水研機構研報，第49号，111 − 119，平成31年
Bull. Jap. Fish. Res. Edu. Agen. No. 49，111−119，2019

Offshore mussel aquaculture: strategies for farming in the changing environment of the Northeast U.S. shelf EEZ

Darien D. MIZUTA[*1,2], Mark S. DIXON[*1], Edward J. MANEY Jr.[*3], Mark FREGEAU[*3], and Gary H. WIKFORS[*1]

Abstract: In many aquaculture producing countries, there is increased interest in moving aquaculture offshore, in particular to areas within national Exclusive Economic Zones. Off the US northeast Atlantic coast, the blue mussel, *Mytilus edulis*, is a promising candidate for cultivation. Environmental research has revealed the area to be suitable for successful mussel farming; yet commercial activity has been slow to develop. This paper offers a brief overview of current knowledge relevant to commercial blue mussel offshore aquaculture, focusing on U.S. Northeast areas and addressing several points related to the activity as a potentially pivotal contributor to American seafood production and safety.

Key words: offshore aquaculture, blue mussel, American Northeast, environmental conditions, feasibility

Introduction

The northeast region historically has been an economic hub for fisheries in the United Sates. The region has a legacy of fisheries for lobster, cod, sea scallops, groundfish, and quahogs. More recently, shellfish aquaculture, mainly oysters and clams in coastal areas, is expanding to occupy a central role in regional fisheries and local cuisine. Increasing interest in expanding shellfish aquaculture to offshore areas prompted requests for lease permits with regulatory agencies, the Arms of Corps and NOAA, for mussel farms. As with any new activity, the initiative was anticipated to cause controversies; however, the perception of offshore aquaculture is particularly negative in US because of a serious misunderstanding about the different kinds of risks associated with different forms of aquaculture and cultured species (Froelich *et al*., 2017). Concurrently, the American situation concerning seafood demand and safety is unsettling. Domestic production meets only 10 % of the national seafood demand; in 2014 the US spent more than 20,317 million dollars on seafood imports. This trade imbalance marks the United States as the largest seafood importer in the world, ahead of the past leader Japan, because of the nation's limited domestic production (Kapetsky *et al*., 2013; **Fig.1**). Imported species include salmon, shrimp, and several shellfish, including the blue mussel, especially from Prince Eduard Island (PEI) in Canada, now the top bivalve import (USDA, 2018; **Fig.2**).

Offshore aquaculture activities are proposed to be located in federal waters of the Exclusive Economic Zones (EEZ), between 3 and 200 NM from shore (Environmental Law Institute, 2015), but shore-based access requirements limit the activity to areas with 100 m maximum depth (Kapetsky *et al*., 2013; **Fig.3**). Another possible limitation for aquaculture development is climate change. Expected warming and salinity changes, decreased pH, and accompanying indirect effects, are expected to present many risks to farming operations, including:

2017年２月28日受理（Accepted on February 28, 2017）
*1 Northeast Fisheries Science Center (NEFSC), NOAA, 212 Rogers Ave, Milford, CT 06460 U. S. A.
*2 National Academy of Sciences, 2101 Constitution Ave NW, Washington, DC 20418 U. S. A.
*3 Cat Cove Marine Lab, Salem State University, 352 Lafayette Street Salem, MA 01970 U. S. A.
E-mail: darien.mizuta@noaa.gov

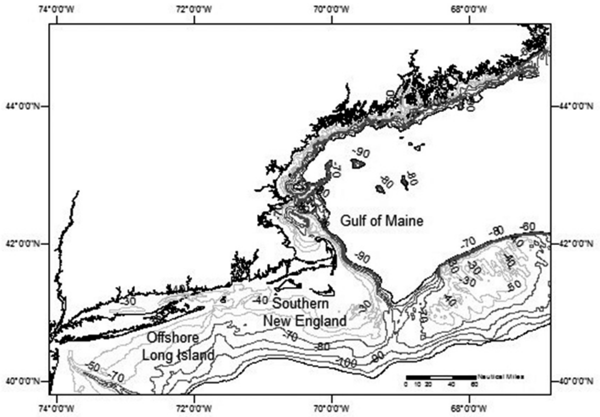

Fig. 1. Map of New England area and the Long Island with depths up to 100 m that are prospective sites for offshore aquaculture development, especially mussel farming.

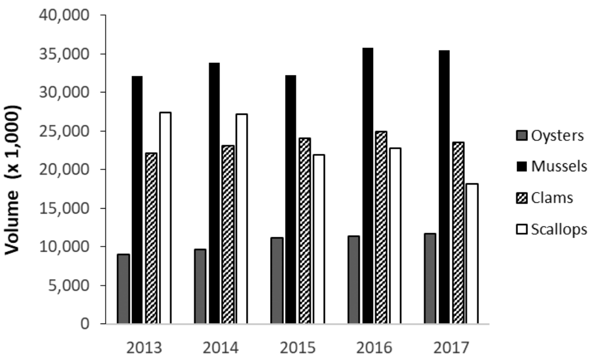

Fig. 2. American bivalve shellfish imports for the period of 2013 to 2017 (Department of Commerce, 2018).

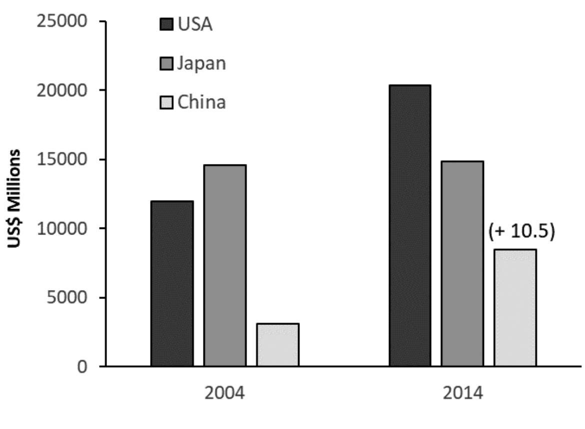

Fig. 3. Comparison of US, Japan and China annual expenditures with seafood imports. Values between brackets show variation between both years (FAO, 2016).

increased incidence of diseases and mortalities, shifts in local biodiversity, declining primary production, altered time of spawning, increased harmful algal blooms, and a variety of physiological responses affecting mussel performance (Allison *et al.*, 2011; Jo *et al.*, 2012; Pershing *et al.*, 2015; Hare *et al.*, 2016; Gobler *et al.*, 2017).

Although research conducted at trial farms addressed many fundamental aspects of mussel farming with encouraging results (Langan and Horton, 2003; Lindell, 2016), these studies lacked the ability to secure the development and establishment of an offshore aquaculture industry that is essentially non-existent more than a decade after initial research. In part, stalled commercial development can be attributed to failure to convince prospective entrepreneurs that risks can be managed and that policy makers are ready to implement a predictable permit process. Such communication among diverse sectors is usually a long-term process. This reticence on the part of both commercial and regulatory participants, and the aforementioned risks associated with expected environmental change, justifies the necessity for contemporary research to address persistent doubts and knowledge gaps and to encourage industry development; while at the same time assuring protection of the environment at prospective farming areas. This paper clarifies recurrent concerns about offshore mussel farming feasibility and builds on the current state of knowledge to encourage the development of sustainable offshore mussel farming activities in the New England area and worldwide.

Why go offshore?

Seafood security can be met only with a national fishery strategy that incorporates aquaculture production, which thus far is mainly limited to coastal areas. Space limitations and competition in coastal areas has triggered interest in expanding aquaculture offshore (Klingler and Naylor, 2012). Additionally, offshore areas also are considered to be more advantageous locations because of potentially compromised coastal water quality and sanitary safety, as well as concerns about negative visual impact and improved spatial use (Kapetsky *et al.*, 2013). Ecological concerns have been raised about shellfish density in near-shore farms possibly contributing to top-down phytoplankton depletion starving local food webs (see for example: Gibbs, 2004). Such concerns are relatively small in areas with considerable water exchange, such as the open ocean (Comeau, 2013). Furthermore, there is a consensus among the pioneer researches on the topic that damaging bottom sedimentation resulting from shellfish farming in offshore areas is unlikely because of higher water circulation and greater depth facilitating dispersal of organic matter prior to sedimentation (Crawford *et al*., 2003; Cheney *et al*., 2010; Gallardi, 2014). Comparisons between inshore and offshore sites also revealed the increased distance from shore contributed to superior mussel quality related to epibiontes because offshore there are impoverished fouling communities, which is largely attributed to limited dispersal abilities (Atalah *et al*., 2016). Offshore, the probability of disease spread also is diminished (Röckmann *et al*., 2017), and parasites such as trematodes, commonly found in coastal mussels, were not present in farms off Massachusetts where little biofouling was found (Maney and Fregeau, 2018, pers. obs.). These results are similar to successful crops obtained from offshore farms in Germany, where health conditions with regard to parasites and fitness were described as excellent (Brenner *et al*., 2012; Buck *et al*., 2017).

The Native Blue Mussel as a suitable species

There are environmental and economic benefits to targeting mussels, in this case the Blue mussel *Mytilus edulis*, as a species for offshore aquaculture in the study area. Mussels, as suspension-feeding bivalves, require no artificial feeds – the origin of most negative perceptions towards aquaculture. Mussels assimilate in situ primary production, growing fast, and promoting nutrient assimilation (Cheney *et al*., 2010; Galimany *et al*., 2017). In high-energy, open-ocean environments, mussel culture is performed with submerged long-lines in middle-depths to avoid the harsh conditions at the surface (Buck, 2007). Mussel attachment to hard substrate by byssus organs and threads constitutes another advantageous characteristic of the species to suit offshore culture (Cheney *et al*., 2010). When exposed to high levels of toxicity during a harmful algal bloom (HAB) event, which are common in the study area, the blue mussel can recover quickly from the toxic effects after ingesting another non-toxic phytoplankton (Galimany *et al*., 2008). For domoic acid, produced by indigenous *Pseudo-nitzschia* species (Fuentes and Wikfors, 2013), the recovery takes place in a matter of hours (Novaczek *et al*., 1992), thus significantly shortening security-related harvest closures and related costs of those delayed harvests in comparison to other bivalve species such as oysters that accumulate and eliminate toxins at slower rates (Shumway, 1990).

Encouraging prospects, even in the face of climate change challenges

The blue mussel was identified as a highly vulnerable species in an assessment conducted considering climate-change-induced projections for several environmental factors such as temperature, salinity, air exposure, pH, and others (Hare *et al*., 2016). Pershing *et al*. (2015) considered a section of the study area, the Gulf of Maine, as the quickest-warming oceanic area in the world, with 3 possible seawater warming scenarios ranging from 0.02 to 0.07 °C/year. Considering these alarming forecasts, a "habitat suitability assessment" was warranted to project the long-term sustainability of offshore aquaculture enterprises in this region. The importance of environmental conditions as a critical step in site selection was already portrayed in an FAO publication summarizing global offshore aquaculture potential assessments, dedicated in its entirely to environmental conditions rather than prohibited/permitted areas based upon policy (Kapetsky *et al*., 2013).

Mizuta and Wikfors (in review) performed a habitat suitability assessment of southern New England and Long Island EEZ areas, using NOAA's open source climatological and remote-sensing data of temperature and chlorophyll a from the period of 2005 to 2012. The rationale for this work is based upon direct and indirect temperature effects, controlling energy allocation to reproduction, as well as affecting byssus tenacity and adherence to farming ropes (Lachance *et al*., 2008). This study provided new insights into the necessity that long-lines in an offshore farm be submerged to depths where temperature is suitable for the species. Results suggested mussel ropes be submerged during summer to a minimum of 15 m depth in northern areas and 20 m depth in southern areas of New England where temperature is between 10-14 °C and phytoplankton biomass is also abundant. During winter, temperatures are around 5 °C, which do not inhibit filtration and are thus consistent with positive growth. From those thresholds, deeper deployments could be used to adapt to future warming scenarios, providing confidence that mussel farming offshore of southern New England and New York is resilient to climate change by simple adjustment of culture depth to adapt to changing seasonal conditions.

Phytoplankton to sustain growth is available in the area, where winter/summer averaged concentrations were above the limiting level of 0.5 mg/m^3 determined for offshore mussel farming according to FAO's assessment (for details please refer to Kapetsky *et al.*, 2013, page 53). Based upon the ideal depths previously mentioned, mussels would take advantage of maximum chlorophyll concentrations that are well above the limiting level. For instance, in initial trials in offshore areas in New Hampshire, mussels achieved harvest size in 1.5 year and a 900-m rope produced up to 12,000 kg mussel/year (Langan and Horton, 2003). In an offshore experimental farming site off Cape Ann, Massachusetts, mussels grew better than coastally at a rate of 0.5 mm/month (Maney *et al.*, 2018). Similarly, mussels of different species, blue, Mediterranean, and greenshell mussels, reportedly grew faster offshore in comparison to inshore control sites, a result attributed to better water exchange and relatively more stable environmental conditions (Cheney *et al.*, 2010). Nevertheless, there are ongoing plans for validation of suitability of selected sites by assessing the performance of mussels in situ with a portable flow-through device employed in several mussel research projects near shore (described in details in Galimany *et al.*, 2013).

One of the industry's known challenges is seed availability; mussel seeds are rarely produced in hatcheries, and natural variation in wild spat availability is inevitable (Buck *et al.*, 2017). In Massachusetts experimental spat collection has been successful; abundant seed could be collected during summer in 2016 on submerged, longline ropes at 15 m depth that after 10-12 months of deployment produced 7 kg/m of mussels of good quality and taste (Maney *et al.*, 2018). With the possibility of changes in spawning season resulting from climate change, research is ongoing to better assess recruitment. Previous spat collection experiments conducted offshore New Hampshire also showed seed collection feasibility, reaching 2,000 seed/m when seed size was 25 mm in shell length[1] (Langan and Horton, 2003). (Fig.4)

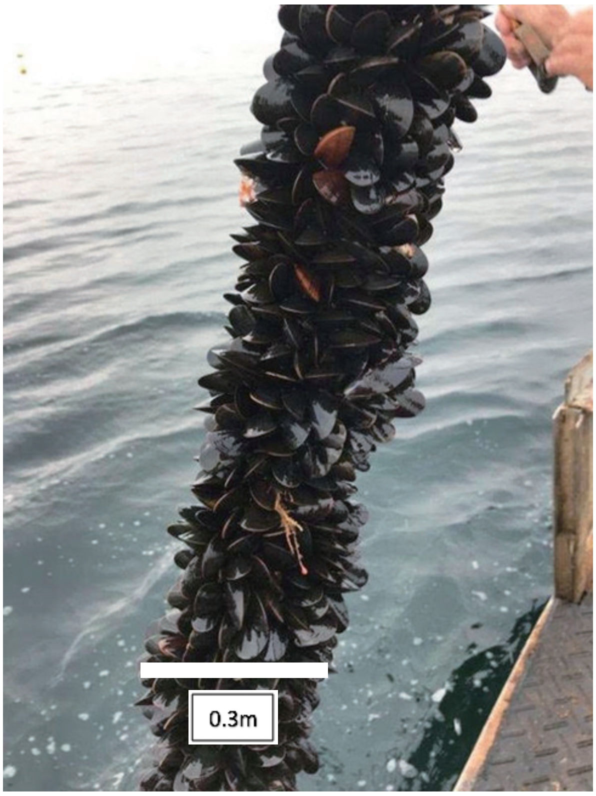

Fig. 4. Successful spat settlement on the header line of the Cat Cove Marine Laboratory trial farm, proving local availability of seeds and future possibility of seed collection. The naturally set spats grew to 5.5 cm in 10 - 12 months.

The extreme rainfall and river flow events associated with climate change prediction in coastal areas is expected to decrease resilience of mussels in coastal estuaries, thus offshore allocation of aquaculture can also mitigate for the decreased in suitable framing areas on the coast (Allison *et al.*, 2011). In relation to the robustness of the mooring

[1] Length here is defines as the distance between shell umbo and extremity in the same valve.

system, until present, the offshore farm system and attached mussels in the experimental off Cape Ann have withstood the local storms.

Opportunities for multifunctional marine structures

Pressures for adoption of clean energy in the Northeast area has led to adoption of offshore wind farm construction plans by Maine and New Hampshire, and Massachusetts has at present an offshore area leased, but still not in use (Baranowski *et al*., 2017), while Rhode Island hosts an active windfarm off of Block Island. Thus, co-siting of wind power and aquaculture offers an opportunity for clean energy and seafood production to be performed in the same area. The idea is not new and was proposed as early as the 1990's in association with oil and gas platforms (Caswell, 1991; Kaiser *et al*., 2011) and most recently more focused mainly in co-location with windfarms (Van Den Burg *et al*., 2017). Aquaculture would take advantage of platform structures to moor farming systems and use space between turbines, a multi-use marine spatial planning initiative already being promoted in both Germany and The U.K. (Corbin *et al*., 2017; Stelzenmuller *et al*., 2017). Concurrently, production of multiple species, especially in different trophic levels, referred to as integrated multitrophic aquaculture or IMTA, has been widely discussed. Species such as bivalves, fish, deposit feeders, and marine plants each consuming different artificial food, available phytoplankton, organic particulates, or dissolved nutrients, could, in theory, maintain background nutrient levels through recycling.

Offshore mussel as a potential "niche-market" product

Despite the scientifically-based environmental suitability of waters offshore of the Northeast for mussel culture, investments in aquaculture may be awaiting even more favorable economic prospects. Although required farming technology is more elaborate than coastal long-lines, and expectedly more costly, economic analysis proved the offshore culture feasibility, provided that good production is achieved (Kite-Powell, 2011). Offshore mussel farming has been characterized by a shorter grow-out period, lower intensity of biofouling, and less risk of predation losses, which should decrease production costs. In truth, to be economically feasible domestic aquaculture needs to match neither cost nor production dictated by competitors (Knapp, 2008), but it can take advantage of the shift to value-added markets. There are other approaches to guarantee profit by exploring niche-markets (Knapp, 2008), such as the selection for traits possibly valued by consumers (for example a golden shell color) and informative labels that appeal to the increased willingness of US consumers to pay for environmentally-friendly and local products (Coddington, 1990; Kecinski *et al*., 2018), compensating the relative lower value of common mussel products in relation to other shellfish. Because mussel cultivation is relatively more sustainable than other types of aquaculture, cultivated mussels are naturally "green." The shift to cultivation in cleaner, US open-ocean areas and away from imports to locally-produced seafood increases traceability, boosting the potential for offshore-produced seafood to be marketed as "sustainably-sourced" and "premium" in seafood markets and restaurants.

Discussion

Shellfish consumers tend to prefer seafood produced in their own nation (see for example Anacleto *et al*., 2014); therefore, increasing seafood production in the U.S. is positive for the national economy and is expected to increase product quality available to American seafood consumers. Historically, fishery activities were mostly conducted with respect to demand, often overlooking environmental sustainability. In the present, such a careless attitude has no place in local markets; therefore, it is in the best interest of seafood producers, policy makers, scientists, and the general public that aquaculture production is increased in the most sustainable way and be resilient to environmental changes, because growth in seafood production is dependent upon aquaculture. This is especially true for the U.S. Northeast where fisheries and shellfish production have been important historical economic activities fostering many jobs and local culture.

Offshore aquaculture studies in the U.S. have pointed to the technical, ecological, and economic feasibility of the activity that is already in advanced development in other nations such as Germany, Belgium, Italy, UK, and France (Buck *et al.*, 2017). Even in face of climate change, offshore aquaculture of blue mussels seems to be adaptable and resilient with proper management. Accordingly, it should not be a question of "whether to," but a question of "how to" best promote development of offshore aquaculture. Each country is expected to identify most suitable species, locations, and cultivation systems (Cheney *et al.*, 2010). For example, in Japan, where eating mussels is not part of the tradition, offshore culture can be performed with the Japanese scallop (*Pactinopecten yessoensis*), using the already established knowledge developed for pearl oyster culture. The sharing of offshore aquaculture related knowledge will allow for more rapid development of activity.

This research article compiling updated offshore scientific knowledge and generalizing research findings is expected to support management and contribute to awareness in stakeholders and the general population. Puzzling problems such as farming designs that guarantee the safety of marine protected species - should interactions occur - that are abundant in the areas are still to be solved. With fast-developing technology and current integrated science-based management that follows an environmental sustainability framework, however, offshore mussel aquaculture can be developed with the benefit of lessons learned from decades of incremental improvements in management of capture fisheries (Finley, 2017).

Acknowledgment

The authors would like to thank the Japanese research team that organized the 45th United States-Japan National Resources Symposium in Hiroshima for their warm welcome. We also would like to thank Captain Bill Lee, FV Ocean Reporter (Rockport, MA) for his assistance, Legal Sea Foods as an industry partner and financial supporter and to acknowledge the supports received through a research travel grant from the NOAA Office of Aquaculture, and the postdoctoral fellowship from NRC Research Associateship Program from the National Academy of Sciences.

References

Allison E. H., Badjeck M. C., and Meinhold K., 2011: The implications of global climate change for molluscan aquaculture, in "Shellfish Aquaculture and the Environment" (ed. by Shumway S. E.), Wiley-Blackwell, West Sussex, pp. 461-490.

Anacleto P., Barrento S., Nunes M. L., Rosa R., and Marques A., 2014: Portuguese consumers' attitudes and perceptions of bivalve molluscs. *Food Control*, **41**, 168-177.

Atalah J., Fletcher L. M., Hopkins G. A., Heasman K., Woods C. M. C., and Forrest B. M., 2016: Preliminary assessment of biofouling on offshore mussel farms. *J. World Aquacult. Soc.*, **47(3)**, 376-386.

Baranowski R., Oteri F., Baring-Gould I., and Tegen S., 2017: State of wind development in the United States Region. Technical NREL/TP-5000-67624, Report National Renewable Energy Laboratory, U.S. Department of Energy.

Brenner M., Buchholz C., Heemken O., Buck B. H., and Koehler A., 2012: Health and growth performance of blue mussels (*Mytilus edulis L.*) from two different hanging cultivation sites in the German Bight: A nearshore−Offshore comparison. *Aquacul. Int.*, **20**, 751-778.

Buck B. H., 2007: Experimental trials on the feasibility of offshore seed production of the mussel *Mytilus edulis* in the German Bight: installation, technical requirements and environmental conditions. *Helgol. Mar. Res.*, **61**, 87-101.

Buck B. H., Nevejan N., Wille M., Chambers M., and Chopin T., 2017: Offshore and multiuse aquaculture with extractive species: seaweeds and bivalves, in "Aquaculture Perspective of Multi-Use Sites in the Open Ocean" (ed. by Buck B. H.and Langan R.), Springer Open, Switzerland, pp. 23-69.

Caswell M., 1991: Co-development of coastal resources: oil versus mariculture. *Contemp. Econ. Policy*, **9(1)**, 92-100.

Cheney D., Langan R., Heasman K., Friedman B., and Davis J., 2010: Shellfish culture in the open ocean: lessons learned for offshore expansion. *Mar. Technol. Soc. J.*, **44 (3)**, 55-67.

Coddington W., 1990: It's no fad. Environmentalism is now a fact of corporate life, Marketing News, October 15, 7pp.

Comeau L. A., 2013: Suspended versus bottom oyster culture in eastern Canada: Comparing stocking densities and clearance rates. *Aquaculture*, **410-411**, 57-65.

Corbin J. S., Holmyard J., and Lindell S., 2017: Regulation and Permitting of Standalone and Co-located Open Ocean Aquaculture Facilities, in"Aquaculture Perspective of Multi-Use Sites in the Open Ocean" (ed. by Buck B. H. and Langan R.), Springer Open, Switzerland, pp. 187-229.

Crawford C. M., Macleod C. K. A., and Mitchell I. M., 2003: Effects of shellfish farming on the benthic environment. *Aquaculture*, **224**, 117-140.

Department of Commerce, 2018: U.S. Census Bureau. Aquaculture trade – Recent years and top countries. Available at: https://www.ers.usda.gov/data-products/aquaculture-data/.

Environmental Law Institute, 2015: U.S. Army Corps of Engineers Regulation of Offshore Aquaculture (February 2015). Available at: www.eli.org.

FAO, 2016: SOFIA – State of World Fisheries and Aquaculture, FAO, Rome. Available at: http://www.fao.org/fishery/sofia.

Finley C., 2017: All the boats on the ocean – how government subsides led to global overfishing, University of Chicago Press, Chicago, 206pp.

Froelich H. E., Gentry R. R., Rust M. B., Grimm D., and Halpern B. S., 2017: Public perceptions of aquaculture: evaluating spatiotemporal patterns of sentiment around the world. *PloS One*, **12(1)**, e0169281.

Fuentes S. and Wikfors G. H., 2013: Control of domoic acid toxin expression in *Pseudo-nitzschia multiseries* by copper and silica: Relevance to mussel aquaculture in New England (USA). *Mar. Environ. Res.*, **83**, 23-28.

Gallardi D., 2014: Effects of Bivalve Aquaculture on the Environment and Their Possible Mitigation: A Review. *Fish Aquac. J.*, **5(3)**, 105.

Galimany E., Sunila I., Hegaret H., Ramos M., and Wikfors G. H., 2008: Experimental exposure of the blue mussel (*Mytilus edulis, L.*) to the toxic dinoflagellate *Alexandrium fundyense*: Histopathology, immune responses, and recovery. *Harmful Algae*, **7**, 702-708.

Galimany E., Rose J. M., Dixon M. S., and Wikfors G. W., 2013: Quantifying feeding behavior of ribbed mussels (*Geukensia demissa*) in two urban sites (Long Island Sound, USA) with different seston characteristics. *Estuar. Coast.*, **36**, 1265-1273.

Galimany E., Wikfors G. H., Dixon M. S., Newell C. R., Meseck S. L., HenningD., and Rose J. M., 2017: Cultivation of the Ribbed Mussel (Geukensia demissa) for nutrient bioextraction in an urban estuary. *Environ. Sci. Technol.*, **51(22)**, 13311-13318.

Gibbs M. T., 2004: Interactions between bivalve shellfish farms and fishery resources. *Aquaculture*, **240**, 267-296.

Gobler C.J., Doherty O. M., Hattenrath-Lehmann T. K., Griffith A. W., Kang Y., and Litaker R. W., 2017: Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *PNAS*, **114(19)**, 4975-4980.

Hare J., Morrison W. E., Nelson N. W., Stachura M. M., Teeters E. J., Griffis R. B., Alexander M. A., Scott J. D., Alade L., Bell R. J., Chute A. S., Curti K. L., Curtis T. H., Kircheis D., Kocik J. F., Lucey S. M., McCandless C. T., Milke L. M., Richardson D. E., Robillard E., Walsh H. J., McManus M. C., Marancik K. E., and Griswold C. A., 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. *PloS One*, **11(2)**, e0146756.

Jo Q., Hur T. B., Cho K. C., Jeon C. Y., and Lee D. C., 2012: Potential Influence of Climate Change on Shellfish Aquaculture System in the Temperate Region. *Korean J. Malacol.*, **28(3)**, 277-291.

Kaiser M. J., Snyder B., and Yu Y., 2011: A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico. *Ocean Coast. Manage.*, **54**, 721-730.

Kapetsky J. M., Aguilar-Manjarrez J., and Jenness. J., 2013: A global assessment of offshore mariculture potential from a spatial perspective, FAO Fisheries and Aquaculture Technical Paper 549, FAO, Rome.

Kecinski M., Messerb K. D., and Peob A. J., 2018: When cleaning too much pollution can be a bad thing: a field experiment of consumer demand for oysters. *Environmental Economics*, **146**, 686-695.

Kite-Powell H. L., 2011: Business planning for mussel longline operations. Offshore Mussel Aquaculture Farming Workshop (WHOI, February 7, 2011). Available at: http://www.mbl.edu/bell/scientific-aquaculture/2011-mussel-farming-workshop/.

Klinger D. and Naylor R., 2012: Searching for solutions in aquaculture: charting a sustainable course. *Annu. Rev. Environ. Resour.*, **37**, 247-276.

Knapp G., 2008: Economic Potential for U.S. Offshore Aquaculture: An Analytical Approach, in "Offshore Aquaculture in the United States: Economic Considerations, Implications & Opportunities" (ed. by Rubino M.), NOAA Technical Memorandum NMFS F/SPO-103, U.S. Department of Commerce, Silver Spring, 263pp.

Lachance A. A., Myrand B., Tremblay R., Koutitonsky V., and Carrignton E., 2008: Biotic and abiotic factors influencing attachment strength of blue mussels Mytilus edulis in suspended culture. *Aquat. Biol.*, **2**, 119-129.

Langan R. and Horton F., 2003: Design, Operation and economics of submerged longline mussel culture in the Open Ocean. Bull. *Aquacul. Assoc. Canada*, **103(3)**, 11-20.

Lindell S., 2016: Hatchery and nursery for improved production of blue mussels. Annual Report of the Northeast Fisheries Aquaculture Center, for the period of 2015 and 2016, United States Department of Agriculture, Maryland, pp. 16-30. Available at: http://agresearch.umd.edu/nrac/annual-reports#overlay-context=nrac/publications-0.

Maney E. Jr., Fregeau M., and Lee B., 2018: First year results from offshore shellfish aquaculture in Federal waters of the Atlantic. 38Th Milford Aquaculture Seminar, 8-10 January, NOAA Fisheries, Shelton.

Novaczek I., Madhyastha M. S., Ablett R. F., Donald A., Johnson G., Nijjar M. S., and Sims D. E., 1992: Depuration of domoic acid from live blue mussels (*Mytilus edulis*). *Can. J. Fish. Aquat. Sci.*, **49**, 312-318.

Pershing A. J., Alexander M. A., Hernandez C. M., Kerr L. A., Le Bris A., Mills K. E., Nye J. A., Record M. R., Scannell H. A., Scott J. D., Sherwood G. D., and Thomas A. C., 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350(6262)**, 809-812.

Röckmann C., Lagerveld S., and Stavenuiter J., 2017: Operation and Maintenance Costs of Offshore Wind Farms and Potential Multi-use Platforms in the Dutch North Sea, in "Aquaculture Perspective of Multi-Use Sites in the Open Ocean" (ed. by Buck B. H. and Langan R.), Springer Open, Switzerland, pp. 97-113.

Shumway S., 1990: A review of the effects of algal blooms on shellfish and aquaculture. *J. World Aquacult. Soc.*, **21(2)**, 65-104.

Stelzenmuller V., Gimpel A., Gopnik M., and Gee K., 2017: Aquaculture site-selection and marine spatial planning: the roles of GIS-based tools and models, in "Aquaculture Perspective of Multi-Use Sites in the Open Ocean" (ed. by Buck B. H. and Langan R.), Switzerland, pp. 131-148.

USDA, 2018: Aquaculture trade – recent years and top countries. Available at: https://www.ers.usda.gov/data-products/aquaculture-data.aspx.

Van den Burg S. W. K., Kamermans P., Blanch M., Pletsas D., Poelman M., Soma K., and Dalton G. J., 2017: Business case for mussel aquaculture in offshore wind farms in the North Sea. *Mar. Policy*, **85**, 1-7.

Annotated bibliography

(1) Allison E. H., Badjeck M. C., and Meinhold K., 2011: The implications of global climate change for molluscan aquaculture, in "Shellfish Aquaculture and the Environment.Shumway" (ed. by Shumway S. E.), Wiley-Blackwell, West Sussex, pp. 461-490.

The authors of this chapter instead of developing models predicting possible climate changes, discuss the impacts of the climate to shellfish aquaculture and market based on an extensive review of different relevant chemical and physical elements affecting the oceans. Authors also suggest mitigation and management plans that can be applied for the sustainability of the shellfish farming.

(2) Buck B. H. and R. Langan R. (Eds.), 2017: Aquaculture Perspective of Multi-Use Sites in the

Open Ocean, Springer Open, Switzerland, 404pp.

The entire book, to which we refer many chapters, is an important compilation of the status of research on general offshore aquaculture around the world, with each chapter treating relevant issues such as different species, technical designs, experimental trials, management and related policy.

(3) Hare J., Morrison W. E., Nelson N. W., Stachura M. M., Teeters E. J., Griffis R. B., Alexander M. A., Scott J. D., Alade L., Bell R. J., Chute A. S., Curti K. L., Curtis T. H., Kircheis D., Kocik J. F., Lucey S. M., McCandless C. T., Milke L. M., Richardson D. E., Robillard E., Walsh H. J., McManus M. C., Marancik K. E., and Griswold C. A., 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. *PloS One*, **11 (2)**, e0146756.

Authors in this study conducted a climate vulnerability assessment, as impacts to abundance or productivity, on 82 fish and invertebrate species in the Northeast U.S. Shelf including exploited, forage, and protected species. Exposure factors were defined as: ocean surface temperature (upper 10 m), ocean surface salinity (upper 10 m), surface air temperature, precipitation, surface pH (upper 10 m), currents, and sea-level rise. Results showed high vulnerability of diadromous and benthic invertebrate species, including the blue mussel, while positive effects were identified to some species. The findings of this paper are important to enable appropriate adaptive fisheries and conservation management.

(4) Kapetsky J. M., Aguilar-Manjarrez J., and Jenness J., 2013: A global assessment of offshore mariculture potential from a spatial perspective, FAO Fisheries and Aquaculture Technical Paper 549, FAO, Rome.

In this publication from FAO, offshore aquaculture is assessed in an international context addressing species and desirable conditions for farming, besides potential for different areas in the world. It is and introduction to siting decision and sustainable aquaculture development.