JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(9), 133–155
https://doi.org/10.12911/22998993/190642
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Received: 2024.05.23
Accepted: 2024.07.21
Published: 2024.08.01

The Benefits of Biofouling – Promoting the Growth of Benthic Organisms to Enhance Ecosystem Services

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ABSTRACT

For the marine industry biofouling has a negative reputation. On ship hulls, the accumulation of these unwanted plants and animals can lead to increased drag, fuel consumption, and greenhouse gas emissions. Offshore platforms are also subject to biofouling which can result in corrosion and hydrodynamic loading, thus shortening their lifespan. While the harmful impacts of biofouling are commonly reported throughout the literature, biofouling can also benefit both aquatic and human populations. Common biofouling organisms act as natural filtration systems, thus improving water quality. Many of the same flora and fauna serve as a food source, and structures could be designed to lessen the impacts of fouling on hydrodynamic forces. In addition, microfouling species commonly found in biofilms have the potential to be harnessed as biofuel sources and can be a component of the carbon cycle. The following review discusses the benefits of biofouling and why ecological engineering initiatives may aid in ecosystem restoration versus the use of antifouling techniques for preventative growth.

Keywords: biofouling, filtration, biofuels, carbon sequestration, ecological engineering.

INTRODUCTION

The world population continues to grow, and with it, the expansion of marine infrastructure into coastal and offshore regions, a concept referred to as "ocean sprawl" [Firth et al., 2016]. These structures may include oil platforms, aquaculture gear, artificial reefs, shipwrecks, and coastal urbanization, which is not limited to seawalls, floating docks, etc. The addition of these structures result in ecological and environmental changes, including disruption in ecological connectivity, changes in biodiversity, and eutrophication [Duarte 2014; Bishop et al., 2017]. Previous reviews focus on the effects of offshore structures on traditional macrofauna (i.e., sea turtle, dolphins, manatees, sharks, etc.), but neglect to discuss the implications of epibenthic communities and their services. With the increased ocean and coastal development, these substrates provide additional surface area for the recruitment and settlement of benthic plants and animals, known as biofouling. Although often viewed as problematic, biofouling can provide various functions that are beneficial to both aquatic and human populations such as: natural filtration, food for both aquatic and terrestrial organisms, and assist in carbon sequestration. The methods by which biofouling is managed is therefore important [Swain, 2017] and throughout this review we will discuss in more detail the benefits of biofouling, emphasizing the importance of promoting organism recruitment along with increasing ocean development, as opposed to eliminating or preventing the growth.

What is biofouling?

Marine biofouling is the unwanted settlement of plants and animals on submerged surfaces. Typically, biofouling starts off with a biofilm or slime layer comprised of microorganisms [Flemming and Wingender 2010; Lejars et al., 2012], such as bacteria and microalgae (i.e. diatoms), along with supplemental organisms including micro fungi, heterotrophic flagellates, and sessile ciliates [Flemming et al., 2009; Salta et al., 2013]. Once a biofilm layer has established, higher organisms known as macrofouling, will begin to colonize the surface. These organisms can be grouped either as soft or hard fouling. Soft fouling is characterized by their non-calcareous outer structures allowing them to alter shape under flow. Soft fouling includes algae, tunicates, sponges, and sea anemones. In contrast, hard fouling has either a calcareous or keratin external structure, making them rigid and able to maintain their body shape under flow conditions. Hard fouling organisms include barnacles, molluscs, and calcareous tubeworms [Coutts and Dodgshun 2007; Hunsucker et al. 2016]. While biofouling is often thought of as a multi-stage process, the steps can also occur in parallel with some steps not occurring at all [Qian et al., 2007; Lejars et al., 2012].

Consequences of biofouling

The attachment of both microorganisms and macrofouling organisms can be problematic for the shipping industry and offshore structures (e.g. oil platforms and wind farms) due to their functional and economic impact. When biofouling is present, this adds weight increasing drag and fuel consumption for marine vessels [Hunsucker et al. 2016]. For ship hulls, a thin biofilm layer can increase the resistance of a ship's movement through the water by 11% and additional macrofouling pressure can cause resistance up to 80% for Frigates [Schultz 2007] with slower commerce ships seeing larger penalties. Furthermore, heavy slime on ship hulls can cause fuel consumption to rise approximately 10.3% which equates to an estimated cost of $1.2 million per ship (estimates based on Arleigh Burke class destroyers - DDG-51) per year [Schultz et al., 2011]. Aquaculture systems are also suspectable to biofouling with main concerns including the restriction of water exchange, cage deformation, the biofouling organisms severing as possible hosts for viruses [Fitridge et al., 2012]. For offshore structures, biofouling leads to an increase in weight and diameter, as well as altering the water flow around an object. This contributes to the hydrodynamic loading of a structure [Jusoh and Wolfram 1996]. The added weight accelerates fatigue of the structure. The accumulation of fouling on structures can obstruct inspections making monitoring more difficult to determine the status and therefore delaying intervention [Yan and Yan 2003; Maduka et al., 2023]. Moreover, corrosion via microbial organisms tends to be a large contributor to fatigue of offshore structures and often speeding up deterioration. Corrosion can lead to cracks which allow leaks, weakening the foundation. For offshore infrastructures, visual inspections, evaluating weight loss, acoustic emission testing, and modelling are important in determining the wear due to organismal presence. This data can determine the proper protocol (e.g. using different alloy elements, coatings, cathodic protection, linings, and metal cladding) for preventing further damage.

Biofouling prevention

Due to the problems associated with biofouling, methods (chemical, electrical, radiation, mechanical) haven been developed for removal and prevention. However, these methods can be detrimental to both local and global ecosystems [Piola et al., 2009; Coutts et al., 2010; Woods et al, 2012]. The most common form of biofouling prevention is the use of marine coatings (i.e., specialized paints for aquatic environments). Antifouling coatings contain biocides that prevent the settlement of biofouling organisms, whereas fouling release coatings reduce the attachment strength of organisms making them susceptible to removal under hydrodynamic stress [Swain 1999; Whomersley and Picken 2003; Lejars et al., 2012]. The infamous tributyltin self-polishing copolymer paint (TBT) was the most successful antifouling paint produced, covering 70% of the world's fleets [Yebra et al., 2004]. However, the chemicals within TBT had several adverse effects on the environment causing the thinning of oyster shells and the alterations in developmental sex organs for *Nucella* sp. [Yebra et al., 2004]. Since, the International Maritime Organization (IMO) banned the use of TBT coatings, companies have been trying to develop TBT-free paints that perform just as well as the latter. Copper based coatings are now one of the most common antifouling coatings. While antifouling coatings have evolved to an extent, new issues have arisen such as nutrient overloading. In a study by Srinivasan and Swain [2007], copper release rates in two different marinas (Port Canaveral, Florida and the Indian River Lagoon, Florida) averaged 1.4 tons×yr^{-1} and 3.8 tons×yr^{-1} respectively. However, release can vary based on environmental conditions [Lagerström et al., 2020]. For example, in San Diego, California, the mean value of copper released from Naval vessels were 3.8 up×cm^{-1}·day^{-1} [Valkris et al., 2003] whereas in the Dubrovnik Port, Croatia averaged 344.7 g×17 hr^{-1} stay [Carić et al., 2016]. With close to 350 cruise ships [Florida-Caribbean Cruise Association, 2019], 6115 container ships [United States Department of Agriculture, 2024], millions of recreational boats, and 6000 offshore structures [Bull and Love 2019] these numbers are only a fraction of the potential copper release rates. Other consequences of metal loading include biocide tolerance [Piola et al., 2009]. With the wide use of copper based coatings, many biofouling organisms are beginning to demonstrate tolerance such as bryozoans [Piola and Johnson 2006] and barnacles [Hunsucker et al., 2019].

As mentioned, other techniques involve chemicals, radiation, and mechanical treatments, but each lack consideration for non-target organisms and the surrounding environment. Chlorine has been the most common chemical used for disinfecting drinking water and cooling intake pipes due to its inexpensive nature. However, chlorination can affect surrounding biofouling organisms such as mussels and barnacles, which are capable of water filtration. Chlorination has been observed to decrease barnacle larvae survival in a study conducted by Venkatnarayanan et al. [2016]. Studies focused on the direct effects of ultraviolet (UV)-A, -B, and -C, demonstrate the harmful effects on target species but have not identified how surrounding organisms are affected. UV-B in marine environments cause reduced productivity in phytoplankton [Santas et al., 1998; Wulff et al., 2008; Finch and Stubblefield 2016], yet UV-C radiation has a higher potency. While UV-C is completely absorbed by the stratospheric ozone layer it can be supplied via an external source, that causes lesions in the DNA that cannot be repaired leading to cell lysis and furthermore death of the subject [Bak et al., 2009; Cooke 2010; Salters and Piola 2017]. Less detrimental biofouling methods include mechanical cleaning, such as power washing, scraping, and grooming (i.e., a gentle habitual cleaning practice), [Tribou and Swain 2010; Hearin et al., 2015]. But these also have the potential to release organisms [Woods et al., 2012], pathogens [Georgiades et al., 2021], and microplastics [Tamburri et al., 2022] into the water column and to new environments [Scianni et al., 2023].

A study in Sweden, Bergman and Ziegler [2019], observed the environmental impacts of mechanical cleaning (like a car wash) and hull covers (that cover the boat while it's in the marina limiting the oxygen and light supply to the growth resulting in death) as alternatives to antifouling coatings. They found that no matter the percentage of copper (7% vs 13%), emissions rose in the marina, and were amplified when the hull was cleaned. A third of the total emissions were found in the soil. Although, for boats with non-toxic coatings (epoxy) hull cleaning and covering were great when it came to reducing toxic emissions, but hull covers proved to be the best. While negligible compared to coatings, emissions were still present from production and materials used for each [Bergman and Ziegler 2019]. The further concern of in-water cleaning is this can accelerate the coatings release rates. When grooming ROVs were used in synergy with antifouling coatings, release rates of zinc were 43907.83 ug×L^{-1} and copper 818.54 ug×L^{-1} [Shin et al., 2023]. This release of zinc and copper resulted in higher mortality rates and morphological defects in reared olive flounder embryos [Shin et al., 2023]. With the success in biofouling prevention, it appears that consequences tend to arise too, begging the question, to what extent do we consider biofouling good?

BENEFITS OF BIOFOULING

Ocean sprawl and benthic communities

Artificial surfaces are known to colonize quicky and can harbour more exotic/invasive species than natural substrates. For example, exotic mollusc species (*Perforatus perfortus* and *Mytillus galloprovincialis*), micro-grazers, and filter feeders were all found to favour seawalls more than natural rocky outcroppings in Spain [Ortega-Jiménez et al., 2021]. These artificial surfaces can serve as stepping stones between locations, potentially altering the ecosystem, biodiversity, and ecological connectivity [Schulze et al., 2020]. Alterations to the ecosystem can be advantageous by housing threatened species, providing a reef habitat, aid in increasing fish populations, and provides a refuge for species which soft sediments persist. In fact, Spielmann et al., [2023] found that decommissioning offshore structures results in losing hard fouling and unique species. Though, this may not be the case for all situations.

Figure 1. A depiction of a biofouling gradient on a monopile. Diversity of the biofouling community decreases with depth. Algae dominants at the air/water interface, hard fouling is abundance at midpoint regions, with biofilm and sometimes hydroids typifying the community close to the seafloor

In the Chesapeake Bay and Mediterranean Sea, jellyfish polyps have been seen attached to surfaces such as dock pilings in densities exceeding 10,000 individual polyps × m^{-2} [Duarte et al., 2013]. These artificial surfaces provide protection, shade, and allow for rapid colonization, which is the suspected add in the formation of the jellyfish blooms. Unfortunately, many near shore structures may cause problems for the local population, but these offshore platforms can be beneficial for the ecosystem.

Offshore platforms tend to be more diverse than natural substrates and can house unique species. For example, pilings in the Sydney Harbor were described to have a greater a biomass than natural rocky shores, with 5–9 taxa that were exclusively found on pilings [Mayer-Pinto et al., 2018]. These structures can be beneficial for locations that contain soft sediments which lacks a substrate for biofouling to attach. The introduction of artificial structures is typically thought of as bad, because it puts native species at risk. Nevertheless, the concept of invasive species dispersion over long distances has not been fully investigated, and this translocation can vary by species, water flow, and proximity. Off the shore of California, the invasive bryozoan *Wateripora* spp. has been observed on rocky reefs, artificial coastal habitats, and offshore oil and gas platforms and is thought to be spreading via these platforms [Page et al., 2019]. When modelled it was found that larva have limited dispersal and settle out closely (4–5 km) to their release sites showing limited evidence that these rigs act as stepping stones for dispersal [Page et al., 2019].

Barriers and fragmentation become a concern with ocean sprawl. Typically, these structures are thought to impede water flow and genetic flow, but anthropogenic substrates can also act as a corridor for pelagic larvae that may be lost. When modelling the dispersal of pelagic larvae of barnacles and gastropods, offshore habitats increased the number of larvae in the water column increasing the success of settlement and metamorphosis [Adams et al., 2014]. This concept can even be extended out to threatened or endangered species. Using a particle tracking software coupled with larval behaviour of the coral species *Lophelia pertusa*, Henry et al. [2018] identified that oil and gas platforms can be a significant conservation device for protected species because they can form highly interconnected networks for coral ecosystems. While connectivity is greater when these platforms are closer together, it demonstrates how corals can travel to untouched areas and be a supply to degraded zones.

While biofouling can be problematic, there are certain situations in which it should be promoted. Most of the biofouling literature discusses the consequences of biofouling and antifouling / prevention strategies; the benefits have yet to be consolidated or truly highlighted. This review will focus on the benefits of allowing biofouling to accrue on surfaces such as dock pilings, sea walls, and offshore infrastructure. Allowing for this increased growth will benefit inshore coastal environments as well as offshore habitats. Specifically, the following benefits will be addressed: biodiversity, food source, water filtration, biofuel production, hydrodynamics, and carbon sequestration. In addition, we suggest ecological engineering techniques for promoting biofouling which can be used to transform existing structures or incorporated into the design phase of new installations.

Biodiversity

The biofouling community is a very diverse assemblage of both mobile and sessile organisms. The flora and fauna which comprise biofouling communities' range in size from bacteria such as the cyanobacterium, *Oscillatoria subbrevis* (1 to 20 μm), to species like the giant barrel sponge (*Xestospongia muta*) which can reach up to 1.8 m in diameter [Hutchinson et al., 2006, McMurray et al., 2014]. Some organisms like encrusting bryozoans are low form and prostrate against a surface. In this case, individuals (each approximately 0.5 mm) form colonies up to 1 m in diameter. Other animals stand erect from the surface, like the arborescent bryozoans that can rise to 2–5 cm [O'Dea and Okamura 1999; Ryland 2005] or sea anemones, such as *Diadumene lineata*, at a height of 3 cm into the water column [Glon et al., 2020].

The diversity of a biofouling community varies based on environmental conditions - temperature, salinity, food availability, etc. For instance, the length of *Conopeum seurati* (encrusting bryozoan) correlates with changes in temperatures [Stępień et al., 2017]. Ascidians have been found to have a negative relationship with salinity, while hydroids and sea anemones have a positive correlation with nitrite concentrations [Mhaddolkar Sonali et al., 2019]. In general, some of the most diverse biofouling accumulations are found on surfaces which lack antifouling or biofouling prevention methods. Biofouling and the overall diversity of the community changes with regards to depth, and location in the intertidal zone (Figure 1). Using observations from offshore monopiles and wave energy converters, trends can be made with regards to diversity and overall community composition. At the water interface down to about 0.5 m, the biofouling community is dominated by algae, such as the following species: *Acrosiphonia arita* (green algae), *Chorda filum* (brown algae), and *Polysiphionia* sp. (red algae) [Nall et al., 2017]. Barnacles tend to fill in the gaps [Krohling et al., 2006]. Tubeworms [Nall et al., 2017], tunicates [Otsuka and Dauer 1982; Nall et al., 2017], hydroids [George and Thomas 1979; Krohling et al., 2006], and mollusc species [Bailey-Brock 1989; Krohling et al., 2006] also settle within this zone. As depth increases and sunlight begins to diminish, the presence of algae subsides and other soft fouling organisms (sponge, tunicates, sea anemones etc.) are common [George and Thomas 1979] with a notable increase in hard fouling organisms: tubeworms, encrusting bryozoans, and mollusc [Okamura 1986; Bailey-Brock 198]. At the bottom or the sea floor, biofilms dominate and the overall diversity is very low. Some hydroids have been observed at this depth, but there is typically little to no hard fouling organisms [George and Thomas 1979].

A diverse community allows for an ecosystem to function. On a dock located in Visakhapatnam Harbour, India, at least 100 different biofouling taxa were identified including: polychaetas, bivalves, crustaceans, ascidians, and amphipods [Pati et al., 2015]. Biofouling communities not only support sessile or attached communities but can be used as a food source and habitat for mobile organisms, creating a miniature ecosystem (Figure 2). At a commercial marine aqua centre located off the coast of Italy, the biofouling community was assessed, identifying 110 taxa (48 sessile and 62 mobile): polychaetes, ascidians, bryozoan, bivalves, and isopods [Pica et al., 2019]. Mobile organisms include those which are preying on benthic organisms, like the predatory polychaeta, *Nereis pelagica*. Some also find shelter amongst the three-dimensional biofouling community, such as juvenile spiny lobsters (Figure 3b; *Panulirus argus*), grass shrimp (*Palaemonetes pugio*), green porcelain crabs (*Petrolisthes armatus*), and juvenile seahorses (*Hippocampus erectus*) [Hunsucker et al., 2021]. Biofouling helps connect marine trophic levels, providing a link between the attached community to those found in the pelagic. The sheepshead (*Archosargus probatocephalus*) has been found to be associated with dock pilings because of its preference for feeding on barnacles [Richard Personal observation]. Adult grey snapper (*Lutjanus griseus*) and Atlantic spadefish (*Chaetodipterus faber)* have also been seen to interact with biofouling communities while in search of food [Hunsucker et al., 2021].

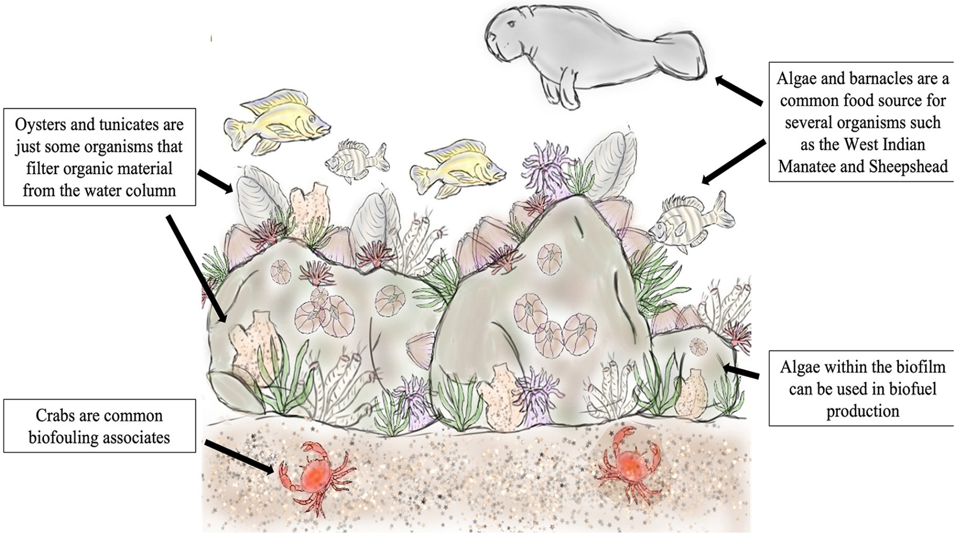


Figure 2. A depiction of a biofouling community and its associates on a rocky outcropping

Biological indicators

Water systems act as a sink for naturally occurring waste and the biproduct of human consumption. Present challenges for the marine environment include microplastics, oil pollution, chemical dumping, eutrophication, metals, fertilizers, greenhouse gases, and pesticides. In light of this, an update in our marine monitoring system is needed. The intention with most monitoring is to quantify the level of stress on the environment. Traditional methods for monitoring include hand taken measurements such as using a thermometer for temperature, and refractometers to measure salinity, marine sensors such as a YSI, or data loggers. However, these often do not demonstrate the effects on the surrounding biota especially those that are not visually seen. The use of sensors or instrumentation to monitor water quality and other physical parameters are common methods to understand environmental changes for management (e.g., wastewater treatment). However these can also be susceptible to biofouling accumulation which can result in inaccurate data unless properly maintained through prevention methods, such as those described above. Another monitoring technique involves the use of biofouling as a biological indicator. A biological indicator is a term used to describe the reaction of marine life to abiotic and biotic factors within an ecosystem [Zaghloul et al., 2020]. Features of a biological indicator would include the accessibility to sample and the ability of the organisms to live in a wide range of environmental conditions. Benthic organisms in particular make good indicators because of their limited mobility, constant availability, and their resiliency [Kennedy and Jacoby 1999; Zaghloul et al., 2020]. A few examples of biological indicators are discussed below, although more detail can be found in [Zaghloul et al., 2020].

There are over 1000 barnacle species worldwide, which are found in almost every habitat including mangroves, rocky intertidal zones, and coastal infrastructure [Xu et al., 2020]. The ability to accumulate particles such as microplastics, and their accessibility makes barnacles a candidate as a biological indicator. In addition, these organisms are sessile making them easily sampled in nature, but can also be utilized in laboratory trials. Brittle stars, polychaetes, oyster, and coral have also shown to be great indicators. In Hong Kong, 4 common barnacle species (*Amphibalanus amphitrite*, *Fistulobalanus albicostatu*s *Tetraclita japonica*, *Capitulum mitella*) gut contents were sampled to represent the accumulation of microplastics pollution [Xu et al., 2020]. Microplastics were found in 84% of barnacles sampled with a median abundance between 0 and 8.63 particles g^{-1} of wet weight [Xu et al., 2020]. In a separate study, barnacles were observed for zinc pollution. Zinc and manganese granules were found in the stomach and tissues of barnacles sampled from Wales, UK. Below the Telform Suspension bridge, concentrations of high levels of zinc, between approximately 1000-4000 ppm, were identified in the soft tissues of barnacle species [Walker et al., 1975].

Aquatic *Chironomids* have likewise proven to be good indicators of heavy metal pollution. When exposed to varying levels of metal toxins (copper, cadmium, lead), *Chironomids* were able to absorb high levels proving their ability to be biological indicators [Lagrana et al., 2011]. The oyster species, *Ostera equestris*, and the coral species, *Tubastrea coccinea*, were investigated for their potential as a bioindicator for contamination events in North America where oil tends to seep from the rigs enhancing the presence of petroleum in the region [Pie et al., 2015]. Concentrations of total petroleum polycyclic aromatic hydrocarbons (TPAH) in *O. equestris* and *T. coccinea* ranged from 2.52 to 95.55 ng×g^{-1} and 8.73 to 79.23 ng×g^{-1} respectively depending on the month, showing that oil rig invertebrates can be used to show contamination and recovery rates [Pie et al., 2015]. Algae have also recently been used as indicators because of their sedimentary nature, large biomass, and are easy to identify. Chakraborty et al., [2014] measured heavy metal content in the water and sediments in India and compared the levels measured to those within macroalgae. They found that heavy metal concentrations for example, iron in seawater and sediments tended to be lower or equal to iron levels in algae depending on the species. These examples prove that just relying on marine instrumentation doesn't predict the contamination toxicity for the local biota and using a combination of both (instrumentation and biota) would give a whole ecosystem view.

Food source

Both the flora and fauna of the biofouling community are an important food source for aquatic herbivores, omnivores, carnivores, as well as humans. Manatees are aquatic herbivores which are known for their love of seagrass but also their ability to eat other submerged aquatic vegetation, some directly attached to man-made surfaces. The West Indian manatee (*Trichechus manatus manatus*) which can be found in Chetumal Bay and in various locations around Florida, has been seen feeding on the benthic cyanobacteria and green algal species *Anabaena* spp., and *Spirogyra* spp. respectively [Reynolds 1981; Castelblanco-Martinez et al., 2009]. Manatees graze on fouling covered man-made structures including boat hulls, pilings, and instrumentation [Oppenheimer and BenDor 2012; Hunsucker and Richard personal observation]. In addition to seagrass and green algae, *Chelonia mydas*, the Green Sea Turtle (Figure 3a), feeds on tunicates (i.e. *Salpidae* spp. and *Doliolidae* spp.) and small crustaceans like shrimp larvae [Amorocho and Reina 2007; Santos et al., 2011]. Seagrass meadows are declining worldwide [Orth et al., 2006], possibly resulting in manatees and turtles turning to these secondary sources of food for their primary consumption.

Other possible food items within a biofouling community include bivalves (oysters, mussels) and crustaceans (crabs, shrimp, barnacles). The

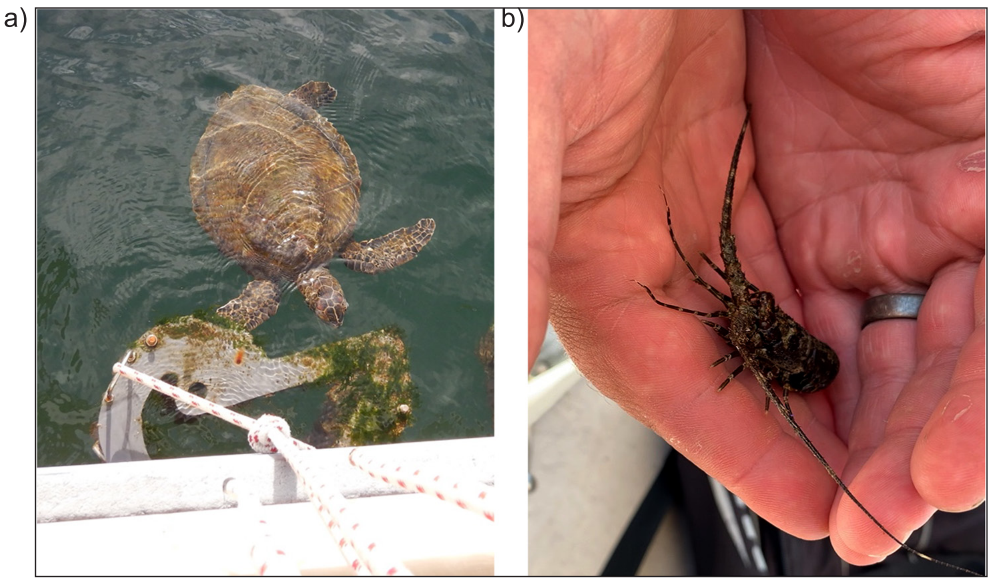


Figure 3. Images of biofouling associates observed at the Center for Corrosion and Biofouling testing facility located at Port Canaveral, Florida: (a) a green sea turtle feeding on green algae attached to a test rig; (b) a juvenile spiny lobster that had fallen off a testing surface

common starfish, *Asterias rubens,* and the European green crab prey on the blue mussel, *Mytilus edulis*, which has been found to grow and foul surfaces within the northern Atlantic Ocean [Laudien and Wahl 2004; Leonard et al., 1999]. Fish are another predator of bivalves, for instance, there are seven different species of catfish (e.g. *Pterodoras granulosus* and *Pimelodus maculatus*) that prey on the golden mussel (*Limnoperna fortune*) [García and Protogino 2005]. Several mullet species (e.g. grey mullet and striped mullet) have a diverse food diet of copepods, benthic diatoms, polychaetas, and nematodes, all of which may be members of the biofouling community [Eggold and Motta 1992; Blay 1995; Islam et al., 2009]. Sheepshead, a fish found mostly in the western Atlantic Ocean, have teeth that allow them to pry barnacles from surfaces [Sedberry 1987; Wenner and Archambault 2006]. Not only do the sheepshead have the anatomy to macerate barnacles before consuming but they also prefer this as a food option. In Florida (USA), recreational anglers can harvest up to 100 pounds of barnacles per person per day and use them to chum for sheepshead [Florida Fish and Wildlife Conservation Commission, 2024]. Conversely, the fishing license also allows the angler to scrape barnacles off pilings, allowing them to sink, and attract sheepshead [Florida Fish and Wildlife Conservation Commission, 2024].

Mussels and oysters are commonly found within biofouling communities but are also a major contributor to global aquaculture production. Shellfish make up about 60% of the world's aquaculture production producing more than 40 million tons in just the United States, valuing over $26 million a year [Crovato et al., 2019; Wijsman et al., 2019]. Clams and oysters contribute 38% and 33% of the global production respectively while mussels and scallops make up the rest [Wijsman et al., 2019].

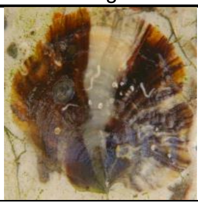
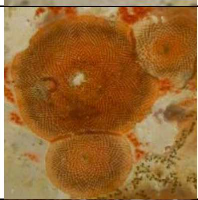
Traditional seafood includes crab, lobster, and shrimp but in certain areas worldwide, barnacles are considered a delicacy for humans. There are two classifications of edible barnacles: lepadomorphs, commonly referred to as the gooseneck barnacle and balanomorphs referred to as the acorn barnacle [López et al., 2010]. Areas that consume these types of barnacles include Spain, Portugal, Japan, Canada, etc. [López et al., 2010]. The gooseneck barnacles of the genus *Pollicipes* were previously the most common barnacle for consumption and recently has been overfished resulting in a shift to other species [López et al., 2010]. Due to over exploitation of *Pollicipes*, harvesting of the gooseneck barnacle has been concentrated predominantly off the coast of Portugal. An average of 260 listed harvesters can be found in Portugal, with 3 protected areas specifically for the harvesting of *Pollicipes* [Carvalho et al., 2017]. Over the past several years, crustaceans, many of which are biofouling species or associates, have increased as a food item in human culture due to the associated health benefits and convenient access to them [Myrland et al., 2000; Olsen 2003].

Filtration

Many organisms present within the biofouling community obtain food through either suspension or filter feeding. This mode of nutrition actively removes particles from the water column (e.g. detritus, phytoplankton, zooplankton), which then pass through the organism, retaining those particles deemed food. Water is then released, but in a cleaner, clearer state then when it was ingested. One of the most important ecological factors associated with filter feeding organisms, is their removal of organic material from the water column, playing a role in repairing or maintaining water quality. In addition, filter feeding or filtration provided by the organisms, contributes to the function of the ecosystem, connection between pelagic and benthic environments, and accelerates the migration of chemical elements [Ostroumov 2005; Beck et al., 2011].

Filter feeding organisms vary in shape, size, and morphology (Table 1). Oysters are known for their ability to filter large volumes of water. The Eastern oyster, *Crassostrea virginica*, can filter particles up to 6 μm at a rate of 6.80 $L \cdot hr^{-1}$ [Riisgård 1988]. The body size of the oyster can influence the overall amount of water which can be filtered, as seen by Yukihira et al., [1999], who determined the clearance rate of pearl oysters (*Pinctada margaritifera* and *P. maxima*). They discovered an individual with a body size of approximately 0.1 g had an average clearance rate of 2.8 $L \cdot hr^{-1}$. Individuals with medium sizes (~1 g) would have a clearance rate of about 11.5 $L \cdot hr^{-1}$ and large individuals (~10 g) would have a clearance rate of 47.1 $L \cdot hr^{-1}$ [Yukihira et al., 1998]. Other mollusc species such as the Atlantic ribbed mussel, *Geukensia demissa*, can filter particles around 4 μm in size at a rate of 6.15 $L \cdot hr^{-1}$ [Riisgård 1988]. In addition to oysters, many other

Table 1. Filtration rates of various biofouling organisms. Filtration rates are depicted as either liter per hour (L·hr^{1}) or as function of total dry weight (g$^{-0.84}$)

Functional group	Representative image	Scientific name	Common name	Particle size	Clearance/Filtration rate	Reference
Oyster		*Crassostrea virginica* *Pinctada margaritifera* *Pinctada maxima*	Eastern oyster Black-lip pearl oyster Pearl oyster	2 - ≥ 6 μm ≥ 3–4 μm ≥3–4 μm	6.80 L·hr^{-1} 2.8 L·hr^{-1}– 47.1 L·hr^{-1} –	Riisgård [1988] Yukihira et al., [1998] Yukihira et al., [1999]
Mussel		*Geukensia demissa* *Mytilus galloprovincialis*	Ribbed mussel Mediterrian mussel	≥ 4 μm -	6.15 L·hr^{-1} 1.31-1.91 L·hr^{-1}	Riisgård [1988] Cottingham et al. [2023]
Barnacle		*Balanus perforatus*	-	–	0.1 L·hr^{-1}	Anderson [1981]
Bryozoan		*Celleporella hyalina*	Encrusting bryozoan	≥ 6 μm	0.01 L·hr^{-1} (individual) 0.38–0.55±1.4 L·hr^{-1} (colony)	Riisgård and Manriquez [1997]
Bryozoan		*Electra pilosa*	Arborescent bryozoan	4 - ≥ 6 μm	0.26 mL·hr^{-1} (individual) 3.01 L·hr^{-1} (colony)	Riisgård and Goldson [1997]
Sponge		*Ascidiella aspersions* *Molgula manhattensis* *Clavelina lepadiformis* *Ciona intestina*	– Sea grapes Light-bulb Sea squirt Sea vase	1–3 μm – 2–5 μm	54.4 g$^{0.84}$ – 46.4 g$^{0.84}$	Randløv and Riisgård [1979]
Tunicate		*Styela plicata*	Pleated sea squirt	≥ 10 μm	2.64 L·hr^{-1}– 4.30 L·hr^{-1}	Draughon et al., [2010] Sumerel and Finelli [2014]
Tubeworm		*Sabella penicillus*	Feather Worm	3 - ≥ 6 μm	13.62 L·hr^{-1}	Riisgård and Ivarsson [1990]

organisms within the fouling community can filter a significant portion of water, impacting the overall health of the water system. Barnacles, one of the most common fouling organisms, use their cirri to capture their food items. Anderson [1981] investigated the feeding mechanism and the rate of the barnacle species *Balanus perforatus*. It was determined that *B. perfortaus* filters water at a rate of 0.1 L·hr^{1}. Colonial biofouling organisms also use filtration as a feeding mechanism. Zooids of the encrusting bryozoan species, *Celleporella hyaline,* filter particle above 6 μm at a rate up to

0.01 L·hr^{-1} but within a colony (4 colonies with approximately 3200 zooids) their clearance rates range from 0.38 to 0.55 ± 1.4 L·hr^{-1}. [Riisgård and Manriquez 1997]. Ascidian species, *Ascidiella aspersions* and *Molgula manhattensis* can filter particles that were 2 to 3 µm in diameter at a rate of 54.4 g per dry weight (g$^{-0.84}$) [Randløv and Riisgård 1979]. Other ascidians, *Clavelina lepadiformis* and *Ciona intestinalis* were able to filter particle sizes that were 2 to 5 µm at a 46.4 g$^{-0.84}$ [Randløv and Riisgård 1979].

In recent years, there has been a global increase of nutrient concentrations within coastal ecosystems, resulting in higher algae abundance and cascading impacts like anoxia and fish kills. Filter feeders, especially oysters, become a beneficial function to the whole ecosystem itself especially during these times of eutrophication, helping to reduce excess algae. Unfortunately, there is a global decline in oyster reefs during the last century, reducing the main filter feeders from our water systems [Beck et al., 2011; Zu Ermgassen et al., 2013]. However, promoting the abundance of biofouling communities can assist in water filtration and the overall health of many of our coastal environments. A diverse fouling community can filter particles between 1 to 40 µm [Mook 1981]. Layman et al. [2014] calculated the filtration rates of fouling communities on dock piling in the Loxahatchee River (Florida, USA). The community consisted of barnacles, bryozoans, tunicates, sponges, molluscs, and several other filter feeding organisms. The filtration capacity of a single dock was estimated to 11.7 million L·hr^{-1}, contributing approximately 30% to the total filtration capacity of the Loxahatchee River [Layman et al., 2014]. In Sicily, Montalto et al. [2020] investigated the clearance rates of two different stages (Group A – successional recruitment and Group B – seasonal recruitment) of biofouling communities under various oxygen conditions (normal, intermediate, and hypoxic) within an enclosed aquaculture fish cage. Biofouling communities consisted of crustaceans (barnacles and amphipods), tunicates (ascidians), polychaetes and seaweeds. It was found that Group A had a clearance rate between 1.22 and 3.01 L·hr^{-1} per weight, while Group B varied between 0.50 to 5.62 L·hr^{-1}·g per weight, which did not change with oxygen concentrations [Montalto et al., 2020]. They stated that biofouling within enclosed aquaculture structures could reduce environmental impacts and benefit production that reduce spending cost for sustainability [Cottingham et al., 2023]. In a different location, the Swan-Canning Estuary in Southwest Australia, is dealing with eutrophication which has been amplified by the long dry summers, reducing streamflow into rivers and estuaries. As part of a national program, they were looking for nature-based solution using a reef forming native mussel species *Mytilus galloprovincialis* [Cottingham et al., 2023]. In a laboratory experiment *M. galloprovincialis* showed a clearing rate of 1.9 L·hr^{-1} during winter months to 1.3 L·hr^{-1} during summer months. When extrapolated out to a fully contrasted and mature reef (approximately 1.2 ha with 1000 individuals×m^{-2}), this would clear about 35% of the entire volume of the estuary (approximately 5×10^{10} L) removing 42.7 tons of organic matter [Cottingham et al., 2023].

Biofuels

Over the past several decades fossil fuels and diesel fuels have increased in demand. Approximately 88% of global energy comes from fossil fuels, and these are in limited supply, which will soon be depleted over time [Fernandes et al., 2007; Milano et al., 2016]. Technological advancements have modified how biofuels are developed. The first generation of biofuels were created from food and crops, then later generations

Table 2. Examples of fouling algal species that have been tested as a source for biofuels

Algae type	Scientific name	Reference
Green algae	*Chlorella* sp.	Brennan and Owende [2010]; Chiu et al., [2008]; Zhang et al., [2018]
Green algae	*Dunaliella salina*	Brennan and Owende [2010]; Dragone et al., [2010]
Green algae	*Botryococcus braunii*	Brennan ad Owende [2010]; Dragone et al., [2010]; Shen et al. [2015]
Green algae	*Chlamydomonas reinhardtii*	Dragone et al., [2010]
Diatom	*Navicula sp.*	Opute [1974]
Diatom	*Nitzschia palea*	Opute [1974]
Diatom	*Amphora exigua*	Orcutt and Patterson [1975]

were created by harvesting wood and non-edible crops such as tobacco and *Jatropha*, a plant native to Cuba used for medicinal use [Shahare et al., 2017; Prabhakaran et al., 2017]. New sources of biofuels involve the use of microalgae. The micro-organisms are great candidates for biofuels because they are highly diverse, make up about 40% of the marine's primary production, environmentally flexible, and can use light and nutrients to create energy [Hildebrand et al., 2012; Milano et al., 2016]. Many of the microalgae which have the potential as biofuels can be found in biofilms (Table 2), due to their ability to either directly attach to a substrate or via secondary attachment though a pre-existing colony. Examples of biofilm forming species that are being investigated or in use as biofuels include: *Navicula* sp. [Opute 1974], *Chlorella* sp. [Chiu et al., 2008; Zhang et al., 2018], *Dunaliella* sp., and *Botryococcus braunii* [Brennan and Owende 2010; Dragone et al., 2010; Shen et al., 2015].

Microalgae can produce a wide variety of biofuels (i.e. algal fuel, oilgae, or third-generation biofuel). Microalgae have two sources of energy: lipids that are used to produce biodiesel and carbohydrates used to produce ethanol [Demirbas 2010; Demirbas 2011; Mata et al., 2013]. The lipid oils in microalgae can make up 50% to 80% of its form, while carbohydrates can make up 50% of its dry weight [Chisti 2007; Ho et al., 2012]. The carbohydrates are composed of starch, glucose, cellulose, or hemicellulose and polysaccharides [Yen et al., 2013]. Microalgae with fatty acids containing 14 to 20 carbons are typically used for biodiesel production. This is determined by lipid content and lipid productivity [Yen et al., 2013]. Lipid production of microalgae has now been determined to be higher than the use of feedstock, making it easy for cultivation and processing [Gupta et al., 2017]. Lipid production of microalgae can be up to 20 times higher than oil seed plants [Prabhakaran et al., 2017; Menegazzo and Fonseca 2019]. The fast growth rate coupled with it being environmentally friendly, makes the use of microalgae a great substitute for fossil and diesel fuels [Milano et al., 2016; Shahare et al., 2017].

While algal based biofuels have great potential, there are some concerns as to up-scaling production to meet the global demand. Several reviews go into detail about considerations for large scale production [Hannon et al., 2010 ; Singh et al., 2011; Pate 2013], but we will highlight two major hurdles: where to grow the algae, and the cost associated with production. The U.S. Energy Information Administration (EIA) reports that roughly 20 million barrels of petroleum are used per day in the USA alone. Hannon et al. [2010] stated this means that 30 to 50 million acres of land would be required to meet the US demand for algal based biofuels. Optimal locations for production would require abundant solar energy and average daily temperatures of 12.8 °C (55 °F) or above [Pate 2013]. Based on these criteria that would leave Hawaii, California, Arizona, New Mexico, Texas, Louisiana, Georgia, and Florida to be the best locations for algal farms [Pate et al., 2007]. These locations would also require an efficient water supply. If situated near water basins this is not a problem, however evaporation loss along with the demand of freshwater aquifers could become a problem.

Once a location is determined, cost of production becomes the next hurdle. Currently there has not been any case studies using microalgae fuels on an industrial scale. At this moment open water systems (ponds) and a closed bioreactor (PBR) are two suggested ways for large scale production. Ponds are considered because they are low cost and can be a by-product of high-rate wastewater algal ponds [Craggs et al., 2012]. For PBRs these systems tend to be more costly because the system needs to have sufficient light and be able to cycle nutrient sources [Hannon et al., 2010]. While each system has their advantages and drawbacks, this is only part of the cost. While oil extraction is simple it can be expensive in terms of equipment and energy required for extraction, which is only tacked on to the cost of converting these oils to liquid fuels. Davis et al. [2011] modeled the cost difference between the systems and found that price of biofuels in a pond or PBR could be on the scale of \$9.84 or \$20.53 per liter, respectively. Therefore, as it stands currently the future of algal derived biofuels is at a disadvantage.

Improvement of hydrodynamic forces

The increase in hydrodynamic forces from biofouling has been well described for ships [Lackenby 1962; Schultz 2007; Hunsucker et al., 2016] and offshore structures [Heaf 1979; Sarpkaya and Isaacson 1981]. A lesser described phenomenon is that biofouling and more generally surface roughness could reduce a portion of the hydrodynamic forces acting on bluff bodies under certain conditions. Hydrodynamic force per unit length of a fixed structure can be approximated in terms of the drag and inertia force by Morison's equation [Morison et al., 1950].

$$F = F_d + F_I \quad (1)$$

$$F_d = \frac{1}{2}\rho C_d D|U|U \quad (2)$$

$$F_I = \rho C_m \frac{\pi D^2}{4}\frac{dU}{dt} \quad (3)$$

where: F_d and F_I – the drag and inertia force respectively, ρ – seawater density, C_d – the drag coefficient, C_m – the inertia coefficient, D – diameter of the structural member, U and dU/dt – represent the undisturbed particle velocity and acceleration.

The maximum forcing from the drag and inertia terms are out of phase due to the respective dependence on velocity and acceleration. The predominance of these constituents is often described in terms of the Keulegan-Carpenter number *KC* [Keulegan and Carpenter 1958].

$$KC = \frac{U_m T}{D} \quad (4)$$

where: U_m – the amplitude of the horizontal particle velocity normal to the cylinder, T – the period of the particle velocity, D – the diameter of the structure. The *KC* – number is proportional to the normalized distance travelled by the fluid particle during a half wave cycle.

Figure 4a and Figure 4b from Sarpkaya [1976] shows the respective dependence of C_m and C_d on Reynolds number and relative roughness (k/D) for oscillatory flows ($KC = 20$) respectively. The Reynolds number is defined in terms of the horizontal particle velocity U, member diameter D, and kinematic viscosity v.

The possible reduction in inline hydrodynamic force on a bluff body due to biofouling arises from 1) reducing the form drag at flows near critical Reynolds number or 2) a reduction in inertial coefficient in low *KC* numbers for fixed structures. Around the critical Reynolds number, there is a reduction in drag that is referred to as the *drag crisis*. The transition to turbulence delays flow separation that reduces the wake behind the object and results in a reduction of form drag. The presence of biofouling or roughness promotes the onset of turbulence and causes the transition to occur at lower Re_D. However, the drag reduction is limited to a narrow range in Re_D which will change as the relative roughness increases and vary as a function of the free stream turbulence [Norberg, 1987].

The drag and inertia coefficients used in Morison's equation are inversely proportional due to their phase relationship of velocity and acceleration respectively. As biofouling and roughness causes the drag coefficient to increase, the inertia coefficient decreases. There exists a narrow portion where the net effect of biofouling or roughness could reduce the overall hydrodynamic loading on the structure provided the diameter did not increase significantly. This is going to be in the low to intermediate range of the *KC* number where the wave height is much less than the diameter of the structure and the hydrodynamic forces are inertia dominant.

The practical achievability of using biofouling to reduce the hydrodynamic force on an object is limited in scope and the structure would

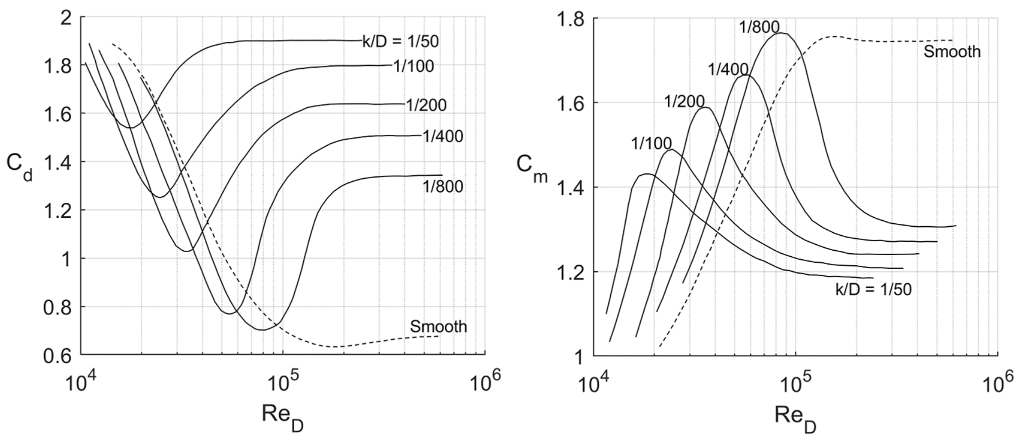


Figure 4. (a) Drag (Cd) and (b) Inertial coefficients (Cm) for oscillating flow from Sarpkaya [1976] as a function of Reynolds number and relative roughness (k/D) for KC = 20

need to be purposely designed and maintained to utilize these principles.

Carbon sequestration

Today greenhouse gases and other anthropogenetic activities (i.e., land use change, deforestation, biomass burning, draining of wetland, soil cultivation, and fossil fuel combustion) have caused some of the highest carbon (CO_2) emission readings to date. Dunne et al. [2020] states that CO_2 emissions in 2019 reached 409.8 ± 0.2 ppm, which is higher than the average recorded between 1981–2010. There are 5 carbon sinks, the largest being the ocean, which absorbs approximately 30% of atmospheric carbon, although it is not evenly distributed [Sabine et al., 2004]. The highest concentrations are found in the North Atlantic (subtropical surface waters) storing 23% of the global oceanic anthropogenetic CO_2 [Sabine et al., 2004]. Vertically within the ocean, the highest concentrations are found in near-surface waters due to the air-sea gas exchange.

There has been a long interest in stabilizing atmospheric CO_2. One strategy is to sequester CO_2 from the atmosphere through natural techniques [Lal, 2008]. Carbon is important to both the physical and biological processes of marine life [Golléty et al., 2008]. Phytoplankton, and many benthic and sessile organisms secrete calcium carbonate to form their skeletal material and are considered a large part of the marine biological pump that removes CO_2 from circulation [Lerman and Mackenzie 2005]. As carbon enters the ocean the reaction with seawater creates calcium carbonate ($CaCO_3$) a common form of carbon used for the calcification of several marine organisms such as mollusk, barnacles, clams, and corals. Marine algae such as *Chorella* sp., *Gracilaria corticata*, *Sargassum polycystum* and *Ulva lactuca* have also been shown to utilize 50–100% of dissolved carbon in laboratory studies for photoautotrophic growth [Chiu et al., 2008; Kaladharan et al., 2009]. However, when high levels of CO_2 are present absorption decreases. This proves troublesome when considering the trend in carbon production.

As CO_2 concentrations increase in the ocean, solutions are needed to help mitigate for excess carbon. One possibility may be farming calcareous shell forming organisms which would remove carbon from our coastal waters. The mussel *Mytilus galloprovincialis* has been estimated to produce 13,662 $g \cdot m^{-1} \cdot y^{-1}$ of bicarbonate [Munari et al., 2013]. While lower, barnacle species *Elminius modestus* and *Chthamalus montag* were able to produce 450.2 $g \cdot m^{-1} \cdot y^{-1}$ and 31.5 $g \cdot m^{-1} \cdot y^{-1}$ of bicarbonate respectively [Golléty et al., 2008]. However, removal of calcium is not limited to bivalves. The polychaetes, *Ditrupa arietina*, has a calcification rate that ranged between 13.9 to 541.8 $g \cdot m^{-1} \cdot y^{-1}$ [Medernach et al., 2000]. Furthermore, many fouling associates use $CaCO_3$ for development, including the brittle star, *Ophiothrix fragil*, which has been identified to absorb 6.8 mol $CaCO_3$ $m^{-2} \cdot y^{-1}$ [Migné et al., 1998]. Although, significant amounts of carbon are removed this theory is controversial due to the biproduct produced when forming shells. Due to the calcification of both *E. modestus* and *C. montag* an estimated 47% of carbon would be the biproduct added back into the ocean [Golléty et al., 2008]. Nevertheless, barnacles and calcareous organisms can potentially play a role in the reduction of carbon in our coastal waters.

Ecological engineering for enhanced biofouling

As human population grows, so does the human footprint in our oceans and coastal ecosystems. Ocean sprawl is becoming more significant. Bull and Love [2019] stated that there are approximately 6000 offshore structures globally, each of these with their own set of environmental impacts associated with construction, operations, and decommissioning. The installation of offshore structures affects the surrounding marine life by altering the biogeochemical cycling, reducing reproductive potential, causing disorientation leading to avoidance of structures, changes in productivity, and are known to be pathways for non-native species. Additionally, these structures can cause chemical contamination via heavy metals, pesticides, and the use of antifouling coatings that emit chemicals such as copper into the water column [Dafforn et al., 2015]. During construction and the operation of these structures, noise, largely affects fish and marine mammals. Fully operational structures can impact marine life via collisions, avoidance, and the disruptions of marine mammal communication. Though the decommissioning phase can potentially have the greatest impact on marine life. There are two forms of removal for offshore structures, mechanical or explosives, which both have their own impacts [Bull and Love 2019]. Mechanical removal uses large abrasive tools and is typically a slower form of deconstruction than using explosives.

While ocean sprawl appears problematic, if the associated infrastructure is designed correctly, it can provide a suitable substrate for biofouling organisms to settle and have a positive impact leading to independent ecosystems in places where natural substrates are not located. The concept of eco-engineering has become increasingly popular in recent years with the goal to integrate human society with resources from the environment. This can be achieved for both pre-existing and new structures. There are five categories that eco-engineering strategies fall under [Mitsch 2012]: 1) using eco-engineering to reduce or solve a pollution problem, 2) using eco-engineering to copy the natural system to reduce a resource problem, 3) using eco-engineering to recover or support a system after a natural disturbance, 4) modifying an existing ecosystem in an ecologically sound way and, 5) using eco-engineering in a way to benefit mankind without destroying the ecosystem balance. Some examples are discussed below.

Rigs-to-reefs is a program created to turn decommissioned rigs (i.e., oil, wind, etc.) into artificial reefs [Dafforn et al., 2015; Bull and Love 2019]. The transition into reefs eliminates the confounding effects of removal, and instead works to attract organisms, acting as a bridge for surrounding ecosystems. Reef balls, typically made of a concrete hybrid, have been used as an artificial habitat for both flora and fauna. They allow for marine growth like soft and hard corals and arborescent bryozoan [Harris 2009]. Reef balls in Indonesia have proven to be effective with over a total of 600 coral colonies that formed on 30 different reef balls [Bachtiar and Prayogo 2010]. Henry et al., [2018] demonstrated how offshore structures can increase connectivity of protected species which can potentially improve the resilience of a species in a complex system. One way to facilitate growth of protected species without being overtaken by invasives could be to pre-seed structures with these protected species. Ohayashi et al., [2022] seeded surfaces with two dominate benthic species found in the Southwest Atlantic Ocean, of Brazil, a colonial ascidian (*Symplegma rubra*) and colonial sponge (*Mycale angulosa*). While communities seeded with ascidians had similar species richness to unseeded, this was due to unsuccessful seeding which resulted in most of the colonies dying within the first sampling period. However, the substrates successfully seeded with the sponge had a reduction of 71% in species richness compared to unseeded. The sponge grew to cover 97% creating a homogenous community. Other studies conducted by Strain et al. [2020] and Bradford et al. [2020] found similar results with intertidal species suggesting an effective strategy to mitigate the occurrence of exotic species. Overall, the enhancement of biofouling would increase biodiversity, leading to a healthier water system.

For new infrastructures, the goal is to create microhabitats that support various size, shape, and trophic levels of fouling organisms. Grooves and crevices provide spaces for organisms to hide from predators, and to attract native species [Dyson and Yocom, 2015]. The addition of various sized holes is a way to create tidepools. As the tide goes out, water will remain within the holes acting as a mini tidepool. Strain et al. [2018] found that both crevices and holes resulted in greater diversity for both sessile and mobile organisms. Seawalls are commonly used in coastal settings, however associated ecological problems include shading and sediment accretion. Seawalls are vertical surfaces with no slopes which limits the ability for organisms to settle. Seawall stairs are one way to give a vertical surface horizontal features [Dyson and Yocom, 2015]. Habitat and vegetation baskets added to the seawalls can create microhabitats, places of refuge for some smaller organisms like juvenile fish and provide a substrate with vegetation to an area that is lacking [Browne and Chapman 2014; Dyson and Yocom 2015]. Creating natural-like surfaces would help support the native community and could have the potential to reduce invasive species within an area, as invasive and exotic species tend to settle on artificial structures compared to natural surfaces [Mitsch, 2012]. Maher et al., [2019] deployed experiments that demonstrated that the design of porous monopiles for the foundations of offshore wind turbines not only solved internal corrosion problems but also created habitats for marine life with the potential to enhance the productivity of local ecosystems. Using these techniques are some ways to promote and support natural biofouling communities.

CONCLUSIONS

In today's world, biofouling is considered inconvenient, problematic and in some cases detrimental to marine infrastructure and the maritime industry resulting in new prevention and removal techniques. However, these techniques (e.g. marine coatings, chlorination, biocides, mechanical removal, etc.) were developed with a specific target in mind, but do not consider non-target organisms or the surrounding environment. While biofouling isn't always desirable it is a key component to healthy marine ecosystems and sustainability. Biofouling not only connects benthic and pelagic systems by providing shelter and food but provides a natural filtration system to help maintain water quality for marine life. Moreover, enhancing biofouling formation creates a diverse community that could benefit ecosystem services provided by these organisms We as humans also depend on such species for food and biofuels.

Human infrastructures such as seawalls, docks, oil platforms, and wind farms are continuing to expand into the marine environment, and we need to consider the positive impacts of biofouling. Eco-engineering techniques should be considered either as modifications to existing structures or in the design phase of new structures. Even small additions, such as creating grooves, crevices, and holes within a substrate would allow for more growth. An example of a project which modifies existing structures, is the addition of Living Dock restoration mats to piers and docks [Rech et al., 2023]. The mats, which consisted of 80 dead oyster shells, are attached to the pilings allowing for the accumulation of growth over time. The biofouling growth which developed included filter feeding organisms, as well as economic and ecological important mobile species: juvenile spiny lobsters (Figure 3b), seahorses, and juvenile stone crabs [Hunsucker et al., 2021, Gilligan et al., 2022]. With increase ocean sprawl we need to consider what is more important, protecting structures that can potentially destroy ecosystems or developing structures that can coexist with marine life.

Acknowledgements

The authors are grateful to the Center of Corrosion and Biofouling department for their testing facility which is funded by the Office of Naval Research. Publication of this article was funded in part by the Open Access Subvention Fund and the John H. Evans Library at Florida Institute of Technology.

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