Best Practices Guide for Nitrogen Remediation using Oyster Aquaculture

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Summary/Audience statement

This document is designed as a guide for those interested in growing oyster and potentially other shellfish, with an eye toward nitrogen remediation in coastal waterways. The details presented here stem from a 2-year study of the three most popular gear sets used in southeastern MA.

Problem Statement

Coastal communities face deteriorating water quality and overall health of coastal ecosystems due to excessive inputs of anthropogenic nitrogen (N) (e.g., from septic systems, fertilizer and atmospheric deposition) known as N loading. N loading has caused negative ecological and economic impacts on coastal communities and coastal areas (Paerl, 1997, 2009) and has been linked to harmful algal blooms, habitat alteration and loss (e.g., loss of Eelgrass beds) (Hauxwell et al., 2001), as well as coastal hypoxia and anoxia (Pomeroy et al., 2007; Rabalais et al., 2014). Economic implications include direct losses to tourist-based economies and potentially huge impacts on residents (e.g., multibillion-dollar sewering projects).

Towns are under regulatory, legal, economic and environmental pressure to implement strategies to improve water quality. In 2012, the Waquoit Bay National Estuarine Research Reserve (WBNERR) hosted a formal Coastal Training Program (CTP) Decision-Maker Needs Assessment involving Cape Cod local officials. This study revealed that reducing nitrogen pollution and restoring water quality is the top environmental issue that officials seek information on to guide management actions. This need has been repeatedly emphasized in follow-up surveys done at regional CTP decision-maker workshops.

Cape Cod recently completed an area-wide water quality management planning process to determine best ways for municipalities to work together to investigate and implement effective and affordable solutions. The resulting Cape Cod 208 Water Quality Plan identifies several non-traditional nitrogen remediation strategies that have promise for helping to restore water quality at a lower cost than sewering alone. Cape towns are now investigating if/how they may integrate one of these strategies into their water quality management plans: shellfish aquaculture.

Shellfish affect N loads in coastal waterway through a number of processes. First, as N enters coastal waters it can stimulate growth of phytoplankton (primary producers) which convert N dissolved in the water into biomass. It is this additional chlorophyll-rich biomass that gives impaired waters a greenish tinge. The consumption of this biomass in the water column and sediments can lead to a draw down in oxygen concentration and an increase in hydrogen sulfide (producing the rotten egg smell of some impaired coastal waters) production in the sediments or even the water column. Excess N must be removed from coastal waters in order to avoid this deleterious cascade of events.

Why Oysters

Why oysters, and not quahogs, other shellfish or even macroalgae? All these options may be appropriate in different situations for removing N from coastal ecosystems and could have a role in remediating our coastal waters. A mixed aquaculture approach, growing multiple species or rotating species year to year can also be effective. Oysters are not the only option but they are a natural part of New England coastal ecosystems, and their abundance has declined over the last few centuries due to overfishing, habitat change and changing uses of our shorelines. In colonial days oysters were so common that they were a navigation hazard for ships, and their consumption drove a major economic market. Oysters, like many shellfish, also have the benefit of being filter feeders, collecting particles in the water column for food. They filter enormous volumes of water each day, up to 11.5 L h^{-1} (Cerco and Noel, 2007), though this rate can be affected by factors including temperature, salinity, oxygen availability and oyster size (zu Ermgassen et al., 2013). Unlike many shellfish, oysters can filter nearly all particles in the water column between 5 and 100 µm in size (Riisgård, 1988), and they sort these particles on the gill, selecting some for food and some for excretion. The carbon and nitrogen content of the particles selected for food can be assimilated into the tissue of the oyster (biomass) or excreted in fecal pellets. Particles not selected for food on the gill are packaged into larger particles by mucous and ejected from the animal, these larger particles are called pseudofeces. Both feces and pseudofeces are denser than the phytoplankton/particles, resulting in much faster transport of material to the sediment. This has two important effects. First, removing particles/phytoplankton from the water column to the sediments will clear up waters by decreasing turbidity. Second, the movement of carbon and N to the sediments may stimulate natural microbial processes that remove N.

Excess Nitrogen and How Oysters Affect Nitrogen Cycling

Oyster biodeposits (feces and pseudofeces) can affect the N cycle by transporting N and carbon (C), in the form of organic matter (OM), from the water column to the sediments. These biodeposits can alter sediment chemistry since they contain twice as much the concentrations of carbon, nitrogen, and phosphorus compared to particles settling out naturally from the water column (Jordan et al., 1987). In oxygen-depleted/ anoxic waters and sediments many naturally-occurring microorganisms can use nitrate (NO_3^-) instead of oxygen to metabolize their food, expelling harmless N_2 (~70% of the air we breathe) or N_2O as the byproduct to the atmosphere. These processes may also be active even in the oxygenated water column within anoxic interiors of large particles such as fecal pellets or pseudofeces.

Nitrogen is an element that is present in all organisms, one of the six major elements required for life (carbon, hydrogen, oxygen, nitrogen, phosphorous and sulfur). Nitrogen in coastal ecosystems is mostly found as the dissolved chemical species ammonium (NH_4^+) and nitrate (NO_3^-) or as biomass (i.e., N-containing organic matter or OM). NH_4^+ NO_3^- have different behaviors in the environment but are directly linked to human activity. As human population in the coastal zone has increased, septic and wastewater releases to coastal waters have become major management concerns. For example, on Cape Cod, human derived (anthropogenic) N enters coastal ecosystems mostly through septic systems in the form of ammonium (Talbot et al. 2003; Bowen et al. 2007). In an oxygen containing aquatic environment ammonium is quickly converted to NO_3^- by sediment or water column bacteria. This important chemical change results in a N species that is able to accumulate quickly. While plants may consume NO_3^- as a growth nutrient (converting the N back to OM), NO_3^- is largely untouched by other organisms in the aerobic terrestrial environment, and thus travels to coastal waters. Since coastal waters collect inputs from across larger watersheds, nitrate may build up to high levels and once it reaches sunlight coastal waters it acts as a fertilizer that stimulates phytoplankton growth, producing OM (biomass). The build-up of OM and its ultimate degradation in the coastal ecosystem is behind many of the drivers of low ecosystem health. It can lead to a cascade of effects that cause water quality to deteriorate by increasing turbidity and accelerating oxygen depletion when the increased biomass dies and is degraded either in the water column or in the sediments.

For N to be removed from the environment, it must be moved from the NO3- and NH4 pools (soluble pools) to the few gaseous pools, and primarily to dinitrogen (N_2), that can escape from the water column and sediments. Movement between the soluble and gaseous pools is controlled by naturally-occurring biological reactions in coastal ecosystems. however, these processes require different ecological settings and specific metabolic pathways, some of which require aerobic conditions, and others requiring anaerobic conditions. Under aerobic conditions the degradation of OM results in production of NH_4^+. As discussed above, under aerobic conditions this NH_4^+ is quickly oxidized to NO_3^-, a process called of nitrification. However, respiration of OM can lead to depletion of oxygen and ultimately to anoxic conditions, particularly in the sediments. In anoxic environments, NO_3^- and NH_4^+ can be used by certain groups of microorganisms for respiration instead of oxygen. The biological, anaerobic process of converting NO_3^- to gaseous N_2 is called denitrification (DNF). Likewise, NH_4^+ can be transformed to gaseous N_2 through the biological process of anaerobic ammonia oxidation (anammox). These processes, when complete, remove N from the marine environment because gaseous N_2 escapes from the system into the atmosphere. These two pathways are carried out by diverse groups of microorganisms using well-characterized metabolic reactions with known genetic marker genes. When we examine genetic material isolated from environmental samples the expression levels of these genes reflect the activity of the microorganisms that can perform DNF or anammox in the ecosystem. DNF is considered the major N-removal process, though in most environments the balance of N-removed by DNF vs. anammox is not well understood (Kartal et al., 2007). A third biological process can compete with DNF for NO_3^- called dissimilatory reduction of nitrate to ammonium (DNRA), which converts NO_3^- under anerobic conditions back to NH_4^+. This conversion back to NH_4^+can lead to **storage** rather than **removal** of N. The environmental factors that control the DNF/DNRA balance are not yet well understood, however DNRA tends to be favored under strictly anaerobic conditions, and when sulfide levels increase. Sulfide is known to inhibit the enzymes involved in DNF and might also have a role on the enzymes involved in DNRA, however this requires further investigation.

Installing Oyster Aquaculture

At present, the Town of Falmouth uses three different types of growing gear, which are commonly referred to as floating bags, Oyster-Gro (or midwater condos), and bottom cages. All three of these gear types can be used for primary grow-out of first-year oyster seed as well as secondary grow-out of second-year oyster seed. In the following section we will discuss general considerations for deploying each of these three popular types of gear on Cape Cod. We choose to explore these gear types after consulting a major regional gear supply house which indicated these gear types represent the top sellers.

Site Selection Considerations

When examining different gear types for growing oysters, it is important to consider geographical aspects of the growing area. These characteristics include site access, water depth, wind and wave exposure, substrate composition, and permitting.

1. Site access – How will you access the farm? Are there easy places to launch boats if required, bring in vehicles for deployment and harvest? Is access tide dependent? Some gear types are heavier than others, some can be serviced from a boat, while others require walking access.
2. Water depth – How will you maintain the gear during the growing season? Is the water shallow enough to walk the farm? Can be tended with a small boat? If the water depth requires a boat, how deep are the oysters and will a winch or davit be needed to retrieve gear for routine maintenance?
3. Wind/wave exposure – Is your site protected from strong waves and wind or exposed? Some gear types have a lower surface profile than others.
3. Substrate/sediment type – How will the gear be fixed to the bottom? Can you walk on the bottom?
4. Permitting – What are the regulations and regulatory bodies in your locale? Is a shellfish survey needed prior to permitting? What other regulations are required by the municipality?

Gear type commonalities

All three types of gear hold animals in mesh bags that have a sealed and open end. The open ends of the bags can be closed with a PVC fastener, which allows for easy access. These bags also come in multiple mesh sizes. As the oysters grow, larger mesh sizes are used. Bottom cages and Oyster-Gro systems hold these mesh bags inside the larger gear frames.

Gear type differences

Where these gear types differ is their placement in the water column, which allows the seed to be grown at the water surface, in the middle of the water column, or just above the sediment bottom. These variations in position explain differences in vulnerability of the gear to damage from storms, the cost of the equipment and labor to construct, deploy and maintain the systems, as well as differences in overall growth of the oysters.

Floating Bags

How the system works

The floating bag system utilizes many bags connected end to end. After site selection, installation starts with aligning temporary stakes to mark where anchor devices (e.g., auger poles) will be placed. Plots can be kept square by measuring the diagonal lengths which helps with aesthetics and possibly robustness of the installation. Main-lines are installed between each pole on the perimeter of the area, floatation on the main-line allows the bags to rise and fall with the tide. Bags are attached to the main-line end to end with the clip and loop of adjacent bags. While installing the floating bag system, maximum water depth is not a factor in site selection; the system can be installed in both shallow- and deep-water sites. Bottom substrate is also not a primary factor in site selection. It is however a secondary factor to consider because the main-line needs anchoring, giving the bags something to clip into. This system should be oriented relative to the direction of prevailing winds to limit tension on the system because it is vulnerable to damage from storms and sustained high winds.

Maintenance

Routine maintenance of the floating bag system is needed. Bi-weekly flipping of each bag, such that each previously submerged side is then out of the water. This helps ensure the oysters do not grow into the mesh and it limits fouling of the bag. It also allows the oysters to be tumbled. This is important because jostling the oysters chips off the growing edge and allows for a stronger shell to be formed. Floating bags can remain attached to the main-line and to each other when flipped. Typically flipping is done by walking the farm or by small boat if the water depth is greater. This maintenance is less labor-intensive and less time-consuming than for the other gear systems discussed here. Depending on the site water-depth, performing maintenance on a low tide may be beneficial. A floating bag system is relatively inexpensive compared to the other two types of gear. In 2018, the cost of a 90-bag floating array was $2,078.85. Even though this is the cheapest option for gear, labor is required to assemble the system components.

Oyster Growth

Data collected from August to October of 2018 indicated that shell height (length from umbo to bill) increased from an average 35.9 mm to 68.8 mm in the floating bag system for first-year oysters. In 2019, during the growing period from July to August, the oysters grew from an average 15.7 mm to an average of 44.5 mm. Data from 2018 indicated the oysters started at an average mass of 8.1 g and finished around 44.5 g. In 2019, the seed started out at an average of 0.5 g and ended at 8.7 g. Second-year oysters in 2018 began in May at an average of 52.4 mm and ended in October at roughly 99.0 mm. In 2019 oysters started at an average of 49.1 mm and ended at an average of 87.0mm over the same period. Average oyster mass in 2018 increased from 17.2 g to 90.0 g and in 2019, from 12.4 g to 47.2 g. From this information, we see that first-year oysters in 2018 experienced an intermediate increase in shell height when compared to other systems tested. In 2019, first-year oysters had a similar increase in shell height compared to the other two systems. First-year oysters showed a similar increase in mass compared to oysters in the bottom cage systems in both 2018 and 2019. Second-year oysters in floating bags experienced the greatest increase in shell-height compared other systems in both 2018 and 2019. In 2018, second-year oysters experienced the greatest increase in mass in the floating bags, but in 2019 they only experienced an intermediate increase in mass when compared to other systems. One can conclude that the floating system yielded the largest and fastest growing second-year oysters and intermediate size first-year oysters compared to the bottom cage and the Oyster-Gro systems.

Pros	Cons
Best growth of second-year oysters	Labor to construct bags
Can be used in shallow or deeper water	More prone to damage
Cost	
Ease of maintenance	

Oyster-Gro (midwater condos)

How the system works

The Oyster-Gro or midwater condo system is made of a plastic-coated wire cage structure, arranged with 3 separate compartments for bags horizontally, and 2 separate compartments for bags vertically (3x2 compartment layout). Bag compartments are accessed by opening a hinged door, secured with an elastic and a clip fastener. Large, hard plastic floatation buoys are fixed to the top of the cage, keeping the cage submerged below the surface of the water. The cages can be strung together end to end and similar to the floating bag system, the poles that are driven into the substrate have main-lines that are buoyed with flotation, allowing the cages (and the bags inside) to rise and fall with the tide, but always under the water surface. This system should be positioned considering the direction of the prevailing winds to limit the tension, as it has the highest above water profile, making it vulnerable to damage from storms and sustained high winds. Given the mass of the structure plus oysters, and vulnerability of the system to wind damage, stranded cables may be employed between the cages to increase the strength of the system. Bottom substrate and maximum water depth are not primary factors in site selection. Minimum water depth, however, is a factor because enough water is needed to keep the cages above the substrate on a low tide.

Maintenance

The maintenance for Oyster-Gro systems is more involved than for floating bags. The bags are held inside the frames and need to be scrubbed of fouling agents and debris, flipped to the opposite side and placed back into the condo bi-weekly. To access the bags, the condo needs to be flipped so that the floatation is under the cage, and the compartments are out of the water. This flip helps ensure the oysters do not grow into the mesh. It also allows for the oysters to be tumbled as for the floating bag system. This form of maintenance is labor-intensive and time-consuming. Depending on the site water-depth, performing maintenance on a low tide may be beneficial. As for costs, the Oyster-Gro system is the most expensive when compared to the other two types of gear. In 2018, the cost of a 90-bag midwater array (15 cages) was $3,559.50. Even though this is the most expensive option for gear, it is durable, and there are little to no labor costs needed to make the system ready for deployment. Anchoring the system is an additional labor cost, but cost varies on the type of anchoring system used.

Oyster Growth

Pros	Cons
Best growth of first-year oysters	Most expensive

Can be used in shallow or deeper water	Maintenance more intensive
	More prone to damage

Data collected from May to October of 2018 indicated that shell height increased from an average 34.6 mm to 79.3 mm. In 2019, during the growing period the oysters grew from an average 16.8 mm to an average of 46.6 mm. In 2018 the oysters started at an average mass of 7.5 g and ended at 27.2g. In 2019, the seed started out at an average of 0.6 g and ended at 11.9 g. Second-year oysters in 2018 began in May at an average of 52.9 mm and ended in October at an average 89.60 mm. In May of 2019 the oysters started at an average of 57.1 mm and ended in October at an average of 81.0 mm. Average oyster mass in 2018 increased from 16.8 g to 84.1 g and in 2019, it increased from 17.0 g to 58.2 g. From 2018 data we see that first-year oysters experienced the greatest increase in shell height in the Oyster-Gro systems when compared to other systems tested. In 2019, first-year oysters had a similar increase in shell height compared to the other two systems. First-year oysters also experienced the greatest increase in mass in both 2018 and 2019 in the Oyster-Gro systems. Second-year oysters experienced an intermediate increase in shell-height compared with other systems in both 2018 and 2019. In 2018, second-year oysters experienced an intermediate increase in mass, but in 2019 they experienced the greatest increase in mass compared to other systems tested. From these data, one can conclude that the Oyster-Gro system yields the largest and fastest growing first-year oysters and intermediate size second-year oysters.

Bottom Cages (bottom condos)

How the system works

Bottom cage systems are made of a plastic-coated wire cage structure arranged with 3 separate compartments for bags horizontally, and 2 separate compartments for bags vertically (3x2 compartment layout). Bag compartments are accessed by opening a hinged door, secured with an elastic and clip fastener. "Feet," or "legs" are attached to the bottom of the cage, that keep the cage positioned about 3 in. from the bottom. Bottom substrate and maximum water depth are not primary factors in site selection. However, a firm substrate is needed to ensure cage stabilization. Minimum water depth is also a factor because enough water is needed to keep the cages submerged at low tide. Unlike the midwater or floating systems, bottom cages are resilient to storm damage.

Maintenance

The bags held inside the cages are removed, scrubbed of fouling agents and debris, flipped to the opposite side and placed back into the cages bi-weekly. To access the bags, each cage is flipped on its side so that cage compartments are out of the water. This flip helps ensure the oysters do not grow into the mesh. It also allows for the oysters to be tumbled, resulting in better growth. This form of maintenance is more difficult and time-consuming than for the floating gear system due to the difficulty of flipping the heavy cages. If in deep water, a winch on a small boat may be beneficial. The bottom cage system is in the middle of the cost range of the three systems tested. In 2018, the cost of a 90-bag bottom cage array (15 cages) was $2,583.75. Fortunately, there are little to no labor costs needed to make the system ready for deployment.

Oyster Growth

Data collected from May to October of 2018 indicated that shell height increased from an average 43.4 mm to 62.72 mm. In 2019, during the growing period the oysters grew from an average 16.4 mm to an average of 45.1 mm. Data from 2018 indicated the oysters started at an average of 6.8 g and ended at 21.4 g. In 2019, the seed started out at an average of 0.7 g and ended at 8.8 g. Second-year oysters in 2018 began in May at an average of 51.6 mm and ended in October at roughly 87.1 mm. From May to October in 2019, the oysters started at an average of 50.9 mm and ended at 71.1 mm. Average oyster mass in 2018 increased from 14.1 g to 60.4 g and in 2019, it increased from an average 173.4 g to 35.4 g. From this information, first-year oysters experienced the smallest increase in shell height when compared to other systems in 2018. In 2019, first-year oysters showed a similar increase in shell height compared to the other two systems. First-year oysters also experienced a similar increase in mass in both 2018 and 2019. Second-year oysters experienced the smallest increase in both shell height and mass compared to the other systems. From these data, we see that bottom cages yielded oysters with smaller or at best, similar shell height and mass compared to the other systems tested.

Pros	Cons
Site preparation and deployment are easier.	Maintenance can be difficult.
Can be used in shallow or deeper water.	Smallest first- and second-year oysters
Resistant to storms	

Effect of the three systems on N removal

Oyster aquaculture can remove N from the ecosystem in a few ways. The biggest contribution to N removal is accomplished by harvesting the oysters (removing their biomass from the ecosystem). It is estimated that tissue assimilation is the dominant form of N removal for individual oysters, but after reaching harvestable size, denitrification can become the dominant process (Carmichael et al., 2012). The amount of N in the oyster biomass roughly scales with size and a lot of research has gone into determining this multiplier. Observations of oyster N content vary, but in general, ranges from 0.3-0.9 dry wt% of the dry weight of the oyster (Reitsma et al., 2017 and ref. there in). Thus, for an average sized oyster ~0.2-0.3 g of N is stored in tissue and shell. For a million-animal farm that translates to up to 300 kg of total N sequestered in the oyster biomass over the entire growth period of the animal. Of course, the amount of N removed from the water body would be determined by the difference between this final mass and the starting mass entering the farm (i.e., net growth).

The second way oysters stimulate N removal is by enhancing the naturally-occurring microbial processes that lead to removal of N in underlying sediment. Bacterial communities underlying all gear types examined here enhanced nitrogen removal when compared to control sediments that had not oysters. While nitrogen fluxes, used as a proxy to quantify the N_2 gas emitted, also increased over the course of the summer at our control site, this pattern was magnified at each of the oyster gear sites. Early in the spring and summer N flux was similar between our different gear sites and bare sediments (~0.25 mM N_2 m^{-2} d^{-1} or ~0.672 g N_2 $site^{-1}$ day^{-1}). However, during the peak productivity period from the end of July until the end of the growing season in October, each gear type is associated with a 2-4-fold higher N removal rate than the bare sediments. While the N fluxes from the control sediment increased to ~0.8 mM N_2 m^{-2} d^{-1} (~2.0 g N_2 $site^{-1}$ day^{-1}) the gear sites increased to 1.5 N_2 m^{-2} d^{-1} (~4.0 g N_2 $site^{-1}$ day^{-1}) for the floating bags, 2.0 N_2 m^{-2} d^{-1} (~5.4 g N_2 $site^{-1}$ day^{-1}) for the Oyster Gro' and 2.5 N_2 m^{-2} d^{-1} (~6.7 g N_2 $site^{-1}$ day^{-1}) for the bottom cages.

Consistent with these N flux increases we see changes in the activity of specific nitrogen related processes. Under all gear sets, denitrification was stimulated relative to background. However, we do have indications that when conditions become sulfidic, DNRA begins to compete with denitrification, thus decreasing the effectiveness of oyster aquaculture at removing additional N through sediment denitrification. This is mainly because DNRA leads to the production of ammonium that will be eventually released in the water column and will not be able to escape in the atmosphere as it would be in the case of nitrogen gas. The competition between denitrification and DNRA is likely controlled, among others, by the amount of carbon accumulation. As carbon accumulates below aquaculture sites due to inputs of feces and pseudofeces as well as biofouling, this leads to microbial processes that increase sulfide production. Bottom cages trap the highest concentrations of particulate carbon in the sediments and thus are the most likely of the three gear sets to result in shifts toward DNRA. We observed this shift starting to occur below bottom cages in Waquoit Bay, in spite of the fact that the bottom cages still produced the highest N_2 production rates. This suggests that N_2 production below bottom cages would be even greater if sulfidic conditions could be avoided by changing the location of the installation year to year. Any deployment of gear should consider this balance between denitrification and DNRA since it can shift the coastal sediments from nitrogen removal (desired) to nitrogen retention (undesired). In addition, the organic carbon but more importantly and sulfide content of the sediments should be measured routinely to detect when the site should be moved in the next season. This is crucial since some sediments compared to others can be sulfidic by nature and thus addition of organic carbon can activate DNRA (nitrogen retention) in the expense of DNF which is promotes nitrogen removal. The organic matter and sulfide measurements can be made by many commercial labs. The samples of sediment are relatively easy to collect for these measurements, and the analyses cost can be affordable.

At the Oyster Gro site and to a lesser extent, under the floating bags, we observed a potential piston pumping action of the gear during high wind and waves that introduces oxygen into the sediments due to the movement of gear and the pressure waves induced. This O_2 circulation into surficial sediments did not appear to have a negative effect on the N_2 removal rates, despite the fact that denitrification is a process that works better when oxygen is not present in the sediments. This can be explained from the ability that coastal denitrifiers have to continue the process of denitrification under short-term exposure to oxygen. This behavior is a potential adaption that denitrifiers maintain in the coastal sediments in order to overcome the effects of the occurring tides that expose the sediments frequently to oxygen (Marchant et al. 2017, and references therein). On the contrary, the presence of oxygen via the piston pump action seemed to affect DNRA (nitrogen retention process) that is a strictly anaerobic process and increases when sulfide accumulated. As already mentioned, sulfide accumulation can derive from accumulation of organic matter that can lead to anoxic and sulfidic conditions in the sediments.

We suggest that growers periodically measure carbon, nitrogen and sulfide content of their sites, and work with local experts to directly measure N_2 removal if they wish to optimize the contribution of their installation to coastal N removal. While the amount of N_2 removal in the sediment may be small compared that of the total oyster biomass, it is a non-trivial contribution and an ongoing process. Also, the long-term effect of N_2 removal via denitrification can continue to the sediments even after the oysters are removed for the site (Ray et al., 2020). Besides, it is important to maintain a healthy sediment ecosystem and not drive the system to be sulfidic by farming too large an oyster biomass in the overlying waters for long of a period of time. Local hydrodynamics will impact what this period of time is.

Conclusions

By monitoring the overall nitrogen biogeochemistry of these oyster aquaculture installations and monitoring nitrogen fluxes and microbial processes in Waquoit Bay (Falmouth MA) over a 2-year period we report that all three gear types stimulate sediment denitrification relative to similar control sediments (Mara et al., 2021). Microbial community analysis shows that the activity of sediment communities responds to the presence of the oysters. Rates of N removal increase drastically from the end of July to the end of the growing season, during peak productivity in Waquoit Bay, however, they were significantly greater under all aquaculture sites than at the control site, particularly under bottom cages. This indicates that heterotrophic denitrification may be stimulated by released organic material from the oysters. Floating bags and the suspended Oyster Gro' gear can distribute oyster biodeposits and fouling organic material over larger areas than bottom cages, diluting the impacts of enhanced denitrification (Lunstrum et al., 2018). But we argue Oyster Gro and floating bags (to a lesser extent) gear can also limit DNRA, a nitrogen-retaining process that competes with denitrification when conditions become sulfidic because these gear types increase oxygenation of surface sediments and disperse organic deposits over a greater area.

The hydrodynamic setting (water depth, bottom characteristics, exposure to wind and waves), the method of oyster cultivation, and the stocking density of the oysters, can all affect nitrogen cycling via influences on pools of organic matter, nitrate and O_2 (Lunstrum et al., 2018). Sulfur and sulfur-speciation related site-specific sediment biogeochemistry should be considered prior to deployment of oysters if nitrogen removal is a priority because both can affect nitrogen cycling (Mortazavi et al., 2015). Monitoring of sulfide and organic content of sediments at aquaculture sites can help stakeholders to predict whether anticipated nitrogen removal rates at their site will follow patterns observed in Waquoit Bay.

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