Hil ipsandi ut quatia volorpos aspid et qui as ea ad molorepe nist, tem faccus ut molupta sinus.
Tet et aut debitatem quissi reniendenda dolum apiet

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POLICY FORUM

ENVIRONMENTAL REGULATION

Dissolved oxygen and pH criteria leave fisheries at risk

Regulations have not kept pace with scientific understanding of coastal hypoxia and acidification

By **Stephen J. Tomasetti** *and* **Christopher J. Gobler**

Changes in human population centers and agricultural fertilizer use have accelerated delivery rates of nitrogen and phosphorus to coastal waters, often stimulating rapid accumulations of primary production (*1*). Whereas resulting eutrophication processes are of less environmental relevance in well-mixed, ocean ecosystems, when they occur in warm, stratified, and/or poorly mixed waters, they can result in hypoxia [depletion of dissolved oxygen (DO)] and acidification (decrease in pH), both of which individually can have adverse effects on aquatic life, affecting a suite of physiological processes and increasing mortality rates (*2*, *3*). Only recently, however, have studies of aquatic hypoxia begun to consider coeffects of low pH (*4*). Many ecologically and/or economically important shellfish and finfish that experience decreased survival and/or growth when exposed to hypoxia are further impaired by concurrent acidification (*4*). Yet although scientific understanding of DO and pH variability and documentation of coastal hypoxic and acidification events have improved, regulatory reform has not kept pace. We suggest that more stringent DO and pH numeric criteria be considered to account for the negative effects of low pH on marine life and the combined impairment from low DO and low pH.

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Global ocean DO levels have been decreasing because of both climate change and increased nutrient export from land to sea (*5*). Most commonly, coastal hypoxia is eutrophication-induced, whereas the persistence and severity of hypoxic events are often modulated by climatic factors. Rising sea surface temperatures, for example, lower oxygen solubility and contribute to water-column stratification, restricting the vertical mixing of atmospheric oxygen into deeper waters (*5*). Still, rates of DO decline in the nearshore environment outpace those of the open ocean (*5*), underscoring the direct influence of anthropogenic nutrient loading on coastal water bodies and the need for careful regulatory policies and effective management.

Similarly, pH levels are affected by a combination of local and global processes acting on differing spatial and temporal scales. Globally, ocean assimilation of rising atmospheric CO_2 has resulted in a 0.1 unit decrease in ocean pH since preindustrial times, with decreases of an additional 0.2 to 0.3 units predicted for the end of the century (*6*). Acting over shorter temporal and smaller spatial scales, increased freshwater input, upwelling, and eutrophication can elicit additional local depression of pH in coastal waters to levels that can exceed the changes anticipated for the open ocean at the end of the century (*7*).

Within many eutrophic coastal systems, the production of respired CO_2 constitutes a major source of acidity and, therefore, intensifies acidification (*8*, *9*). Eutrophication-induced increases in CO_2 can interact synergistically with ocean acidification to lower pH levels below those predicted by the sum of eutrophication and ocean acidification alone, owing to the reduced buffering capacity of hypoxic, metabolically acidified waters (*8*). Thus, hypoxic waters are necessarily acidified, and many organisms exposed to hypoxic stress must also cope with acidification (*4*).

DO AND PH CRITERIA

The global proliferation of coastal hypoxia and acidification underscores a universal need to adopt and implement DO and pH regulations reflective of evolving environmental conditions. In recent decades, the acceleration of climate change, advancements in in situ monitoring technology, and emerging experimental data have collectively established a new global paradigm in which policies developed in the 20th century are, in some cases, misaligned with conditions needed to protect marine life. In the United States, the Clean Water Act (CWA) establishes the basic structure for ameliorating and preventing surface water impairment. Because many countries have developed seawater quality standards partly modeled on U.S. standards, similar policy challenges can be found internationally—for example, in China (*10*) and Brazil (*11*).

Among its many provisions to restore and protect national waters, the CWA authorizes U.S. states, territories (henceforth referred to as states), and approved tribes to establish water-quality standards for waters of the United States, including territorial seas (*12*). Federally approved water-quality standards consist of at least three elements: (i) designated uses (protection and propagation of fish, shellfish, and wildlife; recreation), (ii) water-quality criteria to protect designated uses, and (iii) antidegradation requirements that safeguard unimpaired waters. When water-quality standards are not satisfied by existing restraints on pollution, such waters can be reported to the U.S. Environmental Protection Agency (EPA) through the 303(d) impaired waters list (*12*). Inclusion on the 303(d) list prompts further action, by which the total maximum daily loads of pollutants (often nutrients in the case of hypoxic areas) required to ameliorate conditions can be determined, and mitigation measures may be implemented (*12*).

The EPA provides recommended criteria for DO and pH in coastal waters to guide the development of state standards (*13*, *14*). Although the EPA-recommended DO criteria are based on a decade of data collection (*13*), this occurred before the establishment of the field of ocean acidification. As such, the majority of studies on which policy has been established had used nitrogen gas to establish low-DO conditions (*13*), an approach that can inflate pH values—creating unrealistic, basified conditions—and that ignores any additional acidification stress that coastal organisms may endure under hypoxia (*4*). In addition, state derivations of the recommended pH criterion can permit pH levels now known to cause harm or death to coastal organisms (*3*) and can be expressed as a deviation from a naturally occurring pH range, for which there is often insufficient historical baseline data to clearly define (*15*).

DO minima allowable under state standards vary considerably, ranging as high as 6.5 mg liter^{-1} and as low as 2 mg liter^{-1}, despite the EPA guidance criteria of 2.3 mg liter^{-1} and 4.8 mg liter^{-1} for adult-juvenile survival and adult-juvenile-larval growth, respectively (*13*), evidencing state efforts to modify recommended criteria to protect the diverse marine taxa within regional ecosystems. In some states, saltwater DO criteria may be high enough (for example, Oregon, 6.5 mg liter^{-1}) to partially or entirely account for additional acidification stress. However, states with acute or chronic minima $\leq$3 mg liter^{-1} (for example, New York and Texas) may require a reevaluation that considers DO thresholds of local marine life under concurrent hypoxia and acidification stress, given that the negative effects of low DO and low pH can be more severe when experienced concomitantly (*4*). Moreover, future DO levels of 2.3 mg liter^{-1} could potentially have more severe negative effects on coastal animals relative to today owing to intensification of ocean acidification, particularly given the nonlinear depression of pH in hypoxic systems (*8*).

Despite the increased attention and research dedicated to ocean acidification over the past two decades, the EPA-recommended numeric saltwater criterion for pH has remained unchanged for more than 40 years (*14*). Revision of water-quality criteria follows solicitation of data, comment from the public, and evaluation of available information by the EPA. From 2009 to 2010, responding to concern over the effects of ocean acidification on coastal waters, the EPA considered revision of the recommended marine pH criterion and concluded that the data available regarding ocean acidification were insufficient to warrant changes to the currently recommended pH criterion (*9*). Acknowledging the importance of pH conditions to aquatic life, the EPA encouraged states to monitor and assess their local water bodies for acidification-related pH impairment (*9*, *15*).

Most coastal states (15 of 28) specify a pH minimum for coastal and/or estuarine waters identical to the limit recommended by the EPA: 6.5 pH units (*14*). In some states, the pH criterion consists solely of a permissible range of pH values (for example, Georgia, 6.0 to 8.5, and Maryland, 6.5 to 8.5). Many important coastal organisms experience deleterious physiological consequences and substantial mortality at pH values above the lower bounds of these ranges (*3*, *15*). In addition to pH minimum values, many states adopt standards with criteria that limit the divergence of pH from "natural" conditions in coastal and/or estuarine waters. Impermissible excursions from natural conditions vary by state (ranging from >0.1 to >1.0 pH units) but most commonly are >0.2 pH units, which is consistent with the EPA-recommended criterion, although it should be noted that the EPA recommends this criterion for open ocean waters (*14*). It is challenging to define natural reference conditions for pH because pH is influenced by local (direct acid deposition), regional (nutrient loading and eutrophication), and global (ocean acidification) anthropogenic processes acting and interacting over differing temporal scales, and long-term datasets reporting the temporal variability of pH with the certainty required to detect 0.1- to 0.2-pH unit deviations are scarce (*15*). The absence of explicitly defined natural reference conditions renders standards based on deviations from these conditions ineffectual.

It has been suggested that in some cases, pH is not the most biologically relevant acidification-related parameter to measure and that new criteria to address acidification should be developed for other variables, such as calcium carbonate saturation state, a measure related to the ability of some organisms to calcify (*15*). Although establishing such criteria could benefit aquatic life, such as in certain state waters with designated uses related to shellfisheries, widespread state monitoring of calcium carbonate saturation state requires additional measurements (of either total alkalinity, dissolved inorganic carbon, or CO_2 partial pressure) and is currently unrealistic for many states owing to the complexity and cost of performing accurate and precise analyses. Accordingly, until more feasible analytical methods become available, refinement of states' pH criteria is seemingly the most viable managerial approach to protect aquatic life from acidification-related impairment.

Beyond the water-quality standards effective under the CWA, several nonfederal policy approaches may help alleviate coastal hypoxia and acidification, including reducing coastal erosion, land-use changes (*9*), and/or regulating onsite septic systems. Without consideration of pH and DO together, many fisheries and important coastal resources are left more vulnerable than expected, especially given projections of future, climate change–induced reductions in ocean DO and pH. Therefore, increasing allowable DO minima to accommodate acidification stress, amending designated pH threshold values to biologically nonharmful levels, assessing the coeffects of low DO and low pH on more marine taxa to guide future criteria, and improving pH-monitoring efforts to more clearly define natural pH conditions are all appropriate approaches that would ultimately lead to the improved protection of fisheries and aquatic life. ■

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