Aquaculture-based tools to enhance fisheries resiliency during climate change

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Introduction

There are considerable geophysical and biological unknowns associated with climate change, however a preliminary vulnerability assessment of U.S. commercial and recreational fisheries suggests that some 1.7 million jobs and $200 billion in economic activity are at risk (Hare et al. 2016). These uncertainties should not slow or prevent forward thinking and the thoughtful examination and adaption of current fishery and aquaculture management tools and knowledge in an effort to prepare farmers, fishers, tribes, states, and federal agencies to respond to climate change.

This paper presents several aquaculture based tools: fisheries enhancement and restoration, ocean acidification mitigation, and socio-economic planning, that are proven approaches that can mitigate or manage for climate change effects on the Nation's fisheries resources.

Impacts of a Changing Climate

The rate, magnitude and duration of global and latitudinal climate change are uncertain; however, the atmosphere and oceans are warming, snow levels and sea ice are declining and sea level is rising, and the concentration of dissolved CO_2 is steadily increasing. These changes are altering marine physical, chemical and biological processes that impact ocean salinity and circulation, gas and nutrient cycling, pH, primary production and multiple physiological processes on a cellular scale. Certain areas have already experienced dramatic changes in rainfall frequency and intensity, storm intensity and extended periods of drought. These drivers are inducing, shifts in coastal and open-ocean vertebrate, invertebrate, plant and planktonic species abundance, geographic distribution, migration patterns, and timing of seasonal activities. Changes in species distribution and abundance will have major positive and negative effects on the complex biotic and abiotic factors that comprise fisheries: management, productivity, location and accessibility, ecosystem services, socioeconomic viability, and provision of food security at local, national and international levels (Pörtner et al. 2014).

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An initial climate change vulnerability assessment for 82 marine vertebrate and invertebrate species of the northeastern United States coastal shelf found high to very high risk for approximately half the species assessed with diadromous and benthic invertebrate species exhibiting the greatest vulnerability (Hare et al. 2016). These critical climate change effects may be amplified or compounded by existing anthropogenic stressors such as: unsustainable harvests of fish and shellfish; habitat damage and destruction; reduced or amplified freshwater discharge; increased sedimentation, nutrient and chemical pollution; and greater coastal development (Koehn et al. 2011).

Responding to Climate Change

Responding to climate change has been posited as efforts to mitigate climate change (e.g., reducing anthropogenic atmospheric emissions) or adaptive (e.g., managing natural and human systems to enhance resilience) to minimize effects at local and regional scale. These adaptive efforts can include: habitat conservation, restoration or enhancement; fishery harvest management (target species and gear); and aquaculture-based fisheries enhancement and restoration. The adaptive efforts should be considered as options that are not mutually exclusive, but may be employed alone, or in combination, to achieve localized or regional scale goals (Koehn et al. 2011).

I. Aquaculture-Based Fisheries Enhancement and Restoration: A Potential Climate Change Resilience Tool

By John Corbin, Paul Zajicek, and Jim Parsons

As already noted, climate change has, and will continue to have, direct or indirect effects on wild stocks. Some of these effects have been recognized but, for most, the long-term consequences are largely unknown. The first resilience tool fishery managers should adopt to address climate effects on wild stocks is to reexamine habitat restoration options or revise fishery management regulations. When it becomes, after thorough biological and environmental assessments and extensive vetting with ecosystem and watershed researchers and stakeholders, clear that stock enhancement is viable, then, and only then, should a stock enhancement option be considered.

An adaptive option relative to species management that has been practiced in the United States since at least the mid-1800s is marine stock enhancement of fish and shellfish (Roosevelt 1862; Stickney 1996). Despite this long history, marine enhancement activities for certain fish species were curtailed in the 1950s for "…lack of evidence of its effectiveness in fisheries management (Leber, 2013: 1140)." Concurrently, fishery scientists realized the inherent values associated with the stocking of hatchery fish (Brannon et al. 2004):

> We suggest that artificial propagation should be viewed as a powerful tool in the conservation of wild fish by the ability it gives management to maintain population structure in the presence of stochastic environmental perturbations, population crashes and selective fisheries (p. 24).

And they argued:

> We are among those scientists that advocate hatchery reform. Hatchery management in the greater part of the twentieth century neglected stock structure and the need for synchrony between life history forms and their specific stream environments (p. 26).

The drive to reform aquaculture-based fisheries enhancement and restoration has evolved over the last 20 years from a strictly hatchery-driven effort (e.g., releasing large numbers of hatchery-produced fingerlings) to a multi-faceted, integrated management tool with a variety of endpoints that can contribute in a positive way to the adaptive management of species population and mitigation of ecosystem impacts triggered by climate change (Blankenship and Leber 1995; Lorenzen et al. 2010; Lorenzen 2014). These endpoints or objectives were described by Lorenzen et al. (2012) and Leber (2013) to include:

1. Sea ranching – recurring release of juveniles for harvest as commercial or recreational fisheries at a larger size.
2. Stock enhancement – recurring release of juveniles to augment natural populations.
3. Restocking – time-limited release of juveniles to restore depleted spawning biomass.
4. Supplementation – moderate release of cultured fish to reduce extinction risk or conserve genetic diversity.
5. Reintroduction – limited releases to reestablish a locally extinct population.

The different endpoints constitute management systems with quite different requirements in terms of hatchery, habitat and harvest practices. In addition to the above endpoints, and specific to managing climate change impacts, is a related practice variously referred to as translocation, managed relocation, assisted migration or assisted colonization. This involves the intentional introduction of a species to an area outside of its native range to assist species that cannot adapt to new environments or naturally disperse to favorable areas (Lawler and Olden 2011).

The Responsible Approach to Marine Stock Enhancement – A Multi-faceted Integrated Approach

Marine stock enhancement has been implemented with different levels of planning and background studies in the United States and around the world. However, the current state of the science and documented experience concludes that critical to successfully achieving all of these objectives, and implementing marine species translocation, is the application of the Responsible Approach to Marine Stock Enhancement (Responsible Approach) (Lorenzen et al. 2010)[2]. The Responsible Approach is described in stages to ensure key elements are implemented in the appropriate sequence for new project development or reforming existing stocking processes (Table 1). In particular, the authors argue it is important to conduct a broad-based and rigorous appraisal of the enhancement potential contributions to government's fishery management goals, prior to more detailed research and technology

[2] Implicit to the updated Responsible Approach is adherence to local, regional, state, federal or tribal regulations.

development and operational implementation. Experience dictates this basic requirement applies to both development of new and/or reform of existing enhancement approaches[3].

Table 1. The Three Stages of Responsible Marine Stock Enhancement

Stage I: Initial appraisal and goal setting

1. Understand the role of stock enhancement within the fishery system.
2. Engage stakeholders and develop a rigorous and accountable decision making process.
3. Quantitatively assess contributions of stock enhancement to fisheries management goals.
4. Prioritize and select target species and stocks for enhancement.
5. Assess economic and social benefits and costs of stock enhancement.

Stage II: Research and technology development including pilot studies

6. Define stock enhancement system designs suitable for the fishery and management objectives.
7. Develop appropriate aquaculture systems and rearing practices.
8. Use genetic resource management to avoid deleterious genetic effects.
9. Use disease and health management.
10. Ensure that released hatchery fish can be identified.
11. Use an empirical process for defining optimal release strategies.

Stage III: Operational implementation and adaptive management

12. Devise effective governance arrangements.
13. Define a stock management plan with clear goals, measures of success and decision rules.
14. Assess and manage ecological impacts.
15. Use adaptive management.

Case Studies of Responsible Stock Enhancement in the United States

In the United States stock enhancement of coastal waters for salmonids and inland fresh waters is a time-honored approach to enhancing and restoring fish populations. State fisheries management agencies release over 1.7×10^9 hatchery-reared fresh and salt water fish of over 100 types annually. On an average, the same agencies expend 21% of their budgets on practical enhancement activities. Additional stocking is carried out by private entities and individuals, sometimes without authorization. Many such programs successfully maintain fisheries in highly modified habitats where natural recruitment is limited, or have contributed to the restoration of endangered species and stocks (Lorenzen 2014).

The salmon hatcheries of Southeast Alaska are a notably example of a public and private non-profit stock enhancement effort, initiated in 1974, that embodies key elements of the Responsible Approach that includes government oversight and permitting and detailed planning, quantitative assessment and genetics, health and disease control, and management policies. Alaskan salmon hatcheries significantly contribute to commercial, sport, personal and

[3] For in-depth information concerning marine stock enhancement or restoration that includes an extensive publication library, visit SCORE: Science Consortium for Ocean Replenishment (http://www.stockenhancement.org/index.html).

subsistence harvest. Between 2006 and 2015, pink salmon accounted for an annual average of 73% of Alaska hatchery salmon returns by number, followed by chum (21%), sockeye (4%), coho (2%), and Chinook salmon (<1%) (Stopha 2016). Not included in these values are numbers of hatchery salmon caught for cost recovery or broodstock purposes. These hatchery-sourced contributions to yields from commercial and recreational salmon fisheries in Alaska are widely considered a successful demonstration of the long-term use of the stock enhancement as an effective tool to assist fisheries management (Heard 2012).[4]

However, the Responsible Approach, and the science underpinning it, is relatively new as a fisheries management tool and is not yet in wide spread use in the United States or around the world (Born et al. 2004; Lorenzen et al. 2013). The work required to complete its three stages requires long term commitment by government and its partners and significant, dedicated staff and funding resources. Fortunately, progress is being made and pertinent examples have been completed and published that demonstrate implementation of the stages and components.

As an example of Stage I implementation, Camp et al. (2013) completed an integrated assessment of stock enhancement role in current and future management of a red drum (Sciaenops ocellatus) marine recreational fishery. The authors recommend developing adaptively managed experimental stockings in an effort to synthesize information from stakeholder input, angler effort (target and non-target species), and stocked fish recruitment dynamics to reduce biological and socioeconomic uncertainty and inform subsequent stockings. Garlock et al. (2016) used a fisheries model to provide quantitative estimates of the enhancement potential of multiple candidate stocks. Such studies play a key role in Stage I implementation because they help to "weed out" enhancement or restoration proposals that have little chance of success before major investments in technology development or hatchery infrastructure.

As an example of Stage II implementation is the Ocean Resources Enhancement and Hatchery Project (OREHP), a long-term pilot-scale program to augment white seabass (*Atractoscion nobilis*) population in California. Since the start of releases in 1986, the program has released several million marked hatchery fish of which several thousand have been recaptured in research surveys. These data have been analyzed to assess post release dispersal, growth and survival of hatchery-reared white seabass and results have allowed the program to improve its culture, acclimatization, and release strategies (Hervas et al. 2010).

An example of Stage III implementation is the Hatchery Reform Process in the Pacific Northwest of the United States (Paquet et al. 2011). Working cooperatively with harvest, habitat and hatchery managers, a team of scientists has reviewed hundreds of salmonid hatchery programs. Modelling was used to determine the best system design for each program, using an approach based on best available science, goal identification, scientific defensibility, and adaptive management. In a recent application to the Columbia River basin, Hatchery Reform solutions improved the conservation status of many populations (25% for steelhead trout, more than 70% for Chinook and coho salmons) while also providing increased harvest (Paquet et al. 2011).

[4] For a global perspective, please see: Lorenzen et al. 2016. Chapter 13 Fish Stock Propagation *in* The First Global Integrated Marine Assessment: World Ocean Assessment I. United Nations, Division for Ocean Affairs and Laws of the Sea (http://www.un.org/depts/los/global_reporting/WOA_RegProcess.htm accessed June 23, 2016).

An example of invertebrate population restoration consistent with the Responsible Approach is the coral species and habitat restoration program of the Coral Restoration Foundation (http://www.coralrestoration.org/) under authority and permit granted by the Endangered Species Act. The Foundation is entirely focused upon elkhorn and staghorn coral stock enhancement in the Gulf of Mexico, Caribbean and South Atlantic. The work is conducted within the framework of the Recovery Plan for Elkhorn (*Acropora palmata*) and Staghorn (*A. cervicornis*) Corals (NMFS 2015). Stages I and III of the Responsible Approach are addressed by the Recovery Plan, as authorized by the Endangered Species Act. The Foundation, lead federal agency, and other stakeholders (state and territorial agencies, public and private coral scientists and other non-profit entities) address Stages II in an adaptive manner to achieve the goals of the Recovery Plan. Progress has been documented in various publications that have described assessment and monitoring, genetic resource management, and culture and stocking (Steven Miller, Nova Southeastern University, personal communication; Ken Nedimyer, Coral Restoration Foundation, personal communication).

At ten year intervals the American Fisheries Society has assessed the contributions of hatcheries to natural resource management and issued recommendations to guide public and private sector stocking efforts. Responsible Approach Stages I, II and III implementation are exemplified in their recent guidance document entitled, Hatcheries and Management of Aquatic Resources (HaMAR) that provides recommendations for public or private efforts to stock finfish, crustaceans, mollusks, reptiles and other aquatic biota for recreational, commercial or conservation purposes. The effort to create the guidance was unique in that it was built upon a foundation of three prior assessments that occurred in 1985, 1995 and 2004, a scoping survey that incorporated responses from 450 public and private practitioners from 48 states and three Canadian provinces, and a topic-specific 2013 symposium of contributed papers. The assessment and guidance examines and summarizes prior and current knowledge and practice concerning habitat restoration and management; the uses, expectations, and limitations of hatcheries and hatchery reared fish; monitoring and adaptive management; hatchery operations and techniques; the use of conservation hatcheries; fish health and disease issues; biosecurity; the genetic integrity of stocks; interactions between hatchery and wild fish; and risk assessment (Trushenski et al. 2015).

In general, the HaMAR considerations represent an update and expansion of the previous assessments described and are intended to provide aquatic resource managers with timely and comprehensive guidance regarding hatcheries. This update utilizing assessments, opinion surveys and symposium presentations concluded there is now a need for more emphasis on integrated hatchery, habitat and harvest management approach and greater specificity in considering the use of hatcheries and hatchery-origin fish. In particular, the following priority topics were identified as extremely relevant to the discussions which reflect the tenets of the Responsible Approach (Trushenski et al. 2015):

- Habitat restoration and management efforts as companions to stocking.
- Establishing appropriate uses for hatchery-origin fish and defining expectations for stocking programs.
- Understanding the limitations of hatchery-origin fish and stocking programs.

- Tagging hatchery-origin fish to make monitoring the effects and effectiveness of stocking possible.
- Monitoring and flexible/adaptive management of stocking programs.
- Monitoring that provides decision-makers with evidence needed to objectively evaluate enhancement effectiveness.
- Hatchery operation and propagation techniques;
  - Types of enhancements and complementary modes of hatchery operation.
  - Conflicting mandates.
  - Controlling the costs of hatchery operation.
- Culture of imperiled species and conservation hatcheries.
- Fish health and access to disease management tools.
- Biosecurity.
- Strategies to maintain genetic integrity and diversity in hatchery-origin fish.
- Biological and other interactions between wild and hatchery fish.
- Risk assessment and decision-making
- Effective communities and engagement of stakeholders.

International Efforts in Marine Stock Enhancement

Worldwide, though current information is scarce, 64 counties reported activity in marine and coastal stocking of fish and shellfish with over 30 billion individuals of over 180 species being released of which 46 species are exclusively for marine environments. Europe and North America have relatively the highest number of countries participating, with Asia and Oceania next. Clearly, aquaculture-based fisheries enhancement and restoration of commercially or recreationally important fish is widely practiced and can be a viable management option, in combination with harvest regulation and habitat restoration, to address the increasing global demand for aquatic protein (Born et al. 2004). Two examples, the Republic of Korea (ROK) and Japan underscore the point.

In the late 1990's, the ROK developed hatchery technologies for juvenile rock fish and sea bream. Since that time seed production and release of fish have successfully enhanced domestic fishery resources and increased income for fishermen. In the beginning stages of seed production, government facilities took the lead in technology development and seed distribution, but in recent years private companies have played an increasing role. Between 1986 and 2012, 46 marine species including abalone, various flatfish, sea bream and sea slugs were targeted and 1,410 million juveniles of fish and shellfish species were stocked in coastal waters. It is noted that the ROK widely applied various habitat restoration tools, e.g., artificial reefs, with fish releases, where habitat was identified as the primary factor limiting production (Lorenzen et al. 2016).

Japan, as a nation with the highest per capita seafood consumption in the world, has an urgent need to sustain and increase supplies from its domestic fisheries. The Japanese efforts in recent years reportedly involve over 80 species of marine fish, mollusks and crustaceans and release of many millions of early life stage stock. The primary enhanced marine fisheries are the yesso scallop, Kuruma prawn, red sea bream, and flounders. Enhancement efforts for salmon have also been very successful. Impacts on domestic fisheries by enhancement efforts are significant;

estimated at 90% of the chum salmon catch, 50% of Kuruma prawn, 75% of red sea bream, almost all the scallop harvest and 40% of the flounder catch (Kitada et al. 1992). Techniques developed over many years of research are utilized to support hatchery releases in coastal shelf waters include habitat restoration, predator removal and behavioral conditioning.

Stock Enhancement Conclusions and Recommendations

Aquaculture-based fisheries enhancement and restoration can be an effective tool to supplement traditional fisheries management approaches to adapting to the challenges of global climate change. Internationally, many countries have incorporated releases of hatchery produced stock into their planning and management efforts to maintain fishing industries, recovery at-risk species and provide food, employment and income to coastal communities. Enhancements are likely to become more widespread as burgeoning demand for seafood and increasingly severe human impacts on the coastal oceans create greater public demand for proactive management and as more effort is placed on implementing a responsible approach, which will result in greater numbers of success stories.

The science base for marine stock enhancement continues to advance rapidly and has now reached a point where enhancement systems can be designed effectively and their potential contribution to habitat and harvest management goals quantitatively evaluated. This signifies a transition from a research-oriented endeavor to a management-oriented endeavor. Enhancement policies are likely to be instrumental in bringing enhancement approaches into the management framework in constructive and responsible manner (Lorenzen et al. 2013),

The Responsible Approach offers an **integrative, quantitative and careful approach** for developing and managing effective aquaculture-based fisheries enhancement and restoration that exemplifies an adaptive natural resource management strategy appropriate to the challenges inherent to climate change. Successful implementation will require sustained investment in theoretical and applied research, employment of a range of scientific disciplines, regulatory and non-regulatory management, and funding similar to the nation’s investments in at-risk species recovery.

To prepare for effective implementation, the following recommendations should be addressed:

1. Define conditions under which stock enhancement should not be considered as a management tool.
2. Develop estimates of the rate, magnitude of climate change effects at local, regional and continental scales.
3. Conduct strategic assessments by: a) identifying species or stocks that may benefit from aquaculture-based enhancement/restoration, b) modeling potential enhancement of the most important and sensitive species or stocks, and c) assessing the availability or developmental needs for aquaculture technologies to culture the prioritized species or stocks.
4. Use quantitative modeling tools incorporating harvest and habitat goals to pre-screen potential enhancement and restoration initiatives to identify those most likely to be effective and to develop realistic implementation plans.

5. Conduct real-world tests of genetic, population and ecosystem models applicable to fisheries management and stock enhancement/restoration.
6. Use adaptive-management experiments in pilot tests as well as the implementation phase to progressively refine and improve enhancement strategies.
7. Develop and test the means to quantify the socio-economic impact of stock enhancement.
8. Utilize the Responsible Approach to assess and reform existing marine stock enhancement or species restoration programs.

II. Potential aquaculture approaches to mitigate the impacts of Ocean Acidification

By Robert Rheault

One third of the CO_2 released into our atmosphere from fossil fuel combustion quickly dissolves into ocean waters where it forms carbonic acid. The projected impacts of continued fossil fuel combustion include depression of ocean pH and aragonite saturation coefficient. While the impact of this change on marine organisms is still largely unknown, there are concerns that marine calcifiers (shellfish, corals, pteropods, and coccolithophorans) ability to deposit calcium carbonate will be inhibited. There are also indications that elevated CO_2 levels may interfere with fish behavior. Approximately 200 million years ago when CO_2 levels reached the levels we are predicting for the next 50-100 years, there were mass extinctions in the marine environment. At this point we cannot rule out a similar event and significant disruption of the marine food chain with global implications (Fabry et al. 2008).

Mitigation of acidification in hatcheries by buffering water

It has been demonstrated that certain calcifiers, notably shellfish, are particularly susceptible to high CO2 levels during the early larval stages (Waldbusser et al. 2014). Shellfish larvae cultured on the west coast during coastal upwelling events are exposed to high concentrations of CO_2 as corrosive deep waters from the Pacific oxygen minimum zone are delivered to the coastal shelf by prevailing summer southerly winds. During these upwelling events CO_2 levels in coastal waters are often elevated to 1000ppm CO_2 or higher, levels comparable to what most ocean waters are expected to see by the end of the century. It is estimated that as much as 30% of the CO2 in these coastal upwelling events is of anthropogenic origin from the combustion of fossil fuels. Bivalve larvae exposed to these low pH waters are challenged to deposit shell and rarely survive the initial 24-48 hours of development.

Fortunately, hatchery operators have learned to monitor intake pH and CO_2 levels and have learned to buffer the incoming seawater with soda ash or sodium bicarbonate. (Barton et al. 2012) This elevates the pH and the aragonite saturation coefficient and larval survival is greatly improved. Once the shellfish larvae have developed past this initial delicate phase, it appears that they are able to grow and develop normally, albeit at slower rates despite depressed aragonite saturation conditions.

While it is still unclear how ocean acidification will impact most marine organisms, if we find that impacts are restricted to the larval phase, then there may be an opportunity to rebuild populations that are impacted by acidification by using hatchery techniques and buffered seawater.

There are probably some limitations on how effective this strategy could be as a stock enhancement tool. There would be significant expenses involved in developing adequate hatchery capacity, but we at least know that the technique has merit. There are dozens of shellfish hatcheries around the world with production capacities on the order of many billions of larvae annually. This of course pales in comparison to the production of natural shellfish larvae from existing healthy natural populations such as sea scallops or even wild oysters.

Mitigating the impacts of ocean acidification through selective breeding

Aquaculture producers and land farmers have demonstrated the tremendous power of conventional selective breeding programs to enhance the expression of certain traits simply by selecting and breeding top performers with desirable phenotypic traits. In just a few generations breeders have been able to achieve remarkable improvements in survival in the face of certain diseases and increases in growth rates or crop yields.

There have been a limited number of transgenerational studies on the impacts of ocean acidification (reviewed by Ross et al. 2016). However, there appears to be some indication that there may be significant genetic variation within certain genomes that may allow some species to adapt to high-CO2 conditions. Parker et al. were the first to demonstrate positive intergenerational carryover effects in the oyster *Saccostrea glomerata*. Larvae from parental stock that had been exposed to low pH waters showed enhanced survival compared with larvae from unchallenged parents.

Experiments on selective breeding of corals at Mote Marine Lab in Florida have shown great promise in the potential of developing low-pH adapted lines of corals to repopulate damaged reefs (Vaughn, unpublished data).

It is not likely that these “carryover effects” are the result of conventional evolutionary shifts in the genome as these rely on random mutations and generations of selection pressure. It is more likely that these are the result of mechanisms such as parental compensation or epigenetic gene expression (Ross et al. 2016).

If selective breeding approaches are to be successful in developing low-pH adapted lines of organisms, it is imperative that significant investments in breeding programs for commercially important species be initiated promptly. The timescale for a projected tripling of CO2 concentrations is on the order of decades and the nature of selective breeding efforts is that they require multiple generations of selection to be effective.

There will be significant concerns about the impact of genetic bottlenecks and potential impacts to the wild genome of organisms (see discussion of the Responsible Approach to Stock Enhancement in Section I), but if the alternative is extinction, then these concerns arguably become secondary.

Mitigation of ocean acidification with seaweed production

By John Forster

Seaweed production in coastal waters could be a mechanism to absorb some of the dissolved carbon dioxide in seawater and help to reduce the impacts of ocean acidification. It is important to recognize that the changes are likely to be small and localized and that there are diurnal and seasonal factors to consider.

Seaweed farms may also provide ancillary benefits such as providing habitat for some marine species and absorption of wave energy during storms, and assimilation of excess nutrients that are implicated in coastal eutrophication. Seaweeds have proven nutritional benefits as a food that does not have the associated costs of land use, freshwater or fertilizer (Scigliano 2012, World Bank 2016).

Seaweed production is increasing in several globally and there is also growing interest in the U.S. In Maine several seaweed farmers are now in business and are receiving favorable media coverage both for their products and operations. A trial project has also just been started in Washington State sponsored by the Paul Allen Foundation and managed by the Puget Sound Restoration Fund specifically to examine the potential of seaweed production for OA mitigation.

However, even if seaweed farming is shown to increase coastal resiliency, wide spread development in US coastal waters will take decades. The potential to mitigate OA on a nationwide scale is limited given the vast amounts of CO2 emitted globally by human activity. Scigliano (2012) discusses this in *Sweetening the Waters* where he describes the volumes of CO2 in upwelled waters off the Pacific Northwest coast and the enormous scale of the seaweed farms that would be needed to have a significant impact. For this reason the focus of Puget Sound Restoration Fund research project has the limited objective of using seaweed cultured on floating rafts to create inshore OA refuges where sensitive life stages of certain marine species might be protected.

There are several obstacles to establishing large-scale seaweed culture projects in the U.S. First, demand for seaweed for food or biomass is currently small. If seaweed farms are to be developed for coastal protection, production costs will need to be reduced and markets for these products will need to be greatly expanded. It seems unlikely that we can count on a significant public subsidy to cover projected gaps between the cost of production and the revenues of sales once production is ramped up to significant scale.

Presently, seaweed farmers in Maine are mostly selling limited volumes into premium niche markets that are not especially price sensitive. However, price and products with mass-market appeal will become much bigger issues if large-scale industry expansion is contemplated. It is conceivable that production costs and volumes might reach levels that make production of biofuel feasible. There has been much prior work in this field (Chynoweth 2002) and the Department of Energy through is ARPA- E program actively encouraging proposals for new research on seaweed production for biomass, but the gap between the vision and the reality is still wide.

Perhaps the most significant obstacle to large-scale expansion of seaweed farms in the U.S. will be the designation of vast areas in U.S. coastal waters for seaweed farms. Setting aside large areas for aquaculture has been a challenge in both state and federal waters for decades. While marine aquaculture has flourished in many other maritime countries, progress here has been slow. This is mostly due to multiple use conflicts, fears of potential impacts and a cumbersome regulatory scheme that increases risk and cost for potential investors.

III. Potential aquaculture approaches to mitigate the impacts of sea level rise and habitat loss

By Robert Rheault

Large-scale habitat destruction and disturbance is expected as sea level changes. Assessments estimate sea level increases of up to 4 feet are possible by the year 2100 (Rahmstorf 2007, Melillo et al. 2014). Coastal barrier beaches are expected to migrate inland, marshes may be submerged, rocky/gravel and cobble habitats may be buried or degraded by silt runoff, and coastal infrastructure (sewage treatment plants, docks and working waterfronts, transportation hubs) may become inundated.

Oyster aquaculture techniques are a proven tool for restoring and rebuilding oyster reefs and the fish communities they support (especially where such habitat is limiting). Every year the state-run oyster hatchery at Horn Point in Maryland has been producing hundreds of millions of larvae for spat-on-shell to be planted in sites both to support fisheries as well as to populate restorations sites in sanctuaries for the ecosystem services these reefs are known to provide (Cohen and Grizzle 2007; Cohen et al. 2007). For each hectare of oyster bottom it is estimated that approximately $4,000 is added to future commercial fisheries landings because of enhanced survival and recruitment of juvenile fish associated with oysters, oyster reefs and shell (Grabowski et al. 2012).

Oyster reefs are also known to stabilize bottom, and slow erosion by absorbing some of the storm surge energy and resisting the mobilization of sediments during storms. Shoreline stabilization techniques can include shellfish as part of living shoreline designs to adapt to sea level rise (Arkema et al., 2013; La Peyre et al.; 2015; Popkin, 2015). Oyster reefs are being constructed in Alabama to protect sensitive marsh habitat and slow erosion in coastal lowlands. (Grabowski et al. 2012) There are certainly limits to how effective an oyster reef can be in mitigating erosion, and a sub-tidal reef will do little to absorb wave energy when severe storms are accompanied by significant surge and wave heights in excess of a few meters.

Certain types of commercial aquaculture gear used in growing kelp, shellfish or fish can absorb and dissipate wave energy and could slow erosional forces and provide some measure of protection for the beaches and marshes behind them. The types of gear and the amount of wave energy they dissipate has not yet been assessed and documented from an engineering standpoint. There is a tremendous variety of gear types including on-bottom, suspended, floating and longline gear. Some culture methods employ large floating rafts, fixed pilings and various types of cages and trays, either floating or suspended at various depths in the water column. While the energy dissipation of these gear types has not yet been assessed, the horizontal extent of the culture array and the types of gear involved will vary greatly in their impacts.

IV. Aquaculture can provide economic resilience for fishing communities

By David Wallace and Robert Rheault

As a result of the predicted climate impacts, global fish catches are predicted to decline by 43 to 60 percent by 2050. This would represent a global economic loss of $17-41 billion (Hare et al. 2016). Career opportunities in the fishing industry will be impacted with ripple effects across the support industries and communities that depend on fisheries. Aquaculture can allay concerns about food security and provide economic opportunity if the industry has tools to guide adaptation (Merino et al., 2012; Glavovic et al., 2015; Hobday et al., 2015). Aquaculture has a proven history of cultivating novel species (Stickney & Treece 2012) and developing new gear (Langan 2012; Lekang 2013), and this spirit of and capacity for innovation could help bridge the gap between current and future marine seafood production. Coastal communities relying on wild and farmed seafood will need flexibility to adjust to ecological, economic and social consequences of climate change (Pinsky & Mantua, 2014), and aquaculture provides a potential solution.

The economic resilience of these communities can be enhanced by ensuring the availability of alternate employment opportunities in related industries such as aquaculture. The survival of supporting industries such as processing, transportation, boatbuilding, equipment supply and outboard repair will be enhanced in communities that support robust aquaculture industries in addition to fisheries.

Aquaculture offers a natural career alternative for fishermen because both vocations rely on similar skill sets. Fishermen transitioning to aquaculture find that they already have most of the basic skills required to succeed as shellfish or fish farmers. Both vocations demand hardy individuals who are able to tolerate working hard in tough weather conditions. Skills sets such as seamanship, hydraulic maintenance and repair, knots, and boat handling are immediately transferrable for those working on the water whether they are catching fish or growing fish.

Seafood professionals are already finding that aquaculture is providing a steady supply of fish and shellfish that in many communities is offsetting declines in fisheries landings in many communities. As fisheries stocks continue to be stressed, it is projected that aquaculture can provide a reliable and sustainable source of seafood for the growing human population (Merino et al., 2012; Hollowed et al., 2013). A seafood dealer doesn't care if the fish or shellfish he or she is selling is wild or cultured, as long as there is enough product to fill the coolers and keep the trucks full. The town ice plant can offset lost sales to fishermen with increased sales to shellfish farmers. The equipment supplier who sells rope, buoys gloves, rain gear and boots will welcome additional revenue from farmers to compensate lost revenue from fishermen who are tied up at the docks because of tightening quotas or declining abundance. The same firms that used to sell lobster pots and fish traps to Southern New England fishermen are able to stay in business despite the collapse of Area 2 lobster stocks because they have found a rapidly growing customer base in oyster farmers.

Indeed, a robust aquaculture industry serves to buoy the economy in general. Jobs are created in similar industries such as seafood processing and marketing, while ancillary jobs are created in supporting professions such as research, law, insurance, and accounting. Multiplier impacts of both fisheries and aquaculture have established widely disparate estimates, but it is clear that both industries have significant impacts on other areas of the economy supporting local housing, retail, restaurant industries as well as hardware suppliers, fuel providers, and much more[i] (Kaliba and Engle 2004, Murray 2014).

Aquaculture represents an effective strategy for communities to improve both their environmental and economic resiliency to change. It has the potential to easily absorb displaced fishermen and other seafood industry professionals while offering them greater job security and enhanced career prospects. It can buoy other industries also under threat from environmental, regulatory and economic changes while supporting job creation and economic prosperity in general (Murray 2014).

Examples of economic resilience in fishing communities associated with aquaculture:

1. **Shellfish aquaculture in Virginia**
   In the late 50's Mid-Atlantic oyster harvests went into steep decline because of overharvest, habitat decline and the emergence of two parasitic oyster diseases. Virginia oystermen were struggling. Several firms on the Eastern shore embraced clam aquaculture and invested in hatcheries. In just a few decades the clam farming grew to an industry valued at over $30M. The development of hatchery breeding programs at VIMS allowed the selective breeding of disease resistant lines of oysters and triploids that has ushered in a second wave of aquaculture development. In 2015 aquaculture landings in Virginia topped $48 million, supporting over 400 direct jobs (Hudson and Murray 2016). In Northhampton County, VA cultured shellfish landings in 2013 were valued at over 6X the value of commercial wild fisheries (Murray 2014).

2. **Atlantic Salmon Pens In Maine**
   In rural down east Maine there are few employment opportunities. Employment opportunities were on the ocean or in the timber industry. Decades ago vibrant fisheries in both state and federal waters provided income for a large percentage of the down east Maine population. Declining quotas on federally managed species have eradicated many of these jobs, while the state managed lobster fishery has restricted access that limits new entrants.

Over the same period of time, Maine has enjoyed robust growth in salmon aquaculture. In 2007 Maine's salmon industry had a landed value over $55 million and aquaculture peovided over 750 jobs (O'Hara et al. 2007). Aquaculture was part of the solution to rebuilding the lives of young fishermen who are unable to get permits in the limited access fisheries. They were able to use the skills that they developed as deck hands to sustain their families as aquaculture operators.

V. Conclusions

In the preceding section we have described various aquaculture-based tools that might contribute to the resiliency of fishing communities faced by various climate change-related challenges.

None of these approaches is likely to be a solution to the many stressors faced by fish populations or the fishing communities that rely on these stocks for their economic survival. Rather, each of these techniques points to methods and techniques that hold some potential to soften the impacts and allow these communities to adapt and preserve some of the working waterfront infrastructure and fisheries-based revenues in the face of the projected climate-related changes.

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