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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