Coastal Habitats
8. Oyster Bed Restoration

DEFINITION

Oysters are a type of bivalve shellfish that reside in most coastal regions in the continental United States. As ecosystem engineers, thousands of oysters form large reefs as they attach to a hard substrate or to other oysters (NRC n.d.). Oysters inhabit both salt and brackish waters in coastal areas, providing valuable shelter for other marine species. While oysters spend most of their life cycle attached to a shell, they begin their lives as free-floating larvae (NOAA 2022). Oysters are a cornerstone of coastal ecosystems and fisheries, providing structural protection to the coast as well as improving water quality (NOAA 2022). Additionally, oysters are a staple of the seafood industry, with domestic oyster sales valued at $284.9 million in 2018 (AgMRC 2022). Oyster reefs are on the decline, with 85% of historic global oyster reefs lost (Seavey et al. 2011). This is primarily because of overharvesting, nutrient pollution, and sedimentation (NOAA 2022). To reverse this decline, oyster reef restoration and conservation initiatives attempt to restore oyster populations by lessening harvesting pressure, reducing nutrient loads, and enhancing reef habitats. Common restoration techniques include placing cultch material, installing artificial reef structures, oyster seeding, and oyster aquaculture (Olander et al. 2020a).

TECHNICAL APPROACH

Oyster reef restoration projects seek to improve the conditions for oyster reef foundation by providing hard substrates for the oysters to latch onto and, in some cases, by adding oysters to the reef area. However, many external factors influence the health of oyster reefs, including algae blooms, nutrient pollution, sedimentation, and oil spills (Olander et al. 2020b). Addressing these external factors through community engagement and other nature-based solutions such as riparian buffers will make oyster reef restoration more successful.

1. **Substrate enhancement**: Substrate is placed on the bottom of a waterbody to provide a surface for oysters to attach to. The shape, material, and location of the substrate can vary; a technique should be selected based on its desired outcome, such as shoreline stabilization or increased oyster harvest (Olander et al. 2020a).
    - **Structurally simple:**
        - **Subtidal, intensively harvested:** To restore oyster habitat, cultch material (substrate) is placed along the bed of the waterbody (Figure 1). Oyster shells are recognized as the ideal hard structure for oyster substrate and are often procured through recycling programs with restaurants (Uddin et al. 2021). However, because oyster shells are scarce, alternative substrates are often used alone or mixed with shells. A variety of alternatives have been used, including porcelain, dredged shells, limestone, noncalcium stone, other shells

besides oyster shells, and concrete. Each substrate has varying ecological, chemical, and structural outcomes that should be weighed before beginning a project (Goelz et al. 2020). Once the cultch material has been collected, it is then placed along the bed of the subtidal zone.

- **Structurally complex:**
  - **Subtidal:** While structurally simple oyster reef restoration is cheap and easy to install, the loose cultch material can be buried by sediment or degraded by wave action (Olander et al. 2020c). Larger structures with a vertical component can serve as a starting point for oyster accumulation. Artificial reef structures can be used, including oyster balls, oyster pyramids, precast concrete structures, rocks, and structures made of limestone (Figure 2; VIMS 2023). Artificial reef structures have lower larval recruitment rates than natural reefs because larvae often have trouble detecting them via chemical cues released by other oysters. Oyster colonization of artificial reefs functions as a positive feedback loop. Once oysters have attached themselves to the artificial reef, then more oysters will be attracted to the reef (Walles et al. 2016).

Figure 8.1 Depositing shell material into the water to create an oyster reef

Photo courtesy US Army Corps of Engineers New York

- **Intensively harvested:** Intensively harvested artificial reefs are built primarily to reap the fisheries benefits as opposed to the water quality and shoreline protection benefits that oyster reefs provide. Intensively harvested, or *open*, reefs are generally much narrower and shorter than reefs closed to harvesting (Boulton et al. 2014).
- **Not intensively harvested:** Many restored oyster reefs are closed to intensive harvesting practices such as dredging or intensive tonging (Olander et al. 2020a). One of the advantages of not harvesting the oyster reef is that it provides a refuge for fish and crustaceans, which can then be harvested. Studies have shown that protecting an oyster reef yields a more economically valuable fish stock than if the reef was harvested for oysters instead (Grabowski and Peterson 2007).

Figure 8.2 Oyster castle artificial reef structure in the Delaware Bay

Photo courtesy US Fish and Wildlife Service

- **Intertidal:** Intertidal oyster reef restoration projects use the same structures (oyster balls, oyster pyramids, and others) as subtidal projects but are often paired with living shorelines to enhance shoreline protection. An important consideration for intertidal projects is that the artificial reef structures must be inundated at least 50% of the time to be suitable for oyster habitation. For projects that want to maximize wave and coastal flooding attenuation benefits, placing the structures in the intertidal zone is recommended (Morris et al. 2021). Intertidal reefs are not generally harvested for oysters, because oyster harvesting reduces the height of the reef, limiting the ability of the reef to attenuate waves (Wiberg et al. 2019). Thus, the benefits of oyster harvesting and wave attenuation are largely mutually exclusive and projects in the intertidal zone usually target the coastal protection benefits.
- **Oyster aquaculture**: Oysters raised in more intensively managed conditions for harvest is considered a nature-based solution because of the benefits it yields beyond its sale for consumption. Oyster aquaculture retains the water quality, coastal defense, and cultural benefits that natural oyster reefs provide (van der Schatte Olivier et al. 2020). Additionally, aquaculture reduces the demand for wild-caught oysters, allowing natural oyster reefs to regenerate. There are a variety of oyster aquaculture methods, including on-bottom, off-bottom, cage, and rack-and-bag culture. Methods vary widely based on the environmental conditions and cultural preferences of the region (Webster 2007).

2. **Oyster introduction:** Substrate placement can be followed by reef enhancement practices, such as oyster seeding or placing oysters in the reef area (Olander et al. 2020a). *Oyster seeding* refers to the process of raising juvenile oysters in a hatchery and placing them on a hard substrate to grow the reef. While seeding can provide a critical boost to reefs struggling with larval recruitment, it is expensive and has exhibited mixed results (Geraldi et al. 2013). Placing oysters in the reef area, often termed *stock enhancement*, is similar to oyster seeding except that the introduced oysters are adults instead of juveniles. Oysters are reared in "spawner sanctuaries" and then moved to the recipient reef, where they build reef structure and facilitate the natural recruitment of oyster larvae (Brumbaugh and Coen 2009).

Invasive species are a problem in oyster reefs, with invasive crabs and whelks (a group of carnivorous sea snails) causing trophic cascades that result in a decline of native oysters. Atlantic coast species are invasive on the Pacific coast, meaning that invasive species can easily integrate themselves into a similarly structured ecosystem (Kimbro et al. 2009). Oysters themselves are often vectors of invasive invertebrate species and algae, making it paramount for oyster restoration projects to be located within the natural range of the oyster species (David 2020).

OPERATIONS AND MAINTENANCE

After oyster bed restoration, ongoing invasive species removal is required. Crab traps and snail harvesting are the most effective ways to reduce populations of invasive species (NOAA 2023). In structurally simple projects, additional cultch material may need to be added if the oyster bed is not keeping up with the rate of sediment accretion and is at risk of being buried (Coen et al. 1999).

FACTORS INFLUENCING SITE SUITABILITY

- ✓ **Healthy native shellfish populations:** Healthy shellfish populations nearby indicate that the water quality and sediment concentration are good enough to host a successful oyster reef. If there are no oyster populations nearby, ribbed mussel populations can serve as a proxy for environmental health (VIMS 2023).
- ✓ **Water depth at least 1 ft at low tide**: Intertidal oyster reefs are subject to winter freezing, which will cause oysters to die off. Reefs in deeper water are less subject to being frozen (VIMS 2023).
- ✓ **Firm bottom:** A firm bottom gives a hard substrate for oysters to latch onto. It also provides a stable support for artificial reef structures to be placed on and reduces the risk of the reef being buried under sediment (VIMS 2023).
- ✓ **Accessible:** If a site cannot be reached by boat or overland routes, then it will be difficult to conduct monitoring and transport equipment needed for the restoration project. Artificial reef structures are very heavy and cannot be transported by hand (VIMS 2023).
- ✓ **Water temperature between 68–90°F:** Adult oysters can survive across a broader range of temperatures (30–120°F) but prefer more moderate temperatures. Larval oysters need consistent temperatures to survive (MCNY n.d.).
- ✗ **Salinity below 5 ppt:** Oysters thrive in areas with moderate salinity but cannot tolerate areas with low salinity or freshwater (VIMS 2023).
- ✗ **Soft mud:** Soft mud promotes the shifting and destabilization of artificial reef structures, disrupting the recruitment of oyster larvae. Furthermore, oyster reefs are more likely to be covered in sediment in areas with soft mud (VIMS 2023).
- ✗ **Disease:** As sessile organisms, oysters are especially prone to contracting pathogens. If nearby reefs have suffered from disease, then the restoration project should be sited elsewhere (Theuerkauf and Lipcius 2016).
- ✗ **Water deeper than 26 ft:** Deeper water is usually more acidic, and oysters cannot survive in highly acidic conditions (MCNY n.d.). This is increasingly becoming a prominent issue as climate change fuels ocean acidification (Ben-Achour 2022).
- ✗ **Poor water flow:** Oysters need good water flow to bring them the nutrients they need to survive. Areas adjacent to dredged channels often have good water flow, while wetlands do not (Boulton et al. 2014).

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
A Step-By-Step Guide for Grassroots to Reef Rehabilitation	Guidebook	2008	The Reef Ball Foundation	Global	Covering both coral and oyster reefs, this guide details the use of artificial reef substrates in restoration. The authors cover permitting, site suitability, developing a timeline, and assessing site damage.	✓	✓	✓	—
Oyster Restoration	Website	2018	National Oceanic and Atmospheric Administration (NOAA)	National	NOAA provides a plethora of information relating to oyster restoration, including case studies, ideal substrates, and the use of remote sensing. Also provided is information about sustainable aquaculture and oyster gardening.	✓	—	✓	✓
Oyster Habitat Restoration Monitoring and Assessment Handbook	Guidebook	2014	NOAA, The Nature Conservancy (TNC), Florida Atlantic University, University of Southern Alabama	National	Focusing on monitoring considerations, this guide helps projects match their restoration goals with the appropriate monitoring metrics. In addition to providing common monitoring variables, the authors also discuss site selection and global oyster decline.	—	✓	✓	—
Oyster Model Inventory: Identifying Critical Data and Monitoring Approaches to Support Restoration of Oyster Reefs in Coastal US Gulf of Mexico Waters	Guidebook	2021	US Geological Survey	Gulf of Mexico but most of the information is more broadly applicable	There are many models that help determine if the environmental conditions are appropriate for oyster reef restoration. This guide helps managers parse through these models while also examining environmental drivers that influence oyster health.	—	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Strategic Framework for Oyster Restoration Activities	Guidebook	2017	*Deepwater Horizon* Oil Spill Natural Resource Damage Assessment Trustees	Gulf of Mexico	This guide covers all stages of oyster restoration projects, leading managers through the process from planning to monitoring. The authors also cover the ecological connectivity of oyster reefs, threats to oyster populations and funding sources.	✓	✓	✓	✓
GEMS Phase I Report: Oyster Reef Restoration	Report	2020	Nicholas Institute for Energy, Environment & Sustainability; The Harte Research Institute; TNC	Gulf of Mexico	This guide helps link specific management actions to desired ecosystem services, as management choices have a large impact on which benefits a project will yield. Additional topics covered include oyster reef restoration techniques, socioeconomic outcomes of restoration and multiple case studies.	✓	—	—	✓
Restoration by Design: Great Bay Estuary, New Hampshire	Guidebook	2021	TNC	Atlantic Coast	Following the course of one specific project, the authors illustrate techniques that can be used for oyster restoration. The book delves into bathymetric surveys, community engagement, and larval recruitment.	✓	✓	✓	✓
Oyster Reef Resiliency Design Guide	Guidebook	N/A	Texas General Land Office	Gulf Coast but most of the information is more broadly applicable	This guide gives a helpful overview of the major components of oyster restoration. Filled with easy-to-read diagrams and charts, the authors help bridge the gap between engineering designs and overall project goals.	✓	—	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Oyster bed restoration can be an alternative to several gray infrastructure approaches that reduce the effects of shoreline erosion and coastal flooding: bulkheads, riprap/revetments, seawalls, groins, and artificial breakwaters. The ability of an oyster bed restoration project to replace or supplement one of these gray infrastructure types depends strongly on the project's location and whether it is designed to create the necessary outcomes. Certain environmental conditions may require gray infrastructure rather than oyster bed restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of oyster bed restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Reduced flooding:** Oyster reefs are dynamic, three-dimensional coastal defense structures that are highly effective at attenuating waves and preventing coastal flooding. Oyster reefs reduce the amount of wave energy that impacts the shore, preventing water from traveling further inland. Oyster reefs can work in tandem with gray infrastructure such as dikes, lowering wave height so that it will not overtop the dike (Borsje et al. 2011).
- **Sea level rise adaptation and resilience:** Oyster reef restoration promotes reef accretion, allowing the reef to grow vertically as sea level rises. As reefs recruit more oysters, the amount of skeletal shell material and biodeposits increase as well. Pores in the reef structure capture sediment, facilitating sediment accretion along the coast (Rodriguez et al. 2014).
- **Storm protection:** Oyster reefs are resilient to severe storms as their strong structure can withstand powerful waves. Reefs mitigate land loss as a result of severe storms because of their ability to hold sediment in place. Oyster reefs built on hard substrates such as reef balls are better able to withstand storms, as the concrete can serve as a storm surge barrier (Walles et al. 2016).

Social and Economic

- **Resilient fisheries:** While protected oyster reefs do not allow large shellfish harvests, they can still support recreational oyster harvesting such as low-intensity tonging or hand collection (Olander et al. 2020a). Closed reefs help restore finfish stocks, as oyster reefs provide finfish with increased shelter from predators and food sources (Gilby et al. 2018). Restored oyster reefs that are open to intensive harvesting fuel oyster fisheries, which can be an economic engine for communities if harvesting occurs at sustainable levels (Breitburg et al. 2000).
- **Reduced erosion:** While degraded and overharvested oyster reefs can erode, oyster reef restoration facilitates accretion. The structurally complex nature of oyster reefs traps sediments, capturing the substrate needed to maintain land. Oyster reefs also

serve as a physical barrier shielding the coast from the direct impact of waves, reducing tidal erosion. This is especially true for intertidal restoration projects as the erosion reduction benefits become greater the closer the oyster reef is to the shore (La Peyre et al. 2015).

- **Mental health and well-being:** Oyster reef restoration improves the quality of green space, boosting mental health and psychological well-being.
- **Property and infrastructure protection:** Many coastal roadways and other vital infrastructure experience rapid rates of erosion. Oyster reefs help defend these utilities by reducing erosion rates, lessening the impact and associated rebuild costs after storms (Olander et al. 2020a). This is especially important given that many coastal communities are served by only a singular access point.
- **Jobs:** Workers will need to be hired to perform the restoration activities, boosting the local economy.
- **Cultural values:** Oysters have a profound influence on culture, with fashion, art, and architecture all inspired by oyster reefs. Indigenous communities use oysters in art and to make tools, connecting people to the environment (Thomas et al. 2022).
- **Food security:** Many communities rely on subsidence fishing for local oysters and finfish as a major source of protein. Additionally, oyster aquaculture is a source of sustainable protein that is resilient to climate change (Azra et al. 2022).

Ecological

- **Improved water quality:** Oyster reefs are highly effective at filtering water, with an adult oyster filtering as much as 50 gal of water each day (CBF 2007). Oysters get nutrition by extracting food from the water. During this process, oysters capture excess pollutants, nutrients, and sediments, significantly improving water quality. Water quality benefits are dependent on the salinity, sedimentation rates, and dissolved oxygen levels around the reef, with a healthy reef able to filter more water (La Peyre et al. 2014).
  - **Decreased nitrogen concentrations:** Oyster reefs help facilitate denitrification, reducing nutrient pollution in the surrounding water. Oysters serve as a carbon source for the denitrifying bacteria, mediating the denitrification process. As nitrogen concentrations increase, so does the rate of denitrification, suggesting that it is difficult to saturate oyster reefs as a nitrogen sink (Smyth et al. 2015).
  - **Lower water turbidity:** When filtering water, oyster reefs absorb suspended sediments, lowering turbidity. Additionally, the complex structure of oyster reefs traps sediments, taking them out of the water stream (Sharma et al. 2016).
- **Enhanced biodiversity:** Oyster restoration projects have been successful in bringing back biodiversity, providing habitat and food for finfish, birds, and invertebrates. However, restored oyster reefs do not often have equivalent levels of biodiversity as undistributed reefs, highlighting the importance of oyster conservation (Hemraj et al. 2022).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the nature-based solutions strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about barriers specific to oyster reef restoration are included here.

- **Expense**
- **Capacity**
- **Public opinion**
- **Conflict with other land uses**
- **Regulation**
- **Lack of effectiveness data**

Economic

- **Overharvesting:** Many oyster reef restoration projects are undertaken primarily to replenish oyster stocks, providing economic opportunities to local communities. However, if oysters are harvested at rates faster than they can reproduce, then the oyster reef will start to erode. Intensive tonging and dredging destroy the height and width of oyster reefs. This drives further oyster decline as oysters grow faster and bigger when they are higher on reef structures (NOAA 2022).
- **Channel dredging:** Dredging to widen and deepen shipping lanes has a negative impact on nearby oyster reefs. While oyster reefs can absorb sediment, large quantities of sediment suspended by dredging can cause a reduction in filtering efficiency, reef burial via sediment deposition, and disturbance of hard substrates that oysters need (Wilber and Clarke 2010).
- **Temporary fisheries closure:** Even if overharvesting is not an issue, oyster harvesting is generally prohibited for up to two years after the restoration work has ended. This allows the reef time to enhance larval recruitment and get established (TPWD 2022). While this may harm some subsistence fishers, it is necessary to promote a successful restoration project.

Community

- **Human health impacts:** Disease is a major threat to the oyster aquaculture industry, with pathogens completely destroying oyster reefs. Furthermore, oyster diseases are difficult to predict and controlling them is difficult given the ability of pathogens to be transmitted over long distances in marine environments. Many factors play a role in oyster disease, including temperature, salinity, pH, the presence of disease vectors like phytoplankton, and the oyster microbiome. Hotter water temperatures help transmit pathogens, a critical concern given the impacts of climate change (King et al. 2019). Eating raw oysters that carry *Vibrio* bacteria can cause severe illness, with some vibriosis infections being fatal. This can be avoided by thoroughly cooking oysters before consuming them (CDC 2021).

- **Pollution:** Oysters are especially prone to aquatic pollution because of their nature as filter feeders. Nutrient pollution, toxins, and microplastics in the water are often ingested by oysters, increasing oyster mortality, and resulting in bioaccumulation further up the food chain (Scircle et al. 2020).
- **Coastal development:** Increases in coastal development drive land reclamation and dredging projects, which disturb oyster reef habitat. Additionally, urban land cover alters the sedimentation processes that allow coral reefs to accrete (Beck et al. 2009). Effluent from wastewater treatment plants also harms oysters, resulting in closures for oyster harvesting (EPA 2021).

Ecological

- **Ocean acidification:** Ocean acidification, which is caused by increased carbon dioxide emissions, reduces the availability of calcium carbonate in the water. This is an impediment to oyster reef creation as oysters need calcium carbonate to build their shells. Ocean acidification results in decreased calcification rates and oyster size and increased oyster mortality and developmental issues (Lemasson et al. 2017).
- **Surges of low salinity:** Major precipitation events, such as hurricanes, result in coastal flooding and a subsequent release of freshwater into brackish and salty coastal waters. Oysters cannot tolerate extremely low salinity conditions, resulting in mass oyster die-offs after storms (Du et al. 2021).
- **Harmful algae blooms:** Macroalgae thrive off elevated concentrations of nitrogen and phosphorus caused by nutrient pollution. This results in hypoxic concentrations and eutrophication, which causes an increase in sedimentation, burying oyster reefs (Ansell et al. 1998). Algae blooms produce toxins that accumulate in oysters, which result in mass die-offs (Jepsen 2020).

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
New York Billion Oyster Project	New York City Harbor, NY	Billion Oyster Project, New York Harbor School	Oyster cages, placing cultch material, oyster shell recycling, building structurally complex reefs	16	~65 million	9 years (ongoing)	Throughout New York's five boroughs, the Billion Oyster Project is working on 15 oyster restoration projects. Most of the projects use structurally simple substrate enhancement via placement of recycled oyster shells. Other projects have used structurally complex reefs as a part of living breakwaters.	Sea level rise, coastal flooding, severe storms	To minimize labor costs and enhance environmental education, the project has partnered with New York City Public Schools to have students volunteer at restoration sites.
Louisiana Oyster Cultch Project	Louisiana Coast	NOAA, Louisiana Natural Resources Trustees, Louisiana Department of Wildlife and Fisheries	Placing cultch material	1,421	N/A	2 years	As a part of the restoration efforts in the wake of the Deepwater Horizon oil spill, contractors placed cultch material (limestone and concrete) in six different sites across Louisiana.	No	Monitoring showed a substantial increase in oyster recruitment. However, these gains were centered around a few locations despite the same technique being used across the state.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Little Choptank River Oyster Restoration Project	Little Choptank River, MD	NOAA, US Army Corps of Engineers (USACE), Maryland Department of Natural Resources, University of Maryland, Chesapeake Bay Program	Oyster seeding, placing cultch material	358	28.6 million	5 years	Workers reared more than 1.78 billion seed juvenile oysters in setting tanks before releasing them into the river. Stone was used as a cultch material to help enhance the substrate.	Sea level rise, coastal flooding, severe storms	The COVID-19 pandemic required managers to be flexible as they tried to keep the project on schedule.
Half Moon Reef Oyster Restoration Project	Matagorda Bay, TX	TNC, Texas General Land Office, **US Fish and Wildlife Service,** USACE, Texas A&M University	Constructing a structurally complex reef	54	5 million	2 years	Contractors installed 32 rows of oyster-encrusted rocks that rose 3 ft from the water's bed, providing structural complexity.	Coastal flooding, severe storms	The project was a success, with oyster size increasing 551% in the three years after the project was completed.
Olympia Oyster Restoration Project	Olympia, WA	Swinomish Indian Tribal Community, US Navy, Washington Department of Fish and Wildlife	Placing cultch material, oyster seeding	N/A	1 million	9 years	Volunteers placed cultch and oyster larvae across a tidal channel in the Swinomish Reservation. In areas with high predation, oysters were placed in mesh bags for protection.	No	To avoid exposing oyster larvae to the air, damp rags were placed over the cultch containing the larvae as it was transferred from the nursey to the restoration site.

Bolding indicates DOI affiliates.

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Acknowledgments

The Department of the Interior's Nature-Based Solutions Working Group provided input and feedback on the DOI Nature-Based Solutions Roadmap throughout its development. This work was supported by the US Geological Survey National Climate Adaptation Science Center.

Citation

Warnell, K., S. Mason, A. Siegle, M. Merritt, and L. Olander. 2023. *Department of the Interior Nature-Based Solutions Roadmap*. NI R 23-06. Durham, NC: Nicholas Institute for Energy, Environment & Sustainability, Duke University. https://nicholasinstitute.duke.edu/publications/department-interior-nature-based-solutions-roadmap.

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