Participants in 45th UJNR Aquaculture Panel Symposium, held in International Conference Center Hiroshima, Hiroshima, Japan, October 16 – 17, 2017

Preface

The UJNR (The U.S.-Japan Cooperative Program in Natural Resources) Aquaculture Panel was established in 1968, and the business meeting and symposium have been held every year since 1971. Through the long history of UJNR, Aquaculture Panel has contributed to the development of aquaculture researches of both countries by means of various cooperative activities, such as the exchange of scientists and literatures, and the promotion of joint research projects. The Aquaculture Panel is highly appraised as one of the most active UJNR panels in both countries.

The 45th Business Meeting of the UJNR Aquaculture Panel was conducted at Conference Center Hiroshima, Hiroshima Prefecture, Japan on October 16, 2017, and the Scientific Mini-Symposium was held at the same venue from October 17 to 18. The symposium theme was "Potential of aquaculture to mitigate impacts of environmental change", which was under the 10th Three-Year Plan, "Marine Aquaculture in a Changing Environment", commenced in 2017. Fifteen oral presentations were made on topics such as environmental change, environmental remediation, biological response to environmental change and ecosystem approach to aquaculture, and seven poster presentations were also made on broader topics related to aquaculture during the two-day symposium.

The proceedings of the 45th UJNR Aquaculture Panel Scientific Mini Symposium "Potential of aquaculture to mitigate impacts of environmental change" is published as the special issue of the Bulletin of Japan Fisheries Research and Education Agency. With great pleasure, this UJNR proceedings containing high quality papers authored by selected American and Japanese aquaculture scientists will hopefully help improve the aquaculture environment programs, which is expected to contribute to the development of the aquaculture industry in both the United States and Japan.

Finally, I would like to express my sincere gratitude to the colleagues involved in the UJNR Aquaculture Panel for their efforts in the preparation and organization of the symposium. I would also like to deeply thank the editorial board members for publishing the proceedings.

Fuminari Ito, Ph.D.
Chair of UJNR Aquaculture Panel
Executive Director
Japan Fisheries Research and Education Agency

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Abstracts of Poster Presentations

Program

The 45th Scientific Symposium of UJNR Aquaculture Panel

Potential of aquaculture to mitigate impacts of environmental change

Date:

October 16	13：30-17：30	Oral Session, Poster Session
October 17	9：00-16：00	Oral Session during lunch break

Venue:

International Conference Center Hiroshima, 1-5 Nakajima-cho, Naka-ku, Hiroshima-shi, Hiroshima, 730-0811, Japan

Aim of the Symposium

Environmental change impacts fisheries and aquaculture in many ways. Nutrient pollution is driving eutrophication and dead zones; ocean acidification is changing water chemistry, and climate change is already influencing our food supply, fresh water availability, weather and way of life. Aquaculture will be impacted by, and can also impact, these environmental changes over various time and spatial scales. Aquaculture of finfish, shellfish and seaweed have different threats, benefits and opportunities related to environmental change. Understanding the global and regional trend of climate change, effects of environmental change on ecosystem and aquaculture, technical improvement of aquaculture, and aquaculture industrial adaptation to climate change are all research priorities of the National Ocean and Atmospheric Administration (NOAA), the United States Department of Agriculture (USDA) and the Japan Fisheries Research and Education Agency (FRA). The primary focus of this symposium will be on the potential of aquaculture to mitigate impacts of environmental change, such as sequestering carbon, bio-extraction of nutrients and CO_2, and ocean acidification. We hope to exchange ideas and discussion which will be beneficial in exploring science and technology that will enable aquaculture to sustain in a changing environment and be used to mitigate the anthropogenic impacts on environment. We also hope the exchanged ideas will be developed into our collaborative research efforts to resolve key issues and assist strengthening of aquaculture industry in the United States and Japan.

Monday, October 16, 2017

Registration: 13：00-13：30

Opening Session

Welcome Remarks

Fuminari Ito (Japan Panel Chair, Executive Director, Headquarters, FRA)
…………………………………………………………………………………… 13：00-13：40

Aim of the Symposium

Takuro Shibuno (Director,National Research Institute of Aquaculture, FRA)
…………………………………………………………………………………… 13：40-13：50

Session I. Keynote Presentation and Introduction of NOAA grants

(Moderators: Paul Olin and Junya Higano)

1. New direction of management policies in the Seto Inland Sea, Japan in the changing environment
   Osamu Matsuda (Professor Emeritus, Hiroshima University) ………… 13：50-14：30

Break …………………………………………………………………………………… 14：30-14：50

2. Marine aquaculture's role in providing nutritional security in a changing environment
   Mike Rust (US Panel Chair, NOAA Fisheries Office of Aquaculture) … 14：50-15：30
3. An overview of NOAA grants on aquaculture and the environment
   Shiyu Rachel Wang (Knauss Fellow, NOAA Headquarters, Office of Aquaculture)
   …………………………………………………………………………………… 15：30-15：55

Session II. Environmental Change

(Moderators: Takuro Shibuno and Mathew Poach)

4. Oligotrophication and its measures in the Seto Inland Sea, Japan
   Katsuyuki Abo (National Research Institute of Fisheries and Environment of Inland Sea, FRA) ……………………………………………………………………… 15：55-16：20
5. Assessment and future prediction of climate shift impacts on the macroalgal ecosystem and cultivation in the Seto Inland Sea
   Jeffrey Silverstein (USDA Agricultural Research Service) …………… 16：20-16：45

Poster Session

Poster presentation ………………………………………………………………… 16：45-17：30

Tuesday, October 17, 2017

Session III. Environmental Remediation

(Moderators: Natsuki Hasegawa and Darien Mizuta)

6. Coastal management using oyster-seagrass interactions for sustainable aquaculture, fisheries and environment
   Masakazu Hori (National Research Institute of Fisheries and Environment of Inland Sea, FRA) ………… 9：00– 9：25
7. Marine sediment conservation using benthic organisms
   Katsutoshi Ito (National Research Institute of Fisheries and Environment of Inland Sea, FRA) ………… 9：25– 9：50

Break ………… 9：50–10：10

Session IV. Biological Response to Environmental Change

(Moderators: Satoshi Watanabe and Brett Dumbauld)

8. Coastal acidification amplifiers along the US East coast: concerns for shellfish production
   Matt Poach (NOAA, Northeast Fisheries Science Center) ………… 10：10–10：35
9. Growth variation in long blades kelp *Saccharina longissima* in eastern Hokkaido, Japan
   Natsuki Hasegawa (National Research Institute of Aquaculture, FRA) ………… 10：35–11：00
10. Harmful algal blooms and shellfish aquaculture in a changing environment
   Leila Basti (Tokyo University of Marine Science and Technology) ………… 11：00–11：25

Lunch Break ………… 11：25–13：00

Session V. Ecosystem Approach to Aquaculture Part 1

(Moderators: Masakazu Hori and Cheng Sheng Lee)

11. Ecosystem approach to marine aquaculture
   Kay McGraw (NOAA, Office of Habitat Conservation) ………… 13：00–13：25
12. Spatial Planning for Shellfish Aquaculture and Seagrasses in US West Coast Estuaries: Considerations for Adapting to an Uncertain Climate
   Brett Dumbauld (U.S. Department of Agriculture, Agricultural Research Service) ………… 13：25–13：50
13. Offshore mussel aquaculture: strategies for farming in the changing environment of NE Atlantic EEZ
   Darien Mizuta (NOAA, Northeast Fisheries Science Center) ………… 13：50–14：15

Session VI. Ecosystem Approach to Aquaculture Part 2

(Moderators: Katsuyuki Abo and Kay McGraw)

14. Nutrient environment in Gokasho Bay, effects of fish aquaculture on inorganic nutrient levels

    Satoshi Watanabe (National Research Institute of Aquaculture, FRA) ………………………… 14：15–14：40

15. Challenges and opportunities of IMTA in Hawaii and beyond

    Cheng Sheng Lee (Director, Center for Tropical and Subtropical Aquaculture, U.S. Department of Agriculture) ………………………… 14：40–15：05

Break ………………………… 15：05–15：25

Open Discussion: Development of collaborative research projects … 15：25–15：50

(Moderators: Fuminari Ito and Mike Rust)

Science Symposium Closing ………………………… 15：50–16：00

Mike Rust (US Panel Chair, NOAA Fisheries Office of Aquaculture)

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New direction of management policies in the Seto Inland Sea, Japan, in a changing environment

Osamu MATSUDA*

Abstract: The Seto Inland Sea, the largest enclosed coastal sea in Japan, covers an area of 23,000 km^2 and was originally renowned as a productive fishing and aquaculture ground with scenic beauty. However, since the coastal basin in the watershed around the sea is home to 30 million people, and impact of human activities on the sea has been very strong. During Japan's period of rapid economic growth in the mid-1960s to mid-1970s, industrialization of the coastal area, increase in the number of factories and expansion of landfills in waterfront areas caused a rapid increase in water pollution with a reduction in shallow water area and destruction of the marine environment. In order to conserve the environment of the region, the Law on Temporary Measures for the Environment Conservation of the Seto Inland Sea was enacted in 1973. This law was made permanent in 1978 as the Law on Special Measures for the Environment Conservation of the Seto Inland Sea ("The Seto Inland Sea Law"). More than 40 years have now passed since the enactment of the legal system. During the time, changes of both the natural and socio-economic environments around the sea were remarkable. And, recently, 2015 became the year for a particularly important change of direction for management because major revisions of both "The Seto Inland Sea Law" and the governmental Basic Program based on the Law were made. In the newly revised Basic Program, two major aims of the previous Basic Program (conservation of water quality and conservation of natural landscape) were reformed into four new major aims, including conservation and restoration of coastal environment, conservation and appropriate management of water quality, conservation of natural and cultural landscapes, and sustainable utilization of fish resources. These recent changes indicate that not only passive conservation but also positive conservation, such as restoration of coastal environment, became very important targets. The new direction of the management reflects the changing environment of the Seto Inland Sea. After WWII, the first major target was water pollution control, including toxic substances. Then, the target turned to red tides due to eutrophication. Recently, major targets are changing to lowered biological productivity and diversity due to oligotrophication and deteriorated habitat. Therefore, the main approaches of management also changed from water quality control by restrictive measures to restoration of habitat, such as tidal flats and sea grass beds, by promotion of participatory creative activities. New direction is also supported by the concept of *Satoumi*, which includes restoration of biodiversity, biological productivity, habitat and well balanced nutrient cycle by the intervention of positive human activities. These recent shifts of the management policies are expected to contribute to recovering productive fishing and aquaculture grounds in the Seto Inland Sea in the future.

Key words: coastal management, environmental conservation, Seto Inland Sea, *Satoumi*

2018年８月31日受理（Accepted on August 31, 2018）
* Hiroshima University (Professor Emeritus), Higashi-Hiroshima, 739-8528, Japan
E-mail: matsuda036@go3.enjoy.ne.jp

Introduction

Brief History of the Seto Inland Sea

The Seto Inland Sea, the largest enclosed coastal sea in Japan (**Fig.1**), has long history in which plenty of ecosystem services have been provided. However, serious environmental changes due to land-based human activities occurred during the postwar reconstruction age after WWII. Rapid economic growth during 1960s to 70s was accompanied by serious water pollution, eutrophication and destruction of habitat, such as tidal flats and sea grass beds, in the shallow coastal areas. Among many countermeasures, the Seto Inland Sea Law (Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea), which was first enacted in 1973 and applied only to the Seto Inland Sea, played an important role. Major functions of "the special law" were area wide total pollution load control (TPLC) and suppression of land reclamation.

Brief Introduction to *Satoumi*

What does *Satoumi* mean? Why is so much attention paid to *Satoumi* nowadays? In Japanese, "*Sato*" means local village or community where people live their life and "*Umi*" means the sea. Therefore, the simple literal meaning of *Satoumi* is the sea associated with local village or community. In reality, *Satoumi* is a traditional Japanese coastal ecosystem and landscape management system that was found in many coastal areas throughout Japan in days gone by Sustainable community-based management of the local sea areas has a long history in Japanese tradition.

However, during the nation's high economic growth, this type of traditional coastal management has gradually deteriorated due to changes in the local community and life style of the people. As a result, social demand to create a new type of *Satoumi* defined as high biological productivity and high biological diversity in the coastal seas with positive human intervention has arisen and grown strong. In Japan, community-based habitat restoration activities have been gaining ground in recent years partly because the concept of *Satoumi* was incorporated into official institutional systems of national policy. Since *Satoumi* originated in Japan and is sometimes said to have grown up in the Seto Inland Sea, *Satoumi* exemplifies the close relationship between the deterioration of the sea and active conservation of the area by local people (**Fig.2**).

Recently, a new concept for coastal sea management called *Satoumi* has been noticed not only in its original place of Japan but also in many other countries, including both western and Asian. Multilingual editions of books on *Satoumi*

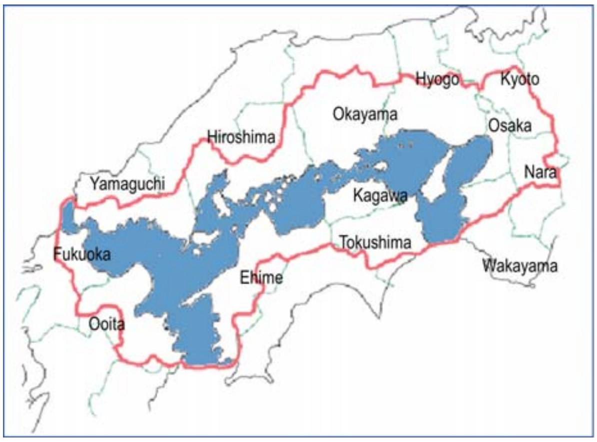

Fig. 1. Outline of the Seto Inland Sea, its watershed and location of 13 prefectures around the Sea. The applied area of "The Seto Inland Sea Law" is almost equal to the watershed area of all rivers flowing into the Sea, where ca. 30 million people live. (Source: The Association for the Environmental Conservation of the Seto Inland Sea)

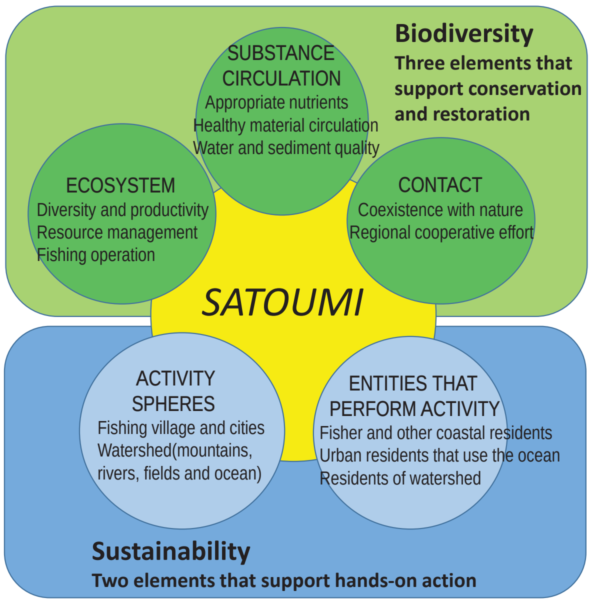

Fig. 2. Five important elements of *Satoumi* concept. Three objectives to be improved (upper) and two indicators on activities (lower). (Source: Sato-Umi net)

published by such international organizations as the United Nations University and the Secretariat of the Convention on Biological Diversity (CBD) also contribute to expanding *Satoumi* activities in the world.

Change of the Environment and Ecosystems

The TPLC system has significantly improved water quality in terms of COD, Total Nitrogen (TN) and Total Phosphorus (TP). For example, the number of the occurrences of red tide decreased from about 300 a year at the peak to about 100 a year recently. Concentration of TN and TP in sea water also decreased, and recently, it has cleared the legal environmental standard of Japan in many areas of the Seto Inland Sea. However, since suppression of land reclamation does not mean total ban of land reclamation, the effect of the policy was restricted. As a result, shallow areas -- in particular tidal flats and sea grass beds -- have been drastically lost during the last 50 years.

Changes in the pollutant load from land and changes in water quality in the Seto Inland Sea due to the TPLC system is very clear. The load of COD, TN and TP decreased during the years of 1979 to 2014. Generally, concentration of TN and TP in sea water is proportional to the TN and TP load per unit area of the sea. This means that water quality in terms of TN and TP has been much improved in general. However, decreased nutrient concentrations in sea water has led to the new issue of artificial oligotrophication, which caused insufficient growth in *Nori* (laver) culture.

Meanwhile, changes in biodiversity in the Seto Inland Sea have not been systematically monitored. However, biodiversity seems to have decreased judging from the evidence that the number of observed sea shore animals of at various stations around Kure area that are members of long monitored species has decreased drastically from the mid-1960s. Tidal flats and sea grass beds around the Seto Inland Sea decreased mainly due to land reclamation and, therefore, natural coastlines disappeared (**Fig.3**). These events indicate that the habitat condition has deteriorated. Fish catch data indicate that fisheries

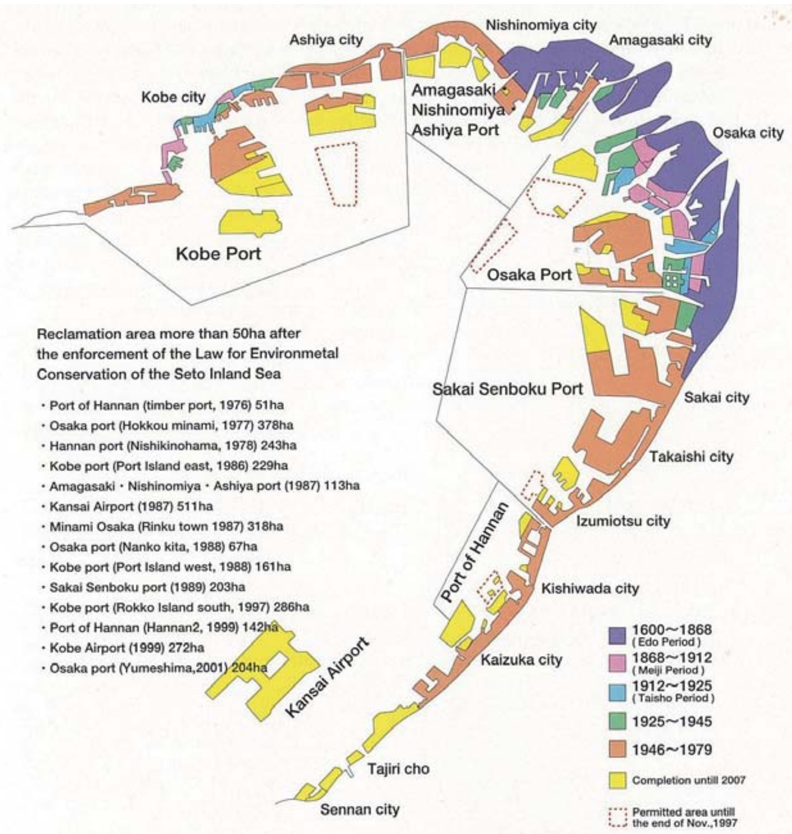

Fig. 3. Result of historical land reclamation in Osaka Bay. Natural shorelines and shallow areas, such as sea grass beds and tidal flats, disappeared. (Source: The Association for the Environmental Conservation of the Seto Inland Sea)

production is decreasing after a peak in the mid-1980s. From these results, it can be said that the ecosystem services available are decreasing in the Seto Inland Sea, although water quality has been improved to some extent.

Major environmental and related problems in the Seto Inland Sea in recent years can be summarized as following.

In broad sense:

- Deterioration of the ecosystem, natural resources and ecosystem services
- Decrease of biological diversity and biological productivity (fish catch)
- Weakened relationship between humans and the sea

In narrow sense:

- Occurrence of red tides and oxygen depletion in bottom waters
- Deterioration of the benthic environment and sediment quality
- Disappearance of biological habitat for spawning and as nursery grounds
- Insufficient nutrients for laver *(Nori)* culture ground in winter

Recent Shift of Management Policy in the Seto Inland Sea

Environmental conservation and management policy firstly made emphasis on water pollution control. However, this kind of passive conservation policy is gradually being shifted to active conservation, such as *Satoumi,* which includes restoration of biodiversity, biological productivity, habitat and a well-balanced nutrient cycle between land and sea. Holistic approaches, such as ecosystem-based management (EBM) and integrated coastal management (ICM), are also being incorporated in new policy. In the recently revised governmental Basic Program for the Environmental Conservation of the Seto Inland Sea (2015), based on the revised Seto Inland Sea Law (2015), 2 major aims of the previous Basic Program (1. conservation of water quality, 2. conservation of natural landscape) are reformed into 4 major aims (1. conservation and restoration of coastal environment, 2. conservation and appropriate management of water quality, 3. conservation of natural and cultural landscapes, 4. sustainable utilization of fish resources) (**Fig.4**). Therefore, the simplified major change of the aim is from a focus on water quality control to more holistic restoration of environmental and fish resources, which can lead to abundant and bountiful coastal seas.

Present Status of *Satoumi*

Historically, *Satoumi* has evolved as the traditional Japanese way of coastal management in which local communities co-existed with nature. In the *Satoumi* concept, people's livelihoods and their culture are deeply involved, biological productivity is sustained, and biological diversity is protected and conserved, while ecosystems are able to be sustained and material cycling is maintained. These community efforts were undertaken in a comprehensive and integrated

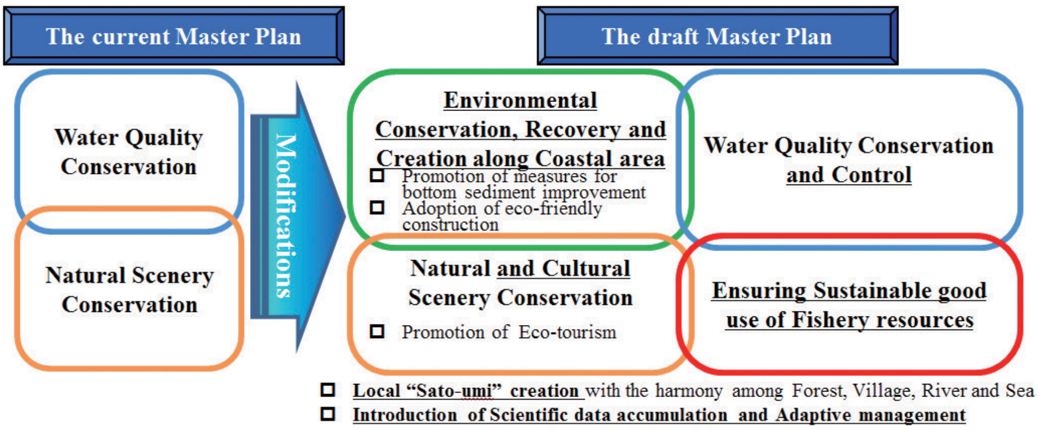

Fig. 4. Outline of recent revision of the governmental Basic Program, based on the revision of "The Seto Inland Sea Law" (2015). (Source: Ministry of the Environment)

manner from upland forest and rivers to coastal seas. Therefore, the concept of *Satoumi* primarily provides holistic management of watersheds, including forests, rivers, local communities and coastal environments. Combining *Satoyama*, focuses on forest and agricultural land, with *Satoumi* is also expected to help develop a Japanese model of integrated coastal management (ICM).

In many *Satoumi*-like coastal seas in Japan, sustainable community-based management of the sea has historically been conducted in a traditional manner. However, during the nation's high economic growth after World War II and due to social changes associated with the economic development of the nation, this type of traditional coastal management gradually declined because of the changes in local communities and life styles of the people. During the same period, coastal environments, habitats and living resources were also seriously damaged by water pollution, eutrophication and land development, as a result of urbanization and industrialization of coastal areas. Instead of obtaining efficiency and convenience due to industrial development, valuable capital, such as the natural environment, natural resources and natural landscape was lost. As a result, social demand to create and establish a new type of *Satoumi*, defined as high biological productivity and high biological diversity in the coastal seas with positive human intervention, has arisen and gradually gained ground. In other words, a "*Satoumi* Renaissance" is taking place in order to restore once lost rich and healthy coastal seas by community-based participatory activities. In seas where *Satoumi* activity is necessary, natural environmental conditions and the ecosystems are so deteriorated they cannot recover naturally without support by human behavior.

In Japan, community-based habitat restoration activities have also been gaining ground in recent years. This is partly because the concept of *Satoumi* was incorporated into official institutional systems of national policy, such as the Basic Ocean Plan (2008), based on Basic Ocean Act (2007), and some national environmental strategies.

The Governor's and Mayor's Conference for Environmental Conservation of the Seto Inland Sea has been seeking new policy, based on the concept of *Satoumi* since 2004. Some local governments out

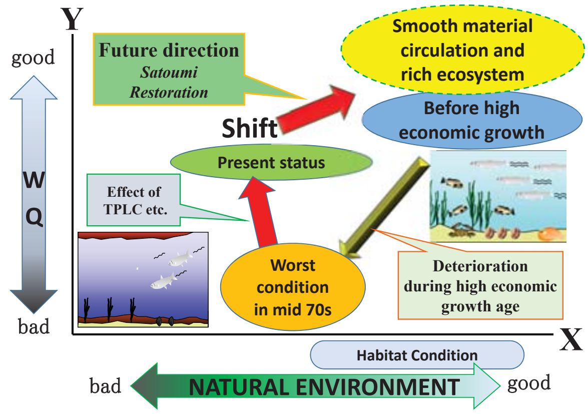

Fig. 5. Conceptual view of future directions and necessary shifts of environmental management in the Seto Inland Sea. (Reformed figure by the author based on Ministry of the Environment)

of Seto Inland Sea area also introduced the *Satoumi* concept as official policy. For example, Kagawa prefecture has always promoted *Satoumi* as an official policy. And, recently, based on the revised special Law and revised governmental Basic Program on the Seto Inland Sea, every local government of prefectures around the Seto Inland Sea revised the environmental management plan at the prefecture level by the end of 2016. This new management plan at each prefecture level reflected the shift toward the *Satoumi* concept directly and will promote *Satoumi* activities. The above mentioned *Satoumi* policy of Kagawa prefecture was incorporated into the revised prefecture plan. This kind of enhanced policy will promote local activities for the creation of *Satoumi* elsewhere in the near future.

Future Direction under New Policy

The conceptual view on future directions of environmental management in the Seto Inland Sea is presented in **Fig.5**. In this figure, past, present and future environmental conditions are indicated on an X-Y axis. The horizontal axis shows natural environmental conditions, such as habitat condition, and the vertical axis shows water quality. Recent shifts mean that not only is improvement of water quality needed but also more active conservation, such as restoration of deteriorated habitat and promotion of *Satoumi* activities, are necessary.

This shift of management policy may help local sea areas to realize smooth material circulation and rich ecosystems.

In close relation to *Satoumi*, ecosystem-based management (EBM), community-based management (CBM) and ICM are also very important concepts for coastal management in the near future. Since *Sato* means community and *Satoumi* also focuses on the relationship between humans and nature, *Satoumi* can be a type of diversified CBM. *Satoumi* is also focusing on biological diversity and biological productivity. Therefore, *Satoumi* can be a part of EBM. Besides, combination of *Satoyama* and *Satoumi* can be a type of ICM, including both land and sea. Similarities and differences among *Satoumi*, CBM, EBM and ICM should be made clearer and easier to understand in the near future.

The next possible step of coastal management under the new policy might be as follows. Integration of science into management decisions and managing habitats through application of biological information from all available data sources is necessary. Recognizing the importance of ecological networks from forests and rivers to the sea, including the human dimension, is also necessary. A comprehensive management of the material flow from hilltop to the coastal environment is essential for successful costal management. Managing coastal habitats by participatory activities of people, based on increasing public awareness, adopting appropriate legislation and enforcement, is also essential. Coordination across sectors to improve governance and efficiency and addressing trans-boundary issues are most important in the future of coastal management. In order to restore once lost rich and healthy coastal seas in deteriorated areas, *Satoumi* can play a role in active conservation measures to restore deteriorated ecosystems. Valuable coastal areas, such as tidal flats and sea grass beds, which were already lost by land development, were historically a kind of commons or shared space for people. And, therefore, to take back these kinds of common spaces for people is also an important role of *Satoumi* in the future.

Annotated bibliography

(1) Matsuda O., 2008: Eutrophication and its Cause/Consequence: The Case of the Seto Inland Sea, in "Asia-Pacific Coasts and Their Management" (ed. by Mimura N.), Springer, The Netherlands, pp. 78-92.

This is a case study on the management of the eutrophic Seto Inland Sea.

(2) Secretariat of the Convention on Biological Diversity (CBD) (2011), Biological and Cultural Diversity in Coastal Communities – Exploring the Potential of *Satoumi* for Implementing the Ecosystem Approach in the Japanese Archipelago, CBD Technical Series No. 61, Montreal, 118pp.

This volume provides relevance of *Satoumi* to biodiversity issue and case studies of *Satoumi* activities from Hokkaido northernmost area to Okinawa southernmost area of Japan.

(3) Okaichi T. and Yanagi T. (ed.) ,1997: Sustainable Development in the Seto Inland Sea Japan-From the Viewpoint of Fisheries, Tera Scientific Publishing Company, Tokyo, 329pp.

This book provides valuable information on the Seto Inland Sea until 1990s.

(4) Stickney R. R. and McVey, J. P. (ed.) ,2002: Responsible Marine Aquaculture, CABI Publishing, Maryland, 391pp.

This is a milestone work on the development of sustainable and responsible marine aquaculture.

(5) Okaichi, T. (ed.) ,2003: Red Tides, Tera Scientific Publishing Company, Tokyo, 439pp.

This book provides comprehensive aspects of red tides such as phenomena, organism, ecological problems, environmental relevance and mechanism of outbreaks.

(6) Yanagi T., 2007: Sato-Umi: A New Concept for Coastal Sea Management, Terra Scientific Publishing Company, Tokyo, 94pp.

This book was written by the first proposer of the concept of Sato-Umi (*Satoumi*).

(7) Matsuda O., 2012: Western Japan cluster: Seto Inland Sea as *Satoumi*, in "*Satoyama-Satoumi* Ecosystems and Human Well-Beings" (ed. by Duraiappah A. K., Nakamura K., Takeuchi K.,

Watanabe M., and Nishi M.), United Nations University Press, Tokyo, pp. 381-402.

This is a comprehensive reference of the Seto Inland Sea and also a part of the result of Sub-Global Assessment on Japanese Satoyama and *Satoumi*.

(8) Matsuda O., 2012: Combining Activities of *Sato-Umi* and *Sato-Yama* in Japan: Towards a New Type of Integrated Coastal and Watershed Management, in "The Dilemma of Boundaries-Toward a New Concept of Catchment" (ed. by Taniguchi M. and Shiraiwa T.), Springer, The Netherland, pp. 221-234.

This paper describes the possibility of integrated coastal management by connecting *Sato-Umi* and *Sato-Yama*.

(9) Berque J. and Matsuda O., 2013: Coastal Biodiversity Management in Japanese *Satoumi*. *Mar. Pol.*, **39**, 191-200.

This paper refers to relevance of *Satoumi* to biodiversity management.

(10) Matsuda O., 2014: Predicting and promoting the future state of coastal seas with special emphasis on *Satoumi*, in "Connectivity of Hills, Humans and Oceans, Challenge to Improvement of Watershed and Coastal Environments" (ed. by Shimizu N., Tateno R., Kasai A., Mukai H., and Yamashita H.), Kyoto University Press, Kyoto, pp.209-221.

Some aspects of future perspective of *Satoumi* were described in this paper.

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Marine aquaculture's role in providing nutritional security in a changing environment

Michael B. RUST*

Abstract: The world produces less than 2 % of its food, fiber and biofuel from the sea despite the fact that oceans cover 70 % of the earth and receive 70 % of its solar energy. Instead we use 70 % of available freshwater and 40 % of our land through agriculture to feed and clothe ourselves. Future world food security plans developed by governments and international agencies often focus mainly on improving agriculture with an occasional nod toward fisheries, but rarely consider what aquaculture, especially marine aquaculture could provide. Marine aquaculture represents a food production approach that uses less freshwater, feed and land resources than agriculture, is more energy efficient and emits fewer greenhouse gasses than agriculture. In addition, marine aquaculture is relatively buffered from some aspects of climate change. For example, marine aquaculture does not suffer from droughts or floods, and is buffered from extreme storm events and temperature changes. Properly sited and managed, marine aquaculture can provide ecosystem services that help wild stocks persist under changing environmental conditions. Finally, the nutritional quality of aquaculture products is high relative to terrestrial products, increasing the nutritional quality of the diet for society. Marine aquaculture needs to articulate the advantages it represents to world nutritional security so discussions and planning for future food security under a changing climate can be informed.

Key words: N/A

Annotated bibliography

(1) U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015 – 2020 Dietary Guidelines for Americans, 8th Edition, December 2015. Available at https://health.gov/dietaryguidelines/2015/guidelines/.

Every five years the US government reviews current nutritional research and analyzes US food consumption patterns to develop guidelines. Seafood is chronically under consumed by all age groups and both sexes. This has real impacts on human health and results in increased heart disease, stroke and dementia in the US population. Americans consume about half of what is recommended for optimal human health.

(2) Forster J. and Radulovich R., 2015: Chapter 11 - Seaweed and food security, in "Seaweed Sustainability" (ed. by Tiwari B. K. and Declan J. T.), Academic Press, San Diego, pp. 289-313.

Makes the case for a marine agronomy based on seaweeds analogous to terrestrial agronomy that currently provides the majority of our food and fiber.

(3) Hall S. J., Delaporte A., Phillips M. J., Beveridge M., and O'Keefe M., 2011: Blue Frontiers: Managing the Environmental Costs of Aquaculture, The WorldFish Center, Penang, Malaysia.

Provides a comparison between aquaculture and terrestrial production from an environmental perspective.

2018年８月31日受理（Accepted on August 31, 2018）
* NOAA Office of Aquaculture, 1315 East-West Highway, Silver Spring MD. 20910, U. S. A.
E-mail: mike.rust@noaa.gov

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An overview of NOAA grants on aquaculture and the environment

Shiyu Rachel WANG*

Abstract: NOAA funds extramural research on aquaculture and environmental change through three major competitive grants: Small Business Innovation Research (SBIR) Program, Saltonstall-Kennedy (SK) Grant Program and Sea Grant Program. From 2002 to 2016, NOAA has spent $9.2 million U.S. dollars on research projects focus on the interactions between aquaculture and the environment, with $6.5 million federal funds and $2.7 million matching funds. Annual spending fluctuated with a maximum of $1.3 million in 2005 and a minimum of $0.14 million USD in 2002 and zero spending in 2009. Out of the three major funding programs, Sea Grant funded 75 % of the entire spending. A total of 43 projects on aquaculture and related topics including nutrient removal, carbon fixation, ocean acidification, waste treatment and related topics were completed. Analysis of the impact of these projects is planned. An understanding of NOAA's spending can help identify research gaps, evaluate impact, inform policy and allocate budget related to aquaculture in a changing environment.

Key words: N/A

Annotated bibliography

(1) Love D. C., Gorski I., and Fry J. P., 2017: An Analysis of Nearly One Billion Dollars of Aquaculture Grants Made by the US Federal Government from 1990 to 2015. *J. World Aquac. Soc.*, **48(5)**, 689-710.

The authors conducted a study on U.S. federal spending for aquaculture by tracking 2957 federal research grants awarded through different agencies from 1990 to 2015. For the past quarter century, 1.04 billion US dollars were spent on aquaculture research with about 90 % of federal funds and 10 % matching funds. Aquaculture production sciences received the most funding (27 %) out of 13 major disciplines in aquaculture, followed by aquatic animal health and disease (17 %). Environment related aquaculture topics including water and waste management and environmental interactions received 7 % of the total federal funding across all related agencies. Comparing the U.S. domestic aquaculture production with the federal spending, the authors concluded a 37-fold return in federal government investments in aquaculture since 2000. This study can be used as a framework to track and assess federal agencies' spending on different topics of aquaculture, identify research gaps and inform policy making and grant allocation.

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* NOAA Headquarters, Office of Aquaculture,1315 East-West Highway, Silver Spring MD. U. S. A. 20910
E-mail: shiyu.wang@noaa.gov

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Oligotrophication and its measures in the Seto Inland Sea, Japan

Katsuyuki ABO[*1] and Tamiji YAMAMOTO[*2]

Abstract: The Seto Inland Sea experienced eutrophication during the period of high economic growth and then subsequent oligotrophication due to reduction of inflow load. The nutrient concentration in the seawater peaked in the beginning of 1970's, and thereafter, it has been decreasing. Dissolved inorganic nitrogen (DIN) has remarkably decreased in recent years following the decrease in dissolved inorganic phosphorus (DIP). As a result, Nori (*Pyropia*) production has decreased in recent years due to bleaching of leaves caused by DIN deficiency. Recent slack in fisheries production was also likely influenced by the nutrient depletion as evidenced by the fish catch using a compact trawl. The process of both eutrophication and oligotrophication that occurred in the Seto Inland Sea can be explained by hysteresis. We introduce several countermeasures to the oligotrophication in the Seto Inland Sea. In particular, to improve Nori production, local nutrient supply was experimentally augmented, such as by application of fertilizer, temporary discharge of dam water, sediment plowing, and ad hoc operations of relaxing sewage treatment water.

Key words: fisheries production, nutrient, oligotrophication, Seto Inland Sea

Introduction

The Seto Inland Sea had been known as a beautiful and bountiful sea with a rich ecosystem. However, during the period of high economic growth, eutrophication progressed, and fishery damage caused by harmful algal blooms became frequent. Since the Interim Measures Law concerning Conservation of the Environment of the Seto Inland Sea (later the Special Measures Law) was enacted in 1973, the water quality of the Seto Inland Sea has improved by a series of measures such as reduction of inflow load. On the other hand, oligotrophication has become a problem in recent years (Yamamoto, 2003), and it caused a decrease in Nori (*Pyropia*) production due to bleaching of leaves because of nutrient depletion (Murayama *et al*., 2015; Tada *et al*., 2010). In addition, it is also pointed out that the decrease in fisheries production, such as small pelagic fish and demersal fish, is related to nutrient reduction (Tanda and Harada, 2012). Here, we describe the changes in and current situation of water quality in the Seto Inland Sea and discuss the influence of load reduction on the lower trophic ecosystem and fishery production. We also introduce nutrient supply methods, which were experimentally conducted as countermeasures for bleaching Nori.

Variation of water quality

Fisheries research institutions surrounding the Seto Inland Sea have been monitoring the monthly water quality since 1973. The monitoring has been carried out using similar methods over time, and it can elucidate the process of cultural oligotrophication in the Seto Inland Sea. **Fig.1** shows the variations of annual averaged concentrations of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) in the surface layer of the Seto Inland Sea. The DIN concentration was extremely high in the 1970s, decreased sharply in the 1980s, and then remained flat. After that, it decreased again in the latter half of

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*1 National Research Institute of Fisheries and Environment of Inland Sea, Fisheries Research and Education Agency, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*2 Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8528, Japan
abo@fra.affrc.go.jp

the 1990s and remains at low levels in recent years. According to the pollutant discharge loads in the Seto Inland Sea (**Fig.2**), the load of chemical oxygen demand (COD) sharply decreased in the latter half of the 1970s, and the load of total nitrogen (TN) decreased after the latter half of the 1990s, which is in good agreement with the decreasing period of the DIN concentration. On the other hand, the DIP concentration remained flat after decreasing until the early 1980s. The load of total phosphorus (TP) has sharply decreased in the first half of the 1980s following reduction of the load of COD in the latter half of the 1970s, which is consistent with the decreasing DIP concentration. However, there was no decrease in DIP concentration corresponding to the TP load reduction in the early 2000s.

Regarding water quality in each sub-area (**Fig.3**), DIN started to decrease in the 1980s in the western part, then it tended to decrease in the 1990s in the eastern and central parts of the Seto Inland Sea. The decreasing rate of DIN concentration in the surface layer of each sub-area was 0.16 to 0.26 μM per year, but it was largest in the eastern part, Osaka Bay and Harima Nada (Abo *et al.*, 2018). On the other hand, the DIP concentration had no large variation over the entire Seto Inland Sea, but the molar ratio of DIN and DIP has changed from 16 - 17 to 8 - 10 in the past 30 years, i.e., it has changed from a value close to the Redfield ratio to nitrogen deficiency (Tanda *et al.*, 2014).

Variation of fisheries production

Recently, fisheries production in the Seto Inland Sea has been stagnant. Especially for Nori (*Pyropia*) culture, the influence of nutrient deficiency due to cultural oligotrophication is crucial to production. The annual production of Nori in the Seto Inland Sea increased in 1970s due to the maturation of the aquaculture technology and reached 4 billion sheets in the 1980s. In the 1990s, it remained at more than 3.5 billion sheets. However, it decreased sharply in the 2000s and has been around 2 billion sheets in recent years (**Fig.4**). The sharp decrease in the Nori production after 2000 coincided with the decrease in DIN concentration mentioned above. Since the late 1990s, bleaching of Nori leaves caused by nitrogen

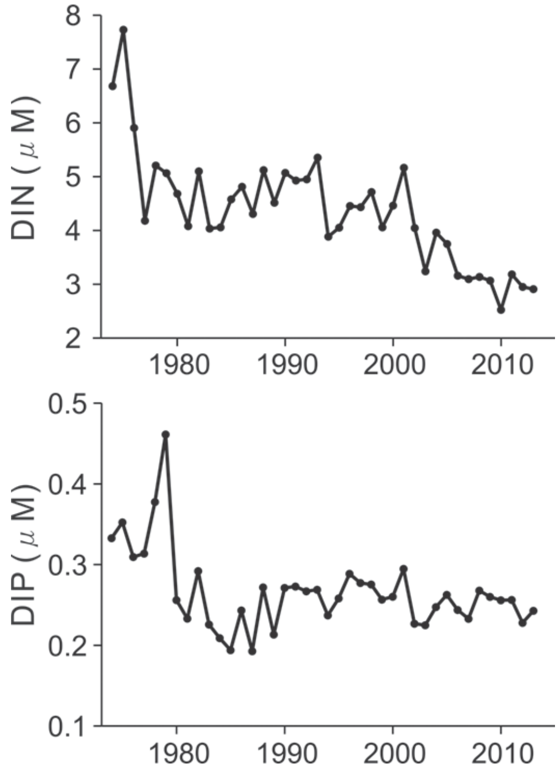

Fig. 1. Temporal variations in annual averaged concentration of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) in the surface layer of the Seto Inland Sea, Japan.

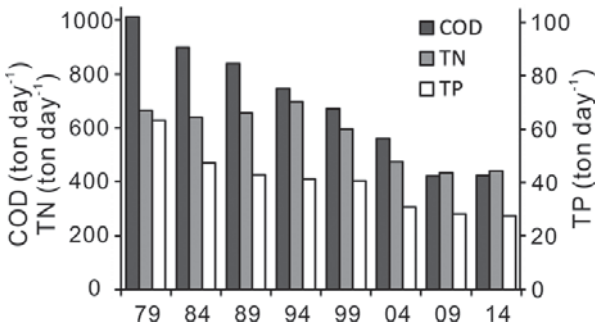

Fig. 2. Five-year changes in the generated loads of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) flowing into the Seto Inland Sea, Japan.

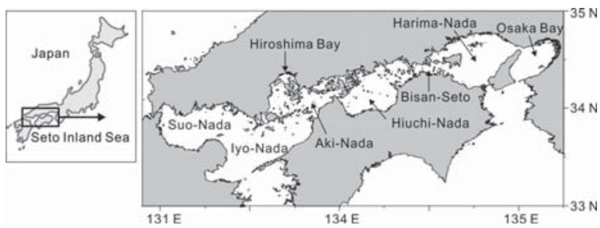

Fig. 3. Map of the Seto Inland Sea and sub-areas.

depletion occurred frequently. The bleaching of Nori leaves is said to occur at DIN concentrations of 3 μM or less in the eastern part of the Seto Inland Sea (Murayama *et al.*, 2015). DIN deficiency is the main cause of the recent decrease of Nori production, but global warming may also cause a decrease in Nori production because water temperature rise could have shortened the culture period.

The fish catch of the Seto Inland Sea peaked in the beginning of the 1980s, but the catch in 2014 was less than 160,000 tons, which is one third of the peak production (**Fig.5**). The cause of the catch decline is not clear. Although land reclamation during the rapid economic growth period in Japan and overfishing could be responsible for the decrease in fish catch, oligotrophication is pointed out as a decisive factor in the decrease in fishery production. Tanda and Harada (2012) revealed that fluctuations in catch of sand lance *Ammodytes personatus* in Harima-Nada in the eastern part of Seto Inland Sea synchronized with fluctuations in the DIN concentration, with 2-3 years lag. There was also a tight relationship between 0-year-old sand lance and DIN concentration. From these analyses, they concluded that nutrient depletion affected early survival and growth of sand lance larva. Tarutani and Nakajima (2011) showed the correlation between pollutant discharge load and the catch of demersal fish and shellfish in Osaka Bay. They also suggested bottom-up material flow may play a role in recent decreases in fisheries production in Harima-Nada.

As for Nori, which requires nutrients for growth, reduction of nutrient load directly contributes to the decrease in production. As coastal ecosystems are largely affected by various human disturbances (Jackson *et. al*, 2001), it is important to clarify the processes occurring in the ecosystem scientifically.

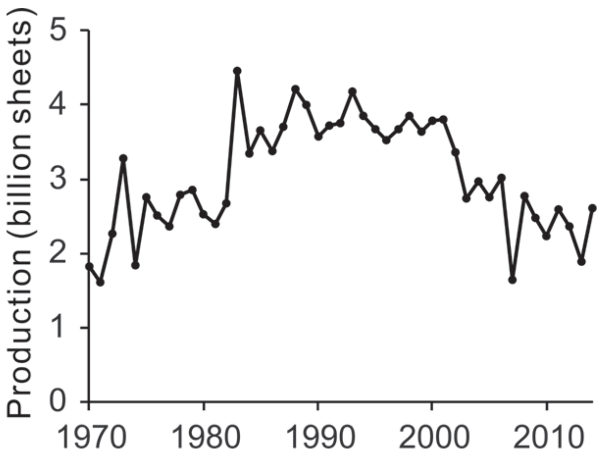

Fig. 4. Annual variation of Nori (*Pyropia*) production in the Seto Inland Sea, Japan.

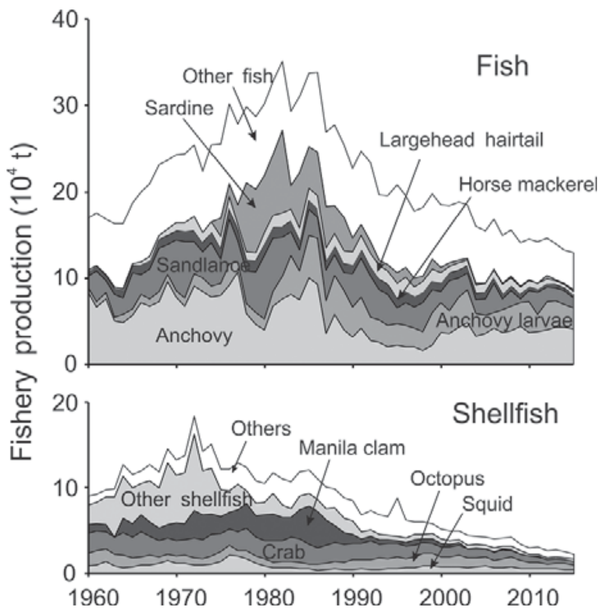

Fig. 5. Annual variations of fish catch (upper) and shellfish production (lower) in the Seto Inland Sea, Japan.

Processes of eutrophication and oligotrophication

Along with the eutrophication and oligotrophication that occurred in the Seto Inland Sea, hysteresis was observed (Yamamoto, 2015). The pattern of increased fisheries production during eutrophication was different from that during oligotrophication (**Fig.6**). Although fisheries production should return to the original position at the end of oligotrophication process, as mentioned theoretically by Scheffer (1989), fisheries production in the Seto Inland Sea did not return to the original position; it decreased to a much lower level (**Fig.6**). Ecosystem structure might have changed or overfishing may be a cause. The cause of this issue is still under debate and remains to be solved.

Practical measures against oligotrophication

In the Seto Inland Sea, experimental attempts to supply nutrients to fishing grounds have been made as a measure against the oligotrophication. Especially to prevent the bleaching of Nori laver, fertilizer application, temporary discharge of dam water, relaxing discharge of sewage treatment water, etc., were carried out. A fundamental issue that is common to these techniques is the diffusion feature of seawater in the sea. Once we apply one of these techniques, added nutrient is diluted in a short time. For example, relaxing the discharge of sewage treatment water has been conducted to increase DIN concentration in the treated water to the allowable levels by suppressing denitrification and/or nitrification processes, with restriction during the winter Nori growing season. Evaluation by numerical simulation reproduced the dispersion pattern of a high nutrient water mass to the Nori cultivation area, which was monitored by field observations (Abo *et al*., 2012; Harada *et al*., 2018).

In order to sustain fisheries production in the oligotrophic Seto Inland Sea, effective measures may be different in each sub-area because of differences in terms of geography, oceanography, fisheries activity, and other social backgrounds. Even in the totally oligotrophic state it is in, oxygen depletion in the bottom water and/or harmful algal blooms occur in some sub-areas. Therefore, different measures applicable to each different sub-area are required. Furthermore, ideal water quality could be different among various stakeholders; some might desire higher water transparency, while others might desire high fisheries production. We, therefore, need an organization or council with various stakeholders representing different standpoints in each sub-area.

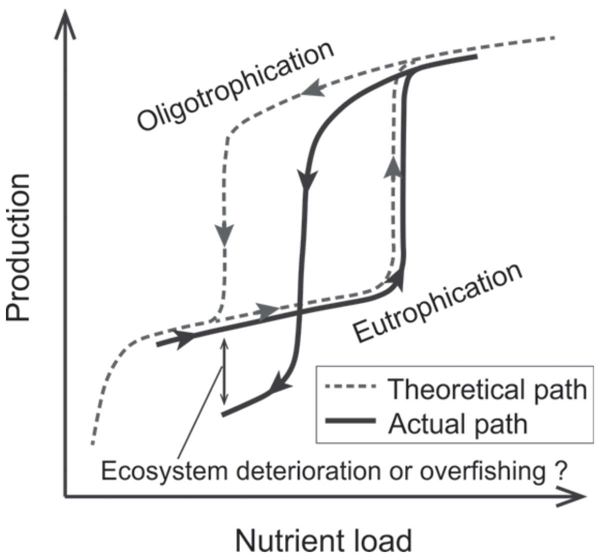

Fig. 6. The theoretical path and the actual path observed in the Seto Inland Sea as an example of hysteresis.

References

Abo K., Akiyama S., Harada K., Nakaji Y., Hayashi H., Murata K., Wanishi A., Ishikawa Y., Masui T., Nishikawa S., Yamada K., Noda M., and Tokumitsu S., 2018: Long-term variations in water quality and causal factors in the Seto Inland Sea, Japan. *Bull. Coast. Oceanogr.*, **55**, 101-111. (in Japanese with English abstract)

Abo K., Tarutani K., Harada K., Miyahara K., Nakayama A., and Yagi H., 2012: Effects of nutrient discharge on Nori aquaculture area in Kako River estuary. *J. JSCE, Ser.B2, Coast. Eng.*, **68 (2)**, I_1116-I_1120.

Harada K., Abo K., Kawasaki S., Takesako F., and Miyahara K., 2018: Influence of DIN derived from ports and treated sewage effluent on nori (*Pyropia*) farms of the northeastern part of Harima Nada. *Bull. Jpn. Soc. Fish. Oceanogr.*, **82**, 26. (in Japanese with English abstract)

Jackson J. B. C., Kirby M. X., Berger W. H., Bjorndal K. A., Botsford L. W., Bourque B. J., Bradbury R. H., Cooke R., Erlandson J., Estes J. A., Hughes T. P., Kidwell S., Lange C. B., Lenihan H. S., Pandolfi J. M., Peterson C. H., Steneck R. S., Tegner M. J., and Warner R. R., 2001: Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*, **293(5530)**, 629-637.

Murayama F., Shimizu Y., and Takagi S., 2015: The relationships between nutrient concentration in the coastal area of Okayama prefecture, the color tone of fresh thalli (*Pyropia*) and the unit price of dried nori. *Nippon Suisan Gakkaishi,* **81**, 107-114. (in Japanese with English abstract)

Scheffer M., 1989: Alternative stable states in eutrophic, shallow fresh water systems: A minimal model. *Hydrobiol. Bull.*, **23**, 73-83.

Tada K., Fujiwara M., and Honjo T., 2010: Water quality and nori (*Porphyra*) culture in the Seto Inland Sea. *Bunseki Kagaku,* **59**, 945-955. (in Japanese with English abstract)

Tanda M., Akashige S., Ariyama H., Yamanoi H., Kimura H., Dan H., Sakamoto H., Saiki Y., Ishida Y., Kotobuki H., and Yamada T., 2014: Nutrient environment and fisheries in the Seto Inland Sea. *Journal of Fisheries Technology*, **7**, 37-46. (in Japanese with English abstract)

Tanda M. and Harada K., 2012: Nutrient environment and Fishery Production in Harima-nada, Eastern Seto Inland Sea, Japan. *Aquabiology*, **34**, 132-141. (in Japanese with English abstract)

Tarutani K. and Nakajima M., 2011: Effect of nutrient reduction on fisheries resources in enclosed sea waters. *J. Jpn. Soc. Water Env.*, **34(A)**, 47-50. (in Japanese)

Yamamoto T., 2003: The Seto Inland Sea- Eutrophic or oligotrophic?. *Mar. Pollut. Bull.*, **47**, 37-42.

Yamamoto T., 2015: Cultural oligotrophication in the Seto Inland Sea, in “Oligotrophication in inland and sea waters” (ed. by Yamamoto T. and Hanazato T.), Chijinshokan, Tokyo, pp. 55-87. (in Japanese)

Annotated Bibliography

(1) Abo K., Akiyama S., Harada K., Nakaji Y., Hayashi H., Murata K., Wanishi A., Ishikawa Y., Masui T., Nishikawa S., Yamada K., Noda M., and Tokumitsu S., (accepted): Long-term variations in water quality and causal factors in the Seto Inland Sea, Japan. *Bull. Coast. Oceanogr.*, **55**.

The long-term variations in water quality in the Seto Inland Sea were investigated based on the routine observation data of the local fisheries experimental stations. The water temperature increased due to the global warming and the nutrient decreased due to oligotrophication. The reduction of DIN and DIP concentrations were largely affected by land load reduction.

(2) Abo K., Tarutani K., Harada K., Miyahara K., Nakayama A., and Yagi H., 2012: Effects of nutrient discharge on Nori aquaculture area in Kako River estuary. *J. JSCE, Ser.B2, Coast. Eng.*, **68 (2)**, I_1116-I_1120.

Effects of nutrient discharge on Nori aquaculture area were investigated. The Nori production in the winter season were sustained by nutrient discharge from the river, sewage treatment plant and industrial effluent. A numerical simulation evaluated the effects of nutrient control operation of the sewage treatment plant on the nutrient environments of the aquaculture area.

(3) Yamamoto T., 2002: The Seto Inland Sea–eutrophic or oligotrophic?. *Mar. Pollut. Bull.*, **47**, 37-42.

This was the first study showing the Seto Inland Sea was in the state of ‘cultural oligotrophication’ caused by the reduction of nutrient loading. This study indicated that the measures to reduce phosphorus had caused a change in phytoplankton species composition, thereby altering the food web structure, suggesting that this might be the major cause of the reduction of fishery production.

(4) Yamamoto T. and Hatta G., 2004: Pulsed nutrient supply as a factor inducing phytoplankton diversity. *Ecol. Model.*, **171**, 247-270.

A numerical model was constructed to elucidate whether phytoplankton species diversity could be increased by an environmental fluctuation such as a pulsed nutrient supply. Diatom showed large fluctuations in cell density in response to pulses of nutrients, while dinoflagellate showed preference for continuous nutrient supply mode. Dam construction, which is one of the causes of oligotrophication, usually flattens variability in the freshwater discharge, hence lead to dinoflagellate dominancy.

(5) Yamamoto T., Tateno S., Hata K., Mizushima K., Goda Y., Takahashi S., Tarutani K., Saito H., and Tanimoto T., 2017: Designing an effective action plan for sustainable local resources and the coastal environment: A case study of Mitsu Bay, Hiroshima, Japan. Proceedings of International Conference "Managing risks to coastal regions and communities in a changing world" (EMECS'11 - SeaCoasts XXVI, St. Petersburg, 22-27.08.2016). Moscow, RIOR Publ., ISBN978-5-369-01628-2, DOI: 10.21610/

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This study proposed measures for sustainable fishery production in an oligotrophic bay (Mitsu Bay). Water quality was extremely good (oligotrophic), therefore improvement of sediment quality was necessary. As oyster cultivation was popular in this bay, improvement of sediment quality using oyster shells could contribute to the formation of a recycling-oriented society.

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Assessment and future prediction of climate change impacts on the macroalgal bed ecosystem and cultivation in the Seto Inland Sea

Goro YOSHIDA[*1], Hiromori SHIMABUKURO[*1], Setuo KIYOMOTO[*2], Tatsuru KADOTA[*2], Taku YOSHIMURA[*2], Noboru MURASE[*3], Mikio NODA[*3], Shoichi TAKENAKA[*4], Yoshimi KONO[*4], Toshiharu TAMURA[*5], Norio TANADA[*6], Xiaojie YU[*7], Naoki YOSHIE[*7], and Xinyu GUO[*7]

Abstract: Macroalgal bed ecosystems are an important platform for coastal biological production and fisheries. After the late 1990s, rapid decline or disappearance of macroalgal beds, generally called *Iso-yake*, has been spreading along the coast of western Japan where there is an influence of warm ocean currents. This phenomenon has been occurring with an increasing trend in water temperature in recent decades and is considered to be an impact of the climate change.

The Seto Inland Sea is the largest semi-enclosed sea area in Japan, and macroalgal beds in the area are still intact with no prominent sign of *Iso-yake*. However, water temperature in the Seto Inland Sea has also been increasing for a few decades, and according to climate change scenarios, negative impacts to macroalgal beds and their ecological functions are possible in the future in the area. Against this background of concern, we conducted research on the assessment and future prediction of climate change impacts on the macroalgal bed ecosystem in the Seto Inland Sea and associated sea areas. The research consisted of 1) field monitoring of macroalgal beds and associated spatio-temporal variation in water temperature, including along the coast of Kyushu (Nagasaki) where loss or changes of macroalgal beds has created a large social problem; 2) experiments on physiology and behavior of key species in macroalgal bed ecosystems (macroalgae and herbivorous fish) with respect to temperature and other conditions to understand the mechanisms of the ecosystem shift; 3) construction of an original physical model to reproduce past temperatures in the environment and predict future ones in the applicable ocean areas; and 4) interpreting the impact of future water temperature conditions predicted by the model on macroalgal beds. In addition, impacts on macroalgal cultivation, which is an important industry in the Seto Inland Sea, were also assessed. In this paper, some of the main results and conclusions are introduced.

Key words: macroalgal bed, macroalgal cultivation, climate change, Seto Inland Sea

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[*1] National Research Institute of Fisheries and Environment of Inland Sea, Japan Fisheries Research and Education Agency, 2-17-5 Maruisihi, Hatsukaichi, Hiroshima 739-0452, Japan
[*2] Seikai National Fisheries Research Institute, Japan Fisheries Research and Education Agency, Taira-machi, Nagasaki, Nagasaki 851-2213, Japan
[*3] National Fisheries University, Japan Fisheries Research and Education Agency, Nagata-honmachi, Shimonoseki, Yamaguchi 759-6595, Japan
[*4] Fisheries Research Center, Ehime Research Institute of Agriculture, Forestry and Fisheries, Shitaba, Uwajima, Ehime 798-0104, Japan
[*5] Ehime Prefectural Government, Ichibancho, Matsuyama, Ehime 790-8570, Japan
[*6] Fisheries Research Division, Tokushima Prefectural Agriculture, Forestry and Fisheries Technology Support Center, Minami-cho, Kaifu-gun, Tokushima 779-2304, Japan
[*7] Center for Marine Environmental Studies, Ehime University, Bunkyo-cho, Matsuyama, Ehime 790-8577, Japan
E-mail: gorogoro@affrc.go.jp

Introduction

Macroalgal bed ecosystems offer various ecosystem services, which substantially contribute to human welfare. Among the services provided by the macroalgal beds, their contributions as nursery grounds, habitats and actual fishery grounds of commercially important fishes and shellfishes are significantly important in Japan.

However, rapid disappearance of macroalgal beds and subsequent desertification of the seafloor, which is a phenomenon generally called '*Iso-yake*', has been spreading along the Japanese coast (Fisheries Agency, 2007). In particular, along the coast of western Japan (that is, central Honshu, Shikoku and Kyushu coastal areas facing the Pacific Ocean and East China Sea), where the warm currents *Kuroshio* and *Tsushima-danryu* flow offshore, nearly 20 % of the macroalgal beds have already been lost since the early 1990s when a nationwide research of macroalgal bed distribution was conducted (Akimoto and Matsumura, 2010). Most of the lost beds were constituted by warm-temperate kelp, mainly macroalgae belonging to the genus *Ecklonia*, and macroalgae belonging to Family Sargassaceae, which were the most important foundation species along temperate rocky shores in Japan. As a result, production of fisheries resources that rely on these beds (such as abalones) has been decreasing tremendously in those regions (Serisawa *et al*., 2004).

Increasing coastal water temperatures over several recent decades and an increase in browsing of herbivorous animals (fishes and invertebrates like sea urchins) on macroalgae associated with the temperature rise are considered direct factors in the *Iso-yake* occurrence (Fisheries Agency, 2007). In addition, in some areas in western Japan, sub-tropical macroalgae and corals expand their distribution as the 'original' macroalgal beds decline (Tanaka *et al*., 2012). Ocean area along Kuroshio is one of the hot-spots showing a much larger increase in surface seawater temperature than the global mean, and temperate coastal ecosystems in the 'hot-spots', which also includes the Australian coasts, eastern coastal area of South America, etc., have been suffering from `tropicalization' (Vergés *et al*., 2014).

The Seto Inland Sea is the largest semi-enclosed sea area in Japan, situated between western Honshu and Shikoku Islands and connected with the Pacific Ocean via the Bungo and Kii Channels. In contrast with the drastic change in the macroalgal beds along the Shikoku and Kyushyu areas being affected by the warm currents, macroalgal beds in the Seto Inland Sea have remained productive and still contribute to the coastal fisheries, which are important industries in this region (Yoshida *et al*., 2011). This is attributable to the special environmental characteristics of the Seto Inland Sea, which experiences little direct effects of the Kuroshio and maintains lower water temperature conditions than those of the Pacific coastal regions.

However, water temperature in the Seto Inland Sea is also showing an increasing trend (+0.11 ~ 0.33 ℃/ 10 y at surface, National Research Institute of Fisheries and Environment of Inland Sea, 2015). If it continues to increase according to the present scenarios of climate change, macroalgal beds in the Seto Inland Sea are also feared to be greatly diminished and fisheries relying on these macroalgal beds will be seriously damaged (Yoshida, 2018).

In addition to the importance of fisheries, macroalgal cultivation, such as for *nori* (laver, *Pyropia* spp.) and *wakame* (sea mustard, *Undaria pinnatifida*), is also an important industry in the Seto Inland Sea. Macroalgal cultivation occupies over 20 % of the total production value (131 billion yens in 2012) of fisheries and aquaculture of the Seto Inland Sea. However, increases in water temperature can also have a great impact on the cultivation because these macroalgae are so sensitive to higher temperature conditions.

United against these future fears, we joined the research project by Ministry of Agriculture, Forestry and Fisheries named "Technology development for circulatory food production systems responsive to climate change" (2013-2017) and conducted research on predicting climate change impacts on macroalgal bed ecosystems and cultivation in the Seto Inland Sea and its connecting waters. The research consisted of 1) field monitoring of macroalgal beds and associated spatio-temporal variation in water temperature, including along the coast of Kyushu (Nagasaki) where loss or changes of macroalgal beds has created a large social problem; 2) experiments on physiology and behavior of key species in macroalgal bed ecosystems (macroalgae and herbivorous fish) with respect to temperature and other conditions to understand the mechanisms of the ecosystem shift; 3) construction of an original physical model to reproduce past temperatures in the environment and predict future ones in the applicable ocean areas; 4) interpreting the impact of future water temperature conditions predicted by the model on macroalgal beds; and 5) macroalgal cultivation. In this paper, we introduce the outline of our research and show some of the main results and conclusions.

Outline of the research

Field monitoring and surveys of macroalgal beds along spatio-temporal environmental gradients in western Japan

To find any specific relationship between change of macroalgal beds and the environment, including water temperature conditions, we have been conducting field monitoring and surveys in two areas in western Japan.

One area is along the coast of Nagasaki Prefecture (north-western Kyushu) where *Iso-yake* has been a serious social problem since the late 1990s. The monitoring was begun in 1998 when drastic changes in macroalgal beds were first observed. Beds of a warm temperate kelp *Ecklonia kurome* were greatly damaged by browsing of herbivorous fish, such as *Siganus fuscescens*, *Calotomus japonicus* and *Kyphosus bigibbus*, along the coast of Nomo-Zaki, Nagasaki Peninsula. Extremely high summer water temperatures seriously damaged the kelp in 2004 and 2008, and in combination with heavy browsing, kelp beds completely disappeared in Nomo-Zaki until 2013. Sargassaceous plants, the other major member of rocky macroalgal beds, seemed to be more tolerant to high temperature than the kelp, but heavy browsing concentrated on *Sargassum* after the kelp disappearance. The number of *Sargassum* species in the beds has gradually decreased, and *S. macrocarpum* became the dominant species until 2011. However, this species also disappeared due to browsing and the effects of a typhoon soon after kelp had disappeared. After those large brown algae disappeared, only small undergrowth macroalgae, such as *Colpomenia sinuosa* and *Padina* spp., constituted the macroalgal beds. Similar situations were observed in many places in Nagasaki Prefecture, but expansion of corals and tropical *Sargassum* species were observed in some places after kelp and temperate *Sargassum* beds disappeared (Kiyomoto *et al*., 2018).

The other area of the survey was the western Seto Inland Sea and Bungo Channel, which connects the western Seto Inland Sea and Pacific Ocean. We set many survey stations along a geographical north to south transect from Hiroshima Bay in the Seto Inland Sea to southern Uwa Sea, which is an eastern part of the Bungo Channel, and conducted surveys on the macroalgal bed vegetation in 2013-14. Within this relatively small geographical area (ca. < 200 km in distance), there is a large surface water temperature gradient, especially during winter, in which the annual minimum temperature drops below 10 ℃ in Hiroshima Bay but never drops below 15 ℃ in the southern Uwa Sea (Yoshida *et al*., 2011). We found clear shifts in macroalgal vegetation along the temperature gradient in beds 1) composed of kelp + *Sargassum*, 2) composed of only *Sargassum*, 3) with no large brown algae but small undergrowth algae, and 4) with tropical *Sargassum* and some corals in the *Iso-yake* landscape (barren seafloor with crustose coralline algae) (Shimabukuro *et al*., 2018). Interestingly, this geographical shift in the vegetation was analogous to the temporal shift in vegetation observed in Nagasaki after the late 1990s.

These results indicated that there were discrete steps in the vegetative changes as macroalgal beds declined or turned into an *Iso-yake* situation, and water temperature increase was a strong driving factor of the change. The field monitoring and surveys also indicated that warm-temperate kelp was the most vulnerable to increasing seawater temperature.

In-house experiments on the effects of water temperature rise on key organisms in macroalgal bed ecosystems

Physiological vulnerability of kelp and *Sargassum* to high temperature conditions and behavioral characteristics of rabbit fish (*Siganus fuscescens*), which is one the major herbivorous fish, was examined by indoor experiments in our research (Murase and Noda, 2018). The experiments were also aimed at finding some threshold temperature conditions relating to the macroalgal bed ecosystem changes caused by physiological limits or the effects of browsing behavior.

High-temperature tolerance in *Ecklonia kurome*, which is a main kelp species in the Seto Inland Sea and Kyushu, was tested. Young sporophytes of *E. kurome* exhibited slight growth under 28 ℃, but under 29 ℃, the growth rate was negative and they were dead within 9 days of culture. It was reported that upper temperature limits for survival of the kelp *Ecklonia bicyclis*, one of the main temperate kelps in Japan, was also 29 ℃, so it is difficult for kelp beds in western Japan to be persistent when summer water temperatures exceed 29 ℃ for a relatively long period, a situation that has recently come to occur frequently. Sargassaceous plants are more tolerant to high temperature conditions, and upper limits of temperature for survival of main temperate species such as *S. patens* and *S. macrocarpum* are about 30-31 ℃. We also found that photosynthetic activity of *S. macrocarpum* never declined under 30 ℃, whereas that of *E. kurome* declined soon after being transferred to the experimental condition of 30 ℃.

Rabbitfish showed a preference of macroalgal species for browsing, but both kelp and Sargassaceous plants could be grazed by rabbitfish. However, the ability of grazed plants to regenerate was larger for Sargassaceous plants than kelps because some species of *Sargassum* are able to regenerate the basal part (holdfast or stem) of the plant (Yatsuya *et al*., 2012).

Rabbitfish grazed more under higher temperature. They grazed little under 20 ℃, and browsing almost stopped at 15 ℃. Browsing behavior was affected not only by temperature, but also the size of its school. More macroalgal tissue was grazed by an individual fish as the size of the school of the fish grew, although actual intake by the fish was getting smaller. That means a large amount of macroalgal tissue was wasted without being assimilated by fish and more grazed tissues were scattered on the seafloor when the school of the fish was large.

These results described recent drastic changes in macroalgal beds. Extremely high summer water temperature can cause large-scale decline of kelp beds. Though some kelp or *Sargassum* beds get over the catastrophic event, browsing of herbivorous fish concentrates on the remaining beds, which means the size of fish school attacking each bed becomes larger. The loss of macroalgae by browsing accelerates and the beds disappear rapidly. And, if damage is so large as to restrain macroalgal reproduction, the change proceeds irreversibly.

Construction of a physical model for numerical-simulation of the temperature environment in the Seto Inland Sea and *Kuroshio* coastal area – Reproduction of past temperature history and collation with current macroalgal bed distribution

To understand how current macroalgal bed distributions were determined by water temperature conditions and how they will change according to future climate change, we constructed an original *Kuroshio* - Seto Inland Sea hydrodynamic model in our project. The objective of the model is to reproduce and understand past interannual variations in water temperature, salinity and currents in the Seto Inland Sea and Kuroshio region, as well as to develop a tool for future prediction of these physical conditions in response to climate change.

The main characteristic of the model was a high resolution 1 km grid because macroalgal beds distributes very locally as a narrow belt along the coast, in general, and outputs of the model should exhibit the physical conditions corresponding to the distribution. Also, parameters corresponding to the effects of tide and river discharge were incorporated in the model as well as general ocean model parameters like heat fluxes and wind stress, etc., because these parameters can substantially affect the physical conditions of coastal areas, especially those in the Seto Inland Sea.

On the other hand, we illustrated current macroalgal bed distribution in the Seto Inland Sea and Kuroshio coastal region in western Japan on a GIS map. Nationwide research on macroalgal bed distribution in Japan was conducted in the early 1990s under the initiative of the Ministry of the Environment, but after that, no research on a nationwide scale has been conducted. However, loss of macroalgal beds due to spreading of *Iso-yake* has become prominent in various places since the late 1990's, and many local governments (prefectures) troubled with *Iso-yake* expansion have conducted their own original research on the status of macroalgal beds in their local areas (Akimoto and Matsumura, 2010). We referred to their reports for constructing the map of the current distribution from late 1990's to 2014. For some areas, we used the results of our field surveys described above (for Uwa Sea area of Ehime Prefecture) and the results of interviews.

Comparisons of macroalgal bed distribution in early 1990's and current distributions on the map indicated great losses of temperate macroalgal beds of kelp and *Sargassum* in areas directly exposed to the Pacific Ocean (e.g., Kochi and Miyazaki Prefecture). Along the coast of the Bungo and Kii Channels (Oita, Ehime and Tokushima Prefectures), the southern boundary of kelp bed distribution has shifted northward a few tens of kilometers during these approximately 20 years.

The current macroalgal bed distribution was overlayed with the outputs of surface water temperature (SST) conditions reproduced by the *Kuroshio*-Seto Inland Sea Physical Model (Shimabukuro *et al*., 2018), and it was determined what kind of SST outputs best fitted and most explained the macroalgal bed distribution. One clear result was shown in the distribution of kelp beds. The current distribution of kelp beds in the Seto Inland Sea and Bungo Channel was clearly within the area where the total days of SST < 15 ℃ (daily mean) was over 70 days / year (mean of 1993 - 2014). Under 15 ℃, activities of herbivorous fish almost stop even though kelp maintains its high productivity under that temperature condition (Yatsuya *et al*., 2014). Therefore, a duration of 70 days without herbivory is considered to be needed for persistent establishment of kelp beds.

Prediction of future water temperature conditions and macroalgal bed distributions in the Seto Inland Sea

Using the *Kuroshio* - Seto Inland Sea hydrodynamic model we constructed the future water temperature environment and macroalgal bed distributions reflecting that environment for the relevant sea areas. The prediction was based on the scenarios RCP 2.6 and RCP 8.5 in IPCC AR 5. The boundary condition of the outer region of the corresponding area of the model referred to the output of the atmospheric ocean coupled model MIROC 5 corresponding to AR 5 (by National Research Institute of Fisheries Science). Predictions were made for the decades of the 2050s and 2090s, respectively.

Under both RCP scenarios, surface water temperature increase is larger in the Seto Inland Sea area than in the coastal area facing the Pacific Ocean and in Bungo and Kii Channels. Also, water temperature increase from the current (2010s) was larger in winter than in summer in the Seto Inland Sea. In summary, under the RCP 8.5, a scenario of comparatively high greenhouse gas emissions, water temperature increases + 2 ~ 4 ℃ in the 2050s (mean of the 10 years, the same hereafter) and + 4 ~ 6 ℃ in the 2090s compared to the current temperatures both in winter and summer, though the degree of temperature increase is quite different locally among sea areas. Under RCP 2.6, in which measures against greenhouse gas emissions are the most effective, water temperature increases + 1 ~ 3 ℃ in the 2050s from current levels but its rise thereafter was predicted to be little up to the 2090s.

According to the prediction of future water temperature environment, the distribution of kelp beds in the Seto Inland Sea was also predicted (Shimabukuro *et al*., 2018). Two criteria were used for the prediction, including a warm condition criterion and a cool condition, which regulates the kelp distribution. For the cool condition criterion, kelp beds can be maintained at the places where the total days of SST < 15 ℃ (daily mean) is over 70 days / year, which was mentioned in the former section. For the warm condition criterion, kelp beds cannot be maintained when ambient daily mean SST reaches 29 ℃ over 6 consecutive days. This was the survival limit of the kelp *Ecklonia kurome* determined in the indoor experiment.

Applying these criteria on the predicted SST output of the model, future kelp bed distribution in the Seto Inland Sea was predicted. Kelp beds will remain only in Iyo-Nada and Aki-Nada sea areas in the 2050s and will completely disappear in the Seto Inland Sea by the 2090s under the RCP 8.5 scenario. On the contrary, under the RCP 2.6 scenario, in which future temperature rise will be moderate, most of the current kelp beds were predicted to remain into the 2090s.

Effect of climate change on macroalgal cultivation

As mentioned in Introduction, macroalgal cultivation, such as for *nori* (laver) and *wakame* (sea mustard), is an important regional industry in the Seto Inland Sea, but water temperature is extremely important as it is for natural macroalgal beds. "Seedlings" of *nori* and *wakame* are cultured in artificial tanks on land during the summer as a minute generation of conchocelis (*nori*) or gametophytes (*wakame*). As ambient water temperature decreases in autumn, juvenile thalli of *nori* or *wakame* begin to be cultured in the cultivation field. Ambient water temperature of 23 ℃ is recommended at the start of the culture, but the water temperature in autumn has been increasing in the last several decades in the Seto Inland Sea. As a result, suitable seasonal timing for the start of cultivation has been delayed by 10 to 20 days since the 1980s.

Recently, production in *wakame* cultivation has been affected by the changes in water temperature (Tanada, 2016), though production of *nori* cultivation has been more affected by nutrient depletion, which is also a recent serious problem in the Seto Inland Sea (Abo *et al*., 2015). In *wakame* cultivation, seedlings are produced in an ambient condition in outdoor tanks, so its production is easily affected by abnormal weather (e.g., extremely high air temperature in summer). In addition, many producers tend to begin cultivation in autumn according to the old-fashioned cultivation schedule without waiting for the appropriate water temperature drops. All of these events lead to significant loss of seedlings due to physiological damage or herbivory under high temperature conditions. As a result, in the Naruto district, where the largest production area of *wakame* exists, shortages and quality deterioration of seedlings have been causing sharp declines in recent production, which is now less than 40 % of the peak in early 1990s (Tanada, 2016).

Further, the seasonal duration in which both *nori* and *wakame* can be produced was predicted to be shortened in the future. In 2090s, the seasonal timing at which ambient seawater temperature drops below 23 ℃ will be delayed by about 4 weeks and 5.5 weeks from the current under the RCP 2.6 and 8.5 scenarios, respectively. Under these conditions, cultivation has to be begun in mid-winter (January) and cultivation will be impossible in the current first half of the production season. The duration in which water temperature drops below 15 ℃ is also predicted to be shortened, and thus, cultured *nori* and *wakame* will be exposed to more heavy herbivory of fish.

Conclusions and future prospect for adaptations

We predict temperate macroalgal beds composed of kelp in the Seto Inland Sea will disappear by the end of this century under the RCP 8.5 scenario in which an extreme water temperature increase was predicted by the model simulation. As most of the beds were predicted to remain under the RCP 2.6 scenario, it will be a great value for the coastal ecosystem and fisheries or human lives relying on these ecosystems to make maximum efforts to reduce greenhouse gas emissions. In addition, macroalgal beds in some areas were more likely to remain than those in other areas, possibly due to physical characteristics, such as tidal currents or upwellings, specific to these areas. These areas should be preferentially subject to conservation of macroalgal beds. Combined with existing *Iso-yake* countermeasures protecting macroalgal beds from browsing pressures by herbivorous animals, productivity and ecological functions of these macroalgal beds will be preserved effectively.

As these macroalgae are originally cold-water species, it will become more difficult to cultivate *nori* and *wakame* with increasing seawater temperatures. For immediate measures, breeding of varieties tolerant to higher water temperatures and their application will be effective, but they are still in the early stage of development. In the *wakame* cultivation industry, seedling production is still performed in its traditional and extensive way by the *wakame* farmers. Artificial seedling technology has proved to be effective for a stable mass supply of seedlings, avoiding the influence of weather conditions (Tanada *et al*., 2015). Practical spreading of this technology among the farmers will be important for maintaining *wakame* production. However, when future water temperature increases exceed the adaptable range of this macroalgal cultivation, introduction of new cultured macroalgae, which are tolerant to warmer condition and with high economic values, will be needed. *Hijiki* (*Sargassum fusiforme*) and *tosaka-nori*

(*Meristotheca papulose*) are candidates, and there are an increasing number of producers who have started cultivating them. Even in macroalgal cultivation, it will be necessary to develop countermeasures against browsing of herbivorous animals, similar to macroalgal bed conservation countermeasures.

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References

Abo K., Nakagawa N., Abe K., and Tarutani K., 2015: Nutrient dynamics and nutrient level management for *Nori* (*Pyropia*) culture in the eastern Seto Inland Sea. *Aquabiology*, **218**, 274-279. (in Japanese with English abstract)

Akimoto Y. and Matsumura T., 2010: Available past information on seaweed bed distribution and changes in seaweed bed area in Japanese coastal waters, in "Monitoring and maintenance of seaweed beds" (ed. by Fujita D, Murase N., and Kuwahara H.), Seizando-Shoten, Tokyo, pp. 17-24. (in Japanese)

Fisheries Agency, 2007: Isoyake Taisaku Guidelines, 208pp. (in Japanese)

Kiyomoto S., Kadota T., Taneda T., and Yoshimura T., 2018: Transition of seaweed bed along the western coast of Kyushu. *Aquabiology*, **236**, 210-219. (in Japanese with English abstract)

Murase N. and Noda M., 2018: Influence of change in temperature on the growth of macroalgae and browsing pattern by herbivorous fish. *Aquabiology*, **236**, 226-232. (in Japanese with English abstract)

National Research Institute of Fisheries and Environment of Inland Sea, 2015: Results of past 40 years of fisheries monitoring program in the Seto Inland Sea – long-term variation of oceanographic conditions, 256pp. (in Japanese)

Serisawa Y., Imoto Z., Ishikawa T., and Ohno M., 2004: Decline of *Ecklonia cava* population associated with increased seawater temperatures in Tosa Bay, southern Japan. *Fish. Sci.*, **70**, 189-191.

Shimabukuro H., Yoshida G., Kato A., and Guo X., 2018: Prediction of changing seawater temperature and transition of seaweed bed distribution in the next 100 years. *Aquabiology*, **236**, 233-242.

Tanada N., 2016: Development of a practical method for mass seedling production using free-living gametophytes and a new cultivar tolerant to warm waters for early harvesting of *Undaria pinnatifida* (Harvey) Suringar. *Aquabiology*, **225**, 464-471. (in Japanese with English abstract)

Tanada N., Dan A., Kusaka K., Oka N., and Hamano T., 2015: A new practical method for mass seedling production of *Undaria pinnatifida* (Harvey) Suringer using free-living gametophytes that originated from single zoospores and its application for commercial cultivation. *Algal Resour.*, **8**, 23-36.

Tanaka K., Taino S., Haraguchi H., Prendergast G., and Hiraoka M., 2012: Warming off southwestern Japan linked to distributional shifts of subtidal canopy-forming seaweeds. *Ecol. Evol.*, **2**, 2854-2865.

Vergés A., Steinberg S. D., Hay M. E., Poore A. G. B., Campbell A. H., Ballesteros E., Heck K. L., Booth D. J., Coleman M. A., Feary D. A., Figueira W., Langlois T., Marzinelli E. M., Mizerek T., Mumby P. J., Nakamura Y., Roughan M., van Sebille E., Gupta A. S., Smale D. A., Tomas F., Wernberg T., and Wilson S. K., 2014: The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. *Proc. Royal Soc. B*, **281**, 20140846.

Yatsuya K., Kiyomoto S., Yoshida G., and Yoshimura T., 2012: Regeneration of the holdfast in 13 species of the genus *Sargassum* grown along the western coast of Kyushu, south-western Japan. *Sorui*, **60**, 41-45. (in Japanese with English Abstract)

Yatsuya K., Kiyomoto S., and Yoshimura T., 2014: Seasonal changes in biomass and net production of *Ecklonia kurome* Okamura community off Gounoura, Iki Island, northern Kyushyu, Japan. *Algal Resour.*, **7**, 67-77. (in Japanese with English Abstract)

Yoshida G., Terawaki T., Yamashita A., Arai S., and Tarutani K., 2011: Variation in *Sargassum* forest characteristics along the coastal water temperature gradient from the Seto Inland Sea to the Bungo Channel sea area. *Aquabiology*, **195**, 337-343. (in Japanese with English abstract)

Yoshida G., 2018: Climate change impact on macroalgal bed ecosystem-Threatening environmental shift approaching to the Seto Inland Sea-. *Aquabiology*, **236**, 203-209. (in Japanese with English abstract)

Annotated bibliography

(1) Yoshida G., Terawaki T., Yamashita A., Arai S., and Tarutani K., 2011: Variation in *Sargassum* forest characteristics along the coastal water temperature gradient from the Seto Inland Sea to the Bungo Channel sea area. *Aquabiology*, **195**, 337-343. (in Japanese with English abstract)

Authors surveyed characteristics of five *Sargassum* forests along the geograohical temperature gradients from the western Seto Inland Sea to the Bungo Channel area. Luxuriant forests with many temperate *Sargassum* species and a kelp (*Ecklonia kurome*) were observed at the two stations in the Seto Inland Sea (Hiroshima Bay and Iyo-nada sea). Analogous flora and luxuriance was also observed in the northern part (the Sata-Misaki Pen.) and central part (the coast of Uwajima-City) of the Bungo-Channel though increase of coralline algae and sea urchins which symbolizes ‘marine desert’ (*Iso-yake*) was also observed. At the southern part (the coast of Ainan-cho), sub-tropical *Sargassum* and corals appeared and replaced the temperate *Sargassum* and *Ecklonia*. Relationship of the shift of *Sargassum* forests observed and the notable gradient in coastal water temperature along the two sea areas was discussed.

(2) Tanaka K., Taino S., Haraguchi H., Prendergast G. and Hiraoka M., 2012: Warming off southwestern Japan linked to distributional shifts of subtidal canopy-forming seaweeds. *Ecol. Evol.*, **2(11)**, 2854-2865.

Along the coast of Kochi Prefecture, southwestern Japan, macroalgal bed of temperate kelp (*Ecklonia cava*) has been tremendously decreasing and it has serious impact on abalone fishery. In addition, the authors clarified by field surveys that temperate *Sargassum* species which are also important constitutes of macroalgal beds have been replaced by tropical species, *S. ilicifolium*. Behind these events, the coastal water temperature has been increasing since the 1970s at the rate of 0.3 ℃/decade in the annual mean. In addition to the trend, the authors considered that those events became prominent in 1998 when the largest ENSO occurred and extremely high water temperature observed in the year accelerated the change.

(3) Tanada N., 2016: Development of a practical method for mass seedling production using free-living gametophytes and a new cultivar tolerant to warm waters for early harvesting of *Undaria pinnatifida* (Harvey) Suringar. *Aquabiology*, **225**, 464-471. (in Japanese with English abstract)

The production of *wakame*, *Undaria pinnatifida* in cultivation in Tokushima, which is one of the largest producing area in Japan, has been decreasing seriously after the 1990s. The decrease is supposed to be due to water temperature increase, especially during autumn when seedlings of *Wakame* are started to be cultured in the sea, because the seedlings are sensitive to high temperature conditions at that stage. Authors developed new techniques in mass seedling production and its control, and it can enable to make new cultivars of *Wakame* which can have tolerance to high temperatures.

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Coastal management using oyster-seagrass interactions for sustainable aquaculture, fisheries and environment

Masakazu HORI[*1], Franck LAGARDE[*2], Marion RICHARD[*2], Valerie DEROLEZ[*2], Masami HAMAGUCHI[*1], and Mitsutaku MAKINO[*3]

Abstract: Coastal environments of the world have been exposed to eutrophication for several decades. Recently, the quality of coastal waters has been gradually and successfully improved; however, this improvement has caused another issue in coastal ecosystem services: oligotrophication. While oligotrophication, with higher water transparency, has recovered benthic macrophyte vegetation, which have been depressed by phytoplankton derived from eutrophication, local stakeholders have suggested that oligotrophication reduces pelagic productivity and, therefore, fishery production in coastal ecosystems. In contrast, oligotrophication with high transparency has recovered benthic primary productivity, including seagrass vegetation. Seagrasses are quite important for climate change mitigation and adaptation, such as through carbon storage, acidification mitigation, and protection from sea-level rise and storm surges, affects which have been welcomed by other stakeholders. Therefore, harmonizing coastal fishery with environmental conservation goals is now essential for the sustainable use of ecosystem services. Here, we present the scope of our study based on an interdisciplinary approach, including ecological actions, socio-economical actions and psychological actions. We chose to focus on the interaction between oyster aquaculture and seagrass vegetation as a typical ecological action. Coastal organisms have adapted their traits to the environment over a long period of time, so restoration of mixed coastal habitats represents reconstruction of the original process of coastal production. Subtidal seagrass vegetation with intertidal oyster reefs is the original mixed habitats in Japan, which would be expected to enhance coastal production by improving the production efficiency without adding nutrients. A simple field experiment with carbon and nitrogen contents and stable isotope analyses revealed that oyster spats cultivated on a tidal flat adjacent to seagrass beds had higher nitrogen contents and higher $\delta^{13}C$ ratios than spats cultivated in an offshore area using only pelagic production. This result suggests that utilization of the traditional mixed habitats, which enables oysters to use both pelagic and various benthic production, has potential to sustain food provisioning services for humans even in an oligotrophic environment.

Key words: Oyster aquaculture, *Zostera marina*, blue carbon, Indigenous and local knowledge, Integrated coastal management

Introduction

Coastal environments of the world have been exposed to eutrophication with red tides for several decade (Selman and Greenhalgh, 2009; Yanagi, 2015). Also, in the Inland Seas of the Japanese

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*1 National Research Institute of Fisheries and Environment of Inland Sea, Fisheries Research and Education Agency, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*2 Station de Sete, IFREMER, Sete 34203, France
*3 National Research Institute of Fisheries Science, Fisheries Research and Education Agency, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan
E-mail: mhori@affrc.go.jp

coast, eutrophication in 1970 to1980s had become very serious, and red tide blooms, hypoxia and other biological/chemical problems have appeared frequently. The eutrophication has promoted the shift from inshore boat fishing toward oyster and seaweed aquaculture due to massive pelagic phytoplankton abundances and nutrient loads. As a result, oyster aquaculture has become an important producer of seafood in coastal areas (Tsurita *et al*., 2017).

Recently, as public awareness of marine pollution has become higher, the quality of coastal waters has been gradually and successfully improved in some regions (Matsuda, 2015). In the Seto Inland Sea, legal control of nutrient loading has successfully reduced nutrients and toxic materials input from factories and rivers to coastal areas. However, some coastal stakeholders suggest that the improvement, which is called oligotrophication, is now causing another issue in coastal ecosystem services (Collos *et al*., 2009; Yamamoto and Hanazato, 2015). It is suggested that oligotrophication has reduced pelagic productivity in coastal ecosystems, sometimes resulting in the decrease of fishery catch because the coastal fishery system in some regions has adapted to the eutrophic environment. In Seto Inland Sea, most of the recent fishery-target species are derived from pelagic production (Hori and Tarutani, 2015), which is now decreasing year by year. In addition, oyster aquaculture, especially Pacific oyster culturing, is a typical fishery that has been prospering with eutrophication, but it has been recently exposed to serious shortage of natural spats, resulting in the decline of the harvest.

In contrast, oligotrophication with high transparency has recovered benthic primary productivity, including seagrass vegetation. Seagrasses are quite important for climate change mitigation and adaptation, such as through carbon storage and protection from sea-level rise and storm surges (Arkema *et al*., 2013; Duarte *et al*., 2013). These effects are welcomed by other stakeholders concerned with environmental issues. Therefore, harmonizing sustainable coastal fisheries and aquaculture with environmental conservation is now essential for the sustainable provision of ecosystem services. This would not be achieved simply by additional nutrient reloading.

In this paper, we will introduce some of our ideas and demonstrations for establishing both sustainable fishery and water-quality improvement, with a special focus on the interaction between oyster aquaculture and seagrass vegetation as a typical case. First, we introduce the scope of our study based on an interdisciplinary approach, including ecological actions, socio-economical actions and psychological actions. Second, we explain the result from our global manipulative experiment with nutrient loading into seagrass beds, suggesting the possibility that nutrient reloading would cause the decline of seagrass distribution again. The last is the result from a field experiment to clarify the effect of oyster-seagrass interaction on the trophic aspect of cultured oysters, including how the nitrogen and carbon composition of cultivated oyster spats tissues can reflect the difference in potential food resources with and without eelgrass vegetation under oligotrophication.

Short Materials and Methods

The Seto Inland Sea (coordinates at its centre: 34.1667°N, 133.3333°E) in Japan and the Thau Lagoon (coordinates at its centre: 43.41°N, 3.6241°E) in France were chosen as study sites for this research (**Fig.1**). The Seto Inland Sea is located in the southwestern part of the main island of the Japanese archipelago. Rafted aquaculture using natural spats of the native Pacific oyster *Crassostrea gigas* is flourishing in many areas of the Seto Inland Sea. The annual production in the Seto Inland Sea accounts for more than 60 % of the national production of Japan. Along with

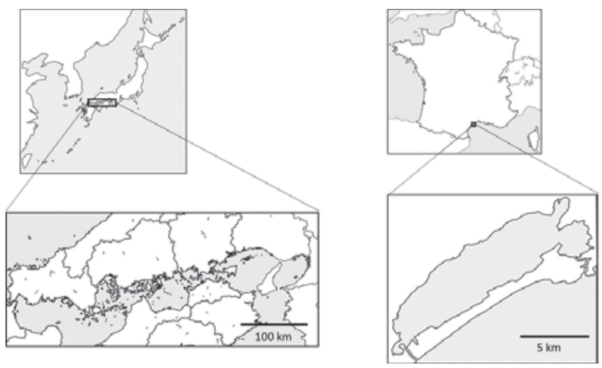

Fig. 1. Study sites, the Seto Inland Sea, Japan (left figure) and Thau Lagoon, France (right figure). These figures were revised from Hori *et al*. (2018).

oligotrophication, eelgrass recovery in the Seto Inland Sea has become apparent over the last decade due to legal restrictions on nutrient input from the watersheds. It has been estimated that the area of sea grass meadows had increased from 6000 ha to about 10,000 ha by 2011 (Hori and Tarutani, 2015).

The Thau Lagoon is the largest lagoon located on the southern French coast in the Mediterranean Sea. The lagoon is famous for oyster farming using non-native Pacific oyster spats cemented on longlines. The longlines with the spats are hung on oyster tables established in the nearshore zone. About 10% of the French national production of oysters is cultivated there; it is the largest oyster farming area in the Mediterranean Sea. It has been suggested that the recovery of eelgrass beds is still proceeding, and now the area of sea grass distribution extends up to 800 ha (Hori, personal communication with Syndicat mixte du bassin de Thau). The expansion of eelgrass meadows was observed even within oyster farming areas in June 2016.

The Thau lagoon (coordinates at its centre: 43.41°N, 3.6241°E) is the largest lagoon located on the southern French coast in the Mediterranean Sea. The lagoon is famous for oyster farming using non-native Pacific oyster spats attached on longlines by a specific cement to the spats. The longlines with the spats are hung on oyster tables established in the nearshore zone. About 10 % of the French national production of oysters is cultivated there: the largest oyster farming area in the Mediterranean Sea. It has been suggested that the recovery of eelgrass beds is still proceeding, and that now the area of sea grass distribution extends up to 800 ha (Hori, personal communication with Syndicat mixte du bassin de Thau). The expansion of eelgrass meadows was observed even within oyster farming areas in June 2016.

Schematic of an interdisciplinary approach adopted in this study

As a first step to establish harmony between sustainable oyster aquaculture and seagrass conservation under oligotrophication in both study sites, we devised a management strategy based on an interdisciplinary approach, which consists of ecological, socio-economic and socio psychological actions (Hori *et al.*, 2018). First, the ecological actions aimed to improve or maintain the ecosystem functioning and ecosystem services of a target ecosystem consists of two processes: investigations to understand the ecological condition of the ecosystem functioning and the ecosystem services in the target ecosystem and then management for the sustainable supply of ecosystem services based on the knowledge acquired by the investigation. The socio-economic aspect is important to convey the change of an ecosystem state and ecosystem services to the recipient human community. The socio-economic actions also consist of investigations and management, which are firstly aimed at clarifying the commodities and value chains to the human community from oyster and recreational businesses, as well as the interface between ecosystem services and socio-economic activities in the target ecosystem, which is regarded as a Social-ecological system approach (Makino *et al.*, 2018). Second, the actions aim to identify the effect of the changes in ecosystem functioning and ecosystem services on the structure of these chains and to draft adaptive tactics for the changes in the target ecosystem. The fundamental purpose of socio-psychological actions was to identify the potential stakeholders and their well-being in the recipient community and to influence their view on nature's values. Some of the ecosystem functioning and services cannot be appreciated based purely on financial aspects, and therefore, we need to develop a psychological method to directly identify well-being.

Nutrient loading manipulation in seagrass beds as a possible ecological action

Nutrient reloading would be a simple action to mitigate the effect of oligotrophication. However, there is a possibility that the nutrient reloading may cause the decline of seagrass vegetation again like previous eutrophication in the 1970s. We participated in a global experiment spanning the northern hemisphere to demonstrate the relationship among eelgrass ecosystem functioning, the associated epifaunal diversity and nutrient loading (Duffy *et al.*, 2015). In the experiment, we established an experimental site of seagrass bed in western Seto Inland Sea and then conducted nutrient loading by fertilization and epifaunal diversity manipulation during the same period using the same equipment as other sites of the world. Although the fundamental aim of the world experiment was to clarify the indirect effect of epifaunal diversity on eelgrass growth via epiphyte removal on leaves by meso-grazers in hemisphere scale, the result of fertilization from the Seto Inland Sea can suggest whether the nutrient loading decrease eelgrass vegetation or not.

Oyster spats cultivation in seagrass beds as a possible ecological action

We established a field experiment in the Seto Inland Sea to clarify trophic contribution of eelgrass beds to the growth of oyster spats as a feasibility study of the oyster-seagrass interactions (Hori *et al*., 2018). We established an experimental area (5 m × 5 m) in the lower intertidal zone on the tidal flat with seagrass vegetation, set a raft floating on the sea surface 200 m offshore from the tidal flat, and hung a replicate of three cages at a depth of 2 m from the sea surface using vinylon ropes. Thirty spats of each of three species (*Crassostrea gigas, C. nippona and C. sikamea*) hatched from the same lot were put into the cages on the tidal flat, and the other half of the spats of each species were put into the cages hanging from the raft. The experiment was conducted for two months from November 2016 to January 2017. The fundamental motive of this field experiment was also derived from the social concern in the local community of stakeholders. In both the Seto Inland Sea and the Thau Lagoon, it has been a concern of local oyster fishermen and oyster farmers whether the increased seagrass meadows have any positive or negative effects on oyster production and sustainability in the near future. We especially analysed the carbon and nitrogen concentration and the stable isotope ratios of the oyster spats to demonstrate the effect of different food resources on their nutritional condition. Such differences are derived from the different sources of primary production in both the pelagic ecosystem (using raft culture) and the benthic ecosystem utilized by ground culture in the tidal flat.

Results and Discussion

Schematic of an interdisciplinary approach adopted in this study

Based on this approach, we are now proceeding with the research on clarifying the interactions between oyster farming and eelgrass beds to estimate the possibility of the oyster farming using seagrass beds as an ecological action in our management (**Fig.2**). We have three working hypotheses at the moment. First, oyster farming using seagrass beds can maintain or improve coastal productivity even in healthy environmental conditions undergoing oligotrophication. To our knowledge, there is no case study directly demonstrating the effect of oyster-seagrass interactions on ecosystem functioning of target ecosystems, although there are some modelling studies on the material cycling in a coastal ecosystems, including oyster and seagrass beds (Kishi and Oshima, 2008). Further studies are needed to demonstrate this hypothesis.

The second hypothesis is that seagrass beds maintain or improve conditions for oysters to reduce potential pathogens, enabling more hygienic culture practices, and to mitigate ocean acidification. This requires a study of the effect of the change in environmental condition by seagrass beds on the quality of oysters, which will potentially enhance the value of oyster products. In other regions, it was reported that there was a 50% reduction in the relative abundance of potential bacterial pathogens capable of causing disease in humans and marine organisms when seagrass beds are present (Lamb *et al*., 2017).

The third hypothesis is that seagrass beds can support oyster production and improve its quality and sustainability. This requires studies on the trophic effect of the change in ecosystem functioning induced by seagrass beds on oyster production as a dominant ecosystem service in our study sites (see the section on the oyster spats experiment below).

Nutrient loading manipulation in seagrass beds as a possible ecological action

Duffy *et al*. (2015) suggested the global experiment revealed that higher epifaunal diversity significantly affected higher eelgrass ecosystem functioning, while any significant effect of experimental fertilization was not detected on a global scale. However, in the individual result from Seto Inland Sea under

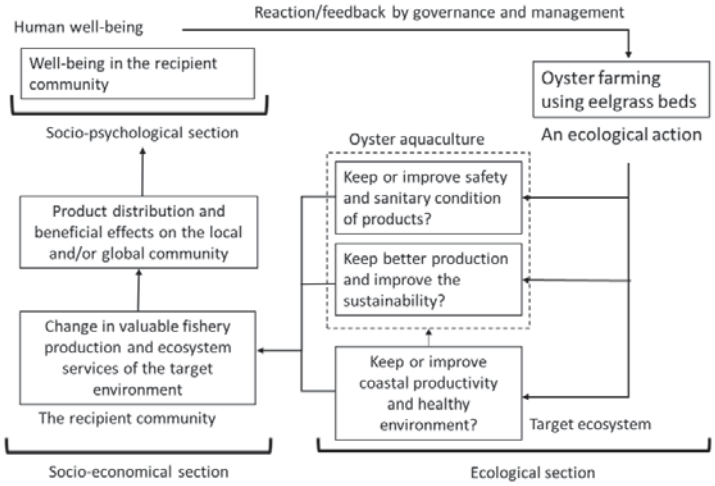

Fig. 2. The hypothetical pathways that the oyster-eelgrass interaction positively affect the recipient community via the change in ecosystem goods and services. This figure is revised from Hori *et al.* (2018).

oligotrophication, fertilization had a significant interactive effect on the ecosystem functioning and epifaunal diversity (**Fig.3**). The fertilization significantly decreased the eelgrass growth when epifaunal diversity was low (Two-way ANOVA: $F = 4.627$, $p = 0.038$), suggesting a context dependent possibility that nutrient reloading decreased macrophyte vegetation, resulting in a failure to harmonize sustainable coastal fisheries with environmental conservation.

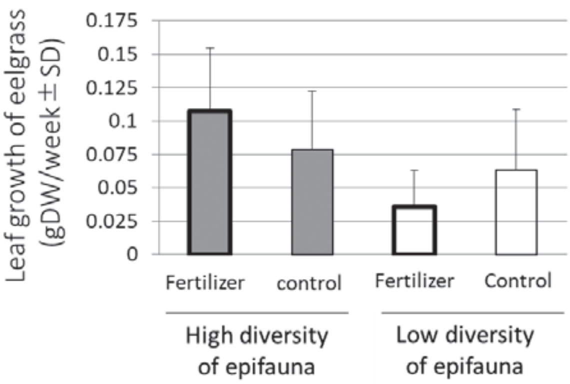

Fig. 3. The result of 2-way factorial experiment with grazer exclusion and fertilization in the Seto Inland Sea. The grazer exclusion significantly decreased epifaunal diversity and indirectly increased epiphyte biomass on eelgrass leaves, resulting in a significant difference in eelgrass leaf growth between fertilization and control plots.

Oyster spats cultivation in seagrass beds as a possible ecological action

The feasibility experiment of oyster spat cultivation exhibited some results that support the third hypothesis in our interdisciplinary approach to oyster-seagrass interactions. Among three *Crassostrea* species we cultivated, especially *C. sikamea* exhibited significant differences in the N/C ratio (**Fig.4**) and soft tissue part ratio (**Fig.5**) between the spats on the tidal flat and those from the offshore raft after two months, but there was no significant difference in the shell growth. In addition, there was a clear difference in the stable carbon isotope ratio between the spats on the tidal flat and those from the offshore raft in all three species after two months. This was presumably because the oyster spats from the offshore rafts used only pelagic production (pelagic POM: - 22.00 ‰, Hamaoka, unpubl. data, 2017, from this study site), while the oyster spats on the tidal flat can use both pelagic and benthic production (Benthic POM on tidal flat: - 17.00 ‰, seagrass: - 10.50‰, Hamaoka unpubl. data, 2017). These results suggest that utilization of benthic production can facilitate the nitrogen content of cultivated oysters, which would provide a higher quality food provision service for human beings.

In oligotrophic environmental conditions, our first ecological action aims to facilitate total productivity based not only on pelagic production by increasing the nutrient level, but also various benthic products, including seagrass beds. Interactive resource subsidies between eelgrass and oysters can include supplying epiphytes and detritus as food resources for oysters and nutrients and POM as resources for eelgrass and eelgrass-associated organisms. Seagrass-oyster interactions would become a key factor to improve bio-resource cycling and increase

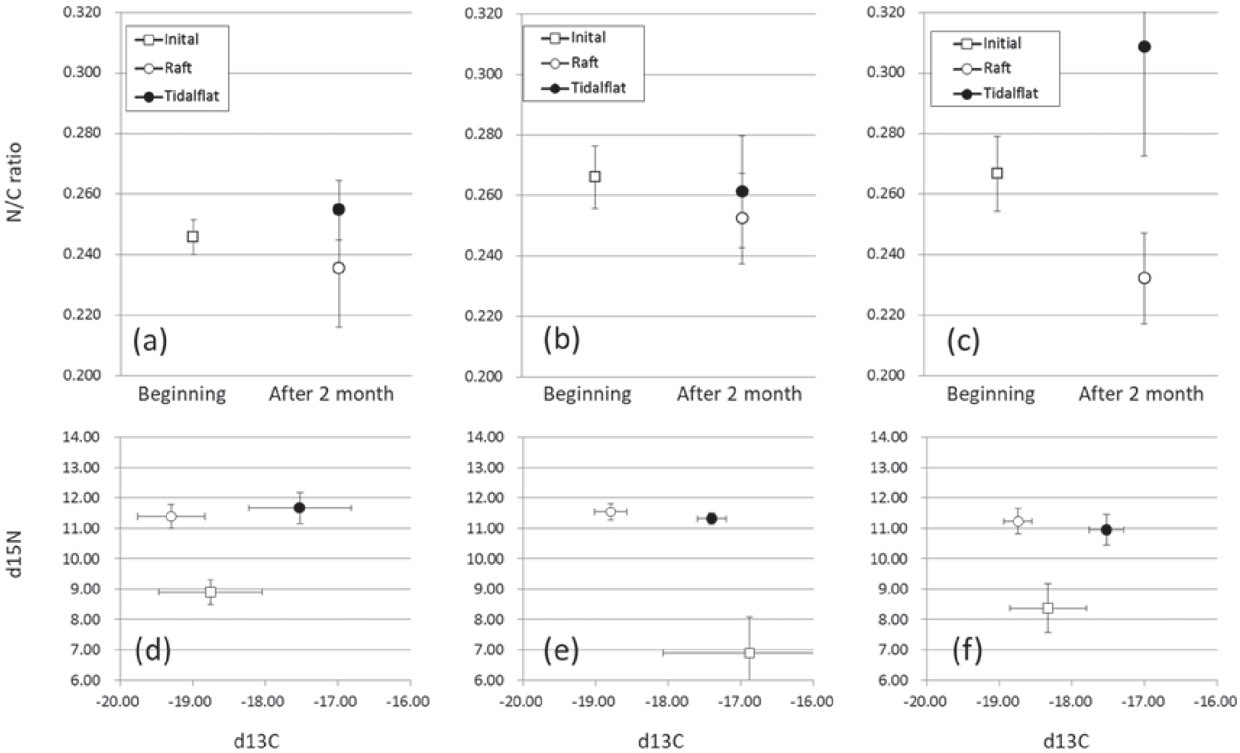

Fig. 4. The results of N/C ratio of (a) *Crassostrea gigas*, (b) *C. nippona*, and (c) *C. sikamea* and the result of the relationship between carbon and nitrogen stable isotope composition of (d) *C. gigas*, (e) *C. nippona*, and (f) *C. sikamea* at the beginning (initial) and the end of the experiment (raft and tidal flat). The assumption of variance homogeneity was kept in each statistical test for the difference in N/C ratio of (c) *C. sikamea* (P = 0.154) and the carbon stable isotope composition of (d) *C. gigas* (P = 0.551), (e) *C. nippona* (P = 0.731), and (f) *C. sikamea* (P = 0.793). These figures were revised from Hori *et al.* (2018).

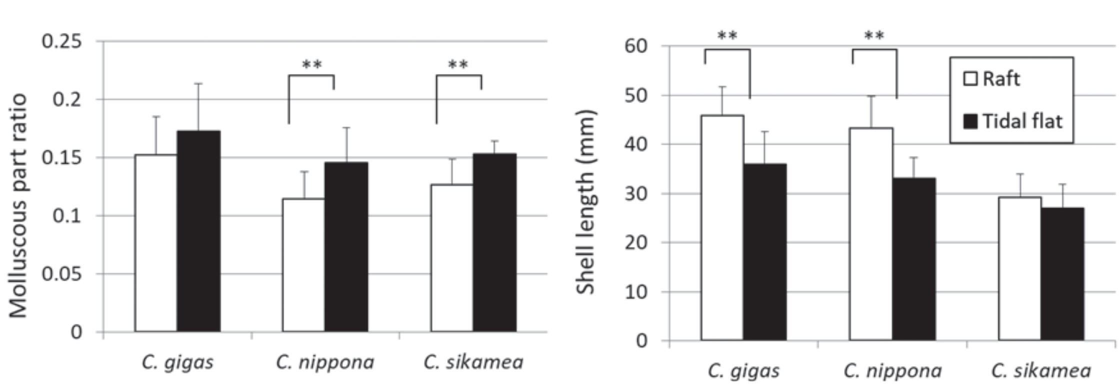

Fig. 5. The difference in the ratio of soft tissue weight (gDW) to total weight (gDW) of each oyster species (left figure) and longest part of shell length (right figure) between the spats cultivated on the tidal flat and those from the offshore raft. Significant p-values are represented by asterisks: *p < 0.05; **p < 0.01; ***p < 0.001. These figures were revised from Hori *et al.* (2018).

the turnover efficiency of ecosystem functioning in the study area. If the above three hypotheses are successfully verified, the recipient human community in the socio-economical section of our approach can get both valuable products and a better environment. The change in the community by the ripple effect of the ecological action would cause the change in the well-being of the stakeholders of the target ecosystem.

For example, oyster-eelgrass interactions would keep high water-transparency and better sanitary conditions, which is also beneficial for recreational use. Larger distribution of eelgrass beds can absorb more carbon dioxide from the atmosphere and store it as organic carbon, which can mitigate ocean acidification and, moreover, offset the carbon emissions from oyster aquaculture and recreational activities. This kind of local offset system of carbon emission can contribute to the promotion of the Paris Agreement adopted at UNFCC-COP21. Our study has only just been initiated, so we have to make steady progress to identify wise-use and better management for oligotrophic coastal ecosystems through these ecological, socio-economical and socio-psychological actions in the future.

References

Arkema K. K., Guannel G., Verutes G., Wood S. A., Guerry A., Ruckelshaus M., Kareiva P., Lacayo M., and Silver J. M., 2013: Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Change*, **3**, 913-918.

Collos Y., Bec B., Jauzein C., Abadie E., Laugier T., Lautier J., Pastoureaud A., Souchu P., and Vaquer A., 2009: Oligotrophication and emergence of picocyanobacteria and a toxic dinoflagellate in Thau Lagoon, southern France. *J. Sea Res.*, **61**, 68-75.

Duarte C. M., Losada I. J., Hendriks I. E., Mazarrasa I., and Marba N., 2013: The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change*, **3**, 961-968.

Duffy J. E., Reynolds P. L., Boström C., Coyer J. A., Cusson M., Donadi S., Douglass J. G., Eklöf J. S., Engelen A. H., Eriksson B. K., Fredriksen S., Gamfeldt L., Gustafsson C., Hoarau G., Hori M., Hovel K., Iken K., Lefcheck J. S., Moksnes P.-O., Nakaoka M., O'Connor M. I., Olsen J. L., Richardson J. P., Ruesink J. L., Sotka E. E., Thormar J., Whalen M. A., and Stachowicz J. J., 2015: Biodiversity mediates top-down control in eelgrass ecosystems: a global comparative-experimental approach. *Ecol. Lett.*, **18**, 696-705.

Hori M. and Tarutani K., 2015: Changes in the distribution of seagrass vegetation with relation to the possible regime shift from pelagic-dominant to benthic-dominant system in Seto Inland Sea, in “Issues of oligotrophication in ocean and lakes” (ed. by Yamamoto T. and Hanazato T.), Chijinshokan press, Tokyo, pp. 129-148. (in Japanese)

Hori M., Hamaoka H., Hirota M., Lagarde F., Vaz S., Hamaguchi M., Hori J., and Makino M., 2018: Application of the coastal ecosystem complex concept toward integrated management for sustainable coastal fisheries under oligotrophication. *Fisher. Sci.*, **84**, 283-292.

Kishi M. J. and Oshima Y., 2008: The role of benthos and epiphyte on the material cycle in Akkeshi lake, Japan, in “Monitoring and Modeling Lakes and Coastal Environments” (ed. by Mohanty P. K.), Springer, Netherlands, pp. 151-158.

Lamb J. B., van de Water J. A. J. M., Bourne D. G., Altier C., Hein M. Y., Florenze E. A., Abu N., Jompa J., and Harvell C. D., 2017: Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. *Science*, **355**, 731-733.

Makino M., Hori M., Hori J., Nanami A., Tojo Y., and Tajima H., 2018: Understanding the integrated policy for harmonizing the marine ecosystem conservation and sustainable uses: a case of Sekisei lagoon, Japan. Selected papers in Oceans'18 MTS/IEEE Kobe/Techno-ocean 2018.

Matsuda O., 2015: Towards rich Seto Inland Sea, considerable change of the basic plan on Seto Inland Sea approved by the cabinet. *Yutakana Umi*, **36**, 7-12. (in Japanese)

Selman M. and Greenhalgh S., 2009: Eutrophication: policies, actions, and strategies to address nutrient pollution, WRI Policy Note 3, World Resources Institute, Washington, D. C., 16pp.

Tsurita I., Hori M., and Makino M., 2017: Fishermen and conservation: sharing the case study of Hinase, Japan, in "Marine Protected Areas: Interactions with Fishery Livelihoods and Food Security" (ed. by Westlund L., Charles A., Garcia S. M., and Sanders J.), FAO-FA Technical Paper 603, FAO, Rome, pp. 43-50.

Yamamoto T. and Hanazato T., 2015: Issues of oligotrophication in ocean and lakes, Chijinshokan press, Tokyo ,195pp. (in Japanese).

Yanagi T., 2015: Eutrophication and oligotrophication in Japanese estuaries: the present status and future tasks, Springer, Dorderecht, 97pp.

Annotated bibliography

(1) Hori M., Hamaoka H., Hirota M., Lagarde F., Vaz S., Hamaguchi M., Hori J., and Makino M., 2018: Application of the coastal ecosystem complex concept toward integrated management for sustainable coastal fisheries under oligotrophication. *Fish. Sci.*, **84**, 283-292.

Harmonizing coastal fisheries with water-quality improvement has become an essential factor for the sustainable use of coastal ecosystem services. Here, we present the scope of our study based on an interdisciplinary approach including ecological actions, socio-economic actions and socio-psychological actions. We chose to focus on the interaction between oyster aquaculture and seagrass vegetation as a typical ecological action using the coastal ecosystem complex (CEC) concept. Coastal organisms have adapted their traits to the environment over a long period of time, so that restoration of the CEC represents reconstruction of the original process of coastal production. Subtidal seagrass vegetation with intertidal oyster reefs is the original CEC in Japan, which would be expected to enhance coastal production by improving the production efficiency without adding nutrients. A simple field experiment examining carbon and nitrogen contents and stable isotope ratios revealed that oyster spats cultivated on a tidal flat adjacent to seagrass beds had higher nitrogen contents and higher $\delta^{13}C$ ratios than spats cultivated in an offshore area using only pelagic production. This result suggests that utilization of the CEC, which enables oysters to use both pelagic and benthic production, has potential to sustain a food provisioning service for humans, even in oligotrophic conditions.

(2) Pernet, F., Malet N., Pastoureaud A., Vaquer A., Quere C., and Dubrica L., 2012: Marine diatoms sustain growth of bivalves in a Mediterranean lagoon. *J. Sea. Res.*, **68**, 20-32.

Carbon stable isotopes and fatty acids were measured in the suspended particulate organic matter (POM) of the Thau lagoon to study its qualitative temporal changes in relation to environmental factors and to identify the food sources of bivalves over a one-yr-cycle in relation to their growth. Reciprocally, the impact of shellfish farming on POM was also studied. Oysters and mussels were sampled and measured for biometry, stable isotopes and fatty acid composition. Water samples were collected at two sites, both inside and outside of the shellfish farming area, to determine concentrations in POM, chlorophyll a (Chl *a*) and stable isotopes. Carbon isotopes and fatty acids in bivalves reflected seasonal changes in food sources, which varied consistently with the environment. Seasonal changes in $\delta^{13}C$ and fatty acids in the bivalves suggested that dietary phytoplankton contribution varied according to season. Terrestrial organic matter and bacteria can contribute to the diet of bivalves during non bloom periods. Mussels seemed to rely more on diatoms and less on terrestrial organic matter and bacteria than oysters did, particularly when phytoplankton biomass was low during the summer. Although one- and two-yr-old oysters showed similar $\delta^{13}C$, their fatty acid dynamics differed slightly. Periods of high growth rate in bivalves were mainly fuel led by diatoms, thus highlighting the importance of seasonal blooms of micro phytoplankton during the critical period of bivalve growth and gamete production. Although there was no significant effect of shellfish farms on Chl *a* and POM $\delta^{13}C$, consistent differences indicate that stable isotopes could be used successfully to investigate the effects of bivalve aquaculture.

(3) Morimoto N., Umezawa Y., San Diego-McGlone M. L., Watanabe A., Slringan F. P., Tanaka Y., Regino G. L., and Miyajima T., 2017: Spatial dietary shift in bivalves from embayment with river discharge and mariculture activities to outer seagrass beds in

northwestern Philippines. *Mar. Biol.*, **164**, 84.

To investigate the spatial variation in bivalve food sources along a pollution gradient and assess bivalve contribution to biogeochemical cycles in tropical coastal ecosystems, the $\delta^{13}C$ and $\delta^{15}N$ values of bivalves and their potential food sources were studied in northwestern Philippines. In a semi-enclosed embayment affected by river discharge and mariculture activities, bivalves depended primarily on ^{13}C-depleted suspended particulate organic matter such as phytoplankton and/or fish feeds. However, toward the relatively oligotrophic seagrass beds, the bivalve food source gradually shifted to more ^{13}C-enriched resuspended and/or settled particles. Furthermore, in the outer seagrass beds exposed to the open ocean, bivalves mainly relied on similar food sources, such as detritus of microalgae, regardless of the distance from the embayment. These trends appear to reflect the ready availability of the food sources. Especially in the outer seagrass beds, a semiclosed material cycle within the vicinity of the sea bottom likely emerged between bivalves and algae, but not between the phytoplankton in the overlying water column. This resulted in a relatively weak benthic-pelagic coupling for bivalves. These cycles would need to be taken into account when estimating the biogeochemical cycles in eutrophicated coastal areas.

(4) Duarte C. M., Losada I. J., Hendriks I. E., Mazarrasa I., and Marba N., 2013: The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change*, **3**, 961-968.

Marine vegetated habitats (seagrasses, salt-marshes, macroalgae and mangroves) occupy 0.2 % of the ocean surface, but contribute 50 % of carbon burial in marine sediments. Their canopies dissipate wave energy and high burial rates raise the seafloor, buffering the impacts of rising sea level and wave action that are associated with climate change. The loss of a third of the global cover of these ecosystems involves a loss of CO_2 sinks and the emission of 1 Pg CO_2 annually. The conservation, restoration and use of vegetated coastal habitats in eco-engineering solutions for coastal protection provide a promising strategy, delivering significant capacity for climate change mitigation and adaption.

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Bull. Jap. Fish. Res. Edu. Agen. No. 49，45－51，2019

Marine sediment conservation using benthic organisms

Katsutoshi ITO[*1], Mana ITO[*1], Takeshi HANO[*1], Toshimitsu ONDUKA[*1], Kazuhiko MOCHIDA[*1], Nobuaki SHONO[*2], and Ryuhei NAKAMURA[*2]

Abstract: Estuaries and coastal zones used for fish aquaculture are often polluted by organic contaminants and anthropogenic chemicals. Bioremediation has been recognized as an efficient technology to clear environmental pollutants. The authors therefore studied environmental remediation using benthic organisms and have shown that some annelids are adaptable to polluted environments. For example, *Capitella* cf. *teleta*, a polychaete inhabiting the sediment beneath a fish farm, displayed high protease activity, whereas *Perinereis nuntia*, a polychaete inhabiting an estuary, displayed high cellulase activity. Additionally, the oligochaete *Thalassodrilides* cf. *briani* was found to survive highly hypoxic and sulfidic sediments contaminated with various pollutants and was shown to biotransform 1-nitronaphthalene, a toxic and carcinogenic chemical, into substances that are nontoxic to fish.

In another experiment in which these three benthic species were maintained in polluted sediments, the polychaetes *P. nuntia* and *C.* cf. *teleta* markedly increased redox potential (Eh) and decreased the level of acid volatile sulfides relative to the oligochaete *T* cf. *briani*. Furthermore, the concentration of polycyclic aromatic hydrocarbons (PAHs) in the sediment with all three species was significantly lower than the initial level. *T* cf. *briani*, especially, showed a marked ability to degrade the PAHs in the sediment. These results indicate that benthic organisms have species-specific remediation properties and ecological functions in organically polluted sediments.

We are also working on the development of a real-time measuring device for determining the Eh in the sediment under fish farms as Eh is a comprehensive parameter to monitor the degree of contamination of these sediments.

Key words: annelid, bioremediation, environmental pollutants, Polychaeta, *Oligochaeta*, polycyclic aromatic hydrocarbons

Introduction

Estuaries and coasts are crucial for the life histories of many aquatic organisms. The estuarine and coastal sediments accumulate organic matter from both marine and terrestrial sources (Jorcin, 2000; Hu *et al*., 2009; Zhang *et al*., 2009). In the sediments of coastal areas where aquaculture is conducted, considerable organic enrichment is caused by the input of large amounts of unconsumed fish food and fish feces. This eutrophication causes anoxic conditions and an increase in sulfides (Pawar *et al*. 2002; Tanigawa *et al*, 2007), leading to serious problems, such as algal blooms and the elimination of the benthic community and seagrass (Holmer *et al*., 2008; Leon *et al*., 2010). Polycyclic aromatic hydrocarbons (PAHs), which are products of the incomplete combustion of fossil fuels, contaminate estuarine and coastal sediments in areas associated with human activity (WHO, 1998). Therefore, remediation of organically polluted

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[*1] National Research Institute of Fisheries and Environment of Inland Sea, Fisheries Research and Education Agency, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
[*2] Biofunctional Catalyst Research Team, RIKEN Center for Sustainable Resource Science (CSRS), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
E-mail: katsuit@affrc.go.jp

sediment is necessary for maintaining ecological balance, biological diversity, and the sustainable development of aquaculture.

One pollutant of interest is 1-nitronaphthalene (1NN), a nitrated polycyclic aromatic hydrocarbon (nitro-PAH) that is formed during the incomplete combustion of organic compounds (Nielsen, 1984). Such compounds are formed mainly by the reaction of PAHs with nitrogen oxides in polluted air (Atkinson and Arey, 1994). Nitro-PAH products are more toxic to many organisms than are the parent PAHs (Yaffe *et al*., 2001). Yaffe *et al*. (2001), using an environmental model, reported that 1NN had the highest concentration potential among nitro-PAHs in the Los Angeles Basin in Southern California, USA.

Macrofauna, especially sediment-dwelling polychaete and oligochaete worms, are known to affect sediment characteristics biologically, chemically, and physically through feeding activity, bioturbation, ventilation, and irrigation, resulting in mineralization and organic degradation in the sediments (Banta *et al*., 1999; Volkenborn *et al*., 2007; Giere, 2006; Heilskov *et al*., 2006; Quintana *et al*., 2011). The activities of some polychaetes are closely related to the remediation of contaminated sediments and water (Licciano *et al*., 2005; Palmer, 2010).

Organic matter in the environment is decomposed chemically by many enzymes (e.g., proteases, cellulase phosphatases, and carbohydrases). Some enzymes have been utilized to estimate organic matter decomposition in water and sediment in estuarine and coastal environments (Hiroki *et al*. 2003; Arnosti *et al*. 2009). The polychaete *Capitella teleta* (formerly *Capitella* sp. I; Blake *et al*., 2009) has been reported to remediate organically contaminated sediment by enhancing the decomposition rate of the organic matter of the sediment under fish farms (Tsutsumi and Montani, 1993; Kinoshita *et al*., 2008). Moreover, some benthic organisms, including *C. teleta* and *Nereis diversicolor*, can degrade oil, acyclic hydrocarbons, and the PAHs, such as fluoranthene and pyrene in sediment (Gilbert *et al*., 1994; Grossi *et al*., 2002; Madsen *et al*., 1997; Christensen *et al*., 2002), indicating that they can contribute to the remediation of sediments polluted by PAHs.

In this proceeding, we introduce research results targeting organic pollutants, chemical pollutants, and the remediation of polluted sediment using annelids.

Materials and Methods

Animals

The benthic organisms used in this study (**Fig.1**) are as follows: the nereidid polychaete *Perinereis nuntia*, opportunistic *polychaete Capitella* cf. *teleta*, and oligochaete *Thalassodrilides* cf. *briani*. Nereidid worms, including *P. nuntia*, are common in intertidal and shallow marine waters and are widely distributed off the coasts of Asia and in the southern hemisphere (Wilson and Glasby, 1993; Muir and Hossain, 2014). *P. nuntia* is a large-sized species, very common in Japan, and is often found burrowing in sand under stones in estuaries and on sheltered beaches, sometimes in near-anaerobic conditions. This species is used as a model species for pollutants and has the potential to be used for wastewater treatment through its ability to reduce organic matter (Palmer, 2010). *C.* cf. *teleta* is frequently observed in the sediment under fish farms in Japan and is a small- to medium-sized species. *Capitella* species are opportunistic and can tolerate hypoxia and sediment toxicants (Gamenick *et al*., 1998; Bach *et al*., 2005; O'Brien and Keough, 2013).

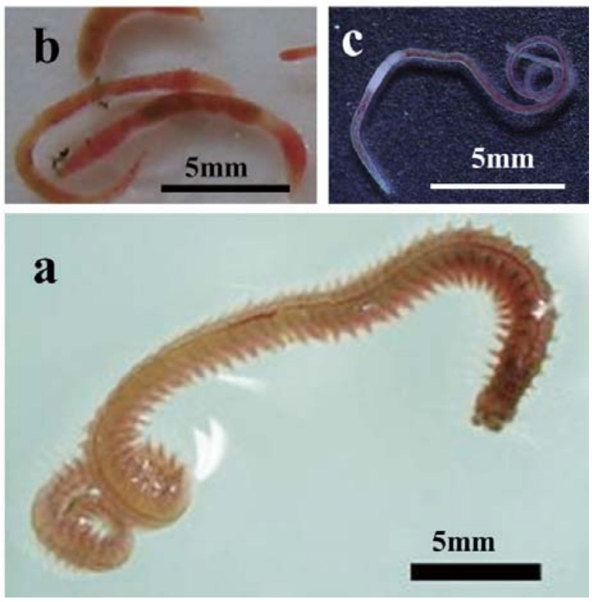

Fig. 1. Nereidid polychaete *Perinereis nuntia* (a), opportunistic polychaete *Capitella* cf. *teleta* (b), and oligochaete *Thalassodrilides* cf. *briani* (c).

T. cf. *briani* are distributed in the sediments of many areas including China, North America, and Western Australia (Erséus, 1990; Milligan, 1996).

Enzyme activities of the benthos

The whole body of each *P. nuntia* and *C*. cf. *teleta* worm, was homogenized in 10 mM sodium phosphate buffer (PBS; pH 7.5) using a pestle on ice. The homogenate was centrifuged for 30 min at 10,000 rpm at 4 °C, and then the supernatant was used for the determination of enzyme activities. Protease activity was measured using milk casein as a substrate according to the procedure of Kashiwagi (2004). Cellulase activity was measured at 37 °C for 24 h in 10 mM PBS (pH 7.5) with 0.8 % carboxymethyl cellulose as the substrate. Reducing sugars produced by the reaction were determined by the dinitrosalicylic reagent method (Miller 1959). Glucose was used as the standard.

Chemical pollutants catabolism tests with annelids

The residual 1NN in seawater following metabolism by both of the annelids was examined. Each replicate used 300 *T*. cf. *briani* individuals (total weight: 0.1 g), 5 *P. nuntia* individuals (average weight: 90 mg/individual; total weight 0.42 g). 1NN test solutions were made by adding the necessary amount of stock solution to pre-filtered (GFC filter, Whatman, Maidstone, UK) seawater. Animals were exposed to 1NN at 170 μg/L for 5 days in the dark at 20 °C in aquaria containing seawater and quartz sand. The residual 1NN concentration in seawater was analyzed by GC-MS at 0, 2, and 5 days.

Remediation of polluted sediment using annelids.

Artificial microcosms, consisting of clear glass columns (diameter 9.0 cm, height 12.2 cm) filled with 150 g of sediment (Sediment was collected from Hatsukaichi Marina of Hiroshima, Japan, an active harbor in which many fishing boats travel) and 300 mL seawater filtered through sand and activated carbon, were prepared. Approximately 150 mg biomass of one benthic worm species−P. nuntia (mean ± standard deviation) (n = 5 ± 0), *C*. cf. *teleta* (n = 59 ± 5), or *T*. cf. *briani* (n = 160 ± 6)−was added to each of three microcosms. A fourth column, without benthic organisms, was prepared as a control. Three replicate columns were prepared for each treatment.

The benthic worms were fed a commercial fish diet (N400; Kyowa Hakko, Tokyo, Japan) once every 3 days (5 % of total biomass per day; approximately 22.5 mg). The columns were closed and kept in an incubator at 20 °C for 50 days. For the initial sediment sample, a column was prepared as described above and kept overnight to allow the mud to settle. After removing the overlying water, the oxidation-reduction potential (ORP), acid volatile sulfides (AVS), loss on ignition (LOI measured as organic matter), and concentration of PAHs in the sediment were measured.

After 50 days, the overlying water was removed from all test microcosms, and the ORP (mV) of the sediment was measured at 2 cm depth using an ORP meter (D-55, Horiba, Kyoto, Japan). AVS was measured using a Hedorotech-S gas detection tube (GASTEC, Kanagawa, Japan). Benthic organisms were sorted from a subsample of the whole sediment sample. The living infauna were cleaned in seawater and their biomass measured; total column biomass was estimated from this measurement. The concentrations of 16 PAHs were measured in the whole sediment samples.

Results and Discussion

Enzyme activities of the benthos

The protease activity of *Capitella* cf. *teleta* (89.7 µg/mg) was about 10 times those of *P. nuntia brevicirris* (8.0 µg/mg). High cellulase (endo-β-1,4-glucanase) activity was detected in *P. nuntia brevicirris* (3.2 µg/mg), whereas the activity was scarcely detected in *Capitella* cf. *teleta*. The high protease activity of *Capitella* cf. *teleta* enabled it to survive in the sediment under a fish farm, where it degrades organic matter. In contrast, the high cellulase activity of the estuary-dwelling *P. nuntia brevicirris* allowed it to degrade organic matter originating from terrestrial areas.

Chemical pollutants catabolism tests with annelids

In the 1NN metabolism tests with annelids, the 1NN concentration in seawater did not decrease significantly from the initial concentration of 170 μg/L without animals present. However, in all animal treatments, the concentrations in the seawater decreased significantly (*T*. cf. *briani*: 23.3 %; *P. nuntia*:

32.6 %) after 2 days. After 5 days, the concentrations in the seawater were 3.0 ± 0.2 μg/L in the *T*. cf. *briani* tank, and 14.3 ± 2.1 μg/L in the *P*. *nuntia* tank. The ability of the *T*. cf. *briani* to biotransform 1NN was significantly greater than that of the *P*. *nuntia* ($p < 0.01$). Furthermore, *T*. cf. *briani* can survive in highly hypoxic and sulfidic sediments contaminated with various pollutants, and have been shown to biotransform 1NN, a toxic and carcinogenic chemical, into substances that are nontoxic to fish.

Remediation of polluted sediment using annelids

The annelid's effects on physicochemical properties, such as organic matter (LOI), Eh, AVS, and the degradation of PAHs, were assessed. Eh levels were significantly higher, and AVS levels lower, in the sediments of the polychaetes *P*. *nuntia* and *C*. cf. *teleta* than they were in those of the oligochaete *T*. cf. *briani* or the control (without benthic organisms). Total PAH concentration significantly decreased from the initial level in all three groups; *T*. cf. *briani* displayed a marked ability to reduce PAHs in sediment. These results indicate that benthic organisms have species-specific remediation properties and ecological functions in organically polluted sediments.

Real-time device for measuring Eh in sediment

In our group, sediment remediation tests using benthos were carried out in the field, such as at fish farms. Periodic surveys conducted by sediment sampling and diving were necessary to verify the effects of the annelids. The Eh is a comprehensive parameter, which can be used to monitor the degree of contamination of the sediment under a fish farm. Currently, we are working on the development of a real-time device for measuring Eh in the sediment under fish farms.

In fact, we are operating a real-time measurement in a 3-ton water tan and confirmed that the processes by which the organic matter in the sediments was being removed by remediation with annelids were successfully monitored, demonstrating that it is possible to measure redox potential in real time even in the field. In future, in the case of a fish farm where organic pollution has advanced, we plan to use an appropriate benthic species to restore the bottom sediment. To observe the progress of the remediation, we plan to use real-time measuring to trace the Eh. If sediment pollution progresses, we will implement countermeasures, such as increasing the number of benthic organisms or decreasing the feed volume. This allows not only for evaluating the healthy conditions of benthic systems, but even facilitating the remediation potential of benthic organisms to improve the toluene of sediment ecosystems against over feeding on fish farms.

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References

Arnosti C., Ziervogel K., Ocampo L., and Ghobrial S., 2009: Enzyme activities in the water column and in shallow permeable sediments from the northeastern Gulf of Mexico. *Estuar. Coast Shelf Sci.*, **84**, 202-208.

Atkinson R. and Arey J., 1994: Atmospheric chemistry of gas-phase polycyclic aromatic hydrocarbons: formation of atmospheric mutagens. *Environ. Health Perspect.*, **102**, 117-126.

Bach L., Palmqvist A., Rasmussen L. J., and Forbes V. E., 2005: Differences in PAH tolerance between *Capitella* species: Underlying biochemical mechanisms. *Aquat. Toxicol.*, **74**, 307-319.

Banta G. T., Holmer M., Jensen M. H., and Kristensen E., 1999: Effects of two polychaete worms, *Nereis diversicolor* and *Arenicola marina*, on aerobic and anaerobic decomposition in a sandy marine sediment. *Aquat. Microb. Ecol.*, **19**, 189-204.

Blake J. A., Grassle J. P., and Eckelbarger K. J., 2009: *Capitella teleta*, a new species designation for the opportunistic and experimental *Capitella* sp. I, with a review of the literature for confirmed records. *Zoosymposia*, **2**, 25-53.

Christensen M., Andersen O., and Banta G. T., 2002: Metabolism of pyrene by the polychaetes N*ereis diversicolor* and *Arenicola marina*. *Aquat. Toxicol.*, **58**, 15-25.

Erséus C., 1990: The marine Tubificidae (Oligochaeta) of the barrier reef ecosystems at Carrie Bow Cay, Belize, and other parts of the Caribbean Sea, with descriptions of twenty-seven new species and revision of *Heterodrilus, Thalassodrilides* and *Smithsonidrilus*. *Zool. Scripta.*, **19**, 243-303.

Gamenick I., Vismann B., Grieshaber M. K., and Giere O., 1998: Ecophysiological differentiation of *Capitella capitata* (Polychaeta). Sibling species from different sulfidic habitats. *Mar. Ecol. Prog. Ser.*, **175**, 155-166.

Giere O., 2006: Ecology and biology of marine Oligochaeta - An inventory rather than another review. *Hydrobiologia*, **564**, 103-116.

Gilbert F., Rivet L., and Bertrand J. C., 1994: The in vitro influence of the burrowing polychaete *Nereis diversicolor* on the fate of petroleum hydrocarbons in marine sediments. *Chemosphere*, **29**, 1-12.

Grossi V., Massias D., Stora G., and Bertrand J. C., 2002: Burial, exportation and degradation of acyclic petroleum hydrocarbons following a simulated oil spill in bioturbated Mediterranean coastal sediments. *Chemosphere*, **48**, 947-954.

Heilskov A. C., Alperin M., and Holmer M., 2006: Benthic fauna bio-irrigation effects on nutrient regeneration in fish farm sediments. *J. Exp. Mar. Bio. Ecol.*, **339**, 204-225.

Hiroki M., Yabe T., Nohara S., Utagawa H., Satake K., Koga T., Ueno R., Kawachi M., and Watanabe M., 2003: Evaluation of an organic matter decomposing function from hydrolytic enzyme activities of tidal flat sediments in Japan. *Jap. J. Limnol.*, **64**, 113-120. (in Japanese with English abstract).

Holmer, M., Argyrou M., Dalsgaard T., Danovaro R., Diaz-Almela E., Duarte C. M., Frederiksen M., Grau A., Karakassis I., Marbà N., Mirto S., Pérez M., Pusceddu A., and Tsapakis M., 2008: Effects of fish farm waste on Posidonia oceanica meadows: Synthesis and provision of monitoring and management tools. *Mar. Pollut. Bull.*, **56**, 1618-1629.

Hu L., Guo Z., Feng J., Yang Z., and Fang M., 2009: Distributions and sources of bulk organic matter and aliphatic hydrocarbons in surface sediments of the Bohai Sea. *China. Mar. Chem.*, **113**, 197-211.

Jorcin A., 2000: Physical and chemical characteristics of the sediment in the estuarine region of Canan´eia (SP), Brazil. *Estuaries*, **431**, 59-67.

Kashiwagi Y., 2004: Enzymes of filamentous fungi in fermentation. MAFF Microorganism Genetic Resources Manual No. 16, 1-16.

Kinoshita K., Tamaki S., Yoshioka M., Srithonguthai S., Kunihiro T., Hama D., Ohwada K., and Tsutsumi H., 2008: Bioremediation of organically enriched sediment deposited below fish farms with artificially mass-cultured colonies of a deposit-feeding polychaete *Capitella* sp. I. *Fish. Sci.*, **74**, 77-87.

Leon S. D., Mae S., Diego-McGlone S., Lourdes M., and Reichardt W., 2010: Impact of polychaete infauna on enzymatic protein degradation in marine sediments affected by intensive milkfish farming. *Aquacult. Res.*, **41**, 11.

Licciano M., Stabili L., and Giangrande A., 2005: Clearance rates of *Sabella spallanzanii* and *Branchiomma luctuosum* (Annelida: Polychaeta) on a pure culture of *Vibrio alginolyticus*. *Water Res.*, **39**, 4375-4384.

Madsen S. D., Forbes T. L., and Forbes V. E., 1997: Particle mixing by the polychaete *Capitella* species 1: Coupling fate and effect of a particle-bound organic contaminant (fluoranthene) in a marine sediment. *Mar. Ecol. Prog. Ser.*, **147**, 129-142.

Miller G. L. 1959. Use of dinitrosalicylic acid reagent for determination of reducing sugar. *Anal Chem,* **31**, 426-428.

Milligan M., 1996: Identification manual for the aquatic Oligochaeta of Florida. Vol. II. Estuarine and nearshore marine oligochaetes. Florida Department of environmental Protection, Tallahassee, Florida, 239pp.

Muir A. I. and Hossain M. M. M., 2014: The intertidal polychaete (Annelida) fauna of the Sitakunda coast (Chittagong, Bangladesh), with notes on the Capitellidae, Glyceridae, Lumbrineridae, Nephtyidae, Nereididae and Phyllodocidae of the "Northern Bay of Bengal Ecoregion". *Zookeys*, **27**, 1-27.

Nielsen T., 1984: Reactivity of polycyclic aromatic hydrocarbons towards nitrating species. *Environ. Sci. Technol.*, **18**, 157-163.

O'Brien A. L. and Keough M. J., 2013: Detecting benthic community responses to pollution in estuaries: A field mesocosm approach. *Environ. Pollut.*, **175**, 45-55.

Palmer P. J., 2010: Polychaete-assisted sand filters. *Aquaculture*, **306**, 369-377.

Pawar V., Matsuda O., and Fujisaki N., 2002: Relationship between feed input and sediment quality of the fish cage farms. *Fish. Sci.*, **68**, 894-903.

Quintana C. O., Hansen T., Delefosse M., Banta G., and Kristensen E., 2011: Burrow ventilation and associated porewater irrigation by the polychaete *Marenzelleria viridis*. *J. Exp. Mar. Bio. Ecol.*, **397**, 179-187.

Tanigawa T., Tamashita A., and Koizumi Y., 2007: Effect of effluents from a new fish farming site on the benthic environment. *Bull. Fish. Res. Agen.*, **19**, 69-77.

Tsutsumi H. and Montani S., 1993: Utilization of biological activities of capitellid polychaete for treatment of "hedoro" (organically enriched sediment) deposited on the marine bottom below fish net pen culture. *Nippon Suisan Gakkaishi,* **59**, 1343-1347.

Volkenborn N., Hedtkamp S. I. C., van Beusekom J. E. E., and Reise K., 2007: Effects of bioturbation and bioirrigation by lugworms (*Arenicola marina*) on physical and chemical sediment properties and implications for intertidal habitat succession. *Estuar. Coast. Shelf Sci.*, **74**, 331-343.

WHO, 1998: Selected non-heterocyclic polycyclic aromatic hydrocarbons. Environmental Health Criteria 202. World Health Organization, Geneva.

Wilson R. S. and Glasby C. J., 1993: A revision of the *Perinereis nuntia* species group (Polychaeta: Nereididae). *Rec. Aust. Museum*, **45**, 253-277.

Yaffe D., Cohen Y., Arey J., and Grosovsky A. J., 2001: Multimedia analysis of PAHs and nitro-PAH daughter products in the Los Angeles Basin. *Risk Anal.*, **21**, 275-294.

Zhang L., Yin K., Wang L., Chen F., Zhang D., and Yang Y., 2009: The sources and accumulation rate of sedimentary organic matter in the Pearl River Estuary and adjacent coastal area, Southern China. *Estuar. Coast. Shelf Sci.*, **85**, 190-196.

Annotated bibliography

(1) Ito K., Nozaki M., Ohta T., Miura C., Tozawa Y., and Miura T., 2011: Differences of two polychaete species reflected in enzyme activities. *Mar. Biol.*, **158(6)**, 1211-1221.

Polychaetes constitute most of the benthic macroinvertebrates in estuarine and coastal environments. We investigated the utilization of organic matter in two polychaete species, *Capitella* sp. I and *Perinereis nuntia brevicirris*, living in different coastal habitats. The protease activity of *Capitella* sp. I (89.7 μg/mg) was about 10 times that of *P. nuntia brevicirris* (8.0 μg/mg). High cellulase (endo-β-1,4-glucanase) activity was detected in *P. nuntia brevicirris* (3.2 μg/mg), whereas scarcely any was detected in *Capitella* sp. I. We isolated cDNA clones of protease mRNA from *Capitella* sp. I and of cellulase mRNA from *P. nuntia brevicirris*. The high protease activity of *Capitella* sp. I enabled it to survive in the sediment under a fish farm, where it degrades organic matter. In contrast, the high cellulase activity of the estuary-dwelling *P. nuntia brevicirris* allowed it to degrade organic matter originating from terrestrial areas.

(2) Ito K., Ito M., Onduka T., Ohta K., Torii T., Hano T., Mochida K., Ohkubo N., Miura T., and Fujii K., 2016: Differences in the ability of two marine annelid species, *Thalassodrilides* sp. and *Perinereis nuntia*, to detoxify 1-nitronaphthalene. *Chemosphere*, **151**, 339-344.

Bioremediation is a promising method for remediating environmentally polluted water. We investigated the abilities of two benthic annelid species to biotransform 1-nitronaphthalene, a nitrated polycyclic aromatic hydrocarbon. We used an oligochaete, *Thalassodrilides* sp. (Naididae), collected from the sediment beneath a fish farm and a polychaete, *Perinereis nuntia*, which was obtained from a commercial source. Populations of both organisms were exposed to 1400 μg/L of 1-nitronaphthalene in seawater for 3 days in the dark at 20 °C. The concentration of the pollutant decreased to 12 μg/L in the seawater containing the *Thalassodrilides* sp. and to 560 μg/L in the seawater containing *P. nuntia*. The 1-nitronaphthalene concentration in the bodies of the animals increased from 12 to 94 μg/kg in *Thalassodrilides* sp. and from 0.90 μg/kg to 38,000 μg/kg in *P. nuntia*. After 3 days, 99 % and 40 % of the 1-nitronaphthalene had been biotransformed in the *Thalassodrilides* sp. and *P. nuntia* experimental groups, respectively. We then tested the acute toxicity of residual 1-nitronaphthalene from the same water using mummichog (fish) larvae. After the larvae had been exposed for 96 h, the percentage of apparently unaffected larvae remaining was 83.3 % in *Thalassodrilides* sp. group but only 16.7 % in the *P. nuntia* group. Clearly, of the two species we studied, *Thalassodrilides* sp. had a superior ability to convert 1-nitronaphthalene into substances that were nontoxic to mummichog larvae. Therefore, we recommend the use of this species for bioremediation of chemically polluted sediments.

(3) Ito M., Ito K., Ohta K., Hano T., Onduka T., Mochida K., and Fujii K., 2016: Evaluation of bioremediation potential of three benthic annelids in organically polluted marine sediment. *Chemosphere*, **163**, 392-399.

This study aimed to evaluate the possible remedial effects of three marine benthic annelids on organically polluted sediments from the waters of Hatsukaichi Marina, Hiroshima, Japan. Two polychaetes, *Perinereis nuntia* and *Capitella* cf. *teleta*, and an oligochaete, *Thalassodrilides* sp., were incubated in sediments for 50 days. Their effects on physicochemical properties, such as organic matter (loss on ignition), redox potential (Eh), acid volatile sulfides (AVS), and degradation of polycyclic aromatic hydrocarbons (PAHs), were assessed. The polychaetes *P. nuntia* and *C.* cf. *teleta* significantly increased Eh level and decreased AVS level compared with the oligochaete *Thalassodrilides* sp. and control (without benthic organisms). Total PAH concentration significantly decreased from the initial level in all three groups; *Thalassodrilides* sp. had a marked ability to reduce PAHs in sediment. These results indicate that benthic organisms have species-specific remediation properties and ecological functions in organically polluted sediments.

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Monitoring coastal acidification along the U.S. East coast: concerns for shellfish production

Matthew POACH[*1], Daphne MUNROE[*2], James VASSLIDES[*3], Ian ABRAHAMSEN[*4], and Nicole COFFEY[*5]

Abstract: In coastal systems endangered by acidified water, it becomes paramount to understand the link between acidification and its environmental drivers. Embayments along the US Mid-Atlantic coast are particularly vulnerable to local amplification of ocean acidification due to eutrophic conditions, low alkalinity freshwater input, and episodic upwelling of acidified water. To better understand these drivers, two research studies were conducted along the coast of New Jersey, U. S. A. The first study was conducted during the summer of 2014 at the Aquaculture Innovation Center (AIC) of Rutgers University located in Cape May, NJ. The AIC is an important research hatchery that currently supports the local oyster aquaculture industry through the production of disease resistant and triploid seed oysters. The second study, which began in the summer of 2017, focused on elucidating the range of pH and aragonite saturation (Ω_{Ar}) conditions experienced in Little Egg Harbor Bay, NJ, an important shellfish farming and fishing location. At the AIC, temperature, salinity, dissolved oxygen (DO), turbidity and pH were continuously monitored at the intake pipe located in the Cape May Canal. The pH at the intake showed diurnal variations that tended to mirror the DO signal. The largest drop in pH was measured in July of 2014. This pH drop was decoupled from the DO signal. The occurrence of consistent Southwesterly winds and cooler surface water temperatures along the coast before the pH decrease indicated that upwelling was occurring. A strong shift in the winds likely pushed upwelled water inshore to the intake. The lowest pH reading coincided with a decrease in salinity due to higher river discharge and strong winds. These results show that hatcheries along the NJ coast need to be aware that upwelling and freshwater input may bring reduced pH conditions that can negatively impact shellfish production, and highlights the need for continued monitoring. Starting in May of 2017, temperature, salinity, DO, turbidity, pH and carbon dioxide partial pressure (pCO_2) were continuously monitored at a station in Little Egg Harbor off Beach Haven. Sensor temperature, salinity, pH and pCO_2 data were used to calculate Ω_{Ar}. Results indicated that DO and pH conditions are likely not detrimental to local shellfish production. There was no indication that upwelling occurred during the monitoring period so no conclusions could be reached about the potential for summertime upwelling to impact shellfish production in Little Egg Harbor.

Key words: coastal acidification, upwelling, shellfish aquaculture, hatchery

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*1 NOAA/NMFS, James J Howard Marine Sciences Laboratory, Highlands, NJ 07732, U. S. A.
*2 Rutgers University, Haskin Shellfish Research Laboratory, Port Norris, NJ 08349, U. S. A
*3 Barnegat Bay Partnership, Ocean County College, Toms River, NJ 08753, U. S. A.
*4 University of Pittsburgh, Pittsburgh, PA 15260, U. S. A.
*5 University of Delaware, Newark, DE 19716, U. S. A.
E-mail: matthew.poach@noaa.gov

Introduction

Human carbon dioxide (CO_2) emissions have raised atmospheric CO_2 levels from 180 ppmv in the 19th century to over 400 ppmv today (IPCC, 2014; Tans and Keeling, 2018). Of that CO_2 increase, ~ 1/3 has been absorbed by the oceans (Sabine *et al.*, 2004) and has impacted the ocean's carbonate chemistry in a process known as ocean acidification (OA). The increase in surface water pCO_2 leads to a decrease in pH and carbonate ion concentrations (Caldeira and Berner, 1999; Caldeira and Wickett, 2003). A reduction in the carbonate ion concentration also reduces carbonate ion saturation state (Ω), which can result in an undersaturated condition for carbonate minerals. These changes in carbonate chemistry are particularly detrimental to the early developmental stages of shellfish as the larvae tend to precipitate the more-soluble aragonite-form of calcium carbonate (Barton *et al.*, 2012; Waldbusser *et al.*, 2015). Aragonite undersaturation has been shown in laboratory experiments to reduce survival and growth of shellfish larvae (Barton *et al.*, 2012; Gazeau *et al.*, 2013; Gobler *et al.*, 2014; Talmage and Gobler, 2010; Waldbusser *et al.*, 2013; Waldbusser and Salisbury, 2014).

While OA monitoring has historically been focused on offshore regions, commercially important bivalve aquaculture and fisheries are located in the coastal zone where the CO_2-system is impacted by the additive effects of natural and anthropogenic processes at both global and local scales (Feely *et al.*, 2010; Cai, 2011; Bauer *et al.*, 2013; Duarte *et al.*, 2013; Breitburg *et al.*, 2015). In productive estuarine environments, the system is further driven toward increasing acidity from local generation of CO_2 due to microbial decomposition of labile organic carbon and by injection of waters undersaturated with respect to carbonate via upwelling or storm events. With high rates of photosynthesis and respiration in these systems, they can be expected to experience greater fluctuations in pH and Ω compared to the open ocean. Importantly, increased respiratory CO_2-production and upwelling events that lower Ω and adversely impact estuarine chemistry may co-occur with the timing of the economically driven production of larval shellfish at hatcheries or spawning in wild populations. For example, coastal acidification has caused hatchery larval production problems costing the oyster farming industry in the U.S. Pacific Northwest over $100 million and threatening 1000's of jobs (Washington State, 2012).

Global aquaculture production is expanding and now accounts for half of world food fish and shellfish production (Naylor *et al.*, 2009). Shellfish aquaculture is particular a widely practiced way of producing food in coastal areas that helps meet the needs of a rapidly growing global human population (Foley *et al.*, 2011; FAO, 2016). Most commercially and recreationally important fish and shellfish species depend on estuarine ecosystem services at some point in their life cycle. An assessment of the vulnerability and adaptation of U.S. shellfisheries to ocean acidification (OA) found that the most socially vulnerable communities are spread along the U.S. East Coast and Gulf of Mexico (Ekstrom *et al.*, 2015). Their analysis also found that a number of socially vulnerable communities lie adjacent to water bodies that are exposed to a high rate of OA or at least one local amplifier, indicating that these places could be at high overall vulnerability to OA.

Shellfish production was once vitally important to the economy of the state of New Jersey (Ford, 1997). From 1870 to 1930, the Barnegat Bay-Cape May area produced about 20 % of all market oysters harvested in the state. This production had declined significantly by the 1950's due to overfishing, salinity changes, and disease. The quahog fishery also saw a decline after the 1950's mainly due to pollution which caused bed closures. The decline of shellfish populations along the New Jersey coast over the last century has prompted significant efforts at their restoration. As a result of coastal acidification processes, the shellfish industry in New Jersey is likely already experiencing acidification conditions stronger than the open ocean. Since modern shellfish aquaculture production relies entirely on reliable and consistent larval production in hatcheries, understanding coastal ocean acidification (coastal OA) in the Northeast U.S. is a matter critical to the stability and sustainability of this industry. In coastal systems endangered by acidified water, it becomes paramount to understand the link between acidification and its environmental drivers.

In order to understand the carbonate chemistry experienced by coastal estuaries and their shellfish resources, two different monitoring studies were conducted, one at Rutgers University's Aquaculture Innovation Center (AIC) located in Cape May and the other at a marina in the southernmost segment of the Barnegat Bay - Little Egg Harbor Estuary complex, NJ, U.S.A. (**Fig.1**). The AIC is an important research hatchery that currently supports the New Jersey oyster aquaculture industry through the production of disease resistant and triploid seed oysters. The Barnegat Bay - Little Egg Harbor estuary is currently undergoing eutrophication (Fertig *et al.*, 2014), which may impact shellfish restoration in this estuary.

Materials and Methods

AIC: At the AIC, the carbonate chemistry of intake water was monitored during the summer of 2014. From June 15 through July 20, temperature, salinity, dissolved oxygen (DO), and pH were measured every 15 minutes at the AIC's intake pipe located in the Cape May Canal. Parameters were monitored using a YSI EXO™2 water quality sonde that was installed 1 meter off the bottom next to the intake. Probes were calibrated according to manufacturer recommendations prior to deployment. Probe calibration was also performed at the end of the deployment. After sensor retrieval, data were downloaded and subjected to quality control analysis. Quality control consisted of the identification and removal of missing or erroneous data due to sensor malfunction as well as identification and removal of outliers. Correlations between pH and other measured parameters were examined through regression analysis.

Little Egg Harbor (LEH): During the Spring of 2017, the Little Egg Harbor estuary monitoring station was installed at a bay side pier located at Morrison's Marina in Beach Haven, NJ. The installation consisted of a YSI EXO™2 water quality sonde to measure temperature, salinity, DO, and pH and a Pro-Oceanus CO_2Pro-CV™ sensor to measure pCO_2. In July, a SeaFET™ pH sensor was attached to the pCO_2 sensor. Sensors were installed ~ 1 meter off the bay bottom. YSI sensor readings were collected every 15 minutes while the pCO_2 and SeaFET™ pH sensors took a reading every 30 minutes. Sensor data was stored by a Campbell® Instruments CR-6 datalogger. Data sets were retrieved hourly through cellular telemetry to a desktop computer. Downloaded data were subjected to quality control analysis, which consisted of the identification and removal of missing or erroneous data due to sensor malfunction as well as identification and removal of outliers. The sampling line for the pCO_2 and SeaFET™ sensors fouled often compromising the data and leading to their removal in mid-August. Data recorded during an 11 day period in June and a 12 day period in July displayed a reasonable range of values for pCO_2. During those periods the pCO_2 explained 89 % of variation in pH indicating that the data was likely valid as the YSI pH and the pCO_2 sensors were independent of each other. In July the SeaFET™ pH was similar to YSI pH. As the SeaFET™ sensor shared the same sample intake as the pCO_2 sensor the similarity between the two independent pH readings provide additional support for the quality of the YSI pH data and pCO_2 data (**Fig.2**). The valid YSI pH and pCO_2 data along with their corresponding depth, salinity, and temperature data were used to calculate the aragonite saturation state (Ω_{Ar}) by the CO_2SYS_xls program (Pierrot *et al.* 2006).

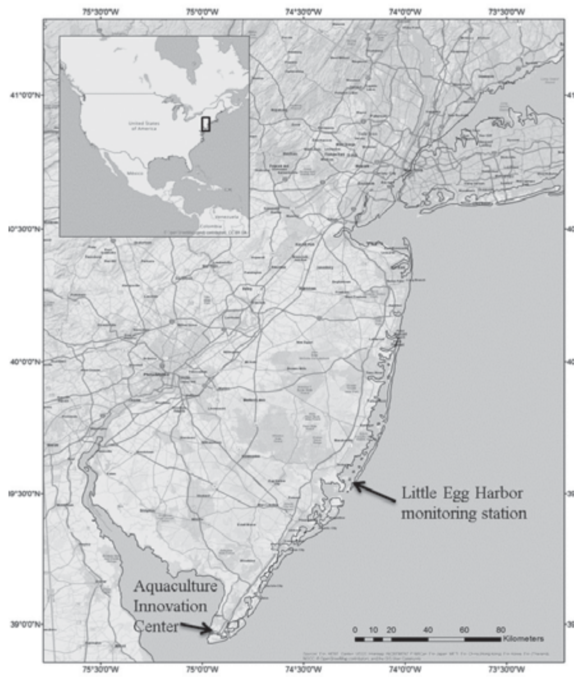

Fig. 1. Map showing the coast of New Jersey with the two monitoring sites indicated.

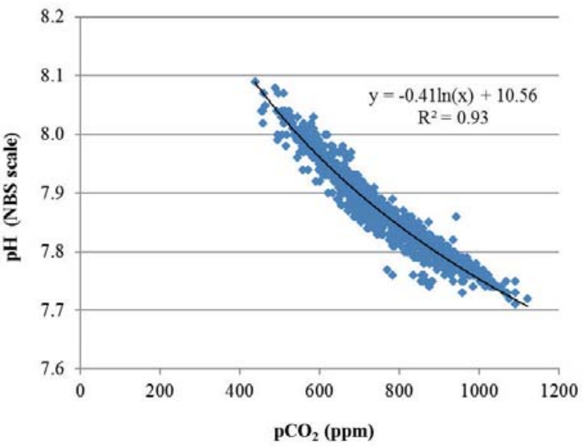

Fig. 2. Regression relationship between pCO_2 and YSI pH measured in the LEH estuary during June and July.

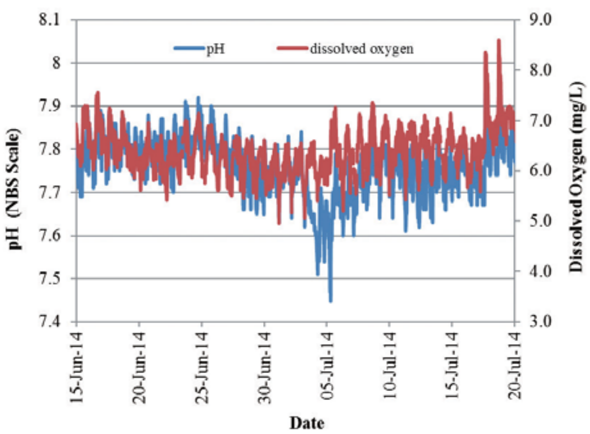

Fig. 3. The pH as measured on the NBS scale and dissolved oxygen in mg/L recorded during the study period by a YSI water quality sonde installed one meter off the bottom and next to the intake pipe for the Aquaculture Innovation Center.

Results and Discussion

AIC: From June 15th to July 20st of 2014, pH ranged from 7.45 to 7.99 while DO ranged from 4.95 to 8.60 mg/L (**Fig.3**). The coarse scale trend for pH tended to mimic that for DO. Both tended to show a general diurnal trend of increasing values during the day and decreasing values at night. These trends were expected because during the day net photosynthesis will increase both DO and pH, while net respiration during the night will decrease both. Even though pH and DO exhibited similar patterns, DO accounted for only 35 % of the variation in pH. The relationship between pH and DO noticeably diverged during July 3rd through the 5th (**Fig.3**). During this period the decreases in pH were not associated with similar decreases in DO. The lowest pH values of the study were measured during this period with the lowest value of 7.45 measured on the morning of July 5th. Low correlation between pH and DO can result from factors in the coastal environment that can affect pH without a change in DO such as the input of low pH water from either coastal upwelling or freshwater inflow. Upwelled water tends to have a pH lower than the average surface ocean pH due to higher net respiration rates in bottom water. Once this water reaches the surface it will equilibrate rather quickly with atmospheric O_2, while pCO_2 remains relatively unchanged due the slow rate of CO_2 degassing. Likewise, most rivers in New Jersey have low alkalinity which would lead to a different relationship between pH and O_2 in river water than in ocean water.

An examination of other environmental data indicated that the drop in pH observed from July 3rd through the 5th likely resulted from a combination of both coastal upwelling and freshwater input. From July 1st through the 3rd there were strong south / southwest winds (**Fig.4**), which are necessary to drive upwelling along the New Jersey coast. The premise that upwelling was occurring during this period was supported by colder sea surface temperatures along the coast on July 2nd (**Fig.5a**). Cold water along the coast on July 5th (**Fig.5b**), indicated that upwelling was still occurring even though the winds were blowing strongly out of the northeast on July 4th then out of the northwest on July 5th. This change in wind direction along with its strength is likely the reason why low pH water made it to the AIC's intake. Similar pH drops were not recorded at other dates when there were strong upwelling favorable winds. Strong southerly winds occurred between July 13th and 15th; yet during or immediately after this period, pH did not drop below 7.6. The difference between this period of southerly winds and the previous was the lack of strong northerly winds immediately after July 15th. The distinction between these two events strongly suggests that an abrupt shift to strong

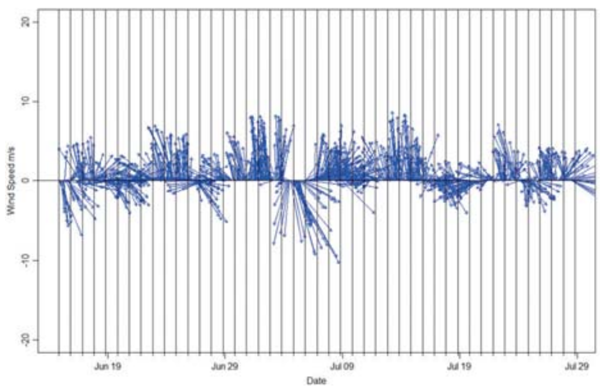

Fig. 4. Wind stick vector plot for winds during the study period as measured by the weather station located at the Cape May - Lewes ferry terminal which is adjacent to the Aquaculture Innovation Center. Arrows point in the compass direction toward which the wind is blowing (*i.e.* a northward pointing arrow indicates a south wind). Arrow heads mark the magnitude of the winds.

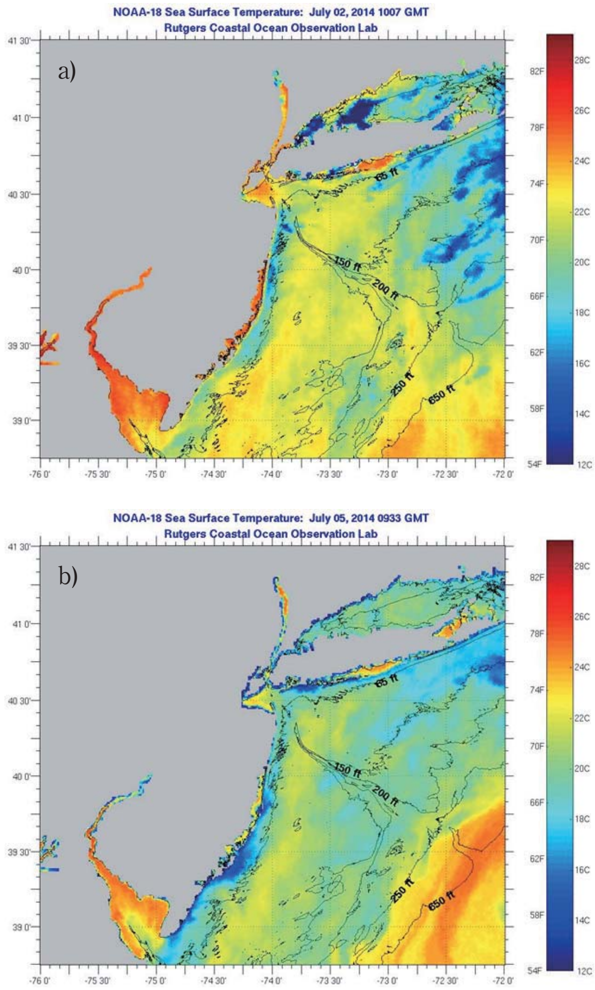

Fig. 5. Satellite AVHRR-derived images of sea surface temperature from NOAA-18 satellite for a) July 2nd at 10:07 Z and b) July 5th at 09:33 Z. (Images from Rutgers Coastal Ocean Observation Laboratory at https://marine.rutgers.edu/cool/sat_data/)

northerly winds following sustained southerly winds helps to push upwelled water inshore along the New Jersey coast.

While upwelling and strong northerly winds would explain the decrease in pH on July 4th; the lowest pH of 7.45 on July 5th coincided with the lowest salinity reading during the study period. Salinity dropped to a low of 21.3 ppt after an early morning high of 29.3 ppt (data not shown). This salinity decrease coincided with a high river discharge and outgoing tide. This indicates that river water likely contributed to the lowest pH reading. Along with freshwater input, upwelling and strong northerly winds were also likely contributors as there was a higher river discharge on June 15th, yet on that date salinity and pH did not drop lower than 25.9 and 7.69, respectively.

These results indicate that both upwelling and freshwater input can reduce the pH of source water for the AIC. To assess the potential for those drivers to affect shellfish production it is necessary to consider the magnitude, duration, and timing of pH decreases. During this study the pH decreased to levels that have been shown to decrease survival and to delay metamorphism of *C. virginica larvae* (Gobler and Talmage, 2014; Talmage and Gobler, 2009). It should be noted, however, that these negative effects weren't exhibited until after more than three days of constant exposure. The reduced pH event at the AIC lasted two days and was not constantly held low as intermittent increases occurred due to tidal changes. Fluctuating pH has been shown to lessen the negative effects of constantly low pH on survival of *C. virginica larvae* (Clark and Gobler, 2016; Keppel *et al.*, 2016). When only considering the pH data, the previous research suggests that the short duration of the reduced pH event along with the fluctuation in pH levels would not be stressful enough to impact oyster product in the facility (Shaw *et al.*, 2013). But the decrease in pH wasn't the only change that would have been stressful for oyster production. The decrease in pH on July 5th was also accompanied by an additional stress of a sudden decrease in salinity. While no studies have looked at the effects of short-term salinity decreases on larvae of *C. virginica*; in studies of gastropod larvae, short term salinity decreases resulted in increased mortality (Diederich *et al*., 2011; Montory *et al*., 2014; Montory *et al*., 2016). Decreased salinity has also been shown to exacerbate the negative effects of lower pH on *C. virginica* juveniles (Dickinson *et al*., 2012; Waldbusser *et al*., 2011). Even if the reduction in salinity was temporary; this additional stress may shorten the exposure time necessary for reduced pH to affect oyster larvae.

As for event timing, the AIC conducts the majority of its oyster spawning during the late winter-spring period. High river discharges accompanied by strong northerly winds are more likely to occur during that time period (Hughes, 2011; Joesoef, 2015); while upwelling is limited to the summer season. This means that freshwater input has a higher potential to impact AIC operations than upwelling. While upwelling will likely not affect spring hatchery operations, it occurs during the most sensitive time of year for natural coastal populations of shellfish. In coastal New Jersey, oysters and clams spawn during the summer. Summer is also when eutrophic systems can develop hypoxic conditions with associated acidification. These conditions can be exacerbated by upwelling as it not only transports acidified water but also nutrients that further drive eutrophication.

LEH: For June and July of 2017, YSI pH ranged from 7.71 to 8.15 while DO ranged from 4.4 to 9.57 mg/L (**Fig.6**). As with the AIC data, the coarse scale trend for pH mimicked that for DO, with increasing values during the day and decreasing values at night. Conversely, pH trends in June and July mirror the trends in pCO_2, which ranged from to 438 to 1122 μatm (**Fig.7**). The fluctuations in pH and pCO_2 produced levels that ranged from present-day averages for the open ocean to averages predicted for the open ocean at the end of the 21st century due to ocean acidification (Bopp *et al*., 2013). The paired values for YSI pH and pCO_2 produced values for Ω_{Ar} ranging from 0.75 to 1.87 (**Fig.8**). Most Ω_{Ar} values were between 1 and 1.5. The Ω_{Ar} dropped below 1 for an extended period on June 6th and then again on June 7th. This likely resulted from a strong east wind

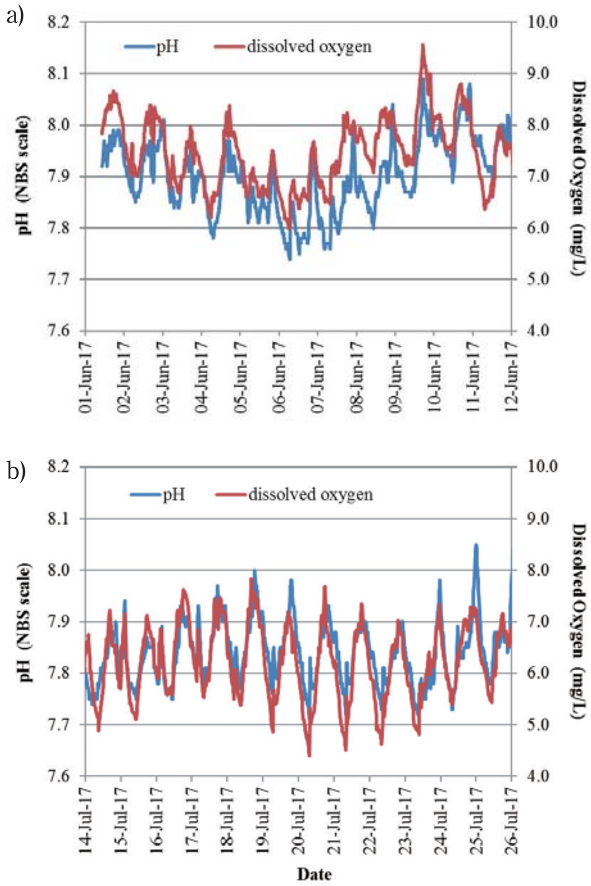

Fig. 6. Trends in pH (blue) and dissolved oxygen (red) measured at the intake to the AIC hatchery by a YSI EXO™2 water quality sonde during a) June and b) July of 2017.

during both days that helped to build up water levels in the estuary.

These results are evidence of the dynamic environment to which estuarine organism must adapt. It is this dynamic nature that makes it difficult to predict the effects of acidification on bivalves common in Northeastern U.S. estuaries. While constant exposure to pCO_2 and pH levels similar to the lowest recorded here have been shown to affect the survival, metamorphosis, growth, and physiology of *Mercenaria mercenaria, Argopecten irradians*, and *Crassostrea virginica* larvae (Gobler and Talmage, 2014; Miller *et al*., 2009; Talmage and Gobler, 2009); effects were not seen when exposure periods were shorter (Boulais *et al*., 2017; Talmage and Gobler, 2009). Such shorter exposure periods may occur under fluctuating pH conditions leading to the mitigation of

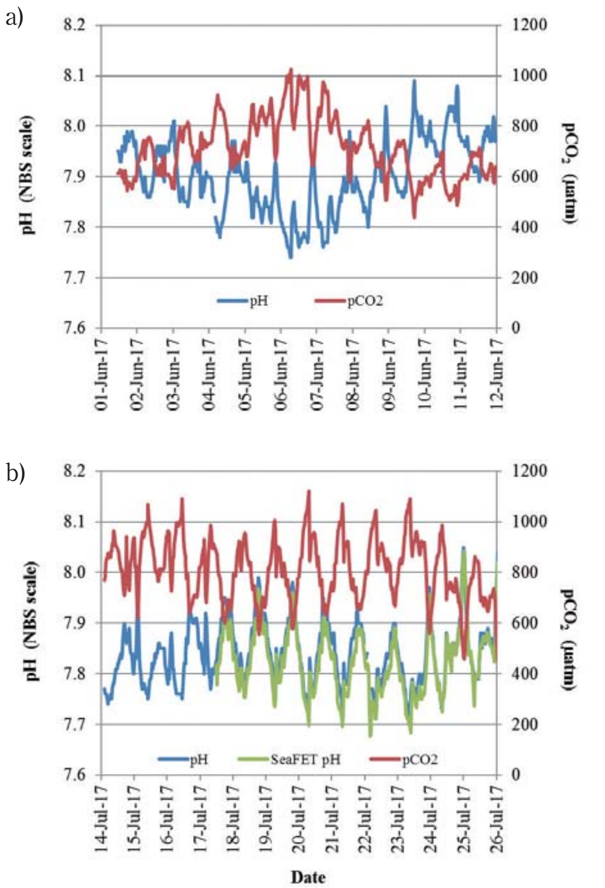

Fig. 7. Trends in pH measured by a YSI EXO™2 sonde (blue) and a SeaFET™ (green) and pCO_2 measured by a CO_2Pro-CV™ sensor in LEH estuary during a) June and b) July of 2017.

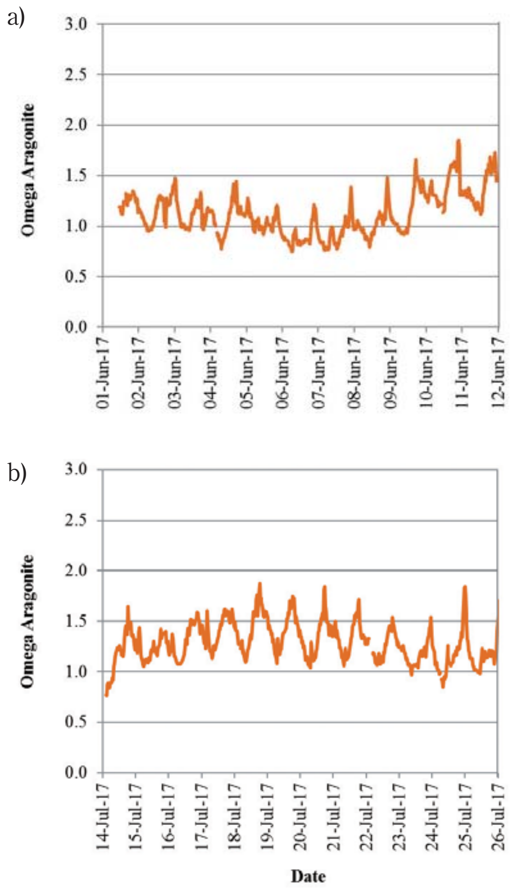

Fig. 8. Trends in aragonite saturation state, omega aragonite, measured 1 meter off the bottom in LEH estuary during a) June and b) July of 2017.

low pH impacts on bivalves (Frieder *et al*., 2014). Very few studies of acidification effects on local bivalve species have included a fluctuating pH treatment. In studies that have included fluctuating treatments, pH was decrease to levels below the lowest pH levels recorded here (Clark and Gobler, 2016; Gobler *et al*., 2017; Keppel *et al*., 2016). The levels of pH and pCO_2 recorded here likely did not lead to negative impacts because Ω_{Ar} rarely dropped below 1. Still, even fluctuating pH conditions can produce negative impacts in bivalves when compared to static levels that are similar to the average of the fluctuations. In order to understand the impacts of fluctuations in pH reported for LEH, more studies need to be conducted that incorporate similar pH ranges.

The LEH is considered to be undergoing eutrophication (Fertig *et al*., 2014). Eutrophic estuaries can experience extended periods of hypoxic and anoxic conditions in summer that also lead to depressed pH (Gobler and Baumann, 2016). Hypoxic conditions and its associated acidification have negative effects on marine organisms that are both additive and synergistic (Wallace *et al*., 2014). Even though LEH is considered mildly eutrophic, DO levels did not drop below 4 mg/L (**Fig.6**). The DO values recorded here appear to be representative of summertime values for the Barnegat Bay – LEH system (Glibert *et al*., 2010; NJDEP, 2014). This system is shallow and well mixed which deters the occurrence of extremely low DO levels (Glibert *et al*., 2010). The levels of both DO and pH measured during the monitoring period indicate that this area of LEH is likely not experiencing oxygen or carbonate conditions that are detrimental to shellfish production.

The LEH monitoring site was chosen because it is near the mouth of Great Bay, which is a site of recurrent summertime upwelling (Glenn *et al*., 2004). A decrease in pH indicative of upwelled water did not occur during the June and July monitoring periods highlighted here. While it is possible for upwelling to occur and not be pushed far enough inshore to be captured at this sensor location; upwelling was not indicated in the coastal sea surface temperature data during June or July. More monitoring is necessary to determine if upwelled water has the potential to impact the LEH ecosystem. Determining if upwelling can enter LEH is important because it not only brings lower pH water but also additional nutrients to fuel productivity during the warmer more productive time of the year. These excess nutrients can exacerbate eutrophication.

Acknowledgment

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References

Bauer J. E., Cai W. J., Raymond P. A., Bianchi T. S., Hopkinson C. S., and Regnier P. A. G., 2013: The changing carbon cycle of the coastal ocean. *Nature*, **504**, 61-70.

Bopp L., Resplandy L., Orr J. C., Doney S. C., Dunne J. P., Gehlen M., Halloran P., Heinze C., Ilyina T., Séferian R., Tjiputra J., and Vichi M., 2013: Multiple stressors of ocean ecosystems of the 21st century: projections with CMIP5 models. *Biogeosciences*, **10**, 6225-6245.

Boulais M., Chenevert K. J., Demey A. T., Darrow E. S., Robison M. R., Roberts J. P., and Volety A., 2017: Oyster reproduction is compromised by acidification experienced seasonally in coastal regions. *Sci. Rep*., **7**, 3276. doi:10.1038/s41598-017-13480-3

Breitburg D. L., Salisbury J., Bernhard J. M., Cai W. J., Dupont S., Doney S. C., Kroeker K. J., Levin L. A., Long W. C., Milke L. M., Miller S. H., Phelan B., Passow U., Seibel B. A., Todgham A. E., and Tarrant A. M., 2015: And on top of all that… Coping with ocean acidification in the midst of many stressors. *Oceanography*, **28**, 48-61.

Cai W. J., 2011: Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?. *Annu. Rev. Mar. Sci.*, **3**, 123-145.

Caldeira K. and Berner R., 1999: Seawater pH and atmospheric carbon dioxide. *Science*, **286**, 2043-2043.

Caldeira K. and Wickett M. E., 2003: Anthropogenic carbon and ocean pH. *Nature*, **425**, 365-365.

Clark H. R. and Gobler C. J., 2016: Diurnal fluctuations in CO_2 and dissolved oxygen concentrations do not provide a refuge from hypoxia and acidification for early-life-stage bivalves. *Mar. Ecol. Prog. Ser*., **558**, 1-14. doi:10.3354/meps11852

Dickinson G. H., Ivanina A. V., Matoo O. B., Pörtner H.O., Lannig G., Bock C., Beniash E., and Sokolova I. M., 2012: Interactive effects of salinity and elevated CO_2 levels on juvenile Eastern oysters, *Crassostrea virginica*. *J. Exp. Biol.*, **215**, 29-43. doi:10.1242/jeb.061481

Diederich C. M., Jarrett J. N., Chaparro O. R., Segura C. J., Arellano S. M., and Pechenik J. A., 2011: Low salinity stress experienced by larvae does not affect post-metamorphic growth or survival in three calyptraeid gastropods. *J. Exp. Mar. Biol. Ecol.*, **397**, 94-105.

Duarte C.M., Hendriks I. E., Moore T. S., Olsen Y. S., Steckbauer A., Ramajo L, Carstensen J., Trotter J. M., and McCulloh M., 2013: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, **36**, 221-236.

Feely R. A., Alin S. R., Newton J., Sabine C. L., Warner M., Devol A., Krembs C., and Maloy C., 2010: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuar. Coast. Shelf Sci.*, **88**, 442-449.

Fertig B., Kennish M. J., Sakowicz G. P., and Reynolds L. K., 2014: Mind the data gap: identifying and assessing drivers of changing eutrophication condition. *Estuaries and Coasts*, **37**, S198-S221. doi:10.1007/s1223701397465

Foley J. A., Ramankutty N., Brauman K. A., Cassidy E. S., Gerber J. S., Johnston M., Mueller N. D., O'Connell C., Ray D. K., West P. C., Balzer C., Bennett E. M., Carpenter S. R., Hill J., Monfreda C., Polasky S., Rockström J., Sheehan J., Siebert S., Tilman G. D., and Zaks D. P. M., 2011: Solutions for a cultivated planet. *Nature*, **478**, 337-342.

FAO, 2016: The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all, Rome, 200pp.

Ford S. E., 1997: History and present status of molluscan shellfisheries from Barnegat Bay to Delaware Bay, in "The History, Present Condition, and Future of the Molluscan Fisheries of North and Central America and Europe, Vol. 1. Atlantic and Gulf Coasts" (ed. by MacKenzie Jr. C. L., Burrell Jr. V. G., Rosenfield A., and Hobart W. L.), NOAA Tech. Rept. NMFS 127, pp. 119-140.

Frieder C. A., Gonzalez J. P., Bockmon E. E., Navarro M. O., and Levin L. A., 2014: Can variable pH and low oxygen moderate ocean acidification outcomes for mussel larvae?. *Glob. Chang. Biol.*, **20**, 754-764.

Gazeau F., Parker L. M., Comeau S., Gattuso J. P., O'Connor W. A., Martin S., Portner H. O., and Ross P. M., 2013: Impacts of ocean acidification on marine shelled molluscs. *Mar. Biol.*, **160**, 2207-2245.

Glenn S., Arnone R., Bergmann T., Bissett W. P., Crowley M., Cullen J., Gryzmski J., Haidvogel D., Kohut J., Moline M., Oliver M., Orrico C., Sherrell R., Song T., Weidemann A., Chant R., and Schofield O., 2004: Biogeochemical impact of summertime coastal upwelling on the New Jersey Shelf. *J. Geophys. Res.*, **109**, C12S02. doi:10.1029/2003JC002265

Glibert P. M., Madden C. J., Boynton W., Flemer D., Heil C., and Sharp J. H., 2010: Nutrients in estuaries: a summary report of the National Estuarine Experts Workgroup (2005–2007). US EPA report 68-C-02-091 and EP-C-07-025, United States Environmental Protection Agency, Washington, D.C., 188pp.

Gobler C. J. and Talmage S. C., 2014: Physiological response and resilience of early life-stage Eastern oysters (*Crassostrea virginica*) to past, present and future ocean acidification. *Conserv. Physiol.*, **2**. doi:10.1093/conphys/cou004

Gobler C. J., DePasquale E. L., Griffith A. W., and Baumann H., 2014: Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLoS One*, **9(1)**, e83648. doi:10.1371/journal.pone.0083648

Gobler C. J., Clark H. R., Griffith A. W., and Lusty M. V., 2017: Diurnal fluctuation in acidification and hypoxia reduce growth and survival of larval and juvenile bay scallops (*Argopecten irradians*) and hard clams (*Mercenaria mercenaria*). *Front. Mar. Sci.*, **3**, 282. doi:10.3389/fmars.2016.00282

Hughes C. P., 2011: The climatology of the Delaware Bay/sea breeze. M.S. thesis. School of Marine Science and Policy, University of Delaware, 129pp. [Available online at http://udspace.udel.edu/handle/19716/10659.]

IPCC, 2014: Climate Change 2014. Synthesis report, Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by Pachauri R. K. and Meyer L. A.), IPCC, Geneva, Switzerland, 151pp.

Joesoef A., Huang W.-J., Gao Y., and Cai W.-J., 2015: Air–water fluxes and sources of carbon dioxide in the Delaware Estuary: spatial and seasonal variability. *Biogeosciences*, **12**, 6085–6101. doi:10.5194/bg-12-6085-2015

Keppel A. G., Breitburg D. L., and Burrell R. B., 2016: Effects of co-varying diel-cycling hypoxia and pH on growth in the Juvenile Eastern Oyster, *Crassostrea virginica*. *PLoS One*, **11**, e0161088. doi:10.1371/journal.pone.0161088

Miller A. W., Reynolds A. C., Sobrino C., and Riedel G. F., 2009: Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS One*, **4**, e5661. doi:10.1371/journal.pone.0005661

Montory J. A., Chaparro O. R., Pechenik J. A., Diederich

C. M., and Cubillos V. M., 2014: Impact of short-term salinity stress on larval development of the marine gastropod *Crepipatella fecunda* (*Calyptraeidae*). *J. Exp. Mar. Biol. Ecol.*, **458**, 39-45.

Montory J. A., Chaparro O. R., Navarro J. M., Pechenik J. A., and Cubillos V. M., 2016: Post-metamorphic impact of brief hyposaline stress on recently hatched veligers of the gastropod *Crepipatella peruviana* (*Calyptraeidae*). *Mar. Biol.*, **163**, 1-10.

Naylor R. L., Hardy R. W., Bureau D. P., Chiu A., Elliott M., Farrell A. P., Forster I., Gatlin D. M., Goldburg R., Hua K., and Nichols P. D., 2009: Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci. U.S.A*, **106**, 15103-15110. doi:10.1073/pnas.0905235106

New Jersey Dept. of Environmental Protection (NJDEP), 2014: Dissolved Oxygen Levels in Estuarine & Near Shore Waters. Environmental Trends Report, NJDEP, Office of Science. https://www.nj.gov/dep/dsr/trends/

Pierrot D., Lewis E., and Wallace D. W. R., 2006: MS Excel program developed for CO_2 system calculations, ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi:10.3334/CDIAC/otg.CO2SYS_XLS_CDIAC105a

Sabine C. L., Feely R. A., Gruber N., Key R. M., Lee K., Bullister J. L., Wanninkhof R., Wong C. S., Wallace D. W. R., Tilbrook B., Millero F. J., Peng T.-H., Kozyr A., Ono T., and Rios A. F., 2004: The oceanic sink for anthropogenic CO_2. *Science*, **305**, 367-371.

Shaw E. C., Munday P. L., and McNeil B. I., 2013: The role of CO_2 variability and exposure time for biological impacts of ocean acidification. *Geophys. Res. Lett.*, **40**, 4685-4688. doi:10.1002/grl.50883

Talmage S. C. and Gobler C. J., 2009: The effects of elevated carbon dioxide concentrations on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*). *Limnol. Oceanogr.*, **54**, 2072-2080. doi:10.4319/lo.2009.54.6.2072

Talmage S. C. and Gobler C. J., 2010: Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *Proc. Natl. Acad. Sci. U.S.A*, **107**, 17246-17251.

Tans P. and Keeling R., 2018: Trends in atmospheric carbon dioxide, Mauna Loa, Hawaii, Earth System Research Laboratory Global Monitoring Division, NOAA. https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

Waldbusser G. G. and Salisbury J. E., 2014: Ocean acidification in the coastal zone from an organism's perspective: multiple system parameters, frequency domains, and habitats. *Annu. Rev. Mar. Sci.*, **6**, 221-247.

Waldbusser G. G., Brunner E. L., Haley B. A., Hales B., Langdon C. J, and Prahl F. G., 2013: A developmental and energetic basis linking larval oyster shell formation to acidification sensitivity. *Geophys. Res. Lett.*, **40**, 2171-2176. doi:10.1002/grl.50449

Waldbusser G. G., Hales B., Langdon C., Haley B. A., Schrader P., Brunner E. L., Gray M. W., Miller C. A., and Gimenez I., 2015: Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nat. Clim. Chang.*, **5**, 273-280.

Waldbusser G. C., Voigt E. P., Bergschneider H., Green M. A., and Newell R. I. E., 2011: Biocalcification in the Eastern Oyster (*Crassostrea virginica*) in relation to long-term trends in Chesapeake Bay pH. *Estuaries and Coasts*, **34**, 221-231. doi:10.1007/s12237-010-9307-0

Washington State Blue Ribbon Panel on Ocean Acidification, 2012: Ocean acidification: from knowledge to action, Washington State's strategic response (ed. by Adelsman H. and Binder L. W.), Washington Department of Ecology, Olympia, Washington. Publication no. 12-01-015.

Annotated bibliography

(1) Barton A., Hales B., Waldbusser G. G., Langdon C., and Feely R. A., 2012: The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol. Oceanogr.*, **57**, 698-710.

The authors report results of a monitoring study designed to evaluate the response of Pacific oyster (*Crassostrea gigas*) larvae, grown at a commercial hatchery on the Oregon coast, to natural changes in carbonate chemistry associated with periodic seasonal upwelling during the summer of 2009. During the study the intake waters experienced aragonite saturation states from 0.8 to 3.2 and pH from 7.6 to 8.2. They observed significant negative relationships between aragonite saturation states at the time of spawning and subsequent growth and production of larvae over the size range of 120 to 150-mm shell length. This was one of the first studies to link failures in seed oyster production to more corrosive water from coastal upwelling.

(2) Booth J. A.T., McPhee-Shaw E. E., Chua P., Kingsley E., Denna M., Phillips R., Bograd S. J., Zeidberg L. D., and Gilly W. F., 2012: Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Cont. Shelf Res.*, **45**, 108-115.

The authors reviewed a decade-long data set to examine oxygen and pH variability on the inner shelf off of Central California. Results show regular inundation of cold, hypoxic and low pH water. The source-water for these periodic intrusions originates in the offshore, midwater environment above the local OMZ, generally between 50–100 m but occasionally deeper. Pulses of the greatest intensity arose at the onset of the spring upwelling season, and fluctuations were strongly semidiurnal and diurnal. Arrival of cold, hypoxic water on the inner shelf appears to be driven by tidal-frequency internal waves pushing deep, upwelled water into nearshore habitats. These observations are consistent with the interpretation that hypoxic water is advected shoreward from the deep, offshore environment where water masses experience a general decline of temperature, oxygen and pH with depth.

(3) Ekstrom J. A., Suatoni L., Cooley S. R., Pendleton L. H., Waldbusser G. G., Cinner J. E., Ritter J., Langdon C., van Hooidonk R., Gledhill D., Wellman K., Beck M. W., Brander L. M., Rittschof D., Doherty C., Edwards P. E. T., and Portela R., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nat. Clim. Chang.*, **5**, 207-214. doi:10.1038/nclimate2508

Authors present a spatially explicit, multidisciplinary analysis of the vulnerability of coastal human communities in the United States to ocean acidification. Their results highlight US regions most vulnerable to ocean acidification, reasons for that vulnerability, important knowledge and information gaps, and opportunities to adapt through local actions. Results indicated that 16 of the 23 bioregions around the United States are exposed to rapid OA (reaching Ω_{Ar} 1.5 by 2050) or at least one amplifier; 10 regions are exposed to two or more threats of acidification. The marine ecosystems and shelled molluscs around the Pacific Northwest and Southern Alaska are expected to be exposed soonest to rising global OA, followed by the north-central West Coast and the Gulf of Maine in the northeast United States. Communities highly reliant on shelled molluscs in these bioregions are at risk from OA either now or in the coming decades. In addition, pockets of marine ecosystems along the East and Gulf Coasts will experience acidification earlier than global projections indicate, owing to the presence of local amplifiers such as coastal eutrophication and discharge of low-Ω_{Ar} river water. This analysis can be used to help prioritize societal responses to ocean acidification.

(4) Gobler C. J. and Baumann H., 2016: Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. *Biol. Lett.*, **12**, 20150976. doi:10.1098/rsbl.2015.0976

As climate change progresses, the effects of atmospheric CO_2 on coastal acidification will intensify; and, while hypoxia is a much studied stressor for coastal organisms, the combined effect of hypoxia and acidification has only recently become a focus for scientists. The authors conduct a meta-analysis of published research that studied the combined effects of pH and dissolved oxygen variability on marine organisms. The authors conclude that low DO is a greater stressor to most marine organisms than low pH conditions, although worse effects can occur through the synergistic interaction of the two. While most traits under concurrent low DO and low pH appeared to be additively affected, every study reviewed also found synergistic interactions in at least one instance. They also conclude that neither the occurrence nor the strength of these synergistic impacts is currently predictable, and therefore, the true threat of concurrent acidification and hypoxia to marine food webs and fisheries is still not fully understood. Addressing this knowledge gap will require an expansion of multi-stressor approaches in experimental and field studies.

(5) Wallace R. B., Baumann H., Grear J. S., Aller R. C., and Gobler C. J., 2014: Coastal ocean acidification: The other eutrophication problem. *Estuar. Coast. Shelf Sci.*, **148**, 1-13. doi:10.1016/j.ecss.2014.05.027

To assess the potential for acidification in eutrophic estuaries, the authors characterized the spatial and temporal patterns of DO, pH, pCO_2, and Ω_{Ar} in four, semi-enclosed estuarine system across the Northeast US: Narragansett Bay, Long Island Sound, Jamaica Bay, and Hempstead Bay. Multi-year monitoring datasets were assessed to define seasonal patterns in pH and DO while cruises were conducted to vertically and horizontally resolve spatial patterns of acidification during the seasonal onset, peak, and decline of hypoxia in these estuaries. They utilized three approaches for this study: 1) The analysis of monthly monitoring data across Long Island Sound; 2) Vertical measurements of water column conditions across Narragansett Bay, Long Island Sound, and Jamaica Bay; and 3) Continuous, horizontal mapping of conditions across Jamaica Bay and Hempstead Bay. Low pH conditions (< 7.4) were detected in all systems during summer and fall months concurrent with the decline in DO concentrations. While hypoxic waters and/or regions in close proximity to sewage discharge had extremely high levels of pCO_2, (> 3000 μatm), were acidic pH (< 7.0), and were undersaturated with regard to aragonite ($\Omega_{Ar} < 1$), even near-normoxic but eutrophic regions of these estuaries were often relatively acidified (pH < 7.7) during late summer and/or early fall. This study revealed that acidification is an annual feature of eutrophic estuaries across the Northeast US that co-occurs with seasonally low oxygen. The spatial and temporal dynamics of DO, pH, pCO_2, and Ω_{Ar} suggest that they are all ultimately driven by high rates of microbial respiration. The degree of acidification observed in these systems during summer are within ranges that have been shown to adversely impact a wide range of marine life.

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Growth variation in long blade kelp *Saccharina longissima* in eastern Hokkaido, Japan

Natsuki HASEGAWA[*1], Toshihiro ONITSUKA[*2], Sayaka ITO[*3], and Tomonori AZUMAYA[*2]

Abstract: *Saccharina longissima* (Naga-konbu in Japanese) is distributed in shallow Pacific coastal areas from eastern Hokkaido (Kushiro and Nemuro) to Chishima Island. It is a commercially important Laminariacean kelp species in this area. The variations in the blade size of *S. longissima* (age 1+) were analyzed in Habomai, eastern Hokkaido, Japan. The fisheries cooperative association of Habomai in Nemuro monitored the blade size of the kelp in the harvest grounds along more than 15 km of coastline in May and June from 2000 to 2014. The monitoring data showed that the blade weight varied among years, and the growth of blade weight was greater in 2002 and 2009 then the other years. The kelps had a poorer growth of the blade in 2001, 2011 and 2013. Correlation analysis revealed that the coefficients between the blade weight in May and the monthly mean water temperature in spring to autumn in the previous year were negative but positive in winter to spring in the same year. Generalized linear regression model (GLM) analysis of the blade weight in May also revealed that the growth models including only monthly mean water temperature (January, April, July and October in the previous year, January, April during in the same year) and longitude effectively estimated the variation of the annual mean weight. Correlation analysis also revealed that the mean wet weight of *S. longissima* in May represents the growth condition of the kelp of the year, and it is useful for predicting the annual fisheries production in this area. These results suggested that the weight growth of *S. longissima* is affected by the ambient water temperature both in the previous and the same years. High temperature in the preceding autumn and extremely low temperature in the preceding winter to spring reduce the blade weight in the summer harvest season. Therefore, the increasing trends of water temperature in recent years may be one of the factors decreasing the fisheries production of the kelp in eastern Hokkaido.

Key words: *Saccharina longissima* (Naga-konbu), *Laminariacean* kelp, growth, water temperature, eastern Hokkaido

Introduction

Seaweeds, including kelps, are fundamental species of the coastal ecosystem, serving as a nursery, refuge, forage and spawning habitat for many organisms (Steneck *et al*., 2002). In addition, kelp species have especially high growth rates, and wild harvest and culture of Laminariacean kelp species are important for the fishing industry in the Pacific coastal areas, such as northern Japan (Mizuta, 2003). *Saccharina longissima* (Naga-konbu in Japanese) is one of those kelp species, which grows up to more than 10 m in blade length (**Fig.1a**). *S. longissima* used to be classified as *Laminaria longissima* (Miyabe), but

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*1 National Research Institute of Aquaculture, Japan Fisheries Research and Education Agency, 422-1, Nakatsuhamaura, Minamiise, Watarai, Mie, 516-0193, Japan
*2 Hokkaido National Fisheries Research Institute (Kushiro Laboratory), Japan Fisheries Research and Education Agency, 116 Katsurakoi, Kushiro, Hokkaido, 085-0802, Japan
*3 Hokkaido National Fisheries Research Institute (Akkeshi Laboratory), Japan Fisheries Research and Education Agency, 2-1 Tsukushikoi, Akkeshi-cho, Akkeshi-gun, Hokkaido, 088-1108, Japan
E-mail: hasena@fra.affrc.go.jp

most *Laminaria* species including this species were taxonomically reorganized into the genus *Saccharina* through a multi-gene molecular investigation (Lane *et al*., 2006; Yotsukura, 2010). The kelp is distributed in shallow Pacific coastal areas (**Fig.1b**) from eastern Hokkaido (Kushiro and Nemuro) to the Chishima Islands. Its distribution area is under the influence of the cold Oyashio current, and the water temperature varies seasonally from sub-zero to 20°C. This kelp is the main harvested species in eastern Hokkaido (**Fig.1c, d**), mostly used for tsukuda-ni (preserved food cooked with sweetened soy sauce) and kelp rolls, making use of its soft texture, whereas other kelp species with harder blades are widely used for broth. The annual total fishery production of the kelp species in Kushiro and Nemuro, where *S. longissima* is the main harvested species, is around 10 thousand tons in dry weight, with a gradual decreasing trend in recent years (**Fig.2**, Hokkaido Regional Agricultural Administration Office, 2017). A similar trend is seen in other kelp species in other areas in Hokkaido. Akaike (2017) suggested that there is a high probability change of the marine environment has affected the production of kelp species in Hokkaido. The present study focused on determination of the environmental factors affecting the variation in the growth and fisheries production of *S. longissima* (Miyabe) in eastern Hokkaido, Japan.

Materials and methods

The fisheries cooperative association of Habomai has been monitoring the blade size of the *S. longissima* in May and June in its harvest grounds along more than 15 km of coastline in Nemuro, eastern Hokkaido (from 43.30°N, 145.67°E to 43.39°N, 145.82°E, **Fig.3**). In each monitoring, one to 20 sporophytes of the kelp were collected using long handle gears in 28 to 40 locations, and the blade length, maximum width and the wet weight of the kelp were measured. The variations in the blade size of the kelp over age 1+ (2nd year sporophyte) from 2000 to 2014 were analyzed in this study. *S. longissima* is a perennial species, and the kelp over age 1+ is targeted for fisheries harvest using long handle gears between June and October. Thin bladed sporophytes identified as less than age 1+, were excluded from the calculative analysis. The

Fig. 1. *Saccharina longissima*. (a): overview of sporophytes, (b): lower intertidal to upper subtidal habitats, (c) and (d): drying process on artificial stone fields.

incongruous sporophytes, with unknown collection sites and unusual weight to length ratio, were also excluded from the analysis.

Effects of environmental factors on the blade weight in May were estimated using correlation analysis. Blade weight was used for the representative variable of *S. longissima* size in the correlation analysis. Monthly average water temperature in Kushiro, monthly mean daylight hours and wind speed in Nemuro in the previous and same years were used as the environmental factors in this analysis. Moreover, the effects of water temperature on the blade weight in May were estimated using a generalized linear regression model (GLM) because the correlation analysis revealed that only coefficients between the blade weight in May and the mean water temperature had significant trends throughout the years (see Result and Discussion). To avoid the multi-collinearity of the mean water temperature among successive months, monthly mean water temperature for January, April, July and October, which were selected as the representative months of each quarter of the year, were used as the dependent variables for the GLM analysis. In addition, GLM analysis was also performed between the mean blade weight in May and the monthly mean water temperature, with a significant correlation with the former ($P < 0.05$). But January in the previous year and January, March in the same year were excluded to avoid multi-collinearity (see Results and Discussion). Longitudes of the sampling sites were also used as explanation variables for locations in these models. Dependent variables (blade weight in May) were assumed to follow the gamma distribution (log link). Model selection based on Akaike's information criterion (AIC) was then performed, and those with the minimum AICs were regarded as the best fit model. Monthly mean water temperature in Kushiro was calculated from the temperature of the intake water for the experimental facilities of Hokkaido National Fisheries Research Institute (Kushiro Laboratory), Japan Fisheries Research and Education Agency (42.949° N, 144.442° E), which is located 100 km west of the study area in Habomai. Monthly average daylight hours and wind speed were obtained from the Automated Meteorological Data Acquisition System (AMeDAS) in Nemuro

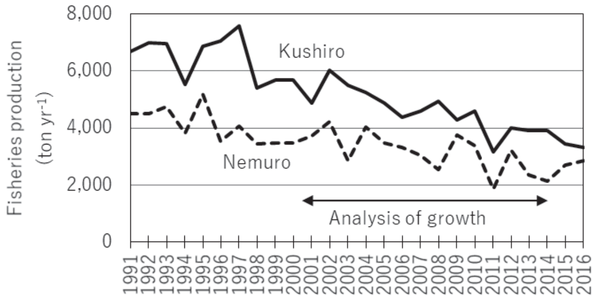

Fig. 2. Fisheries production of kelp species in eastern Hokkaido (Kushiro and Nemuro). *Saccharina longissima* is assumed to contribute about 70 % of the fisheries production of kelps in this area. Values are in dry weight.

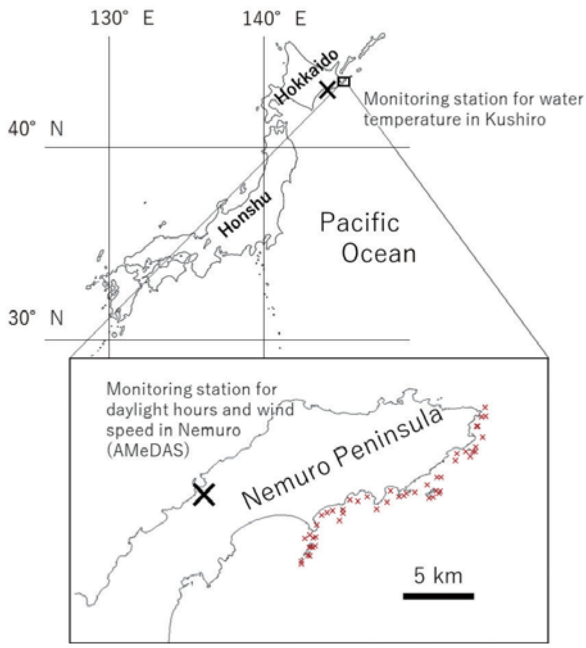

Fig. 3. Monitoring sites for *Saccharina longissima* in Habomai area and monitoring stations for water temperature in Kushiro and daylight hours and wind speed in Nemuro, eastern Hokkaido, Japan.

(43.331°N, 145.586° E). Relationships between mean blade weight in May and June, the mean blade weight in May and fisheries production of kelp species in Nemuro (Hokkaido Regional Agricultural Administration Office, 2017) were analyzed for each site using a correlation analysis. In the correlation analysis, blade weight and fisheries production were transformed logarithmically. The significance of the correlation coefficients was tested by Pearson's product-moment correlation, and $P < 0.05$ was considered statistically significant.

Results and discussion

From the 15 year monitoring data, 4,149 sporophytes and 469 site mean blade weights and 4,543 sporophytes and 396 site mean blade weights were used for the analysis for May and June, respectively, in this study of *S. longissima*. The monitoring data showed that the blade weight in May varied among years (**Fig.4**). Overall, mean of the blade weight in May was 703 ± 174 gWW (grams wet weight ± standard deviation (SD)). The mean blade weight in May was heavier in 2002 and 2009 than the overall mean + SD, whereas the mean weight was lighter in 2001, 2013 and 2011 than the overall mean - SD. Correlation analysis revealed that coefficients between the blade weight in May and monthly mean water temperature displayed certain trends throughout the years (**Fig.5 and 6**); the correlation coefficients between the mean blade weight in May and the mean water temperature in the previous spring to autumn were negative (r = -0.28 to -0.08), and those between the mean blade weight in May and the mean water temperature in winter and spring in the same year were positive (r = 0.33 to 0.48). The mean blade weight in May had a significant

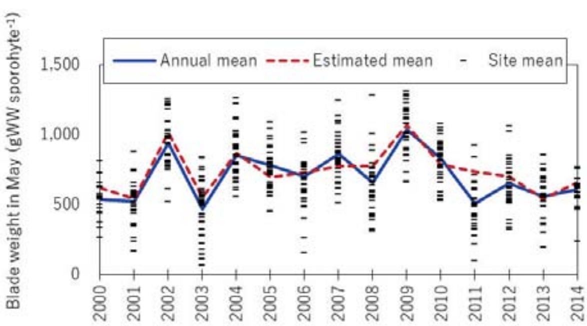

Fig. 4. Monitored and estimated blade weight of *Saccharina longissima* in May in Habomai area, eastern Hokkaido, Japan. Values are in wet weight (WW). Dashed line shows the estimated weight by the model including longitudes and monthly mean water temperatures (January, April, July, October during same year and January, April during same year).

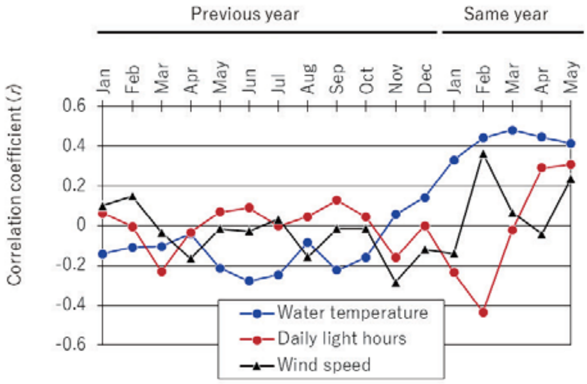

Fig. 5. Variations in correlation coefficient between site mean blade weight of *Saccharina longissima* in May and monthly mean water temperature, daylight hours and wind speed.

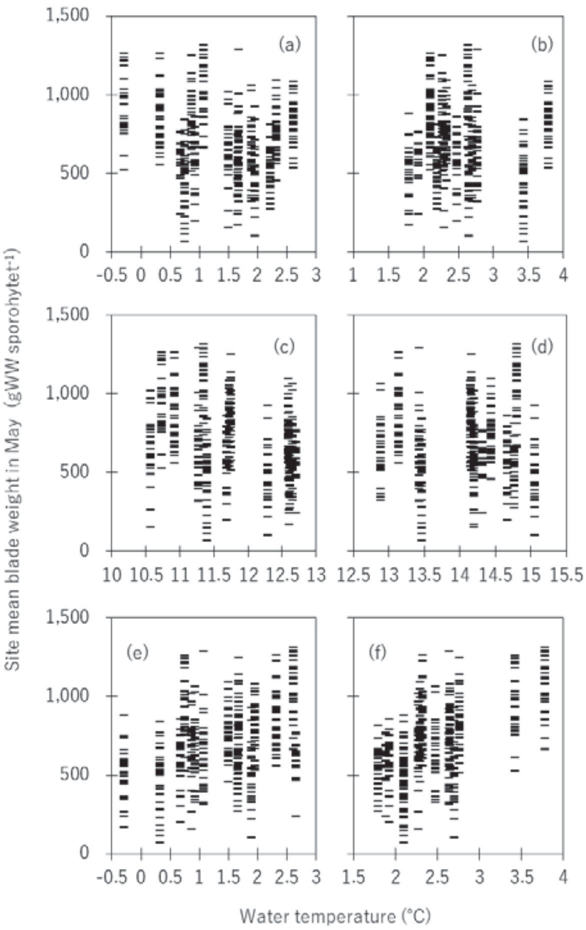

Fig. 6. Relationships between site mean blade weight of *Saccharina longissima* in May and monthly mean water temperature. (a): January, (b): April, (c): July, (d): October in the previous year, (e): January, (f): April in the same year.

correlation with the mean water temperature, except for in April, August and November in the previous year. The mean blade weight in May was significantly correlated with the mean daylight hours in March (r = -0.23), September (0.13), and November (-0.16) in the previous year and January (-0.24), February (-0.43) and April (0.29) in the same year. The mean blade weight in May was also significantly correlated with monthly mean wind speed in January (r = 0.10), February (0.15), April (-0.16), August (-0.16), September (-0.18), November (-0.28), and December (-0.12) in the previous year and January (-0.14) and March (0.36) in the same year. However, unlike water temperature, neither the daylight hours nor the wind speed showed correlative tends with the blade weight throughout the years.

The GLM analysis of the blade weight in May revealed that the model including water temperature in February, May-July, September, and December in the previous year and February and April in the same year was the best fit model, with the smallest AIC value of 6,329 (**Table 1**). The model including only water temperature of each quarter of the year and longitude also had a smaller AIC value (6,347) than the null model (6,513), and it effectively estimated the variation of the mean weight in May (**Fig.4**). In this model, the mean blade weight in May had a negative GLM coefficient with the quarterly mean water temperature in April to October in the previous year and positive coefficients in January and April in the same year, which was similar to the trend shown in the correlation coefficient analysis. The GLM coefficient of the longitude was positive both in the best model and the model including only water temperature and longitude.

Overall, mean of the blade weight in June was 1,038 ± 210 gWW. The mean weight in June ranged between 716 ± 169 gWW in 2014 to 1,385 ± 252 gWW in 2009. The per site mean blade weight in June was positively correlated with the blade weight in May, with a correlation coefficient of 0.45 (**Fig.7**), and the mean blade weight in May was positively correlated with fisheries production of the kelp in Nemuro, with a correlation coefficient of 0.58 (**Fig.8**). These results revealed that the blade weight of *S. longissima* in May remarkably represents the growth situation of the kelp of the year and is useful to predict the fisheries production in this area. This association

Table 1. Result of generalized linear model analysis of site mean blade weight of *Saccharina longissima* in May in Habomai, eastern Hokkaido Japan. Values of each variable represent mean estimate coefficient ± standard error. Check marks represent the independent variables included in each model.

Independent variables			Null model	Estimate coefficient	Full model	Best model	Estimate coefficient	Full(Best) model
Intercept				-141.70 ± 35.41	✔	✔	-144.89 ± 36.08	✔
Water temperature								
	Previous year	January					0.08 ± 0.03	✔
		Februrary		0.06 ± 0.04	✔	✔		
		March		0.05 ± 0.05	✔			
		April					-0.10 ± 0.03	✔
		May		-0.08 ± 0.03	✔	✔		
		June		-0.09 ± 0.03	✔	✔		
		July		0.06 ± 0.03	✔	✔	-0.09 ± 0.02	✔
		August						
		September		-0.04 ± 0.03	✔	✔		
		October		0.01 ± 0.04	✔		-0.08 ± 0.02	✔
		November						
		December		-0.07 ± 0.03	✔	✔		
	Same year	Januray					0.13 ± 0.02	✔
		Februrary		0.22 ± 0.05	✔	✔		
		March						
		April		0.20 ± 0.04	✔	✔	0.23 ± 0.03	✔
Longitude				1.02 ± 0.24	✔	✔	1.05 ± 0.25	✔
AIC			6,513		6,331	6,329		6,347

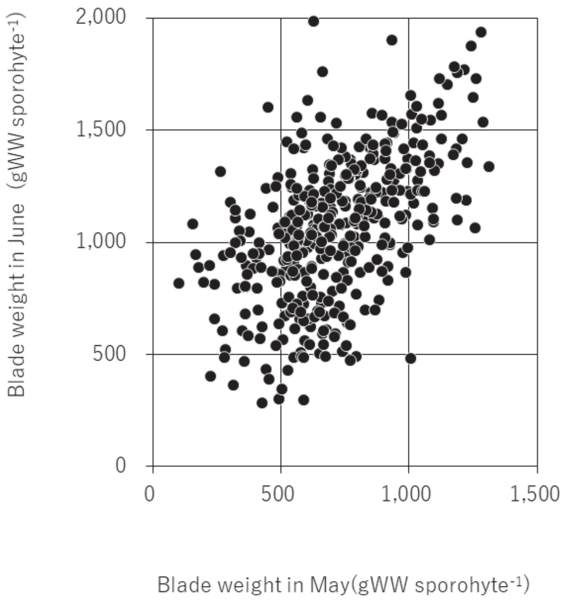

Fig. 7. Relationship between site mean blade weight of *Saccharine longissima* in May and June. Values are in wet weight (WW).

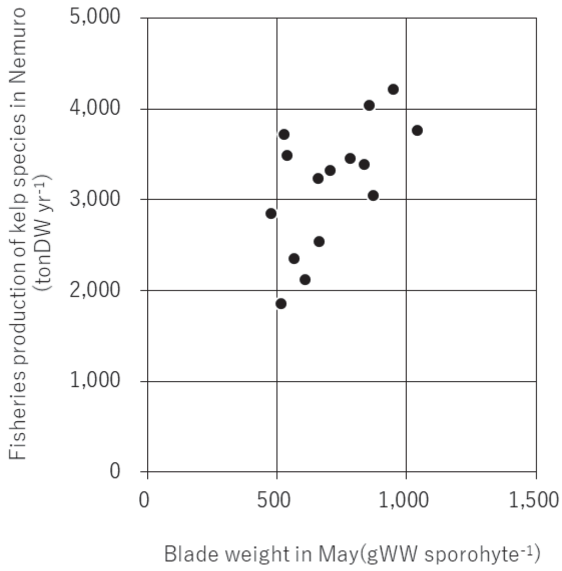

Fig. 8. Relationships between annual mean blade weight of *Saccharine longissima* in May and annual fisheries production of kelp species in Nemuro, where *S. longissima* was the main harvested kelp species. Blade weight and fisheries production are in wet weight (WW) and dry weight (DW), respectively.

occurred despite the fact that the fisheries production of the kelp was often affected by the number of days of harvest and fishermen (Shinada *et al.* 2014).

Growth status of the age 1+ sporophytes until May is an important factor in determining the fisheries production of the kelp in this area, and GLM analysis and correlation analysis feasibly revealed that the growth was affected by the ambient water temperature. High temperature in the previous autumn and extremely low temperature in the previous winter to spring reduced the blade weight of the kelp in the summer harvest season. Sasaki (1973) reported that regeneration of *S. longissima* sporophytes starts around November, with a daily growth rate of blade length ranging from 5 to 10 mm day-1 until March, and growth reaches the maximum of 68 mm day-1 during May and June. Early decrease of water temperature in the previous year might cause early start of regeneration of the sporophytes, and the growth of sporophytes might be enhanced by warmer conditions during winter and spring, when water temperature is below 4℃ in this area. Meanwhile, Kirihara *et al.* (2003) reported that the growing densities of age 1+ sporophytes of *S. japonica* in early summer were negatively related with the water temperature in the previous spring. Moreover, Shinada *et al.* (2014) concluded that dissolved inorganic nitrogen concentration in March and sea urchin (consumer of kelp) biomass were important for changes in first year biomass of *S. japonica* var. *ochotonids*, but there were no clear relationships between the kelp biomass and water temperature. These relationships between growth and biomass of *S. japonica* and water temperature were different from the results of our study probably due to the differences in species and age of kelps.

General trends in the blade weight variation in May was well-estimated by the models that included quarterly mean water temperature and longitude, but there was a large difference between the estimated and actual mean blade weight in 2011, during which the tsunami generated by the great east Japan earthquake hit this area with the wave height over 4.5 m (Japan Meteorological Agency, 2013). Disturbance caused by the tsunami might have damaged the blades and inhibited the kelp growth. In addition, drift ice physically scrapes off the kelps from the rocky substrates and causes declines in the fisheries production. However, intense drift ice increases the fisheries production of the kelp in the following year through creating a new substrate for the kelp (Sasaki 1973).

In the GLM analysis, longitude was shown to positively affect the blade weight in May. This may be explained by the ocean currents in the study area. In the coastal area of eastern Hokkaido, large amounts of nutrients are supplied by the first branch of the Oyashio current, which runs westward (Tanaka *et al*., 1991). Therefore, the faster growth of the sporophytes might be attributable to the higher nutrient supply in eastern part of the monitoring area, located upstream in the Oyashio current.

In conclusion, water temperature is an important environmental factor to determine the growth of *S. longissima*. In the sea off Kushiro (offshore of eastern Hokkaido), an upward trend in sea surface temperature (SST) is clear during autumn, in which regeneration of S. longissima sporophytes starts, both on a long-term basis and since the year 2000 (**Fig.9**, Global Environment and Marine Department, Japan Meteorological Agency, 2017). In addition, since 2000, SST during the spring growing season of *S. longissima is* frequently below the grand mean from 1981 to 2010. This trend in water temperatures may be one of the factors decreasing the growth and the fisheries production of the kelp in eastern Hokkaido, and there is a concern that the deterioration of the kelp fisheries may be aggravated if the present water temperature trend persists.

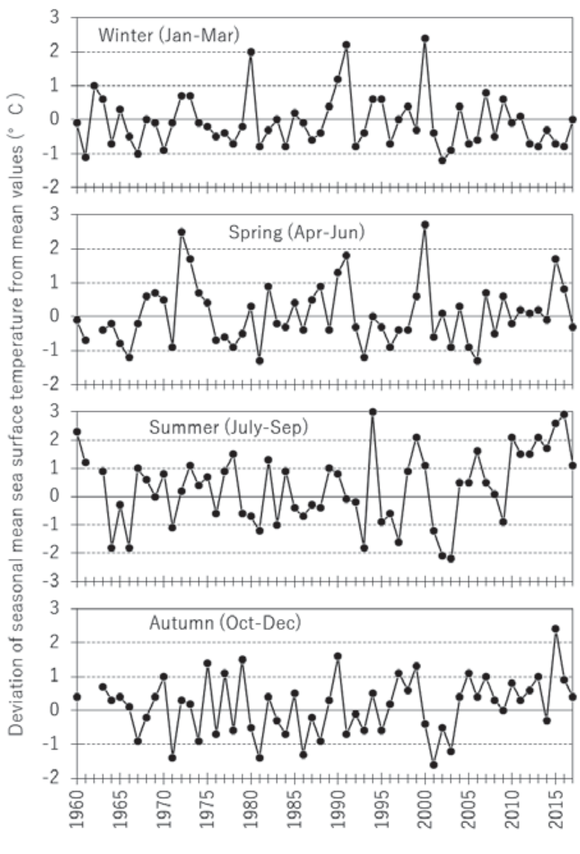

Fig. 9. Deviation of seasonal mean sea surface temperature from the grand mean values in sea off Kushiro (offshore of eastern Hokkaido, Japan). The grand mean values for each season were calculated from the seasonal mean sea surface temperature from 1981 to 2010. Data was obtained from Global Environment and Marine Department, Japan Meteorological Agency (2017).

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We express our respect for long term monitoring of kelp by fisheries cooperative association of Habomai and are grateful to Y. Fuchigami for organizing these monitoring data. This study was carried out under the framework of the conference on kelp research in Nemuro city.

References

Akaike S., 2017: Sea has changed? ~ Change of kelp fisheries and marine environment ~. Hokusuishidayori, **95**, 9-12. (in Japanese)

Global Environment and Marine Department, Japan Meteorological Agency, 2017: Long-term change tendency in surface water temperature near Japan. https://www.data.jma.go.jp/kaiyou/data/shindan/a_1/japan_warm/japan_warm.html, (Press: 12th, March 2018)

Hokkaido Regional Agricultural Administration Office, 2017: Annual report of agriculture, Forestry and Fishery statistics in Hokkaido (Fisheries), 74pp. (in Japanese)

Japan Meteorological Agency, 2013: Report on the 2011 off the Pacific Coast of Tohoku Earthquake by Japan Meteorological Agency, Part 1. *Technical report of the Japan Meteorological Agency*, **133**, 1-354. (in Japanese)

Kirihara S., Nakamura T., and Notoya M., 2003:

Effect of water temperature on the growth of *Laminaria japonica* (*Laminariales, Phaeophyceae*) at the coast of Shiriyazaki, Shimokita Peninsula, Japan. *Aquacult. Sci.(Suisanzoshoku)*, **51**, 273-280. (in Japanese with English abstracts)

Lane C. E., Mayes C., Druehl L. D., and Saunders G. W., 2006: A multi-gene molecular investigation of the kelp (*Laminariales, Phaeophyceae*) supports substantial taxonomic re-organization. *J. Phycol.*, **42**, 493-512.

Mizuta H., 2003: Distribution of Laminaria species in coastal Oyashio region and their nutritional requirements. *Bull. Coat. Oceangr.*, **41**, 33-38. (in Japanese with English abstracts)

Sasaki S. (ed), 1973: Studies on the life history of *Laminaria angustata* var. *longissima (M.) Miyabe*. Hokkaido Kushiro Fish. Exp. Stn., Kushiro, 141pp. (in Japanese)

Shinada A., Nishida Y., Kuribayashi Y., Goda H., Kawai T., and Akaike S., 2014: Effect of marine environment on annual changes in first year biomass of *Saccharine japonica* var. *ochotensis* at Rishiri island, Japan. *Fish. Eng.*, **51**, 39-45. (in Japanese with English abstracts)

Steneck R. S., Graham M. H., Bourque B. J., Corbett D., Erlandoson J. M., Estes J. A., and Tegner M. J., 2002: Kelp forest ecosystem biodiversity, stability, resilience and future. *Environ. Conserv.*, **29**, 436-459.

Tanaka K., Sato Y., and Kakuda T., 1991: Seasonal changes in nutrient concentrations in the coastal area of eastern Hokkaido. *Bull. Hokkaido Nat. Fish. Res. Inst.*, **55**, 161-172. (in Japanese with English abstracts)

Yotsukura N., 2010: The hierarchy of Laminariales in Japan. *Algal Resources*, **3**, 193-198. (in Japanese with English abstracts)

Annotated bibliography

(1) Sasaki S., 1973: Studies on the life history of *Laminaria angustata* var. *longissima (M.) Miyabe*. Hokkaido Kushiro Fisheries Experimental Station, Kushiro, 141pp.

This paper was published in 1970s when this species increasingly became of high fisheries importance around eastern Hokkaido, Japan. The author summarized the life history of *Laminaria angustata* var. *longissima (M.) Miyabe*., which has been recently renamed as Saccharina longissima. This paper includes the studies about the life history of two seasonal germinal groups in winter and summer to provide information for stock enhancements, the importance of suspended culture, reviewing position of the *S. longissima* in Japanese kelp fisheries with evaluating the factors affecting its fisheries production such as the floating ice. Some parts of these studies were published in Journal of Hokkaido Fisheries Experimental Station in Japanese. Although the marine and social environments for *S. longissima* fisheries have markedly changed since 1970s, intensive studies such as one done by Sasaki (1973) have not been conducted since then.

(2) Yotsukura N., 2010: The hierarchy of Laminariales in Japan. *Algal Resources*, **3**, 193-198.

This paper reviews the hierarchy of laminarialean algae which has been proposed by molecular phylogenetic analyses. There is a variety of laminarialean species in Japan's coastal areas where some species including *Saccharina longissima* are harvested or cultured on a large scale. These species have been classified based on morphological characteristics although there are variations in its morphology among its growth stages and environmental conditions. Author enumerated 37 laminarialean species belonging to 7 families in Japan.

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Harmful algal blooms and shellfish aquaculture in changing environment

Leila BASTI[*1], Kiyohito NAGAI[*2], Susumu SEGAWA[*3], Yuji TANAKA[*1], Toshiyuki SUZUKI[*4], and Satoshi NAGAI[*4]

Abstract: Shellfish aquaculture is mainly carried out in sheltered coastal areas that are affected by several anthropogenic stressors, including eutrophication, pollution, biofouling, invasive species, expanding diseases, and harmful algal blooms. In particular, harmful algal blooms (HAB) have been known to cause fish and shellfish kills; contamination of fish, but mainly shellfish, with potent toxins that cause mild to severe poisonings in humans; and in many cases, alteration of ecosystem functions. In shellfish, notably in bivalve molluscs, in addition to mass mortalities, HAB are known to cause acute to chronic physiological and pathological alterations that lead to impediments to aquaculture farms via reduction of bivalve fitness or following closure of production due to long-term contamination with toxins detrimental to human health.

The frequency, magnitude, duration, and in several cases, the geographic distribution of HAB have been increasing, putting shellfish aquaculture farms under further stress. Several factors have been attributed to such increase in HAB, including climate change. Range expansions of some cosmopolitan HAB species associated with warming ocean temperature have been reported across the North Atlantic and North Pacific. In addition, range expansions of some other cosmopolitan HAB species have been projected across the North Western European Shelf-Baltic Sea system and North East and South East Asia, associated with increased nutrient loads under projected climate change scenario A1B of the IPCC, IPSL-CM4. Warming water temperature driven by climate change is also expected to induce thermodynamic changes in physiological functions of shellfish, with potential shifts in their thermal sensitivity and performance, and it is also expected to alter the responses of bivalves to HAB.

In this mini-review, the effects of HAB and ocean warming – and other climate driven stressors like ocean acidification – on these important cultured shellfish species will be discussed in light of the findings of relevant studies reported in the literature.

Key words: harmful algal blooms, shellfish, aquaculture, climate change

Introduction

Human consumption from aquaculture exceeded that from wild resources for the first time in 2014, and aquaculture has become the fastest growing food production system in the world (FAO, 2014). Despite the expansion of aquaculture activities to offshore production, most of the mariculture activities are still carried out in sheltered coastal areas (Trujillo *et al*., 2012). These areas are subjected to several anthropogenic stressors, including eutrophication, pollution, biofouling, invasive species, expanding

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*1 Department of Ocean Sciences, Tokyo University of Marine Science and Technology, Minato, Tokyo 108-8477, Japan.
*2 K. Mikimoto and Co. Ltd., Osaki Hazako, Hamajima-Cho, Shima, Mie 517-0403, Japan
*3 Department of Aqua Bioscience and Industry, Tokyo University of Agriculture, 196 Yasaka, Abashiri 099-2493, Japan
*4 National Research Institute of Fisheries Science, Fisheries Research and Education Agency, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan
E-mail: lbasti1@kaiyodai.ac.jp

diseases, and harmful algal blooms (HAB) (Rogers and Laffoley, 2011).

HAB pose a significant threat to marine and freshwater ecosystems as they cause a wide range of cascading impacts either via their increased biomass or via the production of potent toxins and bioactive compounds (Burkholder, 1998). These HAB have increased over the past decades with associated increases in their effects on ecosystems and related human activities, including tourism, fishing, and aquaculture (Smayda, 1990; Hallegraeff, 1993; Van Dolah, 2000; Zingone and Enevoldsen, 2000; Allen *et al*., 2006; Matsuyama and Shumway, 2009). In addition, a wide diversity of HAB species causes intoxication of humans following the consumption of seafood products, mainly bivalve molluscs that have accumulated their toxins, leading to closures of shellfish beds and long-term suspension of production in aquaculture farms (Van Dolah, 2000). Several species of HAB have also been known to cause mass mortalities of aquatic organisms and numerous documented deleterious effects on the physiology of cultured shellfish (Landsberg, 2002; Basti *et al*., 2018a).

Coastal areas witnessing expansion of HAB events are also at risk of impacts from climate change-driven forcing, including sea level rise; alteration in nutrients, sediment and salinity regimes; changes in circulation patterns, water residence time and upwelling; frequency and intensity of storms; ocean warming; and ocean acidification (Scavia *et al*., 2002; Caldeira and Wickett, 2005; Harley *et al*., 2006; Domingues *et al*., 2008; Ruckelshaus *et al*., 2013). The impacts of HAB on shellfish aquaculture, mainly bivalve molluscs, and the potential impacts of climate-driven changes on the interactions HAB-shellfish are reviewed.

Effects of harmful algal blooms on shellfish

HAB affect shellfish aquaculture by causing acute, chronic, and sublethal effects in several species of shellfish (Shumway, 1990; Landsberg, 2002). In shellfish, in addition to mass mortalities, HAB affect the behavior and physiology of several commercially important species. Reduction of filtration, respiration, and valve gaping have been reported in several cultured species, including clams, oysters, mussels, and scallops. Several pathologies in almost all organs of bivalve molluscs have also been shown to be caused by species of HAB, including inflammation, necrosis and atrophy (Shumway and Cucci, 1987; Gainey and Shumway, 1988: Bricelj *et al*., 1996; Basti *et al*., 2009; Basti *et al*., 2011a; Haberkorn *et al*., 2010a; Haberkorn *et al*., 2010b; Hégaret *et al*., 2012). Several pathologies in almost all organs of bivalve molluscs have also been shown to be caused by species of HAB, including inflammation, necrosis and atrophy. Modulation of the immune system, antioxidant system and neuroenzymatic activity, as well as modification of the physiological energetics, can also occur (Hégaret and Wikfors, 2005; Basti *et al*., 2016). The reproduction and the recruitment of shellfish are also affected by several species of HAB, with numerous recruitment failures reported from the field, in addition to several negative effects in gametes, fertilization, embryos and larvae of clams, oysters and scallops (Basti *et al*., 2011b; Basti *et al*., 2013; Basti *et al*., 2015a; Banno *et al*., 2018). In addition, HAB have been shown to affect the susceptibility of shellfish to diseases and, thus, facilitate the expansion of diseases in aquaculture farms (e.g. Da Silva *et al*., 2008; Hégaret *et al*., 2010; reviewed in: Landsberg, 2002; Basti *et al*., 2018a).

Effects of warming and ocean acidification on shellfish

The effects of climate change on the world ocean are being documented worldwide (IPCC, 2007; Doney *et al*., 2012). Climate-driven changes in the physical and chemical systems of the oceans are inducing changes in the biological systems as well as human uses of ocean resources. Warming water temperature has already been shown to affect the survival, growth, reproduction, health and phenology of marine organisms (Doney *et al*., 2012). Warming could result in changes in the primary production and food web structure and function and, thereafter, changes in life history processes such as spat-fall of shellfish, as well as physiological stresses leading to decreased growth and production (Allison *et al*., 2011). In a literature review, Compton *et al*. (2007) found that warming will have more impacts on the survival, range and productivity of tropical than temperate shellfish species, which might lead to shift in species cultured in aquaculture farms in the future oceans. On the other hand, ocean acidification (OA) has been shown to affect calcifying organisms, including mussels, clams and oysters. Despite the extensive literature on the effects of OA on marine organisms, generalization on the biological effects of OA remains disputable, especially that the mechanisms of sensitivity to long-term exposures to OA are not well understood (Berge *et al*., 2006; Gazeau *et al*., 2007; Cochran *et al*., 2009; Miller *et al*., 2009; Talmage and Gobler, 2010; Allisson *et al*., 2011; Waldbusser *et al*., 2011; Barton *et al*., 2012). There is little information, however, on the effects of both warming and OA on shellfish. For instance, in a short- and long-term laboratory studies, the fertilization and early-life development of Sydney rock oyster were shown to be severely affected by the synergistic effects of warming and OA (Parker *et al*., 2009).

Impacts of harmful algal blooms and climate change on shellfish aquaculture

Evidence that climate change has been influencing HAB events at a global scale has been accumulating (Moore *et al*., 2008). Climate-driven changes in temperature, irradiance, chemical composition of seawater, nutrients, water stratification, grazing pressures, phytoplankton species, and strain interactions is expected to affect the prevalence and toxicity of HAB (Wells *et al*., 2015). Changes in HAB prevalence and toxicity will affect the responses of shellfish to these global stressors as well as aquaculture activities. For instance, warming water temperature has been shown to affect the metabolism of the most widespread HAB toxin (Paralytic Shellfish Toxins) in commercial oysters from Australia (Farrell *et al*., 2015). Similarly, increased temperatures and OA were shown to increase production of HAB toxins and negative effects in shellfish (Tatters *et al*., 2013; Basti *et al*., 2015b; Basti *et al*., 2018b). These data show that climate-driven warming and OA may increase future risks of HAB effects on shellfish physiology and aquaculture farms.

References

Allen J. I., Anderson D., Burford M., Dyhrman S., Flynn K., Glibert P. M., Granéli E., Heil C., Shellner K., Smayda T., and Zhou M., 2006: Global Ecology and Oceanography of Harmful Algal Blooms, Harmful Algal Blooms in Eutrophic Systems, GEOHAB Report 4IOC and SCOR, Paris and Baltimore, 74pp.

Allison E. H., Badjek 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.), John Wiley & Sons Ltd, Chichester, pp. 461-490.

Banno K., Oda T., Nagai K., Nagai S., Tanaka Y., and Basti L., 2018: Deleterious effects of harmful dinoflagellates and raphidophytes on egg viability and spermatozoa swimming velocity in the Japanese pearl oyster *Pinctada fucata martensii*. *J. Shellfish Res.*, **37**, 41-48.

Barton A., Hales B., Waldbusser G. G., Langdon C., and Feely R. A., 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnol. Oceanogr.*, **57**, 698-710.

Basti L., Nagai K., Shimasaki Y., Oshima Y., Honjo T., and Segawa S., 2009: Effects of the toxic dinoflagellate *Heterocapsa circularisquama* on the valve movement behavior of the Manila clam *Ruditapes philippinarum*. *Aquaculture*, **291**, 41-47.

Basti L., Endo M., and Segawa S., 2011a: Physiological, pathological, and defense alterations in Manila clams (short-neck clams), *Ruditapes philippinarum*, induced by *Heterocapsa circularisquama*. *J. Shellfish Res*., **30**, 829-844.

Basti L., Go J., Higuchi K., Nagai K., and Segawa S., 2011b: Effects of the toxic dinoflagellate *Heterocapsa circulariquama* on larvae of Pearl oyster *Pinctada fucata martensii* (Dunker, 1873). *J. Shellfish Res*., **30**, 177-186.

Basti L., Nagai K., Tanaka Y., and Segawa S., 2013: Sensitivity of gametes, fertilization, and embryo development of the Japanese pearl oyster, *Pinctada fucata martensii*, to the harmful dinoflagellate, *Heterocapsa circularisquama*. *Mar. Biol*., **160**, 211-219.

Basti L., Nagai S., Go J., Okano S., Nagai K., Watanabe R., Suzuki T., and Tanaka Y., 2015a: Differential inimical effects of *Alexandrium* spp. and *Karenia* spp. on cleavage, hatching, and two larval stages of Japanese pearl oyster *Pinctada fucata martensii*. *Harmful Algae*, **43**, 1-12.

Basti L., Endo M., Segawa S., Shumway S. E., Tanaka Y., and Nagai S., 2015b: Prevalence and intensity of pathology induced by the toxic dinoflagellate, *Heterocapsa circularisquama*, in the Mediterranean mussel, *Mytilus galloprovincialis*. *Aquat. Toxicol*., **163**, 37-50.

Basti L., Nagai S., Watanabe S., Oda T., and Tanaka Y., 2016: Neuroenzymatic activity and physiological energetics in Manila clam, Ruditapes philippinarum, during short-term sublethal exposure to harmful alga, Heterocapsa circularisquama. *Aquat. Toxicol*., **176**, 76-87.

Basti L., Hégaret H., and Shumway S. E., 2018a: Harmful algal blooms and shellfish, in "Harmful Algal Blooms: A Compendium Desk Reference" (ed. by Shumway S. E., Burkholder J. M., and Morton S. L.), John Wiley & Sons Ltd, Chichester, pp. 135-190.

Basti L., Suzuki T., Uchida H., Kamiyama T., and Nagai S., 2018b: Thermal acclimation affects growth and lipophilic toxin production in a strain of cosmopolitan harmful alga *Dinophysis acuminata*. *Harmful Algae*, **73**, 119-128.

Berge J. A., Bjerkeng B., Pettersen O., Schaanning M. T., and Øxnevad S., 2006: Effects of increased seawater concentrations of CO_2 on growth of the bivalve *Mytilus edulis* L. *Chemosphere*, **62**, 681-687.

Bricelj V. M., Cembella A. D., Laby D., Shumway S. E., and Cucci T. L., 1996: Comparative physiological and behavioral responses to PSP toxins in two bivalve molluscs, the softshell clam, *Mya arenaria*, and surfclam, *Spisula solidissima*, in "Harmful and Toxic Algal Blooms" (ed. by Yasumoto T., Oshima Y., and Fukuyo Y.), Intergovernmental Oceanographic Commission of UNESCO, Paris, pp. 405-408.

Burkholder J. M., 1998: Implications of harmful marine microalgae and heterotrophic dinoflagellates in management of sustainable marine fisheries. *Ecol. Appli.*, **8 (Suppl.)**, S37-S62.

Caldeira K. and Wickett M. E., 2005: Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res.* **110**. doi:10.1029/2004JC002671

Cochran K., De Yo C., Soto D., and Bahri T., 2009: Climate change implications for fisheries and aquaculture, FAO Fisheries and Aquaculture Technical Paper 530, Rome, 212pp.

Compton T. J., Rijkenberg M. J. A., Drent J., and Piersma T., 2007: Thermal tolerance ranges and climate variability: a comparison between bivalves from differing climates. *J. Exp. Mar. Biol. Ecol.*, **352**, 200-211.

Da Silva P.M., Hégaret H., Lambert C, Wikfors G. H., Le Goïc N., Shumway S. E., and Soudant P., 2008: Immunological responses of the Manila clam (*Ruditapes philippinarum*) with varying parasite (*Perkinsus olseni*) burden, during long term exposure to the harmful alga, *Karenia selliformis* and possible interactions. *Toxicon*, **51**, 563-573.

Domingues C. M., Church J. A., White N. J., Gleckler P. J., Wijffels S. E., Barker P. M., and Dunn J. R., 2008: Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature*, **453**, 1090-1093.

Doney S. D., Ruckelshaus M., Duffy J. E., Barry J. P., Chan F., English C. A., Galindo H. M., Grebmeier J. M., Hollowed A. B., Knowlton N., Polovina J., Rabalais N. N., Sydeman W. J., and Talley L. D., 2012: Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.*, **4**, 11-37.

FAO, 2014: The State of World Fisheries and Aquaculture - Opportunities and Challenges, FAO, Rome, 223pp.

Farrell H., Seebacher F., O'Connor W., Zammit A., Harwood D. T., and Murray S., 2015: Warmer temperature acclimation impacts metabolism of paralytic shellfish toxins from *Alexandrium minutum* in commercial oysters. *Glob. Chang. Biol.*, **21**, 3402-3413.

Gainey L. G. and Shumway S. E., 1988: A compendium of the responses of bivalve molluscs to toxic dinoflagellates. *J. Shellfish Res.*, **7**, 623-628.

Gazeau F., Quiblier C., Jansen J. M., Gattuso J. P., Middelburg J. J., and Heip C. H. R., 2007: Impact of elevated CO_2 on shellfish calcification. *Geophys. Res. Lett.*, **34**, L07603.

Haberkorn H., Lambert C., Le Goïc N., Guéguen M., Moal J., Palacios E., Lassus P., and Soudant P., 2010a: Effects of *Alexandrium minutum* exposure upon physiological and hematological variables of diploid and triploid oysters, *Crassostrea gigas*. *Aquat. Toxicol.*, **97**, 96-108.

Haberkorn H., Lambert C., Le Goïc N., Moal J., Suquet M., Guéguen M., Sunila I., and Soudant P., 2010b: Effects of *Alexandrium minutum* exposure on nutrition-related processes and reproductive output in oysters *Crassostrea gigas*. *Harmful Algae*, **9**, 427-439.

Hallegraeff G. M., 1993: A review of harmful algal blooms and their apparent global increase. *Phycologia*, **32**, 79-99.

Harley C. D. G., Hughe A. R., Hultgren K. K., Miner B. G., Sorte C. J. B., Thronber C. S., Rodriguez L. F., Tomanek L., and Williams S. L., 2006: The impacts of CC in coastal marine systems. *Ecol. Lett.*, **9**, 228-241.

Hégaret H. and Wikfors G. H., 2005: Time-dependent changes in hemocytes of eastern oysters, *Crassostrea virginica*, and northern bay scallops, *Argopecten irradians irrandians*, exposed to cultured strain of *Prorocentrum minimum*. *Harmful Algae*, **2**, 187-199.

Hégaret H., Smolowitz R. M., Sunila I., Shumway S. E., Alix J., Dixon M., and Wikfors G. H., 2010: Combined effects of parasite, QPX, and the harmful-alga, *Prorocentrum minimum* on northern quahogs, *Merecenaria mercenaria*. *Mar. Environ. Res.*, **69**, 337-344.

Hégaret H., Brokordt K. B., Gaymer C. F., Lohrmann K. B., García C., and Varela D., 2012: Effects of the toxic dinoflagellate *Alexandrium catenella* on histopathogical and escape responses of the Northern scallop *Argopecten purpuratus*. *Harmful Algae,* **18**, 74-83.

IPCC, 2007: Climate Change 2007: Mitigation of Climate Change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, UNEP, Geneva.

Landsberg J. H., 2002: The effects of harmful algal blooms on aquatic organisms. *Rev. Fish. Sci.*, **10**, 113-390.

Matsuyama Y. and Shumway S. E., 2009: Impacts of harmful algal blooms on shellfisheries aquaculture, in "New Technologies in Aquaculture: Improving Production Efficiency, Quality and Environmental Management" (ed. by Brunell G. and Allan G.), CRC Press, Woodhead Publishing, pp. 580-609.

Miller A. W., Reynolds A. C., Sobrino C., and Riedel G. F., 2009: Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS One*, **4**, e5661. doi:10.1371/journal.pone.0005661

Moore S. K., Trainer V. L., Mantua N. J., Parker M. S., Laws E. A., Backer L. C., and Fleming L. E., 2008: Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environ. Health*, **7 (Suppl. 2)**, S4.

Parker L. M., Ross P. M., and O' Connor W. A., 2009: The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster *Saccostrea glomerata* (Gould 1850). *Glob. Chang. Biol.*, **15**, 2123-2136.

Rogers A. D. and d'A Laffoley D., 2011: International Earth system expert workshop on ocean stresses and impacts, Summary report, IPSO, Oxford, 18pp.

Ruckelshaus M., Doney S. C., Galindo H. M., Barry J. P., Chan F., Duffy J. E., English C. A., Gaines S. D., Grebmeier J. M., Hollowed A. B., Knowlton N., Polovina J., Rabalais N. N., Sydeman W. J., and Talley L. D., 2013: Securing ocean benefits for society in the face of climate change. *Mar. Policy*, **40**, 154-159.

Scavia D., Field J. C., Boesch D. F., Buddemeier R. W., Burkett V., Cayan D. R., Fogarty M., Harwell M. A., Howarth R. W., Mason C., Reed D. J., Royer T. C., Sallenger A. H., and Titus J. G., 2002: Climate change impacts on US coastal and marine ecosystems. *Estuaries*, **25**, 149-164.

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

Shumway S. E. and Cucci T. L., 1987: The effect of the toxic *Protogonyaulax tamarensis* on the feeding and behavior of bivalve molluscs. *Aquat. Toxicol.*, **10**, 9-27.

Smayda T. J., 1990: Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic, in "Toxic Marine phytoplankton: Proceedings of the 4th International Conference on Toxic Marine Phytoplankton" (ed. by Granéli E., Sundström B., Edler L., and Anderson D. M.), Elsevier, New York, pp. 29-40.

Talmage S. C. and Gobler C. J., 2010: Effects of past, present and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *P. Natl. Acad. Sci. USA*, **107**, 17246-17251.

Tatters A. O., Flewelling L. J., Fu F., Granholm A. G., and Hutchins D. A., 2013: High CO_2 promotes the production of paralytic shellfish poisoning toxins by *Alexandrium catenella* from Southern California waters. *Harmful Algae*, **30**, 37-43.

Trujillo P., Piroddi C., and Jacquet J., 2012: Fish farms at sea: the ground truth from Google Earth. *PLoS One*, **7**, e30546.

Van Dolah F. M., 2000: Marine algal toxins: origin, health effects, and their increased occurrence. *Environ. Health Perspec.*, **108**, 133-141.

Waldbusser G. G., Voigt E. P., Bergschneider H., Green M. A., and Newell R. I. E., 2011: Biocalcification in the Eastern Oyster Crassostrea virginica in relation to long-term trends in Chesapeake Bay pH. *Estuar. Coast.*, **34**, 22-231.

Wells M. L., Trainer V. L., Smayda T. J., Karlson B. S. O., Trick C. G., Kudela R. M., Ishikawa A., Bernard S., Wulff A., Anderson D. M., and Cochlan W. P., 2015: Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae*, **49**, 68-93.

Zingone A. and Enevoldsen H. O., 2000: The diversity of harmful algal blooms: a challenge for science and management. *Ocean Coast. Manage.*, **43**, 725-748.

Annotated bibliography

(1) Glibert P. M., Allen J. I., Artioli Y., Beusen A., Bouwan L., Harle J., Holmes R., and Holt J., 2014: Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: projections based on model analysis. *Glob. Chang. Biol.*, **20**, 3845-3858.

Using a global modeling approach, the effects of nutrient loading and climate change on the projected distributions of two genera of harmful algae in coastal ecosystems of three regions of the globe were examined. Range expansions and retractions were found for the two genera suggesting future shifts in the vulnerability of coastal ecosystems to HAB events, increased regional HAB impacts on aquaculture leading to increase in the risks to human health and ecosystem services and associated economic consequences.

(2) Basti L., Endo M., Segawa S., Shumway S. E., Tanaka Y., and Nagai S., 2015: Prevalence and intensity of pathology induced by the toxic dinoflagellate, *Heterocapsa circularisquama*, in the Mediterranean mussel, *Mytilus galloprovincialis*. *Aquat. Toxicol.*, **163**, 37-50.

The study examines the effects of temperature on the pathologies induced by the shellfish-killing harmful alga, *Heterocapsa circularisquama*, in the Mediterranean mussel, *Mytilus galloprovincilias*. The study shows that increased temperature leads to increased prevalence and intensity of pathologies in the mussels in several vital organs, including gills and intestines. The study shows that warming temperature may increase the effects of the harmful alga on mussels even at low cell density, possibly reducing the overall health of the mussels. It also shows that the range expansion of the harmful alga associated with increased winter water temperature may put bivalve aquaculture farms under further risks of mass mortalities and production failure.

(3) Filgueira R., Guyondet T., Comeau L. A., and Tremblay R., 2016: Bivalve aquaculture-environment interactions in the context of climate change. *Glob. Chang. Biol.*, **22**, 3901-3913.

The study examines the interactions between bivalve aquaculture and the environment (bay geomorphic type, freshwater input), in the context of climate change (sea level rise, temperature, precipitation). Based on a factorial deign of 336 scenarios, the modeling showed that temperature is the strongest climate change driver to affect bivalve aquaculture as it can influence their metabolism. Differences in thermal tolerance of the cultured bivalve species would determine "winners" from "losers".

(4) Gobler J. C., Dohrty 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. *Proc. Natl. Acad. Sci. USA*, **114**, 4975-4980.

The study models the trends in growth rates and duration of bloom seasons of two species of the most toxic and widespread harmful algal blooms in the North Atlantic and North Pacific oceans using high-resolution SST (sea surface temperature) over the past three decades. Increasing water temperature associated with climate change have expanded the niches of these toxic algae (*Dinophysis acuminata* and *Alexandrium fundeyense*) and might contribute to an expansion of the associated human health threat via the consumption of shellfish contaminated with diarrheic shellfish poisoning (DSP) and paralytic shellfish poisoning (PSP).

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Defining an ecosystem approach to aquaculture (EAA) for federal waters of the United States

Katherine A. McGRAW* and Michael B. RUST

Abstract: The increase in world population, along with increased demand for seafood as a source of human nutrition, and stagnant wild fisheries catches, will necessitate the growth and diversification of marine aquaculture globally. However, marine aquaculture development in many countries, including the United States, lags behind that of freshwater aquaculture. The United States (U.S.), despite having the world's largest Exclusive Economic Zone (EEZ), imports about 90 percent of the seafood consumed domestically (by value). One solution to the seafood import deficit is to pursue the development of marine aquaculture including offshore aquaculture in the EEZ, also known as federal waters.

Various laws and regulations give the National Oceanic and Atmospheric Administration (NOAA) oversight of fisheries in federal waters. NOAA's National Marine Fisheries Service (NMFS) has long recognized the importance of implementing ecosystem-based fisheries management in order to explicitly account for environmental changes and make trade-off decisions for actions that affect multiple species; however, this approach needs to be investigated for American aquaculture. In many respects, US marine aquaculture may already be managed with an ecosystem approach owing to the various environmental laws which underlie its regulation and management.

If marine aquaculture is to grow in accordance with US laws and social values there need to be guidelines and a framework for this effort, just as there is for capture fisheries. In order to benefit from marine aquaculture opportunities that are in line with these laws and values, the NOAA Office of Aquaculture is exploring an Ecosystem Approach to Aquaculture (EAA). The NOAA EAA is based on the definition of Ecosystem Based Fishery Management as defined under the US fisheries laws (Magnuson-Stevens Act). This exercise may also serve to guide research, and as the first step in articulating a more detailed approach for implementation of ecosystem-based management of marine aquaculture. This paper provides an overview of NOAA's Ecosystem Approach to Aquaculture, including a definition of EAA, rationale for development of the document, and some of the expected benefits of EAA.

Key words: ecosystem approach, offshore aquaculture, federal waters

Introduction

Marine aquaculture as it is now practiced in other countries, is a relatively recent development in the United States (Knapp and Rubino, 2016). The top marine species cultured and harvested in the US are: oysters, clams, mussels, shrimp, and salmon (NOAA, 2017); and much lesser amounts of yellowtail, moi, seabass, and seabream (**Fig.1**). Marine aquaculture production has incrementally increased in both volume and value since 2009. Marine aquaculture production in 2015 was 96.6 million pounds, a 6.6 % increase over 2014 production and a $7.9 million (2.1 %) increase in value (NOAA, 2017).

There is a huge potential to increase and expand marine aquaculture globally and in the US. In their

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* NOAA Office of Aquaculture 1315 East-West Hwy, Silver Spring, MD 20910, U. S. A.
E-mail: Kay.McGraw@noaa.gov

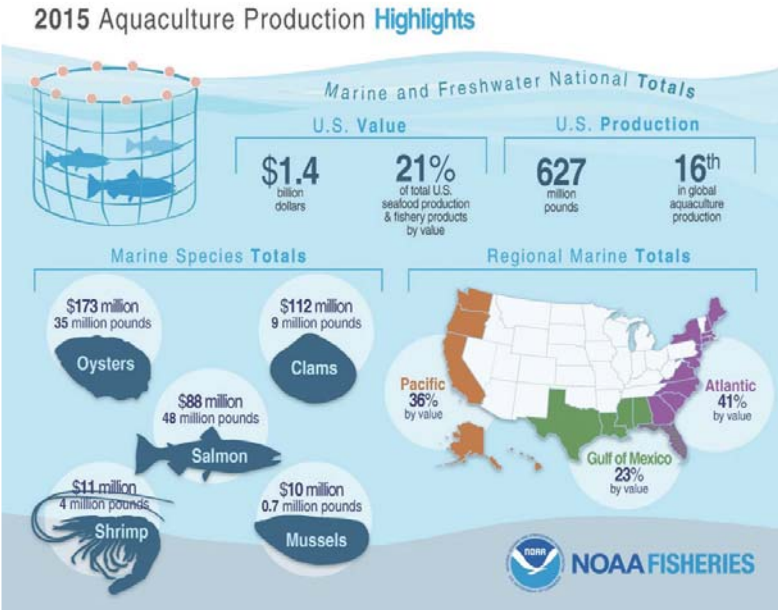

Fig. 1. U.S. Aquaculture production statistics for 2015. (NOAA, 2017)

studies, Kapetsky *et al.* (2013), Gentry *et al.* (2017), and Oyinlola *et al.* (2018) found that, even with many constraints, there are vast areas in the world's oceans that are suitable for offshore marine aquaculture. For example, Gentry *et al.* (2017) estimated that marine aquaculture could produce the equivalent of current wild-capture fisheries using less than 0.015 % of the global ocean area – a "surface area less than Lake Michigan". Kapetsky *et al.* (2013) also calculated that most countries would only need to have aquaculture in less than 1 % of their EEZ to produce all the seafood they currently require. In the U.S., production could be vastly increased by utilizing more offshore, or federal, waters (Kapetsky *et al.*, 2013). Indeed, there are many factors driving the development and expansion of marine and offshore aquaculture[1], as explained below. However, doing this in an environmentally sound and sustainable way requires a balance that allows for the production of more seafood, while also protecting native species, maintaining a healthy, productive, and resilient ecosystem, fish habitats, and a viable seafood industry. One option to account for the attainment of such diverse goals may be initiated through the articulation of an Ecosystem Approach to Aquaculture (EAA).

What is an ecosystem approach to aquaculture?

Based on a similar NOAA definition for an Ecosystem Approach to Fisheries, we define an Ecosystem Approach to Aquaculture as follows:

An ecosystem approach to aquaculture is a systematic method of managing aquaculture that:

- is in a geographically specified area;
- contributes to the resilience[2] and sustainability[3] of the ecosystem[4];

1 "Offshore Aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbor or shore base is often but not always a factor" (Drumm, 2010).

2 Resilience can be defined as the capacity of a(n) (eco)system to persist or maintain function in the face of exogenous disturbances. That is, the capacity of an ecosystem to tolerate disturbance (e.g., such as intensive fishing) without collapsing into a different state that is controlled by a different set of processes. This is primarily encapsulated by two elements, resistance to and recovery from pressure (NOAA, 2016).

3 FAO defines sustainability (as synonymous with sustainable development) as "the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in the agriculture, forestry and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (Welcomme and Barg, 1997)

4 In the NOAA Fisheries context, the term "ecosystem" means a geographically specified system of fisheries resources (including aquaculture), the persons that participate in that system, the environment, and the environmental processes that control that ecosystem's dynamics (Murawski and Matlock, 2006). Aquaculturists, fishermen and the associated support communities are understood to be included in the definition.

- recognizes the physical, biological, economic, and social interactions among the affected aquaculture-related components of the ecosystem, including humans;
- seeks to optimize benefits within a diverse set of environmental and social constraints;
- is adaptive over time.

Our definition of EAA adheres closely to some others, such as that of the Food and Agriculture Organization (Soto *et al*., 2008a), which defines EAA as follows: "*The ecosystem approach to aquaculture is a strategic approach to development and management of the sector aiming to integrate aquaculture within the wider ecosystem such that it promotes sustainability of interlinked social-ecological systems*".

Our EAA definition fits within this more general FAO definition, and is consistent with the specific mandates and guidelines in the U.S.'s aquaculture law (National Aquaculture Act [NAA]) and fisheries law (Magnuson-Stevens Fishery Conservation Act [MSA]). It also respects other environmental laws under which the US operates and manages aquaculture to fulfill its mission (see the section on "Major Laws" below for more information on these).

EAA includes considerations of interactions among aquaculture, fisheries, protected species, habitats, and other ecosystem components, including the human communities that depend upon them and their associated ecosystem services. EAA examines not only the broader suite of factors that affect aquaculture efforts, but also considers the potential impacts (positive and negative) of aquaculture on other parts of the ecosystem (e.g., on nutrients, plankton, fish species, habitats, marine mammals and so on). "Societal goals" consider and include any relevant economic, social, and other factors valued by society in the context of, or relating to aquaculture. EAA is cognizant of both human and ecological considerations and seeks to optimize returns to both as much as possible. This is an attempt to create a common framework that leads to ecosystem resiliency.

In many ways EAA is similar to the Japanese concept of "*Sato-Umi*" *which is defined as "a coastal area with high productivity and biodiversity due to human interaction" (Yanagi, 2005), or "a seascape where human-ecosystem interaction has resulted in increased biodiversity and productivity, thus improving the health of the environment and its ecosystem services*" (Mizuta and Vlachopoulou, 2017).

Purpose

The purpose of this paper is to articulate principles of marine aquaculture development and activity within the context of the National Oceanic and Atmospheric Administration's (NOAA's) multiple stewardship missions and broader social, environmental and economic goals. Meeting this objective will help NOAA to integrate environmental, social, and economic considerations in management decisions concerning aquaculture. The EAA will also serve to reaffirm that aquaculture is an important component of NOAA's efforts to maintain healthy and productive marine and coastal ecosystems while providing seafood. Implementation of the EAA involves balancing competing uses of the marine environment, creating employment and business opportunities in our communities, and enabling the production of safe and sustainable seafood.

Why have an ecosystem approach to aquaculture?

Although aquaculture is considered a "fishery" under the US fisheries law (MSA), marine aquaculture is also farming and adheres to all the other environmental laws and regulations pertaining to all marine activities and all farming activities. A separate ecosystem approach is needed for marine aquaculture because it differs from capture fisheries in several important structural aspects. First of all, the potential impacts from aquaculture on wild fisheries stocks are indirect[5] (habitat, stress, genetics), while capture fishing deals with direct (harvest) and indirect impacts (habitat destruction, genetic impacts, stress and so on). Some of the indirect effects of aquaculture can be managed to be positive and produce enhanced environments for wild stocks and

[5] None of these directly remove members of wild populations from the ecosystem. This is in contrast to harvest from wild capture where the whole point is to remove members of the wild populations from the ecosystem.

other forms of aquaculture. For example, nutrients in the marine environment either provided by, or taken up by, aquacultured organisms can be used to mitigate oligotrophication or eutrophication, respectively. Aquaculture structures can be designed to provide habitat. Hatcheries may produce organisms for release to rebuild wild stocks. Second, the management options for marine aquaculture are greater, and of a different nature than for fisheries. The main control for wild fisheries is management of harvest and habitat. Control over the harvestable biomass in wild fisheries is largely by acts of nature. Control over the harvestable biomass in aquaculture is much more in the hands of people. Recruitment in aquaculture is controlled by a hatchery, but even more so, the quality of recruits in terms of growth and survival to harvest are determined by genetics, nutrition, environmental conditions and husbandry, which are all at least partially under the control of humans. Because of the greater number and diversity of control points, the application of an ecosystem approach to aquaculture is more complex and differs in priorities from an ecosystem approach to fisheries.

For NOAA, this is not a new way of thinking, but just the adaptation of an ecosystem approach to a different endeavor that is not specifically resource extractive. It is time to define a NOAA ecosystem approach for aquaculture –and explore the same way of thinking the agency has advocated with regard to capture fisheries and other NOAA efforts.

Tables 1. Federal permits required for offshore aquaculture operations in federal waters of the Gulf of Mexico[7]

Agency	Statutes/Authorities	Purpose
U.S. Army Corps of Engineers (USACE)	Section 10 of the Rivers and Harbors Act and some sections of Clean Water Act	Required in navigable waters of the U.S. to protect navigation for commerce
National Oceanic and Atmospheric Administration (NOAA)	Magnuson- Stevens Fishery Conservation and Management Act (Magnuson- Stevens Act)	Required for operating offshore aquaculture facility in Federal waters of the Gulf and other areas of federal waters
U.S. Environmental Protection Agency(EPA)	Sections 402 and 403 of the Clean Water Act	Required for the discharge of pollutants into waters of the U.S.

Major laws and mandates governing aquaculture in the US

US marine aquaculture is arguably already managed with an ecosystem approach owing to the environmental laws which underlie its regulation and management (**Table 1**). There are laws in the United States that compel NOAA to manage marine fisheries and aquaculture so that the environment is considered and impacts minimized. Two of these are the Magnuson-Stevens Act[6] (MSA) and the National Aquaculture Act (NAA). In terms of ecological considerations, the MSA essentially states that fisheries will be managed in a way that:

- integrates ecosystem considerations into fishery conservation and management actions,
- minimizes the impacts of fishing on ecosystem components, and
- conserves important ecosystem components from non-fishing threats.

Similarly, the National Aquaculture Act (NAA) dictates that aquaculture will be conducted to:

- promote and support the development of private aquaculture;
- promote coordination among the various federal agencies that have aquaculture programs and policies;
- Provide a legal mandate for NOAA Fisheries to support the development of the U.S. marine aquaculture industry.

The NAA also allows for the use of aquaculture to enhance and restore species. The NAA is primarily administered by the U.S. Department of Agriculture (USDA), which is the lead Federal agency for aquaculture in the U.S., along with the U.S. Department of Commerce (of which NOAA is a part) and the U. Department of the Interior. NOAA is specifically directed to support the development of

6 Although the term "aquaculture" is not mentioned specifically in the MSA, NOAA has a legal opinion that equates aquaculture to fisheries; therefore, aquaculture endeavors in federal waters are also required to follow the same standards.

7 In the Gulf of Mexico, federal waters begin at 3 nautical miles from shore in Louisiana, Mississippi and Alabama and 9 nautical miles from shore in Texas and Florida, and extend to approximately 200 nautical miles from the coast. (NOAA, 2017)

the U.S. marine aquaculture industry, an increasingly important economic component of marine ecosystems, and use of aquaculture to enhance and restore species for commercial, recreational and restoration purposes. In addition, some types of aquaculture in federal waters are regulated under MSA in the Gulf of Mexico, and are under consideration by other Councils.

In addition to the MSA and the NAA, there are many other statutes and authorities that govern marine aquaculture permits and operations in the U.S. Some of the federal laws are listed in the **Tables 1 - 3**. Taken together, these laws, along with other regulations, enable federal oversight and enforcement to help protect the marine environments and the biota inhabiting them (e.g., endangered species, fish and wildlife, and essential fish habitat). Others pertain to navigation and fossil fuel extraction activities, as well as historic and cultural artifacts.

In addition to these federal laws, individual states and local government within states may also have others that are applicable to state waters.

The Coastal Zone Management Act (CZMA) was passed by Congress in 1972 and is administered by NOAA. It provides for the management of the nation's coastal resources, including the Great Lakes. The goal is to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone."

One of the programs of the CZMA is the National Coastal Zone Management Program (NCZMP), which comprehensively addresses the nation's coastal issues through a voluntary partnership between the federal government and coastal and Great Lakes states and territories. The program provides the basis for protecting, restoring, and responsibly developing the nation's diverse coastal communities and resources.

Currently 34 coastal states participate in the NCZMP. While state partners must follow basic requirements, the program also gives states the flexibility to design unique programs that best address their coastal challenges and regulations. By leveraging both federal and state expertise and resources, the program strengthens the capabilities of each to address coastal issues, including aquaculture activities.

Thus, aquaculturists wishing to obtain permits to build and operate aquaculture facilities in coastal and federal waters must go through an arduous process, designed primarily to protect the environment, to obtain them. Once their projects are operational, they must still adhere to federal and state laws governing water pollution, threatened and endangered species, marine mammals (i.e., entanglement in gear), and others. This legal landscape helps ensure that aquaculture in U.S. marine waters is conducted in accordance with the environmental aspects of the principles of an ecosystem approach to aquaculture. The current system does not consider broad scale social and economic considerations in permit decisions for aquaculture. An EAA might help to provide for a more diverse set of considerations in permit decisions.

Tables 2. Federal authorizations required for offshore aquaculture operations in federal waters of the Gulf

Agency	Statutes/Authorities	Purpose
Authorizations		
U.S. Coast Guard (USCG)	33 U.S.C. 1221 *et seq* 33 CFR §66	Ensure safe navigation Authorize Private Aids to Navigation
Authorizations for Aquaculture Operations Co-Located with OCS		
Bureau of Ocean Energy Management (BOEM)	Outer Continental Shelf Lands Act; Energy Policy Act of 2005; 30 CFR	Required for any offshore aquaculture operations that utilize or tether to existing oil and gas facilities
Bureau of Safety and Environmental Enforcement (BSEE)	Outer Continental Shelf Lands Act	

What are some of the benefits of EAA?

As interest in aquaculture in the U.S. has increased, so too has the debate about the potential economic, environmental, and social effects of aquaculture. There are environmental challenges posed by aquaculture when it is done poorly (e.g., habitat destruction, excess nutrient discharges, water use demands, invasive species, genetic impacts and effects on protected species). There are also socioeconomic challenges, for example, competition for the use of marine space and potential effects of increased aquaculture production on prices of wild caught fish. However, aquaculture practiced in consideration of the ecosystem can result in many

Tables 3. Required federal consultations and reviews. Agencies with permitting decisions for aquaculture facilities including NOAA, EPA and USACE, will apply the relevant and applicable provisions of the laws identified below to their federal actions. Many of these consultations and reviews may occur in tandem with the permit application review process

Consultation or Review	Description of the Requirement
Endangered Species Act	Section 7 of the Endangered Species Act (ESA) requires any federal agency that issues a permit to consult with NOAA's National Marine Fisheries Service (NMFS) and/or the U.S. Fish and Wildlife Service (USFWS), *if* issuance of the permit may adversely affect ESA- listed species and/or the designated critical habitat for ESA-listed species. The Section 7 consultation process requires an analysis of the effects of the proposed action on ESA-listed species and designated critical habitat based on the best available science. The analysis must determine if the proposed action is likely adversely affect an ESA-listed species and/or designated critical habitat. If the analysis determines the issuance of a proposed permit will adversely affect an ESA-listed species, but will not jeopardize its continued existence, then reasonable and prudent measures and implementing terms and conditions that minimize the adverse impacts must be developed.
Essential Fish Habitat	The Essential Fish Habitat (EFH) provisions of the Magnuson-Stevens Act requires federal agencies to consult with NMFS when activities they undertake or permit have the potential to adversely affect EFH.
National Historic Preservation Act	Section 106 of the National Historic Preservation Act (36 CFR Part 800) requires any federal agency issuing a permit to account for potential effects of the proposed aquaculture activity on historic properties, *e.g.*, shipwrecks, prehistoric sites, cultural resources. If a proposed aquaculture activity has the potential to affect historic properties these details must be provided by the applicant as part of the application packages.
Fish and Wildlife Coordination Act	The Fish and Wildlife Coordination Act requires any federal agency issuing permits to consult with USFWS and NMFS if the proposed aquaculture activities could potentially harm fish and/or wildlife resources. These consultations may result in project modification and/or the incorporation of measures to reduce these effects.
National Marine Sanctuary Resources Act	Section 304(d) of the National Marine Sanctuaries Act (NMSA) requires that any federal agency issuing permits to consult with NOAA's National Marine Sanctuary Program (NMSP) if the proposed aquaculture activity is likely to destroy or injure sanctuary resources. As part of the consultation process, the NMSP can recommend reasonable and prudent alternatives. While such recommendations may be voluntary, if they are not followed and sanctuary resources are destroyed or injured in the course of the action, the NMSA requires the federal action agency(ies) issuing the permit(s) to restore or replace the damaged resources.

environmental, economic, and social benefits while avoiding the challenges listed above.

Resilience and sustainability

Aquaculture can contribute to the resilience and sustainability of seafood. NOAA defines resilience as the capacity of a system to persist or maintain function in the face of exogenous disturbances. That is, the capacity of an ecosystem to tolerate disturbance without collapsing into a different state that is controlled by a different set of processes. This is primarily encapsulated by two elements: resistance to, and recovery from, pressure. (NOAA, 2016)

NOAA defines fisheries sustainability as a "characteristic of resources that are managed so that the natural capital stock is non-declining through time, while production opportunities are maintained for the future. Fishing is sustainable when it can be conducted over the long-term at an acceptable level of biological and economic productivity without leading to ecological changes that foreclose options for future generations" (Sutinen *et al.*, 2000; Blackhart *et al.*, 2006). This definition somewhat applies to aquaculture, but is not a perfect fit due to aquaculture's ability to scale with seafood demand versus capture fisheries' dependence on a fixed supply. There is no "natural capitol stock" to manage. The World Bank (The World Bank 2014) puts it this way:

Aquaculture is projected to be the prime source of seafood by 2030,…for an aquaculture system to be truly sustainable, it must have:

- ***Environmental sustainability** — Aquaculture should not create significant disruption to the ecosystem, or cause the loss of biodiversity or substantial pollution impact.*
- ***Economic sustainability** — Aquaculture must be a viable business with good long-term prospects.*
- ***Social and community sustainability** — Aquaculture must be socially responsible and contribute to community well-being.*

Sustainable aquaculture is a dynamic concept and the sustainability of an aquaculture system will vary with species, location, societal norms and the state of knowledge and technology.

Fig. 2. Example of Olympia oyster (Ostrea lurida Carpenter 1864) restoration plot in Puget Sound, WA. (Photo credit: NOAA Fisheries)

Fig. 3. A diver surveys coral pieces being cultured for coral reef restoration. (Photo credit: NOAA Fisheries).

More efficient use of resources and feed

Aquaculture is one of the most efficient agricultural systems, and is typically better than terrestrial farming in terms of feed conversion (Hall *et al.*, 2011; Brummett, 2013), greenhouse gas emissions, land use, energy efficiency and freshwater use (Nijdam *et al.*, 2012). Aquaculture as practiced in the US provides food at a smaller global environmental cost than agriculture, while developing an EAA could produce this food with even a smaller negative environmental cost, or potentially while providing environmental benefits.

Restoration

- Aquaculture plays a prominent role in restoring populations of marine fish and shellfish. Hatcheries provide organisms to rebuild oyster reefs (**Fig.2**), coral reefs (**Fig.3**), enhance wild fish populations (e.g., salmon, red drum, flounder), and rebuild populations that are threatened or endangered (e.g., salmon and abalone, **Fig.4**).
- Fish hatcheries have long been used to augment both freshwater and marine fish populations. Many salmon runs in the U.S. are supplemented by salmon hatcheries in an effort to rebuild natural salmon populations that have declined due to various limits to natural recruitment, or to provide catch in excess of what would be available naturally

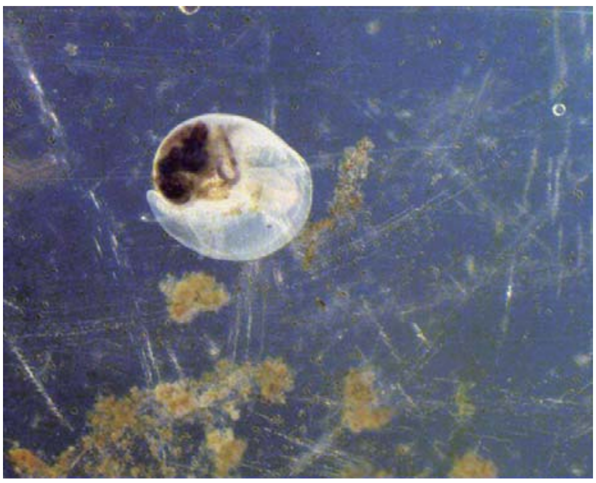

Fig. 4. Two month old white abalone larva cultured in a hatchery. Photo credit: Kristin Aquilino, NOAA

(Hess *et al.*, 2012). In addition, aquaculture can be used to restore physical and ecosystem function.

For example, one use of hatchery-reared oysters in the U.S. is in the creation of "living" or "green" shorelines to reduce erosion and wave action in vulnerable coastal areas (Fig.5). In these projects, oyster reefs are built using hatchery-reared oysters (set on shell) in conjunction with seagrass or submerged aquatic vegetation (SAV), marsh grass, and sometimes other structures to increase habitat and vegetation along shorelines and help prevent erosion. In some subtidal oyster reef restoration projects, hatchery-reared oysters are placed as an outer layer on mounds of clean shell (Fig.6).

Fig. 5. Volunteers restoring marsh grass in a coastal "living shorelines" restoration project. (Photo credit: NOAA Fisheries)

Ecosystem services

There is growing recognition of the ecosystem services provided by aquaculture in the U.S. and other countries. Restoration practitioners have increasingly pursued bivalve, sea grass and kelp restoration as a component of restoring historical baseline water quality conditions and functioning of ecosystems (Rice, 2000). For example, restoration of oyster reefs (Fig.7) can restore water clarity, help reduce phytoplankton blooms caused by excess nutrient loading and decrease turbidity (Everett *et al.*, 1995; Carroll *et al.*, 2008). Like bivalves, seaweed also removes and sequesters carbon and nitrogen; and the structures of all types of aquaculture (cages, ropes, buoys, rafts, etc.) may provide habitat for aquatic animals (North, 1987; Phillips, 1990; Zhen-hua and Wei-ding, 2007).

Aquaculture of filter feeders (e.g., oysters and mussels) and macro-algae can enhance resilience of the estuarine ecosystem to eutrophication (Jackson *et al.*, 2001; Lotze *et al.*, 2006) and help enhance habitat functions. (Carroll *et al.*, 2008; Wall *et al.*, 2008). Conversely, much of the ocean is oligotrophic, and the addition of nutrients from fed aquaculture in these types of areas may lead to enhanced ecosystem services, biodiversity, and greater resiliency (Machias

Fig. 6. Rock Point Oyster Company Shellfish Farm in Quilcene, WA. (Photo credit: Jenifer Rhoades, NOAA IOOS Program). Bagged spat on shell like this can also be used in oyster restoration as well as living shoreline restoration projects.

Fig. 7. Oyster reef in the southeast U.S. (Photo credit: NOAA Fisheries)

Fig. 8. Flounder in seagrass bed. (Photo credit: NOAA Fisheries)

Fig. 9. Collection of white anemones (Metridium senile) and other diverse invertebrates on a walkway float of a net pen in Puget Sound, Washington. (Photo credit: Jack Rensel, Rensel Associates Aquatic Sciences, Arlington, WA)

et al., 2004; Machias *et al.*, 2005; Diana, 2009). There has been much work on attempting to balance nutrient inputs from fed aquaculture with nutrient extraction by filter feeders and macro-algae on a local scale (Chopin *et al.*, 2001; Chopin *et al*, 2008; Neori, 2008; Barrington *et al.*, 2009; Troell *et al.*, 2009; Chopin, 2015). This approach has been called Integrated Multi-Trophic Aquaculture (IMTA). EAA benefits from the mass balance nutrient relationships illuminated by IMTA studies, but differs by considering the nutrient (trophic) background of the host environment and its ability to benefit from additions or reductions in ambient nutrients from aquaculture at various ecosystem scales and under different temporal patterns.

When marine organisms of all types are cultured by using structures (long lines, cages, net-pens) the structures themselves may also provide habitat and attachment surfaces for many other organisms such as ascidians, sponges, anemones, and mollusks. It is well known that natural and enhanced oyster reefs are habitat for many different species (Bahr and Lanier, 1981; Breitburg and Miller, 1998; Coen *et al.*, 1999; Posey *et al.*, 1999). However, gear used in all types of aquaculture may also provide similar habitat benefits. For example, Powers *et al.* (2007) found that plastic mesh used in bottom clam culture had significantly greater macroalgal/epifaunal biomass per unit than sandflats and were similar to that provided by natural seagrass. Also, the kinds of invertebrates and juvenile fishes utilizing the clam leases were similar to seagrass habitat. Overall the biogenic habitat created by the aquaculture gear was more diverse than without the gear (**Fig.8**). In addition, Rensel and Forster (2007) surveyed fish net pens in Puget Sound, Washington to quantify the types and volumes of biofouling organisms and found that the typical net pen system there was populated by a diverse group of over 100 species of seaweeds and invertebrates, many of which are important components of the food web (**Fig.9**). Some were also commercially important (e.g., mussels and kelp).

Economic Sustainability

The collapse of some fisheries, plus other economic and environmental factors (e.g., fleet consolidation, hurricanes) have resulted in a loss of jobs for some fishers and support industries in coastal areas involved in the seafood business. Aquaculture has the potential to stimulate the economy in some locations by directly providing jobs in aquaculture, and indirectly by servicing boats, seafood processing, marketing, transportation, and other positions that help keep and maintain working waterfronts (Rubino, 2008). For example, results of one modeling study predict that the number of jobs created across all sectors per thousand metric tons of production per year would be 102 jobs for mussels, 261 for salmon, 475 for cod, and 683 for scallops (Posadas, 2004). When the development is properly scaled for the location and region, it can create entrepreneurial opportunities that have a ripple effect in local economies (Soto *et al.*, 2008b).

Monitoring and adaptive management

Adaptive management (**Fig.10**) is "*a decision process that promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood*" (Williams *et al.*, 2009). It is a process that allows for flexible decision making that takes some degree of uncertainty into consideration and adjusts actions and decisions to resolve the issue or problem. The process improves understanding of a resource system and tests key assumptions through monitoring. Monitoring and adaptive management are key to developing ecologically resilient and sustainable aquaculture projects. Adaptive management is a tool which should be used not only to change a system, but also to learn about the system. Because adaptive management is based on a learning process, it improves long-term management outcomes. In this way, decision making simultaneously meets one or more resource management objectives and, either passively or actively, accrues information needed to improve future management (Holling, 1978).

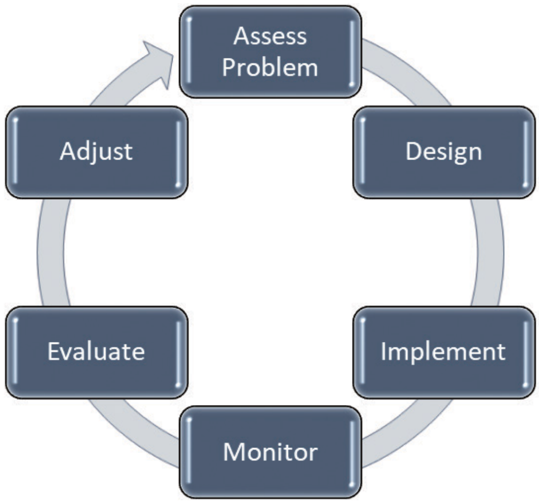

Fig. 10. Conceptual diagram of the six-step adaptive management cycle (adapted from Fig. 1.1 in Williams *et al.* (2009)).

Conclusion

NOAA's National Marine Fisheries Service has long recognized the importance of implementing ecosystem-based fisheries management in order to explicitly account for environmental changes and make trade-off decisions for actions that affect multiple species; however, this approach has not been applied specifically to aquaculture. If marine aquaculture is to grow in accordance with societal values, there need to be guidelines and a framework for this effort, just as there are for capture fisheries. Based on a similar definition for an Ecosystem Approach to Fisheries, we define an Ecosystem Approach to Aquaculture as follows: An ecosystem approach to aquaculture is a systematic method of managing aquaculture that: 1) is in a geographically specified area, 2) contributes to the resilience and sustainability of the ecosystem, 3) recognizes the physical, biological, economic, and social interactions among the affected aquaculture-related components of the ecosystem, including humans; 4) seeks to optimize benefits among a diverse set of societal goals and 5) is adaptive over time. The stage is set for an ecosystem approach to aquaculture to flourish in the US. The current small US marine aquaculture industry is an example of where EAA is already guiding responsible and sustainable development. EEA principles are being used in the US, but not as a management paradigm and the use of EEA tools is not widely recognized.

Many factors affecting the success of marine aquaculture in the US are unknown; however, Knapp (2008) cites several examples of offshore aquaculture ventures that indicate a bright future for aquaculture expansion in the U.S. There is increasing interest in, and need for, a more robust marine aquaculture industry in the U.S., including finfish, seaweed, and bivalve farms. The impetus for aquaculture expansion in the U.S., from both an economic and food sustainability perspective, has never been greater.

References

Bahr L. M. and Lanier W. P., 1981: The ecology of intertidal oyster reefs of the South Atlantic coast: a community profile, US Fish and Wildlife Service. U. S. Department of Interior, Washington D. C., 105pp.

Barrington K., Chopin T., and Robinson S., 2009: Integrated multi-trophic aquaculture (IMTA) in marine temperate waters, in "Integrated mariculture: a global review" (ed. by Soto D.), FAO Fisheries and Aquaculture Technical Paper No. 529, FAO, Rome, pp. 7-46.

Blackhart K., Stanton D. G., and Shimada A. M., 2006: NOAA Fisheries Glossary. NOAA Technical Memorandum NMFS-F/SPO-69, U.S. Department of Commerce, NOAA, Silver Spring, 61 pp. An on-line version of this glossary is available at: http://www.st.nmfs.gov/st4/documents/F_Glossary.pdf.

Breitburg D. and Miller T., 1998: Are oyster reefs essential fish habitat? Use of oyster reefs by ecologically and commercially important species. *J. Shellfish Res.*, **17**, abstract only.

Brummett R., 2013: Growing aquaculture in sustainable ecosystems, Agriculture and Environmental Services Department Notes, No. 5, The World Bank, Washington D.C., Available at: http://documents.worldbank.org/curated/en/556181468331788600/pdf/788230BRI0AES00without0the0abstract.pdf.

Carroll J., Gobler C. J., and Peterson B. J., 2008: Resource-restricted growth of eelgrass in New York estuaries: light limitation, and alleviation of nutrient stress by hard clams. *Mar. Ecol. Prog. Ser.*, **369**, 51-62.

Chopin T., 2015: Marine Aquaculture in Canada: Well-Established Monocultures of Finfish and Shellfish and an Emerging Integrated Multi-Trophic Aquaculture (IMTA) Approach Including Seaweeds, Other Invertebrates, and Microbial Communities. *Fisheries*, **40**, 28-31.

Chopin T., Buschmann A. H., Halling C., Troell M., Kautsky N., Neori A., Kraemer G. P., Zertuche-González J. A., Yarish C., and Neefus C., 2001: Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *J. Phycol.*, **37**, 975-986.

Chopin T., Robinson S. M. C., Troell M., Neori A., Buschmann A. H., and Fang J., 2008: Multitrophic integration for sustainable marine aquaculture, in "The Encyclopedia of Ecology, Ecological Engineering" (ed. by Jorgensen S. E. and Fath B. D.), Elsevier, Oxford, pp. 2463-2475.

Coen L. D., Luckenbach M. W., and Breitburg D. L., 1999: The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives, in American Fisheries Society Symposium 22, pp. 438-454.

Diana J. S., 2009: Aquaculture Production and Biodiversity Conservation. *Bioscience*, **59**, 27-38.

Drumm A., 2010: Evaluation of the promotion of offshore aquaculture through a technology platform (OATP), Marine Institute, Galway, 46pp.

Everett R. A., Ruiz G. M., and Carlton J. T., 1995: Effect of oyster mariculture on submerged aquatic vegetation: an experimental test in a Pacific Northwest estuary. *Mar. Ecol. Prog. Ser.*, **125**, 205-217.

Gentry R. R., Froehlich H. E., Grimm D., Kareiva P., Parke M., Rust M., Gaines S. D., and Halpern B. S., 2017: Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.*, **1**, 1317.

Hall S. J., Delaporte A., Phillips M. J., Beveridge M., and O'Keefe M., 2011: Blue frontiers: managing the environmental costs of aquaculture, The WorldFish Center, Penang, 92pp.

Hess M. A., Rabe C. D., Vogel J. L., Stephenson J. J., Nelson D. D., and Narum S. R., 2012: Supportive breeding boosts natural population abundance with minimal negative impacts on fitness of a wild population of Chinook salmon. *Mol. Ecol.*, **21**, 5236-5250.

Holling C. S., 1978: Adaptive environmental assessment and management, John Wiley & Sons, New York, 377pp.

Jackson J. B., Kirby M. X., Berger W. H., Bjorndal K. A., Botsford L. W., Bourque B. J., Bradbury R. H., Cooke R., Erlandson J., and Estes J. A., 2001: Historical overfishing and the recent collapse of coastal ecosystems. *Science*, **293**, 629-637.

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 No. 549, FAO, Rome., xvii + 181pp.

Knapp G., 2008: Economic potential for US offshore aquaculture: an analytical approach, in "Offshore aquaculture in the United States: Economic considerations, implications and opportunities" (ed. by Rubino M. C.), NOAA Technical Memorandum NMFS F/SPO-103, U.S. Department of Commerce, NOAA, Silver Spring, pp. 15-50.

Knapp G. and Rubino M. C., 2016: The Political Economics of Marine Aquaculture in the United States. *Rev. fish. sci. aquac.*, **24**, 213-229.

Lotze H. K., Lenihan H. S., Bourque B. J., Bradbury R. H., Cooke R. G., Kay M. C., Kidwell S. M., Kirby M. X., Peterson C. H., and Jackson J. B., 2006: Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science*, **312**, 1806-1809.

Machias A., Karakassis I., Giannoulaki M., Papadopoulou K., Smith C., and Somarakis S., 2005: Response of demersal fish communities to the presence of fish farms. *Mar. Ecol. Prog. Ser.*, **288**, 241-250.

Machias A., Karakassis I., Labropoulou M., Somarakis S., Papadopoulou K., and Papaconstantinou C., 2004: Changes in wild fish assemblages after the establishment of a fish farming zone in an oligotrophic marine ecosystem. *Estuar. Coast. Shelf Sci.*, **60**, 771-779.

Mizuta D. D. and Vlachopoulou E. I., 2017: Satoumi concept illustrated by sustainable bottom-up initiatives of Japanese Fisheries Cooperative Associations. *Mar. Policy*, **78**, 143-149.

Murawski S. A. and Matlock G. C., 2006: Ecosystem science capabilities required to support NOAA's mission in the year 2020, NOAA Technical Memorandum NMFS-F/SPO-74, U.S. Department of Commerce, NOAA, Silver Spring, 97pp.

Neori A., 2008: Essential role of seaweed cultivation in integrated multi-trophic aquaculture farms for global expansion of mariculture: an analysis. *J. Appl. Phycol.*, **20**, 567-570.

Nijdam D., Rood T., and Westhoek H., 2012: The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy,* **37**, 760-770.

NOAA, 2016: National Marine Fisheries Servie Policy Directive 01-120: Ecosystem-based Management Policy of the National Marine Fisheries Service (ed. by N. M. F. Service), NOAA, Silver Spring, 8pp. Available at http://www.nmfs.noaa.gov/op/pds/index.html.

NOAA, 2017: National Marine Fisheries Service (2016), Fisheries of the United States 2016, NOAA Current Fishery Statistics No. 2016, U.S. Department of Commerce, NOAA, Silver Spring, 134pp. Available at: https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2016-report.

North W. J., 1987: Oceanic farming of Macrocystis, the problems and non-problems, in "Seaweed Cultivation for Renewable Resources" (ed. by Bird K. T. and Benson P. H.), Developments in Aquaculture and Fisheries Sciences, Elsevier, Amsterdam, pp. 39-67.

Oyinlola M. A., Reygondeau G., Wabnitz C. C. C., Troell M., and Cheung W. W. L., 2018: Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS One*, **13**, e0191086.

Phillips M., 1990: Environmental aspects of seaweed culture, in "Regional Workshop on the Culture and Utilization of Seaweeds" (27-31 Aug, 1990), Cebu, pp. 27-31.

Posadas B. C., 2004: Potential economic impact of commercial offshore aquaculture in the Gulf of Mexico, Mississippi-Alabama Sea Grant College Program publication number MASGP 04-036, Mississippi State University, Biloxi, pp. 1-21.

Posey M. H., Alphin T. D., Powell C. M., and Townsend E., 1999: Use of oyster reefs as habitat for epibenthic fish and decapods, in "Oyster reef habitat restoration: a synopsis and synthesis of approaches" (ed. by Mann M. W. R. and Wesson J. A.), Virginia Institute of Marine Science Press, Gloucester Point, pp. 229-237.

Powers M. J., Peterson C. H., Summerson H. C., and Powers S. P., 2007: Macroalgal growth on bivalve aquaculture netting enhances nursery habitat for mobile invertebrates and juvenile fishes. *Mar. Ecol. Prog. Ser.*, **339**, 109-122.

Rensel J. and Forster J., 2007: Beneficial environmental effects of marine finfish mariculture, Final Report to the National Oceanic and Atmospheric Administration, #NA040AR4170130, Washington D. C., Available: https://www. wfga. net/documents/marine_finfish_finalreport. pdf. (April 2014).

Rice M., 2000: A review of shellfish restoration as a tool for coastal water quality management. *Envir. Cape Cod*, **3**, 1-8.

Rubino M., 2008: Offshore aquaculture in the United States: economic considerations, implications & opportunities, NOAA Technical Memorandum NMFS F/SPO-103, U.S. Department of Commerce, NOAA, Silver Spring, 263pp.

Soto D., Aguilar-Manjarrez J., and Hishamunda N., 2008a: Building an Ecosystem Approach to Aquaculture, FAO/Universitat de les Illes Balears Expert Workshop (7–11 May 2007, Palma de Mallorca, Spain), FAO Fisheries and Aquaculture Proceedings. No. 14, FAO, Rome, 221pp.

Soto D., Aguilar-Manjarrez J., Brugère C., Angel D., Bailey C., Black K., Edwards P., Costa-Pierce B., Chopin T., Deudero S., Freeman S., Hambrey J., Hishamunda N., Knowler D., Silvert W., Marba N., Mathe S., Norambuena R., Simard F., Tett P., Troell M., and Wainberg A., 2008b: Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures, in "Building an ecosystem approach to aquaculture" (ed. by Soto D., Aguilar-Manjarrez J., and Hishamunda N.), FAO/Universitat de les Illes Balears Expert Workshop (7–11 May 2007, Palma de Mallorca, Spain), FAO Fisheries and Aquaculture Proceedings. No. 14, FAO, Rome, pp. 15-35.

Sutinen J. G., Clay P., Dyer C. L., Edwards S. F., Gates J., Grigalunas T. A., Hennessey T., Juda L., Kitts A. W., and Logan P. N., 2000: A framework for monitoring and assessing socioeconomics and governance of large marine ecosystems, NOAA Technical Memorandum NMFS-NE 158:2000, U.S. Department of Commerce, NOAA, Silver Spring, 32pp.

The World Bank, 2014: Sustainable Aquaculture. (http://www.worldbank.org/en/topic/environment/brief/sustainable-aquaculture).

Troell M., Joyce A., Chopin T., Neori A., Buschmann A. H., and Fang J.-G., 2009: Ecological engineering in aquaculture−potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture*, **297**, 1-9.

Wall C. C., Peterson B. J., and Gobler C. J., 2008: Facilitation of seagrass *Zostera marina* productivity by suspension-feeding bivalves. *Mar. Ecol. Prog. Ser.*, **357**, 165-174.

Welcomme R. and Barg U., 1997: FAO technical guidelines for responsible fisheries-5, aquaculture development, FAO, Rome, 40pp.

Williams B. K., Szaro R. C., and Shapiro C. D., 2009: Adaptive Management: The U.S. Department of the Interior Technical Guide, Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC, 84pp. Available at: https://www2.usgs.gov/sdc/doc/DOI-%20Adaptive%20ManagementTechGuide.pdf

Yanagi T. 2005: " Sato-Umi"; New Concept for the Coastal Sea Management. *Reports of Research Institute for Applied Mechanics, Kyushu University*, **129**, 109-111.

Zhang S. Y., Wang Z. H., Lin J., and Wang W. D., 2007: Variation of fisheries resources in summer and autumn in seaweed beds of Gouqi Island. *Mar. Fish. Res.*, **28**, 45-52. (in Chinese with English abstract)

Annotated bibliography

(1) Soto D., Aguilar-Manjarrez J., and Hishamunda, N. (eds), 2008: Building an ecosystem approach to aquaculture, FAO/Universitat de les Illes Balears Expert Workshop (7–11 May 2007, Palma de Mallorca, Spain), FAO Fisheries and Aquaculture Proceedings. No. 14, FAO, Rome, 221pp.

This FAO report summarizes findings from a workshop co-organized with the Universitat de les Illes Balears that took place from 7–11 May 2007 in Palma de Mallorca, Spain on "Building and ecosystem approach to aquaculture" (EAA). Participants defined the phrase "ecosystem approach to aquaculture" and several main principles that should guide the sustainable development of aquaculture. These included the development of aquaculture consistent with resilience of ecosystem functions; improving human wellbeing; and consideration of other relevant sectors (social, technical, economic, and political). They state that EAA should address the many needs and desires of societies without compromising ecological integrity. The workshop participants also agreed on various ecosystem approaches for different scales (e.g., small or "farm", regional or zone, and global) and that regulations should focus more on the recipient body of water (e.g., stream, estuary, large marine ecosystems) rather than the scale and intensity of production.

(2) Aguilar-Manjarrez J., Soto D., and Brummett R., 2017: Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture: Full document, Report ACS113536, FAO, Rome, and World Bank Group, Washington, DC., 395pp.

The Food and Agricultural Organization of the United Nations and the World Bank Group convened an expert workshop on Site Selection and Carrying Capacities for Inland and Coastal Aquaculture in December 2010 in Northern Ireland. Spatial planning is becoming increasingly important in the growth of aquaculture and the issues involved require an ecosystem approach to management that addresses larger spatial units than just the individual farm or site. The main purpose of the workshop was development of a guide or handbook for aquaculture site selection and carrying capacity estimation within an ecosystem approach to aquaculture that can be used by a broad range of stakeholders. The publication provides useful and practical information and guidance for managers, policy-makers, technical staff, and aquaculturists about zoning, siting, and management based on experiences and examples from ten case studies in countries around the world. They identify relevant processes and activities for various users on different spatial scales in a systematic fashion.

(3) National Oceanic and Atmospheric Administration, 2016: Ecosystem-based fisheries management policy of the National Marine Fisheries Service, National Marine Fisheries Service Policy Directive 01-120. May 23, 8pp.

Several national laws or mandates require the National Oceanic and Atmospheric Administration (NOAA) to manage the nation's living marine resources, including fisheries in a sustainable manner. In order to enable better decision-making among various groups and concerns, (e.g., commercial, recreational, and subsistence fisheries), aquaculture, protected species, biodiversity, and habitats, NOAA is implementing Ecosystem-Based Fisheries Management (EBFM). The policy directive issued in May 2016 is a framework for an ecosystem approach to fisheries, which defines EBFM; describes the benefits of EBFM; discusses how EBFM relates to existing legal authorities and requirements; and establishes a framework of guiding principles for implementing EBFM within NOAA Fisheries. It builds on the NOAA's past progress and commitment to integrating its management programs for living marine resources and considering interactions among fisheries, protected species, aquaculture, habitats, and other ecosystem components, including human communities in decision-making. The policy defines EBFM as "*a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals.*"

The EBFM policy document specifically mentions aquaculture as an ecosystem component, and NOAA includes aquaculture in the term "fisheries". Therefore, this document although mostly intended for commercial fisheries, forms the basis for the development of a separate Ecosystem Approach to Aquaculture (EAA) which recognizes the similarities, but also the distinct differences, between "capture" or "wild" fisheries and aquaculture. Although the EBFM directive focuses on "capture" or "wild" fisheries, the language and concepts in it are also directly applicable to aquaculture and, in most instances, the phrase "ecosystem approach to aquaculture", or EAA could easily be substituted for "ecosystem-based fishery management" (EBFM), and the word "aquaculture" substituted for "fisheries".

Since there are distinct and important differences between capture fisheries and aquaculture, the

NOAA Office of Aquaculture is developing a separate Ecosystem Approach to Aquaculture (EAA). An EAA is the first step or level along a continuum toward a more complex and detailed plan for implementing ecosystem-based management of aquaculture.

(4) National Oceanic and Atmospheric Administration, 2011: Marine Aquaculture Policy, NOAA Office of Aquaculture, Issued June 2011.

The NOAA Office of Aquaculture developed a Marine Aquaculture Policy in 2011 to enable the development of sustainable marine aquaculture within the context of NOAA's multiple stewardship missions and legal mandates. The document defines aquaculture as "*the propagation and rearing of aquatic organisms for any commercial, recreational, or public purpose*". It includes production for food, wild stock replenishment or restoration (for finfish as well as shellfish and other marine organisms), and rebuilding populations of threatened or endangered species. It contains specific goals with regard to aquaculture development and management, and provides the basis for the policy and some background information. The policy also describes the benefits and challenges of sustainable aquaculture in the U.S. and sets forth NOAA aquaculture priorities and actions for implementing the policy in terms of regulations, interactions with various agencies and groups in the U.S., and cooperation with other nations. One of the stated goals in the policy is ecosystem compatibility; that is to say, aquaculture development in federal waters should be compatible with the functioning of healthy, productive, and resilient marine ecosystem. In keeping with this goal, aquaculture operators should be held accountable for protecting the species and environment in which they are working. Other goals include compatibility of aquaculture facilities with other authorized uses of marine waters and basing management decisions on the best available science and information.

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Spatial planning for shellfish aquaculture and seagrasses in US West Coast estuaries: considerations for adapting to an uncertain climate

Brett R. DUMBAULD[*1], Jennifer L. RUESINK[*2], and George G. WALDBUSSER[*3]

Abstract: Shellfish aquaculture has been an important contributor to the local economy of several communities along the US West Coast for almost 100 years and in most of the estuaries where it occurs it has coexisted with the native seagrass (eelgrass, *Zostera marina*). Eelgrass provides numerous ecosystem services including nursery habitat for juvenile fish and invertebrates, but is declining in many locations worldwide, and is therefore now protected by no net loss provisions in US laws and regulations. We have studied the interaction between oyster aquaculture and eelgrass at both the local process scale and at the estuarine landscape scale in Willapa Bay, Washington. While there are important differences, most US West coast estuaries like Willapa Bay are small relative to the nearby coast, experience less riverine influence during the summer growing season and have shorter residence times than estuaries where oysters are cultured on eastern edges of continents, and the majority of culture takes place in intertidal areas. The ecology of eelgrass and cultured Pacific oysters as well as their role as habitat is thus directly influenced by bathymetry and proximity to the coastal ocean. We summarize studies on the interaction between eelgrass and oyster culture at local scales, present data that suggest culture practices are important to consider, but the cumulative interaction is not necessarily negative for eelgrass at the estuarine landscape scale in Willapa Bay. We also briefly summarize studies on the influence of sea level rise (SLR) and sea water chemistry (ocean acidification, OA), two projected changes in climate that are expected to occur over a broader spatial and longer temporal scale. SLR is projected to enhance the presence and interaction of eelgrass with oyster aquaculture in Willapa Bay, though this effect was mostly driven by bathymetry in our simplistic model and landward eelgrass expansion could be restricted elsewhere. OA has already influenced oyster culture especially in commercial hatcheries where it changes aragonite saturation state and the ability of larval oysters to deposit shell. Evidence for direct effects of carbonate chemistry in estuaries like Willapa Bay is more equivocal due to complex interactions, yet still related to the proximity of cold upwelled ocean water which likely influences natural spawning on this coast. The presence of eelgrass may also buffer water chemistry at least over short time scales, but this is less likely to directly affect survival of juvenile than larval oysters and instead eelgrass may impact juvenile oyster growth via this and other mechanisms. These physical effects of structure also influence conspecific eelgrass plants and appear to be more important than water chemistry feedbacks.

Recent initiatives to expand shellfish aquaculture in US west coast estuaries have received increased regulatory scrutiny due in large part to this interaction with eelgrass. Our review suggests that a permit process that simply evaluates and prevents direct negative effects of oyster culture on eelgrass at small spatial and immediate temporal scales would greatly and perhaps unnecessarily restrict expansion of culture operations. A broader adaptive approach could be employed that considers bathymetric and along estuary gradients that affect both of these resources and the services they provide, especially given projected future climate.

Key words: oyster aquaculture, sea level rise, ocean acidification

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*1 Agricultural Research Service, U.S. Dept. of Agriculture, Hatfield Marine Science Center, Newport, OR 97365, U. S. A.
*2 Department of Biology, University of Washington, Seattle, WA 98195, U. S. A.
*3 College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR 97365, U. S. A.
E-mail: brett.dumbauld@ars.usda.gov

Introduction

Seagrasses and Oyster Aquaculture in US West Coast estuaries

Oyster aquaculture became an important contributor to local US West coast economies when the Pacific oyster *Crassostrea gigas* was introduced in the early 1900's and largely replaced the native oyster *Ostrea lurida*, which had been extensively fished commercially and mostly overharvested or succumbed to other factors including pollution (Blake and Ermgassen, 2015; Dumbauld *et al*., 2011; Kirby, 2004; Polson and Zacherl, 2009; Steele, 1964). Pacific oysters were cultured and harvested from leased and privately owned estuarine tidelands, and the industry relied on juvenile seed oysters shipped from Japan through the late 1970's when local hatchery production of oyster larvae succeeded (Chew, 1984). Though the extent and interaction between these resources has only recently been actively quantified at large scales (Dumbauld and McCoy, 2015), these aquaculture operations have coexisted for almost 100 years with the native seagrass (eelgrass, *Zostera marina*), which grows on some of these tidelands. Eelgrass provides numerous ecosystem services including habitat for some fish and invertebrates (McDevitt-Irwin *et al*., 2016), but seagrasses are threatened and declining in many locations worldwide (Waycott *et al*., 2009). Seagrass habitat has been protected by no net loss provisions in US laws and regulations since the late 1970's, but recognition of this wide-scale seagrass loss, as well as increasing threats to and declining populations of other important species that utilize eelgrass as habitat, has heightened concern resulting in re-evaluations of permits for existing aquaculture operations and new restrictions for expanded culture (NMFS, 2017). Reef forming bivalves like oysters are now also widely recognized to provide valuable estuarine habitat and this reef habitat is also threatened (Beck *et al*., 2011; Zu Ermgassen *et al*., 2012). Though oysters raised in aquaculture are not generally allowed to establish reefs, they still provide three dimensional structure and this service has mostly not yet been recognized for Pacific oysters by US west coast managers. This is in part because the oysters are introduced and cultured in US west coast estuaries by humans and thus viewed by scientists and managers as a threat to native habitats like seagrass, despite recent recognition of the omnipresent and embedded role of humans and cultural aspects involved in crafting a sustainable future for these estuarine systems and the role of aquaculture in in both the US and Japan (Broitman *et al*., 2017; Carpenter *et al*., 2009; Mizuta and Vlachopoulou, 2017).

West Coast estuaries function

While there are important exceptions like the Salish Sea in Washington State, most U.S. West coast estuaries are small relative to the extensive spatial extent of the nearby open coastline. Willapa Bay, which is the single largest cultured oyster production site in the US and the third largest estuary on this coast has only a 358 km^2 signature (**Fig.1**), which roughly equals the size of the James River sub-estuary in Chesapeake Bay, which is the largest estuary on the US East Coast with an 11,600 km^2 signature. It is further dwarfed by the Seto Inland Sea in Japan which has a 23,204 km^2 area. The spatial footprint of the oyster culture industry in this estuary is also relatively small (1,764 ha of active culture) on 12,384 ha of privately deeded and leased oyster grounds representing about 58 % of the intertidal area in the estuary (Dumbauld and McCoy, 2015). Estuaries like Willapa Bay also experience less riverine influence during the summer months and have shorter residence times than estuaries where oysters are present on eastern edges of continents (Hickey and Banas, 2003), and the majority of oyster culture takes place across broad intertidal mudflats the which represent about 58 % of the estuarine area. This relatively shallow bathymetry and lack of a strong salinity gradient result in well mixed water column, with often turbid conditions driven primarily by surface winds at least during spring and summer. The US west coast is also adjacent to the California current ecosystem, an eastern boundary upwelling system so estuaries are subject to seasonal events where nutrient rich, high pCO_2 water is transported to the surface and episodic intrusions into these estuaries can significantly lower saturation state and pH (Feely *et al*., 2010; Hauri *et al*., 2013). This physical context clearly influences the distribution and ecology of both cultured Pacific

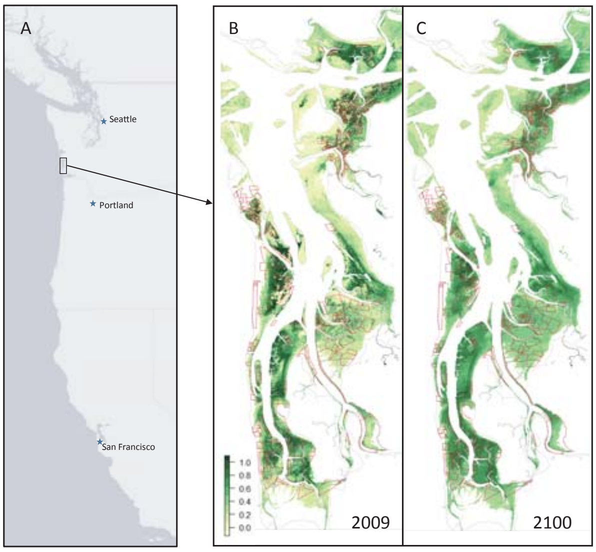

Fig. 1. A) Willapa Bay is the second largest estuary along the US West Coast, south of the Salish Sea west of Seattle, but is small relative to the extent of the nearby coast that greatly influences its hydrography. B) Eelgrass (*Z. marina*) coverage across the tideflat in Willapa Bay based on aerial photography in 2009 and C) the predicted probable densities of eelgrass at year 2100 for the most conservative sea level rise scenarios (RCP 2.6 with 2.0 mm yr-1 sediment accretion) using boosted regression tree models. Numbers on the colorbar correspond to the probability of *Z. marina* presence (zero to 100 %) within - 1.5 and 1.2 meters elevation relative to MLLW for each pixel in the image. Shellfish aquaculture beds are overlaid in red.

oysters and eelgrass in these estuaries, as well as the interaction between them and the role that both of these resources play as habitat for other fish and invertebrates. Natural disturbances due to wind and sediment movement are a regular feature in these soft sediment dominated systems (Norkko *et al*., 2010). In some cases this context already directly influences management. For example Pacific oyster growth is clearly modulated by the distribution of phytoplankton as food and Willapa Bay and growers have long adapted to this by moving oysters from beds located near the southern end of this estuary to beds that are closer to the ocean where food supply is greater and the oysters successfully “fatten” for market (Banas *et al*., 2007).

These larger spatial scales and gradients become important considerations when evaluating the influence of sea level rise (SLR) and sea water chemistry (ocean acidification, OA), two projected changes in climate that are expected to occur over a broad spatial and long temporal scale in these systems. Current management of eelgrass and oysters in the US is largely focused on regulations that stipulate conditions or types of activity that can occur at relatively small scales. While there is a nationwide permit issued for shellfish aquaculture (Nationwide permit 48; ACOE, 2016), it nonetheless stipulates activities that can occur at individual sites and considers no net loss of seagrass at this or even a smaller (individual plant) spatial scale. This is also typically the scale used to evaluate success for seagrass restoration or mitigation for loss. The temporal scale is also relatively short with the year that the permit is issued most often used as the baseline reference and permit lifetime is perhaps up to 5 years over which reference conditions must be re-established or loss mitigated.

Here we briefly review existing data on both eelgrass and oysters as habitat features in Willapa Bay as the single most important US west coast estuary for oyster production and then discuss how these two future changes in climate might be addressed at a broader “seascape” scale. Our intent is to broaden the discussion about the interaction between shellfish aquaculture and eelgrass to this seascape scale and at least contemplate using a longer temporal scale to better define goals and perhaps adaptively manage these two resources over time to meet them. This exploration is consistent with ecosystem-based management in the US and the Japanese concept of *Satoumi*, though the latter explicitly includes a bottom–up social contract with local resource users (Mizuta and Vlachopoulou, 2017). We pose and attempt to address the following questions:

1. How much does the presence of oyster aquaculture affect eelgrass at the broad seascape scale?
2. How do effects differ by culture practice, and are they chronic or transitory from one year to the next?
3. What are the consequences of projected climate change to seagrass at the seascape scale and what should the baseline be? Is no net loss of seagrass based on a single contemporary date a useful

management target?

4. How would management outcomes differ if projected temporal changes to both eelgrass and aquaculture at the seascape scale were incorporated?

Methodology

Methods for collecting data on shellfish aquaculture and seagrass at broad spatial scales differ from those used in most small experimental scale studies. Detailed methods for the studies we conducted in Willapa Bay can be found in Dumbauld and McCoy (2015) and Graham *et al.* (unpublished manuscript, available from the authors), but in general involved the use of aerial color infrared photos (1:20,000) of Willapa Bay taken in 2005, 2006, and 2009. An on ground survey to truth the original photos and collect additional data was conducted in 2006-7 where 4,238 individual locations at intersection points of a 200 m x 200 m grid across the estuarine tideflat were visited and data collected on seagrass cover that would be recognizable in the photographs. This data along with other characters that would help quantify habitat at this seascape scale (oyster shell cover, burrowing shrimp and other benthic fauna burrows, macroalgal cover, sediment composition) were recorded into a Trimble Geo XT ®mapping grade GPS system. The 0.25 m color infrared photos were geo rectified and we extracted mean values for each color band in a 5 m radius around each of the ground survey points to develop a model to predict the probable cover of *Zostera marina* for each pixel in the imagery. All data was imported into R (R Development Core Team, 2015) for analyses. We then created models to predict the relationship between on ground density and color bands and used this to predict probable density of eelgrass for each pixel (mean of 1 m by 1 m values) in the aerial imagery. The photo extracted cover was then used as the actual cover and distribution of *Z. marina* for each year. Spatial data layers for aquaculture were built using data gathered from interviews with individual shellfish farmers including location, species, bed type, and harvest method for each of 458 beds. For most analyses we then created a 5 x 5 m raster layer for presence/absence of oysters and limited this to the 282 active beds with > 90 % culture above + 1.2 m MLLW.

Once these spatial data layers for eelgrass as the dependent variable and shellfish aquaculture (the primary independent variable of interest) were created, the next step involved constructing models to describe the effects of other physical and biotic factors that might influence eelgrass presence quite apart from the effect of aquaculture. This step necessarily involves assembling or collecting spatial data for these factors at this scale. In our case these data included tidal elevation (digital elevation model DEM raster created by measuring this during the ground survey with a Trimble ProXr® unit and combining with existing LiDAR data for the upper intertidal), distance to the estuary entrance (cumulative cost distance m), Euclidean distance to the nearest channel with water present in the aerial photos (m), cumulative wave stress (calculated using average wind speed and direction measured at Toke Pt. in 2009, fetch distance, and tide stage), and salinity using a model based on the 5^{th} quantile of wet season salinity measured at 5 long term monitoring locations in the estuary. Each of these factors was resampled to a 5 x 5 m grid for further analyses and we extracted data from a set of random points outside of aquaculture. We initially used general additive models (GAM's), but have since increased predictive performance using boosted regression tree models (BRT's, Elith *et al.*, 2008), which also model interactions among predictor variables and enable improved internal cross-validation to evaluate effects on eelgrass outside of culture areas. We then similarly extracted eelgrass data from a set of random points across the entire estuarine tideflat for each of the 3 years and compared predicted and observed amounts of eelgrass in areas with aquaculture which were then summed to assess effects.

Finally we evaluated the potential effects of climate change on shellfish aquaculture and seagrass at the estuary scale in Willapa Bay. The effects of sea level rise (SLR) were examined by applying offsets to the DEM to represent 4 local SLR scenarios and predict eelgrass coverage for several scenarios at 3 future endpoints (years 2030, 2050 and 2100) using the same spatial data layers described above. While we have not yet developed spatial layers that allow us to evaluate the more complex effects of enhanced CO_2

and other changes to seawater chemistry, we review data collected along the estuarine gradient in Willapa Bay that could potentially be used in such an analysis. Seawater samples were either collected at discrete sampling locations along an estuarine gradient (details in Ruesink *et al*., 2015; Ruesink *et al*., 2018a) or at a single location over a broad temporal scale (Hales *et al*., 2017) and related to either plankton samples (for oyster larvae) from the same locations, oyster and seagrass data collected at nearby locations, or optimal conditions for oyster larvae based on results of detailed laboratory studies. In both cases discrete seawater samples were analysed for two components of the carbonate chemistry system (dissolved inorganic carbon and the partial pressure of carbon dioxide (pCO_2)) at Oregon State University (Bandstra *et al*., 2006; Barton *et al*., 2012). These values were then used to calculate other parameters of the seawater chemistry system like aragonite and carbonate saturation that directly influence oyster larval growth and survival (Waldbusser *et al*., 2015).

Results and Discussion

Previous research on the interaction between oyster culture and eelgrass in Willapa Bay conducted mostly at a small experimental scale (< 20 m^2 plots), but in some cases up to the shellfish culture bed scale (10 - 75 ha) suggests that:

1 - Eelgrass density declines with oyster density in all intertidal oyster aquaculture areas. This is mostly a threshold function and either due to competition for space where > 20 % shell cover results in less eelgrass (Wagner *et al*., 2012) and/or shading and light in the case of off-bottom longline oyster culture (Ruesink *et al*., 2009; Rumrill and Poulton, 2004; Wisehart *et al*., 2007).

2 - Harvest disturbance significantly affects eelgrass density. Density is lowest in mechanically harvested beds especially right after harvest, but eelgrass growth is slightly greater in these areas and recovery is site specific ranging from 1- 4 years (Tallis *et al*., 2009)

3 - Eelgrass relative growth rate, plant size, and therefore production are affected by oyster aquaculture, but these effects are variable and not always negative (Tallis *et al*., 2009). Effects thus depend on culture method and location. Bivalves have been shown to enhance seagrass growth indirectly via nutrient biodeposition and/or filtering and clearing water which changes the light environment. While oysters were shown to perform both of these services in Willapa Bay (Wagner *et al*., 2012; Wheat and Ruesink, 2013), neither mechanism seemed important at the locations studied because background nutrient conditions were not limiting and the local light environment was more influenced by water flow and sediment. This in turn influenced shoot density resulting in self-shading which also influenced seedling success (Wisehart *et al*., 2007; Yang *et al*., 2013).

Our initial seascape scale study revealed that eelgrass declined slightly over the 3 years we modeled its presence in Willapa Bay, but oyster aquaculture reduced the overall eelgrass presence by less than 1.5 % in any single year (Dumbauld and McCoy, 2015). The general additive model we used to predict eelgrass distribution outside of aquaculture only explained about 50 % of the variation in eelgrass distribution which was likely due to the limited set of variables for which we had spatial data at this scale. Distance to the estuary mouth and tidal elevation were the most significant factors, but these variables were likely only proxies for mechanistic factors like temperature, nutrient availability, flow, and turbidity as they influenced available light discussed above and shown to be important at the local scale. Mixed effects models that considered culture practices revealed that harvest method influenced eelgrass presence, but not type of bed (e.g., oysters raised on longlines, beds only used for small oyster seed, or beds only used for larger oysters to fatten). Results were variable but beds that were mechanically harvested tended to have chronically less eelgrass present than those harvested by hand, yet even these beds had an average of 92 – 99 % of the predicted eelgrass cover present with clear temporal recovery trends across years. Many individual beds had well over the predicted amount of eelgrass present suggesting that aquaculture could enhance eelgrass presence at the seascape scale, perhaps by removing bioturbators or stabilizing substrate.

Separate examinations of eelgrass biometrics along the estuarine gradient in Willapa Bay at least in part confirm these seascape scale patterns. Shoot size, density and above ground biomass varied seasonally (responding to daylength and perhaps temperature), but also with tidal elevation (usually with larger less dense shoots found at lower elevation; Ruesink *et al.*, 2010). Shoot density and above ground biomass also declined from the mouth of the estuary to the upriver end at the same tidal elevation (Ruesink *et al.*, 2015). There were however no consistent trends in relative growth of individual plants along these gradients, and short term reciprocal transplant experiments suggest that plant size and branching are plastic, while life history strategy of source plants (e.g., presence of flowering shoots and seedlings) was more persistent (Ruesink, 2018b). Seedling survival has also been shown to vary along stressor gradients (Yang *et al.*, 2013).

Temporal change

Eelgrass currently covers about 27 % of the tideflat in Willapa Bay and about 43 % of its distribution overlaps with commercial oyster aquaculture which covers about 15 % of the tideflat. Taking a broader temporal view, we also evaluated the potential effects of sea level rise (SLR) as one aspect of a changing climate on this eelgrass oyster aquaculture interaction. Rising global mean sea level will result in changes in water depth in estuaries, but these projections are specific to the region and system given tectonic shifts and sediment accretion/erosion. We modeled seagrass distribution and the interaction with aquaculture in Willapa Bay using two representative rates (4 mm and about 8 mm yr-1, IPCC pathways 2.6 and 8.5 respectively) for three temporal endpoints (2030, 2050, and 2100) and adjusted for expected tectonic uplift and sediment accretion. In addition to elevation, we used the same additional parameters (salinity, distance to mouth, distance to channel, cumulative wave stress) and boosted regression tree models to describe current and future distributions of eelgrass. We could not predict change for these other parameters, but using a boosted regression tree allowed for model cross-validation. Results suggest as much as a 36 % increase in eelgrass cover by 2100 with similar or even greater proportional increases on oyster aquaculture beds. Mean coverage among all beds is projected to increase from 41 % (current) to 44 – 52 % in 2100 and this will occur on as many as 325 beds representing 70 % of all beds (4,195 ha, **Fig.1**). This will represent challenges for the shellfish growers including potential impacts to oyster growth and ability to efficiently harvest product, but also potential regulatory constraints. We have not used similar models to hindcast this interaction for conditions that occurred before Pacific oysters were introduced to Willapa Bay in the 1800's, but historical maps suggest that native oysters (*Ostrea lurida*) once occupied about 17 % of the low intertidal and shallow subtidal area. Based on estimated tidal elevations alone the suitable area for eelgrass is estimated to have been about 3,139 ha (Borde *et al.*, 2003) in the 1850's. We estimated there would have been about a 45 % overlap with these oysters albeit at a mostly lower tidal elevation than today's culture operations, and today eelgrass exists as a monotypic meadow in many of those locations where native oyster beds have not returned.

Large scale temporal changes in seawater carbonate chemistry (ocean acidification, OA) are also expected to influence both seagrasses and shellfish and their interaction in US West Coast estuaries (Feely *et al.*, 2016; Feely *et al.*, 2010; Waldbusser and Salisbury, 2014). Changes to the carbonate mineral saturation state have been shown to negatively affect the acid base balance, biocalcification, and metabolism of oyster larvae (Waldbusser *et al.*, 2015). Because seasonal upwelling of nutrient rich low pCO_2 acidified water is a regular feature in nearshore coastal waters of the California Current ecosystem, episodic intrusions of this water into estuaries where shellfish hatcheries use it have already caused significant issues for the commercial aquaculture industry and practices to mitigate these losses have already been adopted (adding buffering agents and adjusting times when water is drawn, Barton *et al.*, 2015). In contrast, due to their efficient uptake of aqueous CO_2 for photosynthesis, seagrasses are expected to increase in productivity with rising levels in the environment and therein may also have the potential to mitigate effects of this chemistry on other organisms like shellfish (Hendriks *et al.*, 2014; Pacella *et al.*, 2018).

Estuarine water chemistry is however highly variable over both relatively short (daily, diel) and long term (seasonal, annual) temporal scales and

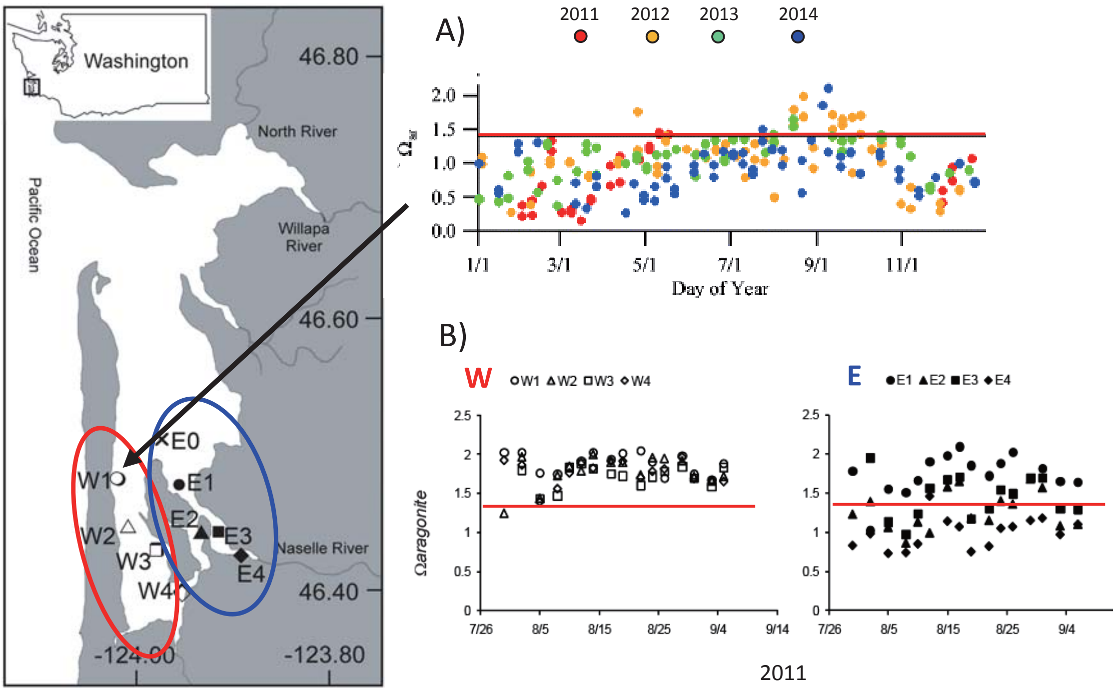

Fig. 2. Seawater carbonate chemistry measured at locations south of the fattening/recruitment line in Willapa Bay, Washington. Shown here are A) aragonite mineral saturation state calculated from observed temperature, salinity, TCO_2 and pCO_2 at Nahcotta in 2011 – 2014 (modified from Hales *et al.*, 2017) and B) aragonite mineral saturation state calculated from the same parameters measured at discrete locations along the western side of the estuary (left graph, red circle) and east side (right graph, blue circle) in 2011 (modified from Ruesink *et al.*, 2018a). Also denoted (red horizontal line) is the threshold for acute effects on oyster larvae.

along spatial estuarine gradient scales within each system. In Willapa Bay as salinity declined and temperature increased along a gradient from the mouth to the Naselle River at the southern end of the estuary, aqueous CO_2 increased and pH was reduced on a single cruise and one point in time during the summer (Ruesink *et al.*, 2015). These parameters were much more variable, especially at both mouth and river endpoints when continuously measured with moored instruments at single locations over the course of a summer month. A strong influence of upwelling events was evident near the estuary mouth, whereas consistent tidal variation in pH occurred near the river endpoint. Less variation was observed at locations near mid-bay, and there were clear differences between conditions in the eastern (Naselle River) and western (Nahcotta) arms of the estuary (Ruesink *et al.*, 2018a). As expected large seasonal fluctuations were observed in temperature, salinity, alkalinity, and TCO_2 over the course of a year at a Nahcotta mooring with some variation between years. pCO_2 and pH varied less over the season than these other parameters and aragonite saturation state was decoupled from them, suggesting there was a very short window during summer when conditions would be favorable for oyster larval development (**Fig.2A**, Hales *et al.*, 2017). There were again differences between the western and eastern half of the estuary with aragonite saturation state generally exceeding critical minimums measured in the laboratory on the western, but not eastern side (**Fig.2B**, Ruesink *et al.*, 2018a).

The direct effects of water chemistry on eelgrass and oyster larval survival and settlement at the population level in the field are more difficult to assess due to the presence of and inability to control multiple other factors/stressors, so results to date are more equivocal. Nonetheless while tissue carbon measured in eelgrass blades increased at eight stations along the estuarine gradient and this was coincident with depleted C-13 reflecting water carbon chemistry gradients, production (relative growth rate) did not vary and instead seemed to be more related to sediment organic content and wave exposure (Ruesink *et al*., 2015). This is consistent with recent measurements which suggest that eelgrass has the capacity to achieve similar productivity across much broader ocean basin and latitudinal scales, despite marked differences in morphometric characteristics (Ruesink *et al*., 2018b). Oyster larvae are most responsive to augmented CO_2 and reduced aragonite saturation in the laboratory as they cross two important and relatively short physiological transitions; initial shell formation and metamorphosis/settlement when metabolic energy allocation is crucial (Pan *et al*., 2015; Waldbusser *et al*., 2015). They are however subject to widely varying conditions over their 2-3 week larval period in the estuary. As noted above, aragonite saturation state was lower on the eastern more river influenced side of the southern end of Willapa Bay versus the western side when examined during three separate summers. Survival of four cohorts of Pacific oyster larvae tracked simultaneously over these 3 summers was similar between these two sides and subsequent settlement generally higher on the eastern side where aragonite chemistry was less favorable (Ruesink *et al*., 2018a). This decoupling of population level effects from water chemistry conditions could have been due to the fact that aragonite saturation conditions on both sides were very close to, but on average above the ~ 1.4 threshold for acute effects established for risk assessments based on laboratory results (Ekstrom *et al*., 2015), that favorable conditions were present during the critical windows or because a multitude of other factors such as temperature, advection, predation, etc. were responsible. Larval condition may also reflect a “carryover” effect from adult brooding conditions and lipid stores in eggs and thus not tie directly to stresses present during the larval period (Barton *et al*., 2015; Hettinger *et al*., 2012).

Eelgrass has also recently been hypothesized to potentially mitigate the negative effects of ocean acidification on bivalves by ameliorating water chemistry via photosynthesis and CO_2 uptake during the day at least at very local scales (Washington State Blue Ribbon Panel on Ocean Acidification, 2012; Hendriks *et al*., 2014). Although respiration at night produces an asymmetrical diel signal for this effect and there is little research on whether the most sensitive bivalve larval stages benefit at this short temporal scale, recent studies suggest that post settlement growth and survival of juvenile oysters is enhanced in eelgrass (WADNR, 2017; Smith, 2016). It is however yet unresolved whether this effect can be attributed solely to water chemistry and distinguished from the effects of other factors like reduced flow in seagrass which results in less sediment but enhanced desirable phytoplankton food intake (Lowe, unpublished). Reduced flow also reduces settlement of fouling organisms that potentially compete with oysters for space and food and also alters the abundance of bivalve predators.

Perhaps most relevant on the broader temporal and estuary wide spatial scales we consider here however is recognition that both of these resources are likely not responding to average conditions and the window of favorable conditions continues to shift and narrow as atmospheric CO_2 concentration continues to rise (Hales *et al*., 2017; Pacella *et al*., 2018). Thus variation about the average and favorable windows of carbonate “weather” in both time and space could be important considerations when considering mitigating and adapting to future climate. Organisms may also have the ability to adapt over time to local conditions, but recognizing where these conditions occur outside of the laboratory and beyond the experimental scale at individual sites will be important.

Conclusions and Management Considerations

Initiatives to expand shellfish aquaculture in US West coast estuaries have received regulatory scrutiny due to interactions with eelgrass, but our research in Willapa Bay, an important estuary for oyster culture on the US West Coast, suggests that context and scale are very important considerations.

While significant small scale and short term temporal effects due to harvest method occur, oyster aquaculture only reduced eelgrass presence in Willapa Bay by less than 1.5 % at the seascape scale and more eelgrass was present than predicted in many aquaculture areas.

Oysters have coexisted with eelgrass in the seascape for a long time in Willapa Bay though the distribution of both across the tidal elevation gradient has changed. Unlike other locations where eelgrass is threatened by eutrophication and other anthropogenic disturbance, our models predicted a 3 – 11 % increase of eelgrass coverage within Willapa Bay oyster aquaculture beds by 2021 given projected sea level rise.

US West Coast shellfish hatcheries have already adapted and modified practices in response to changes in carbonate chemistry that routinely exceed average global conditions projected to occur in the future due to their size and proximity to upwelling conditions along this eastern ocean boundary. This creates a distinct estuarine gradient and temporal variability in conditions that make it difficult to attribute changes in natural oyster spawning and larval settlement to changes in water chemistry. While the long term average trend is for acidified conditions, oysters may be more responsive to extremes and the range of conditions, which in turn must be evaluated along these estuarine gradients where eelgrass seems less directly affected, but the mitigative effects it has on shellfish growth and survival could be important.

References

ACOE, 2016: U.S. Army Corps of Engineers Decision Document Nationwide Permit 48.

Banas N. S., Hickey B. M., Newton J. A., and Ruesink J. L., 2007: Tidal exchange, bivalve grazing, and patterns of primary production in Willapa Bay, Washington, USA. *Mar. Ecol. Prog. Ser.*, **341**, 123-139.

Bandstra L., Hales B., and Takahashi T., 2006: High-frequency measurement of seawater total carbon dioxide. *Mar. Chem.*, **100**, 24-38.

Barton A., Hales B., Waldbusser G. G., Langdon C., and Feely R. A., 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol. Oceanogr.*, **57**, 698-710.

Barton A., Waldbusser G. G., Feely R. A., Weisberg S. B., Newton J. A., Hales B., Cudd S., Eudeline B., Lang. J., Jefferds I., King T., Suhrbier A., and McLaughlin K., 2015: Impacts of Coastal Acidification on the Pacific Northwest Shellfish Industry and Adaptation Strategies Implemented in Response. *Oceanography*, **28**, 146-159.

Beck M.W., Brumbaugh R. D., Airoldi L., Carranza A., Coen L. D., Crawford C., Defeo O., Edgar G. J., Hancock B., Kay M. C., Lenihan H. S., Luckenbach M. W., Toropova C. L., Zhang G. F., and Guo X. M., 2011: Oyster reefs at risk and recommendations for conservation, restoration, and management. *Bioscience*, **61**, 107-116.

Blake B. and Ermgassen P. S. E. Z., 2015: The History and Decline of *Ostrea Lurida* in Willapa Bay, Washington. *J. Shellfish Res.*, **34**, 273-280.

Borde A. B., Thom R. M., Rumrill S., and Miller L. M., 2003: Geospatial habitat change analysis in Pacific Northwest coastal estuaries. *Estuaries*, **26**, 1104-1116.

Broitman B. R., Halpern B. S., Gelcich S., Lardies M. A., Vargas C. A., Vásquez-Lavín F., Widdicombe S., and Birchenough S. N. R., 2017: Dynamic Interactions among Boundaries and the Expansion of Sustainable Aquaculture. *Front. Mar. Sci.*, **4**. doi.org/10.3389/fmars.2017.00015

Carpenter S. R., Mooney H. A., Agard J., Capistrano D., DeFries R. S., Diaz S., Dietz T., Duraiappah A. K., Oteng-Yeboah A., Pereira H. M., Perrings C., Reid W. V., Sarukhan J., Scholes R. J., and Whyte A., 2009: Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc. Natl. Acad. Sci. U.S.A.*, **106**, 1305-1312.

Chew K. K., 1984: Recent advances in the cultivation of molluscs in the Pacific United States and Canada. *Aquaculture*, **39**, 69-81.

Dumbauld B. R., Ruesink J. L., Trimble A. C., and Kauffman B. E., 2011: The Willapa Bay oyster reserves in Washington State: Fishery collapse, creating a sustainable replacement, and the potential for habitat conservation and restoration. *J. Shellfish Res.*, **30**, 71-83.

Ekstrom J. A., Suatoni L., Cooley S. R., Pendleton L. H., Waldbusser G. G., Cinner J. E., Ritter J., Langdon C., van Hooidonk R., Gledhill D., Wellman K., Beck M. W., Brander L. M., Rittschof D., Doherty C., Edwards P. E. T., and Portela R., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nat. Clim. Chang.*, **5**, 207-214.

Elith J., Leathwick J. R., and Hastie T., 2008: A working guide to boosted regression trees. *J. Anim. Ecol.*, **77**, 802-813.

Feely R. A., Alin S. R., Carter B., Bednarsek N., Hales B., Chan F., Hill T. M., Gaylord B., Sanford E., Byrne R. H., Sabine C. L., Greeley D., and Juranek L., 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuar. Coast. Shelf Sci.*, **183**, 260-270.

Feely R. A., Alin S. R., Newton J., Sabine C. L., Warner M., Devol A., Krembs C., and Maloy C., 2010: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuar. Coast. Shelf Sci.*, **88**, 442-449.

Hales B., Suhrbier A., Waldbusser G. G., Feely R. A., and Newton J. A., 2017: The Carbonate Chemistry of the "Fattening Line," Willapa Bay, 2011-2014. *Estuar. Coast.*, **40**, 173-186.

Hauri C., Gruber N., Vogt M., Doney S. C., Feely R. A., Lachkar Z., Leinweber A., McDonnell A. M. P., Munnich M., and Plattner G. K., 2013: Spatiotemporal variability and long-term trends of ocean acidification in the California Current System. *Biogeosciences*, **10**, 193-216.

Hendriks I. E., Olsen Y. S., Ramajo L., Basso L., Steckbauer A., Moore T. S., Howard J., and Duarte C. M., 2014: Photosynthetic activity buffers ocean acidification in seagrass meadows. *Biogeosciences*, **11**, 333-346.

Hettinger A., Sanford E., Hill T. M., Russell A. D., Sato K. N. S., Hoey J., Forsch M., Page H. N., and Gaylord B., 2012: Persistent carry-over effects of planktonic exposure to ocean acidification in the Olympia oyster. *Ecology*, **93**, 2758-2768.

Hickey B. M. and Banas N. S., 2003: Oceanography of the US Pacific Northwest Coastal Ocean and estuaries with application to coastal ecology. *Estuaries*, **26**, 1010-1031.

Kirby M. X., 2004: Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. *Proc. Natl. Acad. Sci. U.S.A.*, **101**, 13096-13099.

McDevitt-Irwin J. M., Iacarella J. C., and Baum J. K., 2016: Reassessing the nursery role of seagrass habitats from temperate to tropical regions: a meta-analysis. *Mar. Ecol. Prog. Ser.*, **557**, 133-143.

Mizuta D. D. and Vlachopoulou E. I., 2017: Satoumi concept illustrated by sustainable bottom-up initiatives of Japanese Fisheries Cooperative Associations. *Mar. Policy*, **78**, 143-149.

NMFS, 2017: WA eelgrass and shellfish aquaculture workshop report (ed. by Hoberecht L.), National Marine Fisheries Service Western Region, Seattle, 64pp.

Norkko J., Norkko A., Thrush S. F., Valanko S., and Suurkuukka H., 2010: Conditional responses to increasing scales of disturbance, and potential implications for threshold dynamics in soft-sediment communities. *Mar. Ecol. Prog. Ser.*, **413**, 253-266.

Pacella S. R., Brown C. A., Waldbusser G. G., Labiosa R. G., and Hales B., 2018: Seagrass habitat metabolism increases short term extremes and long-term offset of CO_2 under future ocean acidification. *Proc. Natl. Acad. Sci. U.S.A.*, **115**, 3870-3875.

Pan T. C. F., Applebaum S. L., and Manahan D. T., 2015: Experimental ocean acidification alters the allocation of metabolic energy. *Proc. Natl. Acad. Sci. U.S.A.*, **112**, 4696-4701.

Polson M. P. and Zacherl D. C., 2009: Geographic distribution and intertidal population status for the Olympia oyster, *Ostrea lurida* Carpenter 1864, from Alaska to Baja. *J. Shellfish Res.*, **28**, 69-77.

R Develoment Core Team, 2015: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna.

Ruesink J. L., Hacker S. D., Dumbauld B. R., and Harbell S., 2009: Scale-dependent and indirect effects of filter feeders on eelgrass: Understanding complex ecological interactions to improve environmental impacts of aquaculture, in “Final Report to the Western Regional Aquaculture Center, 1-25”, Dept. of Biology, University of Washington, Seattle.

Ruesink J. L., Hong J. S., Wisehart L., Hacker S. D., Dumbauld B. R., Hessing-Lewis M., and Trimble A. C., 2010: Congener comparison of native (*Zostera marina*) and introduced (*Z. japonica*) eelgrass at multiple scales within a Pacific

Northwest estuary. *Biol. Invasions*, **12**, 1773-1789.

Ruesink J. L., Yang S., and Trimble A. C., 2015: Variability in Carbon Availability and Eelgrass (*Zostera marina*) Biometrics Along an Estuarine Gradient in Willapa Bay, WA, USA. *Estuar. Coast.*, **38**, 1908-1917.

Ruesink J. L., Sarich A., and Trimble A. C., 2018a: Similar oyster reproduction across estuarine regions differing in carbonate chemistry. *ICES J. Mar. Sci.*, **75**, 340-350.

Ruesink J. L., Stachowicz J. J., Reynolds P. L., Bostrom C., Cusson M., Douglass J., Eklof J., Engelen A. H., Hori M., Hovel K., Iken K., Moksnes P. O., Nakaoka M., O'Connor M. I., Olsen J. L., Sotka E. E., Whalen M. A., and Duffy J. E., 2018b: Form-function relationships in a marine foundation species depend on scale: a shoot to global perspective from a distributed ecological experiment. *Oikos*, **127**, 364-374.

Rumrill S. S. and Poulton V. K., 2004: Ecological role and potential impacts of molluscan shellfish culture in the estuarine environment of Humboldt Bay, Ca, in "Final Annual Report to the Western Regional Aquaculture Center, 22", OR: Oregon Dept. State Lands, South Slough Natl. Estuarine Res.Reserve, Charleston.

Smith S. R., 2016: Seagrasses as potential chemical refugia for acidification-sensitive bivalves (MS thesis), Oregon State University, Corvallis, 66pp.

Steele E. N., 1964: The immigrant oyster (*Ostrea gigas*) now known as the Pacific oyster, Warren's Quick Print, Olympia.

Tallis H. M., Ruesink J. L., Dumbauld B. R., Hacker, S. D., and Wisehart L. M., 2009: Oysters and aquaculture practices affect eelgrass density and productivity in a Pacific Northwest estuary. *J. Shellfish Res.*, **28**, 251-261.

WADNR, 2017: Can eelgrass improve shellfish growth and pH in a halo around the meadow? Washington State Department of Natural Resources. https://www.dnr.wa.gov/publications/aqr_aamt_halo2_eelgrass.pdf

Wagner E. L., Dumbauld B. R., Hacker S. D., Wisehart L. M., and Ruesink J. L., 2012: Density-dependent effects of an introduced oyster, *Crassostrea gigas*, on a native intertidal seagrass, *Zostera marina*. *Mar. Ecol. Prog. Ser.*, **468**, 149-160.

Waldbusser G. G., Hales B., Langdon C. J., Haley B. A., Schrader P., Brunner E. L., Gray M. W., Miller C. A., Gimenez I., and Hutchinson G., 2015: Ocean acidification has multiple modes of action on bivalve larvae. *PloS One*, **10**.

Waldbusser G. G. and Salisbury J. E., 2014: Ocean acidification in the coastal zone from an organism's perspective: Multiple system parameters, frequency domains, and habitats. *Ann. Rev. Mar. Sci.*, **6**, 221-247.

Washington State Blue Ribbon Panel on Ocean Acidification, 2012: Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response (ed. by Adelsman H. and Bender L. W.), Washington State Dept. Ecology, Olympia, 100pp.

Waycott M., Duarte C. M., Carruthers T. J. B., Orth R. J., Dennison W. C., Olyarnik S., Calladine A., Fourqurean J. W., Heck Jr. K. L., Hughes A. R., Kendrick G. A., Kenworthy J. W., Short F. T., and Williams S. L., 2009: Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci. U.S.A.*, **106**, 12377-12381.

Wheat E. and Ruesink J. L., 2013: Commercially-cultured oysters (*Crassostrea gigas*) exert top-down control on intertidal pelagic resources in Willapa Bay, Washington, USA. *J. Sea Res.*, **81**, 33-39.

Wisehart L. M., Dumbauld B. R., Ruesink J. L., and Hacker S. D., 2007: Importance of eelgrass early life history stages in response to oyster aquaculture disturbance. *Mar. Ecol. Prog. Ser.*, **344**, 71-80.

Yang S., Wheat E. E., Horwith M. J., and Ruesink J. L., 2013: Relative Impacts of Natural Stressors on Life History Traits Underlying Resilience of Intertidal Eelgrass (*Zostera marina L.*). *Estuar. Coast.*, **36**, 1006-1013.

Zu Ermgassen P. S. E., Spalding M. D., Blake B., Coen L.D., Dumbauld B., Geiger S., Grabowski, J. H., Grizzle, R., Luckenbach M., McGraw K., Rodney W., Ruesink J. L., Powers S. P., and Brumbaugh R., 2012: Historical ecology with real numbers: past and present extent and biomass of an imperilled estuarine habitat. *Proc. R. Soc. B: Biol. Sci.*, **279**, 3393-3400.

Annotated bibliography

(1) Barton A., Waldbusser G. G., Feely R. A., Weisberg S. B., Newton J. A., Hales B., Cudd S., Eudeline B., Langdon C. J., Jefferds I., King T., Suhrbier A., and McLaughlin K., 2015: Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, **28**, 146-159.

This is the most recent review of the history and science underpinning the effects of changing seawater chemistry on bivalve shellfish larvae and the impacts that have already taken place to the commercial shellfish aquaculture industry on the US West Coast. Multiple authors contributed to this review which addresses a broad audience but covers the leading research on direct effects to bivalve larvae as well as monitoring seawater conditions and adapting to these changes.

(2) Dumbauld B. R. and McCoy L. M., 2015: The effect of oyster aquaculture on seagrass (*Zostera marina*) at the estuarine landscape scale in Willapa Bay, Washington (USA). *Aquac. Environ. Interact.*, **7**, 29-47.

The authors groundtruthed and analyzed aerial photographs taken in three separate years to build spatial layers for seagrass cover in Willapa Bay, Washington, USA. They created spatial layers for shellfish aquaculture and several other factors such as distance to the estuary mouth and intertidal bathymetry that could influence eelgrass and then built a model to evaluate eelgrass cover in areas outside of shellfish aquaculture beds. This model was used to predict expected values within aquaculture beds and compare this with actual values to estimate the effect of aquaculture. The approach is unique in that it examined effects at the estuary scale and over several years and the authors have submitted a second manuscript that uses a similar approach to asses sea level rise.

(3) Dumbauld B. R., Ruesink J. L., and Rumrill S. S., 2009: The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. *Aquaculture*, **290**, 196-223.

The authors review the role of shellfish aquaculture in US West Coast estuaries. While subsequent studies have clarified this role and the interaction between shellfish culture and other estuarine habitats like seagrass, general conclusions remain the same and suggest that most forms of shellfish culture as currently practiced have only short term impacts in West coast US estuaries and habitats like eelgrass are generally resilient to these changes.

(4) Hales B., Suhrbier A., Waldbusser G. G., Feely R. A., and Newton J. A., 2017: The carbonate chemistry of the "Fattening Line," Willapa Bay, 2011-2014. *Estuar. Coast.*, **40**, 173-186.

The authors present detailed data on seawater chemistry (especially pCO_2 and aragonite saturation state) for Willapa Bay, Washington where Pacific oysters have been the mainstay of the oyster aquaculture industry for almost 100 years and there is a long term record of spawning and setting. They reconstruct this record for a longer historical period and their data suggest that recent conditions provide a smaller window of optimal conditions (low aragonite saturation state and warm enough temperatures for oyster spawning) than occurred historically. While they did not sample larvae (see Ruesink *et al.*, 2018a below) and therefore can't confirm effects, they substantiate the complexity of measuring these effects and atrributing them to a single cause in a variable estuary.

(5) Ruesink J. L., Sarich A., and Trimble A. C., 2018a: Similar oyster reproduction across estuarine regions differing in carbonate chemistry. *ICES J. Mar. Sci.*, **75**, 340-350.

These authors measured seawater chemistry in Willapa Bay,Washington, but unlike Hales *et al.* (2017), they also present simultaneously collected data on four cohorts of Pacific oyster larvae that were collected over three summers. The southern end of Willapa Bay has two arms which create distinctly different characteristics because one is much more affected by riverine conditions that cause reduced aragonite saturation relative to the other. Oyster settlement differed greatly between cohorts, but they did not find differences they could attribute to this different water chemistry and instead found thermal conditions were perhaps more important.

(6) Ruesink J.L., Yang S., and Trimble A. C., 2015: Variability in carbon availability and eelgrass (*Zostera marina*) biometrics along an estuarine gradient in Willapa Bay, WA, USA. *Estuar. Coast.*, **38**, 1908-1917.

These authors collected data on eelgrass (*Z. marina*) and seawater chemistry along an estuarine gradient in Willapa Bay, Washington. They demonstrated that while eelgrass responded to carbonate chemistry (increased tissue carbon up estuary where pCO_2 increased due to freshwater input), eelgrass production was unchanged and instead responded more to a gradient with more organic rich sediments at this end.

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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:

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*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

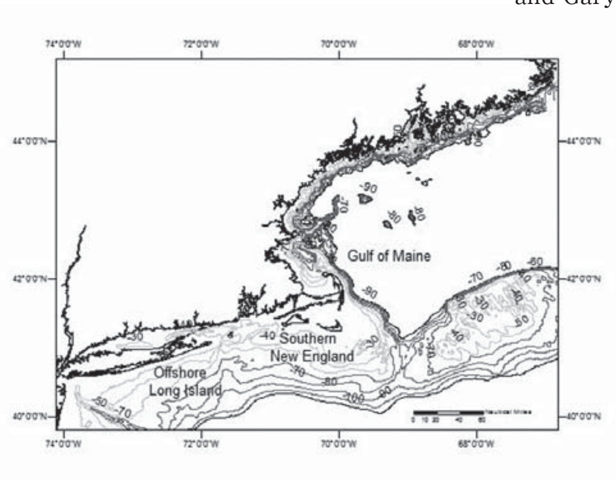

Fig. 1. Map of New England area and the Long Island with depths up to 100 m that are prospective sites for offshore aquaculture development, especially mussel farming.

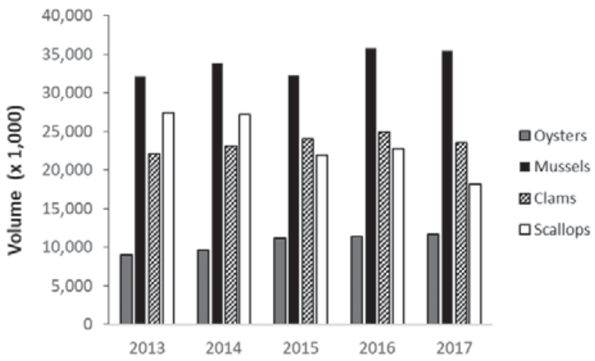

Fig. 2. American bivalve shellfish imports for the period of 2013 to 2017 (Department of Commerce, 2018).

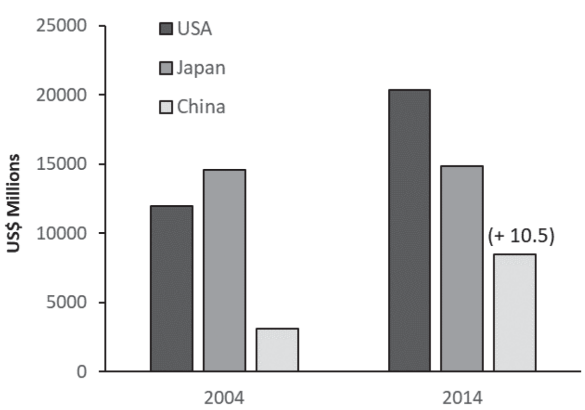

Fig. 3. Comparison of US, Japan and China annual expenditures with seafood imports. Values between brackets show variation between both years (FAO, 2016).

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)**

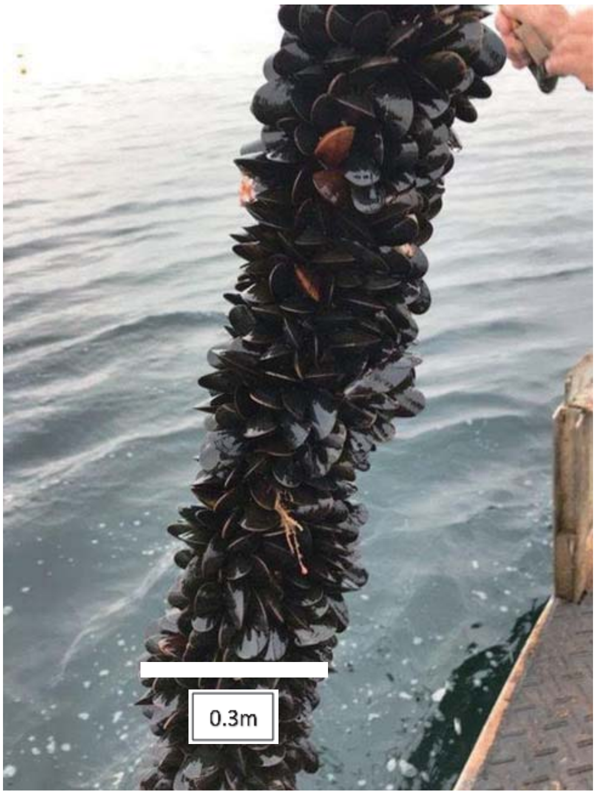

Fig. 4. Successful spat settlement on the header line of the Cat Cove Marine Laboratory trial farm, proving local availability of seeds and future possibility of seed collection. The naturally set spats grew to 5.5 cm in 10 - 12 months.

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).

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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.

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Effects of fish aquaculture on inorganic nutrient levels in Gokasho Bay

Satoshi WATANABE[*1], Masayuki MINAKAWA[*2], Yuka ISHIHI[*1], Natsuki HASEGAWA[*1], and Toshie MATSUMOTO[*1]

Abstract: Eutrophication derived from aquaculture effluent and consequent environmental deterioration are becoming increasingly problematic in many parts of the world. On the other hand, eutrophication has been reduced in coastal waters of Japan because of mitigation efforts over the past thirty years. While such efforts have positive effects on maintaining environmental integrity, excessive reduction of nutrient load to the coastal environment is thought to have reduced the productivity of many fishery resources and unfed aquaculture. Our hypothesis is that putting aquaculture effluent into practical use enhances the production of coastal fisheries and unfed aquaculture. To acquire basic information on the influential extent of aquaculture effluent on carrying capacity of coastal waters, environmental surveys were conducted to investigate the behavior of nutrients and primary production covering the whole bay area and more intensively around the red seabream, *Pagrus major*, aquaculture cages in Gokasho Bay, Mie, Japan. Seawater samples were collected monthly at 3 depths (surface, mid-layer and bottom) at 19 points in the bay, and seasonally at surface and depth of 5 m (i.e. midpoint of the cage depth) at 47 points approximately 20 m apart from one another around the red seabream aquaculture cages. The concentration of the following nutrients was analyzed: dissolved inorganic nitrogen (DIN: NH_4-N, NO_2-N, NO_3-N), PO_4-P and SiO_2-Si. A CTD was used to obtain the vertical profile of temperature, salinity, dissolved oxygen (DO), and chlorophyll *a* from the surface to the bottom. Although the DIN-N and DO levels in December 2016 were comparable to those from the same month in 1980s where aquaculture was more prosperous, the PO_4-P level was an order of magnitude lower probably due to diminished aquaculture production and improved feeding management, including the switch from raw bait to formulated feed. During a diatom bloom observed in November 2016, the depletion of SiO_2-Si implied that the availability of Si, but not N or P, was the limiting factor for the diatom growth in Gokasho Bay. There were spots with higher NH_4-N levels at the center and 20 m outside the red seabream cage area in January 2017. The chlorophyll *a* level was higher and NO_3-N was lower around the cages than in the surrounding water. The observed lower NO_3-N concentration may indicate that the enhanced primary production triggered by the NH_4-N supply from the aquaculture effluent rapidly consumed not only NH_4-N but the background NO_3-N in the area, thereby indicating that DIN-N excreted from red seabream may not travel a long distance from the cages before absorbed by primary producers. In order to fertilize seaweed with red seabream aquaculture effluent, the seaweed should be cultured near the fish cages. The elevation of chlorophyll *a* indicates the possibility of productive co-culture of red seabream and bivalves.

Key words: dissolved nutrients, oligotrophication, primary production

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[*1] National Research Institute of Aquaculture, Japan Fisheries Research and Education Agency, 422-1 Nakatsuhamaura, Minamiise, Mie, 516-0193, Japan
[*2] National Research Institute of Aquaculture, Japan Fisheries Research and Education Agency, 224-1 Hiruda, Tamaki, Mie, 519-0423, Japan
E-mail: swat@affrc.go.jp

Introduction

With the global expansion of aquaculture production, eutrophication derived from aquaculture effluent and consequent environmental deterioration are becoming increasingly problematic in many parts of the world. On the other hand, eutrophication has been reduced in coastal waters of Japan because of mitigation efforts over the past thirty years. The Total Pollutant Load Control System (TPLCS) has been implemented for water pollution management of Seto Inland Sea, Tokyo Bay and Ise Bay since 1979; it regulates the allowable amount of terrestrial nitrogen/phosphorus discharge to the sea. Allowable discharge of aquaculture effluent to the surrounding environment has been regulated by Sustainable Aquaculture Production Assurance Act (APAA) issued by the Fisheries Agency since 1999. Aquaculture operators set the stocking density of their commodities in consultation with prefectural government under APAA.

While such efforts have positive effects on maintaining environmental integrity, excessive reduction of nutrient load to the coastal environment is thought to have reduced the productivity of many fishery resources and unfed aquaculture in Japan. The oligotrophication of coastal waters has reduced the carrying capacity of the coastal ecosystem, resulting in a continuous decline in fishery resources and reduced productivity in unfed aquaculture, which relies on naturally available nutrition. The reduction of benthic fish fisheries production in Seto Inland Sea, for instance, is considered to be related with the declining dissolved inorganic nitrogen (DIN) level in the coastal water (Handa and Harada, 2012). Bleaching of *nori* (*Pyropia yezoensis*) thalli due to insufficient DIN has been problematic in Seto Inland Sea and Ariake Sound since 1990s, causing a great economical loss to the *nori* farmers (Nishikawa and Hori, 2004; Yamamoto, 2003).

Fed aquaculture of finfish usually has high feed conversion ratio (FCR). The FCR of red seabream (*Pagrus major*), for instance, is between about 2.1 and 2.7 when fed artificial diet (Furukawa, 2008; Ono and Nakahara, 2009), meaning that it takes 2.5 kg (i.e. FCR = 2.5) of feed to produce 1 kg of fish. Thus, 1.5 kg of the feed is wasted as feces, metabolites and leftover. Such aquaculture effluents used to be a cause of eutrophication of water and sediment resulting in environmental deterioration. However, eutrophication has subsided due to reduced aquaculture intensity and improved feeding techniques.

Our hypothesis is that moderate eutrophication is favorable for primary production and putting aquaculture effluent into practical use enhances the carrying capacity and, thus, production of coastal fisheries and unfed aquaculture. This paper is a partial report of the long-term periodical monitoring of water quality in Gokasho Bay, Mie, Japan, the results of which will be used as a basis for designing effective integrated multi-trophic aquaculture (IMTA) techniques (Chopin, 2006).

Materials and Methods

To acquire basic information on the influential extent of aquaculture effluent on carrying capacity of coastal waters, environmental surveys have been conducted to investigate the behavior of nutrients and primary production covering the whole area of Gokasho Bay, Mie prefecture, Japan, and also more intensively around the red seabream (*Pagrus major*) aquaculture cages in Hasamaura Cove in Gokasho Bay.

Seawater samples have been collected monthly at 3 depths (surface, mid-layer and bottom) at 19 points in the bay, and seasonally at surface and depth of 5 m (i.e. midpoint of the cage depth) at 47 points approximately 20 m apart from one another around the red seabream aquaculture cages using a Kitahara water sampler since November 2016. An aliquot (12 ml) of the seawater samples were filtered with a 0.2 μm syringe filter and stored at -30℃ until analyses. The concentration of the following nutrients has been analyzed: dissolved inorganic nitrogen (DIN: NH_4-N, NO_2-N, NO_3-N), PO_4-P and SiO_2-Si with an auto-analyzer (TRAACS 800, Bran+Luebbe).

A CTD (RINKO profiler, JFE Advantech) has been used to obtain the vertical profile of temperature, salinity, dissolved oxygen (DO), and chlorophyll *a* at depths of every 10 cm from the surface to the bottom. The DO concentration was calibrated using more precisely analyzed values with a DO meter (MM-60R, TOA DKK) in the laboratory.

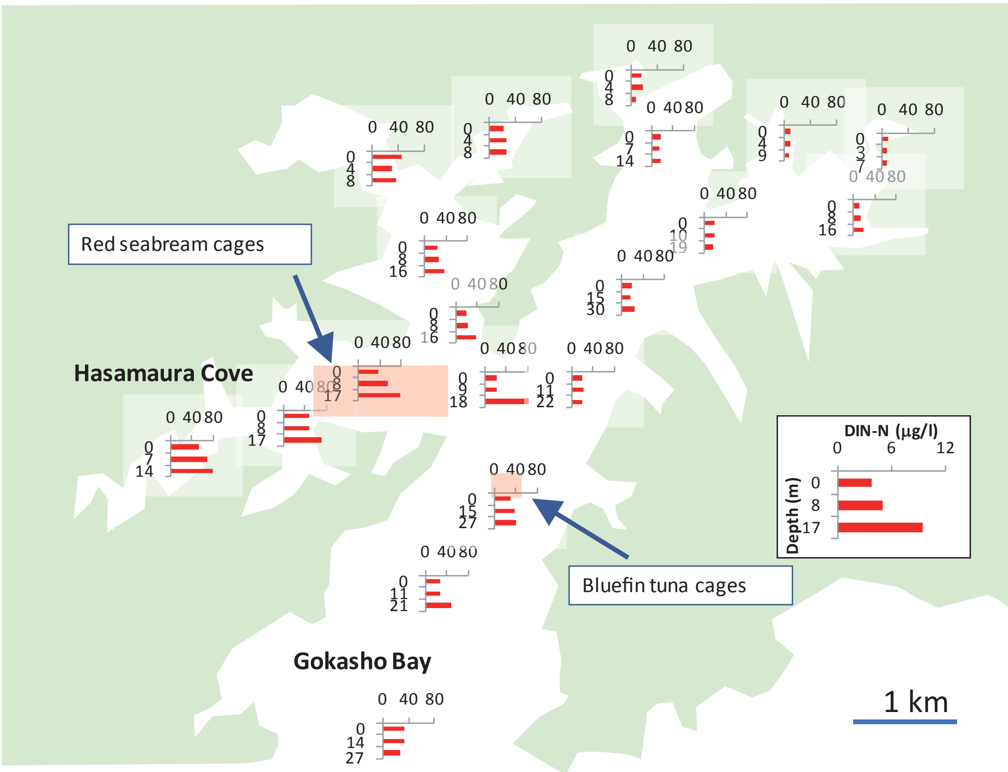

Fig. 1. Dissolved inorganic nitrogen (DIN-N) concentration in Gokasho Bay, Mie, Japan in December 2016.

The chlorophyll *a* concentration was obtained by converting the fluorescence intensity of the CTD, using the relationship between the CTD readings and chlorophyll *a* concentration of cultured phytoplankton (*Pavlova lutheri*) measured with a chlorophyll fluorometer (10 AU fluorometer, Turner Designs).

Horizontal distribution of the nutrients and chlorophyll *a* around the red seabream aquaculture cages were obtained by R software with the Akima add-on package for linear interpolation and mapping.

Results and Discussion

The DIN-N (i.e., the sum of NH_4-N, NO_2-N, NO_3-N) levels were often found to be higher in the area with red seabream aquaculture cages and the inner part of Hasamaura Cove, especially in the bottom water in our monthly water parameter monitoring. An example of the DIN-N concentration distribution in December 2016 is shown in **Fig.1**. The DIN-N concentrations in the red seabream aquaculture area were more than double of those at the mouth of Gokasho Bay opening to the Pacific. The DIN-N concentration did not differ with the depth at the bay mouth, which is considered to be under a strong influence of outer seawater. The PO_4-P concentration showed similar trends with DIN-N (**Fig.2**). These indicate that effluent from red seabream aquaculture elevates dissolved inorganic N and P concentrations in Hasamaura Cove. Higher nutrient concentrations in the bottom water may be partially attributable to decomposition of sediment organic matter on the sea bottom deposited from the fish culture.

A comparison of nutrient levels in the aquaculture area in December was made between 2016 and 1980s. The National Research Institute of Aquaculture conducted water nutrient monitoring in Gokasho Bay in late 1980s (Sugiyama *et al*., 1991), where red seabream and yellow tail (*Seriola quinqueradiata*) aquaculture was more intensive than recent years and self-pollution was an issue (Abo, 2000). The DIN-N concentration was reduced by about 25% from 1980s (the mean of 1986 - 1988) to 2016 (**Fig.3**). The PO_4-P

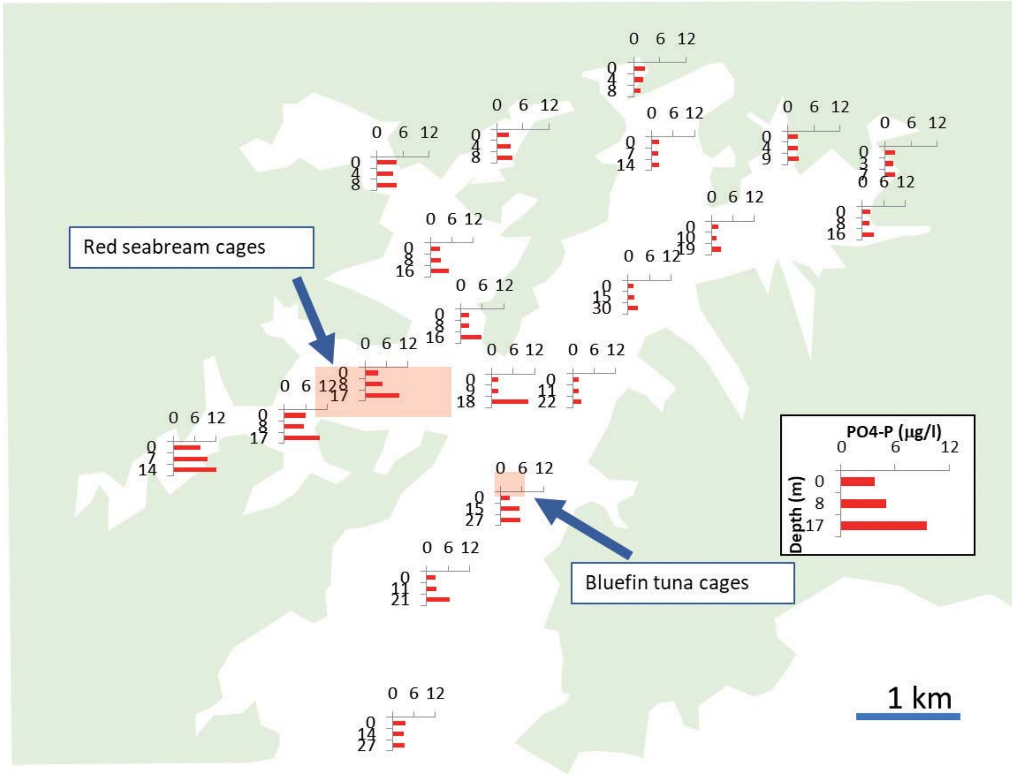

Fig. 2. Dissolved inorganic phosphate (PO_4-P) concentration in Gokasho Bay, Mie, Japan in December 2016.

concentration was reduced by about 80 % (Fig.3). The reduction in the nutrient levels may be related with the reduction of aquaculture production in the area. The large reduction of PO_4-P concentration may also be attributable to the shift of aquaculture feed from raw bait to formulated feed. The DO level has moderately increased in the bottom water. Supposedly, because of the reduced organic loads, and a reduction in harmful algal blooms and hypoxia of the bottom water which have no longer been rampant in Gokasho Bay in recent years.

However, diatom blooms sporadically occur in Gokasho Bay. In the case of a diatom bloom observed in November 2016, chlorophyll *a* concentration was higher in the surface and mid-layer water in the red seabream aquaculture area compared with the other locations in Gokasho Bay, reaching about 27 μg/l (Fig.4). Despite the diatom bloom, neither DIN-N nor PO_4-P were depleted in the aquaculture area, but SiO_2-Si was depleted (Fig.5). Nutrient load from the aquaculture seemed to maintain relatively high DIN-N and PO_4-P concentrations at the depletion level of SiO_2-Si, probably making SiO_2-Si the limiting factor for diatom production in this area. Reduced Si discharge from rivers to the marine environment associated with the entrapment at dams is perceived to enhance production of non-diatom species including harmful red tide species (Harashima, 2008).

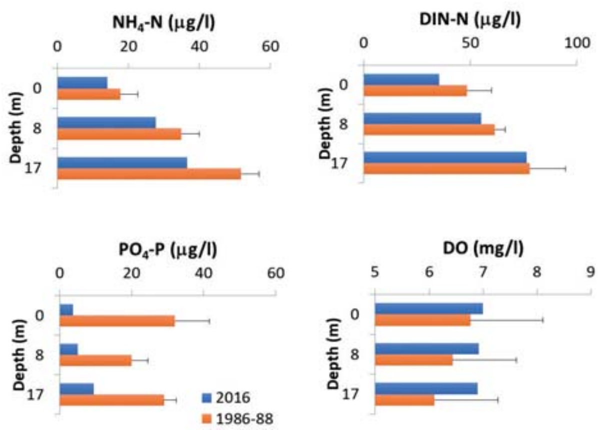

Fig. 3. Dissolved inorganic nutrient and dissolved oxygen levels near red seabream (*Pagrus major*) aquaculture cages in December 2016 and 1980s. Data for 2016 are from this study, and data from 1986 to 1988 are after Sugiyama *et al.* (1991).

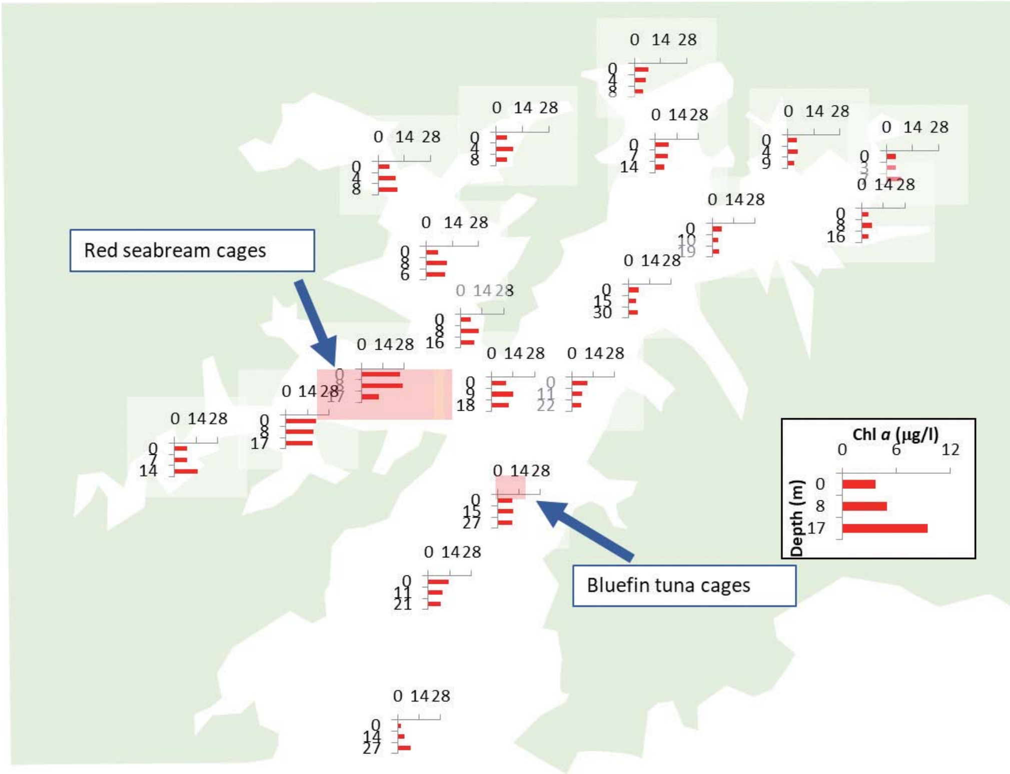

Fig. 4. Chlorophyll *a* concentration in Gokasho Bay, Mie, Japan, in November 2016.

Oligotrophication is problematic in some coastal waters in Japan, reducing unfed aquaculture profitability of some bivalves and seaweed (Handa and Harada, 2012; Yamamoto, 2003). In Gokasho Bay, Hasamaura Cove with red seabream aquaculture had relatively higher dissolved inorganic N and P concentrations, which may be used to enhance unfed aquaculture productivity through integrated multi-trophic aquaculture (IMTA) approach (Robinson and Chopin, 2004; Chopin, 2006).

During the intensive water analysis around the red seabream aquaculture cages in Hasamaura Cove in January 2017, there were spots with a higher NH_4-N level at the center and 20 m outside the cage area (**Fig.6**). The chlorophyll *a* level was higher, and NO_3-N was lower around the cages than in the surrounding water (**Fig.6**). The observed lower NO_3-N concentration may indicate that the enhanced primary production triggered by the NH_4-N supply from the aquaculture effluent rapidly consumed not only NH_4-N but also the background NO_3-N in the area. Under this assumption, DIN-N excreted from red seabream may not travel a long distance from the cages, being readily consumed by localized primary production. In Gokasho Bay, green alga (*Monostroma nitidum*) is intensively cultured. To effectively fertilize the seaweed with the red seabream aquaculture effluent, the seaweed should be cultured near the

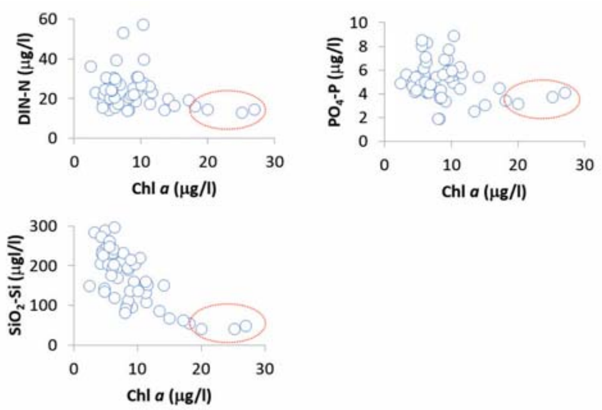

Fig. 5. DRelationship between chlorophyll *a* concentration and DIN-N, PO_4-P and SiO_2-Si concentrations during a diatom bloom in Gokasho Bay, Mie, Japan, in November 2016. Dotted red circles indicate the data from the red seabream aquaculture area in Hasamaura Cove.

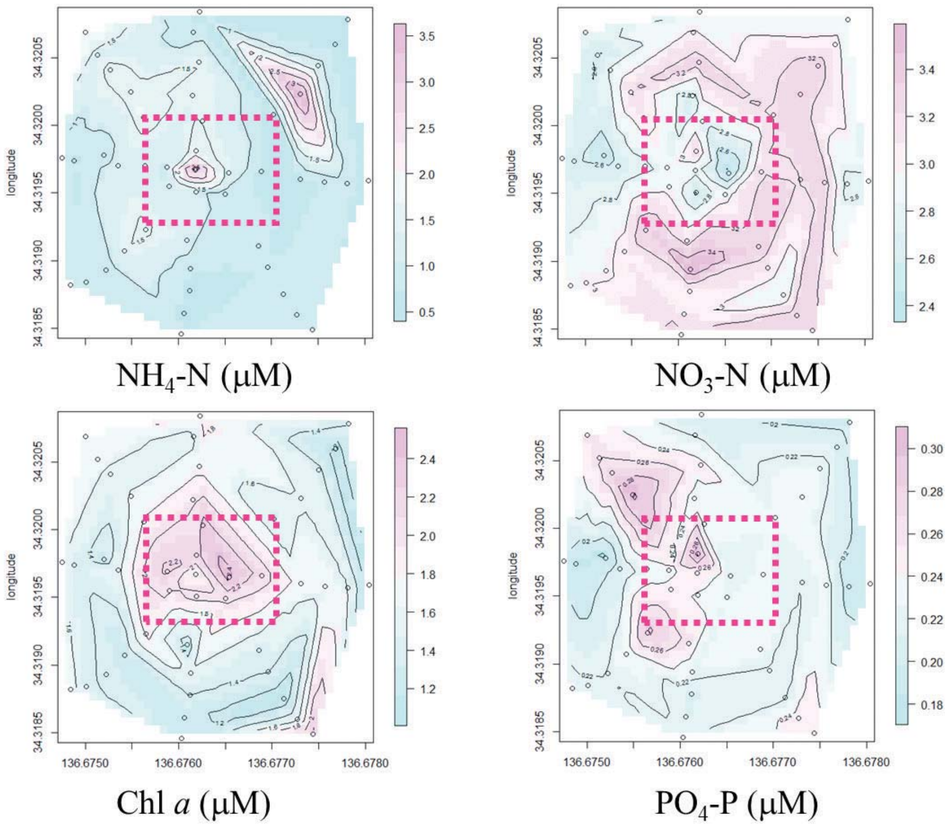

Fig. 6. Horizontal topography of NH_4-N, NO_3-N, chlorophyll *a* and PO_4-P concentrations at 5 m depth around the red seabream aquaculture area. Dotted red rectangles indicate the area with red seabream cages.

cages. The elevation of chlorophyll *a* in the fish cage area indicates that the red seabream aquaculture can increase food availability for aquaculture of bivalves, such as Pacific oyster (*Crassostrea gigas*) and Manila clam (*Ruditapes philippinarum*). Field experiments should be further carried out to design an effective IMTA system including these species.

References

Abo K., 2000: Fluctuation of hypoxic water masses in a fish farming ground of semi-enclosed estuary facing the ocean. *Bull. Natl. Res. Inst. Aquacult.*, **29**, 141-216. (in Japanese with English abstract)

Chopin T., 2006: Integrated multi-trophic aquaculture: what it is, and why you should care and don't confuse it with polyculture, Northern Aquaculture, July/August, pp.4.

Furukawa K., 2008: Utilization of self-feeding to the commercial cultivation of red sea bream Pagrus major. *Nippon Suisan Gakkaishi*, **74**, 902-903. (in Japanese)

Handa H. and Harada K., 2012: Setonaikai toubu (harimanada) no eiyouen kankyou to gyogyou (nutrient environment and fishery in Eastern Seto Inland Sea) *Aquabiology*, **199**, 132-141. (in Japanese)

Harashima A., 2008: Role of the Diatom-Silicon Process in Marine Ecosystem. *J. Environ. Biotechnol.*, **8**, 9-16. (in Japanese)

Nishikawa T. and Hori Y., 2004: Effects of nitrogen, phosphorus and silicon on the growth of the diatom *Eucampia zodiacus* caused bleaching of seaweed *Porphyra* isolated from Harima-Nada, Seto Inland Sea, Japan. *Nippon Suisan Gakkaishi*, **70**, 31-38. (in Japanese with English abstract)

Ono S. and Nakahara N., 2009: Current Conditions and Issues in the Fish Aquaculture Industry. *Aquacul. Sci.*, **57**, 149-164. (in Japanese with English abstract)

Robinson S. M. C. and Chopin T., 2004: Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: summary of the workshop and issues for the future. *Bull. Aquacult. Assoc. Can.*, **104-3: 4-10**, 73-84.

Sugiyama M., Tanaka N., Asakawa A., Sakami T., Iikura T., Toda T., Kitamura S., Honjo T., Shiraishi M., Awaji M., Yamamoto S., Sako H., and Kumada H., 1991: Records of oceanographic observation in Gokasho Bay, Mie Prefecture (1986-89), National Research Institute of Aquaculture, Fisheries Agency, Mie, 49pp. (in Japanese)

Yamamoto T., 2003: The seto inland sea - eutrophication or oligotrophication?. *Mar. Pollut. Bull.*, **47**, 37-42.

Annotated bibliography

(1) Yamamoto T., 1992: Constant uptake of ammonium-N and nitrate-N by *Porphyra yezoensis* thalli. *J. Fac. Appl. Bio. Sci. Hiroshima Univ.*, **31**, 155-159.

The author experimentally determined the uptake rates of ammonium-N and nitrate-N by *Porphyra* (currently *Pyropia*) *yezoensis* using ^{15}N as a tracer. *Pyropia yezoensis* (laver or *nori*) is an important seaweed in Japan. Specific uptake rate of ammonium-N (0.0017/hr) was more than 8 times higher than that of nitrate-N (0.0002/hr). The uptake rates were constant over the 120-minute experiment, unlike in the case of phytoplankton that is known to rapidly absorb nutrients to satiation. Fertilizers with ammonium-N as the main component may be suitable for *nori* aquaculture. The nitrogenous fertilizer should be provided to *nori* at a low concentration over a long duration to avoid induction of phytoplankton bloom.

(2) Kakehi S., Fujiwara T., and Yamada H., 2005: Seasonal variation in the nutrient standing mass and nutrient budget of Ise Bay. *Umino Kenkyu* (Oceanography in Japan), **14**, 527-540.

The authors estimated the standing mass of dissolved inorganic nitrogen (DIN) and dissolved organic phosphorus (DIP) by the linear regression of apparent oxygen utilization (AOU) or the interpolation of the surface and bottom nutrient concentrations to elucidate the seasonal variations in Ise Bay, Japan. The DIN standing mass in the bottom layer ranged from 1500 to 2600 t, tending to be higher in summer than in winter. The DIN was smaller in the surface layer than in bottom layer in summer, and comparable between the two layers in winter. The DIP standing mass showed more distinct seasonal trend. It was 200 t in surface and bottom layer in winter; whereas it increased to 400 t in the surface and 800 t in the bottom later in summer. The temporal change of the standing mass of the nutrients was more dependent upon biological and chemical processes than physical processes such as seawater exchange. Chlorophyll level is inversely related with DIN and DIP in the surface layer in summer, but DIN and DIP are not completely synchronous. The DIP seemed to be released from the sea sediment in summer where hypoxic water is formed in the bottom layer. Denitrification seemed to take place year-round.

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Challenges and opportunities of IMTA in Hawaii and beyond

Cheng Sheng Lee*

Abstract: Available consumable seafood for 7.3 billion population in 2014 was 20 kg per capita (FAO, 2016). To maintain this level of seafood supply for expected 9.7 billion population in 2050, the total world seafood supply requires additional 48 million metric tonnes. With the stagnant yield from capture fisheries, the increase has to come from aquaculture. Although the annual growth of aquaculture production has slowed down, theoretically aquaculture production will reach the targeted production level. However, current intensive mono-aquaculture practices have faced the challenges of sustainability and must change its operation to meet the criteria of sustainable development defined and adopted by UN's 193 Member in 2015. UN members adopted the 2030 Agenda for Sustainable Development and call for an integrated approach that addresses all three dimensions of sustainable development (economic, social and environmental).

Current aquaculture practices consume nature resources and compete with each other. Ecosystem based aquaculture management is essential to co-exist with other social activities and to efficiently utilize natural resources for food production and conservation of nature stocks. Integrated multi-trophic aquaculture (IMTA), an old concept with new knowledge, appears to be the answer to sustainable development in aquaculture. IMTA practice combines the cultivation of fed aquaculture species, and extractive aquaculture species (both organic and inorganic ones) to reduce wastes and to create balanced eco-systems. Additionally, IMTA can play important roles in disease control and management, climate change mitigation, and others. As a result, IMTA has received more and more attentions at the turn of the century. However, the feasibility of IMTA comparing to mono-culture has yet to be documented.

This presentation discusses the sustainability of IMTA by reviewing the practice of IMTA concept in traditional Hawaii aquaculture back to 1000 A.D. to current practices in the U.S. and beyond; updates US-Korea bilateral IMTA project; and challenges of IMTA.

Key words: IMTA, Aquaculture, Sustainability, Hawaii

Introduction

Among food production sectors in agriculture, seafood is the only one still rely on wild caught fish as the main supply channel. Indeed, the harvest of fish has reached the peak and plateaued around 90 million metric tons since early 1990 (**Fig.1**, FAO, 2016). However, as stated by Walsh (2011) "If we're all going to survive and thrive in a crowded world, we'll need to cultivate the seas just as we do the land. If we do it right, aquaculture can be one more step toward saving ourselves. And if we do it well, we may even enjoy the taste of it." With the effort by many stakeholders in seafood business, aquaculture has shown impressed growth (FAO, 2016). In 2014, the statistics showed aquaculture supplied half of edible seafood. Capture fisheries used to contribute major seafood to human consumption as show in this slide

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* Center for Tropical and Subtropical Aquaculture
c/o HNFAS, College of Tropical Agriculture and Human Resources
University of Hawaii at Manoa
1955 East West Road, Ag. Sci. 216, Honolulu, HI 96822, U. S. A.
E-mail: chenglee@hawaii.edu

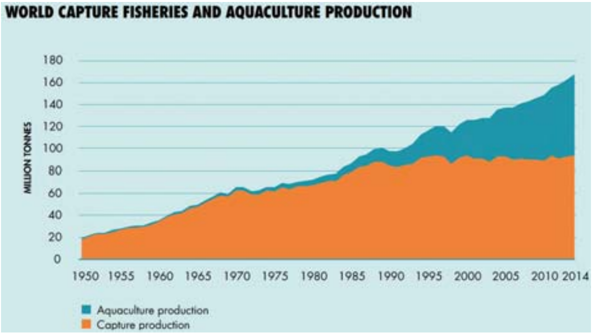

Fig. 1. World seafood production from 1950 to 2014. (FAO, 2016)

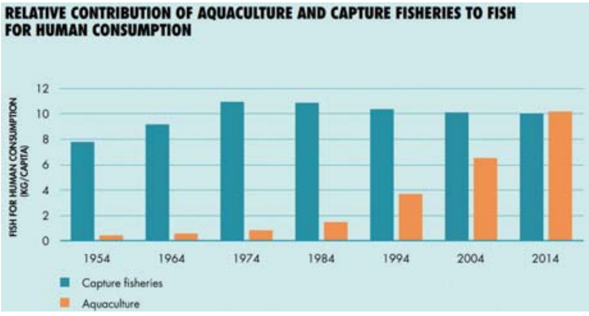

Fig. 2. Contribution to human seafood consumption from capture and aquaculture. (FAO, 2016)

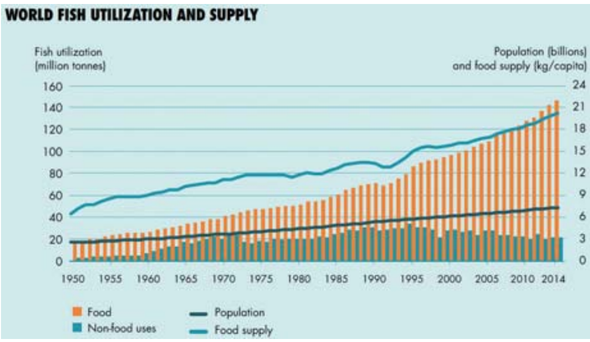

Fig. 3. World population growth and seafood supply. (FAO, 2016)

until 2014 (**Fig.2**). From 1950 to 2014, the food supply increased faster than the population increased (**Fig.3**). The available seafood for the 7.3 billion population in 2014 was 20 kg per person. If the projected 9.7 billion population in 2050 is correct, we need additional 48 million MT seafood to meet the 20 kg per capita level in 2014. Average annual growth rates for aquaculture were over 10 % in both 80s and 90s (FishStat. FAO, 2016). It has decreased since but still around an impressed rate of 6 %. The rate may decrease in the future but we should have enough seafood from aquaculture to meet the demand if the seafood consumption rate remains the same. However, the demand for seafood will probably increase as the population structure changes and several challenges may hamper the increase in aquaculture production. For the sustainable development of aquaculture, integrated approach to overcome the challenges facing aquaculture development is essential. In 2015, 193 members of United Nation adopted the "2030 Agenda for Sustainable Development" (https://www.un.org/sustainabledevelopment/development-agenda/) and its 17 Sustainable Development Goals. They call for an integrated approach that addresses all three dimensions of sustainable development: economic, environmental and social factors. At Global aquaculture alliance (GAA) 2013 meeting, the concluded five major challenges were: health and disease management, feeds, environmental/social Accountability, investment capital and market support. Therefore, a sustainable aquaculture has to be integrated approach and to address key challenges for the development. This paper discusses a practice which may meet all criteria to be a sustainable one.

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a new term (Neori *et al*., 2004) for an old concept. Polyculture has been practiced in China since 2200 BC to fully utilize the nutrients inside an enclosed pond. IMTA takes one step further to reduce the ecological footprint from aquaculture practice and at the same time to create economic diversity and to call for social acceptability (Troell *et al*., 2009). IMTA, therefore, equals to polyculture but polyculture is not necessary an IMTA. Since aquaculture can be the farming of several aquatic organisms which interact through water in shared or connected systems, one organism wastes can be another resource (Butterworth, 2010).

When feed is offered to an aquatic organism, only portion of digested nutrients is incorporated into biomass of the target organism. The rest of unused digested nutrients, along with indigestible nutrients and un-eaten feed will increase nutrients levels and become solid waste in surrounding environment (Reid *et al*., 2007). The quality and quantity of total

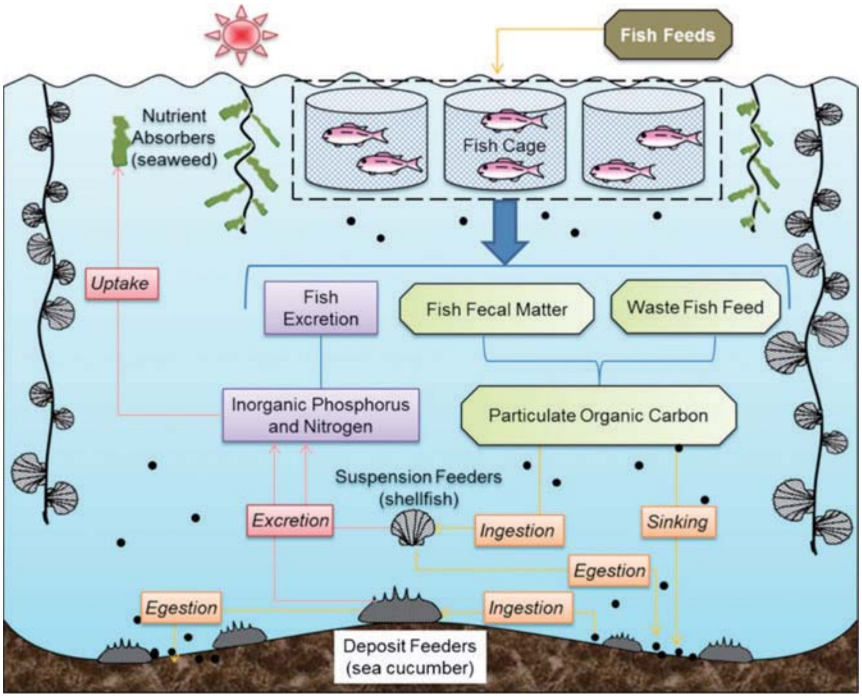

Fig. 4. Conceptual diagram of the integrated multitrophic aquaculture system. (Zhang *et al.*, 2016)

Table 1. Key species have been in IMTA

Key Species Cultured in Modern IMTA Systems
(Integrated mariculture, FAO-529)

Cold Seawater	*Temperate Sea water*	*Warm Seawater*
Salmo	*Pagraus major*	*Sparus aurata*
Oncorhynchus sp.	*Sparus aurata*	*Lates calcarifer*
Gadus	*Dicentrarchus labrax*	*Mugil cephalus*
	Lates calcarifer	*Chanos*
		Epinephelus sp.
Crassostrea sp.	*Mercenaria*	*Crassostea gigas*
Mytilus sp.	*Crassostea sp.*	*Tapes japonica*
Haliotis rufescens	*Ostrtrea edulis*	*Haliotis diversicolor*
Hamarus	*Mytilus*	*Penaeus spp.*
Strongylocentrotus	*Ruditapes semidecussatus*	
Paracentrotus	*Penaeus spp.*	
Laminaria sp.	*Gracilaria sp.*	*Gracilaria changii*
Macrocystis sp.	*Ulva sp.*	*Ulva lactuca*
Porphyra sp.		*Kappaphycus*
Saccharina		
Undaria		
Nereis, Arenicola, sea cucumber	*Nereis, Arenicola, sea cucumber*	*Nereis, Arenicola,sea cucumber, mullet*

nutrients released are determined by the cultivated species and the dominant fraction is in a dissolved form, particular for nitrogen (Troell *et al.*, 2003). To fully utilize all nutrients as a result of feeding, IMTA practice composes of species at different trophic levels may be the solution. An essential component in IMTA are fed aquaculture and extractive aquaculture. The diagram presented by Zhang *et al.* (2016) gives a good illustration (**Fig.4**). IMTA can be implemented in freshwater system or saltwater system at either land based or open water operation. Depending on the water quality and location, a wide variety of species have been tested in IMTA system as shown in **Table 1** (Soto, 2009). Target species can cover all cultivated species from plankton, plant to invertebrate and vertebrate species. The optimal species combination should be based on meeting the goal of sustainable development mention above.

IMTA in Hawaii and USA

The "Ahupua'a" is the basic self-sustaining unit in ancient Hawaii land system, recognizes the connection between resources from mountain to the sea. It has the resources the human community needed and emphasizes the interrelationship in the activities of daily and seasonal life. Ancient Hawaiian fishpond within this land management system also practices this interrelationship concept to stock aquatic species within the aquatic compartment surrounding by coral reef and volcano rock. All target species will compromise with each other on nutritional needs and balance the essential optimal ecosystem for all in the pond. Species including carnivorous, herbivorous, omnivorous, and seaweed can be found in Hawaiian fishpond as stated in Moli'i fishpond (Sato and Lee, 2007). However, number of Hawaiian fishpond has decreased due to the socioeconomic change. Many of the sites have been converted to other social activities for greater economic return.

On December 3 and 4, 2009, an international workshop on "Bioextractive Technologies for Nutrient Remediation" was held to address the management of eutrophication and hypoxia in Long Island Sound. The positive contributions from the bio-extraction of nutrients from use of macroalgae to absorb inorganic nutrients and use of filter and deposit feeders to reduce organic waste released from fish production was presented (Rose *et al*., 2010). The nutrient bioextraction by seaweed and bivalves as reviewed by Yarish and Kim (2017) is very significant. Another benefit of IMTA practice showed by Molloy *et al.* (2011) study that individual blue mussel can remove copepodids from water column. Therefore, co-culture with blue mussel (*Mytilus edulis*) may be the potential alternative method to drug to deal with sea louse (*Lepeophtheirus salmonis*) issue in Atlantic salmon aquaculture. Furthermore, Molloy *et al.* (2014) study found that infectious salmon anaemia virus (ISAV) was ingested by blue mussels and no viable ones were found in digestive gland tissue.

Another type of IMTA practice in Hawaii is aquaponics. The nutrients from fish culture are used as fertilizer for vegetables. Current practices in freshwater system is tilapia with various type of vegetables. Although tilapia is the most popular species, it does not exclude other species which is tolerable to the water quality condition in aquaponics system. Other than the freshwater system, several studies are on-going to test seacucumber and/or seaweed with shrimp, abalone and marine finfish in marine environment. Seacucumber may plan important role in improving the benthic condition by cleaning the detritus at the bottom of rearing facility. The study by Hannah *et al.* (2013) demonstrated seacucumber is able to utilize the heavy fraction of waste from a sablefish farm. Aquaponics has also been practiced in other locations in the US as well. Other practice can be found at the publication by Bellona (2013) and Soto (2009).

Challenges for IMTA

The above background information on IMTA proves this system can protect the surrounding environment around the farm site and diversify products. The concept of IMTA is also supported by the aquaculture industry in Norway. Norwegian aquaculture industry has shown significant growth since 1970s and targeted to triple the production by 2025 from over 1.3 million tonnes level in 2012. However, Bellona report in 2013 (Bellona, 2013) clearly indicated it is an unsustainable target unless IMTA concept is introduced. IMTA is also supported by publics. According to the survey conducted by Yip *et al.* (2012) at Northwest USA, it revealed 44.3 % of consumers favored the IMTA operation and were willing to pay a price premium of 9.8 %.

On contrary to those favor of IMTA, the practice of IMTA in large scale is still very limited. The recent survey conducted by Kinney (2017) also indicated that financial returns for IMTA did not justify the continuous operation of majority farmers. Only two aquaculturists out of eight continued after the initial trial. Therefore, the challenges to the implementation of IMTA have to be overcome. A workshop at Port Angeles, Washington (Thomas, 2011) was conducted to analyze strength, weakness, opportunity, and threat on IMTA regarding ecological, economic and social impacts. Information from this workshop should provide good base for strengthening the positive impacts from the practice of IMTA.

In conclusion, if we do it right, IMTA can overcome at least some of the 4 out of 5 major challenges to aquaculture development. Before IMTA can be widely applied to aquaculture production, more research in IMTA are needed. To fully understand the optimal ration of fed to extractive organisms is critical. The startup cost and profitability have to be improved to be affordable and acceptable by farmers. Then, the research module has to be able to expand to commercial scale. Finally, the products from IMTA have to be distinguishable from other traditional practice to command higher price.

References

Bellona, 2013: Traditional and Integrated Aquaculture. Bellona report 2013, The Bellona Foundation, Oslo, 113pp. https://www.bellona.org

Butterworth Adam, 2010: Integrated multi-trophic aquaculture systems incorporating abalone and seaweeds, Nuffield Australia Project No 0914, 39pp.

FAO, 2016: The state of world fisheries and aquaculture 2016, Contributing to food security and nutrition for all, FAO, Rome, 200pp.

Hannah L., Pearce C. M., and Cross S. F., 2013: Growth and survival of California sea cucumbers (*Parastichopus californicus*) cultivated with sablefish (*Anoplopoma fimbria*) at an integrated multi-trophic aquaculture site. *Aquaculture*, **406-407**, 34-42.

Kinney H., 2017: Aquaculturists' perceptions of Integrated Multi-Trophic Aquaculture (IMTA) (Open Access Master's Theses. Paper 1024), University of Rhode Island, 75pp. https://digitalcommons.uri.edu/theses/1024

Molloy S. D., Pietrak M. R., Bouchard D. A., and Bricknell I., 2011: Ingestion of *Lepeophtheirus salmonis* by the blue mussel *Mytilus edulis*. *Aquaculture*, **311**, 61-64.

Molloy S. D., Pietrak M. R., Bouchard D. A., and Bricknell I., 2014: The interaction of infectious salmon anaemia virus (ISAV) with the blue mussel, *Mytilus edulis*. *Aquac. Res.*, **45**, 509-518.

Neori A., Chopin T., Troell M., Buschmann A., Kraemer G. P., Halling C., Shpigel M., and Yarish C., 2004: Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*, **231**, 361-391.

Rose J. M., Tedesco M., Wikfors G. H., and Yarish C., 2010: International Workshop on Bioextractive Technologies for Nutrient Remediation Summary Report, Northeast Fish. Sci. Cent. Ref. Doc. 10-19, US Dept. Commer., 12pp. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at https://www.nefsc.noaa.gov/nefsc/publications/

Sato V. T. and Lee C.-S., 2007: Keeper of Molii pond, The Oceanic Institute, Waimānalo, 148pp.

Soto D.(ed.), 2009: Integrated mariculture-A global review, FAO Fisheries and Aquaculture Technical Paper 529, FAO, Rome, 184pp.

Thomas S. A., 2011: White paper of Integrated multi-trophic aquaculture: A workshop at Peninsula College September 14-15, 2010, Port Angeles, 46pp.

Troell M., Halling C., Neori A., Buschmann A. H., Chopin T., Yarish C., and Kautsky N., 2003: Integrated mariculture: asking the right questions. *Aquaculture*, **226**, 69-90.

Troell M., Joyce A., Chopin T., Neori A., Buschmann A. H., and Fang J. G., 2009: Ecological engineering in aquaculture - Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture*, **297**, 1-9.

Walsh B., 2011: The end of the line. Times July 7, 2011.

Yarish C. and Kim J. K., 2017: Cultivation of economically important seaweeds in New England for nutrient bioextraction and IMTA systems. Presented at International Symposium on the IMTA September 14 to 15, 2017, Busan.

Yip W., Knowler D., and Haider W., 2012: Assessing the willingness to pay for more sustainably farmed Atlantic salmon in the Pacific Northwest: combining discrete choice experiment and latent class analysis. Paper presented at Western Economics Association International Annual Conference June 29- July 3, 2012, San Francisco.

Zhang J., Kitazawa D., and Yang C., 2016: A numerical modeling approach to support decision-making on design of integrated multitrophic aquaculture for efficiently mitigating aquatic waste. *Mitig. Adapt. Strateg. Glob. Chang.*, **21**, 1247-1261.

Annotated bibliography

(1) Sato V. T. and Lee C.-S., 2007: Keeper of Molii pond, The Oceanic Institute, Waimānalo, 148pp.

An oral history of a man, George Uyemura who spent 70 years of his life at Molii Pond was documented at this book to share his knowledge and experience in managing the fish pond. This book offers a look at the history and methodology of sustainable management of Hawaiian fishponds. It is a start reference book to know more about Hawaiian fishpond.

(2) Soto D. (ed.), 2009: Integrated mariculture- A global review, FAO Fisheries and Aquaculture Technical Paper 529, FAO, Rome, 184pp.

This report contains three desk studies encompassing global views of practices and future prospects for integrated aquaculture in coastal and marine areas in three climatic zones: temperate, tropical and Mediterranean Sea as a special Mediterranean enclosed ecosystem. The commissioned review papers describing integrated aquaculture in coastal and marine environments were technically supervised by Mrs. Doris Soto, Senior Fisheries Officer (FIMA). The activity and the publication have been partly funded through a Japanese Trust Fund Project (Towards Sustainable Aquaculture: Selected Issues and Guidelines). It is a good reference report to get start to know about integrated mariculture.

(3) Thomas S. A. (ed.) 2011: Integrated Multi-Trophic aquaculture: A Workshop at Peninsula College Port Angeles, Washington. *Bull. Aquacul. Assoc. Canada*, **109-2**, 13. https://www.researchgate.net/publication/257819653

This report summarized the first US-based workshop on integrated multi-trophic aquaculture (IMTA). The two days' workshop included presentation and breakout sessions to conduct "strengths-weaknesses-opportunities-threats" (SWOT) analysis for ecological, economic, and social impacts of IMTA. It concluded IMTA could help to move the US toward becoming a major aquaculture producer in the world, because it might resolve some of the issues that seem to be limiting such progress. This is a good reference base for any further SWOT analysis.

(4) Bellona, 2013: Traditional and Integrated Aquaculture. Bellona report 2013, The Bellona Foundation, Oslo, 113pp. https://www.bellona.org

Bellona has been involved in the hunt for new solutions, new resources and new products that will be important for the future. This report points out that salmonid industry has high ambitions for growth, but it must happen in harmony with the ecosystem. It explains why aquaculture should progress from salmonid monoculture to integrated and sustainable ecosystems and how. Also, this progress depends on the aquaculture industry, research institutions and politicians working together. It is a good lesson for other aquaculture industry to learn from a mature salmonid industry to think ahead.

(5) Gunning D., Maguire J., and Burnell G., 2016: The development of sustainable saltwater-based food production systems: a review of established and novel concepts. *Water*, **8(12)**, 598.

This review article examines the potential negative impacts of saltwater mono-aquaculture operations and how the novel approach such as IMTA, constructed wetlands and saltwater aquaponics will mitigate the negative impacts.

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Abstracts of Poster Presentations

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Abstracts of Poster Presentations

1: Possible effects of terrestrial managements on seagrass ecosystem functionings

Christopher BAYNE*, Hideki HAMAOKA, and Masakazu HORI*

* National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
E-mail: bayne@affrc.go.jp

Abstract

Seagrass species function as typical foundation species which support high productivity and diversity because of their high rates of primary production and their ability to provide associated organisms with trophic support, refuge from predation, and spawning substrates. Seagrass associated species, especially herbivorous invertebrates, can regulate the ecosystem functioning of seagrass beds, suggesting that this interaction is an important key to clarify the relationship between biodiversity and ecosystem functioning in coastal ecosystems. Seagrass communities are characterized by wide occurrence in shallow nearshore areas, where there is a boundary between terrestrial and marine ecosystems. Therefore, seagrass communities are often influenced by various factors derived from terrestrial habitats, such as agrichemicals and nutrients through fresh water input. Although terrestrial nutrients are essential for productivity for nearshore marine plants including seagrass species, increased nutrients cause eutrophication and phytoplankton blooming resulting in the degradation of seagrass growth and distribution. Agrichemicals from river, adjacent agriculture fields and forests also have serious effects on seagrass communities; in particular insecticide has caused mass mortality of the seagrass-associated invertebrates, resulting in vulnerable ecosystem functioning of seagrass beds. The inflow of both agrichemical and nutrients into nearshore areas has increased with the change of the adjacent terrestrial management. In this study, we demonstrated interactive effect of insecticide with eutrophication on ecosystem functioning of seagrass beds using manipulative experiments in Seto Inland Sea, Japan. In the manipulation, we used the insecticide carbaryl to exclude invertebrate herbivores and the fertilizer to add nutrients, which is a technique developed by the Zostera Experimental Network (ZEN), a global collaborative network of scientists studying the structure and functioning of ecosystems supported by eelgrass. The technique enables us especially to demonstrate the indirect effect of epiphyte grazing by the associated invertebrates on eelgrass growth (e.g. Whalen *et al*., 2013). The carbaryl loading significantly decreased the density and diversity of herbivorous invertebrates and indirectly increased epiphyte biomass, resulting in a significant difference in seagrass growth, although carbaryl concentrations were within the safety standards even at the experiment site. However, the nutrient addition significantly changed the indirect effect of carbaryl loading on seagrass growth. These results suggest that seagrass-associated herbivores can regulate ecosystem functioning of seagrass beds, and indicate the possibility that both agrichemical and nutrient loading can easily change the seagrass ecosystem functionings even in lower concentration. Both agrichemical and nutrient loading from terrestrial habitat to nearshore areas would be easy to change and vary spatially with land use change, so that we should pay attention to the management for the adjacent terrestrial habitats.

Annotated Bibliography of Key Works

(1) Duffy J., Reynolds P., Boström C., Coyer J., Cusson M., Donadi S., and Fredriksen S., 2015: Biodiversity mediates top–down control in eelgrass ecosystems: a global comparative-experimental approach. *Ecol. Let.*, **18(7)**, 696-705.

This paper investigates top-down and bottom-up effects of adding nutrient and deterrents to eelgrass (*Zostera marina*) beds at 15 sites across the range of this species. They found that removing grazers had a stronger average effect on epiphytic biomass than local addition of nutrients, revealing stronger top-down control by grazers. Also, they found that the influences of biodiversity in their global analysis are very similar to results from other small-scale experiments. These include sites with more genotypically diverse eelgrass with higher crustacean biomass and lower algal biomass at sites with increased grazer species.

(2) Reynolds P., Stachowicz J., Hovel K., Boström C., Boyer K., Cusson M., and Duffy J., 2017: Biogeography of predation pressure in eelgrass across the Northern Hemisphere, Unpublished manuscript, Virginia Institute of Marine Science, Virginia USA.

Studies across broad geographic ranges exploring drivers of change in predator interactions are relatively rare. The authors surveyed predation on a common amphipod prey in eelgrass (*Zostera marina*) beds at 42 sites across the Northern Hemisphere. At all coasts, predation declined with latitude, but declined more in areas where temperature gradients are steeper.

(3) Whalen M., Duffy J., and Grace J., 2013: Temporal shifts in top-down vs. bottom-up control of epiphytic algae in a seagrass ecosystem. *Ecology*, **94**, 510-520.

The authors used a cage-free approach of manipulating mesograzer abundance and epiphytic loading over a temporal period, by using deterrent and nutrient treatments. They found that reduction of mesograzer abundance and increase in nutrients can allow increased epiphytic algae growth on eelgrass (*Zostera marina*). By performing the experiment in the fall and summer, they found that the dominant factors that controlled epiphytic algae abundance changed. In fall, there was a natural decrease in mesograzer abundance, and by adding nutrients, which caused bottom-up factors to dominate, increased epiphyte biomass. In summer, added deterrents, stimulating strong top-down factors, decreased mesograzer abundance and caused an increase in epiphyte biomass. Also, unexpectedly, they found that drift macroalgae indirectly reduced epiphytes by proving structure for mesograzers.

2: Genetic effects of the tiger puffer stock enhancement program on wild population in the sea around Japan

Daisuke KATAMACHI

National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
E-mail: kata79@fra.affrc.go.jp

Abstract

Since 1977, millions of hatchery-reared tiger puffer, *Takifugu rubripes*, juveniles have been released for stock enhancement in the sea around Japan. The stock enhancement program has contributed to catches, however, no information about genetic effects of the program on wild population is available. The genetic effects were evaluated with highly polymorphic DNA marker sets (1962 bp mitochondrial DNA sequences and 11 microsatellite DNA loci) using 316 mature wild adults from nine identified or possible spawning sites in the sea around Japan, 276 wild juveniles in the Ariake Sea which is a possible spawning site and an identified nursery, 85 hatchery-reared juveniles, 150 mature hatchery-released adults in the Ariake Sea. Both types of markers indicated that hatchery-reared and hatchery-released populations had lower genetic variability than wild populations, however, hatchery-released population had closer genetic variability to wild populations. Microsatellite F_{ST} estimates indicated hatchery-reared and hatchery-released populations were significantly different from wild populations. On the other hand, significant differences were observed only between hatchery-reared population and wild populations with mitochondrial Φ_{ST} estimates. Microsatellite F_{ST} estimates and Bayesian clustering analysis revealed population structure of the tiger puffer, however, the population structure was not associated with the history and scale of stock enhancement program. The genetic variability was almost equivalent among wild populations, no significant deviation from Hardy-Weinberg equilibrium and significant linkage disequilibrium were detected from wild populations. Moreover, putative wild juveniles

having a high possibility of being related to mature hatchery-released adults were detected based on relatedness among individuals in the Ariake Sea. These results suggested that there is a high possibility that hatchery-released fish breed in the wild, however, negative genetic effects of the stock enhancement program on wild populations were not likely in the tiger puffer. As one of the factors, it is considered that mature hatchery-released population is composed of multiple groups and year classes and have close genetic characteristics to wild populations.

Annotated Bibliography of Key Works

(1) Araki H., Cooper B., and Blouin M. S., 2007: Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science*, **318**, 100-103.

Captive breeding is used to supplement populations of many species that are declining in the wild. The suitability of and long-term species survival from such programs remain largely untested, however. We measured lifetime reproductive success of the first two generations of steelhead trout that were reared in captivity and bred in the wild after they were released. By reconstructing a three-generation pedigree with microsatellite markers, we show that genetic effects of domestication reduce subsequent reproductive capabilities by ~ 40 % per captive-reared generation when fish are moved to natural environments. These results suggest that even a few generations of domestication may have negative effects on natural reproduction in the wild and that the repeated use of captive-reared parents to supplement wild populations should be carefully reconsidered.

(2) Hamasaki K., Toriya S., Shishidou H., Sugaya T., and Kitada S., 2010: Genetic effects of hatchery fish on wild populations in red sea bream *Pagrus major* (Perciformes, Sparidae) inferred from a partial sequence of mitochondrial DNA. *J. Fish Biol.*, **99**, 2123-2136.

Variation in the mitochondrial DNA transcriptional control region sequence was investigated in wild and hatchery-released red sea bream *Pagrus major* from Kagoshima Bay, where an extensive hatchery-release programme has been conducted for > 30 years. The programme has successfully augmented commercial catches in the bay (released juveniles have been produced from the captive broodstock, repeatedly used over multiple generations). Samples were also obtained from outside the bay, where limited stocking has occurred. Genetic diversity indices measured as number of haplotypes, haplotype richness, haplotype diversity and nucleotide diversity were lower in hatchery-released fish than in wild fish. Genetic differences in wild fish from the bay, especially in the inner bay, compared with fish from outside the bay were detected in terms of decreased genetic diversity indices and changed haplotype frequencies. Unbiased population pair-wise FST estimates based on an empirical Bayesian method, however, revealed low genetic differentiation between samples from the bay and its vicinity. Mixed stock identification analyses estimated the proportion of hatchery-released fish in wild populations in the inner and central bays at 39.0 and 8.7%, respectively, although the precision of the estimates was very low because of the small genetic differentiation between populations and relatively small sample sizes. Hence, the long-term extensive hatchery release programme has affected the genetic diversity of wild populations in the bay; however, the genetic effects were low and appeared to remain within the bay.

(3) Blanco Gonzalez E., Aritaki M., Sakurai S., and Taniguchi N., 2013: Inference of potential genetic risks associated with large-scale releases of red sea bream in Kanagawa prefecture, Japan based on nuclear and mitochondrial DNA analysis. *Mar. Biotechnol.*, **15**, 206-220.

Since 1978, millions of hatchery-reared red sea bream (*Pagrus major*) juveniles have been released in Sagami Bay and Tokyo Bay in Kanagawa Prefecture, Japan. The stock enhancement program has contributed to total catch; however, no information regarding the genetic interactions with wild counterparts is available. Here, we combined 15 microsatellite loci and mitochondrial D-loop sequencing to characterize the genetic resources of red sea bream in Sagami Bay and Tokyo Bay and to elucidate the potential harmful genetic effects associated with fish releases. Both types of markers evidenced higher levels of genetic diversity in wild samples (SB and TB) compared with offspring before stocking (H07 and H08) as well as a hatchery-released sample recaptured in Sagami Bay (HR). Microsatellite F_{ST} estimates and Bayesian clustering analysis found significant genetic differences among samples (F_{ST} = 0.013-0.054), except for the two wild samples (F_{ST} = 0.002) and HR vs. H07 (F_{ST} = 0.007). On the other hand, mitochondrial-based Φ_{ST} suggested haplotypic similarity between SB, H07, and HR. The low effective number of females contributing to the offspring over multiple generations may be responsible for the lack of haplotypic differentiation. Moreover, the putative hatchery origin to three fish (8 %) without deformity in the inter-nostril epidermis was inferred for the first time. Our results showed the usefulness of combining nuclear and mitochondrial markers to elucidate genetic interactions between hatchery-released and wild red sea bream and warned about potential harmful genetic effects should interbreeding takes place.

(4) Nakajima K., Kitada S., Habara Y., Sano S., Yokoyama E., Sugaya T., Iwamoto A., Kishino H., and Hamasaki K., 2014: Genetic effects of marine stock enhancement: a case study based on the highly piscivorous Japanese Spanish mackerel. *Can. J. Fish. Aquat. Sci.*, **71**, 301-314.

We used a before–after control–impact design to quantify the genetic effects of the large piscivorous Japanese Spanish mackerel (*Scomberomorus niphonius*) stock enhancement program on wild populations in the Seto Inland Sea. Samples of 1424 wild and 230 hatchery fish collected from 13 sites around Japan were genotyped using five microsatellite markers. A total of 758 wild and 103 hatchery fish were sequenced for the mitochondrial DNA D-loop region. The population structure of Japanese Spanish mackerel was panmictic around Japan. Hatchery fish had significantly lower genetic diversity indices than did wild fish. However, there was no significant change in any of the diversity indices in the Seto Inland Sea, despite the substantial genetic mixing proportion of hatchery-origin genes (7.8 % – 14.5 % from releases in 2001 and 2002), a conclusion supported by simulations. The estimated effective population size was surprisingly small (~ 430 – 970) but stable in the Seto Inland Sea compared with the large census size. A Ryman–Laikre effect was not likely in the Japanese Spanish mackerel.

3: Assessment of the ichthyotoxicity of harmful marine microalgae *Karenia* spp. using cultured gill cells from red sea bream (*Pagrus major*)

Nobuyuki OHKUBO[*1], Yuji TOMARU[*1], Haruo YAMGUCHI[*2], Setsuko SAKAMOTO[*1], and Kazuhiko MOCHIDA[*1]

[*1] National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
[*2] Faculty of Agriculture, Kochi University, Nankoku, Kochi 783-8502, Japan
E-mail: nobuyuki@affrc.go.jp

Abstract

The present study reports the development of a method to investigate ichthyotoxicity of harmful marine microalgae using cultured red sea bream (*Pagrus major*) gill cells. The cultured gill cells formed adherent 1–2 layers on the bottom of the culture plate, and could tolerate seawater exposure for 4 h without significant alteration in cell survival. The microalgae *Karenia mikimotoi, Karenia. papilionacea, K. papilionacea phylotype-I, Karenia digitate* and *Heterosigma akashiwo* were cultured, then directly exposed to gill cells. Live gill cell coverage after *K. mikimotoi, K. papilionacea phylotype-I,* and *K. digitate* exposure were significantly lower than in the cells exposed to a seawater-based medium SWM-3 and IMK (control cells; $P < 0.05$). Toxicity of *K. mikimotoi* cells was weakened when the cells were ruptured, and was almost inexistent when the algal cells were removed from the culture by filtration. Significant cytotoxicity was detected in the concentrated ruptured cells, although cytotoxicity was weakened in the concentrated of ruptured cells after freezing and thawing; whereas, cytotoxicity almost disappeared after heat treatment. In addition, examination of the distribution of toxic substances from the ruptured cells showed that cytotoxicity mainly occurred in the fraction with the resuspended

pellet after centrifugation at 3000 × g.

4: Asari clam predation by intertidal fishes: feeding habits of immature black porgy, *Acanthopagrus schlegelii* in Yamaguchi Bay, western Seto Inland Sea, Japan

Toshihiro SHIGETA*[1], Mutsumi TSUJINO*[1], Takeshi TOMIYAMA*[2], Yoichi SAKAI*[2], and Hidetoshi SAITO*[2]

*[1] National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*[2] Graduate School of Biosphere Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8528, Japan
E-mail: shigeta@fra.affrc.go.jp

Abstract

Black porgy, *Acanthopagrus schlegelii* (Family: *Sparidae*), is a commercially important fish in Japan. In 2015, commercial catches of the porgy in Japan and the Seto Inland Sea of western Japan were 3,181 metric tons and 1,508 metric tons, respectively. This species is known as a major predator of Asari clam, *Ruditapes philippinarum* in tidal flats. On the other hand, Asari clam is a commercially important species, too. Recently, the clam catches have decreased in Japan. Especially in the Seto Inland Sea, the catches have remarkably dropped to 137 metric tons in 2015 from 45,023 metric tons in 1985 (peak level). Several reports concerning protecting clam beds with netting suggest that predation is one of the most important factors for the survival of the clam. In order to restore Asari clam resource, it is necessary to clarify the habits of the porgy. In this study, we investigated the seasonal occurrence and feeding habits of immature-sized porgy (less than about 25 cm total length) in tidal flats from 2005 to 2017 in Yamaguchi Bay, western Seto Inland Sea. 102 individuals of the porgy (10.4-27.7 cm TL) were collected by rod-and-line fishing there. The monthly catch per unit effort (CPUE: number of fish caught/3 hours/person) of the porgy ranged 0 - 2.9. The CPUE rapidly increased in June. In July, it reached 2.9, the highest annual value, after which the CPUE maintained high values from August to November. From December values were low (0 - 0.4) again. These results indicate that immature *A. schlegelii* occurs seasonally in the tidal flats from June to November. Bases on the stomach contents of the porgy, bivalves such as Asian mussel, *Arcuatula senhousia*, Japanese razor clam, *Solen strictus* were the most important prey items in wet weight. Next, Japanese mud shrimp, *Upogebia* major was the second important one. These benthic animals were in common and are filter feeders on phytoplankton, benthic microalgae, and detritus. Immature-sized porgy preyed on juvenile Asari clams ranging from 2.8 to 18.0 mm shell length. The values of stable isotopes of δ^{13}C and δ^{15}N on black porgy showed -17.6 ～-16.0 ‰ and 16.2～17.7 ‰, respectively. In the Seto Inland Sea of Japan, resources of benthotrophic fish species, such as flatfishes and pufferfishes, which use the estuary in their early life history, have decreased remarkably. For recovery and regeneration of these critical resources, it is necessary to clarify the relationships between organisms and the estuarine ecosystem.

Annotated Bibliography of Key Works

(1) Shigeta T. and Usuki H., 2012: Predation on the short-neck clam *Ruditapes philippinarum* by intertidal fishes: a list of fish predators. *J. Fish. Techol.*, **5(1)**, 1-19. (in Japanese with English abstract)

Recently, commercial catches of the short-neck clam *Ruditapes philippinarum* have decreased in Japan. Especially in the Seto Inland Sea, western Japan, the clam catches have remarkably dropped. Several reports suggest that predation by fishes is one of the most important factors for the survival of the clam. In this review, we made a list of fish species that forage on the short-neck clam in the field. Twenty-three fishes ranging from *Myliobatidae* to *Tetraodontidae* (12 families) are listed in the world. Among them, 21 intertidal fishes (12 families) occur in Japan. It was clarified that five fishes, the Longheaded eagle ray *Aetobatus flagellum*, the Black porgy *Acanthopagrus schlegelii*, the Yellowfin seabream *A. latus*, the Kyuusen wrasse *Parajulis poecilepterus* and the Grass puffer *Takifugu niphobles*, foraged on whole adult-sized clam (> 20 mm shell length). At least, the siphon was cropped by eight fishes including the Stone flounder *Kareius bicoloratus*, the Marbled sole *Pseudopleuronectes yokohamae*, and the Japanese sillago *Sillago japonica*. Meanwhile, the Black porgy and the Kyuusen wrasse preyed on all parts except the foot of the clam. We are continuing to analyze details of the interaction between these intertidal fishes and the short-neck clam.

5: Evaluation of inexpensive Raspberry Pi-based time-lapse camera system for tidal flat ecosystem observation

Naoaki TEZUKA*[1] and Kazumasa OGURI*[2]

*[1] National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*[2] Japan Agency for Marine-Earth Science and Technology, Natsushima, Yokosuka, Kanagawa 237-0061, Japan
E-mail: tezukan9@affrc.go.jp

Abstract

In recent years, changes in the structure of coastal ecosystems, leading to a collapse of conventional fisheries, have been widely reported. Maintaining clam fisheries or aquaculture production in general has becoming increasingly difficult without adequate predator prevention measure, especially in the tidal flats of western Japan, indicating certain changes in the structure of the ecosystem. It is suggested that migratory fish species influence the benthic community structure through predation in the tidal flat ecosystem. However, inadequate information exists on the abundance or frequency of the appearance of migratory fish species in tidal flats; hence, its impacts on the benthic community are unclear. Observation using an underwater time-lapse camera system can be an effective approach to understanding the temporal change in the abundance of migratory fish species in tidal flats and their influence on the ecosystem. We have, therefore, developed and tested an inexpensive Raspberry Pi-based underwater time-lapse camera system to observe the tidal flat ecosystem processes. The Raspberry Pi is an inexpensive single-board computer that can be connected to a dedicated camera module. Our system consists of Raspberry Pi with a camera module, USB battery, time-lapse power control unit, and optional light emitting diode (LED) module and temperature sensor. The camera system uses the command line interface for operation setting, i.e., setting the initial wakeup time, repeat times, and the interval. It takes still and/or video images after wakeup, and then shuts down until the next scheduled wake-up time. We placed the entire system, excluding the LED module and temperature sensor, in an inexpensive underwater housing structure made with polyvinyl chloride (PVC) water pipe sockets and an acrylic window. The camera system successfully captured underwater time-lapse images during observations, except under low visibility conditions, or when biofouling occurs. However, certain improvements are required, which include improving the image quality under low-light conditions by increasing the brightness of the light module, widening the field of view of the image, and adding an anti-biofouling mechanism.

6: Development of Free-Ocean Real-Time Experimental System (FORTES) for in-situ CO_2 manipulation in eelgrass beds

Tatsuki TOKORO*[1,2], Masakazu HORI*[1], Tomohiro KUWAE*[2], Yuichi ISAKA*[3], Hyojin AHN*[3], and Masahiro NAKAOKA*[3]

*[1] National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*[2] Port and Airport Research Institute, Nagase, Yokosuka, Kanagawa 239-0826, Japan
*[3] Akkeshi Marine Station, Hokkaido University, Akkeshi, Hokkaido 088-1113, Japan
E-mail: ttokoro@affrc.go.jp

Abstract

Ocean acidification (OA) causes various effect on

coastal resources. For eelgrass beds, positive and negative effects are expected on different functional groups of biological communities. In addition, the acidification level in coastal ecosystems vary greatly due to the CO_2 consumption and production by marine plants and input of freshwater. To understand the actual influences of OA under such complicated conditions, in-situ field experiments for manipulating CO_2 are promising. FOCEs (Free ocean carbon experiments, Gattuso *et al*., 2014) have already been established in several marine habitats such as coral reefs and *Posidonia* seagrass beds. However, these systems have several problems such as changing in-site hydrodynamic conditions, the needs to electrical power to operate the system, and high installation cost. To overcome such difficulties, we have developed a newly CO_2 manipulating system on the site, named FORTES (Free-Ocean Real-Time Experimental System). The system allows control of the acidification level in the area of square meters of eelgrass beds by supplying a high concentration of CO_2-dissolved water under mostly opened condition. No electrical power is required because this system could be operated by the pressure and buoyancy of injected CO_2. The CO_2-dissolved water is always emitted to the experimental area from the upstream direction even when the current direction changes with tide and other factors. In the test trials of FORTES in eelgrass beds in Oki Island and Akkeshi lagoon in Japan, the acidification level expected in 2100 was reproduced successfully. Furthermore, this system enables the supply of water-soluble nutrients and the deterrent of invertebrate grazers along with the CO_2 for simultaneous control of nutrient levels and grazer densities. This orthogonal design allows the experiments to examine interacting effects of ocean acidification and other factors in the eelgrass bed community.

Annotated Bibliography of Key Works

(1) Gattuso J. P., Kirkwood W., Barry J. P., Cox E., Gazeau F., Hansson L., Hendriks I., Kline D. I., Mahacek P., Martin S., McElhany P., Peltzer E. T., Reeve J., Roberts D., Saderne V., Tait K., Widdicombe S., and Brewer P. G., 2014: Free-ocean CO_2 enrichment (FOCE) systems: present status and future developments. *Biogeosciences*, **11**, 4057-4075.

Free-ocean CO_2 enrichment (FOCE) systems are designed to assess the impact of ocean acidification on biological communities in situ for extended periods of time (weeks to months). They overcome some of the drawbacks of laboratory experiments and field observations by enabling (1) precise control of CO_2 enrichment by monitoring pH as an offset of ambient pH, (2) consideration of indirect effects such as those mediated through interspecific relationships and food webs, and (3) relatively long experiments with intact communities. Bringing perturbation experiments from the laboratory to the field is, however, extremely challenging. The main goal of this paper is to provide guidelines on the general design, engineering, and sensor options required to conduct FOCE experiments. Another goal is to introduce xFOCE, a community-led initiative to promote awareness, provide resources for in situ perturbation experiments, and build a user community. Present and existing FOCE systems are briefly described and examples of data collected presented. Future developments are also addressed as it is anticipated that the next generation of FOCE systems will include, in addition to pH, options for oxygen and/or temperature control. FOCE systems should become an important experimental approach for projecting the future response of marine ecosystems to environmental change.

7: A comparison of environmental and biological parameters at asari, *Ruditapes philippinarum*, fishing grounds in Japan for understanding the cause of recent catastrophic decrease of asari clam

Motoharu UCHIDA*1, Mutsumi TSUJINO*1, Naoaki TEZUKA*1, Toshihiro SHIGETA*1, Yoshitake TAKADA*2, Yuka ISHIHI*3, Satoshi WATANABE*3, Shuhei SAWAYAMA*4, Hiroaki KUROGI*4, and Kentaro NIWA*5

*1 National Research Institute of Fisheries and Environment of Inland Sea, FRA, 2-17-5 Maruishi, Hatsukaichi, Hiroshima 739-0452, Japan
*2 Japan Sea National Research Institute, FRA, 1-5939-

22, Suido-cho, Chuo, Niigata 951-8121, Japan
*3 National Research Institute of Aquaculture, FRA, 422-1 Nakatsuhamaura, Minamiise, Mie, 516-0193, Japan
*4 National Research Institute of Fisheries Science, Yokosuka Station, FRA, 6-31-1 Nagai Yokosuka, Kanagawa 238-0316, Japan
*5 National Research Institute of Fisheries Science, FRA, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan
E-mail: uchida@affrc.go.jp

Abstract

The catastrophic decrease of catch of the asari clam, *Ruditapes philippinarum*, has been observed for the last three decades in Japan's coastal waters. Many factors including overfishing, disease, habitat loss, competition with invasive species, global warming, and altered trophic cascade are suggested to be involved. However, major factor is still not well characterized to explain the widespread and long-term decrease of the catch. We conducted comprehensive comparison of environmental and biological characteristics among asari fishing grounds in Japan. Significant relationship was observed between water nutrient level (*i.e.*, total nitrogen and chlorophyll *a*) and the asari catch. Stable carbon isotope ratio of asari was found to be a useful indicator representing not only the nutrient level but also the asari catch per unit area. Significant relationship was also observed between the benthos biomass (macrobenthos, meiobentos, and nematodes) and the asari catch. All these observations suggest that recent catastrophic biomass decrease is occurring not only for asari but also for wide range of benthic organisms in Japan's coastal waters.

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