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

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

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**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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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

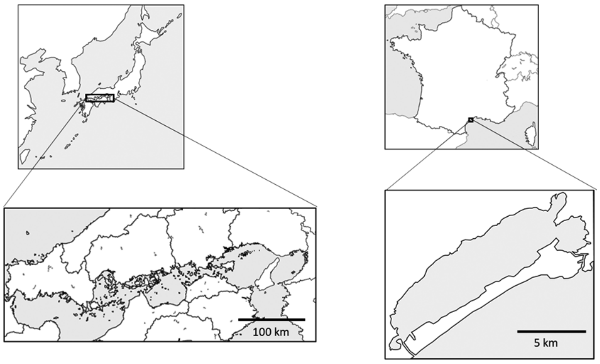

**Fig. 1.** Study sites, the Seto Inland Sea, Japan (left figure) and Thau Lagoon, France (right figure). These figures were revised from Hori *et al*. (2018).

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

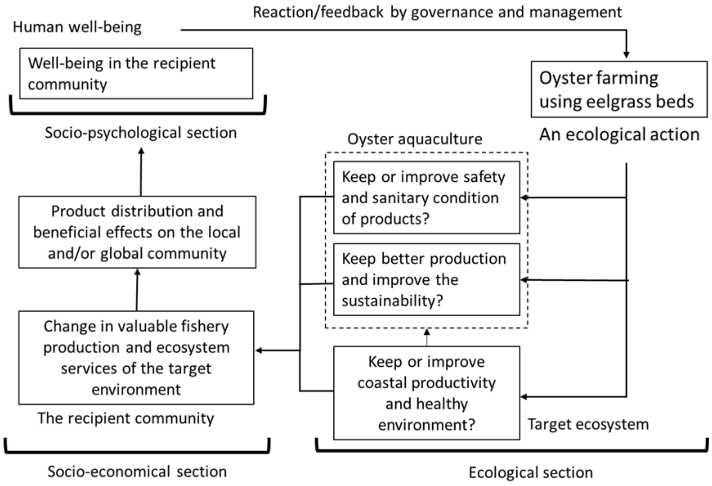

**Fig. 2.** The hypothetical pathways that the oyster-eelgrass interaction positively affect the recipient community via the change in ecosystem goods and services. This figure is revised from Hori *et al.* (2018).

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.

## 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.

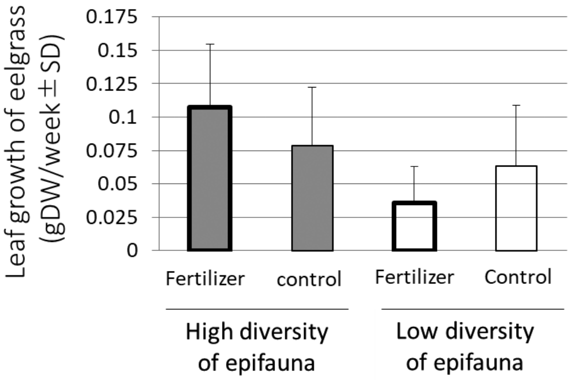

**Fig. 3.** The result of 2-way factorial experiment with grazer exclusion and fertilization in the Seto Inland Sea. The grazer exclusion significantly decreased epifaunal diversity and indirectly increased epiphyte biomass on eelgrass leaves, resulting in a significant difference in eelgrass leaf growth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

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

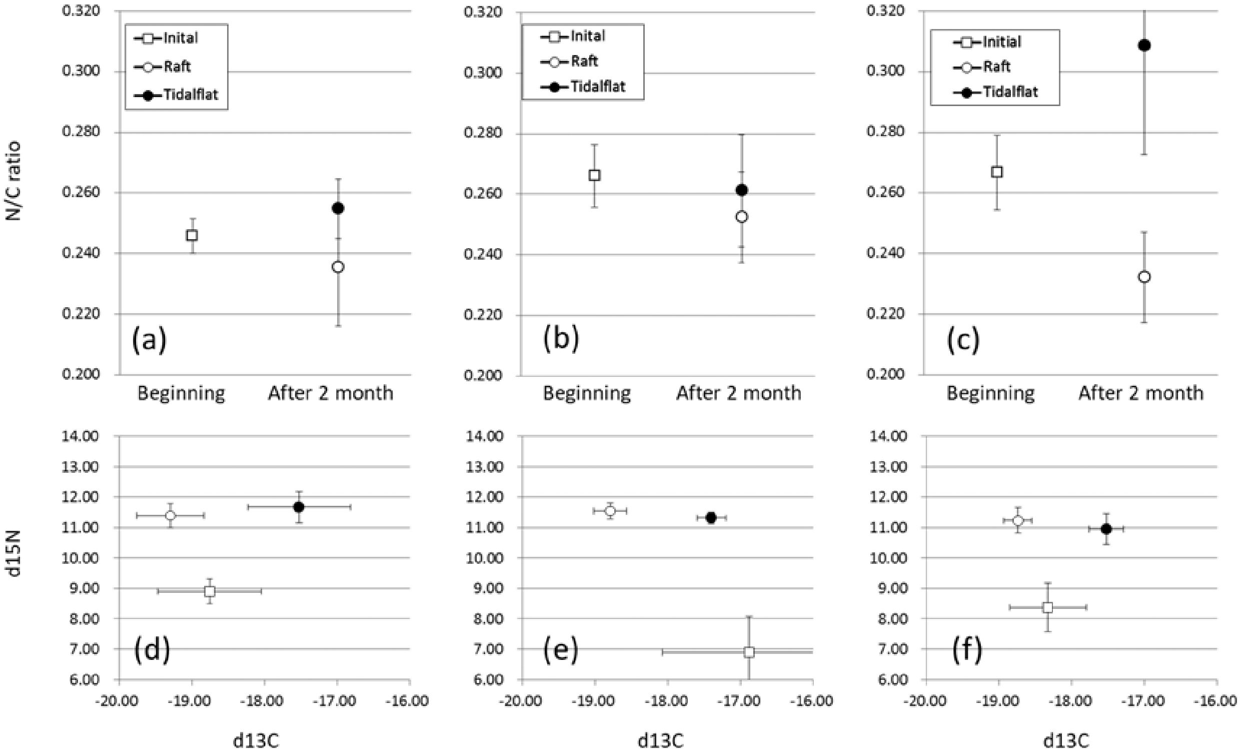

**Fig. 4.** The results of N/C ratio of (a) *Crassostrea gigas*, (b) *C. nippona*, and (c) *C. sikamea* and the result of the relationship between carbon and nitrogen stable isotope composition of (d) *C. gigas*, (e) *C. nippona*, and (f) *C. sikamea* at the beginning (initial) and the end of the experiment (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).

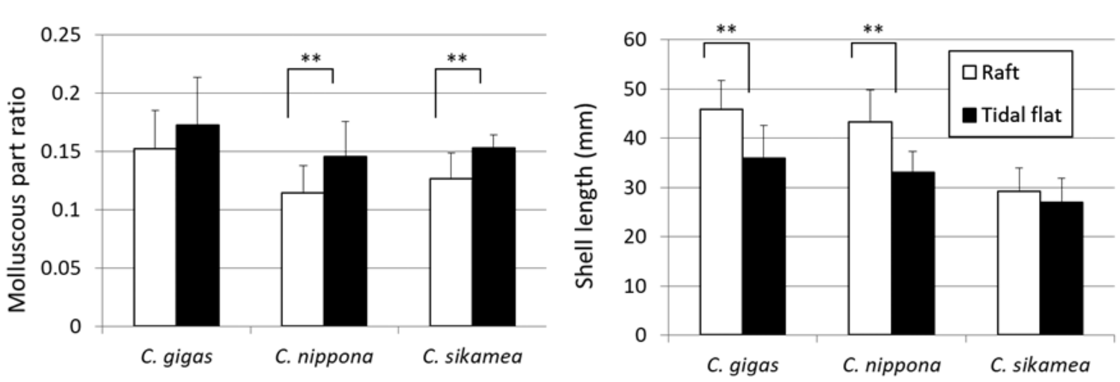

**Fig. 5.** The difference in the ratio of soft tissue weight (gDW) to total weight (gDW) of each oyster species (left figure) and longest part of shell length (right figure) between the spats cultivated on the tidal flat and those from the offshore raft. Significant p-values are represented by asterisks: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

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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.

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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.

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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.