Title: Community science for coastal acidification monitoring and research

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Abstract

Ocean and coastal acidification (OCA) present a unique set of sustainability challenges at the human-ecological interface. Extensive biogeochemical monitoring that can assess local acidification conditions, distinguish multiple drivers of changing carbonate chemistry, and ultimately inform local and regional response strategies is necessary for successful adaptation to OCA. However, the sampling frequency and cost-prohibitive scientific equipment needed to monitor OCA are barriers to implementing the widespread monitoring of dynamic coastal conditions. Here, we demonstrate through a case study that existing community-based water monitoring initiatives can help address these challenges and contribute to OCA science. We document how iterative, sequential outreach, workshop-based training, and coordinated monitoring activities through the Northeast Coastal Acidification Network (a) assessed the capacity of northeastern United States community science programs and (b) engaged community science programs productively with OCA monitoring efforts. Our results (along with the companion manuscript, Rheuban et al. 2021) indicate that community science programs are capable of collecting robust scientific information pertinent to OCA and are positioned to monitor in locations that would critically expand the coverage of current OCA research. Furthermore, engaging community stakeholders in OCA science and outreach enabled a platform for dialogue about OCA among other interrelated environmental concerns and fostered a series of co-benefits relating to public participation in resource and risk management. Activities in support of community science monitoring have an impact not only by increasing local understanding of OCA but also by promoting public education and community participation in potential adaptation measures.

Introduction

Ocean and Coastal Acidification

In the northeastern United States, ocean and coastal acidification (OCA) threatens the livelihoods and wellbeing of coastal communities through its current and future negative impacts on commercially important species and the delivery of coastal and marine ecosystem services (Doney et al. 2020; Ekstrom et al. 2015; Gledhill et al. 2015 and references within, Jewett et al. 2020; Kroeker et al. 2013; Mostofa et al. 2016). Ocean acidification (OA) is driven by global anthropogenic carbon dioxide (CO_2) emissions which are partially absorbed by the ocean, subsequently lowering the pH and decreasing the availability of carbonate ions used biologically (Doney et al. 2009; Orr et al. 2005). Coastal acidification refers to an additional suite of local-scale processes that exacerbate acidification in the nearshore environment by increasing the amount of CO_2 or altering the buffering capacity of coastal waters (Duarte et al. 2012 and references therein; Waldbusser and Salisbury 2014 and references therein; Wallace et al. 2014). These local-scale factors include a) the volume and characteristics of freshwater runoff and riverine inputs to the nearshore environment which can affect the alkalinity, total dissolved inorganic carbon (DIC), and pH of coastal waters; b) nutrient-driven coastal eutrophication which can increase the decay of organic matter in bottom waters, increasing CO_2 concentrations and thus exacerbating acidification, and c) coastal upwelling which can introduce deeper, more acidic ocean water into the nearshore environment.

Regionally, the northeastern United States is particularly vulnerable to OCA because the relatively cold water in this region can hold more CO_2 and low alkalinity glacial and sea ice meltwater mixes into this region from northern sources (Ekstrom et al. 2015; Gledhill et al. 2015; Salisbury et al. 2008). Relatively poorly buffered, low alkalinity river discharge within the region also magnifies vulnerability to OCA in some locations (Hunt et al 2011 a, b). Locally, the drivers of OCA vary on daily, seasonal, and decadal time scales due to tides, diurnal biological processes, seasonal changes in temperature, precipitation, and river discharge, changes in oceanic currents affecting regional water masses, and local atmospheric CO_2 concentration (Salisbury and Jönsson 2018; Townsend et al. 2015; Waldbusser and Salisbury 2014). These dynamics challenge our understanding and forecasting of carbonate system controls in the northeastern United States, necessitating a synthesis of disparate monitoring data for a location-specific understanding of OCA.

Because of OCA's multiple drivers across spatial and temporal scales and its diverse and negative impacts on coastal ecosystem services, OCA constitutes a "wicked problem" for sustainability (Billé et al. 2013; Brown et al. 2010; Galaz et al. 2012; Greenhill et al. 2020; Kates et al. 2001) to which there are no easy comprehensive policy or social solutions. Unlike climate change risks like sea-level rise, storm surge, and flooding, which have generated extensive planning and adaptation tools targeting end-users, there exists a relative dearth of such resources for OCA. Guidance for OCA adaptation can be found within select academic literature (e.g. Cooley et al. 2015; Cooley et al. 2016; Gledhill et al. 2015; Kapsenberg and Cyronak 2019; and Strong et al 2014; and materials from the Alliance to Combat Ocean Acidification, *and papers within this special issue publication*). State OCA action plans (namely California, Oregon, Washington) and Legislative directives and reports (Delaware, Federal, Hawaii, Maine, Maryland, Massachusetts, National Caucus of Environmental Legislators, New Jersey, New York, and Rhode Island) have offered direction for states to confront OCA. The majority of these resources act as comprehensive reviews of OCA science with case studies in each region.

However, prescriptive guidance for adaptation at the community scale requires robust foundational research and monitoring which is not yet available for most communities.

Addressing OCA – through mitigation, adaptation, and remediation activities – at local scales is, nonetheless, possible and is urgently needed (Cooley et al. 2016; Kapsenberg and Cyronak 2019; Kelly et al. 2011; Strong et al. 2014). These actions may require sustained, coordinated activities among individuals, scientists, non-profit organizations, industry, and regulatory agencies, collectively spanning organization and cultural boundaries. Pluralistic engagement with this novel environmental hazard can help catalyze solutions-oriented approaches which extend beyond the scientific assessment of environmental concerns to also include the social, political, and technological dimensions of solving problems associated with OCA (Miller et al. 2014; Waring et al. 2014). Extensive water monitoring that can assess local conditions, discern heterogeneous drivers, and inform local adaptation is a necessary precondition for governance structures tasked with responding to OCA (Tilbrook et al. 2019).

The equipment needed to measure carbonate chemistry parameters that define OCA and distinguish and quantify important drivers are likely to remain cost-prohibitive, time-intensive (requiring training and expertise), and unavailable for wide adoption in the near future (though we note that on the West Coast, Burke Hales at Oregon State University has been working to advance multi-parameter OCA monitoring with community organizations). Alternatively, relating common measures of water quality to patterns of variation that coincide with OCA has critical potential to improve synoptic understanding of this phenomenon and associated risks. Observations including dissolved oxygen concentration, chlorophyll-a concentration, harmful algal blooms, temperature, and salinity are often routinely and reliably measured by a range of government, institutional, and volunteer entities. Increasingly, pH is also measured by these organizations, though with varying levels of accuracy and reliability. Relating these parameters to patterns of OCA offers an opportunity to categorize location-specific vulnerability. Measurements of total alkalinity (TA), which are less frequently collected, are particularly important and can help determine the ability of seawater to resist acidification from multiple sources of CO_2 and organic and inorganic acids. TA measurements can provide important, preliminary insight into the buffering capacity of unique coastal environments (for example, Rheuban et al. 2021). In addition to TA, instrumentation for measuring other direct carbonate system parameters (pH, dissolved inorganic carbon, and pCO_2) is becoming more available over time (Tilbrook et al. 2019). The technological trend of more available monitoring instrumentation for the carbonate system, along with improved characterizations relating broader patterns of water quality with OCA may address a foundational need to expand coastal observations of OCA. Specifically, there is a present opportunity to constrain relationships between levels of salinity and total alkalinity in nearshore environments (Rheuban et al. 2021), thus enabling salinity proxies for total alkalinity, as has been performed in the northwest Atlantic continental shelf (Wang et al. 2017; Wanninkhof et al. 2015) and in other open ocean systems (Cai et al. 2011; Fassbender et al. 2017; Juranek et al. 2011;. Lee et al. 2006; Velo et al. 2013). However, to characterize TA-salinity relationships across coastal systems in the Northeast U.S. requires a highly distributed sampling plan on a scale that perhaps only community-based science organizations can attain. Furthermore, developing TA-salinity relationships could be leveraged to explore archived data from the region to hind-cast acidification and calcium carbonate saturation state from measurements over the past decade.

The need for distributed sampling to investigate salinity / total alkalinity relationships and the broader charge to compile and synthesize water quality data for OCA provide a context for community science efforts involving coastal water monitoring to make substantive contributions to OCA science. It is therefore important for the research community focused on OCA to foster engagement from environmental stewardship and community science organizations, to leverage existing data streams from these programs in OCA syntheses, and to further equip existing programs to collect carbonate system information. In this manuscript we investigate regional capacity to expand marine carbonate system monitoring to new audiences along the northeast U.S. coast, and consider the scientific and social opportunities of engaging community science organizations in region-wide total alkalinity measurements. While a companion paper (Rheuban et al. 2021) describes the scientific methods and results of region-wide sampling, this manuscript outlines a multi-year effort from the Northeast Coastal Acidification Network (NECAN) to provide training, public education, and laboratory services for existing community science organizations. (NECAN is one of six regional Coastal Acidification Network's around the United States that works to support science, monitoring and engagement around OCA).

Community Science

There is growing acknowledgement that community science approaches are increasingly well suited for twenty-first century environmental change research, which often requires data and monitoring over large spatial and temporal scales (Danielsen et al. 2005; Johnson et al. 2014; McKinley et al. 2017; Silvertown 2009). Public participation in science activities builds scientific literacy (e.g. Bäckstrand 2003; Bonney et al. 2009; Danielsen et al. 2005; Lewandowski and Oberhauser 2016), helps communities to prepare for and respond to emerging environmental and social challenges (Bonney et al. 2009), and augments attitudes and behaviors regarding environmental science and stewardship overall (Bonney et al. 2009; Ferkany and Whyte 2012). Broad participation from stakeholders and public audiences has long been acknowledged as an integral component of contemporary resource management strategies (NRC 1999 a, b). Community science is thus an especially beneficial form of research and a good use of public funds (Bond 2005; Crowdsourcing and Citizen Science Act 2017; European Marine Board 2017; Hecker 2018). Alongside professional scientists, community science programs can provide an important, complementary dimension for research (Bäckstrand 2003, Dickinson et al. 2012), including volunteer capacity when agency/research budgets are limited, expert resources scarce, and large geographic scales of research inaccessible by small research teams (Conrad and Hilchey 2011; Dickinson et al. 2012; Poisson et al. 2020). The Crowdsourcing and Citizen Science Act (Section 402 of The American Innovation and Competitiveness Act 2017), states that "crowdsourcing and citizen science projects have a number of additional unique benefits, including accelerating scientific research, increasing cost effectiveness to maximize the return on taxpayer dollars, addressing societal needs, providing hands-on learning in STEM, and connecting members of the public directly to Federal science agency missions and to each other." (Crowdsourcing and Citizen Science Act, Public Law 114-329 (6 January 2017), codified at 15 U.S.C. § 3724.). These features are especially important for *sustainability science* (Kates et al. 2001) related to OCA, as the environmental phenomenon is emergent, complex, and requires management strategies with cross-sectoral implications.

Relative to most community science, water monitoring is a particularly mature form of public scientific engagement, established from decades of partnership across scales of governance and robust support and training resources to ensure data quality (Poisson et al. 2020). Nationwide, more than 1,600 U.S. community science programs actively monitor water quality (Stepenuck 2013). Such programs are especially effective for identifying environmental problems, offering a geographically distributed sampling approach which can triage locations where more targeted measurements may be necessary.

While community monitoring programs are more common for freshwater systems than marine environments (Cigliano and Ballard 2018; Conrad and Hilchey 2011, Njue et al. 2019), water quality measurements from community scientists regularly reach professional data quality standards (Elliott and Rosenberg 2019; Loperfido et al. 2010), and community science programs are widely incorporated in state and federal agency databases which inform management (EPA 2016; Latimore and Steen 2014). The success of such community science monitoring, now with a precedent for extensive documentation and quality control procedures (EPA 2019; Freitag et al. 2016), correlates with increasing accuracy/accessibility and decreasing cost of technology for observations and data collection (e.g. sensing equipment, test kits, GIS, and data repositories) (Buytaert et al. 2014; Catlin-Groves 2012; Khamis et al. 2015; Njue et al. 2019).

However, data management and research inconsistencies remain a challenge for community science data to reach peer-reviewed academic literature, and community science data is often granted less validity within academic and decision-making arenas (Catlin-Groves 2012; Wilson et al. 2018). Instrumentation for water monitoring has inherent observational challenges, depends upon exacting instrument calibration, and requires unique criteria and quality assurance to ensure robust data (e.g. Capdevila et al. 2020). Monitoring water quality in marine environments magnifies many operational hurdles as coastal ocean biogeochemistry is highly variable, the inputs which disperse into coastal systems (water, nutrients, pollution, etc.) are hard to link to sources within specific communities, and safe accessibility to ocean environments can be limited. Additionally, differing sampling intervals for the carbonate system can obscure interpretations of acidification (Pettay et al. 2020), compelling observations to be made with unique, ecologically informed sampling strategies or with continuous monitoring equipment less available among community science programs. These difficulties and the communication and coordination that they require can make regular engagement with – and continued motivation of – community science participants even more challenging.

Furthermore, oceanographic and regulatory communities have not yet established a precedent for what level of precision in OCA monitoring is necessary to justify intervention. Differentiated *Climate Quality* data versus *Weather Quality* data (Newton et al. 2015) do not yet have distinct utilities for local management. Making community science data on OCA conditions operational for decision making foremost requires that data across regions be comparable. The need for standardized monitoring has been repeatedly identified in the northeast region; within a legislatively commissioned report on OCA in Maine in 2015, through previous stakeholder workshops hosted by the Northeast Coastal Acidification Network (NECAN) in 2013-2014, and through consultation with the NOAA Ocean Acidification Program Office. Recognizing broad, increasing interest in monitoring OCA, in 2018, The U.S. Environmental Protection Agency (EPA) developed comprehensive guidelines for measuring carbonate system parameters which targeted community science audiences (Pimenta and Grear 2018). NECAN then coordinated outreach and recruited community science programs to a training program based upon the EPA recommendations.

Few community science programs in the northeastern United States investigate OCA specifically. However, the critical need to fill observational gaps and the importance of sharing EPA guidelines for measuring acidification with community science programs initiated efforts to build capacity for a distributed and coordinated observation system with potential to evaluate OCA conditions. Importantly, expanding civic participation in OCA science and supporting location-based monitoring networks is not just a pathway to obtaining more and better data; it is also a strategy for achieving real solutions to the risks of OCA by connecting local audiences to the science and governance of environmental phenomena which affect their own community. We hypothesized that involving community science programs in OCA research and monitoring is a reasonable approach to attracting diverse audiences to engage with the broader issue of OCA including management, adaptation, mitigation, and education. In this manuscript we test the implications of connecting community science programs with OCA research institutions in the Northeast U.S. We describe an approach to training and supporting community science programs to investigate OCA and share a process to orchestrate simultaneous measurements of total alkalinity at a regional scale. Finally, we consider the significance of incorporating OCA literacy and observation with dimensions of local stewardship and governance, for which community based water quality monitoring programs play a distinct role.

Methods

We conducted a series of outreach and training activities from 2017 to 2020 for community science programs which culminated in a regional monitoring event. Figure 1 shows the sequence of outreach and training activities. Beginning in 2017, members of NECAN reached out to research partners and affiliates to inventory coastal water quality monitoring activities from Long Island Sound to Downeast Maine and compiled a contact list of community science programs. We distributed surveys through email to 57 community science programs monitoring water quality in Connecticut, Massachusetts, and Maine. Surveys used open response questions (see supplemental information S.1.) designed to locate monitoring stations, identify the parameters measured and the equipment used by staff or volunteers, and explore organizational interest in climate change monitoring, and contextual information about the programs constituency, existing collaborations among programs and other institutions, and which environmental issues motivate monitoring efforts. Iterative interactions, predominantly through phone calls, email and occasionally during academic conferences and public forums, refined our initial contact list and we invited representatives from community science programs to a training and workshop series in 2018 focused on guidelines for monitoring acidification with staff scientists from EPA. NOAA Ocean Acidification Program provided support for two informational webinars, three in-person workshops, and for the process of compiling OCA educational and outreach resources as a preliminary toolkit for community scientists.

Members of NECAN hosted three workshops in 2018 in Connecticut, Massachusetts, and Maine. These events were co-organized and co-coordinated with the Connecticut Department of Energy and Environmental Protection, the Connecticut Department of Agriculture, Massachusetts Institute of Technology (MIT) Sea Grant, University of New Hampshire, Maine Sea Grant, University of Maine, University of Maine Cooperative Extension Office, the Senator George J. Mitchell Center for Sustainability Solutions, the EPA Atlantic Coastal Environmental Sciences Division, and the NOAA National Centers for Coastal Ocean Science. Additional partnering programs provided local expertise and workshop presentations, and included Woods Hole Sea Grant, Woods Hole Oceanographic Institution, MIT, and Bowdoin College Shiller Coastal Studies Center. Training focused on approaches for monitoring carbonate system parameters directly while also understanding how common water quality observations relate to OCA (i.e. salinity, nutrient concentration, and oxygen concentration).

Workshop discussions clarified opportunities for coordinated monitoring, identified suitable carbonate system parameters that could be measured among community science groups

(Figure 2, Figure 3), and gauged interest in coordinated sampling. Measuring total alkalinity was determined to be an optimal improvement to existing monitoring activities as the parameter is easily collected through bottle sampling, samples can be preserved within 24 hours of collection, and many laboratories and research institutions are available to analyze samples collected by community science programs. Throughout 2019, members of NECAN convened resources, staff, and laboratory services sufficient to analyze total alkalinity from samples collected by community science programs region wide. To ensure robust data collection, the research team generated a sampling protocol video, written sampling instructions, and training webinars alongside an EPA approved Quality Assurance Project Plan (QAPP). These resources were shared with northeast community science programs and are publicly available at: http://necan.org/shellday.

Simultaneously, through phone calls and emails, members of NECAN recruited additional monitoring participants including research institutions, universities, and student groups. Partners including the Nature Conservancy, EPA, and the Sea Grant programs, along with several community science programs involved in the previous training series worked to publicize plans for the single-day, region-wide monitoring event, "Shell Day." We developed a Shell Day logo and created printed and email newsletters and used these resources to further publicize the event and recruit broader participation. Communication materials were shared through the NECAN website and listserv, the Ocean Acidification Information Exchange, the International Alliance to Combat Ocean Acidification, and various social media and local news outlets including one local television station.

On August 22, 2019, NECAN orchestrated the Shell Day monitoring event with sampling stations spanning from Long Island Sound to eastern Maine (Figure 4). The date was chosen for low and high tides during daytime hours appropriate for voluntary participation. Among dates meeting these criteria, we opted for a day with a morning low tide. Theoretically, this design offered a magnified gradient of conditions of acidification as a low tide in the early morning would be more dominantly influenced by riverine discharge and overnight biological respiration and afternoon conditions driven by greater photosynthesis and oceanic tidal inputs. Water quality monitoring groups recorded temperature and salinity and collected TA water samples during low, mid, and high tide at locations of their choosing. Participating programs recorded additional chemical and biological parameters based upon staff and equipment available to each program. Following sample collection, participants convened at nearby science hubs, delivering water samples for total alkalinity analysis, and meeting to further discuss coastal acidification science and collaborative monitoring initiatives. Sampling methodology and results from the Shell Day data set were published by Rheuban et al. 2021.

Following Shell Day, we distributed surveys to investigate the impact of Shell Day on public OCA education and the potential for ongoing OCA research by community science programs. Surveys were sent to each of the 59 participating programs and 34 responses were received. A full list of survey responses is available within the supplemental materials to this manuscript (S.2.).

Results

Here we present the results of Shell Day in three parts: results from a regional background survey, results from a training series conducted with community science monitors in 2018, and finally results from the Shell Day monitoring in 2019. In 2017 background survey on community science programs in Connecticut, Massachusetts, and Maine investigated where monitoring is taking place, what is measured, how it is measured, who is involved, and if programs prioritize climate change monitoring. Next, we share the results of a training series based upon EPA guidelines for measuring coastal acidification which involved community science programs from the northeastern United States (New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine). Next we present the results from Shell Day, where community science programs and research institutions adjoined for simultaneous, region-wide sample collection at low, mid and high tide on August 22, 2019. Finally, we share survey results after Shell Day which investigated the social impact and public education results of the training program and Shell Day.

Regional Survey Results from 2017

Initial surveys regarding programmatic details of monitoring programs sent in 2017 to 57 community science programs in Connecticut, Massachusetts and Maine received 47 responses from program coordinators (18 in Connecticut, 15 in Massachusetts, and 14 in Maine). All responses regarding organizational purpose and data sharing voiced priorities for credible, informative data (see supplemental material S.1.). There is currently not a single data repository for water quality monitoring information nor for OCA monitoring information within the region, and survey results identified disparate databases utilized among programs (supplemental material S.1. 2).

Equipment used to measure carbonate system parameters among community science organizations (Table 1) include handheld single parameter devices, more sophisticated multiparameter sondes, and laboratory benchtop models from multiple providers (a full list of equipment within supplemental material S.1. 9, S.1. 10).

Community science program coordinators shared that environmental stewardship, protecting natural resources, and concern for climate change were near-ubiquitous program priorities. Responses supported our expectation that monitoring programs in the region would be interested in OCA as a nexus of local concerns and global climate change. For example, when asked, "In your opinion, what might motivate volunteers or *citizen scientists* to be involved with OCA?" one respondent said,

> *"The opportunity to take action and participate in programs that 'fight' climate change. The general public is very concerned about climate change, as we (you) all know. I think providing people with opportunities to be involved in the issue provides an avenue for "doing something" about it, rather than just sitting on the sidelines complaining or lamenting."*

Responses illustrated that volunteer monitoring programs are often a coalition of diverse perspectives (S.1. 7). For example, one respondent stated,

> *"There are different motivating factors for specific interest groups. Shellfish harvesters are motivated by financial self-interest and tradition. Volunteers engaging as 'scientists' are motivated by life-long learning, environmentalism, etc. Educational institutions and educators have interest in engaging students in meaningful real-world problems contributing to a greater good. Volunteers need to be segmented into multiple populations to assess what motivates them, there will be many answers."*

Informed by survey responses, we concluded that our work to frame OCA as a salient issue among audiences would require tailored communication among constituencies throughout stages of outreach, training, and recruitment for monitoring.

Training Series Results

Continued outreach framed OCA within the shared themes voiced by community science programs in our 2017 survey: local water quality, promoting healthy coastal fisheries and ecosystems, habitat protection, and nutrient pollution reduction. We continued communication with training series participants through sharing newsletters, email correspondence, and in-person conversations highlighting that local-scale observations are necessary to connect OCA with previously voiced program priorities.

In 2018, our research team held single-day training workshops in Connecticut, Massachusetts, and Maine informed by EPA "Guidelines for Measuring Seawater pH and Associated Carbonate Parameters in the Coastal Environments of the Eastern United States." Forty community water monitoring programs participated in day-long training workshops.

During workshops, printed maps were populated with sticky note descriptions of monitoring locations and strategies among attending programs. The extent of monitoring stations among embayments and the longevity of sampling (often > 15 yrs) shared in this exercise warranted further development of GIS tools (Figure 3) to compile monitoring stations and pertinent metadata. This work is ongoing, and now also includes data from research institutions in addition to community science data, and has, to date, collectively inventoried 1,170 monitoring stations within the region. More than 70% of recorded stations measure one or more direct carbon system measurements (pH, pCO2, TA, or DIC) (830 of 1170), and 78% of stations collected data using Quality Assurance Project Plans (918 of 1170). This open-access, GIS Story Map (Figure 3) resides through the Connecticut Department of Energy and Environmental Protection and can be found at https://storymaps.arcgis.com/stories/fae30818a6164043a0d368ba0cd7bad3.

Workshops and subsequent communication established that community water monitoring groups, while infrequently measuring the carbonate system directly, have collectively made thousands of nearshore measurements of parameters that relate to carbonate system dynamics. Workshop materials and resources are available on NECAN.org under resources and at http://necan.org/OCACitizenScienceWorkshops; webinars are available at http://www.necan.org/ocean-and-coastal-monitoring-webinars-citizen-scientists).

Shell Day Results

Shell Day, a single-day monitoring event which spanned from Long Island Sound to eastern Maine, piloted a novel OCA research approach connecting scientific laboratories with extensive community science volunteer participation, enabling simultaneous, climate-quality observations at a regional scale. For information on Shell Day data quality see Rheuban et al. 2021 and the supplemental material to Rheuban et al. 2021.

During Shell Day, 59 monitoring organizations participated in collecting samples from one or more stations. A total of 410 TA samples were collected from 86 coastal locations (Figure 4). During water sample collection, participation extended beyond community science programs identified in previous outreach activities to also include colleges, universities, and student groups. Participants were asked to deliver samples to nearby laboratories on the day following sample collection. We leveraged this opportunity to also convene participants for 2-4 hour workshops/celebrations at local laboratories as an approach to continue dialogue and capacity building for OCA and coordinated monitoring. Seven institutional laboratories partnered with this effort, preserved samples within 24 hours of collection, and later analyzed samples for TA. A broader team of researchers interpreted the data set as a regional snapshot and study results were published by Rheuban et al. 2021.

Shell Day Follow-up Survey Results

In the fall of 2020, we sent surveys to the 59 programs who collected samples on Shell Day and received survey 30 responses (a full list of survey responses is included within the supplement to this manuscript). Responses showed that among this subset of Shell Day participants, 140 staff were directly involved in sampling and training, and 44% of programs had never engaged in OCA research. Through attendance in webinars, sample collection, and meetings, Shell Day participants collectively contributed 1,140 hours of volunteer time. Our surveys asked how each community science program disseminated education/information on OCA and Shell Day to their own constituents (Table 2). Specifically, we asked "How many people do you estimate to have already reached through the following activities relating to Shell Day: casual conversation, public speaking, newsletters, and social media (Survey scroll bars allowed respondents to select between zero and three hundred people for each category)". Responses indicated that at the time of the survey, community science programs had already shared information about Shell Day with an estimated 10,880 people. Table 2 comprises a subset of 30 respondents from 59 participating programs and therefore likely underestimates the total outreach conducted by community science organizations who participated in Shell Day.

Survey responses illustrated common themes; the impact of participation in Shell Day on civic engagement, public education, and capacity building. For example, one respondent stated,

> *Participation in Shell Day has had a great effect on how our department is communicating with supporters and local voters as we have a large shellfish fishery on Nantucket that supports our local economy. Monitoring water quality is imperative as this impacts the health of our aquatic organisms, including our important bay scallop industry. With increasing ocean acidification, the health of our shellfish are at risk which has major implications for our local economy. Our participation in Shell Day, in addition to the results it produced, was instrumental in communicating effectively the importance of monitoring our water quality.*

Surveys also indicated that participating in the regional event and prior training series augmented programmatic understanding and interest in OCA science for some organizations (S. 2.1). For example, one respondent stated,

> *Participating in Shell Day has made us consider if we should start monitoring for Coastal Acidification in the brackish section of the river. We are in the middle of creating our strategic plan for the next five years, and one of the priorities that may be added to our monitoring program is taking Coastal Acidification samples.*

Another respondent described more immediate expansion of their monitoring program, saying,

> *Participation in Shell Day has had an effect on our program priorities. We recently applied for and were granted funding for instrumentation to measure alkalinity in our lab so will gradually add this into our routine water quality monitoring program.*

Hosting workshops in Connecticut, Massachusetts, and Maine, and later hosting gatherings at local laboratories following Shell Day sample collection was not only logistically advantageous for the design of this effort, but also fostered place-based, collaborative relationships. More than 50% of respondents indicated novel and sustained collaborations resulting from Shell Day (S. 2.3). The following quotes illustrate a range of collaborations resulting from Shell Day:

"Participation in Shell Day ... reminded our department of the benefits of collaboration and sharing information across different organizations"

"We began working closely with … the UNH Ocean Process Analysis Laboratory, assisting with salinity measurements and also with ... the Jackson Estuarine Lab on sample collection and data logger deployments."

"Since Shell Day, we have been talking with the Center for Student Coastal Research and trying to plan programs to collaborate with them, … such as river cleanups and water sampling opportunities."

In response to the survey question, "Is your organization interested to participate in discrete monitoring events like Shell Day for coastal acidification as part of a regional network in the future?" all completed responses indicated yes.

Discussion

Results from Shell Day substantiated expectations that (a) water quality monitoring programs are positioned to engage in OCA research, (b) distributed sampling approaches are a viable strategy to fill data gaps, and (c) comparative, simultaneous observations among coastal locations have the potential to identify sites with amplified risk to OCA (described fully in Rheuban et al. 2021). OCA Action Plans (the principle planning framework for OCA) typically outline a long-term sequence of information gathering and research, convene disparate agencies and stakeholders to amend existing policies to include OCA, and identify interventions which mitigate impacts and promote adaptation (Cite OA Alliance paper in this issue). Our work has shown that Northeast coastal communities are home to community science programs which are motivated and capable to participate in carbonate system monitoring recommended among OCA Action Plans. Though beyond the scope of our training activities and the 2019 Shell Day event, consistent, long term coordination between community scientists and professional researchers to monitor conditions of acidification at multiple timepoints in the seasonal carbonate system cycle has the potential to act as a rapid condition assessment which can triage locations for further investigation (Rheuban et al. 2021). The need for such approaches to assess vulnerability and data that can inform forecasts is amplified by predictions of increasing variability in climate and ecological paradigms globally and in the Northeast (Brickman et al. 2018; Record et al. 2019; Townsend et al. 2015; US Dept. of Commerce 1999; US Global Change Research Program 2001).

Historically, barriers between climate science and water quality management can arise when recommendations from the research community are developed without decision makers themselves, leading research expectations to inadequately consider the limitations of local management (Jacobs 2002). In contrast, many community science organizations have a rich and sustained history of interfacing with local decision making and may help to bridge divides between academia and management. Research participation from a variety of stakeholders during Shell Day and previous outreach enabled a dialogue about the salience of OCA among other interrelated environmental concerns (e.g. Cash et al. 2002). Thus, the boundary spanning qualities of community science programs may broaden the relevance of OCA among decision-makers and assist the research community in generating science that is relevant to community needs (e.g. Bednarek et al. 2018). Because community science organizations function as communicators and educators to a broad public audience, monitoring training, outreach activities and participation in projects such as Shell Day may help to share public education for OCA and advance local capacity to respond. Adaptation to OCA can garner further public support when decision makers and stakeholders understand that the drivers of OCA relate to existing and shared priorities for clean water, habitat protection, and economic resilience. Various reports have called for research and vulnerability assessments for OCA to better reach and collaborate with information end-users and local decision-makers, thus building mutual understanding that can lead to adaptive action (e.g. Cooley et al. 2015; Jewett et al. 2020; Strong et al. 2014).

Clark et. al 2016's recommendations for sustainability strongly advise researchers not to pursue their search for knowledge in isolation from the broader community. Defining the scope of community engagement in research is a clear challenge. Yet, *sustainability science* practitioners emphasize that sustained engagement and iterative processes are most likely to result in useful research (e.g. van Kerkhoff and Lebel 2006). Similarly, hands-on engagement and collaboration between local actors and experts is likely to be necessary for planning and implementing community resilience efforts for OCA in the Northeast and elsewhere. Our approach to engage community science programs with regional OCA monitoring aligns with these modalities of research and social-ecological problem solving.

Conclusion

The water chemistry results from Shell Day (Rheuban et al. 2021) indicate that community science programs are already able to collect reliable scientific information for OCA with sufficient accuracy to distinguish areas of elevated risk. Evidenced by broad participation in Shell Day and the outreach conducted by community science organizations to their own constituencies on behalf of Shell Day (Table 2), our research shows that engaging community science programs in OCA monitoring is a productive way to reach broad, public audiences. We encourage research organizations and funding institutions to align needs for geographically distributed OCA monitoring with existing water quality monitoring programs, and to provide training and further opportunities for participation. Such efforts, in our view, are essential to build local capabilities to discern coastal carbonate system information, and to connect the stewardship objectives of community science programs to social-ecological challenges presented by OCA.

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List of Organizations who participated in Shell Day activities:

1 Aquacultural Research Corp, 2 Barnstable Clean Water Coalition, 3 Boothbay Region Land Trust, 4 Boston Harbor Island National and State Park, 5 Belfast Bay Watershed Coalition, 6 Bigelow Laboratory, 7 Buzzards Bay Coalition, 8 Cape Cod Cooperative Extension, 9 Committee for the Great Salt Pond, 10 Connecticut Fund for the Environment (Save the Sound), 11 Clean Up Sound and Harbors, 12 Casco Bay Estuary Partnership, 13 Center for Coastal Studies, 14 Cohasset Center for Student Coastal Research, 15 Derecktor Shipyards, 16 Downeast Institute, 17 EPA Atlantic Coastal Environmental Sciences Division, 18 EPA Region 1, 19 Earthwatch/Schoodic Institute, 20 Friends of Casco Bay, 21 Falmouth Water Stewards/Pond Watch, 22 Harbor Watch, 23 Hurricane Island Center for Science and Leadership, 24 Interstate Environmental Commission, 25 Island Creek Oysters, 26 Island Institute, 27 Kennebec Estuary Land Trust, 28 Maine Coastal Observers Alliance, 29 Maine Department of Environmental Protection, 30 Maine Maritime Academy, 31 Marine Biological Lab, 32 Martha's Vineyard Commission, 33 Martha's Vineyard Shellfish Group, 34 Massachusetts Maritime Academy, 35 Mook Sea Farm, 36 North and South River Watershed Association, 37 Nantucket Land Bank, 38 Nantucket Land Council, 39 Nantucket Natural Resources Department, 40 Neponset River Watershed Association, 41 New England Aquarium, 42 New England Science and Sailing, 43 Pleasant Bay Alliance (Friends of Pleasant Bay), 40 Rockport Conservation Commission, 41 Water for ME Foundation, 44 Salem Sound Coastalwatch, 45 Swampscott Conservancy, 46 Salt Ponds Coalition, 47 Save Bristol Harbor, 48 Save the Bay, 49 Setauket Harbor Task Force, 50 Shaw Institute, 51 Town of Mashpee Department of Natural Resources, 52 University of Maine-Machias, 53 University of New Hampshire, 54 UNH Marine Docents, 55 URI Watershed Watch, 56 University of New England, 57 Wampanoag Tribe of Gay Head (Aquinnah), 58 Woods Hole Oceanographic Institution, 59 Woods Hole Sea Grant.

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Figure 1. Process diagram of outreach and collective monitoring from 2017-2020.

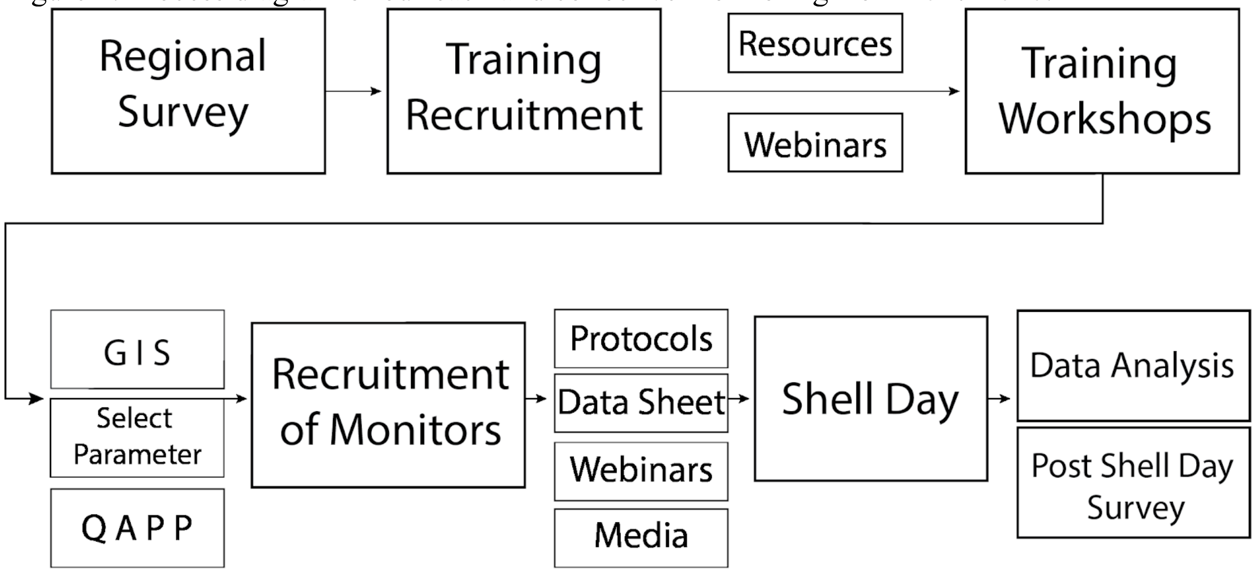

Figure 1. Process Diagram.
Figure 1 shows the sequence of NECAN's engagement with community science programs from 2017-2020, including outreach, training, developing resources for monitoring activities, and coordinating simultaneous monitoring.

Figure 2. Carbon system diagram with related water quality parameters collected by community science programs.

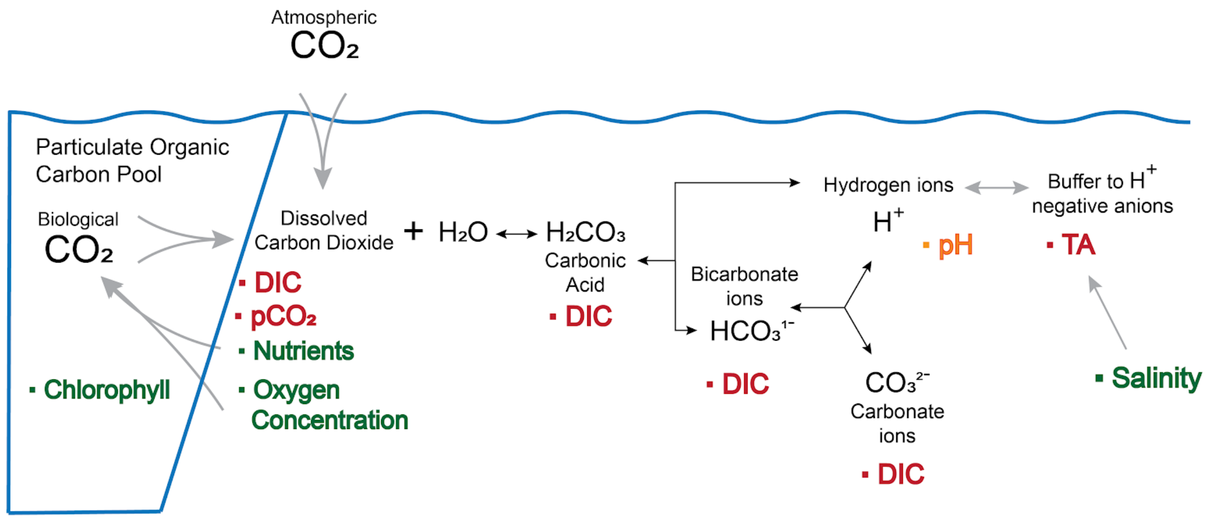

Figure 2. Community Science Measurements and the Carbon System.
Figure 2 situates common water quality measurements among community science programs in a context of biogeochemical interactions driving the marine carbon system. Shown in black are the constituents of the marine carbon system and related factors (hydrogen ions, buffer anions, and dissolved and particulate organic carbon). Parameters shown in red (DIC; dissolved inorganic carbon, pCO2, and TA; total alkalinity) are not commonly measurable by community science programs. pH, shown in yellow, is occasionally measured by community science programs. Parameters shown in green (chlorophyll, nutrient concentrations, oxygen concentration, and salinity) are commonly measured among community science programs in the northeastern United States. Color coding is based on survey results shown in Table 1. Black arrows indicate chemical relationships among constituents of the carbon system while grey arrows and the grouping of observable parameters indicate environmental interconnection. Two of the four direct carbonate system measurements (pCO2, DIC, pH and TA) are required to calculate saturation state (**Ω**), a critical indicator of accretion/dissolution potential for calcium carbonate minerals.

Figure 3. GIS map of northeast United States monitoring programs

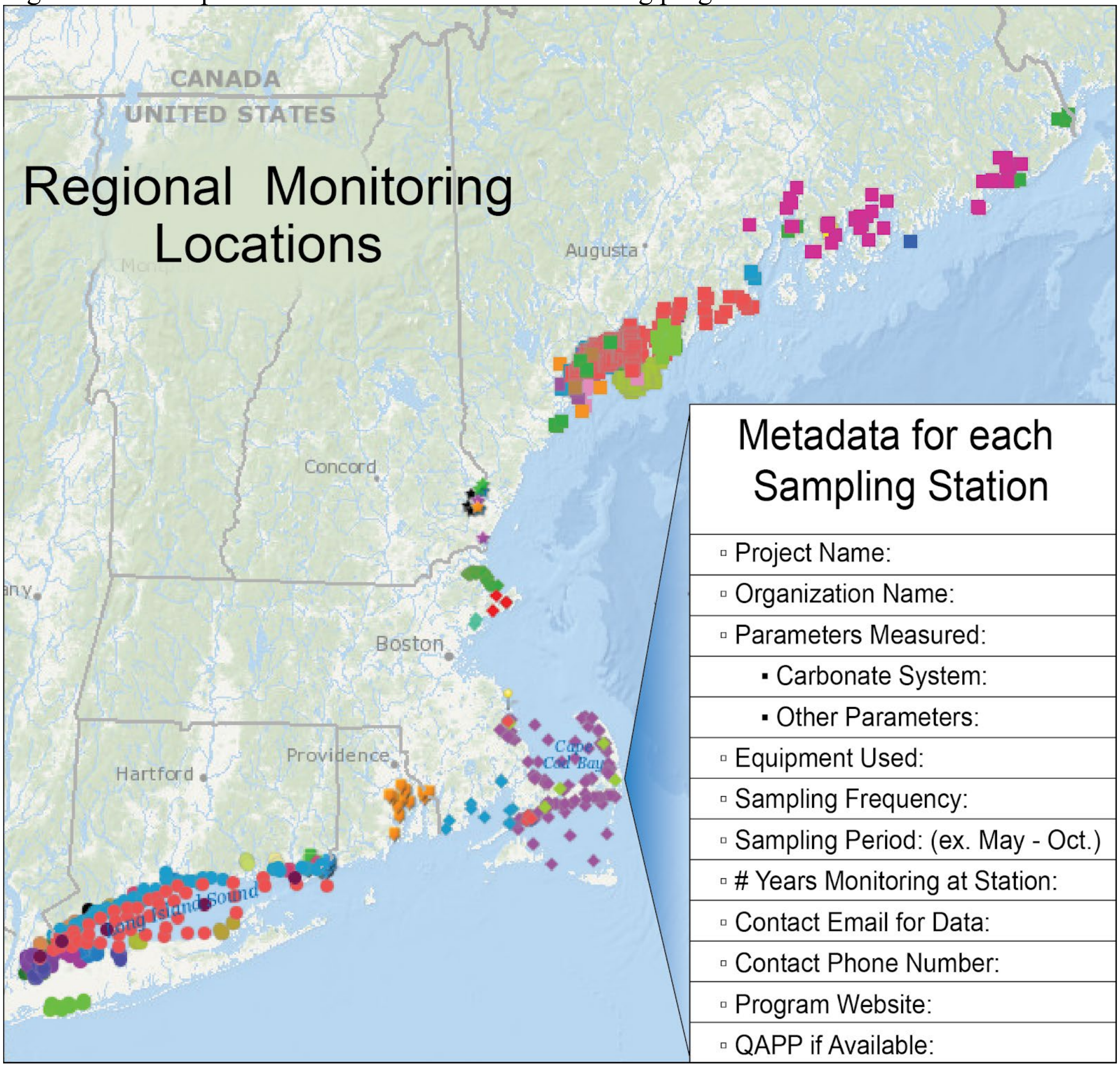

Figure 3

Figure 3 illustrates an open access GIS StoryMap created to compile metadata among community science water monitoring programs in the northeastern United States. This resource is open access and can be found at: https://storymaps.arcgis.com/stories/fae30818a6164043a0d368ba0cd7bad3

Station locations are tagged with project name; group/organization; station name; station description; station latitude and longitude; direct carbonate parameters measured (pH, pCO_2, total alkalinity, total dissolved inorganic carbon); linked parameters (temperature, salinity, nutrients, and other parameters measured on-site); the sampling equipment used for each parameter; the sampling period (#years and seasons monitored for example May- Oct.); the sampling frequency at each site; contact email and contact phone number needed to connect with program staff and access data directly; and a link to available Quality Assurance Project Plans for each program.

Figure 4. Stations sampled during Shell Day single day monitoring event.

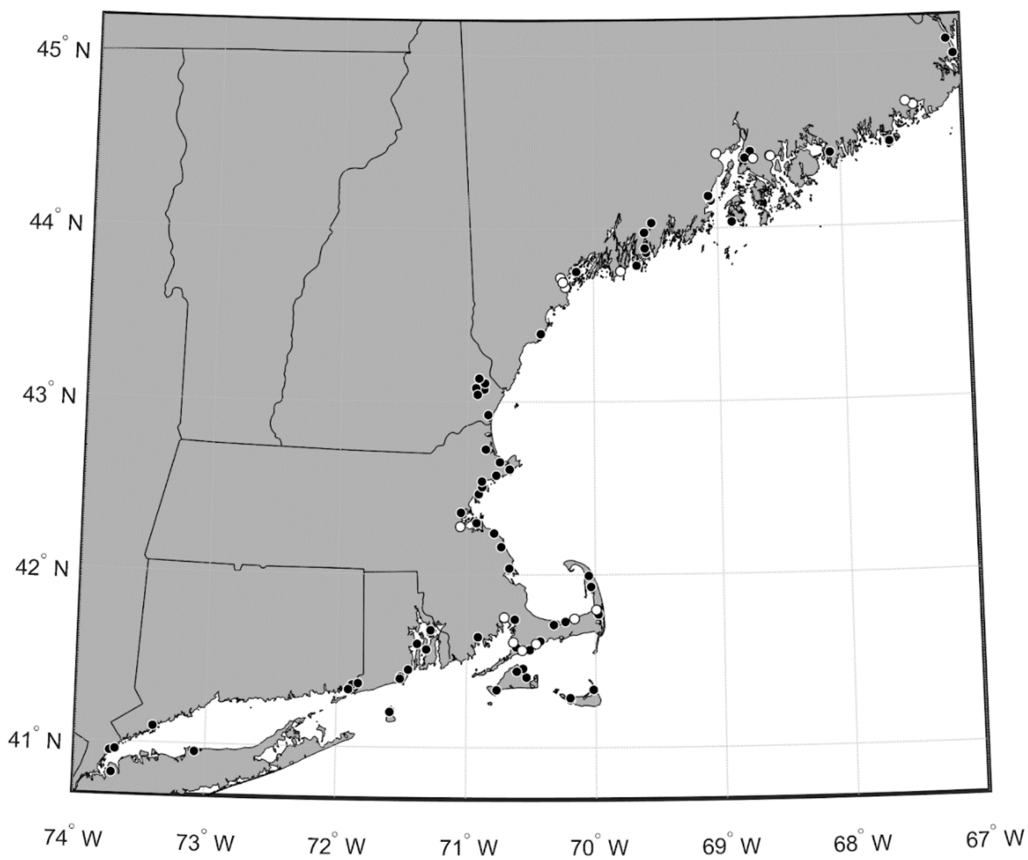

Figure 4.
Figure 4 illustrates the sampling stations for Shell Day, a single-day monitoring event spanning from Long Island Sound to eastern Maine, in which 59 monitoring organizations participated in collecting samples from one or more stations. A total of 410 TA samples were collected from 86 coastal locations White circles indicate stations with magnified vulnerability to acidification, representing extreme values (20th percentiles of lowest mean level of total alkalinity and 80th percentiles for highest standard deviation) in the distribution of the Shell Day data (Rheuban et al. 2020).

Table 1. Parameters measured among community science programs in three states in New England.

	Regional Average	Connecticut	Massachusetts	Maine
Temperature	78%	78%	93%	100%
Biological monitoring	78%	78%	73%	91%
Salinity	67%	67%	73%	82%
Oxygen Concentration or Saturation	56%	56%	67%	64%
Chlorophyll-A	56%	56%	67%	45%
pH	33%	33%	60%	36%
Other Nutrients	33%	33%	60%	36%
Nitrogen	33%	33%	47%	27%
Turbidity	22%	22%	40%	18%
Total Alkalinity	22%	22%	33%	18%
pCO_2	11%	11%	13%	18%
Light Attenuation	11%	11%	13%	9%
Dissolved Inorganic Carbon	11%	11%	13%	9%
Colored Dissolved Organic Matter	0%	0%	7%	18%

Table 1.
Table 1 shows the % frequency of parameters measured among and within Connecticut, Massachusetts, and Maine community water monitoring programs in marine environments. Carbonate system parameters and necessary ancillary measurements for calculating saturation state are highlighted in blue.

Table 2. Outreach conducted by community science programs on behalf of Shell Day.

	The average number of people reached among respondents engaging in each activity (i.e. values of zero excluded).	Range	Total number reached
Casual Conversation	47	5-250	1396
Public Speaking	90	31-300	1791
Newsletters	183	55-300	3653
Social Media	155	15-300	4040

Table 2.

Table 2 shows results from 30 survey respondents to the question, "How many people do you estimate to have reached already [regarding Shell Day] through the following activities (casual conversation, public speaking, newsletters, and social media.)? (Survey scroll bars allowed respondents to select between zero and three hundred people for each category)". At the time of this survey, 30 community science programs had already shared information about Shell Day with 10,880 people.

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