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CITIZEN SCIENCE TO SUPPORT CLIMATE-READY MANAGEMENT OF UNITED STATES FISHERIES

Environmental
Defense
Fund

Citizen Science to Support Climate-Ready Management of United States Fisheries

Authors:

Gemma Carroll
Environmental Defense Fund

Matthew Seeley
Environmental Defense Fund

Christopher Cusack
Environmental Defense Fund

Dustin Colson Leaning
Environmental Defense Fund

Allison Shields
Environmental Defense Fund

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS 1
EXECUTIVE SUMMARY 2
INTRODUCTION 3
  What is citizen science? 5
  Why citizen science? 6
1. U.S. CITIZEN SCIENCE PROGRAMS THAT SUPPORT CLIMATE-RESILIENT FISHERIES MANAGEMENT 7
  1.1 Contributory research programs 7
  1.2 Collaborative research programs 9
  1.3 Co-created research programs 11
2. OPPORTUNITIES TO FILL INFORMATION GAPS WITH NEW OR EXPANDED CITIZEN SCIENCE PROGRAMS 12
  2.1 Environmental change 13
  2.2 Ecological responses 14
    Information to improve stock assessments 14
    Information on rare, invasive and redistributing species 17
    Information on the spread of environmental toxins and disease outbreaks 18
    Information on ecosystem status 19
  2.3 Social responses 19
3. RECOMMENDATIONS FOR INTEGRATING CITIZEN SCIENCE INTO CLIMATE-READY FISHERIES MANAGEMENT 21
  3.1 Establish clear goals 22
  3.2 Design a project that can meet goals 22
  3.3 Recruit the right people 23
  3.4 Retain participants 23
  3.5 Support uptake into management 24
CONCLUSION 24
REFERENCES 25

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EXECUTIVE SUMMARY

The strong record of sustainable fisheries management in the United States (U.S.) is being challenged by the rapid, widespread and unpredictable impacts of climate change. Management decisions are being made in the face of unprecedented shifts in environmental, ecological and socioeconomic conditions, necessitating scientific information at scales that can no longer be met by traditional data sources. A new paradigm of data collection is needed to support climate-resilient management to ensure that U.S. fisheries continue to provide ecological, social and economic benefits for generations to come.

Citizen science presents an opportunity to greatly expand the scale and scope of fisheries data collection, leveraging the vast population of Americans who have “eyes on the water” and a stake in sustainable management outcomes. Citizen science programs can help bridge the gap between scientists, managers and the public, increasing community buy-in to climate-ready management and the representation of diverse stakeholders within management processes.

We reviewed citizen science programs in the U.S. that currently support or could support fisheries management under climate change. We identified a wide spectrum of data types that are being collected by citizens and diverse models of citizen engagement in scientific and management processes. Building from successful programs and a review of data gaps for climate-resilient fisheries management, we then identified seven priority information gaps that new or expanded citizen science programs could be well-suited to fill:

1. **High-resolution ocean data collected from fishing vessels** to improve climate models and early warning systems for extreme climate events.
2. **Length & weight data collected by commercial and recreational fishermen** from harvested and discarded catch to improve stock assessments.
3. **Observations of rare, redistributing or invasive species** to identify climate-driven shifts in fishery distribution and ecosystem structure.
4. **Specimen collection for surveilling climate-induced disease and environmental toxins** to improve forecasts of outbreaks in fisheries and improve public health responses.
5. **Surveys of ecosystem indicators** to inform ecosystem-based fisheries management.
6. **Information on changes in fishermen behavior and perceptions** in response to shifts in fishery availability to improve understanding of climate impacts on community resilience.
7. **Data on the response of markets and supply chains** to changes in fishery availability to enhance community access to local seafood.

We recommend actions to guide the design and implementation of citizen science programs for climate-ready fisheries. These actions are intended to overcome known challenges of citizen science, including misalignment between project goals and management needs, concerns over data quality, the high costs of administering programs, challenges of motivating and sustaining participation, and inertia in management processes. By expanding well-designed citizen science programs, we can direct the enthusiasm and expertise of the public into meaningful work that increases fishery resilience while deepening public engagement in science and management.

INTRODUCTION

Climate change is altering ocean ecosystems with cascading impacts on fisheries and the communities that depend on them (Hoegh-Guldberg and Bruno 2010; Gattuso et al. 2015; Barange et al. 2018). Although the urgency of addressing these challenges is widely acknowledged, large gaps remain in our understanding of climate change impacts at geographic and time scales relevant to fisheries management, and in the ability of existing management processes to adapt to new oceanographic, ecological and social conditions (Holsman et al. 2019). Filling information gaps and implementing “climate-smart” management approaches will be critical to increase the resilience of fisheries to climate change and to safeguard the wellbeing of the millions of people who depend on fishing for food, nutrition and livelihoods (Garcia and Rosenberg 2010; Peterson Williams et al. 2022).

Traditional methods of collecting data for stock assessments and to determine reference points include fishery-dependent methods such as logbooks, at-sea observers, camera-based electronic monitoring (EM) and dock samplers, as well as fishery-independent methods including scientific survey cruises. However, the impacts of climate change on target stocks and ecosystems can be rapid, unexpected and widespread, often outstripping the capacity of conventional data sources to provide information at appropriate scales for management (Schneider 2012; Henson et al. 2017). The mechanisms that underpin stock-specific and ecosystem responses to climate change often remain poorly resolved, and the complex, interactive effects of these changes on fishing fleets, markets and human communities can be difficult to predict (Cheung 2018; Liu et al. 2023).

There is a need for increased observational capacity to inform strategic, pre-season and in-season adaptive management decisions to increase the resilience of fisheries to climate shocks (Holsman et al. 2019; Barbeaux, Holsman, and Zador 2020; Mason et al. 2023). For example, following an extreme heatwave in 2014-2016, Pacific cod (*Gadus macrocephalus*) stocks crashed in the Gulf of Alaska, and the fishery was closed in 2020 (Peterson Williams et al. 2021). Stock assessments failed to identify early warning signs of cod declines, suffering from the National Oceanic and Atmospheric Administration’s (NOAA’s) two-year survey cycle, and misspecification of stock assessment models which had been underestimating fishing mortality and overestimating biomass (Peterson Williams et al. 2021). Incorporating “on the water” observations from fishermen on ecosystem state and low cod availability could have improved precautionary management in the lead-up to the crash and better prepared the fishing community for the climate-induced disaster (Barbeaux et al. 2020; Peterson Williams et al. 2021).

Here we explore the potential for citizen science to provide increased observational capacity and enhance climate-resilient fisheries management in the United States. We explore: 1) data needs for climate-resilient fisheries management, 2) examples of existing citizen science programs that already meet or could meet the identified needs of climate-resilient management in the U.S., 3) remaining data gaps that new citizen science programs could fill, and 4) challenges and opportunities for integrating citizen science into fisheries management frameworks. We highlight case studies where citizen science can be leveraged to increase climate resilience in U.S. fisheries and provide recommendations to guide their implementation and uptake into regional management frameworks.

What is citizen science?

Citizen science presents an emerging opportunity to meet the information needs of climate-resilient fisheries management (Oremland et al. 2022; Bonney et al. 2021; Bonney 2021; Kelly et al., n.d.). Broadly, citizen science can be defined as *non-professional scientists engaging voluntarily in the scientific process* (NOAA 2021). In the fisheries context, citizen scientists can be commercial or recreational fishermen or interested individuals who collect data, analyze data, contribute to project design, form hypotheses to be tested, and provide input into science-based fisheries management. This wide spectrum of tasks can be implemented in a range of scientific and management frameworks, which we summarize here as *contributory research*, *collaborative research*, and *co-created research* (Box 1; Bonney et al. 2009). Each of these frameworks has varying degrees of stakeholder involvement in project design, data collection, data analysis and implementation of science-based management measures (Oremland et al. 2022; Bonney et al. 2021; Schewe et al. 2020; Wendt and Starr 2009).

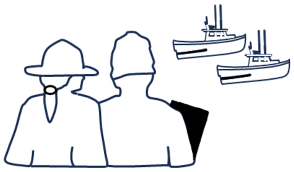
CITIZEN SCIENCE IN FISHERIES RESEARCH AND MANAGEMENT

CONTRIBUTORY RESEARCH

Scientists determine which data are required and engage citizens to collect those data. Experimental design, data validation and standardization tasks are conducted by scientists.

COLLABORATIVE RESEARCH

Citizens and scientists form an intellectual partnership where citizens are incorporated into all phases of research, including the development of research questions and hypotheses.



CO-CREATED RESEARCH

Citizens are closely involved in all phases of research and also participate extensively in the implementation of scientific findings into fisheries management processes.

BOX 1. Citizen science frameworks with varying degrees of stakeholder involvement in project design, collaboration on research questions, and input into science-based management.

Citizen science programs developed under each of these frameworks of participation have made substantial contributions to fisheries research, including helping determine the performance of Marine Protected Areas (MPAs; Ziegler et al. 2024; Freiwald et al. 2018); collecting oceanographic data (Fulton et al. 2019; Van Vranken et al. 2023; Jakoboski et al. 2024; Van Vranken et al. 2020); collecting biological specimens (Fairclough et al. 2014; Wilmoth, Dumke, and Hueffmeier 2020); participating in tagging studies (Guindon et al. 2015); and reporting catches (Gibson et al. 2019; Gundelund et al. 2020; 2021).

Why citizen science?

Citizen scientists represent a vast potential resource for improving our collective understanding of climate change impacts on fisheries (Dickinson, Zuckerberg, and Bonter 2010). Commercial and recreational fishermen interact with fishery resources and ecosystems as a matter of course and often throughout the geographic range of fish stocks (Feist et al. 2021). A huge number of interested individuals live in proximity to the U.S. coastline and have deep local ecological knowledge and attachments to place that make them ideal observers of change in the natural world (Haywood et al. 2016; Haywood et al. 2024). The collective "eyes on the water" of the U.S. public therefore has significantly greater reach than conventional scientific survey methods (Dickinson, Zuckerberg, and Bonter 2010; Bonney et al. 2021; Fairclough et al. 2014), and citizen science has the power to help observe physical, ecological and social processes at the geographic and timescales at which climate change impacts are unfolding (Yochum, Starr, and Wendt 2011; Bonney et al. 2021) .

Traditional research methods can also be expensive, which can limit the scale and scope of scientific data collection and monitoring (Oremland et al. 2022). Citizen science can be a cost-effective way of collecting data at naturally enhanced scales (Yochum, Starr, and Wendt 2011; Fairclough et al. 2014; Conrad and Hilchey 2011; Gouraguine et al. 2019; Kelly et al., n.d.). For example, to study the movements of recreational target species, scientists typically conduct fishing and tagging activities from vessels owned or chartered by the scientists at significant cost, which limits the number of vessel days, the geographic extent of sampling, and the sample size of tagged fish (Oremland et al. 2022). However, if recreational fishermen can be engaged to tag fish independently during their own recreation activities, it is possible to greatly increase the scope of data collection, resulting in larger sample sizes at far lower costs (Guindon et al. 2015; Oremland et al. 2022).

Citizen science has also proven an effective tool to increase scientific literacy and enhance public engagement in conservation and management (Bonney et al. 2016; Mason et al. 2020). Citizen science programs often have educational goals, and citizens who are more aware of and engaged in issues affecting their environment are more likely to act in ways that contribute to individual and collective stewardship of places and resources (Guindon et al. 2015; Haywood et al. 2016; Schewe et al. 2020).

Engagement of fishermen via citizen science programs can help to build inclusivity, trust and buy-in to management processes, especially where stakeholders have traditionally been marginalized or excluded by top-down management structures (Bonney et al. 2016; Schewe et al. 2020). In some cases, fishermen feel limited ownership over data collected by government agencies, through fishery observers or fishery-independent survey methods (Schewe et al. 2020). Incorporating diverse sources of knowledge and perspectives can improve the quality of information used in scientific assessments (Mason et al. 2023; Mills et al. 2023; Runnebaum et al. 2023), and inviting the fishing community to participate in the scientific process can help ensure that the status of resources fishermen observe on the water is reflected in both stock assessments and adaptive management decisions that impact their livelihoods (Wendt and Starr 2009).

1. U.S. CITIZEN SCIENCE PROGRAMS THAT SUPPORT CLIMATE-RESILIENT FISHERIES MANAGEMENT

Over the past decade there has been increasing emphasis on developing ‘climate-ready’ fisheries management advice and a growing interest in citizen science approaches within U.S. state and federal agencies (Slater et al. 2017; Oremland et al. 2022). In 2016, the South Atlantic Fishery Management Council (SAFMC) became the first regional fishery management council to establish a formal citizen science program, and in 2017 the Crowdsourcing and Citizen Science Act was passed, giving federal agencies authority to conduct citizen science activities. In 2020, NOAA identified citizen science as a ‘science and technology focus area’ (NOAA 2020).

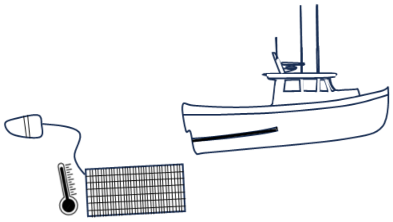
Many citizen science projects have since emerged in the U.S. that are designed to increase scientific capacity and can be leveraged to inform adaptive fisheries management advice under climate change. Summarized below are examples of existing programs with different models of citizen engagement that have successfully incorporated citizen-collected data into climate-resilient fisheries management and/or have strong potential to do so due to the types of data that they collect and their long-term participant buy-in.

1.1 Contributory research programs

Most citizen science in the U.S. is undertaken within frameworks that engage citizens to contribute data to meet research needs established by scientists (Bonney et al. 2021). Contributory research programs may involve initial training and outreach to engage citizens, but usually do not involve sustained collaboration between experienced scientists and members of the public. In the absence of extensive scientific oversight, citizens are best equipped to record observations, take basic field measurements, tag and recapture fish, collect specimens, or conduct simple analyses such as identifying or counting animals from photographs or videos (Bangley et al. 2020; Skov et al. 2021). These data can then be analyzed and used by scientists to address research questions and develop climate-smart fisheries management advice.

Citizens have been engaged to collect important environmental data during their fishing activities. In 2001, the Environmental Monitors on Lobster Traps and Large Trawlers (eMOLT) project was formed from a need for bottom water temperature measurements to enhance scientific understanding and management of the American lobster (*Homarus*

ENVIRONMENTAL MONITORS ON LOBSTER TRAPS & LARGE TRAWLERS



The Environmental Monitors on Lobster Traps and Large Trawlers (eMOLT) project involves more than 50 volunteer lobstermen fishing with temperature probes attached to their lobster traps. Bottom temperature measured by the probes is automatically transmitted via satellite in near-real time to a NOAA server as the gear is retrieved. The program has collected over 20 years of data and over seven million hourly observations of bottom temperatures from fixed locations and depths that have been used to support stock assessments and ocean climate research.

BOX 2.

americanus) fishery (Box 2). Data from sensors attached to fishing gear have been used by fishermen to make decisions on when and where to set their gear and by oceanographers to supplement mooring and survey data, to ground truth and improve regional ocean models and to account for temperature-dependent changes in catchability in lobster stock assessments (Manning & Pelletier 2009; Gawarkiewicz et al. 2012; Li et al. 2017; Zhao et al. 2019). Technological advances have facilitated the automatic, wireless upload of data from private vessels and its seamless integration into ocean observing databases (Van Vranken et al. 2023). This has made citizen-collected oceanographic data a valuable complement to data collected via research cruises, autonomous platforms and satellites to inform operational fisheries management and planning (Zhao et al. 2019; Van Vranken et al. 2020; 2023).

Citizen observations have also benefited from the proliferation of smartphones and app-based platforms that can be used to record *in situ* observations of biodiversity, environmental conditions and fisheries catch (Venturelli et al. 2016; Skov et al. 2021). For example, the iAngler app allows recreational fishermen to create trips and record the type, location and size of their catch (Jiorle et al. 2016). Fish length data have contributed to stock assessments for species including common snook and red drum (Muller and Taylor 2013, Chagaris et al. 2015, Munyandorero et al. 2017, Addis 2018). Similarly, the SAFMC runs the "SAFMC Release" program and uses the SciFish app to record data such as the depth of capture and length of released fish with the goals of improving monitoring and fishing practices for red snapper and shallow water groupers off the southeast U.S. coast.

Tagging fish provides important insight into species ranges and migrations and is often undertaken by enthusiastic volunteer fishermen. For example, NOAA's Cooperative Tagging Program was established in 1954 and is one of the longest-running citizen science programs contributing to fisheries management (Kohler et al. 1998). The program tags tuna, billfish and swordfish, informing international stock assessments and identification of essential fish habitat in U.S. waters. Similar citizen tagging programs exist for sharks, dolphinfish and coastal fishes (Shepherd et al. 2006; Bangley et al. 2020). Citizen tagging programs are becoming increasingly useful for science and management as species distributions shift in response to climate change and have helped identify shifts in distributions and suitable habitat for sharks and pelagic species as coastal waters warm (Hill et al. 2015; Champion et al. 2018; Hammerschlag et al. 2022).

Citizen scientists can also collect samples to send to scientists for analysis, including fin clips, scales, carcasses and water samples (Clarke et al. 2023). Scientists then conduct analyses using these samples, e.g., determining genetic structure from extracted DNA, determining age or trophic ecology from otoliths, assessing toxicology and pathology from tissue samples or identifying species presence or abundance from environmental DNA (Fairclough et al. 2014; Wilmoth, Dumke, and Hueffmeier 2020). Citizen collections can yield widespread sampling of species for diverse purposes beyond the scope of scientific surveys, while benefiting from rigorous analyses being performed in the lab by trained scientists.

In addition to programs targeted at commercial and recreational fishermen, there are numerous citizen science programs for recording ecological observations in U.S. waters. These include platforms for recording observations of whales, turtles, seabirds and reef fish (Diamond et al. 2020; Shanker & Manoharakrishnan 2022). In some cases, these ecosystem observations have been leveraged as indicators for climate-resilient fisheries research and management. For example, the Coastal Observation and Seabird Survey Team (COASST) engages citizens to identify and measure seabird carcasses on U.S. West Coast and Alaskan beaches (Litle et al. 2006; Parrish et al. 2022). Patterns of seabird mortality, including mass seabird die-offs during the 2014-2016 and 2019 marine heatwaves in the North Pacific, have provided a deeper understanding of the climate and ecological conditions that contribute to declines in commercial fisheries including Pacific cod and Walleye pollock in Alaska, and COASST seabird mortality has been considered as an indicator of forage fish availability in ecosystem status reports used to inform total allowable catch for groundfish harvest (Jones et al. 2018; Piatt et al. 2020).

As the volume of data collected by technologies including underwater images and video expands, so does the capacity required to analyze it. Citizens can play an important role in conducting simple analyses of large data streams. For example, citizens have been engaged to identify species from photographs to train machine learning models to automatically identify fish from images and to count deep sea fish to contribute to fishery monitoring in Hawai'i (OceanEYES; Fishial). There are also programs to count fish from video or live feeds to help estimate escapement, contributing to in-season management of fishery resources.

1.2 Collaborative research programs

Collaborative research programs involve deeper engagement of citizens in research development, and long-term partnerships between the fishing community and scientists. In 2006, the California Collaborative Fisheries Research Program (CCFRP) was formed to develop protocols for monitoring the performance of nearly 30 designated MPAs along California's central coast (Box 3; Yochum, Starr, and Wendt 2011). The CCFRP's sampling design benefits from commercial fishing captains using their knowledge to determine where to fish, and the assistance of volunteer anglers to catch fish that are measured and tagged by scientists. Ownership of research priorities is shared by scientists and the fishing community.

CALIFORNIA COLLABORATIVE FISHERIES RESEARCH PROGRAM

The California Collaborative Fisheries Research Program (CCFRP) is a partnership between 36 fishing vessels, 1800 volunteer anglers and six academic institutions, designed to assess the effectiveness of MPA closures on nearshore fish populations. Stakeholders co-developed research priorities and standardized fishing protocols that are used to monitor 12 MPAs and corresponding reference sites across California's coastline. These data have been used in stock assessments and in research related to heatwave impacts on coastal ecosystem resilience.

BOX 3.

This collaborative structure has allowed the CCFRP to collect high-quality biological data, including otoliths, fin clips, ovaries and morphometrics, to contribute to state and federal stock assessments for nearshore groundfish species including China rockfish (Dick et al. 2016), black rockfish (Cope et al. 2016), blue and deacon rockfish (Dick et al. 2017), gopher and black-and-yellow rockfish (Monk and He, 2019), quillback Rockfish (Langseth et al. 2021), vermilion rockfish (Monk et al. 2021 & Dick et al. 2021; ref) and lingcod (Johnson et al. 2021). Additionally, the program has developed scientific studies of public

perceptions and engagement in MPAs and the contribution of MPAs to ecosystem resilience during climate shocks such as marine heatwaves (Ziegler et al. 2023).

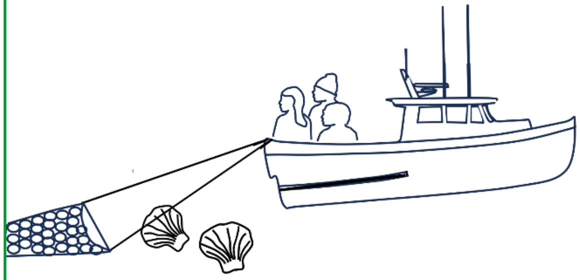
The Northeast Fisheries Science Center Study Fleet is another example of a collaborative framework that has allowed citizen science to contribute to management outcomes. Formed in 2006, the study fleet comprises more than 100 vessels and engages fishermen to collect high-resolution data during their fishing operations. These data have been used to estimate fishery footprints, develop catch-per-unit-effort indices for stock assessments, understand the potential impacts of offshore wind energy development on fishing operations, develop thermal niche models for important target stocks and improve regional oceanographic models.

Collaborative research frameworks have many advantages over contributory research programs both in the scope of data that can be collected by citizens under one programmatic umbrella, and the strength of relationships that can be developed with citizens. While the costs of establishing and maintaining collaborative research programs are high, the administrative burden could be lower than designing multiple programs and associated technology like mobile phone apps to fill individual data needs.

1.3 Co-created research programs

Co-created citizen science programs allow citizens to have close engagement in both the scientific and management process. Fully co-created research programs remain rare in the U.S. and globally. However, fisheries co-management arrangements represent a framework within which citizens can co-develop research to meet their own management goals. In the U.S., most co-management arrangements operate in state waters, including tribal co-management of fish and shellfish on the U.S. West Coast and co-management of the scallop fishery in Maine (Box 4). Within these frameworks, fishery monitoring is often undertaken as a collaboration between fishermen and government agencies, with shared input into science-based management decisions. For example, the Department of Marine Resources in Maine undertakes monitoring of the scallop fishery, including ship-based surveys and tagging experiments. The shells of tagged scallops are returned by fishermen along with information on the date and location of capture for assessments of scallop movement and growth rates (Maine Department of Marine Resources 2023). Management of the fishery is undertaken based on fishermen input into management areas, the timing and length of fishing seasons, daily catch limits, and the establishment of a Scallop Advisory Council with representatives from government and industry to inform and in-season management (Maine Center for Coastal Fisheries 2024).

MAINE SCALLOP FISHERY

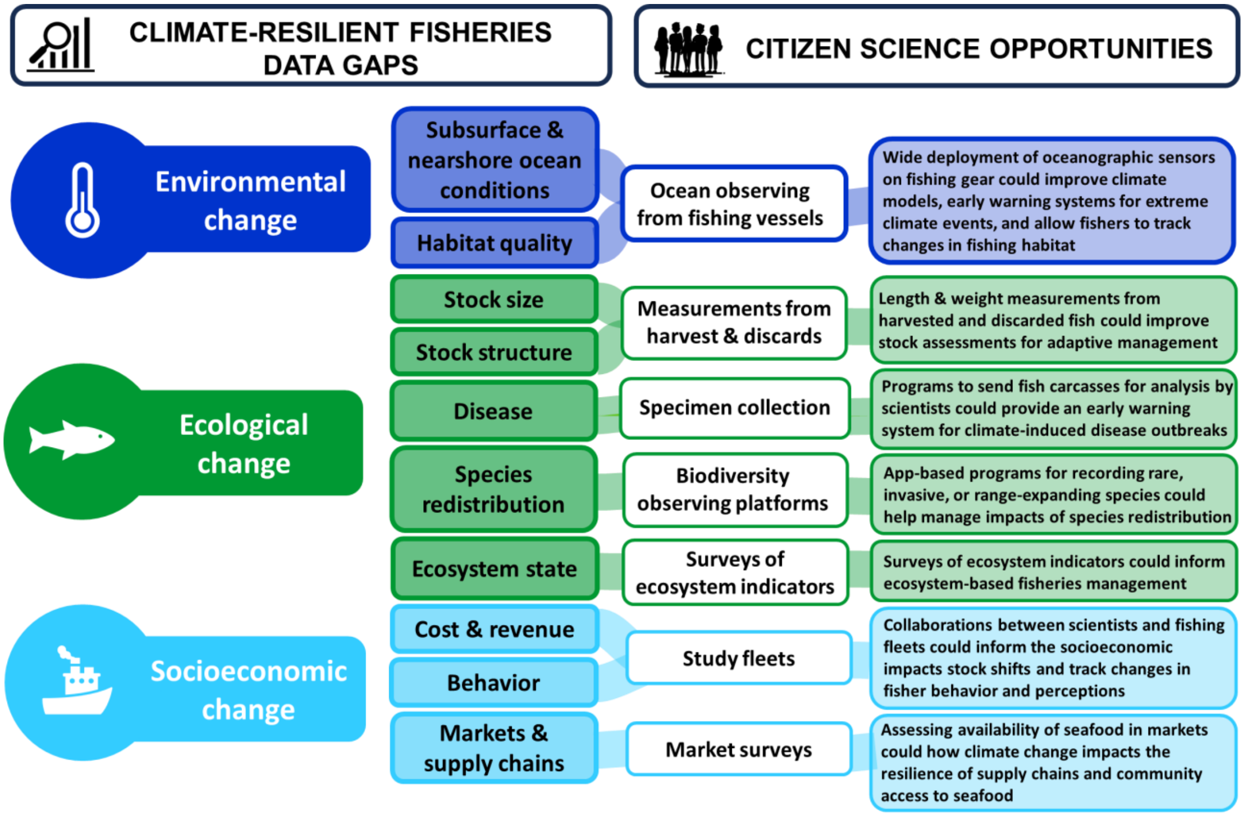


The Maine scallop fishery is co-managed by fishermen and Maine's Department of Marine Resources. Scallop fishermen have played an integral role in the design of management areas, setting the timing and length of fishing seasons, and establishing daily catch limits. To support these management decisions and respond to changes in fishery productivity, fishermen have identified key research priorities that are being addressed by a coalition of fishermen, scientists and students, including assessing larval supply, population connectivity, and environmental change in nearshore scallop beds.

BOX 4.

2. OPPORTUNITIES TO FILL INFORMATION GAPS WITH NEW OR EXPANDED CITIZEN SCIENCE PROGRAMS

While the scope of citizen science programs in the U.S. is increasing, there are important information gaps regarding climate change and its impacts on marine ecosystems that carefully designed citizen science programs could fill. Here we describe information gaps spanning 1) environmental change, 2) ecological responses, and 3) social responses (Figure 1). These changes are interconnected and occur on both long and short timescales, with impacts felt at local, regional and global scales. We outline how citizen science could fill priority information gaps to improve pre-season and in-season adaptive management decisions and long-term fishery planning in the face of climate change (Bell et al. 2020; Collie et al. 2013).



Wide deployment of oceanographic sensors on fishing gear could improve climate models, early warning systems for extreme climate events, and allow fishers to track changes in fishing habitat

Length & weight measurements from harvested and discarded fish could improve stock assessments for adaptive management

Programs to send fish carcasses for analysis by scientists could provide an early warning system for climate-induced disease outbreaks

App-based programs for recording rare, invasive, or range-expanding species could help manage impacts of species redistribution

Surveys of ecosystem indicators could inform ecosystem-based fisheries management

Collaborations between scientists and fishing fleets could inform the socioeconomic impacts stock shifts and track changes in fisher behavior and perceptions

Assessing availability of seafood in markets could how climate change impacts the resilience of supply chains and community access to seafood

FIGURE 1. Data gaps for climate-resilient fisheries management and opportunities to develop targeted citizen science programs to meet management needs under climate change.

2.1 Environmental change

The ocean's climate is undergoing systematic changes including warming, deoxygenation, changes in ocean circulation and upwelling patterns, and ocean acidification (Doney et al. 2020; Johnson and Lyman 2020; Ross, Du Preez, and Ianson 2020; Garcia-Soto et al. 2021). Fishery managers require information on the directions and magnitudes of expected changes in ocean conditions over years to decades, and the time horizons at which expected changes might reach critical thresholds for ecosystem impacts (Tommasi et al. 2017). Fishermen are well-placed to collect oceanographic information to assimilate into ocean climate models, especially if data collection is passive, with low transaction costs for fishermen (Van Vranken et al. 2023; 2020; Jakoboski et al. 2024). In the U.S., vessel-collected data currently contributes to oceanographic observing programs under the eMOLT program on the Northeast shelf, but the technology and infrastructure are now ripe for expansion to a national observing program that engages fishermen to collect ocean data throughout U.S. coastal waters and around the world (Van Vranken et al. 2023).

Citizen-collected oceanographic observations could also help fill gaps for responding to extreme ocean climate events, which are increasing in both frequency and intensity (Perkins, Alexander, and Nairn 2012). For example, marine heatwaves can cause increases in ocean temperatures at magnitudes predicted under end-of-century warming scenarios during events that emerge within days to months (Jacox et al. 2022). Although recent progress has been made in forecasting extreme events at lead times that are relevant to fisheries stakeholders, citizen-collected sub-surface ocean data and observations from nearshore environments could greatly contribute to the accuracy of local and regional early warning systems (Capotondi et al. 2019). These same fine scale observations could also provide analytical tools to assess near-real-time habitat quality for important target species that could make fishing operations more efficient in response to changing climate conditions.

2.2 Ecological responses

Ocean climate change is causing seasonal to decadal-scale shifts in the abundance and distribution of marine life (Hastings et al. 2020). These changes are altering the composition of ecological communities and affecting ecosystem structure and function (Carroll et al. 2024). To manage these impacts, decision-makers need information on observed changes in the size, distribution and structure of target fish stocks to inform management strategies including fishing quotas, the timing and duration of fishing seasons and harvest allocations between management areas and fishing sectors (Collie et al. 2021). Additionally, information on rare or non-target species including invasive or range-expanding organisms and diseases that interact with target stocks are essential to manage indirect impacts of climate change on stock health (Marshak and Heck Jr 2017).

Citizen science is also well-placed to enhance observational capacity to inform extreme events including harmful algal blooms, marine heatwaves, coral bleaching and rapid deoxygenation events. Crowdsourced ecological data in near-real time can inform seasonal ecological forecasts to inform rapid management responses to avoid tipping points that can contribute to fishery collapse and other adverse ecological outcomes (Brodie et al. 2023).

Information to improve stock assessments

Stock assessments require detailed information on the catch, abundance and life history of fishes. The completeness and accuracy of this information is critical to ensure that stocks are being exploited sustainably, particularly as climate change shapes key demographic processes including growth, recruitment, maturity and fecundity (Ianelli et al. 2016). Citizen science has the potential to fill data gaps to improve stock assessments, making them more robust to uncertainties and better equipped to provide adaptive management advice.

We identified information gaps in a selection of 80 U.S. federal stock assessments — approximately ten selected at random from each of the eight fishery management council regions. We removed gaps that could not feasibly be filled by citizen scientists (such as assessment methodology improvements and standardization of datasets), then classified the remaining gaps as having low, moderate or high potential to be filled by citizen science. We recognize the three citizen science frameworks may have varying suitability scores; however, these reports summarize suitability at the contributory research level for comparison purposes. Low suitability indicates a data gap that citizens could be tangentially engaged in (e.g., by collecting samples) but that require specialized analytical skills; moderate indicates a gap that citizens could contribute valuable scientific support to but that require substantial inputs from scientists; and high indicates a gap that a citizen science program would be uniquely positioned to fill. Table 1 describes these data gaps, methodologies for filling data gaps and suitability for citizen science applications.

TABLE 1. Data gaps identified from stock assessments with a brief description and potential method for filling that gap. Suitability refers to how readily the data gap may be filled by citizen scientists on a scale ranging from low, moderate to high.

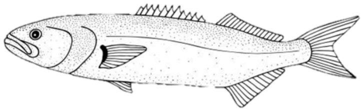
	Data Gap	Definition	Method	Suitability
Life History Information	Species growth rates	Rate at which fish grow	Tag and recapture with species length/weight measurement	High
	Fecundity	Number of eggs produced by a female fish	Extract gonads and count eggs, measure length/weight	Low
	Recruitment	Number of new individuals in the fishable population	Measure length/weight in sample of catch	High
	Maturity	Age/size at which a species reproduces	Measure length/weight/age and examine gonads for maturity	Low
	Maximum age	Oldest age a species can reach	Collect otoliths and measure age	Low
	Age/length keys	Relationship between fish age and length	Collect otoliths and measure length/weight	Low
	Spawning frequency	Number of spawning events	Examine species gonads using a microscope	Low
	Natural mortality	Rate of death from causes other than fishing	Tag and recapture with species length/weight measurement	Moderate
	Data Gap	**Definition**	**Method**	**Suitability**
Fishery Characteristics	Age composition	Age distribution of catch	Collect otoliths and measure length/weight/sex from catch sample	Low
	Recreational fishery release length data	Release length	Measure length of species prior to discard	High
	Commercial fishery release length data	Release length	Measure length of species prior to discard	High
	Discard mortality rates	Proportion of discarded fish that die from discarding event	Field studies: tag fish to track their fate after release or use telemetry (e.g., acoustic tags) to monitor fish behavior and survival post-release. Laboratory studies: place fish in holding tanks or enclosures that simulate natural conditions. Monitor fish for a set period to assess short-term and long-term mortality.	Low
	Gear selectivity studies	How species size and age impacts probability of capture by gear	Compare a new gear type to another gear type with a known selectivity and deploy both gears side by side.	Low

	Data Gap	Definition	Method	Suitability
Stock Structure	Migration patterns	Seasonal and age-related migration	Fishery independent surveys; fishery dependent catch information; telemetry studies	Moderate
	Changes in distribution over time	Shift in species location within and between seasons	Fishery independent surveys; fishery dependent catch information; telemetry studies	Moderate
	Spawning locations	Locations of spawning events	Acoustic tagging; underwater cameras and passive acoustics to monitor potential sites; leverage local and traditional ecological knowledge.	Moderate
	Larval dispersal dynamics	How species larvae are distributed by ocean dynamics	Collect spawning and fecundity information; collect oceanographic data to improve models	Low
	Depth distribution	Distribution by depth	Collect data on depth of gear and catch location	High
	Genetic structure	Determination of breeding populations	Collect genetic samples such as flesh or scales from catch	Moderate
	Spatial structure	Change in species distribution with age/sex	Fishery independent surveys; fishery dependent catch information including length/age/sex; telemetry studies	Moderate
	Data Gap	**Definition**	**Method**	**Suitability**
Ecological Data	Effect of temperature on growth rates	Change in species growth rates with temperature	Laboratory experiments to study effect of temperature on growth rates	Low
	Effect of temperature on distribution	Change in species distribution with temperature	Co-location of temperature-depth and species catch data	High
	Harmful algal bloom dynamics	Location and timing of harmful algal blooms	Visual tracking of red tides	High
	Data Gap	**Definition**	**Method**	**Suitability**
Socioeconomic Information	Demand for fishing	Quantity of fishing effort in response economic factors	Fishermen surveys	High
	Fishermen demographic information	Information on fishermen age/location etc.	Fishermen surveys or use of license databases	High

Of the data gaps identified from stock assessments of U.S. federally managed species, life history information is the most frequently cited information gap, especially for rare or less-commercially valuable species. To fill these data gaps, citizen science has a high suitability to contribute to collecting fish length data to improve estimates of growth, recruitment and mortality, deploying and collecting tags as part of tag-recapture experiments to improve growth and mortality estimates or sending carcasses to scientists for otolith or gonad examination (Fairclough et al. 2014). Citizen science programs could be strategically designed and deployed to collect this information for fisheries where stock assessors and managers have identified data gaps that increase model uncertainty and compromise climate-resilient management.

Recreational release length data is one of the most cited information gaps related to fishery characteristics. This gap can be relatively easily filled by engaging recreational fishermen in citizen science programs, building off successful, regionally focused programs like iAngler and SciFish. For example, assessments of the bluefish fishery in the northeastern U.S. are challenged by a lack of information on the length of released fish, which are larger on average than fish that are landed (Box 5). The Northeast Fisheries Science Center has called for an expansion of volunteer angler surveys to accurately measure, weigh and count discarded fish across a wide spatial extent to improve estimates of total catch for more accurate management advice (MAFMC 2019).

MEASUREMENTS OF RECREACTIONAL BLUEFISH DISCARDS



Along the U.S. east coast, more than 80% of bluefish are harvested by recreational anglers. Smaller bluefish are often preferentially kept, while larger bluefish are discarded due to their high oil content. This complicates estimates of total fishing mortality which cannot be reliably estimated from the size and weight of harvested fish.

Following the successful integration of citizen-collected data into bluefish quotas in 2021, a dedicated program to train anglers to accurately measure, weigh, and count discarded fish could greatly increase the spatial extent of data collection. Such a program would provide stock assessment scientists with a more detailed and accurate picture of bluefish discards to improve management in the face of climate-driven shifts in distribution and reproductive biology.

BOX 5.

Information on rare, invasive and redistributing species

Stock assessments require a large amount of data, and many species remain unassessed due to data or funding limitations. Citizen science provides an excellent opportunity to fill knowledge gaps for rare species for which formal assessments are not possible and targeted research surveys are likely to be expensive and uninformative. For example, a genetic recapture study of tarpon in Florida resulted in 24,572 samples, a number that would have been almost impossible without engaging citizens in data collection (Guindon et al. 2015).

There is also a substantial opportunity for citizen science to contribute to our understanding of where species occur, and to detect climate-driven species redistribution and shifts in ecosystem structure (Middleton et al. 2021). Fishes are generally poorly represented in existing biodiversity observation databases, including the widely known and globally used iNaturalist app, representing less than 2% of > 26 million total observations. Targeted efforts by scientists to increase fishery representation in these platforms have been undertaken in the Great Lakes, with the creation of the Great Lakes Fish Finder App, a partnership between local scientists and iNaturalist (Happel et al. 2020). Similar projects in coastal and offshore ecosystems could greatly expand our understanding of the distribution of many fishery species and effectively monitor invasion frontiers of non-indigenous marine species (Scyphers et al. 2014; Giovos et al. 2019; Encarnação et al. 2021; Kousteni et al. 2022).

Identifying species range shifts is a priority for climate-resilient fisheries management to inform fishery allocations and understand changing ecosystem structure and function. Fishermen are on the water and have deep knowledge of when species observations are “unusual” for their ecosystem. Several citizen science programs specifically designed to identify species outside their normal ranges exist around the world, using apps to record unusual observations on the water (Pecl et al. 2019). Coupled with citizen tagging programs that track the movements of important fishery species, there are strong opportunities for the U.S. to develop targeted programs to expand the spatial and temporal scales of data collection on species distributions as early warnings of species redistribution under climate change (Karp et al. 2018).

Information on the spread of environmental toxins and disease outbreaks

Climate change is reshaping marine host-pathogen relationships and leading to shifts in the ranges and expression of bacterial, viral and parasitic diseases in fishery species (Burge et al. 2014). Climate-mediated spread of toxins from harmful algal blooms (HABs) in finfish and shellfish can have serious implications for human health and devastating impacts on the livelihoods of people engaged in the fishing industry (Ritzman et al. 2018; Moore et al. 2019; McIntyre et al. 2021). Establishing surveillance systems to identify novel pathogens and the spread of diseases and HABs under climate change is therefore a priority for public health agencies, fisheries managers and the seafood industry (Reich et al. 2015). While citizen science already contributes to sampling and processing of fish to assess disease, toxins and toxicants (Cabanellas-Reboredo et al. 2019) and to perform rapid field assessments of HAB intensity (Hardison et al. 2019), there remains significant scope for new citizen science programs to increase the coverage of these efforts and help manage the worsening impacts of marine pathogens under climate change.

Information on ecosystem status

As climate change intensifies, the need for adaptive, ecosystem-based fisheries management is increasing (Barbeaux et al. 2019; Holsman et al. 2020). Considering changes in ecosystem state in management decisions is critical to account for bottom-up processes that affect fishery productivity including climate impacts on predator-prey dynamics, as well as to ensure that fisheries management preserves the integrity of whole ecosystems (Pikitch et al. 2004). In U.S. fisheries, ecosystem considerations are integrated into management decisions via ecosystem status reports that track dozens of ecological indicators (Zador et al. 2017). Careful identification of climate-sensitive ecosystem indicators for which observational capacity could be enhanced by citizens could complement existing research efforts. For example, community-based assessments of seabird abundance, distribution and mortality is a promising approach to increase the scale of monitoring and can provide early warnings of changes in ecosystem conditions relevant to fisheries management (Hazen et al. 2019; Martin et al. 2020; Piatt et al. 2020).

Citizen science also shows promise for sampling ecosystem structure and function via emerging eDNA techniques. Citizens have contributed to national-scale snapshots of coastal fish community assemblages in Denmark via coordinated collections of seawater for eDNA analysis at specific times of the year (Agersnap et al. 2022). Such an approach could greatly expand the scale and scope of assessments of ecosystem structure in the U.S., with the potential to provide rapid, coastwide assessments of shifts in ecosystem structure in response to extreme climate events and long-term climate change.

2.3 Social responses

The responses of fisheries and dependent communities to climate change impacts are highly context specific. Fishermen in different geographic locations or with different catch portfolios are impacted differently by shifts in stock distribution and abundance, even within the same fishery (Selden et al. 2020; Liu et al. 2023). Fisheries with different governance and community structures have different resilience profiles, leading to diverse capacities for adaptation (Mason et al. 2022). Information on how fishermen are responding to climate-driven changes in fish stocks by shifting their total effort, fishing grounds, seasons, gear or catch portfolios is critical to understand how adaptation actions emerge (Bell et al. 2020).

Citizen science programs could help to fill gaps in our understanding of how fisheries are responding to climate change. While vessel tracking, logbook and landings data can be used to assess shifts in fishery distribution and catch, this omits important contextual information about how and why fishermen make decisions and how they are personally impacted by changes in fishery availability (Cruz et al. 2024). Information on the perceptions of fishermen regarding climate change impacts is important to contextualize socio-economic outcomes and design appropriate and effective management responses and public outreach campaigns (Nursey-Bray et al. 2012). This information can be gathered by survey-based and oral history programs to gather fisherman stories of change (Byrd et al. 2022). Expanded collaborative and co-created citizen science programs could give deeper insight into fisherman behavior and sentiments, and how conditions encountered at sea translate to socio-economic outcomes for fishery workers and their communities. Co-created research programs that are designed by fishing communities to help address specific concerns and co-management goals will be increasingly important to enhance adaptive capacity and resilience to climate change impacts.

In addition to information at the fisherman level, data on market dynamics and supply chains are important to help contextualize the economic factors that promote or suppress fishery adaptation. Citizen science programs could play an important role in understanding which communities have reliable access to high quality local seafood. For example, the ‘Eat Like a Fish’ program tasked citizens with finding randomly assigned fishery species from the local ecosystem in marketplaces near their homes to characterize supply chains and seafood access. Similar programs could be expanded to map changing patterns of seafood distribution and access under climate change.

3. RECOMMENDATIONS FOR INTEGRATING CITIZEN SCIENCE INTO CLIMATE-READY FISHERIES MANAGEMENT

Citizen science offers valuable opportunities to gather large-scale data and engage citizens in meaningful activities for the benefit of the nation. However, it also presents significant challenges. In some cases, these challenges have undermined the long-term success of citizen science programs or limited the uptake of data or findings into management processes. To unlock the full potential of citizen science for meeting the needs of fisheries management under climate change, programs need to be carefully designed and implemented to collect the right data in the right ways to address management needs, and to engage the public and decision-makers to ensure sustained support and uptake. Below we identify a series of recommendations for establishing and maintaining citizen science programs to ensure that they can effectively support climate-ready fisheries management (Figure 2).

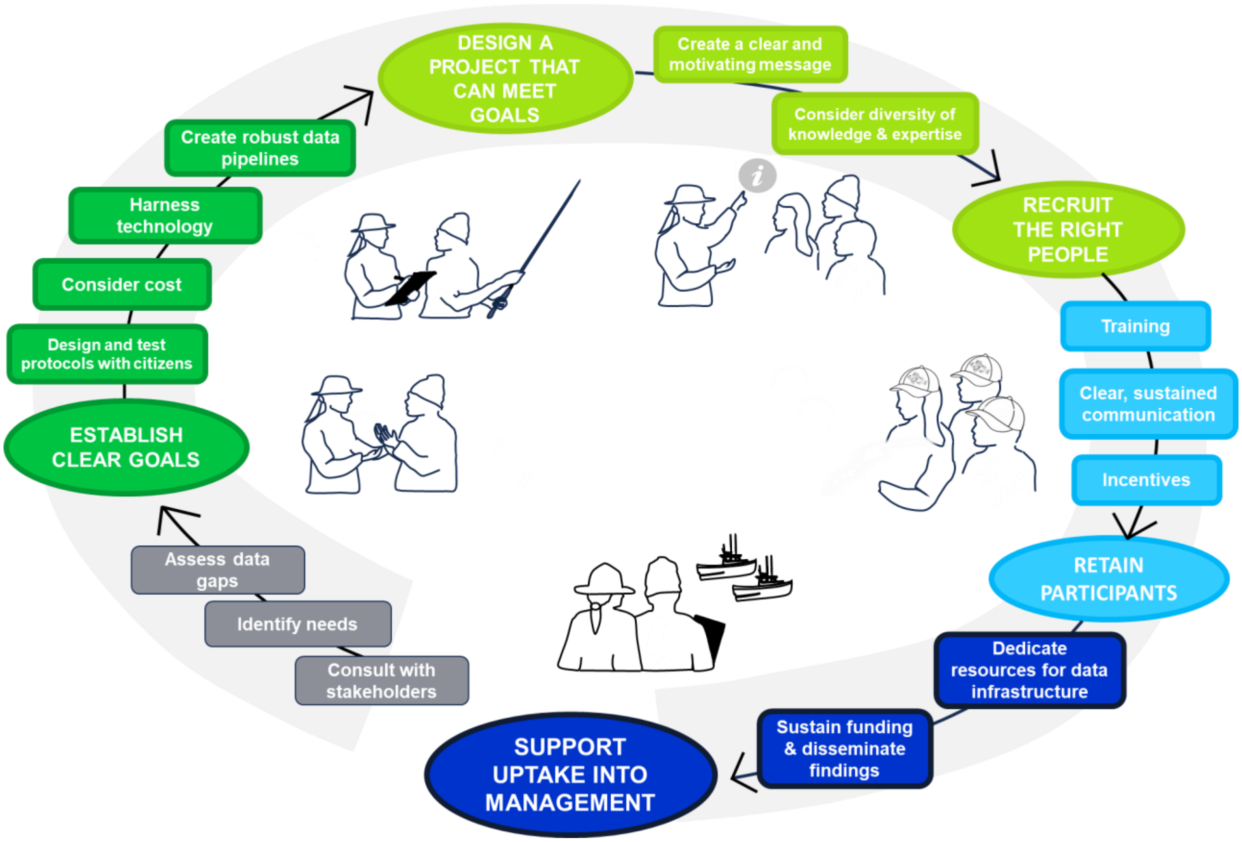


FIGURE 2. A recommended pathway and considerations for designing and implementing successful citizen science programs that contribute meaningfully to fishery management outcomes.

3.1 Establish clear goals

Citizen science programs can most readily improve management outcomes when they are designed with specific goals and end-users in mind. By collaborating closely with stakeholders including managers, fishery scientists, fishermen, community groups, industry groups and the public, researchers can identify collective needs and priorities for enhancing fishery resilience. If there are information gaps preventing action to meet these needs, then filling these gaps could become a goal of a citizen science program. For example, scientists and managers identified that a high priority need for fisheries in the Gulf of Mexico is reducing uncertainty and refining assumptions in stock assessments to inform reference points and catch limits (Chagaris et al. 2019). A citizen science program with the goals of identifying spawning aggregation sites and measuring the size composition of spawning fish could help fill gaps in understanding of fishery selectivity and reproductive potential to increase data and improve assumptions for stock assessment models (Heyman et al. 2019). Having goals clearly defined at the project’s outset can help to ensure that the right data is collected to meet management needs.

The goals of citizen science are not limited to data collection. Citizen science can also have explicit goals relating to public education and outreach, creating or deepening partnerships and trust between scientists and the public, enhancing representation of minority groups in fisheries governance or improving community buy-in to management. These additional goals also need to be clearly defined at the project outset, to design appropriate training, outreach, engagement and communication strategies.

3.2 Design a project that can meet goals

Once goals for the citizen science program have been established, projects should be designed with clear, robust protocols and streamlined processes. For projects that engage citizens to collect data intended for use in stock assessments, care must be taken to ensure that data are sufficiently high quality to meet the stringent requirements of stock assessment scientists and regulators (Schewe et al. 2020; Yochum, Starr, and Wendt 2011; Fairclough et al. 2014). Furthermore, processes for collecting and sharing data should minimize transaction costs for participants and make it easy for them to conduct high quality science. Designing and testing protocols with small groups of citizens from the outset can help ensure that scientists understand the type and quality of data they can expect and remedy sources of error or inefficiency so that protocols are streamlined and effective.

It is important to consider the costs of both establishing and maintaining high quality citizen science programs. Despite the benefits of having a volunteer workforce, the costs associated with citizen science programs can often exceed initial estimates. Effective citizen science programs require sustained investment in administration, support and communication over the long term (Oremland et al. 2022; Fulton et al. 2019). In the project design phase, scientists need to identify the funding required for the intended scale, scope and longevity of the project and the probability of being able to sustain this funding level over the lifetime of the program.

Technology can be harnessed to supercharge citizen science programs, and in many cases, existing technologies can be repurposed or extended to save costs and streamline processes. For example, many anglers already use smartphone apps in relation to their fishing activities, with around 25 active marine recreational angler electronic self-reporting programs with potential application for fisheries science in the U.S. (Midway et al. 2020; Pelagic strategies, 2023). One key opportunity is to develop a centralized angler app platform for a variety of species and geographies or an ‘extendable’ platform (Pelagic strategies, 2023; Bonney 2021).

Establishing robust data sharing, processing and analysis pipelines is also a critical part of successful project design. In contrast to traditional research methods, citizen science observations are often by nature opportunistic, heavily biased to popular fishing locations and species and rarely collected with randomized sampling designs or high-quality information on effort (Moreton et al. 2018). Advances in statistical modeling can address challenges analyzing large, uneven data sets with high uncertainty, but an understanding of how data will be treated can help to improve the quality of product from the outset. For example, when a participant records an observation of a species at sea in an app-based platform, having a field to record an associated level of certainty with their identification or their distance from the organism could improve the end product.

3.3 Recruit the right people

Citizen science programs need to motivate the public to contribute their time and energy to the scientific endeavor. For some programs that are closely aligned with existing hobbies and interests, recruitment may happen organically as word spreads among communities. Other programs will require dedicated outreach to communicate a clear problem that citizens care about and that they feel equipped and excited to help solve.

Citizens also have a wide diversity of knowledge and expertise. Targeting specific groups of citizens with deep knowledge of a system or specific skillsets can support high-quality data collection and analysis (Bonney 2021). Alternatively, targeting children or young adults can help to achieve project goals related to education. Citizen science also provides a great opportunity to address historical inequities related to participation in fishery management, helping to build long-term engagement and trust (Bonney 2021).

3.4 Retain participants

Perhaps even more important than engaging participants is retaining them. Training can support longer term engagement by participants by providing a more meaningful scientific experience, generating a deeper connection to the project, and leveraging investments in time and resources. Project participants that have been trained are likely to conduct better science and show more commitment to a project for longer (Moreton et al. 2020). Training sessions are also an important opportunity for participants to make connections and build community, which can increase their satisfaction with a program and motivate them to continue engaging.

Participants also need clear and effective communication to feel supported and engaged. This can involve having a dedicated point person to address queries and concerns and to troubleshoot issues that arise during the project. Communication and follow up of project milestones and achievements is also critical to retaining participants, so that they feel that their contributions are leading to tangible scientific and/or management outcomes.

3.5 Support uptake into management

Despite the promise and opportunities associated with citizen science, uptake into fisheries management remains limited. This is in part due to the complexities of analyzing data that is not collected using systematic surveys, and a perception that citizen-collected data is prone to error (Earp & Liconti 2019). To increase uptake and trust in citizen science there is a need to provide clear roadmaps for how it can be used as a complementary tool to traditional data sources within management processes (Oremland et al. 2022; Bonney et al. 2021). The goal setting and project design phases of citizen science projects should be a collaborative process that engages end users to ensure a clear on-ramp into fishery management decisions and encourage flexibility in assessment and management pipelines.

Projects should also follow through on producing outputs and products relevant to management and disseminating them via scientific journal articles, the media and agency memos. Proof of successful project outcomes can help support buy-in and secure funding for citizen science projects and ensure their long-term sustainability.

CONCLUSION

Integrating citizen science into fisheries management presents an opportunity to bolster the climate resilience of U.S. fisheries. By leveraging the enthusiasm and insights of engaged citizens, we can expand the scope and scale of data collection necessary to navigate rapidly changing environmental, ecological and social conditions. We show that citizen science programs are already supporting climate-ready fisheries management in the U.S. in some cases, from projects that have improved stock assessments, to collaborative research programs that have enabled “stress-tests” of the efficacy of management measures in response to extreme climate events.

However, key data gaps remain where citizen contributions could make a significant impact, from enhancing climate models to understanding market dynamics. While challenges such as data quality, administrative costs and program sustainability must be addressed, implementing best practices for co-creating projects and fostering deep community engagement can help to mitigate these concerns. Ultimately, embracing citizen science not only enriches our understanding of fisheries but also strengthens the bonds between scientists, managers and the public. By taking proactive steps now, we can cultivate a more resilient and sustainable fishing landscape that reflects a shared commitment to preserving our natural resources amid the challenges of climate change.

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