**Importance of aquaculture to the ocean economy**

Aquaculture, the cultivation of aquatic animals and plants, is one of the fastest growing industries in the world (Bostock *et al.* 2010) and now produces more seafood than wild capture fisheries (FAO 2018). Although marine aquaculture, hereafter called “mariculture”, currently represents only a third of total aquaculture (freshwater/inland aquaculture represents the remainder), this proportion is increasing. In 2016, mariculture produced 38.6 million metric tons (mmt) of seafood worth US$67.4 billion. Over half of this production was shelled molluscs (58.8%), while finfish and crustaceans represented 23% and 17%, respectively (FAO 2018). However, when converted to edible food equivalents, finfish mariculture provides the most food by volume (Edwards *et al.* 2019). Furthermore, fed aquaculture, which requires feed inputs and includes finfish and crustaceans, is growing faster than non-fed bivalve aquaculture, due to increasing demand for these commodities (Tacon et al. 2011; Hasan 2017).

**Impacts of climate change on ocean aquaculture**

Like wild marine species, cultivated marine species are impacted by changing environmental conditions (Weatherdon *et al.* 2016), but unlike wild species, cultivated species can undergo accelerated adaptation through selective breeding (Sae-Lim *et al.* 2017). As with capture fisheries, the impacts of climate change on aquaculture are expected to vary by location, species, and method of production. The primary threats are as follows:

1. Ocean warming is expected to raise mortality rates and lower productivity for higher trophic-level species (Rosa *et al.* 2013).
2. Sea level rise will increase the intrusion of saline water into deltas and estuaries compromising brackish-water aquaculture (De Silva 2012; Garai 2014) and shifting shoreline morphology could reduce habitat availability.
3. Increasing storm strength and frequency poses a risk to infrastructure
4. (De Silva 2012) and increased weather variability has been associated with lower profits (Li *et al.* 2014).
5. Ocean acidification impedes the calcification of mollusc shells (Gazeau *et al.* 2013) resulting in higher morality (Barton *et al.* 2012; Green *et al.* 2012) and increased vulnerability to disease and parasites.
6. Increasing rainfall will increase the turbidity and nutrient loading of rivers, potentially causing more harmful algal blooms (HABs) that reduce production and threaten human health (Himes-Cornell *et al.* 2013; Rosa *et al.* 2013).
7. The emergence, translocation, and virulence of disease, pathogens, and parasites are all impacted by climate change. For example, warming can increases susceptibility to disease, promote the influx of new pathogens (Rowley *et al.* 2014), and increase the toxicity of common pollutants (Fabbri and Dinelli 2013).

**Adaptation to climate change through selective breeding**

Although selective breeding – the breeding of cultivated plants and animals to inherit specific traits – has historically been implemented less in aquaculture than in terrestrial farming (Gjedrem *et al.* 2012), aquaculture species are increasingly being bred to increase productivity and disease resistance (Gjedrem and Baranski 2010). The majority of breeding programs have focused on increasing growth rates and maximizing productivity and have been met with success. For example, Atlantic salmon breeding programs have increased harvest weight by 12% per generation with cumulative genetic gains of ~200% over multiple generations (Janssen *et al.* 2017). Similarly, seabream breeding programs have increased harvest weight by 10-15% per generation with cumulative genetic gains of ~100% over multiple generations (Janssen *et al.* 2017). These cumulative gains exceed the 25-41% total increase in annual growth rate thought to be necessary to offset the most extreme climate-induced decreases in mariculture productivity (Klinger *et al.* 2017). Thus, selective breeding for fast growth rates alone could be sufficient to offset the negative impacts of climate change on mariculture.

Selective breeding for fast growth rates at elevated temperatures could further offset the impacts of climate change on mariculture but has yet to be widely implemented (Gjedrem *et al.* 2012) and has been met with mixed success (Gjedrem and Baranski 2010; Sae-Lim *et al.* 2015). Some selective breeding programs have successfully resulted in a horizontal shift (expand or move the upper thermal limit) of thermal performance curves (Sae-Lim *et al.* 2017) but these breeding programs can be costly (Ponzoni *et al.* 2008; Gjedrem *et al.* 2012). Furthermore, the use of selectively bred fish can pose risks to wild populations and ecosystems (Lind *et al.* 2012). Cultured fish frequently escape from aquaculture facilities (Jensen *et al.* 2010) and can interbreed with wild fish of the same species. Interbreeding can lead to reduced genetic variability and outbreeding depression (reduction in fitness) in wild populations (Hutchings and Fraser 2008). Thus, the benefits of selective breeding must be evaluated against the potential ecological costs of escapement when considering breeding as a tool for climate adaptation.

**Forecasted impacts of climate change on the potential for ocean aquaculture**

Current production potential: Gentry et al. (2017) recently mapped the biological production potential for finfish and bivalve mariculture based on growth potential constrained by depth, temperature, dissolved oxygen, and primary production (bivalve mariculture only) preferences as well as existing human uses. Overall, they estimate an enormous untapped potential for mariculture: bivalve and finfish aquaculture could generate 767.7 million mt (over 2.5 million km2) and 15.6 billion mt per year (over 11.4 million km2), respectively.

Forecasted production potential: Froehlich et al. (2018) extended this work to forecast how finfish and bivalve mariculture would change from now to 2090 under the warming, acidification, and shifts in primary productivity associated with a high emissions scenario (RCP 8.5). They forecast a global increase in the suitable habitat available for finfish mariculture, particularly in polar and subpolar regions. Conversely, they forecast a global decrease in the suitable habitat available for bivalve mariculture. In both sectors, the growth and production potential of the suitable habitat decreases in time. As a result, global mariculture production is likely to decline by mid-century, with bivalves showing the most probable declines.

Caveats: Although Froehlich et al. (2018) forecast declines in the biological potential for global mariculture potential, the relevance of these declines to food and income provisioning is unclear because of (1) the potential for selective breeding to compensate for reductions in habitat availability and growth performance (Klinger *et al.* 2017) and (2) the sheer magnitude of the estimated biological production potential (Gentry *et al.* 2017; Froehlich *et al.* 2018). The sum 16.4 billion mt of mariculture production potential documented is more than 200 times current global aquaculture production (80 million mt, including freshwater production). In other words, if climate change reduced the biological production potential of marine aquaculture by 99%, marine aquaculture would still be doubly productive as today.

For this reason, we use an emerging study (also featured in Blue Paper 1) to compare current and potential country-level aquaculture production. Notably, this analysis extends the work of Gentry et al. (2017) to account not only for environmental constraints on mariculture, but also economic constraints and feed limitations for finfish aquaculture.

**In nearly all countries, current mariculture production is far below capacity, even after accounting for economic and feed constraints. The negative impacts of climate change on mariculture production potential would likely be offset by removing overly precautionary regulations on mariculture and developing new mariculture infrastructure.**

Methods: The true potential for mariculture can be estimated as the biological potential constrained by (1) ocean zoning conflicts; (2) financial feasibility; (3) fishmeal availability; and (4) other social and regulatory barriers. Here, we estimate the true potential for ocean aquaculture by accounting for constraints #1-2 and by evaluating four fishmeal availability scenarios (constraints #3). We do not account for social barriers such as public perceptions of aquaculture sustainability (Froehlich et al. 2017) or regulatory barriers such as precautionary aquaculture permitting (Krause et al. 2015, Knapp and Rubino 2016; constraint #4). However, the farm design employed in the production model employs best practices for aquaculture and thus represents sustainable design under best current knowledge.

Results: Overall, we find that global and county-level mariculture production is significantly under capacity. XXX million mt of bivalve production should be possible at today’s prices for maricultured bivalves (US$1,400 per mt of blue mussels). This is XXX million mt (XXX%) more than current production of XXX million mt. XXX million mt of finfish production should be possible at today’s prices for maricultured finfish (US$7,000 per mt of Atlantic salmon). This is XXX million mt (XXX%) more than current production of XXX million mt. Add sentences about how these patterns vary by country.

If the potential for production is so large, why is current production so low? This gap is likely driven by prohibitive regulatory barriers for developing mariculture operations in many countries (Wardle 2017; Sea Grant 2019). For example, despite having one of the largest EEZs and longest coastlines, the United States has many prohibitive aquaculture regulations and only produces 1% of global bivalve mariculture (FAO 2018). Lessons from effective land-use regulations could help guide efficient mariculture expansion. For example, standards regarding water quality, zoning, ecosystem damage, pollution, pathogen transmission, and fish escapes, as well as a system for monitoring relevant metrics, could be used (Klinger and Naylor 2012). Policy-makers should provide incentives for the creation of competitively priced feed substitutes and scaleable mariculture systems, and disincentives for pollution and other forms of environmental degradation. Beyond abiding by those restrictions, market-based approaches could be developed to efficiently develop ocean space for mariculture.

Implications for adaptation: Overall, these results suggest that the negative impacts of climate change on aquaculture potential may be small relative to the impacts of prohibitive regulations. Thus, elucidating the impact of mariculture on marine ecosystems, identifying best practices for sustainable mariculture production, and the removal of unnecessarily precautionary regulations will all be necessary to foster the growth of mariculture and offset the impacts of climate change.

Insert figure here.

**Figure X.** Percent difference in current and potential **(A)** finfish and **(B)** bivalve mariculture by country.

**Recommendations and key conclusions**

1. **Elucidate the impact of aquaculture on marine ecosystems, identify best practices for sustainable aquaculture production, and remove unnecessarily precautionary regulations to foster the growth of mariculture and offset impacts of climate change.**
2. **Use selective breeding to develop new strains of mariculture species that are resistant to warming, hypoxia, and ocean acidification:** Currently, only 10% of global aquaculture is produced from selectively bred individuals (citation).

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