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Food for Thought

Reflecting on the recent history of coastal Maine fisheries and marine resource monitoring: the value of collaborative research, changing ecosystems, and thoughts on preparing for the future

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The Maine Department of Marine Resources (MEDMR) is a state agency tasked with developing, conserving, researching, and promoting commercial and recreational marine fisheries across Maine's vast coastline. Close collaborations with industry members in each of the 30 or more fisheries that support Maine's coastal economy are central to MEDMR's efforts to address this suite of tasks. Here we reflect on recent decades of MEDMR's work and demonstrate how MEDMR fisheries research programmes are preparing for an uncertain future through the lens of three broadly applicable climate-driven challenges: (1) a rapidly changing marine ecosystem; (2) recommendations driven by state and federal climate initiatives; and (3) the need to share institutional knowledge with a new generation of marine resource scientists. We do this by highlighting our scientific and co-management approach to coastal Maine fisheries that have prospered, declined, or followed a unique trend over the last 25+ years. We use these examples to illustrate our lessons learned when studying a diverse array of fisheries, highlight the importance of collaborations with academia and the commercial fishing industry, and share our recommendations to marine resource scientists for addressing the climate-driven challenges that motivated this work.

Keywords: climate change, coastal marine fisheries, resource monitoring, state agency research.

Introduction

The planning and execution of comprehensive resource monitoring to understand the abundance, distribution, and health of commercially harvested marine species is an ever-evolving task that is essential to effective fishery management and ecosystem research. The northwest Atlantic Ocean has been the source of some of the most productive fishing areas in the world for millennia and is heavily studied by research and management institutions in the United States and Canada. In the United States, the primary fisheries management frameworks are regional Fishery Management Councils and Marine Fisheries Commissions, which are comprised of representatives from multiple stakeholder groups across the region. Scientists of varying expertise play a key role by defining priority data gaps, executing data collection, performing assessments, and presenting results with appropriate context and recommendations to fishery managers (Hare, 2020). For some species, Commission fishery management plans dictate specific research and monitoring requirements, and state agencies within a region generally maintain comparable sampling programmes to best support robust stock assessment efforts. For state-managed fisheries, state agencies will also participate in question-based research, seek funding, collaborate with the fishing industry, and implement unique sampling programmes based on their specific data gaps or management needs. Staff are dedicated to both compiling commercial and recreational landings information as well as conducting resource monitoring assessments and research on the fisheries within their state.

The Maine Department of Marine Resources (MEDMR) is a state natural resource agency with the responsibility of monitoring and helping to develop the marine and estuarine species that support coastal Maine fisheries, encompassing some of the largest and most valuable fisheries in the country (MEDMR, 2023a). The MEDMR Commissioner is a cabinet-level position appointed by the Governor and serves actively in their administration. The Commissioner is supported by five Bureaus (Marine Patrol, Marine Science, Public Health, Sea-Run Fisheries and Habitat, and Policy and Management) led by a team of senior staff, including Bureau directors. MEDMR has statutory authority to manage marine resources within Maine's territorial waters (those waters from the rise and fall of the tide seaward to the 3-nautical-mile/5.6 km line). Licensed fishermen are subject to all of Maine's laws and regulations within the coastal waters of the state (out to 200 miles/322 km). The 5633-km-long coast of Maine currently supports over 30 different fisheries that range from intertidal species such as the common periwinkle (*Littorina littorea*), to the historic Atlantic cod fishery (*Gadus morhua*), and the benthic invertebrates that now dominate the Gulf of Maine (GOM) ecosystem. The seafood sector alone in Maine contributed $3.2 billion in total economic output and resulted in

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over 33300 jobs in 2019; this represents a significant singular contribution for a state with a 2021 gross domestic product of $62.88 billion (Maine Department of Administrative and Financial Services, 2022; Seafood Economic Accelerator for Maine, 2023).

MEDMR scientists monitor and support these large and diverse coastal fisheries by leading fisheries-dependent and independent research, undertaking ecological research, and engaging in collaborative research and a co-management strategy for several fisheries. In the lobster industry, co-management takes the form of lobster "zones" that divide the coast into seven units, each governed by MEDMR and appointed industry councils (Acheson *et al.*, 2000, 2013; and described below). These councils have been granted legislative authority to oversee and make recommendations on research priorities as well as zone-specific fishing practices such as the total number of traps fished, the time of day for fishing, and the number of traps on a line. The Maine soft-shell clam (*Mya arenaria*) industry has another form of co-management where MEDMR oversees commercial clamming efforts with municipalities that can apply to set and enforce local harvest rules (McClenachan *et al.*, 2015; McGreavy *et al.*, 2018).

The utilization of the co-management and collaborative research strategies in Maine has been successful due to decades of investment in building trust as equal partners in these research and management approaches by both commercial fishing industry members and MEDMR scientists. This, paired with the genuine cultural pride that Maine harvesters have in conserving fisheries for future generations, has led to many harvesters across the coast choosing to develop and sustain collaborative research, invest time in the management of these fisheries, and share their hard-won oceanographic and biological observations with the marine resource monitoring community. These industries provide a uniquely unifying cultural identity, for generations of family owned businesses, and a connection to the environment in an isolated part of the northeast USA that has a relatively high cost of living and limited opportunity to sustain a year-round population (Island Institute, 2018). MEDMR staff recognize the level of commitment of Maine's fishing industries and know that identifying shared research and management goals across sectors is essential to developing and sustaining strong fisheries science.

Biological and commercial fishery data are compiled by MEDMR researchers and the MEDMR commercial landings group to be shared with the public, federal research partners, and academic scientists (MEDMR landings, 2023). The primary users of these data are stock assessment scientists that lead species assessments for the Atlantic States Marine Fisheries Commission (ASMFC) and National Marine Fisheries Service (NMFS) and directly inform fisheries management. MEDMR policy staff represent Maine both on the ASMFC as well as the New England Fishery Management Council (NEFMC), and MEDMR science staff design research programmes specifically to support management of these fisheries in Maine as well as to contribute to long-term, high-calibre data about stocks of species that span the GOM. MEDMR scientists also collect data for species that may not be documented in fishery-based efforts. For example, MEDMR scientists conduct recreational catch and effort surveys for the Marine Recreational Information Program (MRIP), which are reported back to NMFS and provide comprehensive datasets for species with high recreational interest such as striped bass (*Morone saxatilis*) (NMFS, 2023), whereas life stage-based assessments conducted by MEDMR scientists for federally endangered Atlantic salmon (*Salmo salar*) are an integral component of annual reporting by the US Atlantic Salmon Assessment Committee to the North Atlantic Salmon Conservation Organization (Hawkes *et al.*, 2022). MEDMR scientists work collaboratively with other natural resource agency scientists across the country and into Atlantic Canada to study species of shared commercial interest and execute international research and management goals.

MEDMR staff know from this broad network of researchers, industry, and resource managers that concerns about the future of commercial fisheries and questions about how to prepare research and monitoring programmes for climate change within natural resource agencies are universal. While only one small data point in a sea of global fisheries, coastal Maine fisheries have seen examples of prosperity, collapse, and some degree of recovery in recent decades, making MEDMR and the range of experiences in Maine a valuable case study for fisheries researchers and natural resource agencies across the world. These experiences inspired a group of science staff members at MEDMR to compile our work, share our approach to diverse challenges over recent decades, and distil our vision for the future of monitoring and researching marine resources. This collation of the broad scope of our work and a concentrated reflection on the past with an eye towards the future also marks one of the starting points of an internal initiative to provide a climate-focused review of the MEDMR monitoring and research programmes. We begin in Part I by identifying three challenges associated with reflecting on the past and preparing for the future. Part II moves into the MEDMR case study, documenting the recent history of a selection of our current programmes and the fisheries they study. We share lessons learned from each programme while considering the three challenges identified.

Part I: identification of challenges

Challenge one: rapid ecosystem changes and shifts in marine resources

The GOM is an oceanographically complex system influenced by the warm Gulf Stream, the cold Labrador Current, and framed by diverse watersheds, coastlines, and bathymetry (Maine Climate Council Science and Technical Subcommittee, 2020). The need to reflect on our past and better understand the future of this complicated system is sharpened by (1) the rapid rises in sea surface temperature (SST) that have already occurred since the 1980s and (2) the ecosystem level shifts that are projected to occur by 2050 (Pershing *et al.*, 2015). Rising SST trends in the last 40 years have been attributed to anthropogenic forces, shifts in the positioning of currents, and broader atmospheric events (Gonçalves Neto *et al.*, 2021). Warming temperatures have already been identified as causing at least in part an increase in suitable lobster habitat as well as an increase of invasive predators such as the European green crab, *Carcinus maenas* (Donahue *et al.*, 2009; Compton *et al.*, 2010; Goode *et al.*, 2019). Research on the biological impacts of warming, ocean acidification, and other facets of ecosystem shifts in the GOM shows the complexity of climate change in that the effects are interactive, species-dependent, and life-stage specific (Gledhill *et al.*, 2015; Maine Climate Council Science and Technical Subcommittee, 2020; Pershing *et al.*, 2021). To capture all facets of climate change in the GOM moving forward will require careful consideration

of programme design and a full suite of life history data for species of interest.

Challenge two: implementation of climate initiatives

The need to better understand our past to prepare for our future has been underscored by the development and implementation of state and regional climate initiatives across the US in complement to global carbon dioxide reduction efforts. The State of Maine enacted the Maine Climate Council (MCC) in June 2019 by bringing together 39 council members plus a Scientific and Technical Subcommittee (STS) to develop strategies "to reduce greenhouse gas emissions by 45% by 2030 and 80% by 2050, as well as achieve carbon neutrality by 2045" with offshore wind development highlighted as a way to help meet these energy goals (Maine Climate Council, 2023). The MCC is supported by six working groups, including a Coastal and Marine Working Group. This Group called upon MEDMR staff and researchers across the state to develop adaptation and mitigation strategies to study and sustain coastal marine industries and environments while supporting the MCC's overarching goals (Maine Climate Council, Coastal and Marine Working Group, 2020). The result of this effort was six strategies with specific recommendations related to promoting habitat restoration, climate-focused marine resource monitoring, and working waterfronts. Both these specific recommendations and the broader MCC align with marine climate and adaptation planning efforts in several US states (reviewed by the Center for Climate and Energy Solutions, 2023) and international resource agencies (e.g. Canada; Department of Fisheries and Oceans, 2018) facing similar climate and fisheries considerations. The work currently done and being prepared for by MEDMR can guide other states and natural resource agencies looking to develop an integrated approach to developing marine resource monitoring in anticipation of climate change impacts.

Challenge three: a new era of marine resource scientists

The final challenge is tied to the core mission of natural resource agencies because the people carrying out the mission are the ones who make all the work possible. In recent years, MEDMR has supported a staff of 170–180, but as of the writing of this manuscript, the department has an estimated 215 employees with 18 additional positions pending and more being added in the next year (personal communication with MEDMR and State of Maine, Human Resources). Many new staff members were added to the science bureaus and are supporting programmes freshly initiated to respond to pressing climate change questions and new challenges within the state. This includes scientists hired to design research to understand the impacts of offshore wind technologies on marine resources and the GOM. The Bureau of Marine Science has also hired nine new staff to support changes in fishery reporting requirements. In compliance with Addendum XXVI to the ASMFC Lobster Management Plan, the lobster fishery had to scale up from 10% harvester reporting (using paper logs) to 100% lobster harvester reporting (electronic), resulting in an influx of catch and social–ecological data from lobster license holders in 2023 (ASMFC, 2018). This will yield an anticipated 250000 trip reports plus additional reports received annually meaning Maine reports will account for ∼42% of all trip level reports that are stored in the Atlantic Coastal Cooperative Statistics Program (ACCSP) data warehouse. For MEDMR staff, this has required a broad scope of work and expansion of the landings programme, including creating an app for harvesters to enter data, providing support to industry on how to report data electronically, and then reviewing these records. At the same time, 11 staff members have retired from MEDMR since March 2020, taking with them up to 40 years each of institutional knowledge and well-developed collaborations. We know from our close relationships with government research programmes around the country that MEDMR is not alone in both the loss of long-time staff while simultaneously ushering in a new generation of scientists tackling climate research. Both the changes in the GOM and within the walls of governmental science entities highlight that now is a crucial time for natural resource scientists across the world to reflect on the past and document institutional knowledge as part of the preparations for the work ahead.

Part II: case study: MEDMR approach to studying coastal fisheries

MEDMR has begun the preparation process by compiling more than two decades of information about the programmes that have studied the GOM's most productive fisheries, the fisheries that have collapsed in this time, and fisheries that have undergone other unexpected changes. Below and in the supplementary data, we review examples from each MEDMR science Bureau of these fisheries and how MEDMR has studied each one during a period of dramatic change (Table 1). While some of these fisheries are specific to the coast of Maine, the range of MEDMR programmes offers insights and lessons learned into a suite of marine resource monitoring and research approaches. Based on this information and MEDMR experiences from sustaining the programmes and working in support of fisheries we describe below, we then share our considerations for the future of marine resource monitoring and lessons learned from studying these valued species in a rapidly changing GOM.

(1) American lobster (*Homarus americanus*)

For Maine, the trap-based commercial American lobster fishery is an essential economic driver for the coastal economy and ecosystem. Lobstering occurs commercially and recreationally across the Maine coast year-round with 2191 recreational and 5643 commercial licenses issued by MEDMR in 2022 with license holders completing >200000 trips. This benthic crustacean annually represents >60% of Maine's marine resource landings by ex-vessel value (68% in 2022). Since 2004, lobster dealers across the coast are required to report landings to MEDMR for each trip, including information about price. The landings peaked in 2016 with >132 million pounds/59874 metric tonnes (mt) harvested. That 2016 peak in landings was also the previous peak in ex-vessel value at >$539 million, but 2021, though lower in landings, exceeded the value at >$739 million. Lobster landings from 1990 to 2022 experienced a gradual increase from the 1990s through the mid-2000s, then a steep rise between 2007 and 2012 (Figure 1; MEDMR landings, 2023).

The MEDMR lobster monitoring programmes include the Lobster Sea Sampling (LSS) Program, Ventless Trap Survey (VTS), Settlement Survey, and Larval Survey (MEDMR, 2023b). From 1967 to 2012, a port-side intercept survey was

Table 1. Select marine species currently or recently studied by the MEDMR.

Species/Fishery	Common name	2022 fishery value in Maine	MEDMR Bureau
Homarus americanus	American lobster	$388 589 931	BMS*
Anguilla rostrata	American eel	$20 166 770	SRFH*
Mya arenaria	Soft shell clam	$16 676 325	BPH*
Brevoortia tyrannus	Atlantic menhaden	$12 066 941	BMS*
Placopecten magellanicus	Atlantic sea scallop	$8 768 193	BMS
Groundfish species	Atlantic cod and more	$3 593 578	BMS*
Strongylocentrotus droebachiensis	Green sea urchin	$2 679 282	BMS*
Clupea harengus	Atlantic herring	$1 889 359	BMS
Alosa pseudoharengus	River Herring	$1 534 276	SRFH
Salmo salar	Atlantic salmon	Confidential	SRFH
Osmerus mordax	Rainbow smelt	Confidential	SRFH
Pandalus borealis	Northern shrimp	Closed	BMS

All value estimates are in USD and represent preliminary values provided by the MEDMR landings group. MEDMR data is stored in an internal database (MARVIN) and non-confidential data is publicly available. Bureau within MEDMR that leads the monitoring and research programmes that support these fisheries in Maine (BMS: Bureau of Marine Science; SRFH: Bureau of Sea-Run Fisheries and Habitat; and Bureau of Public Health). Asterisks indicate these programmes are reviewed in this manuscript, while all other programmes are presented in the supplementary data. For a full list of MEDMR commercial fisheries information: https://www.maine.gov/dmr/fisheries/commercial/landings-program/historical-data.

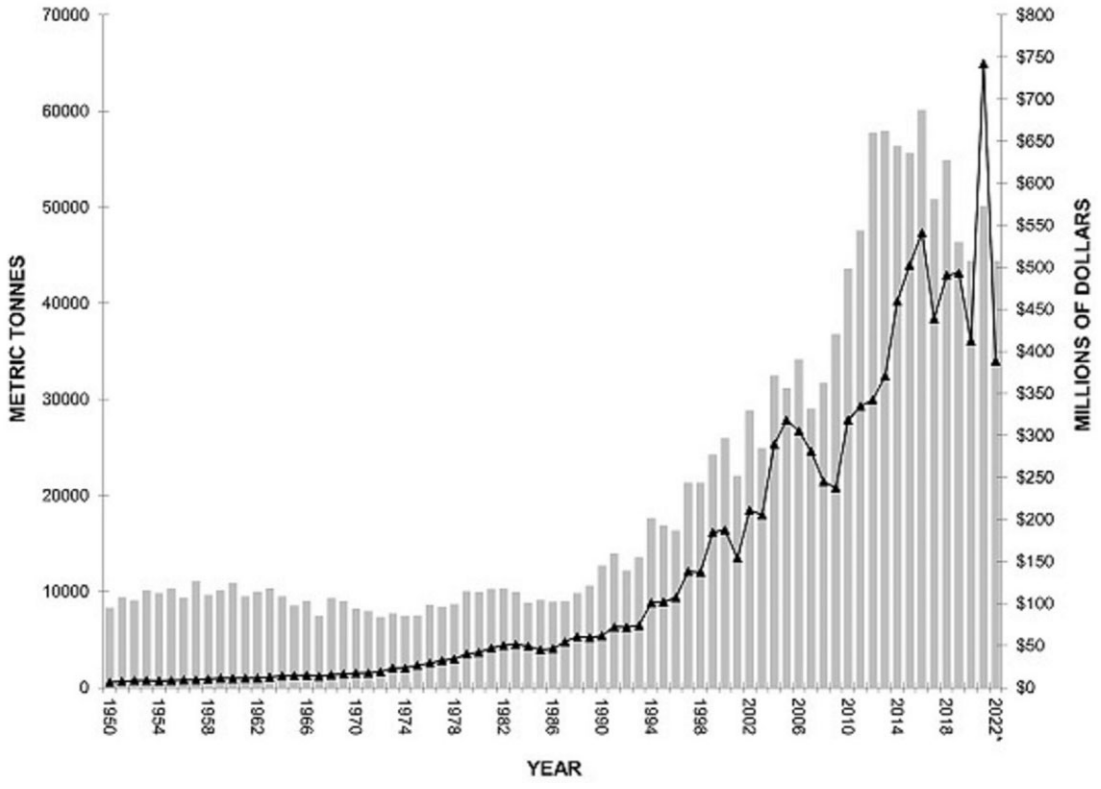

Figure 1. Maine American lobster (*Homarus americanus*) landings (metric tonnes) and ex-vessel value from 1950 to 2022 as reported by the MEDMR landings programme. All 2022 values are considered preliminary, and all data is reported from Maine lobster dealers. Mandatory dealer reporting was started in 2004.

conducted, eventually suspended because of funding and redundancy with growing landings reporting requirements for harvesters and dealers. The MEDMR LSS Program was initiated in 1985 at the request of industry, managers, and scientists to gain insight into the discarded portion of the lobster population that supports the most economically important single-species fishery in Maine coastal waters. Participation by commercial boats is voluntary and not random, but trips are distributed spatially and temporally within each month. Samplers work collaboratively with the captain and record fishing effort information, biological data on lobsters, and any bycatch data. The LSS Program has expanded over time. From 1985 through 1997, three ports were sampled once a month with the same fishermen annually May through November. In 1998, the programme expanded, increasing participation and sampling areas to include all seven Maine Lobster Management Zones (LMZ) from May through November (Figure 2).

The MEDMR VTS began in 2006 as part of a regional effort to develop a fishery-independent trap survey that targets the juvenile lobster population using a random stratified design that can be compared across the region (McManus *et al.*, 2021). While there have been changes over time, the survey design remains stratified by depth with 276 randomly selected sites in 2022. As of the writing of this manuscript,

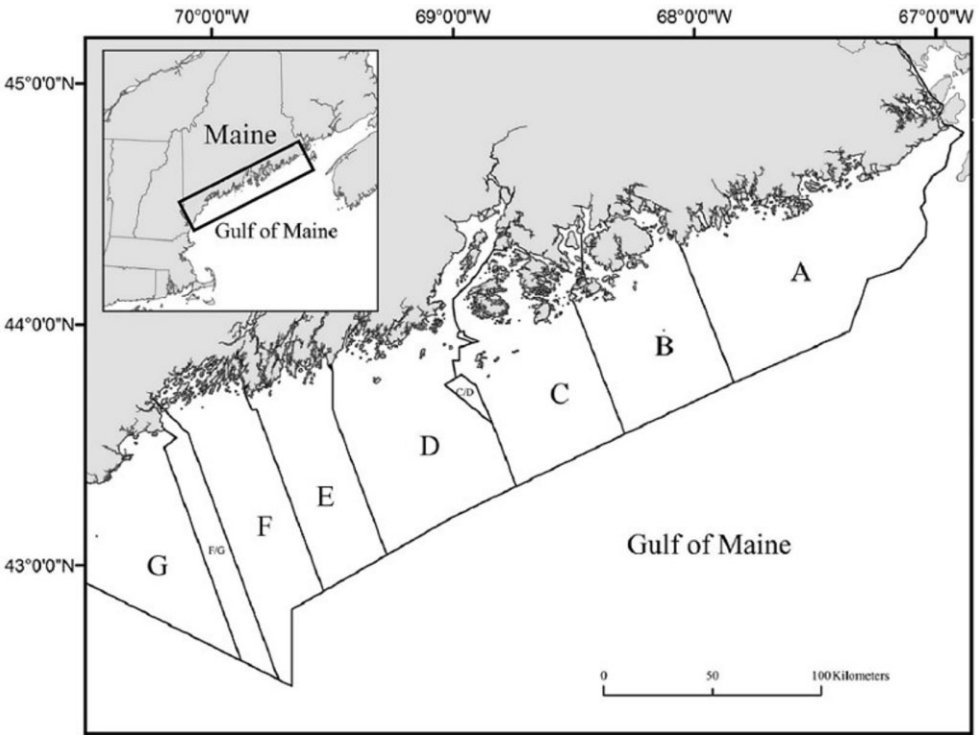

Figure 2. Lobster Management Zones (LMZ) along the coast of Maine. Each Lobster Management Zone (A–G) is scheduled for three LSS Program trips monthly, May through November, in addition to other MEDMR lobster surveys and research.

the VTS programme contracts with nine commercial lobster boats, selected through competitive bid, across the coast to deploy survey traps with no escape vents. Samplers collect similar biological data to the LSS Program for all species observed, with each trap counted and measured separately; temperature is also collected.

The MEDMR Lobster Settlement Survey is a SCUBA diving survey that serves to collect and index newly settled young-of-year (YOY) lobsters. American lobster larvae hatch from eggs in the late spring and early summer, develop through four planktonic larval stages, and then settle on to the sea floor for the remainder of their life history phases (Factor, 1995). These surveys occur annually at fixed sites in October and November after the peak in settlement is presumed to have occurred. MEDMR divers use venturi suction sampling methods with mesh collection bags to survey the half-metre-square quadrats. Data is entered into MEDMR's MARVIN database (see supplementary data for more on MARVIN and MEDMR, 2023b for survey sampling design) and is also submitted to the American Lobster Settlement Index regional collaborative (McManus *et al.*, 2023). The lobster settlement surveys began in 1989 in the western region of the Maine coast as a partnership between the University of Maine and the Bigelow Laboratory for Ocean Sciences (Wahle *et al.*, 2010). In 2000, MEDMR funded and expanded the survey to include a minimum of four sampling stations in each of the seven lobster management zones. By 2005, MEDMR was fully supervising the monitoring effort, and as of present day, MEDMR now samples 40 fixed stations, of which 38 have been sampled consistently since 2001.

MEDMR began conducting a planktonic, pre-settlement larval lobster survey in 2018 after a preliminary 2017 survey implemented in collaboration with Hood College. The four sites in LMZE that are currently sampled from mid-June to September on a biweekly or weekly basis are a subset of an original 12 sites monitored by other research groups using a revised version of this neuston net-based survey design (Incze *et al.*, 2006; Annis *et al.*, 2007). The larval lobster survey occurs on a MEDMR vessel and evaluates the abundance of larvae and documents the seasonal occurrence of larvae each year prior to settlement.

Data from the VTS, LSS, and Settlement programmes contribute directly to the ASMFC American Lobster Stock Assessment, which is completed every 5 years. Many academic partners have used these data to conduct investigations of maturity, fecundity, sex ratio, geographic variation, growth, and trap selectivity that have additionally contributed to the assessment. MEDMR scientists represent Maine in the ASMFC stock assessment process (stock assessment subcommittee and technical committee) and use LSS, VTS, and Settlement data along with their associated analyses to make recommendations to fishery managers and hold discussions with the fishing industry to understand the dynamics of the lobster population and fishery. Biological and environmental data collected by these programmes across life history stages are used to evaluate the potential impacts of management tools used in the lobster fishery, including the minimum harvest size, the protection of ovigerous females, and the number of traps used by harvesters.

(2) Atlantic menhaden (*Brevoortia tyrannus*)

Atlantic menhaden are one of the most ecologically and economically important fish species in the western Atlantic. They

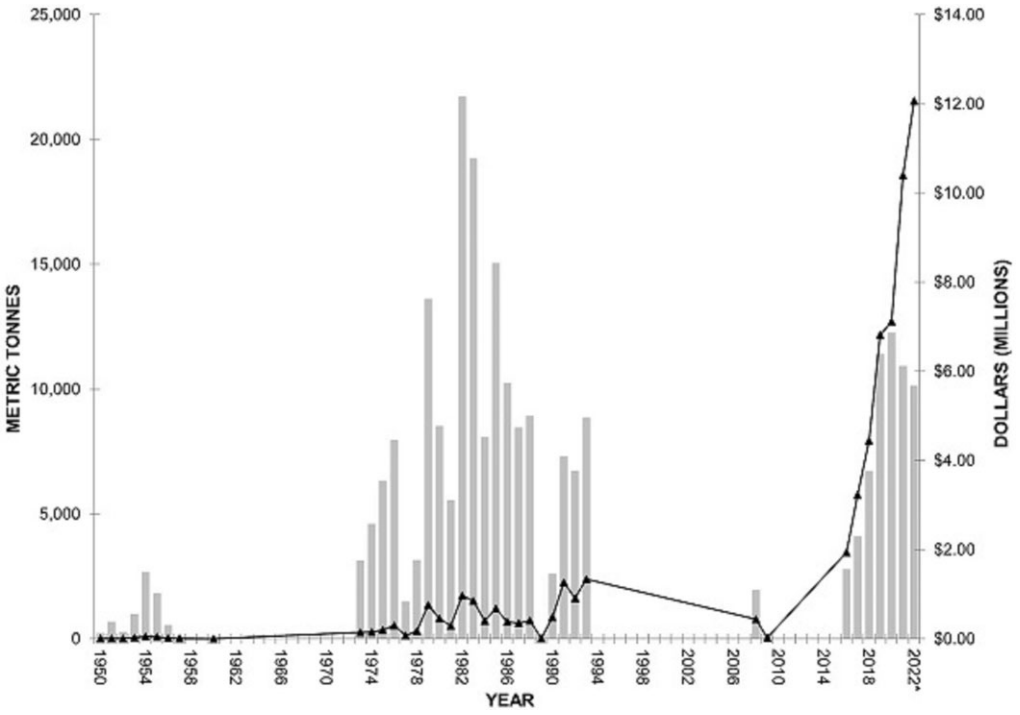

Figure 3. Maine Menhaden (*Brevoortia tyrannus*) landings (mt) and value from 1950 to 2022 as reported by the MEDMR landings programme. All 2022 values are considered preliminary, and 2016–2022 data are from harvester-reported data, value added from average price per pound from dealer data.

are planktonic filter-feeding fish that occur in large migratory schools in estuaries and coastal waters from Nova Scotia to northern Florida (ASMFC, 2019). It is believed that larger, older fish migrate farther north, and these are the fish that make it to Maine's coastal waters (ASMFC, 2019; Liljestrand *et al.*, 2019). In the recreational fishery, fish are most caught by snagging using hook and line. Purse seines and various types of gill nets are the primary commercial gear types used in Maine. In recent years, landings in the state of Maine have increased significantly compared to historical data, with landings in 2016 of 6.1 million pounds (2782 mt) valued at $1.94 million to 22.1 million pounds (10038 mt) valued at $9.5 million in 2021 (MEDMR landings, 2023; Figure 3). MEDMR recorded 507 commercial and 513 noncommercial harvester licenses issued in 2022.

Currently, MEDMR requires daily and weekly electronic landings reports from commercial fishermen depending on gear permit type and the fishery is managed at the state level using a set quota determined each year by ASMFC. Recreational landings are recorded through NOAA's Marine Recreational Fisheries Statistics Survey (MRFSS) and MRIP. MEDMR conducts portside biological sampling of Atlantic menhaden following ASMFC's fishery management plan requirements. These fish are collected from fishing vessels and brought back to the lab to be analysed for length, weight, and age (see supplementary data for detailed methodology and data processing). While the survey and sampling methods have remained relatively consistent, there have been many changes in regulations and assessments both at the state and regional levels during this time frame. MEDMR scientists represent Maine and data collected by MEDMR by serving on the ASMFC Stock Assessment Sub-Committee and Technical Committee for this species. One of the big changes occurred in 2020, when ASMFC started using both the Atlantic Menhaden Single-Species and Ecological Reference Point (ERP) Assessments to define stock status (Chagaris *et al.*, 2020). The ERP assessment evaluates the health of important prey species in an ecosystem context, using a Model of Intermediary Complexity for Ecosystems (termed MICE) to examine Atlantic herring (*Clupea harengus*) and menhaden stock status relative to the predation demand by commercial and recreationally important species such as striped bass, bluefish (*Pomatomus saltatrix*), and spiny dogfish (*Squalus acanthias*). Using this approach, managers were able to examine tradeoffs and set goals in consideration of prey species removal, predator biomass/utilization, as well as incidental impacts on bird and other fish populations (ASMFC, 2020). This is the first use of quantitative ERPs for a forage species in the US, and MEDMR researchers supported the development of this ERP and are currently considering how to best support this type of assessment framework while moving forward in meeting regional sampling requirements. Current data support includes efforts to increase food habits data from important menhaden predators, such as bluefin tuna (*Thunnus thynnus*) and groundfish.

(3) Monitoring in support of commercial shellfish harvesting

In Maine, the soft-shell clam fishery consistently ranks as one of the most valuable fisheries in the state with a value of over $16 million in 2022 (MEDMR landings, 2023). Because bivalve shellfish are filter feeders, they can accumulate biotoxins from toxin-producing phytoplankton species. Monitoring harmful algal blooms (HABs) is essential to supporting the harvest of this species and other bivalves, which is dictated and enforced on the municipal level. MEDMR has taken steps in recent years to develop programmes in light of the lack of coastwide resource monitoring surveys or assessment programmes in Maine to help address resource data

Figure 4. Total weight landed (mt) and value of the landings of ten groundfish species in Maine from 1951 to 2019 as reported by the MEDMR landings programme.

needs. The MEDMR Bureau of Public Health's Growing Area Program ensures bivalve shellfish sanitation for recreational and commercial harvest activities, including both aquaculture and wild harvest. Toxin-producing phytoplankton in the GOM include *Alexandrium* spp., *Pseudo-nitzschia* spp., *Prorocentrum lima*, and *Dinophysis* spp. MEDMR adheres to the National Shellfish Sanitation Program Model Ordinance, which defines management policies, sampling strategies, testing methods, and closure and reopening criteria for biotoxins along with pathogenic bacteria, including *Vibrio* spp. and *E. coli*, viruses, and other deleterious substances (see supplement for MEDMR programme survey methods). Biotoxin monitoring in Maine began in 1957 by request of the US Public Health Service following an epidemic of paralytic shellfish poisoning in New Brunswick, Canada. Once the presence of paralytic shellfish toxin (PST) was confirmed, routine bivalve shellfish testing began in 1958 using the approved biological testing method, mouse bioassay (State of Maine House of Representatives, 1988). Phytoplankton monitoring was incorporated into the programme as an early warning system in 1996. MEDMR transitioned from a biological to a chemical testing method for PST testing in 2014. Phytoplankton cell count triggers for shellfish sampling have been established based on historic data and procedures adopted by other states with similar harmful algal species. *Alexandrium* spp. is prevalent along Maine's coastline during summer months and if toxin is detected or *Alexandrium* cell count triggers are met at any of the "primary" sampling stations, additional nearby "secondary" stations are then also sampled weekly for the duration of the bloom event to define the area of impact. Bivalve shellfish tissue is collected for testing based on corresponding phytoplankton cell count trigger points. Regional closures are instituted on or about 1 May as a management strategy, allowing resources to be primarily devoted to areas of commercial importance.

The primary purpose of the data collected by this programme is for the MEDMR to make bivalve shellfish closure and reopening decisions. Shellfish tissue results from the primary sampling stations collected for PST analysis are distributed weekly via a listserv for research purposes and neighbouring state shellfish authorities' awareness. Phytoplankton counts for all HAB species along with predictive modelling for PST are uploaded weekly during the biotoxin season to MEDMR's website and made available to the public (MEDMR, 2023a).

(4) Groundfish (multiple species)

The New England groundfish fishery encompasses 13 different species, including the Atlantic cod (*Gadus morhua*), arguably the most well-known vertebrate species in this region. Once common in coastal Maine waters, it is now at historically low levels of biomass, with many of its spawning grounds in Maine now gone (Ames, 2004). Other species such as haddock (*Melanogrammus aeglefinus*), white hake (*Urophycis tenuis*), pollock (*Pollachius pollachius*), Atlantic halibut (*Hippoglossus hippoglossus*), and flatfish such as winter flounder (*Pseudopleuronectes americanus*), American plaice (*Hippoglossoides platessoides*), and witch flounder (*Glyptocephalus cynoglossus*) are also species targeted by the groundfish fishery. Each of these species has seen similar declines in abundance from historical overfishing, but some have rebuilt to levels to support commercial and recreational fisheries in Maine. Overexploitation of groundfish stocks occurred after landings peaked in 1954 (45983.44 mt) and today landings remain low in Maine (1470.61 mt in 2019; Figure 4). The boats and primary gear used to target groundfish are bottom trawls, gillnets, and hand gear. Although Maine has a small portion of active vessels in the groundfish fishery (~30 boats landing catch in Maine annually) compared to the past, this fishery is still economically and culturally important to the state (MEDMR landings, 2023).

The groundfish fishery is federally managed by the NEFMC with state management measures aligned with federal guidelines. MEDMR science staff are tasked with representing

Maine on the NEFMC groundfish plan development team (PDT) and staying apprised of regional conversations around the research and management of these species as well as provide feedback on potential meeting actions. Although the fishery is managed under a multispecies fishery management plan, each species in this plan has its own stock assessment and management recommendations, including a minimum harvest size. Recreational catch of these species is recorded through the MRIP, including the Access Point Angler Intercept Survey (APAIS) with sampling occurring onboard headboats during fishing trips. The NOAA Northeast Fisheries Science Center (NEFSC) bottom trawl survey is the main monitoring programme for management, but the MEDMR developed the Maine-New Hampshire Inshore Trawl Survey (MENH survey) in the fall of 2000 to obtain data for the inshore areas of the GOM to study historically important spawning grounds and nursery areas (Ames, 2004, 2012).

The MENH survey is a multispecies survey that provides data for management of multiple species in the GOM. This survey is a peer-reviewed standardized stratified random survey, stratified by depth and longitudinal regions, conducted in the spring and fall every year (Sherman *et al.*, 2005). In the beginning of this survey only three depth strata were sampled, but in the fall of 2003 a fourth depth stratum was added to sample deeper inshore areas with higher intensity than the NOAA survey (MEDMR, 2023c for site map and data portal). Few changes have occurred over the years with most changes being the collection of additional data or parameters for selected species. For example, starting in 2005, the survey started collecting age and maturity data for selected groundfish species to provide additional data for their stock assessments. In 2020, additional environmental data began to be collected to expand on the current environmental data collected (water column temperature, salinity, dissolved oxygen, pH, turbidity, and fluorescence). The survey has now created a long time series for many species and the data collected are used in more assessment models for many groundfish and non-groundfish species, such as American lobster. In addition to being used in stock assessment models and by MEDMR researchers, scientists throughout the country have also used data collected on this survey to evaluate the impacts of climate change on groundfish and other species in the GOM.

(5) American eel or elvers (*Anguilla rostrata*)

The elver fishery has been a financial boon to all parties involved as this fishery is the highest valued (based on price per pound) in the state and potentially the entire east coast of the US. Since 2012, the price has averaged $1676/lb. Landings fluctuated between 1999 and 2011 until they peaked (and almost tripled) in 2012 at just over 21000 lbs/9525 kg (MEDMR landings, 2023). This is a quota-based fishery with a current quota of 9688 lbs/4394 kg split amongst the State of Maine and the four indigenous tribes (Micmac, Maliseet, Penobscot, and Passamaquoddy). The value of this species makes this a competitive fishery in Maine with a cap of 425 licenses and a raffle each year to award the few available licenses. The four tribes issue separate licenses for this species. MEDMR began reporting commercial elver dealer reporting in 1998 (MEDMR issued 16 elver dealer licenses in 2022), and trip-level harvester reporting started in 2007.

MEDMR also conducts life history research and monitoring on this species (MEDMR, 2023d). MEDMR surveys all life phases of the American eel: glass eels represent the young-of-year (YOY), elver phase are young eels migrating from the ocean to freshwater environments, yellow phase are eels growing to adulthood, and silver phase are mature eels returning to the Sargasso Sea to spawn. The annual YOY (glass eel) abundance survey has been carried out at a single location in Maine (West Harbor Pond, 43°51'19.7"N, 69°38'46.5"W) consistently each spring since 2001. This survey uses two specially made eel passages (ramps) attached to the dam at the outlet of the pond to collect in-migrating eels. During sampling, glass-phase eels are separated from elver eels; both stages are quantified by weight or number, then all eels are released into West Harbor Pond. MEMDR has deployed baited eel pots in West Harbor Pond during the summer and early fall each year to survey yellow-phase eels. Lastly, MEDMR conducts an annual survey of out-migrating silver phase eels from this same location by deploying a fyke net near the outlet of the pond to capture silver phase eels leaving in the fall. Each year, MEDMR staff summarize the results of the YOY, yellow eel, and silver eel surveys into a compliance report (see supplement for full methods and reporting).

(6) Green sea urchin (*Strongylocentrotus droebachiensis*)

The Maine green sea urchin fishery began in earnest when a new market for the spiny echinoderm's roe developed in Japan in the late 1980s. Early days of this fishery have been described as a "wild west", with people flocking to Maine's coastal waters in the winter to dive or drag for "green gold". Unfortunately, the early days of widespread, unregulated fishing led the Maine urchin fishery to fit the model of a classic "boom-bust" fishery, where landings from a new fishery are high—then rapidly decline to low levels due to over-fishing (Chen and Hunter, 2003; Berkes *et al.*, 2006). Significant harvesting of this once-considered "pest" species began in Maine in 1987 with no management rules, and by the time management controls began to take shape in 1994, there were 2725 licensed harvesters. Due to steadily declining urchin populations, a moratorium on issuing new harvester licenses began in 1994, making the green sea urchin Maine's first closed access state fishery. A limited, annual lottery allowed for some new licenses between 1999 and 2004, with no new licenses issued since, and urchin recovery in the GOM remains uncertain. A limited urchin fishery is still conducted in Maine with over 200 licenses issued, but with <100 active fishers harvesting urchins from fall to early spring (Hunter, 2022).

Today, harvesters (divers and draggers) use calendars set by the MEDMR with advice from the Sea Urchin Zone Council, an industry co-management group comprised of seven industry elected members (harvesters or dealers) and eight members appointed by the MEDMR Commissioner that may be from the industry or marine science communities. This group meets at least once a year and makes recommendations to the Commissioner on the harvest season, fishery license numbers, and research recommendations (MEDMR, 2023e). Management controls for this fishery include set harvest seasons, daily quota restrictions, and harvest size restrictions. An annual dive survey done in collaboration with industry to evaluate urchin distribution and abundance along the Maine coast was started by MEDMR in 2001, dividing the coast into nine regions for sampling (see supplement for methods). Due to reduced funding and fishery activity in recent years, the dive survey was geographically reduced by more than half in 2011, focusing on the eastern portion of the Maine

coast with the largest urchin abundance. Data provided for fishery management are portside sampling and harvester interviews conducted during the fishing season, landings data reported daily from buyers, and fishing effort reports from harvesters.

Primary users of MEDMR's data include MEDMR managers, the Maine Sea Urchin Zone Council, the Maine State Legislature, and academic institutions. Other MEDMR projects have included an urchin translocation experiment, testing large-mesh diver catch bags and drag escape panels, the development of an urchin population dynamics model, conducting harvester opinion polls, and employing trackers on urchin harvester vessels in specific areas. This is a species and fishery where the MEDMR data collected are used within the state of Maine, and unlike many of the other fisheries we describe is not managed with other state or federal partners.

Descriptions of MEDMR fisheries programmes

These fisheries and associated MEDMR programmes represent only a portion of MEDMR scope of work with coastal Maine fisheries. See the supplementary data for more methodologies and additional programme descriptions, fisheries trends, and MEDMR data management for the programmes described here as well as MEDMR programmes for Atlantic Herring (*Clupea harengus*), Atlantic Salmon (*Salmo salar*), Atlantic Sea Scallop (*Placopecten magellanicus*), MEDMR's database (MARVIN), Municipal River Herring (*Alosa pseudoharengus*, *Alosa aestivalis)*, northern shrimp (*Pandalus borealis*), Rainbow Smelt (*Osmerus mordax*), and the MEDMR Recreational Fishing Program.

Discussion

Lessons learned

Looking back on the last several decades of the commercial fisheries of the GOM, we explored how MEDMR adapted programmes during both the rise and dominance of benthic crustacean species, the near collapse of the groundfish sector, and emergence of fisheries unique to coastal Maine waters. MEDMR and state agency staff across the coast have been called upon by both the Maine Climate Council (MCC) and our industry collaborators to acknowledge the impacts of climate change on the local marine environment and the distribution, abundance, and phenology of the species that supports the region's coastal economy. One facet of our approach to addressing all three of the challenges we describe is to sustain the long-term environmental and resource monitoring programmes that provide increasingly valuable ecosystem and fishery datasets. For example, the MEDMR maintains a sea surface temperature (SST) record going back to 1905 in Boothbay Harbor, making it one of the longest continuous SST datasets in the northwest Atlantic and the longest in the GOM (MEDMR, 2023f). The MENH Inshore Trawl Survey has been collecting benthic ecology and environmental data coastwide since 2000 and has a sustained continuous timeseries in the fall, only missing one survey in the spring during the pandemic when most other surveys were halted (MEDMR, 2023c). This survey was created to meet the need for a standardized survey monitoring in the nearshore area of the GOM, and the consistency across a large area paired with the expansion into oceanographic measurements will be central to addressing the MCC's recommendations related to ecosystem-level research and in support of coast-wide environmental monitoring.

Using these long-term and regionally specific datasets paired with historical literature will also be key for elucidating trends driven by other climate-related forcings and the role commercial species such as Atlantic menhaden play in the ecosystem. As far back as the 1800s, menhaden was reduced into fish oil and fishmeal at coastal reduction plants, but today, menhaden in Maine are primarily used for lobster bait and a small amount for bait in marine recreational fishing (ASMFC, 1999). Modern landing data and historical observations in the GOM support patterns of high abundance periods (1–20 years) followed by periods of disappearance for up to 20 years with these cycles occurring since at least the 1840s (ASMFC, 2022). There have been numerous studies into the causes of these large swings in abundance; possible causes are fishing pressure, broad-scale environmental factors, and other oceanographic processes like the Atlantic Multidecadal Oscillation (Buchheister *et al*., 2016). Without fishery-based observations and documentation, we would lack an understanding of changes in the commercial use of this species and its distribution into the GOM. MEDMR and other GOM researchers have already documented the complexity and begun to understand larger climate impacts on key marine stocks. However, more in-depth analyses and modelling of historical MEDMR data are needed to better plan for future research and resource management decisions that will be applicable to all marine resource scientists and managers.

The ability of natural resource agency staff to nimbly adapt to changes in the ecosystem and social-economic influences is key to successful resource monitoring as MEDMR scientists have done to support commercial fisheries in the face of unexpected natural disasters and external forces. For example, elver fishing in Maine exploded after two international events: the 2012 tsunami in Japan and a crash of the European elver market. Facing potential fisheries closures by ASMFC to control harvest in Maine, the MEDMR contracted with Bluefin Data LLC to develop a swipe card programme called the "Elver System". The "Elver System" has gone through many iterations over the years but has provided the MEDMR with a secure way to ensure that the illegal sale of these highly valuable species is kept to a minimum. MEDMR issues each state license holder a swipe card with their own individual fishery quota that they are responsible for tracking. Since 2014, all elvers sold in Maine have been documented through this swipe card process, marking a novel addition to fisheries quota tracking in the northeast US. This innovation and successful collaboration with multiple stakeholders have made it possible for MEDMR staff to adapt to fundamental shifts in the resource, sustain research, and better prepare for future years of harvest.

Another connective thread between these fisheries and MEDMR's experience studying them is the challenge of monitoring commercial species in a manner that balances the needs of local, state, and regional fishery assessment structures. The soft-shell clam industry, at times rivalling lobster in participation and second in value, has struggled to implement consistent surveys as administered through municipal management and assessment. To protect public health, and perhaps to be a backstop for the lack of coordinated assessment and management, a robust biotoxin programme has maintained a remarkable level of food security for this fishery. This programme is

an example of one that has already had to adapt to a changing ecosystem, as collaborations with other state agencies in 2016 and 2017 confirmed the first documented occurrence of the highly toxic *Pseudo-nitzschia australis* in the GOM and have been observed every year since. The introduction of this species to Maine waters has been hypothesized to have come from the Scotian Shelf based on observations and modelling work with an ultimate origin in the North Atlantic near the United Kingdom and blooms likely sustained in the GOM by warming water temperatures (Clark *et al.*, 2021, 2022). To develop programmes in support of fisheries require MEDMR scientists and other natural resource agency researchers to stay up-to-date on the key growth, reproductive, and movement characteristics of multiple species across trophic levels. We accomplish this through applied research, collaborations with academia, and a willingness to take observations from the field into the realm of survey design. This is a complex task, but as climate change continues to accelerate and cause shifts at the ecosystem level, it will be key to balance the needs of management structures with monitoring programmes that align with the core biology of each species that supports a commercial fishery.

Preparing for the future

In several of the programmes we describe above, new MEDMR researchers have taken over these programmes in the last 5 years from staff that worked for the MEDMR for 20+ years. This transition in leadership comes with the responsibility of carrying these data streams forward in the face of fluctuating or uncertain funding while also meeting universal requests of broader data availability and climate-focused analyses. This also comes with the responsibility of experienced agency staff to share institutional knowledge and observations with new programme leads. The Maine urchin fishery, as described in the previous phase provides one example of this as a species that has experienced high fishing pressure, vulnerability to new predation and warming waters, and multiple forms of research to try to support recovery. Because sea urchins are important algal grazers, the widespread removal of urchins from benthic communities caused an alternate stable state to take hold, replacing urchin barrens with algal-dominated habitat that harbours urchin predators, including large migratory *Cancer borealis* crabs (Steneck *et al.*, 2013). Increased predation along with historically heavy fishing pressure have made the road to recovery for urchins a difficult one. With this knowledge gained from multiple attempted recovery studies shared by career MEDMR employees, new agency research staff are reaching out to both the remaining industry members and external researchers to define new research priorities and directions with the benefit of historical context. Another way staff have met these needs and shared these insights more broadly is by building data portals to disseminate their work and all appropriate metadata needed to understand these decades-long datasets in context (MEDMR 2023c, f; MEDMR landings, 2023). These sustained datasets and accumulated experiences will be central to guiding new researchers tasked with developing programmes to monitor the potential impacts of climate mitigation and adaptation activities, including the development of offshore wind leases in the GOM. Government agencies are uniquely poised to sustain long-term environmental or multi-species programmes, and making investments in these types of work will be key for readying ourselves and our stakeholders for the inevitable impacts of climate change.

New staff investing time in equitable research and co-management relationships will be paramount to continuing MEDMR science programmes into the future. Industry members, such as those within the lobster supply chain, routinely take an active role in MEDMR research projects in addition to active participation in MEDMR monitoring programmes. One example is partnering with Inland Seafood (Boothbay, ME, USA) to hold lobsters in enclosures within their lobster pound to record observations over several months. Another is cooperating with the live lobster packaging facility at Ready Seafood (Portland, ME, USA) to sort through and secure lobsters that meet precise physical guidelines and are also sourced from specific locations. These partnerships have led to productive research projects that use time, money, and space efficiently while drawing on local expertise to improve the setup and execution of our experiments.

Many of the MEDMR monitoring and assessment surveys are built on industry relationships established over long periods of time. One unique aspect of the MENH inshore trawl survey that sets it apart from other fishery-independent surveys in the region is that it is a collaborative survey that works with and uses a commercial fishing vessel as the research platform. Fishermen were directly involved in the development of the survey and are still involved with survey operation and catch processing. Investing in highly collaborative relationships like these under a changing workforce brings novel challenges that many natural resource scientists throughout the world are experiencing. Recognizing the contributions of commercial fishers and incorporating their expertise into multiple aspects of assessment is a well-recognized approach to successful fisheries research and management, and this will be a key part of MEDMR's approach to each of the three challenges (Sampedro *et al.*, 2017; Hare, 2020).

Successful management-science approaches used in Maine for the lobster fishery and other species have collaboration with the fishing industry and on-the-water observations at their core (Acheson *et al.*, 2000). Perhaps the most singular example of this in Maine's most iconic fishery is the long history of "v-notching", a mark made on a uropod of an ovigerous female making it illegal to harvest. This practice was formalized by the Maine legislature in the early 1900s, and in 1995, regional regulation was enacted to mark ovigerous females and forbid them from harvest in the commercial fishery (Acheson and Gardner, 2011). This conservation measure was called into question in the 1980s when opponents (state, interstate, and federal) spoke against the practice and tried to abolish it from the fishery despite its well-established history and ground support from harvesters and across the industry (Acheson and Brewer, 2003). In recent years, MEDMR and other researchers have paired industry knowledge of this practice with MEDMR lobster programme data (which records the presence and type of v-notch on each female) to quantify the immense long-term benefits this conservation measure has had on the population and the GOM fishery (Le Bris *et al.*, 2018; Mazur *et al.*, 2019; ASMFC, 2023). Currently, MEDMR has one of the few broadscale monitoring programmes that studies all life stages of the American lobster from planktonic larvae to adults harvested in the fishery. This scope of life-history data has given MEDMR researchers the context for answering industry questions about potential changes and provide robust feedback on proposed

management or conservation measures, such as proposed changes to harvestable sizes, in addition to providing industry perspectives and interpreting MEDMR datasets for the ASMFC (ASMFC, 2023). Investing in this comprehensive approach to species monitoring will likely prove even more valuable in the face of life-stage-specific responses to changing conditions.

We believe there are lessons to be learned and considerations in MEDMR's recent history for all natural resource agency scientists about how to prepare agency staff, programme managers, and the research community for the multifaceted challenges that inevitably lie ahead. MEDMR is analysing current and historical data for each programme or survey to answer questions about current resource monitoring survey designs relative to shifting resources and assessment methods. For example, do surveys designed to measure population distribution with fixed annual start dates still make sense in the GOM? This will require anticipating the impacts of any survey or programmatic changes to the users of these data. Given the regional nature of most marine fisheries, both in range and management, any changes in methodologies will need to be prepared for by stock assessment scientists or calibrated with state and federal research partners. The investment into building climate-resilient programmes over the coming years will be focused on collaborations with both our industry research partners and university faculty across the region.

State agency scientists regularly work with external biologists, oceanographers, and social scientists to provide data and advance shared research interests. The goal is to continue these collaborations moving forward and encourage researchers in this sector to meaningfully engage in projects that directly support survey design and fisheries management. We have learned collaborations should include regular discussions to develop timely questions, leveraging the investments of state and federally funded programmes to secure expanded funding to support novel work, and sharing results with key stakeholders in a timely manner. Warming temperatures and projected shifts in habitat use will also continue to blur stock boundaries and international stock distinctions, so changes to research and monitoring programmes must be communicated or made in concert with the Department of Fisheries and Oceans or the appropriate international partners (Pershing *et al.*, 2021).

To be successful, such work must involve complex reflection and in-depth understanding of the programmes that comes from documenting institutional knowledge as well as changes identified by experienced research partners and co-managers. As we describe in the preceding sections, we have sustained or fundamentally changed some of these programmes to meet the needs of resource assessment frameworks while groundtruthing our work using the insights of our federal, academic, and industry research partners. The choice that many commercial fishermen make to share observations, participate in research, and work with MEDMR has allowed us to collate observations from across Maine's extensive coastline to anticipate changes in a resource or the GOM ecosystem before formally documented in the research community or in stock assessments. This has allowed MEDMR staff to advocate for these points of view and translate them into key programmatic choices. In order to advance the MEDMR mission both now and in the future, continuing to invest and value the observations and insights of the commercial fishing industry will prove essential. This includes recognizing that the industry's participation in our scientific work can often come as a sacrifice in time that could be invested in their own fishing operations. MEDMR sees the investment in a suite of mutually valuable relationships as integral to the success of marine resource monitoring and assessment moving forward, and we hope to continue to collaborate with other natural resource agencies, academic researchers, and fishing industry members to best prepare and move into the future together.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest

The views and opinions expressed or implied in this article are those of the authors and do not necessarily reflect the position of the State of Maine. The authors declare no conflicts of interest.

Data availability

MEDMR programme data are stored in MEDMR's database (MARVIN; see supplementary data) and available upon request. Commercial fisheries data are compiled by the MEDMR landings group and non-confidential data are available to the public upon request. The MEDMR landings data portal provides non-confidential species landings at the port level that users can download (https://mainedmr.shinyapps.io/Landings_Portal/).

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Author contributions

JDW conceptualized this manuscript and coordinated the drafting and compilation. CW, KK, SL, and CC contributed ideas and overall concept. All authors wrote and reviewed the manuscript.

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