological regime (drawdowns of reservoirs), and the concentration of dissolved organic matter (Driscoll et al. 2013). Abundant wetlands within the NA LCC region promote the formation of MeHg and supply dissolved organic carbon (DOC) that facilitates the transport of Hg to downstream surface waters. Low productivity surface waters in the Adirondacks and other northeastern states impacted by acidic deposition exhibit elevated concentrations of Hg in fish and aquatic wildlife (Driscoll, Han et al. 2007; Yu et al. 2011). In addition, production of MeHg in sediments of estuarine and coastal wetlands and intertidal and shelf zones contributes to contamination of coastal fisheries (Chen et al. 2009, 2012).

Evers et al. (2007) defined biological Hg hotspots as locations that, when compared to surrounding landscapes, are characterized by concentrations of Hg in biota (e.g., fish, birds, mammals) that exceed human or wildlife health criteria. The NA LCC region contains many such hotspots, as evidenced by elevated Hg in fish tissue and common loon (*Gavia immer*) blood. Examples include parts of the Adirondacks and Nova Scotia; several reservoirs subject to drawdown and flooding cycles in New Hampshire and Maine; and areas with high local Hg inputs from hazardous waste sites (e.g., Sudbury River, Massachusetts) (Nobis Engineering 2008).

Within the NA LCC region, elevated MeHg concentrations have been reported in fish (Kamman et al. 2005), amphibians (Bergeron et al. 2011), reptiles (Bergeron et al. 2007), birds (Evers et al. 2005, 2008; Jackson et al. 2011), and mammals (Yates et al. 2005, 2014). Elevated Hg concentration was associated with impaired reproduction in common loons (*Gavia immer*) collected from lakes in New Hampshire and Maine (Evers et al. 2008). In loons from New Brunswick and Nova Scotia lakes, decreased productivity was associated with elevated Hg in loon blood or prey fish (Burgess and Meyer 2008). Bird species of high conservation concern, such as the saltmarsh sparrow, *Ammodramus caudacutus* (Lane et al. 2011), and the rusty blackbird, *Euphagus carolinus* (Edmonds et al. 2010), also have Hg body burdens at concentrations associated with reduced nesting success in the Carolina wren (Evers et al. 2011; Jackson et al. 2011). In a study on 21 salt marshes including 5 National Wildlife Refuges (NWRs) from New York through Maine, Lane et al. (2011) found the highest blood Hg concentrations in saltmarsh sparrows on Parker River NWR (Massachusetts), which receives flow from Hg-contaminated interior watersheds. The authors suggested that GCC-related stressors, including higher temperature, rising water levels, and/or changes in wetting–drying regimes, could increase Hg bioavailability in coastal wetlands.

We anticipate that aspects of GCC such as higher temperatures and changes in precipitation will alter the transport, net methylation, and trophic transfer of Hg (Chen et al. 2012). For example, Selvendiran et al. (2008) observed marked increases in net MeHg production associated with seasonal elevation in temperature in an Adirondack forest watershed wetland. Whether GCC will increase or decrease soil moisture in forests is uncertain (Groffman et al. 2012), and therefore, until projections in soil moisture and its seasonal change can be improved effects on Hg methylation will not be predicted effectively.

A meta-analysis demonstrated a positive relation between MeHg bioaccumulation in aquatic food webs and latitude such that trophic magnification was greater in polar and temperate zones versus tropical zones (Lavoie et al. 2013). The mechanism underlying this pattern is not clear, but implies an inverse relationship between trophic transfer of MeHg and the higher temperatures anticipated under GCC. In field and laboratory studies with the mummichog, *Fundulus heteroclitus*, however, Djikstra et al. (2013) reported greater whole body MeHg concentrations at higher temperatures. The field studies used mesh enclosures to restrict the fish from moving between salt marsh pools located along the Gulf of Maine coastline. Fish were exposed to sediments containing Hg, and there was a natural temperature gradient in the pools similar to GCC-projected increases of 1.5 °C to 4.5 °C for temperate waters. In the laboratory, fish were exposed to dietary Hg for 30 days at temperatures of 15 °C, 21 °C, or 27 °C. In both laboratory and field studies, there was a significant positive relationship between whole body Hg accumulation and temperature.

A temperature–Hg interaction was reported by Hallinger and Cristol (2011) in a field study in Virginia in free-ranging tree swallows (*Tachycineta bicolor*). Breeding success was evaluated from nest boxes at 19 Hg-contaminated sites (mean blood Hg: 3.03 µg/g) and 17 reference sites (mean blood Hg: 0.16 µg/g). Birds were also exposed to varied ambient temperature and precipitation throughout the breeding cycle. High Hg concentrations were associated with reduced hatching and fledging success, and highly exposed birds produced approximately one less fledgling per nest than their reference counterparts. Unusually high ambient temperatures early in the nestling period were associated with reduced reproductive output in polluted sites but not in reference birds. In contrast, little effect of Hg on success of nestlings was observed when temperatures were cooler, and precipitation had no detectable interaction with Hg. Importantly, this study represents the first documentation of negative effects associated with the interaction of GCC metrics and Hg exposure in a bird population. Potential mechanisms of GCC induction of increased Hg toxicity (TICS) as well as Hg impacts on climate adaptation (CITS) were proposed and demonstrated using an adverse outcome pathway (AOP) approach incorporating toxicity and climate adaptation pathways (as described in Hooper et al. [2013] and shown in Figure 2).

Adult common loons in the Rangeley Lakes Region of Maine and New Hampshire with low Hg concentrations exhibited little change in chick production regardless of rainfall (D. Evers, Biodiversity Research Institute, personal communication). Adults with elevated Hg concentrations, however, produced significantly fewer fledged young during the wettest summers. It was thought that adults with lower Hg concentrations exhibited adaptively plastic behaviors that allow adequate fledging success rates across a range of climatic conditions. Adults with elevated Hg concentrations appeared to have less adaptive plasticity, resulting in lowered fitness in wet conditions (an example of TICS, Figure 2) (Hooper et al. 2013).

Freshwater acidification

Acidic deposition is largely comprised of sulfuric and nitric acid derived from sulfur dioxide (SO_2) and mono-nitrogen oxides (NO_x), respectively. These compounds are emitted to the atmosphere primarily by the burning of fossil fuels. Reduced N, largely in the form of ammonia from agricultural emission sources also contributes to acidification (Driscoll et al. 2003). Acidic deposition continues to alter soils in sensitive areas of the NA LCC region, including the Central Appalachians, the Catskills, and Adirondack regions of New York
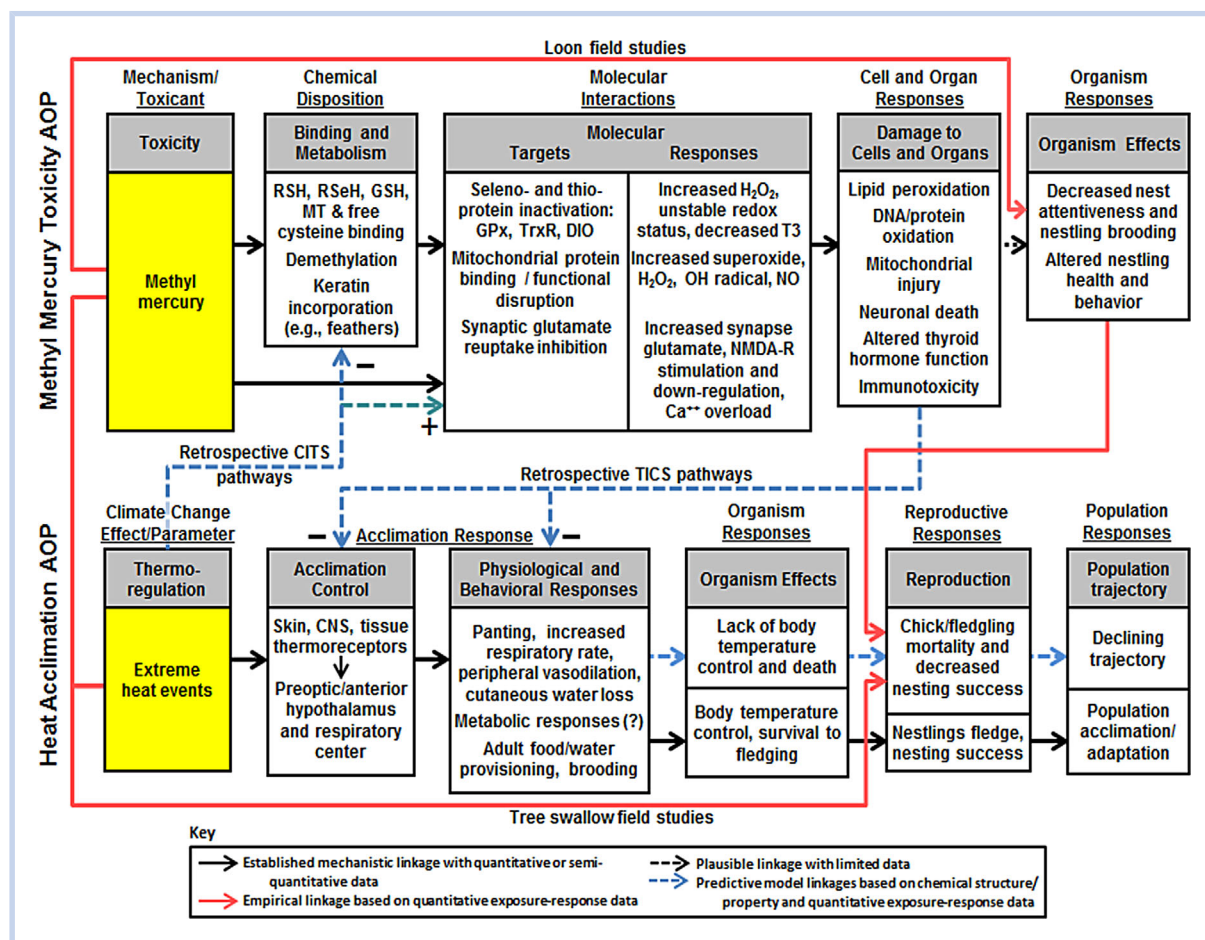
Figure 2. Adverse outcome pathways (AOPs) for investigating direct effects of Hg on adult brood care (Evers et al. 2008) and combined effects of extreme heat events and Hg toxicity in tree swallow nestlings (Hallinger and Cristol 2011). Retrospective pathways for potential climate-induced toxicant sensitivity (CITS) and toxicant-induced climate sensitivity (TICS) mechanisms are indicated. DIO = iodothyronine deiodinase; GPx = glutathione peroxidase; GSH = reduced glutathione; H_2O_2 = hydrogen peroxide; MT = metallothionein; NMDA-R = N-methyl-D-aspartic acid receptor; NO = nitric oxide; OH = hydroxyl; RSH = protein thiol; RSeH = protein selenol; T3 = triiodothyronine; TrxR = thioredoxine reductase. Modified from Hooper et al. (2013).

and forest upland portions of New England and the Maritimes. Effects in soil include depletion of available calcium (Ca^{2+}), magnesium (Mg^{2+}) and other nutrient cations from exchangeable sites, and greater accumulation of S and N. Acidic deposition contributed to declines of red spruce (*Picea rubens*) and sugar maple (*Acer saccharum*) through leaching and depletion of Ca^{2+} and mobilization of Al (Driscoll et al. 2001). Surface water quality is degraded through lowered pH, diminished acid-neutralizing capacity (ANC), and increased dissolved inorganic Al concentrations. Although emissions of SO_2 have decreased over the past 20 years (see below), concentrations of SO_4^{2-} in streams in acid-impacted regions, such as the forested uplands of the NA LCC region, generally remain high compared to background (Fakhraei et al. 2014).

The Adirondacks (Figure 1) is the region in North America most affected by acidic deposition (Driscoll et al. 1991). In a 1991–1994 study of 1812 Adirondack Lakes >1 ha in area, 41% were chronically acidic or sensitive to episodic acidification (Driscoll et al. 2001). Seasonal acidification occurs from the winter and spring pulse of acidity and the corresponding decrease in pH and ANC in streams (Wigington et al. 1996). Episodic acidification occurs in spring snowmelt and large rain events, resulting in sudden pulses of acids and increases in concentrations of dissolved inorganic Al (Baker et al. 1996). In many streams and lakes, decreased pH and

increased dissolved inorganic Al have resulted in physiological changes, greater mortality of sensitive life history stages, and reduced diversity and abundance of aquatic life including zooplankton, macroinvertebrates, and fish (Driscoll et al. 2001).

GCC may adversely affect sensitive tree species in the NA LCC region. This would occur through drought stress and increases in soil freezing anticipated with rising temperature and shifting runoff patterns from early loss of snowpack (Tierney et al. 2001; Smithwick et al. 2013). Snowpack insulates the soil during winter. Under low snowpack conditions, soil freezing events result in the mortality of fine roots, which limits N uptake by trees during the following growing season and contributes to elevated NO_3^- loss and associated acidification.

As a result of the Clean Air Act Amendments of 1990 (CAAA) and the NO_x Budget Trading Program (NBP, initiated in 2003), there have been marked declines in emissions of SO_2 and NO_x and acidic deposition. From 1990 through 2009, there was a 64% decrease in SO_2 and a 70% decrease in NO_x emissions from CAAA and NBP sources nationally (USEPA 2009). Continuous and significant decreasing trends in wet SO_4^{2-} deposition have been observed in Adirondack NY lake watersheds (Waller et al. 2012), declining 33% over the study period (1991–2007). Annual wet NO_3^-

deposition decreased by 32% during the same period. Regional trends in surface water chemistry indicate that acid-sensitive lakes and streams throughout the NA LCC region are recovering slowly in response to decreased acid deposition (Driscoll, Driscoll et al. 2007; Stoddard et al. 1999 2003). For example, the percentage of acidic Adirondack lakes (ANC $<0\,\mu$eq/L) decreased from 15.5% (284 lakes) to 8.3% (152 lakes) since implementation of the regulations (Waller et al. 2012). Coincident with decreases in acidic deposition and recovery of the acid-base status of soils and surface waters, there has been a compensatory increase in concentrations of dissolved organic carbon (DOC) (Driscoll, Driscoll et al. 2007). These increases in DOC can affect chemical and biological endpoints of recovery from acidification, including the toxicity of Al and the extent of thermal stratification in Adirondack Lakes.

It is difficult to assess the extent to which changing climate in the NA LCC region will alter recovery from acidic deposition. Greater overall precipitation and heavier storms would result in greater runoff along the top layers of soil (Chen et al. 1984) that could delay acidification recovery. In contrast, diminished peak discharge during snowmelt associated with loss of snowpack due to higher temperatures would decrease the severity of episodic acidification and associated effects. Pourmoktarian et al. (2012) conducted long-term simulations of hydrochemical responses to future changing climate at Hubbard Brook Experimental Forest in New Hampshire. Their models predicted that increases in temperature projected for the region in future decades will increase net mineralization and leaching of soil nitrogen that accumulated from decades of atmospheric nitrogen deposition. This condition resulted in marked acidification of soil and surface waters due to elevated NO_3^- leaching, causing more severe conditions than had occurred during historical and current acidification from acidic deposition. These simulations also indicated that, in the future, peak conditions of acidification in streams will shift from the spring to the fall. This shift would result in a reduced pulse of toxic monomeric Al, which is released largely by snowmelt (Murdoch and Stoddard 1992).

Eutrophication, harmful algal blooms, and hypoxia

Anthropogenic eutrophication (enrichment of waters by N, P, and the resulting plant growth) is a major concern in coastal, estuarine, and fresh waters of the NA LCC region. Factors responsible include runoff of nutrients from agricultural fertilizers and animal wastes, loadings from wastewater treatment, volatilization and subsequent deposition of ammonium from fertilizers and animal wastes, and atmospheric deposition of nitrogen oxides from fossil fuel combustion (Rabalais et al. 2009 2010). Two eutrophication-associated phenomena are hypoxia (waters with <2 mg/L dissolved oxygen [DO] concentrations) and algal blooms, including HABs that are toxic to fish, wildlife, and humans.

Projected GCC-related increases in surface water temperature and the altered patterns of precipitation are predicted to exacerbate eutrophication due to greater release and runoff of nutrients to water bodies as diverse as Chesapeake Bay (Najjar et al. 2010) and Lake Champlain (Lake Champlain Basin Program 2012). Howarth et al. (2006) projected that riverine loadings of N to northeastern US estuaries will increase in response to GCC-driven higher precipitation and discharge, primarily due to decreases in denitrification in riparian wetlands and low-order streams. They projected that N fluxes from the Susquehanna River to Chesapeake Bay by 2095 may be 16% to 65% greater than in the 1988 to 1993 base period. Using the Howarth et al. (2006) forecasts and the IPCC (2007)-based predictions of increased water temperature, Prasad et al. (2011) calculated that the volume of anoxic (<0.2 mg/L DO) water in the Chesapeake Bay could grow by 3% to 17% by 2030 and 16% to 65% by 2095.

The multiple and interacting stressors leading to eutrophication, HABs, and hypoxia in coastal waters are illustrated in Figure 3 (Rabelais et al. 2014). Here, "anthropogenic activities" include nutrients released from agriculture, wastewater treatment plants, and nonpoint source runoff; and changes in hydrology due to agriculture and urbanization. Positive (+) interactions designate worsening conditions related to algal blooms and hypoxia, and negative (–) interactions designate fewer algal blooms and lessening of hypoxia symptoms. Thus, both GCC and non-GCC related stressors can change the extent and severity of hypoxia and HABs.

A major GCC-related concern is the predicted change in composition and distribution of phytoplankton populations, including the greater presence of toxin producing species. These toxins, if ingested, can poison shellfish, fish, wildlife, domestic animals, and humans (Carmichael 1994; Codd 1995). The algal species in estuaries and oceans releasing these toxins include dinoflagellates, diatoms, cyanobacteria, and raphidophytes. Among these, the cyanobacteria are considered to have a competitive edge over many other algae under projected future climate conditions (e.g., warmer temperatures, increased stratification) and thus are predicted to become more dominant (Carey et al. 2012; O'Neil et al. 2012). Anticipated changes in algal composition and productivity resulting from changing anthropogenic stressors, greater eutrophication, and GCC would also influence existing algal predator-prey relationships (Balayla et al. 2010; Winder and Schindler 2004). Changing environmental and biotic relationships associated with greater eutrophication are also projected to favor development of sporadic or frequent blooms by indigenous or invasive species in estuarine and freshwater habitats (Paerl and Huisman 2009; Lürling et al. 2013).

There is evidence that HABs appear to be an expanding problem within several northeast estuaries that may be exacerbated by GCC. For the Chesapeake Bay, there is a long-term trend of increased phytoplankton biomass and abundance, including the presence of 37 HAB taxa from the Bay and tidal tributaries (Marshall et al. 2009). Although many bloom producing algae do not produce toxins, the aftermath of any large algal bloom may include cell decomposition that is often accompanied by hypoxia and major fish kills. Among potentially harmful bloom producers in the Bay are the dinoflagellates, *Cochlodinium polykrikoides* and *Alexandrium monilatum*. The former has expanded its range and bloom development in lower Chesapeake Bay over the past several decades, and the latter is an invasive species that produced modest reoccurring blooms in the Bay, and the James and York Rivers in Virginia since 2007 (Marshall and Egerton 2009a 2009b). Another dinoflagellate associated with frequent bloom development in Maryland and Virginia estuaries in the past decade is *Karlodinium veneficum*, a known fish-killing species (Goshorn et al. 2004; Marshall and Egerton 2009a). In New England waters, blooms of *C. polykrikoides* (Gobler et al. 2008) and the pelagophyte *Aureococcus amophagefferens*
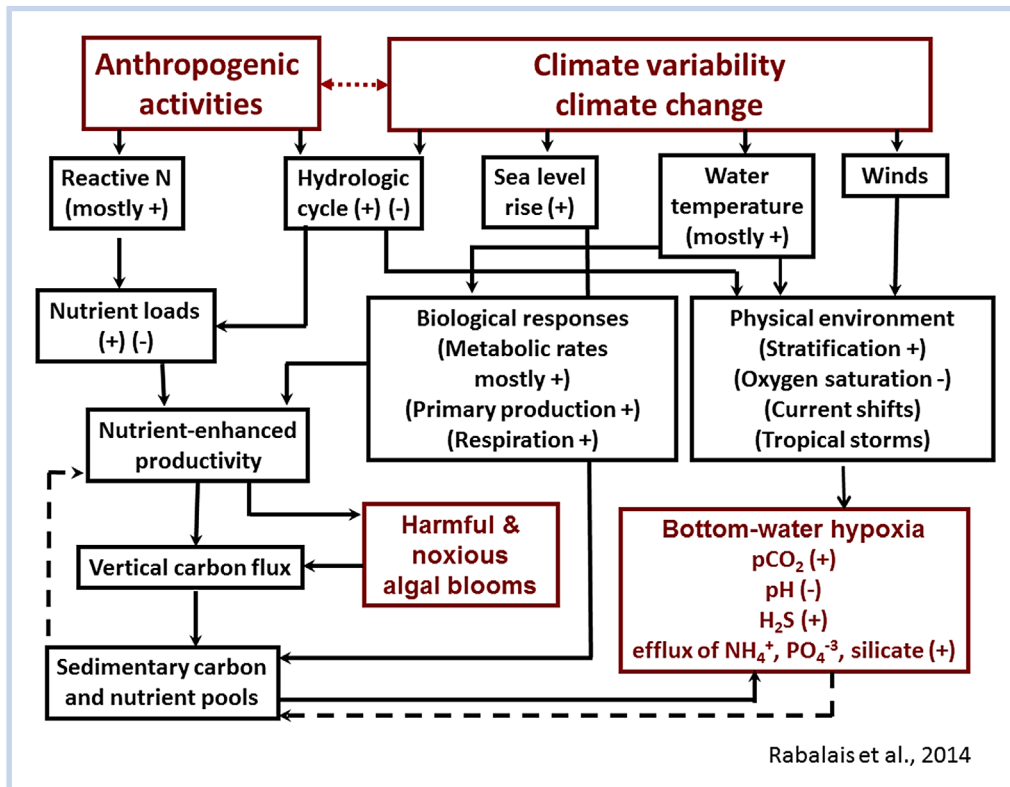
Figure 3. Potential physical and hydrological changes resulting from climate change and their interaction with current and future human activities. The dashed lines represent negative feedback to the system. (Reprinted from Rabalais et al. (2014), with permission).

(Gobler and Sunda 2012) have been documented in relation to nutrient loading.

Lakes within the NA LCC region will also be affected by climate-related factors (e.g., increasing water temperatures, nutrient enrichment, lengthened growing season, and stratification) that affect algal populations (Carey et al. 2012). More frequent outbreaks of HABs were identified as a threat to Lake Champlain (Stager and Thill 2010). Because many reservoirs in the NA LCC region were built decades ago, they are passing into advanced trophic stages that favor HAB development. In a recent survey of 46 Virginia lakes and reservoirs, HAB cyanobacteria, represented by *Microcystis aeruginosa, Aphanizomenon flos-aquae, Anabaena spiroides, Anabaena circinalis, Limnothrix redekei,* and *Cylindrospermopsis raciborskii* were present (Marshall 2013). At least one of these HAB species was observed in 27 of the lakes surveyed. Human health effects associated with ingestion of *Microcystis aeruginosa* cyanotoxins include hepatic and gastro-intestinal illness, and death (Kuiper-Goodman et al. 1999).

Recent autumnal die-offs of hundreds of migratory birds in Chesapeake Bay (2001, 2004, and 2005) appear to be linked to HABs. The most prominent events were at the Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island (PSSERPPI) near brackish impoundments. Dead and dying great blue herons (*Ardea herodias*) were observed and 9 of 22 specimens sent for analysis had detectable quantities of microcystins in the liver (B. Rattner, USGS, personal communication). Necropsies revealed steatitis (excessive abdominal deposits of waxy yellow fat); one of several hypotheses suggests that this condition results from exposure to microcystins in water or prey (Falconer 2005; Armado and Monserrat 2010). In 2012, over 770 sick or dead birds (plus several muskrats, *Ondatra*

zibethicus) were found at PSSERPPI due to exposure to avian botulism and/or a microcystin-dominated HAB. Murphy et al. (2000) suggested that avian botulism can be triggered by HABs. Pathological analysis from the 2012 outbreak confirmed avian botulism in 6 of 17 birds; gut and liver samples from 14 birds, and 1 muskrat had microcystin concentrations (gut–50 to 1500 ppb; liver–79 to 6640 ppb) equal to or higher than those in other US HAB-associated bird and mammalian die-offs (L. Murphy, University of Pennsylvania, personal communication).

Eutrophication-driven hypoxia has increased in the world's coastal waters such that the number of anthropogenic anoxia sites grew from 195 in 1995 to over 400 in 2008 (Diaz and Rosenberg 2008; Rabalais et al. 2010). From 2000 through 2009, hypoxia was observed in 26% of North Atlantic estuaries (including Great Bay, Narragansett Bay, and Long Island Sound) and 42% of mid-Atlantic estuaries (Chesapeake Bay, and coastal waters of Delaware, New Jersey, and New York) (Committee on Environment and Natural Resources 2010). Many GCC-driven processes are likely to increase the extent and magnitude of coastal hypoxia (Figure 3) (Rabalais et al. 2010). In the Chesapeake Bay, greater stratification may result from the sea level rise-associated increased salinity of bottom waters (Kemp et al. 2009). Hypoxia-related mortality of fish, shellfish, and benthic macroinvertebrates would be expected to occur more often, because higher water temperatures have been linked to greater metabolic rates and O_2 requirements (Breitburg 2002; Boesch et al. 2007). In addition to kills from acutely lethal conditions, chronic exposure to low and fluctuating O_2 concentrations impair reproduction, immune responses, and growth of fish and invertebrates (Breitburg 2002). Concerns were expressed for Lake Champlain, where Stager and Thill (2010) projected that prolonged thermal

stratification from increased surface water temperature would lead to greater deep-water hypoxia.

Laboratory studies documented that chronic exposure to hypoxia contributes to reproductive impairment in fish (Wu et al. 2003). Chronic exposure of carp (*Cyprinus carpio*) to 1 ppm DO was associated with lower serum estradiol and testosterone concentrations, slower gonadal development, and diminished fertilization success, hatching rate, and larval survival. In field studies in Florida, young-of-the-year Atlantic croaker (*Micropogonias undulatus*) from hypoxic sites had impaired ovarian and testicular growth and lower androgens compared to those from normoxic sites (Thomas et al. 2007). Although published field studies in the NA LCC region could not be identified, similar effects may be occurring. Other concerns are that hypoxia may exacerbate the toxicity of PAHs in developing fish (an example of CITS) and that PCB exposure may hinder the ability of fish to respond to hypoxia (TICS) (Hooper et al. 2013).

TAXA CASE STUDIES

Here, we assess both direct GCC effects and GCC-contaminant/nutrient interactive effects on amphibians and mussels as examples of sensitive taxa. In addition to the 3 stressors discussed above, we include examples of interactive effects of GCC with pesticides and ionic pollutants, some of which may be associated with application of road salt.

Amphibians

Amphibian population declines and species extinctions are critical global issues. The major known causes are habitat loss, overexploitation, pollution, invasive species, and diseases such as chytridiomycosis (Stuart et al. 2004; Wake and Vredenburg 2008). Hoffman et al. (2010) reported that 41% of the world's amphibian species categorized on the International Union for the Conservation of Nature (IUCN) Red List are listed as threatened with extinction, the highest percentage of all vertebrate taxa. Amphibian occupancy rates in US habitats were surveyed from 2002 through 2011 (Adams et al. 2013), and decreases in both rare and common species were noted. Species in IUCN categories "near threatened" to "critically endangered" had mean occupancy rates decreasing at 11.6% per year, whereas those in "least concern" were decreasing at a lower but biologically relevant rate of 2.7% per year. There were no significant differences in the rate of decreases between regions of the US. According to Adams et al. (2013), GCC may be a contributing factor for the declines in amphibian occupancy combined with habitat loss, disease, and contaminants; effects due to GCC are subtle, however, and difficult to identify.

Within the northeast United States, several species of amphibians are of particular concern (NPARC 2010). Among anurans, 3 species, Carpenter's frog (*Lithobates virgatipes*), Eastern spadefoot (*Scaphiopus holbrookii*), and mountain chorus frog (*Pseudacris brachyphona*) are of special interest because they are found in more than 75% of the State Wildlife Action Plans (SWAPs) as species of concern; 4 others are of high concern because they are listed in 50% to 75% of the SWAPs. Among 6 species of caudates, the Jefferson salamander (*Ambystoma jeffersonianum*) is a species of high regional responsibility because northeastern states represent greater than 50% of its US and Canadian distribution. Five other salamanders are of high concern and 4 of moderate concern.

Amphibians are of particular interest for GCC impacts because their permeable skin and complex life cycle make them vulnerable to changes in temperature and precipitation that affect their aquatic and terrestrial habitats. Amphibians are ectothermic and might experience greater perturbations than endothermic birds and mammals. However, amphibians can maintain body temperatures within a few degrees via behavioral thermoregulation (Bicego et al. 2007).

In a recent review, Li et al. (2013) evaluated lethal and sublethal, direct and indirect, and positive as well as negative effects of GCC on amphibians. They concluded that there is little evidence of acute lethal effects, and data are inadequate to determine whether 3 "universal species responses" to global warming (e.g., changes in phenology [breeding dates]; shifts in geographic distributions; and reduced body size) are currently contributing to amphibian population declines. Li et al. (2013) stated that review of the interaction between climate and the prevalence of chytridiomycosis revealed more evidence for a causal link between temperature variability and the disease than between mean temperature and the disease.

GCC-contaminant interactions are complex and sometimes contradictory. For example, in laboratory tests with amphibians, toxicity of the carbamate insecticide carbaryl increased with water temperature (Boone and Bridges 1999), whereas there are examples of both greater and lesser toxicity at higher temperatures with pyrethroids (discussed by Materna et al. 1995). In nature, an additional consideration is the interaction between toxicity and exposure (Rohr et al. 2011). For some contaminants (e.g., atrazine) (Rohr and McCoy 2010), there are nonmonotonic concentration responses (i.e., changes in direction of response with changes in contaminant concentrations). Some studies on atrazine reported that exposure delayed metamorphosis, whereas others showed accelerated metamorphosis (Rohr and McCoy 2010). Such changes in the duration of the larval phase would affect toxic responses.

The increased seasonal drought and rising temperature predicted for the northeast US (Horton et al. 2014) may individually or in concert result in adverse effects on amphibians. Examples of such GCC-contaminant interactions are the Rohr and Palmer (2005, 2013) laboratory studies of the effects of temperature, desiccation, and sublethal atrazine exposure in streamside salamanders (*Ambystoma barbouri*), native to the Midwest United States. Findings indicated that exposure of larvae to atrazine decreased the adults' ability to resist desiccation some 8 months later. The species prefers cool (~22 °C), moist conditions and uses behavioral adaptations such as huddling and decreased activity to survive warmer, dryer conditions. Despite these adaptations, there was loss of mass and greater mortality in salamanders exposed to 27 °C, a common summer temperature within their range (Rohr and Palmer 2013). Exposure to atrazine shortened time to death. Thus, behavioral adaptations did not fully compensate for exposure to prolonged adverse environmental conditions and atrazine exposure worsened the effects.

Salamanders could be negatively affected in the NA LCC region by GCC-related altered flow patterns of low-order streams and the hydrology of vernal wetlands. These sites tend to dry earlier than ponds favored by many anurans. An alternative possibility to GCC-induced adverse effects, however, is that increasing temperatures and nutrient loading may result in greater species richness in small temperate water bodies (Rosset et al. 2010).

The current and future use of fertilizers and pesticides within the NA LCC region will be affected by economics, environmental regulations, and changes in the types and locations of farms. Warmer temperatures would result in longer growing seasons, differences in types of crops planted or livestock raised, increased use of groundwater, and changes in the quantity and types of fertilizers and pesticides applied (Wolfe et al. 2008). An additional concern is the interaction between nitrogenous compounds and pesticides. For example, Orton et al. (2006) reported that changes in sex ratios (favoring females) in northern leopard frogs (*L. pipiens*) were more marked in response to combined exposure to atrazine and nitrates than to these chemicals alone. At present, the net effect of these interacting factors cannot be predicted.

Two field studies addressed possible GCC-driven changes in the abundance of amphibians within the NA LCC region. Gibbs et al. (2005) compared population changes among 5 species of anurans in New York State between 1973 to 1980 and 2001 to 2002. They identified a net loss of roadside habitats, such as ditches, but no differences in population status among those habitats that still existed. At the local level, population declines were associated with acid deposition, urban development, forest cover, and agriculture. Although mean ambient temperatures in 2001 to 2002 were 0.26 °C warmer than in 1973 to 1980, the difference was not statistically significant. Breeding phenologies for 4 amphibian species were slightly advanced in 2001 to 2002 compared to 1973 to 1980. Whereas these changes might be ascribed to early evidence of GCC, Gibbs et al. (2005) did not consider climate to be a critical factor. Rather, they suggested that reductions in the amount of roadside habitat accounted for the decline in amphibian populations. Lowe (2012) found that populations of the stream salamander, *Gyrinophilus porphyriticus*, in New Hampshire decreased between 1999 and 2010. Based on linear regression, Lowe (2012) determined that the abundance of adults was negatively related to the amount of annual rainfall, which is predicted to increase in the Northeast (Hayhoe et al. 2007). Abundance was not significantly related to mean annual temperature. Lowe (2012) hypothesized that metamorphs may not be able to use flood-avoidance strategies used by larvae and adults, resulting in increased mortality.

Freshwater mussels

Freshwater mussel life history traits, such as dependency on specific host fish, environmentally sensitive larval and juvenile life stages, and their filter-feeding, benthic-dwelling biology, make mussels inherently vulnerable to natural and anthropogenic stressors (Neves et al. 1997; Strayer et al. 2004; Haag 2012). According to Williams et al. (1993) 213 (72%) of the 297 species known in US waters are federal- or state-listed as endangered, threatened, or of special concern, making mussels one of the most imperiled animal groups in the country.

The river systems of the NA LCC region support 32 species of mussels. Included are 2 US-listed endangered species, dwarf wedgemussel (*Alasmidonta heterodon*) and James spinymussel (*Pleurobema collina*), and 1 candidate species, Atlantic pigtoe (*Fusconaia masoni*). The Connecticut River watershed in New England supports the largest known populations of the dwarf wedgemussel. The Penobscot River in Maine and rivers northward to New Brunswick, Canada and the Gulf of Saint Lawrence, support important populations of cool-cold water adapted mussel species such as the eastern pearlshell (*Margaritifera margaritifera*). This species is listed as critically imperiled in Pennsylvania (Pennsylvania Fish and Boat Commission 2011). The dwarf wedgemussel is listed as extirpated from its only recorded Canadian location within the Petitcodiac River drainage of New Brunswick. Two other species from Nova Scotia and New Brunswick, brook floater (*Alasmidonta varicosa*) and yellow lampmussel (*Lampsilis cariosa*), are listed by the provincial governments as species of special concern (New Brunswick 2014 Nova Scotia 2014). Both species are listed as threatened by Maine Department of Inland Fisheries and Wildlife (2014).

Stressors suspected as contributing to declines and extinctions of freshwater mussels occur at local, regional, and global scales. Locally, mussels suffer from habitat alteration (e.g., riparian clearing) that results in greater inputs of fine sediments, contaminants, and nutrients, and the impacts of invasive species. Regional scale stressors include river fragmentation and altered flow regimes, including dams that restrict movement of host fish. At the global scale, mussels suffer from direct and indirect GCC effects, including increased frequency of large floods and severe droughts, changes in stream and lake temperatures, losses of host fish populations, and increased salinization from shifts in human activities (Hastie et al. 2003; Galbraith et al. 2010).

Within the NA LCC region, GCC may affect freshwater mussel populations directly by altering stream temperatures or indirectly through increased loading of sediments, contaminants, and nutrients released from watersheds and stream banks during more frequent heavy storms. These alterations to aquatic systems could affect mussel host fishes, causing changes in their abundance and distribution. Kaushal et al. (2010) studied changes in river and stream temperatures by analyzing historical data in 40 rivers and streams across the United States. They reported significant temperature elevation in 20 rivers and streams (decreases in only 2) and concluded that the greatest increases were near urban areas in the mid-Atlantic states. Both climate change and urbanization, through increases in impervious surface area and loss of riparian areas and canopy cover contribute to the temperature responses. Laboratory studies demonstrated that juvenile and adult mussels in US streams had reduced growth and high mortality at water temperatures of greater than or equal to 32 to 34 °C (Pandolfo et al. 2010; Carey et al. 2013). In laboratory tests with 3 species native to the Midwest and southeastern United States, lethal temperatures affecting 50% of the test group ranged from 25.3 to 30.3 °C (Ganser et al. 2013). Thus, some freshwater mussel species may already be living close to their upper thermal tolerances (Pandolfo et al. 2010), and recent rises in stream temperatures have already resulted in shifting species abundance toward those with greater thermal tolerance (Galbraith et al. 2010).

Mussels are particularly sensitive to ammonia (Strayer and Malcom 2012; USEPA 2013b). Natural sources of ammonia in the environment include excretion of nitrogenous wastes by animals, decay of animal and plant matter, and fixation by bacteria. Anthropogenic sources include wastewater treatment plant effluent, releases from septic systems, runoff of nitrogenous fertilizers from crops, runoff of animal wastes from feedlots and grazing pastures, and industrial processes such as production of cleaning products and fertilizers. The USEPA (2013b) ammonia criteria for freshwater was recently lowered from previous values, based on new data that indicated that the 7 most sensitive genera were freshwater mussels. Ammonia is more harmful to juvenile and adult mussels in the summer,

when water levels are low and temperatures high. Elevated temperatures documented and predicted with GCC result in a greater fraction of ammonia existing in the toxic un-ionized form (NH_3) (USEPA 2013b). Furthermore, ammonia can reach higher concentrations in interstitial porewater of stream substrates compared with overlying water (Frazier et al. 1996). Strayer (2013) stated that concentrations of interstitial NH_3 may rise when DO is low and loadings of reactive N are high.

Strayer and Malcom (2012) concluded that NH_3 was the primary cause of recruitment failure of the eastern elliptio (*Elliptio complanata*) in southeastern New York. They tested whether interstitial NH_3 concentrations differed between sites with recruiting populations versus those with non-recruiting populations. They also tested whether sites differed with respect to fine sediments, interstitial DO, crayfish densities, or presence of American eels (*Anguilla rostrata*), a host species. A relationship with interstitial NH_3 concentrations was found; a threshold of $0.2 \mu g/L$ separated recruiting from failing populations. The authors postulated that NH_3 poses a threat to many mussel species over broad regions of the world.

According to Kaushal et al. (2005) baseline stream salinities are increasing within areas of the NA LCC toward thresholds beyond which ecological communities and ecosystem functions might not recover. Stream salinization refers to an increase in the concentration of total dissolved solids in water and can be detected by increases in ionic pollutants that are acutely toxic to freshwater mussels such as Cl^-, Na^+, K^+, Mn^{+2}, and SO_4^- (Echols et al. 2009; Gillis 2011). In recent decades, increasing percentages of land use as roads and other impervious surfaces has been associated with sharp increases in concentrations of Na^+ and Cl^- in aquatic systems, primarily due to the use of road salt (Kaushal et al. 2005; Environment Canada 2012). Cl^- concentrations in surface waters were elevated substantial distances from roadways due to gradual releases from groundwater, leading to widespread adverse impacts on water quality.

Many parts of Canada have experienced changes to their winter climate over the past decade (Environment Canada 2012). These changes include more freeze-thaw cycles, more frequent and larger storms, freezing rain, and longer periods when temperatures are within the working temperature of salt. Such changes can lead to more winter maintenance activities including greater road salt application. However, Mills and Andrey (2002) stated that empirical relationships between temperature and historic rates of salt use suggest that a warming of 3 to 4 °C could decrease salt and sand use by 20% to 70%. An additional impact of GCC is the increased number and duration of droughts resulting in reduced flow and higher Cl^- concentrations. Clearly, GCC is one of many factors potentially affecting stream salinization, but there is uncertainty regarding the magnitude and direction of impact.

Hence, a future with greater incidence of drought and accompanying higher temperatures, low flows, and salt and ammonia toxicity in streams may prove stressful for many mussel species within the NA LCC region. For example, the preferred habitat of the dwarf wedgemussel is clear, cool, and relatively small streams with abundant sand and small gravel substrate (Michaelson and Neves 1995). Such habitats are vulnerable to excessive ammonia and salt inputs from agriculture, wastewater, road runoff, and shifts in hydrology, and to higher temperatures.

SUMMARY AND RESEARCH RECOMMENDATIONS

For each case study, we summarize key findings and highlight areas requiring additional research. Based on the overarching concern for natural resources in the NA LCC and the need for approaches that provide utility for land and resource managers, we suggest research topics based on the following criteria: 1) whether the results will enhance our understanding of the impacts of these GCC-related stressors on natural resources, especially species of concern; 2) whether the findings can be applied to lead to a reduction of threats driving population losses of threatened and endangered species, certain interjurisdictional fishes, migratory birds, amphibians, and freshwater mussels; and 3) whether the results will reduce uncertainty related to prudent natural resource management.

Stressors

The NA LCC region includes ecosystems sensitive to Hg deposition. Several bird species of high conservation status have Hg body burdens associated with reduced nesting success. We recommend research on the interactive effects of GCC (including changing requirements for water level management of impoundments) on generation and bioavailability of MeHg, and the effects of GCC-driven shifts in species distributions on MeHg exposure.

Freshwater acidification has adversely affected terrestrial and aquatic ecosystems in high elevation areas of New York (Adirondacks), New England, and the Maritimes that are slowly recovering due to decreased emissions of N and sulfur oxides. Research is needed on how GCC will affect that recovery. A byproduct of decreases in acid deposition is enhanced mobilization of dissolved organic matter. Increases in dissolved organic carbon coupled with GCC may alter endpoints of acidification recovery through shifts in biological communities and also affect Hg dynamics (see above). Research is needed to understand how GCC concurrent with decreased acid deposition will alter the structure and function of acid-sensitive watersheds and surface waters.

Eutrophication in many estuaries in the NA LCC region is projected to increase due to greater runoff from watersheds receiving heavier storms and less denitrification in riparian wetlands. Hypoxia in the Chesapeake Bay and other estuaries may be exacerbated by increased stratification. Elevated water temperature favors algal species that produce HABs associated with bird die-offs. Research is needed on the effects of GCC on HABs and avian disease, and how more severe and extensive hypoxia events will affect fish and shellfish populations.

Information should be compiled for other contaminants exhibiting widespread exposure and known toxicity within various NA LCC ecoregions. A priority would be PCBs and legacy organochlorine contaminants that are risk drivers for fish consumption advisories throughout the region. Additional information should be gathered on GCC-contaminant interactions of current use pesticides, PAHs, and endocrine disrupting compounds.

Taxa

Amphibian populations appear to be declining and several northeastern species are of special concern. Information is needed on 1) thermal tolerance and moisture needs of species of concern; 2) effects of multiple stressors (temperature, desiccation, contaminants, nutrients); and 3) the feasibility of approaches to mitigate GCC-related stressors of increased

temperature and seasonal drought, such as manipulation of water levels and providing shelter and canopy cover.

GCC may affect freshwater mussel populations via altered stream temperatures or through increased sediment, contaminant, and nutrient loading from more frequent heavy storms. Freshwater mussels are extremely sensitive to un-ionized ammonia that is more toxic at higher temperatures. The extent to which GCC will exacerbate exposure of mussels to un-ionized ammonia, greater runoff, and reduced porewater DO is unknown. We recommend research to identify mussel species and populations that are vulnerable and those that are resilient to rising stream temperatures, hydrologic shifts, and ionic pollutants, all of which are influenced by GCC.

Scientists should continue to gather information on direct and indirect GCC-related threats to plants, invertebrates, fishes, birds, and mammals identified as priority species by the NA LCC (USFWS 2009) and by other conservation partnerships. This case study approach is applicable to agencies and NGOs working in other geographic areas, and is especially relevant for the other 21 LCCs across North America.

Disclaimer—The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the US Fish and Wildlife Service or US Geological Survey.

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