

Sustainable development of Massachusetts Bay: a literature review, analysis of conflict, and solution proposal

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Abstract

Massachusetts Bay and the surrounding ocean and continental shelf form a valuable temperate ocean system for a variety of stakeholders. However, Massachusetts Bay faces many ecological, economic, and social threats to and problems with its sustainable development. Such problems include repercussions of climate change, industrial pollutants, ineffective governing structures, implications of offshore wind development, overfishing, and nonrepresentation of and ignorance towards indigenous communities. To address these issues, we researched, developed, and will, in this paper, propose solutions. These solutions include reforming and expediting environmental impact assessments, negotiating with anglers for fish harvest quotas, navigating further research into offshore wind development, improving autonomous monitoring and restoration of ecosystems, and encouraging an ecocentric focus in both decision-making and the general public. Specifics for each solution, as well as trade-offs between solutions, are discussed.

Executive Summary

Massachusetts Bay is currently in a crisis of sustainable development with regards to various ecological, economic, and social sectors. This report is composed of our team's approaches towards and proposed solutions for these issues.

1. EIA reform – rigor and representation

Currently, EIAs are mostly conducted on a project basis. Relevant data is already collected biweekly by various agencies, but assessments are only given once every two years by the Environmental Protection Agency (EPA). This is problematic because, even with the necessary data, a project that is detrimental to the environment could take up to two years to be noticed. Thus, the first change we propose is to conduct assessments more frequently – once per month. Such a change would be hugely beneficial for tracking environmental damage and project progress and allowing for the creation of more innovative, experimental pilot programs. The potential issue of overburdening the EPA can be overcome either by hiring more staff or, more cost-favorably, by collaborating with local universities who are already conducting compatible research (such as MIT).

We also propose greater emphasis on indigenous ecocentrism in EIAs by incorporating Massachusetts indigenous representatives into EIA project analysis. This will both address indigenous underrepresentation and make such decision-making more holistic.

2. Negotiating fishing quotas

To address overfishing, a moratorium would in theory be most straightforward and environmentally sound, providing time for the fish population to rebound. However, the trade-off that this has on economic activity is, in practice, too high. For example, the 1992-2024 Canadian moratorium on Atlantic cod displaced 12% of the labor force in Newfoundland and Labrador. Though the government tried to mitigate this impact with transfer payments and retraining programs, these programs were too expensive to sustain and difficult for fishermen to accept. Ultimately, the moratorium was not very successful: the Atlantic cod population rebounded to non-critical levels after three decades, not the predicted two, whereas the economic harm has lasted, and is predicted to last, decades.

The compromise, then, would be to set a quota. The Atlantic States Marine Fisheries Commission has attempted to negotiate a catch limit with fishermen but have faced impassable resistance as the Commission lacked power to continuously enforce and monitor regulations. Thus, for a quota to be effective, more powerful regulators (e.g. MA government) will likely be required.

3. Offshore wind research

To protect the foundations of offshore wind turbines against erosion, scour protection, usually in the form of rocky structures, is installed. Research strongly indicates that scour protection also serves as an artificial habitat for many organisms. Floating turbines, which do not require scour protection, do attract and aggregate fish. If either environment were to exceed fish capacity, any spill-over would be spatially concentrated and easily harvested; safety would need to be ensured. We propose a limited-entry fishery in spill-over areas. This would make sustainable harvest management easier and more precise by concentrating anglers and would soften the blow to fisheries dealt by wind farm installation.

By changing the hydrodynamics of zooplankton aggregation and acting as physical barriers, wind turbines may hinder the feeding and movement of North Atlantic right whales, a critically endangered species. We propose the use of high-resolution satellite imaging and trained task-specific AI to locate zooplankton aggregations and track right whales quickly and remotely.

For each scenario, further research is required. Ecologically-focused scour protection should be piloted and analyzed. A framework for a limited-entry wind farm MPA/fishery should be refined. Finally, satellite data should be taken and analyzed on existing farms and planned farm sites.

4. Integrated monitoring and governance reform

Massachusetts Bay is experiencing climate stressors like ocean acidification, global warming, and hypoxia at higher rates than average where a significant portion of the data is fragmented. Less than half of the bay is continuously monitored and management activities remain highly fragmented across the area which results in ecological disruptions and economic losses. We propose to implement a statewide monitoring system that unifies ocean monitoring and forecasting systems with consolidating physical, chemical, biological data. To facilitate the operation of the system, we propose to create governance reforms for better communication

and collaborative efforts to occur among academic institutions, state agencies, and Tribal Nations. Evidence of how combined monitoring of integrated systems within Europe and California has allowed for reductions in losses from climate-driven damages to marine ecosystems of over twenty percent and reductions in marine heat waves response times.

5. Dynamic restoration using autonomous systems

The current restoration project in Massachusetts Bay is designed for fixed sites and is not suited to quickly evolving climate stress hotspots. In light of mobile and data-informed restoration targets based on real-time measurements of environmental parameters, we recommend using autonomous underwater vehicles, specifically the WHOI REMUS 600. The capabilities of the REMUS 600 in terms of high resolution and rapid response in temperature, dissolved oxygen, pH, and carbonate measurements in temperate systems have already been proven in marine heatwaves and hypoxic events. This restoration system will facilitate targeted and rapid intervention in terms of building carbon garden sites with seagrass, algal colonization, artificial reefs, and shellfish clusters based on areas of greatest ecological value. The dynamic adjusting and scaling of restoration sites will enhance carbon sequestration and resiliency while avoiding fixed-site restoration areas.

6. Spreading indigenous ecocentrism

An ecocentric perspective helps us understand how to live harmoniously with nature while maintaining our standards and needs. Indigenous groups often practice such perspectives. Thus, we propose a goal of intentionally introducing indigenous ecocentrism into the general public and government. This could be achieved through conferences and panels with indigenous leaders, or through exhibitions at museums and universities. The former would be better suited for decision-makers and specific individuals, the latter for the general public.

Introduction

Massachusetts Bay has become an epicenter of ocean warming and acidification, where the consequences of ecological changes progress much faster than the global average. Satellite and SITU observations indicated that the Gulf of Maine has warmed at a rate of 0.48 °C per decade since 1982, nearly three times the global ocean warming rate of 0.15 °C per decade (1). In 2021, the region reached the pinnacle of 12.28 °C, which exceeded the 1982-2011 climatological average of 10 °C by more than 2.28 °C. The 370-day-persisting heatwave caused the bay to register a peak of 2.7 °C in the long-term temperature range of the bay, which signaled a warning about the previously projected scenarios for the region (2). Other than the peak points of temperatures, the Gulf of Maine recorded an 11.4 °C average, 1.4°C higher than the long-term baseline of the and became the highest temperature average among forty-year satellite recording, assessing 5-year intervals each (2). Winter averages, on the other hand, rose 1.2 °C in the 1980s, and 3.7 °C in the 1980s with an average of 2.5 °C increase, exterminating the mortal cold conditions for species and enabling tropical and subtropical organisms to initiate living in the Gulf of Maine. (3). These records showcase that the Massachusetts Bay stands as one of the fastest-warming marine regions in the world based on seasonal thresholds and historical data.

These average temperature increases have also been accompanied by significant declines in dissolved oxygen rates in the bottom of the Massachusetts bay ocean. The observations that have been conducted in the last 30 years pointed out that on average the dissolved oxygen rate have declined with an average of $0.0246\text{--}0.0323\text{ mg L}^{-1}\text{ yr}^{-1}$ by corresponding to a cumulative decrease of $0.8\text{--}1.0\text{ mg L}^{-1}$ since the early 1990s (4). Considering that historically, bottom water dissolved oxygen concentrations were around $7.4\text{--}7.6\text{ mg L}^{-1}$, this represents a 10–14% decrease over the observation period. Concentrations of bottom water DO in regions near the Deer Island outfall have intermittently reduced below 6.0 mg/L , which is a biologically recognized threshold consistent with sublethally stressful levels of DO in sea life. In some instances during late summer, these levels have approached 5.5 mg/L , which is not far below the action levels described in MWRA contingency planning (5). The magnitude of this decrease is significant enough to affect the quality of aerobic habitat for benthic invertebrates and bottom-dwelling fish. Expressed in terms of volume, the observed decrease in dissolved oxygen corresponds to a reduction of approximately 25-35 metric tons of dissolved oxygen per cubic meter in the bottom water over a decade. Based on the current projections, if current habits are persisted, the dissolved oxygen levels will decrease by 5.0 mg L^{-1} by mid century at the bay area (4).

The regional trends of ocean acidification have been supported by other studies focusing on the assessment of the global carbon cycle, where approximately 25 to 30 percent of total anthropogenic CO_2 emissions annually are being absorbed by the global ocean that represents 2.5 to 3.0 gigatons of carbon per year. These direct effects cause a reduction in ocean pH and concentrations of carbonate ions (6). Surface ocean pH concentrations have decreased by approximately 0.1 units since prehistoric times, representing a 30 percent increase in hydrogen ions, with expectations of additional reductions of 0.2 to 0.3 pH units by 2100 in high-emission simulations. Regional coastal systems, such as those in Massachusetts Bay, show higher variability and intensity (6).

In Massachusetts Bay, reduced pH and aragonite saturation state (Ω_a) affect calcifiers in two different ways. The formation of larval shells in bivalve species is negatively affected when Ω_a is below 1.5, a level which is now common during winter and early spring over the northeastern United States coastal region (6, 7). For the Massachusetts Bay and west Gulf of Maine regions, both model output and observations suggest that Ω_a can drop to a level of 1.2 to 1.4 for an extended period of up to several weeks a year, especially in bottom and nearshore regions where reduced buffering capacity limits mitigation of lowered Ω_a (6, 8). Experiments conducted in controlled environments have found effects on reduced pH equivalent to a lowering of 0.2 to 0.3 units, including a decrease of 10-40% in larval calcification rates, an increase of 15-35% in larval mortality, and delays of up to 5 days in early life stage developmental times. Additionally, exposure periods of up to 5-10 days were found sufficient for a substantial reduction in the succeeding settlement establishment and survival, showing that periodic low-pH events can have a large impact despite otherwise auspicious environmental conditions for increased growth (7, 9).

The industrial pollutants, along with climate changes, threaten the water quality in Massachusetts Bay. Monitoring programmes, such as NOAA's Mussel Watch programme, have been set up to track how cumulative impact of pollution on marine life occurs and indicates long-term persistence of PAHs and PCBs through their accumulation in bivalve and sediment samples, demonstrating a long-term stress on bivalve species and thus on the whole ecosystem (10).

Apart from these scenarios, the socio-economic impacts of this will be extreme, as the Massachusetts coastal seafood industry, principally from shellfishing, is a major source with a calculated scale of \$7.7 billion in sales to the economy and providing approximately 87,000 jobs in 2016. Currently, it is especially vulnerable to impacts associated with acidification and rising temperatures as it primarily benefits from species that produce calcium carbonate shells (11, 6). "Without substantive mitigation, projected gross annual losses to the shellfishing industry could exceed 400 million dollars by 2100 from ongoing acidification and continuing ecological degradation" (6).

A dominant and fast-growing sustainable source of energy for New England in the past decade has been offshore wind energy, and for good reason. Offshore wind energy is cost-competitive and directly benefits local communities, turbine construction creates jobs and boosts the local economy, and once built, turbines are emission-free (12). However, offshore wind development also has many significant obstacles.

For one, offshore wind farms create large inaccessible fishing zones for commercial fisheries, directly impacting the local economy. Though temporary noise pollution from pile driving can be significantly limited using technology like double bubble curtains (13), the installed turbines may still upset the hydrodynamics of the surrounding water. These effects, alongside the physical barrier that the monopiles pose, have significant implications for the safety and foraging behavior of the North Atlantic right whale (*Eubalaena glacialis*). The wind's existing hydrodynamic impact is lessened when its energy is harvested via turbines, and the turbine monopiles themselves may disrupt ocean currents, potentially resulting in unprecedented patterns of water movement. These hydrodynamic effects may impact the aggregation of zooplankton upon which right whales feed. However, this impact has not been thoroughly assessed (14, 15). Furthermore, turbine foundations affect the biodiversity and composition of benthic (bottom-dwelling) communities. Effects differ based on the hardness/softness of the seabed in which the turbines are installed and may be positive or negative, but as of yet they are difficult to predict and not well-researched (16).

In addition to offshore wind energy, fisheries in Massachusetts Bay yield great economic value, too. Fisheries provide jobs for local fishermen and others involved in the process of fishing—including fleet maintenance or net crafting; fishermen, by selling the fish caught, then supply local restaurants with necessary ingredients for their sales, which bolsters the local economy by increasing incomes for fishermen and restaurant employees (17). Moreover, the availability of fisheries offers an opportunity for local businesses to sell recreational fishing experiences to customers, further raising the economic value of fisheries in Massachusetts Bay.

Today, however, fisheries are disappearing with the problem of overfishing. Overfishing can be attributed to four main reasons.

1. **Climate change.** Increasing global ocean temperatures have made the North Atlantic Oscillation (NAO)—an index of sea-level pressure differences—become more positive. Each unit increase in the NAO is correlated with a decrease in biomass of fish a year later, persisting for 19 years (18).
2. **Increasing fuel costs**, which has limited the number of nautical miles fishermen can travel to sea, thereby concentrating fishing operations in smaller areas closer to shore, which exponentially stresses the environment (18).
3. **Growth in seafood demand** fueled by increasing awareness of its health benefits and rising popularity of pescatarianism (19) has also significantly increased, motivating fishermen to fish more, though still not at a rate sufficient to meet the demand (18).
4. **Technological advancements** help fishermen catch more fish *at once*, which increases the strain on fisheries per catch. It is important to note that this is distinct from fishermen fishing more *frequently*—they are not fishing more frequently, just catching more per time (18).

As a result of all four factors, the Massachusetts Bay complex system is stressed by overfishing—with fish stocks having decreased by 34% in the past decade—which not only causes imbalances in the ecosystem between different organisms, but also limits the economic value that important stakeholders yield from fisheries (20). Namely, the fishing industry in Massachusetts Bay supports 1.8 billion dollars worth of wages for roughly 40,000 workers in aforementioned industries (21). Continued overfishing could thus begin an economic catastrophe.

Beyond the economic value of the Massachusetts Bay complex system, there is also huge social value associated with the livelihoods it supports. For fishermen, for example, fishing not only provides economic value: for a job like fishing with such high generational value (meaning generations of a family would be fishermen), fishing is embedded into the culture of the family (18). Thus, losing the opportunity to fish could greatly damage the family's social and cultural values, too.

However, arguably the stakeholder whose social values are most threatened by environmental damage in Massachusetts Bay is the local indigenous communities, such as the Wampanoag, the Massachusett, and more (22). Indigenous communities tend to harbor an ecocentric worldview, which means that they view ecology as dominant and hence prioritize protecting ecology in their actions (23). Thus, when the environment is damaged by aforementioned factors, indigenous communities' social values are threatened, which is important to consider

when making decisions about the system not only because their ecocentric practices are valuable to learn from, but also because in Massachusetts, indigenous law supersedes state law. Therefore, not taking into account indigenous perspectives could mean missing out on critical information about the **legality** and **feasibility** of proposed solutions.

Oddly enough, despite this, indigenous communities have not been incorporated into major decision-making processes around Massachusetts Bay. At most, they have been 'given a seat' on certain committees or organizations, but oftentimes, because they lack veto power and majority support, policies may not align with their ideals (24).

Methods

The goal of our research was to identify and compile scientific literature relating to the sustainable development of temperate ocean environments. We divided ourselves naturally by the categories of our research interests: Emma's interest in development economics and research background led her to focusing on the economic value of fisheries and indigenous communities' relationship with the natural environment in Massachusetts Bay; Daniel's experience with renewable energy research led him investigate the different implications of offshore wind energy development; and Ibrahim's observations and investigations regarding the socioeconomic and ecological precautions for mitigating the impacts actions currently being exerted at the bay area. Though initially fragmented, our individual research was eventually synthesized through multiple meetings, helping us illustrate a complex yet significantly more holistic image of the challenges of sustainability in Massachusetts Bay. Examining our system in this way and considering the various perspectives across stakeholders, we forwarded a multi-part solution targeting current problems in Massachusetts Bay in a manner that optimizes outcomes for all stakeholders to the extent possible.

Ibrahim's focus of investigation was about identifying the physical, ecological and governance mechanisms that impact Massachusetts Bay's vulnerable future with having a concentration on fragmented governance systems, statewide monitoring and implementing the use of new technological equipment for process efficiency. In order to prove and conceptualize the existing problems in nature, he drew information from scientific literature like Google Scholar, JSTOR, and ScienceDirect along with institutional reports from various sources including NOAA, MWRA, MIT Sea Grant and the Massachusetts Ocean Acidification Commission. He then analyzed the data frequencies of recurring problems and institutional coordinations to determine what kind of solutions could provide the best remedies where he solidified his theoretical assumptions with already done implementations like Europe Marine Monitoring Network and California Ocean Protection Council. He further examined the technological advancements that could change the sphere of local marine ecosystem fixation and process efficiencies through the incorporation of various modules and AI. *Panarchy* theorem concepts were also used to bolster the management direction of Massachusetts Bay.

Daniel Krewson's research was focused on exploring the impact of offshore wind farms on and navigating offshore wind's trade-offs with other industries/areas, most prominently with fisheries

and conservation. Using tools such as JSTOR and Google Scholar, literature was compiled and examined for relevance, with regards to both topic and date. Once a cohesive body of literature was assembled, trade-off solutions were devised and compared with those proposed or documented in literature. Additionally, more novel technologies, such as very high resolution (VHR) satellite imaging and floating wind turbines, were researched and incorporated into potential solutions. Krewson was also in contact with representatives of the Massachusetts Bays National Estuary Partnership (MassBays NEP) from whom he received a copy of the MassBays NEP 2023-2033 Comprehensive Conservation and Management Plan (CCMP).

Following her interest in development economics while being inspired by *Panarchy* to explore indigeneity in greater depth, Emma Chuo centered her research around evaluating the economic and social impacts of current problems affecting the Massachusetts Bay. Specifically, this included fisheries, arguably one of the most economically significant ecosystem services Massachusetts Bay provides, as well as the interactions of indigenous communities with the Massachusetts Bay complex system—whether with its environment or with its politics. In her process, Chuo initially looked exclusively at scientific papers, believing that they would offer more in-depth examinations of the system; however, realizing that contemporary media often included recent data that more accurately tracked economic performance, and that contemporary media showed more ‘outliers’ to what is expected in the system (they tended to be the ‘breaking news’ of the times), Chuo ended up largely drawing her research from contemporary articles, which worked effectively for her purpose. Chuo leveraged the nature that her research spanned multiple disciplines to offer a wide variety of stakeholder perspectives in discussions, which helped the team forward more holistic solutions altogether.

After all members had thoroughly explored their chosen ecosystem facet, we met to discuss, synthesize our research, and formulate compatible solutions. During these discussions, existing solutions were adapted and new solutions were scrutinized from a different lens by each member. Once specific solutions were reviewed and decided upon, we then created a comprehensive presentation of our research, explaining our system’s problems, our devised solutions, and why, how, and when each should be implemented.

Results & Discussion

Integrating our results, we propose a few solutions that could help resolve the ecological, economic, and social issues in Massachusetts Bay.

First is to change the structure of environmental impact assessments (EIA). Currently, EIAs are conducted on a project basis, where data points are collected biweekly by various agencies (considering relevant metrics like dissolved oxygen levels, concentrations of nitrogen and phosphorus, temperature, and more), but assessments are only given once every two years by the Environmental Protection Agency (EPA) (25, 26). This is problematic because even with the necessary, frequently available data, a project that is detrimental to the environment could take up to two years to be regulated accordingly, resulting in more ecological damage, simply because action was not taken in time. Thus, the first change we propose is to collect data

points at the same intervals, but give out the actual assessments (they serve as ‘verdicts’) at a more rapid rate, too—namely once per month. Such a change seems minor but can be hugely beneficial for tracking environmental damage and tracking project progress, which therefore also expedites innovation by allowing for the creation of more pilot programs to experiment with ideas. Though a potential problem of overburdening the EPA is concerning, it can be overcome either by collaborating with local universities who are already conducting research on Massachusetts Bay (such as the Massachusetts Institute of Technology), or by hiring more EPA staff to work on EIAs (27). The former would seem exceedingly more viable, though, given the current administration’s negligence about environmental threats, and given that the former option would avoid costs of hiring staff by simply working more closely with stakeholders who already have information we need.

A second component of the EIA to be changed is a greater emphasis on indigenous ecocentrism, which can be done by incorporating representatives from aforementioned indigenous groups around Massachusetts Bay into the decision-making process of whether a project meets the standards of an EIA. Although what this will look like exactly is unclear, the presence of indigenous governance and a stronger focus on ecocentrism will hopefully nudge the system towards more stable and resilient equilibria. Simultaneously, it will mitigate indigenous communities’ current lack of underrepresentation in politics while more holistically informing decision-making processes surrounding Massachusetts Bay as indigenous laws, again, supersede state laws.

To address the ecological dimension of the overfishing problem in fisheries, one of the most straightforward solutions would be to completely ban fishing by instituting a moratorium (a temporary ban), providing time for the fish population to rebound, then making fishing available again when the population size is sufficient. In theory, this would be optimal for the environment; however, a moratorium would overlook the irreconcilable tradeoff between economic activity and ecological preservation.

In order to evaluate this scenario, we looked into the case of the Canadian government’s moratorium on Cod in Newfoundland and Labrador from 1992 to 2024 (28), which serves as a good example of what a moratorium might look like if Massachusetts were to implement one, because the two areas are geographically similar and have relatively similar governance models. Unfortunately, the moratorium was largely considered a failure in Canada. The moratorium displaced 12% of the labor force in Newfoundland and Labrador—30,000 workers—causing them to lose their stream of income (29). While the government tried to mitigate this impact with 200-dollar transfer payments and the provision of retraining programs to prepare fishermen and fish plant maintenance workers to work different jobs, the government’s 1.9 billion Canadian dollar fund dried up in 1998, a year before its projected date, which considerably hindered their ability to support the livelihoods of the now unemployed workers (29). Additionally, skills for a completely different job are difficult to acquire in the short period of time workers were given, meaning that many remained unemployed, even with the government’s attempts to help (29). Even in regard to ecology, the moratorium did not achieve its intended effects in an intended timeframe: the population of the Atlantic Cod only rebounded

to non-critical levels after three decades, as opposed to the government-predicted two-decade timeframe (30). Accordingly, the economic harm inflicted by the moratorium lasted decades, while ecological problems were not fully resolved either, inferring that a moratorium may not be the optimal solution.

While fully banning fishing is unfeasible, on the other extreme, the problem of overfishing can also not be fully ignored. The middle ground, then, would be to set a quota. The Atlantic States Marine Fisheries Commission has attempted to negotiate a catch limit with fishermen; however, this proposition faced such huge resistance from fishermen that the quota could not be established, as the Commission lacked power to enforce such regulations and continuously monitor progress afterwards (20). Thus, for the quota to work effectively, regulators with greater legal power (such as the Massachusetts government, or a larger group of similarly-interested organizations) can coalesce to form a more robust force that pressures fishermen to adhere to the quota.

Offshore wind also has the potential to play a serious role in the sustainable development of the Massachusetts bay and continental shelf. With regards to the impact that offshore wind has on biodiversity via habitat disruption and the economy via fishery disruption, one of the biggest potential tools for change is turbine scour protection. In order to protect turbine foundations against scour, the erosion of sediment at the base of the foundation that can affect the turbine's structural integrity, scour protection is installed (31). Presently, the most common turbine foundations are monopile and jacket foundations, both of which require scour protection.

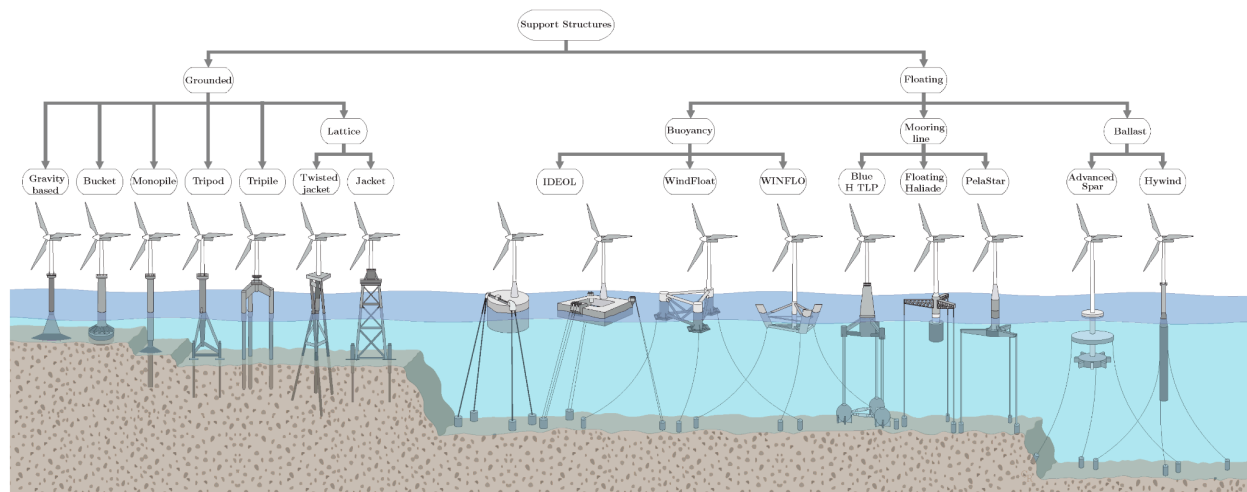


Figure 1: Existing offshore wind turbine foundations, both grounded and floating (32).

In its current state, scour protection is first and foremost a preventative step against turbine damage. However, research strongly indicates its viability as an artificial habitat and ability to bolster and revitalize the ecosystem into which turbines have been introduced. While the installation will likely upset the ecology of soft-bottom benthic organisms, scour protection that resembles the structure of a rocky reef can attract, increase the local abundance of, and

provides a habitat for many hard-bottom-dwelling organisms, such as Atlantic cod, Atlantic herring, mussels, and oysters (33, 34). Scour protection's net long-term impact on the surrounding ecosystem biodiversity and ecology is still unclear (15). At depths where more traditional monopile- or jacket-style turbine foundations would be impractical, floating turbines can be used. The foundations that anchor these turbines to the seabed are much smaller and do not require significant scour protection that could be used in the aforementioned way. However, the floating platforms/turbines themselves, though not able to serve as a habitat for marine organisms, are similarly able to attract and aggregate fish (35). Coupled with the fact that wind farms exclude space on the continental shelf and create large no-take zones for industrial fisheries, wind farms act as *de facto* marine protected areas.

Moreover, this artificial ecosystem would eventually exceed its capacity for organisms, resulting in a spill-over effect. Though the exact per-species impact of such a spill-over has not been thoroughly investigated (36), it is clear that such a spill-over could have significant implications for both industrial and recreational fishers. If a wind farm's artificial environment were to exceed its capacity, any spill-over would be spatially concentrated and could be harvested easily by fishermen, providing that neither fishing equipment nor proximity to the farm pose a large risk to turbine or ecosystem integrity. A similar scenario could occur in floating offshore wind farms, which similarly create large no-take zones for fishermen, indirectly hurting the local economy. Due to their potential to act as fish-aggregating devices, the floating structures on which these turbines are built could also result in a spill-over scenario where excess fish could, within certain safety measures, be harvested.

As an example of how best to take advantage of a spill-over scenario, consider the idea of Fayram and Risi (2007) to designate a specific area around a floating or grounded wind farm as a limited-entry fishery. Their research and conclusions indicate that such a fishery may be widely beneficial. For one, it would make fishery management easier by concentrating anglers in a clearly-defined area, removing ambiguity and imprecision of management that would otherwise be present due to wide spatial distribution of fishers. Harvests and boat entries could be controlled with far more precision, thus increasing ease of sustainable management; anglers would be incentivized to take advantage of this area because of its high fish concentrations (35). Though Fayram and Risi suggest a focus on recreational fishing, a wind farm fishery could be extended to small-scale commercial fishers as well, so long as proper safety precautions are enforced with regards to fishing equipment. However, given that fishermen are incentivized to be cautious so as not to damage their equipment on artificial reef structures or turbine foundations, damage due to equipment may or may not be a concern; this point could be addressed in a laboratory of the described wind farm fishery. Regardless of the realized extent of a spill-over fishery – whether it be commercial, recreational, or both – such an opportunity would, through the tourism and fishing industries, soften the aforementioned blow to large-scale industrial fisheries (and the local economy by extension) that would likely result from much of the wind farm being an industrial no-take zone.

Another point of interest is the previously-discussed impact that wind turbines would have on right whales, both with regards to disrupting feeding behavior and acting as physical barriers.

Turbine impact on hydrodynamics remains an uncertain point of interest. While it is likely that turbine foundations and wind-energy harvesting do impact the hydrodynamics of the surrounding water, the extent of their impact is unclear and difficult to differentiate from the impact of other factors, such as global warming or random variation. It is likely, however, that any potential impact of hydrodynamics caused by the turbines could subsequently and indirectly impact right whales via changes to zooplankton aggregation (14). Furthermore, though installed turbines could serve as obstacles and sources of potential injury to whales, corroborative research has yet to yield any conclusive analysis with regards to whale casualties localized to specific wind farms (37). We would propose a noninvasive and accurate tool with which to better approach both of these issues: satellite imaging. Satellite resolutions of 31 cm by 31 cm per pixel, the highest publicly-available resolution, allow for the identification and differentiation of multiple species of baleen whales (38). These satellites can also be used to locate aggregations of zooplankton by detecting color absorbance differences in ocean water caused by the pigment in their bodies. Together, these two use cases allow for tracking of right whale movement and assessment of available zooplankton that are both entirely remote. If desired, researchers could also train artificial intelligence models on satellite data of whales and zooplankton aggregations to accelerate identification and tracking processes.

The most important next step for all offshore wind scenarios discussed here is further research. For advances in scour protection, this would involve piloting various types of ecologically-focused scour protection on either existing or new monopile turbines, assessing each design's impact on biodiversity and ecosystem productivity. A framework for a limited-entry wind farm MPA/fishery would need to be tested on either existing monopile turbine farms with scour protection ecosystems or on a floating wind farm. If these two solutions were to be developed in parallel, a refined limited-entry fishery management model could be applied to monopile wind farms on which the most ecologically functional scour protection has been installed and researched. Finally, satellite data should be taken both on existing wind farms and on planned wind farm development sites with the goal of investigating the impact of the introduction of wind turbines on hydrodynamics, zooplankton aggregation, and North Atlantic right whale movement and feeding patterns.

Independently, sites for implementing offshore wind farms must be discussed with indigenous groups and must adhere to existing treaties with local tribes to honor their cultural values. Failure to do so would lead to the tradeoff between the economic and social pillars of Massachusetts Bay's problem: indigenous communities would clash with economic goals of those interested in offshore wind development. Thus, while pilot programs are essential, they must be administered in accordance with indigenous perspectives via frequent discussions and progress checks.

Panarchy suggested that indigenous groups tend to pass down knowledge to younger generations in their communities via shared practices and continued traditions. Our research largely confirmed this and further indicates that such communication of indigenous ecological knowledge and the ecocentric perspective would be highly valuable to helping us understand how we, as humans, can live in harmony with nature while still retrieving what we need from it

(23, 39). Thus, another part of our solution proposes expanding the dispersion of knowledge from *within* indigenous groups to *outside* of them, too, which could not only educate the general public more about what we can do to protect the environment while guarding our needs, but also potentially nudge us to view nature as an equal to humans, thereby incentivizing more environment-centric approaches to management and reform in the long-run. This could be achieved through conferences and panels, for example, as speakers can share their thoughts directly and engage in meaningful discussions with one another that spark profound thought; in fact, Harvard University's Salata Institute for Climate and Sustainability has hosted panels with indigenous leaders in 2024 that effectively addressed key points of clash between indigenous governance models and mainstream politics, helping redirect climate efforts (39).

Another way indigenous knowledge can be dispersed efficiently is through exhibitions at museums or universities. This method compared to the previous could be more accessible to the general public, as it would be less academic and formal, thereby expanding the exposure of indigenous ideas to people. However, exhibitions could be more costly to create than panels are to host, and they could be more logistically complex, too; thus, successful exhibitions may require collaboration with local organizations, such as the Woods Hole Oceanographic Institution, which has helped the Wampanoag Tribe craft an exhibition about their shellfish sustenance in 2023 (40). Though data was unavailable explaining the extent to which this exhibition may have helped bolster the visibility of indigenous knowledge, we believe that it would still be net beneficial to include it, especially because it works smoothly with other components of our solution.

The findings show that the primary barrier to managing the effects of climate change in Massachusetts Bay is the fragmentation of monitoring networks. The three primary climate-related factors tracked in Massachusetts Bay, ocean acidification, marine heatwaves, and hypoxia; are measured differently where each has a different resolution and frequency of collection. Less than 45% of Massachusetts Bay is monitored continuously through fixed stations and the remainder 55% is monitored on a seasonal or campaign basis. Several fixed coastal stations collect carbonate chemistry data fewer than four times per year and record temperatures in some nearshore locations with gaps from 180 to 270 days apart. In many areas of the bay, there are separations between permanent moorings that exceed 20 to 30 km, leading to gaps in monitoring of areas of biological activity (41). Therefore, it is impossible to continuously correlate ecological disruption with specific physical or chemical causes. Consequently, it is not until after fisheries experience productivity losses of 10 to 30% from ecosystem impacts, including shellfish mortality, changes in lobster migration patterns, and lower harvest reliability, that the economic impacts on those fisheries can be detected. Therefore, the total cumulative economic exposure to these ecosystems increases by 25 to 40% by being delayed in detection and decreases the effective management of fisheries by 20 to 40% at a community level (42).

Based on the study's discussion, it is clear that the limitations identified in this study can be improved upon by developing a statewide integrated ocean acidification and marine heatwave monitoring and forecasting systems. The European Environment Agency developed an

integrated system to monitor both ocean acidification and warming across multiple regions in Europe beginning in the early 2000s. These monitoring systems provide near-continuous measurements of surface and subsurface temperatures, which show temperature increases between 1.5 and 4°C by 2100 (43). Such systems will also allow us to intervene before we exceed biological thresholds, enabling us to manage marine resources based on this information. Additionally, Europe's verdict of associating the integrated marine environment management system for Europe was a 20% plus reduction in climate-induced marine losses over a 30- to 50-year period in Europe as compared to the average of other developed coastal nations. In Europe, the marine environment management system uses real-time meteorological observations with several predictive models for predicting heatwaves and acidification events; these models provide predictive information with lead times of weeks to months (43). A comparable system in Massachusetts Bay would allow for a continuous integration of NOAA marine heatwave forecasts for proactive adjustments to harvesting schedules, deployment quotas, and harmful algal bloom mitigation.

Fragmentation of governance stands out as another core problem that limits development of information. In Massachusetts Bay, there are many agencies involved in the protection of coastal resources and fisheries, all of which have different functions and areas of responsibility. These agencies include the Department of Marine Fisheries (DMF), Department of Environmental Protection (DEP), National Oceanic and Atmospheric Administration (NOAA), Woods Hole Oceanographic Institute (WHOI), Massachusetts Institute of Technology (MIT) Sea Grant Program and several Tribal Nations. Coordination among these various agencies takes place sporadically and only after an ecological disruption has already occurred. Because there is little or no communication and collaboration among the various agencies, they do not have a common understanding or agreement regarding the significance of ocean acidification, marine heat waves, or hypoxia in relation to coastal resource management. Therefore, decision-making processes remain reactive.

This pattern also aligns with *Panarchy* fundamentals where the governance in Massachusetts Bay reflects a rigidity trap in the conservation phase of the adaptive cycle. Institutional processes prioritize stability and control over learning and coordination. When disruptions like heatwaves or floods occur the system cannot quickly reorganize for adaptation. This ineffective measure of standing hinders adaptive release which emphasizes the core point of *Panarchy* in dynamic institutions for rapid measure taking.

Regardless of how the fragmented ecology services provide information for tracking, this circumstance does not stand as the fate for Massachusetts Bay. The California Ocean Protection Council, for instance, addressed this problem of fragmentation by incorporating the states scientific institutions, tribes, and coastline stakeholders into a unified governance system. The state of California has implemented a unified ocean monitoring program for more than 90 percent of the coastline, measuring temperature, chemistry, and ecosystem parameters, and has incorporated acidification and hypoxia targets directly into fisheries governance. The reaction time to marine heatwave occurrences was shortened by 30 to 40 percent, and revenue variability associated with the 2014-2016 Pacific marine heatwave event had a 20 percent

reduction in declines, which were lowered by 20 percent in highly managed fisheries (44). These results can be seen as the success of movement into the reorganization phase of the *Panarchy* model itself, where the governance structure altered, or did not just remain responsive. The authority to make decisions had become centralized, and no expert power had been lost, and scientific observation linked to policy cues. The amount of marine protection areas increased to around 16 percent of the state's waters, and the warning systems were functional, providing anticipatory harvest strategies instead of closures after the event. Observations had been incorporated, which improved system memory.

Current developments indicate that restoration efforts in Massachusetts Bay have remained stagnant and are temporarily limited in terms of their full effectiveness. To date, programs run by the MassBays National Riverline Partnership and NOAA Fisheries have focused on fixed restoration areas, including salt marshes, seagrass beds, fish migration routes, and designated habitat zones. While these efforts have improved local conditions, they have lacked the ability to adapt to dynamically changing patterns of ocean acidification, marine heatwaves, hypoxia, and carbonate saturation decline (45). As climatic stressors create more predictable locations for disaster hotspots, these programs are failing to effectively address the problems. This limits carbon sequestration potential and reduces the effectiveness of nature-based solutions in temperate ocean systems (46).

These recurring problems could be solved with the deployment of WHOI REMUS 600 that could provide direct intervention based on more accurate environmental data rather than fixed data selection (#). The proposed plan for the system is to intervene in specific locations that needs urgent fixation with low carbon storage, declining pH, and active marine heatwaves. Integration with Massachusetts and NOAA sensor networks will provide perpetual data tracking of pH levels, dissolved oxygen carbonate saturation currents and heatwaves ensuring that biological threshold isn't exceeded. Furthermore, a potential installation of modular carbon garden units like seagrass kelp, artificial reef structures and shellfish clusters carries the potential to increment carbon uptake and habitat structure with having a dynamic intervention sphere for marine ecosystems. Any use of AI based modules or structures could even expand the automatization process and provide a better operational efficiency.

Previous missions of WHOI REMUS 600 have shown that this vehicle can provide prolonged observation in temperate zones. This autonomous vehicle has been employed by Woods Hole Oceanographic Institution on missions up to 72 hours with depths of 600meters, recording continuous data on temperature, dissolved oxygen, salinity, carbonate measurements, and current profiles on the continental shelf and nearshore areas of the Northwest Atlantic (#). Previous missions have also shown that WHOI REMUS 600 has the capacity to handle multi-sensor payloads, which provide accurate navigation, allowing it to quickly monitor sampling when hypoxia is developing, when frontal movements occur, and during marine heatwave events, where REMUS 600 produces data in hours, (#). There is also accurate navigation to within meters of the desired path, allowing REMUS 600 to monitor sampling specifically in the benthic and near-bottom waters, which have been found to have more extreme conditions of acidification as well as reduction of carbonate saturation (#). Based on

this successful historical record of completing the missions with great distinction, REMUS will be a great opportunity for accelerating marine ecosystem maintenance.

Conclusion

As a rich ecosystem with divergent marine ecosystems and living organisms, Massachusetts Bay continues to undergo many ecological, economic, and social pressures. Throughout the exploration and investigation process of the research we have identified rapid ocean warming, marine heatwaves, declining dissolved oxygen, ocean acidification, industrial pollution, overfishing, offshore wind development, and fragmented governance as the key fundamental eradication causes of the area. The evidence from the literature and evaluation of the current circumstances points out that many problems in the area are rooted from fragmentation, delayed response, and limited adaptive capacity.

Addressing these issues first starts with reforming environmental impact assessments that would align with the pace of environmental changes. Incrementing the frequency of assessments will allow further pilot programs to be developed and transparency to be enhanced. Through incorporation of Indigenous representatives of the Massachusetts Bay into the EIA process will strengthen the legitimacy, local ecological understanding and alignment with existing cultural practices. On the fishery management side, negotiated quotas that are maintained with strong enforcement and monitoring will provide ecological protection and economic stability. Through this initiative social harms of existing circumstances and stock plummeting will be reversed.

Significant measure alterations should be done to balance out the negative impacts of energy production and maximizing profit out of wind energy.. According to existing literature, turbine foundations and exclusion areas can be involved in changing habitats and fishing activities in complicated manners. We endorse further studies on the use of offshore wind energy, but this must be accomplished through focused studies, ecological design of scour, and trials of limited-entry fisheries. The application of satellite observation and AI technology may help minimize uncertainty about right whale migration patterns and zooplankton distribution through strong checks and maintenance.

A central discovery evinced through investigations is the existence of fragmented monitoring and governance in Massachusetts Bay. The differing scopes and scales of material collection leaves a large gap in spatial and temporal coverage . Such delays in detection of the problem leads to ecological stress and results. A statewide integrated monitoring and governance reform would facilitate forecasting in taking measures for not exceeding the biological threshold.

Methods of restoration should also better align with technology for efficiency purposes. While fixed-site restoration helps restore local conditions, it cannot keep up with the changing climate-related hotspots of damage. Mobile methods of restoration, such as WHOI REMUS 600, have been identified as a route towards rapid detection and focused response action. There have been identified a variety of tools for methods of restoration, such as seagrass, kelp forests, shellfish, and artificial reefs, holding potential for improvement in carbon sequestration and

habitat complexity, depending on successful implementation and, it would seem, specific applications.

This study maintains certain limitations where more research and experimentation for maintaining accuracy. The reliance of existing literature and institutional reports rather than original field experiments weakens the accuracy of analysis with real life. Many data sets for Massachusetts Bay are inconsistent, incomplete and scattered which limits precise attribution of problems and solutions. Economic impact estimates depend on projections which might not fit with the future climate scenarios. Additionally, some of the approaches aimed at using AI-assisted monitoring and module installation methods for data extraction are still experimental implementations. There is a high degree of variability when considering governance reforms and models of inclusivity for Indigenous policies, making it even more difficult to evaluate actual trial outcomes.

To solidify our statements and findings, further research should be done on prioritizing, pilot testing monthly EIA cycles, validating integrated monitoring workflows, expanding continuous carbonate chemistry and oxygen observations, and measuring ecological outcomes of dynamic restoration sites. Concerns about offshore wind need to be investigated through collaborative, comprehensive, and long-term observation that can differentiate between turbine-induced change and climate trends. There must also be associated studies on social parameters like acceptance and participation models, as well as economic trade-offs.

Ultimately, the topics covered here are only some of the issues present in the Massachusetts Bay and surrounding temperate ocean system. Thus, this paper represents a limited analysis of certain system aspects and does not directly address overarching problems, most notably anthropogenic-driven climate change. While we heavily encourage research into the underlying patterns of behavior and societal function that have made these problems possible, the solutions here serve as an essential stepping stone to a society and economy that is capable of tackling the more challenging conflicts of sustainable development.

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