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TECHNICAL GUIDE TO MARINE AQUACULTURE GEAR

BY

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U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southeast Regional Office
263 13th Avenue South
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NOTICE

DISCLAIMER

This guide is intended to be informational, not prescriptive, and does not provide recommendations or a checklist of project design criteria that would guarantee any federal, state, or local permits or authorizations. The image in Chapter 5 was generated using the Google Gemini artificial intelligence program and is meant to be a descriptive image of a potential future integrated multi-trophic aquaculture system.

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TABLE OF CONTENTS

FIGURES AND TABLES

INTRODUCTION

Marine aquaculture is a vital sector of the United States (U.S.) Blue Economy and its expansion is a strategic priority for the National Oceanic and Atmospheric Administration (NOAA).[1] At the same time that NOAA is investing in a robust domestic aquaculture industry, the agency is also working to ensure environmentally sustainable practices align within its stewardship mission.[2]

Among these responsibilities, there is increased attention to understanding how marine aquaculture systems could be designed and managed to minimize potential risks to protected resources; e.g., species protected under the Marine Mammal Protection Act (MMPA) and listed species and critical habitat designated under the Endangered Species Act (ESA). To evaluate these risks, federal resource managers need a baseline understanding of aquaculture systems and their components. This guide was specifically developed to characterize key components of aquaculture systems to assist federal regulatory processes relevant to the ESA and MMPA. The information in this guide will help inform scientists and managers in designing, testing, evaluating, and permitting aquaculture systems in a broader environmental context (e.g., National Environmental Policy Act (NEPA), ESA and essential fish habitat (EFH) consultations). In addition, this guide may be used to assist other resource managers and permitting agencies in their review of aquaculture projects.

Immense variation exists among aquaculture systems. Designs vary based on the cultured species and environmental conditions, as well as regional industry practices. Rather than attempt to capture all such variations and future possibilities in this guide, we provide a general orientation to aquaculture systems. This illustrated guide describes general gear types, characterizes key system components, covers common language for referring to aquaculture systems, and examines both commercially-operational and experimental gear, to the extent practicable.

This guide describes the components of aquaculture systems deployed and operated in inshore, nearshore, and offshore marine environments. Because there are no standardized, widely-adopted definitions for these delineations, we adopt those published in Price et al.

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[1] NOAA (2023). New Blue Economy. [Available at https://www.noaa.gov/blue-economy]

[2] D. Blacklock, Pennock J., and Schulze-Haugen, M. (2022) "NOAA Aquaculture Strategic Plan (2023-2028)," [Available at https://www.fisheries.noaa.gov/resource/document/noaa-aquaculture-strategic-plan-2023-2028]

2017[3], and use these terms throughout the document insofar as they are useful to describing gear:

* **Inshore:** areas adjacent to the shoreline where environmental dynamics are predominantly tidally influenced, aquaculture is highly visible and easily accessible from the shoreline; this includes intertidal areas such as estuaries and lagoons.

* **Nearshore:** areas less than three nautical miles from shore, visible from but not immediately adjacent to the shoreline; may experience significant exposure, strong flushing currents, winds and ocean circulation, or may be sheltered from open ocean conditions in embayments.

* **Offshore:** areas farther than three nautical miles from shore, not likely visible from shore, having a high degree of exposure to ocean conditions, including significant wave energy, strong flushing conditions, and deeper waters.

In general, while components may be similar between areas, those used for offshore aquaculture systems require stronger and more complex components, including those in mooring and anchoring systems, because of exposure to strong waves, currents, winds, and storms. Inshore and nearshore aquaculture system components are often smaller and require less holding capacity, as operations may be afforded some protection when sited in large bays, or any other sheltered location leeward of a landmass.

This guide starts with a general glossary and pictorial of components common to aquaculture systems (e.g., lines, mooring systems, netting, connectors, and anchors). Subsequent chapters describe a subset of marine aquaculture systems categorized by the species being cultured for harvest (e.g., molluscan shellfish and other invertebrates, macroalgae, and finfish). Each chapter includes illustrative descriptions of different gear systems, a glossary of components specific to that system, and a description of cultured species as relevant to the design, behavior, and management of the system. This guide also includes a chapter on potential future innovations for aquaculture gear and systems. Where relevant to consideration of environmental impacts, these chapters also describe construction, maintenance, and harvest activities. This guide is not intended to be comprehensive, and federal staff may require engineering specifications, drawings, and installation and operational descriptions of the specific systems and components being proposed for any individual operation to complete an assessment.

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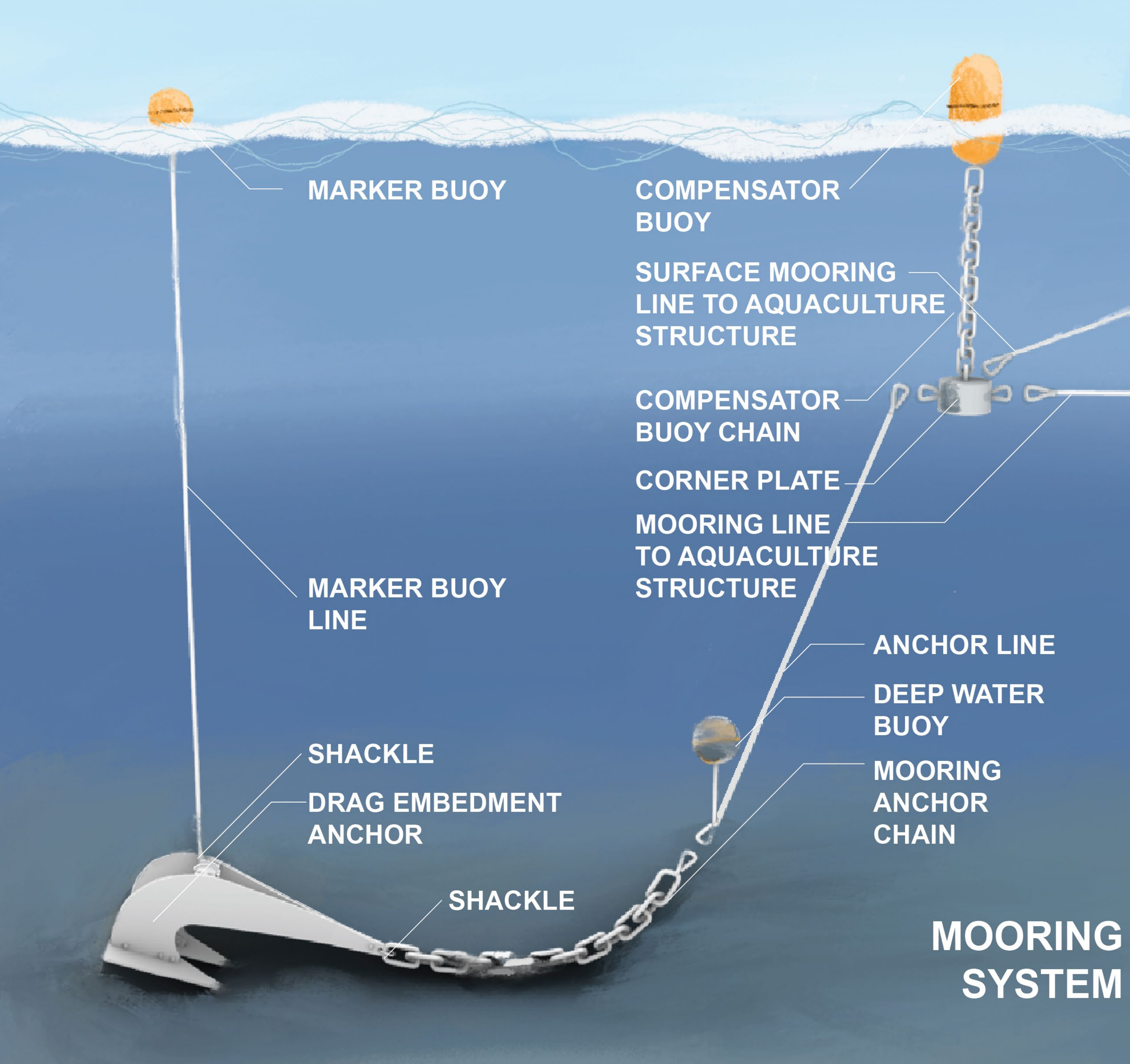
[3] Price, C. S., Keane, E., Morin, D., Vaccaro, C., Bean, D., & Morris Jr, J. A. (2016). Protected Species & Longline Mussel Aquaculture Interactions. *NOAA Technical Memorandum NOS NCCOS*, *211*, 85. [Available at https://coastalscience.noaa.gov/data_reports/protected-species-and-marine-aquaculture-interactions/]

CHAPTER 1



MOORING SYSTEM

CHAPTER 1 : GEAR COMPONENTS

INTRODUCTION

This section provides terminology and descriptions of gear components that are common to many aquaculture systems, such as ropes, netting, and anchors. Some components are critical to ensure the containment of cultivated species, and others are essential for maintaining the stability and positioning of overall systems. The design of an aquaculture system should optimize stability and prevent excessive strain on individual components that could lead to damage or structural failure.

Some aquaculture enterprises may employ licensed, professional engineers or use engineering software to design their systems, especially in the case of custom, novel, complex, and/or offshore farms. Whether or not formal engineering plans have been drawn up for a farm, operators should ensure the appropriate size and strength of components are used to ensure integrity of the gear and system.

The overall design and construction of aquaculture systems and their components vary greatly depending on the farm. This chapter provides a generalized overview of common components of aquaculture systems. Additional components and terminology specific to certain types of aquaculture gear systems will be described in subsequent chapters.

ROPES / LINES

FUNCTION

Ropes (also referred to as lines) are used throughout aquaculture systems for mooring, attachments between components, and cultivation.

MATERIALS

Ropes used in aquaculture are predominantly made from synthetic fibers, most commonly nylon, polyester, polypropylene, and high-performance polyethylene (HPPE).[4,5] All of these fibers are popular in marine applications because they are non-water-soluble and have good chemical resistance. They also come in a variety of sizes and color options, so they can be tailored to the needs of each farm. Fibers with high ultraviolet (UV) resistance are especially useful for components exposed to sunlight (e.g., avian predator netting mounted

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[4]Conides, A., Kallias, I., Cotou, E., Georgiou, P., Gialamas, I., & Klaoudatos, D. (2023). Preliminary Results on the Antifouling Potential of Copper Wire and Dyneema® Fiber Combined Twines for Aquaculture Net Cages. *WSEAS Transactions on Environment and Development*, *19*, 607-612.

[5]Fredriksson, D. W., & Beck-Stimpert, J. (2019). Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico. [Available at https://repository.library.noaa.gov/view/noaa/19836]

above finfish net pens); fibers with low stretch are good at maintaining shape, even in strong currents; and fibers with higher buoyancy have a counterbalance utility in components that may be weighed down (e.g., mussel dropper lines).

FABRICATION

The breaking strength, weight, elasticity (length change with applied tension), durability (ability to withstand wear, pressure, or damage), longevity, and intended use are all factors that determine rope selection. The fabrication process affects these characteristics.

Ropes can generally be divided into two types: braided and twisted (Figure 1.1).[6]

* Braided rope is usually composed of a braided outer coat surrounding an inner core. The outer coat is braided, while the inner core is made with either twisted or braided rope. Some braided rope can have a double outer coating to improve the abrasion resistance. Some braided rope may lack an inner core. Braided rope without a core provides more elasticity and resistance to torsion.
* Twisted rope is composed of multiple strands, each of which consists of several twisted yarns (in either a clockwise or anticlockwise twist). The tighter the twisting, the greater the abrasion resistance and the longer-lasting the rope. A softer, or looser, twist is generally preferred if splicing is needed.

Figure 1.1: Examples of braided rope (left) and twisted rope (right) from Ropes.com

NETTING

FUNCTION

Netting is used to contain cultivated species and to deter wildlife from depredation via physical exclusion (e.g., predator netting). Selecting the appropriate netting to meet

[6]Pan, N., & Brookstein, D. (2002). Physical properties of twisted structures. II. Industrial yarns, cords, and ropes. *Journal of applied polymer science*, *83*(3), 610-630.

performance requirements can be informed by specifications such as strength and durability, buoyancy and sink rates, hydrodynamics, and biofouling resistance.

MATERIALS

Netting can be constructed from nylon, polyester, polypropylene, polyethylene, or HPPE. Netting can also be made from more rigid materials such as plastic, copper alloy mesh (with the added benefit of anti-fouling properties), polyethylene terephthalate, and polyvinyl chloride (PVC) coated galvanized steel wire mesh.[7] Rigid netting can be used to minimize biofouling and external predation.

Polypropylene and nylon are commonly used for netting exposed to sunlight (e.g., bird predator netting), while polyethylene is used for underwater netting. Prior to deployment, netting can be treated with coatings that stiffen the fibers, making them less susceptible to depredation.[8] Net coatings can be latex, acrylic, polyester, epoxy, or alkyd resins, and can be colored to deter certain predators or for farm identification purposes. Guidelines on net coatings ensure that they are applied properly and will not release toxins into the environment.

FABRICATION

Netting is created by weaving plastic or natural fibers or metal wire into a mesh. Steel and other metallic materials susceptible to corrosion are typically coated in a plastic substance for corrosion resistance. Copper alloy is typically not coated due to its innate anti-corrosion properties. For plastic netting, such as netting made with polypropylene or polyethylene, it is important to note that recycled plastic material may not have the same level of durability as virgin plastic material. The size of the mesh and the placement of knots and seams within the overall netting structure influences its strength, integrity and overall performance as well as dictates its preferred use.

Mesh size is measured as the length of a whole stretched mesh (Figure 1.2) or involves counting the number of meshes and is directly related to the hanging ratio or how the netting is attached to its support. Proper attachment and support of the netting is

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[7]Fredriksson, D. W., & Beck-Stimpert, J. (2019). Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico. [Available at https://repository.library.noaa.gov/view/noaa/19836]

[8]Florida Department of Agriculture and Consumer Services (FDACS). (2020). Information and Regulations for Clam Aquaculture: Net Coatings. *FDACS-P-0069 Technical Bulletin #03*. [Available at https://ccmedia.fdacs.gov/content/download/81832/file/information-and-regulations-for-clam-aquaculture-technical-bulletin-3.pdf].

necessary in order to maintain its shape and structure, keep the netting in place and to reliably distribute the forces that may be acting upon it.

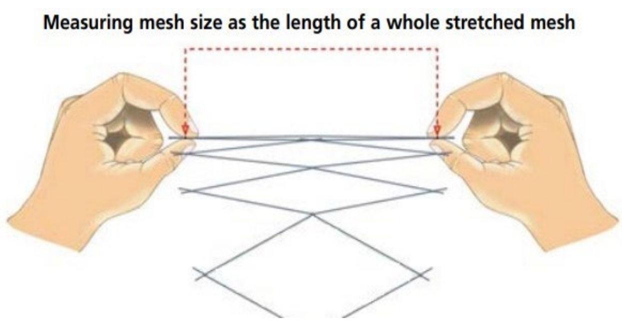

Figure 1.2: Typical methodology for measuring the length of a net mesh[9]

ANCHORS

FUNCTION

Anchors are used in aquaculture systems for maintaining tension and positioning of gear in place. Anchors used in aquaculture systems include drag embedment, direct embedment, and deadweight anchors. The selection of an anchor depends on the seafloor substrate type, total loads, and the design and complexity of the mooring system. A single facility may use a combination of anchor types to achieve the desired results as each anchor types have advantages and disadvantages as shown in Tables 1.1 and 1.2.

[9]Gilman, E., Chopin, F., Suuronen, P., & Kuemlangan, B. (2016). Abandoned, lost or otherwise discarded gillnets and trammel nets. *FAO Fisheries & Aquaculture Technical Paper*, (600).

Table 1.1: Advantages of various anchors, reproduced with modifications[10]

Drag-Embedment Anchor	Direct-Embedment Anchor	Deadweight Anchor
Capacity exceeds 100,000 lbs.	Capacity may exceed 100,000 lbs.	Large vertical reaction component, permitting shorter mooring-line scope
Broad range of anchor types and sizes are available	Broad range of sizes available	No setting distance required
Standard, off-the-shelf equipment can be used; broad use experience exists	May be installed in a variety of soils including rock	Reliable holding force from anchor mass
Continuous resistance can be provided even though maximum capacity is exceeded	Capable of vertical and horizontal loads, permitting shorter mooring-line scope	Simple, onsite constructions are feasible
Usable with wire or chain mooring lines	Dragging is limited	Size is limited only to load-handling equipment
Can be repositioned to manage pre-tension of system	Higher holding capacity-to-weight ratio than any other type of anchor	Economical if material is readily available
Recoverable	Handling is simplified due to its relatively light weight	Reliable on thin sediment cover over rock
-	Accurate placement is possible	Mooring-line connection is easy to inspect and service
-	Does not protrude above the seafloor	Scour of bottom habitat can be avoided through careful design
-	Scour of bottom habitat can be avoided through careful design	-

[10]U.S. Navy (1986). Fleet Moorings: Basic Criteria and Planning Guidelines. Naval Facilities Engineering Command. Design Manual 26.5.

Table 1.2: Disadvantages of different anchor types reproduced with modifications[11]

Drag-Embedment Anchor	Direct-Embedment Anchor	Deadweight Anchor
Incapable of sustaining vertical loading	Anchor is susceptible to cyclic load-strength reduction when used in taut moorings in loose and or coarse-silt seafloors.	Horizontal load resistance is low compared to that for other anchor types
Does not function in hard seafloors; behavior is erratic in layered seafloors	For critical moorings, knowledge of soil engineering properties is required.	Usable water depth is reduced; deadweight can be an undesirable obstruction
Resistance to uplift is low; therefore, large line scopes are required to cause near-horizontal loading at the seafloor	Anchor typically is not recoverable.	Requires large-capacity load-handling equipment for placement
Penetrating/dragging anchors can damage pipelines, cables, etc.	Special equipment needed to install	-
Scour of bottom habitat is common	Not suitable for high horizontal loads	-

DRAG EMBEDMENT ANCHORS

Drag embedment anchors derive their holding capacity from being embedded (buried) in the seafloor, with their holding capacity being directly related to anchor size and embedment depth. Drag embedment anchors typically have three components: the fluke, shank, and pad eye (shackle connection point) (Figure 1.3). Drag embedment anchors rely on horizontal loading to achieve their maximum holding capacity and, therefore, require a chain connection to weigh down the near section of the mooring line. The flukes of the anchor dig in when the anchor is pulled horizontally across the substrate, thus embedding the anchor (Figure 1.4). Some anchor models are designed to flip over to the correct

[11]U.S. Navy (1986). Fleet Moorings: Basic Criteria and Planning Guidelines. Naval Facilities Engineering Command. Design Manual 26.5.

orientation when dragged so they can dig into the substrate. Some degree of scour of the substrate is associated with anchor placement and the dynamics of the attached chain.

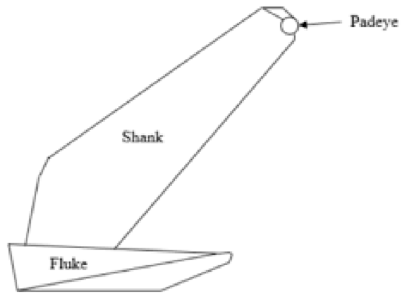

Figure 1.3: Examples of a stingray drag embedment anchor that is used for mooring systems with large loads[12]

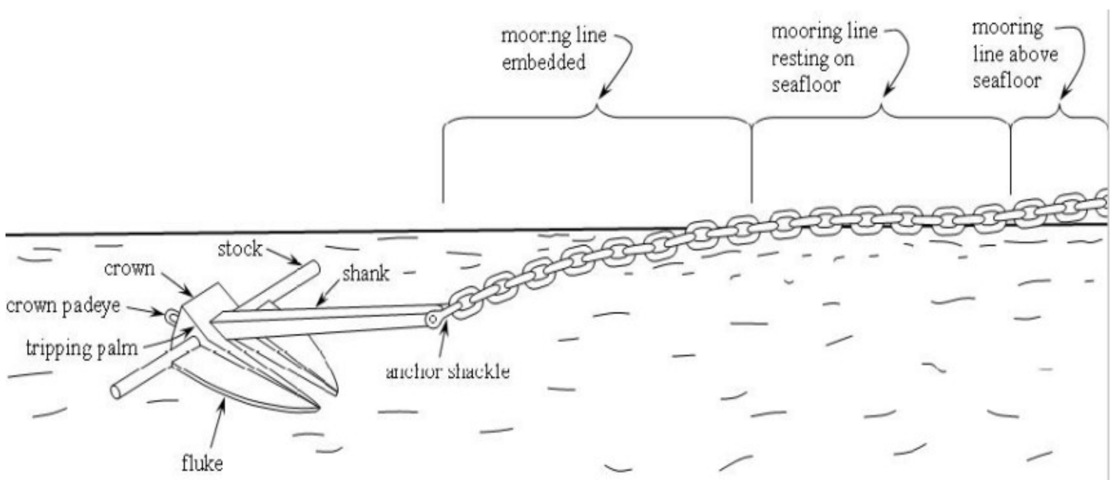

Figure 1.4: Danforth anchor drag embedment anchor system[13]

[12]Miedema, S. A., Lagers, G. H. G., & Kerkvliet, J. (2007). An overview of drag embedded anchor holding capacity for dredging and offshore applications. *WODCON, Orlando, USA*.

[13]Monaco, Tiffany Z. (2013). Experimental Studies of Scale Model Drag Embedment Anchors (DEAs) Subjected to Impulse Forces. Civil and Environmental Engineering - Theses. 4. [Available at https://surface.syr.edu/cie_thesis/4]

DIRECT EMBEDMENT PENETRATING ANCHORS

Direct embedment penetrating anchors (e.g., pile or screw-in) are driven into the seafloor and hold loads both vertically and horizontally. Helical (or screw) anchors (Figure 1.5) consist of helical plates attached to a steel shaft. The helical anchor is secured by twisting it into the seafloor, and the helical plates provide the majority of the holding capacity, similar to the threads on a screw. Helical anchors can be installed by hand or mechanically depending on holding capacity requirements. The length of the mooring line determine the potential for this type of mooring to scour the bottom around the anchor.

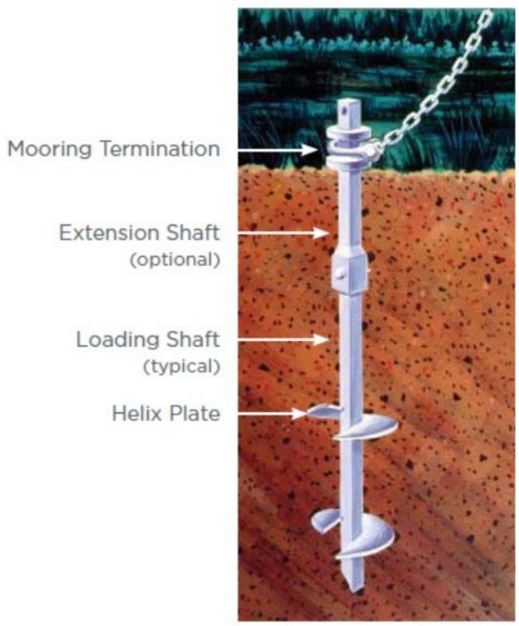

Figure 1.5: Example of a helical (or screw) direct embedment anchor.[14]

DEADWEIGHT ANCHORS

Deadweight anchors come in a variety of shapes, sizes, and materials but are most commonly concrete block structures (Figure 1.6). Their holding capacity is primarily derived from their weight but can also come from the friction occurring between the anchor and seafloor (this capacity is only from horizontal loading). Some models of deadweight anchors, such as mushroom anchors (Figure 1.7), are designed to sink into soft sediment and resist moving by having a large surface that holds mud that adds to the weight and resistance of the anchor. Deadweight anchors weigh less submerged in water

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[14]Scott, Stephen. (2021). Helical Anchors: The Superior Choice for Mooring Applications. [Available at https://blog.hubbell.com/en/chancefoundationsolutions/helical-anchors-the-superior-choice-for-mooring-applications]

than they do on land, due to the buoyant forces of the water acting on the anchor. For example, a concrete deadweight anchor weighing 1,000 lb does not achieve a 1,000 lb holding capacity when submerged because of the buoyancy of the concrete. The length of the mooring line determines the potential for this type of mooring to scour the bottom around the anchor.

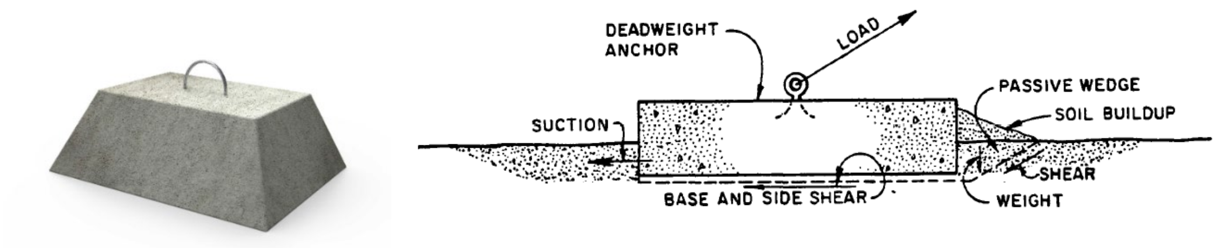

Figure 1.6: Example of a deadweight anchor (with "through-hole" for mooring chain attachment) (Left)[15] and loads acting on a deadweight anchor (Right)[16]

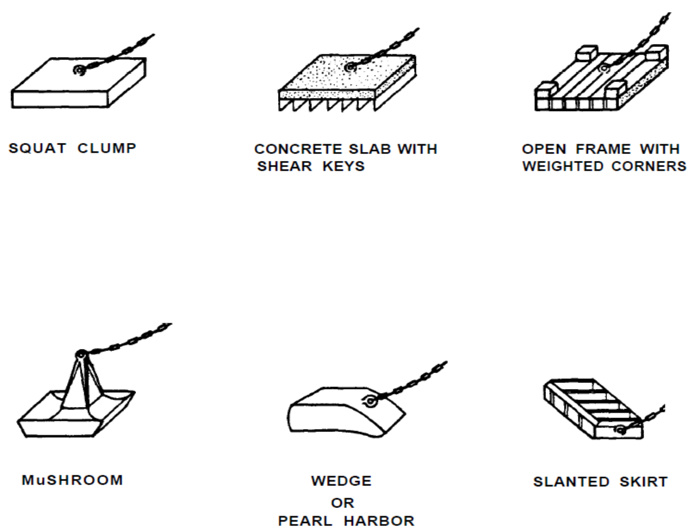

Figure 1.7: Types of deadweight anchors[17]

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[15]Canada Docks. 150 lb concrete anchor. [Available at https://www.canadadocks.ca/shop/dock-accessories/anchors/150lb-concrete-anchor]

[16] U.S. Navy (1986). Fleet Moorings: Basic Criteria and Planning Guidelines. Naval Facilities Engineering Command. Design Manual 26.5.

[17] U.S. Navy (1986). Fleet Moorings: Basic Criteria and Planning Guidelines. Naval Facilities Engineering Command. Design Manual 26.5.

FARM MARKERS

FUNCTION

Farm markers indicate the location of specific components, mark the boundaries of a farm, or serve as warning markers indicating restricted areas. In the U.S., there are regulations and guidelines for farm markers for aquaculture farms, depending on the size of the farm, the location (state or federal waters), and the environment (water depth, etc.). State agencies responsible for issuing aquaculture permits may dictate farm marking requirements for a variety of reasons including navigation or permit number display. The U.S. Coast Guard (USCG) is the federal agency responsible for ensuring safe navigation and farm marking requirements for navigation purposes.

MATERIALS

Farm markers may consist of posts or buoys or a combination of the two. Farm posts can be made from wood, PVC, or steel and the size of the post will vary depending on the size of the farm, water depth, and permit requirements. Buoys can also be used as farm markers. Buoy size requirements are typically related to the dimensions of the buoy's topmark (identification marking at the surface), its shape, and the length and visibility of its daymarks or light signals. Marker buoys (Figure 1.8) are composed of durable plastics or painted steel resistant to UV exposure, are filled with air or foam, and are made more visible by bright coloration, reflective surfaces, and lights. They often have attachment points for ease of deployment and anchoring.

Figure 1.8: Example of a buoy that can be used to mark the boundary of an aquaculture farm[18]

[18]Flotex Navigational Buoy. PL Buoy 900 Series. [Available at https://www.floatex.com/product/pl-900-series/]

BUOYS

FUNCTION

Buoys are used in aquaculture systems to provide buoyancy for the aquaculture gear, tensioning, and as farm markers. Buoys are generally described by their buoyancy, expressed as a weight (in pounds or kilograms) or volume (in gallons or liters), and can be a wide variety of shapes and sizes.

MATERIALS

The material used to construct buoys is largely dependent on their size and intended use. Smaller buoys, like those used for smaller scale shellfish systems, are often filled with air instead of polyurethane foam. In larger scale finfish aquaculture systems, the outer material of flexible buoys can be a UV-resistant polyethylene, and the interior a polyurethane foam. A steel bar may also run through the main body of the buoy for support. Other buoys are made from steel plates with a closed cell foam interior. Buoys are attached to lines or chains using short pieces of line, shackles, swivel-eye nuts secured with a locking nut, or pipe assemblies, which provide extra rigidity.[19]

SUBSURFACE BUOYS

Subsurface buoys, also referred to as midline floats or deep-water buoys, are used below the water's surface (Figure 1.9). These types of buoys keep mooring lines or anchor chain systems off the seafloor, and can provide buoyancy to submerged aquaculture structures or components. Their usage reduces potential abrasion of the mooring line by the seafloor and enables easier access to the mooring line anchoring components.

These buoys can be an effective means for avoiding or reducing scour to benthic substrates and habitat by mooring lines and chains. Subsurface buoys are typically constructed from high-density, corrosion-resistant, rigid materials such as PVC or polyethylene and are filled with either foam or air. Deep-water buoys commonly have multiple attachment points for functionality and may include a pressure release valve.

[19] Fredriksson, D. W., & Beck-Stimpert, J. (2019). Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico. [Available at https://repository.library.noaa.gov/view/noaa/19836]

Figure 1.9: Subsurface buoy attached to a thimble, at depth[20]

COMPENSATOR BUOYS

Compensator buoys absorb energy from currents and waves and relieve tension pressure occurring along a line or aquaculture mooring system, by providing counterbalance (Figure 1.10). Compensator buoys are attached along vertical or horizontal lines and can be used to maintain the respective locations of the lines within the water column. Compensator buoys are typically constructed of polyethylene and have internal air bladders that can be adjusted to provide buoyancy control.

Figure 1.10: Image of a compensator buoy used in aquaculture systems from Tidal Marine with a large plate and swivel eye nut on the top to tie onto mooring lines, which helps absorb shock from rough ocean conditions[21]

CHAINS

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[20] Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. *FAO Fisheries and Aquaculture Technical Paper No. 593*. Rome, FAO. 152 p.

[21]Compensator buoy at Tidal Marine. [Available at https://tidalmarine.com/aquaculture-fisheries\

FUNCTION

Chains are used in aquaculture systems for mooring, equipment positioning, and tension control. In mooring systems, they are most often used to connect the anchor to the mooring line or cable which allows the system to remain in place and withstand nearshore ocean conditions (Figure 1.11). They can also function as weights that ensure the entire system remains at a particular desired depth for optimal performance.

Figure 1.11: Anchor, chain, mooring lines, and buoys for a single line kelp longline system in a nearshore, exposed environment[22]

MATERIALS

The selection of appropriate materials for aquaculture chains is crucial to ensure their performance and longevity in the marine environment. Chains can be made from:

* **Galvanized Steel**: Galvanized steel chains are commonly used in aquaculture because of their strength, durability, and corrosion resistance. The galvanizing process adds a protective layer of zinc to the steel to prevent rust and corrosion or;
* **Stainless Steel**: Stainless steel chains are chosen for their superior corrosion resistance. They are particularly suitable for aquaculture systems exposed to highly corrosive saltwater environments.

FABRICATION

[22]St-Gelais, A. T., Fredriksson, D. W., Dewhurst, T., Miller-Hope, Z. S., Costa-Pierce, B. A., & Johndrow, K. (2022). Engineering a low-cost kelp aquaculture system for community-scale seaweed farming at nearshore exposed sites via user-focused design process. *Frontiers in Sustainable Food Systems*, *6*, 848035.

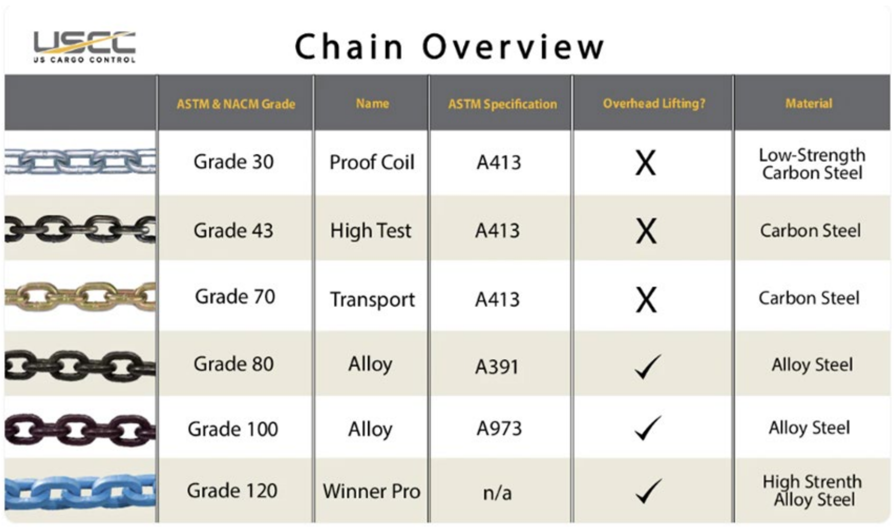
Chains used in aquaculture can vary in link size and strength and often include points of attachment (e.g., shackles) within their design. They can be studless (open-link) or studded, which have a stud in the center of each link (Figure 1.12). Studless chains are used in aquaculture as connection elements between mooring components, such as buoys and corner plates (or rings) of a grid system. Studded chain links can be used in conjunction with mooring lines to provide additional weight, and to maintain the angle between the seafloor and the mooring line within a desired range. Chains of either variety are used to provide tension for aquaculture netting.

Figure 1.12: Studless (left) and Studded (right) chain links [23]

Chain is rated in the U.S. by quality and breaking strength according to American Society of Testing and Materials standards. Chain grades indicate the tensile strength, in Newton per square millimeters (N/mm^2) and what type of material is used to manufacture it (Figure 1.13). The tensile strength of a chain is based on its ultimate breaking strength. The force at which the chain breaks in tension (in units of N) is divided by the area of the two cross sections of a single link (in units of mm).

Steel chain grades used in marine aquaculture range from Grade 30 with a breaking strength of 30 N/mm^2 to Grade 100 with a breaking strength of 100 N/mm^2. When providing an engineering review of a chain used in aquaculture operations, the grade, type of link, and diameter of the chain are important parameters to consider to ensure the structural integrity of the mooring system.

[23]Images of studless and studded chain links. [Available at https://www.qdwaysail.com/]



Chain Overview

	ASTM & NACM Grade	Name	ASTM Specification	Overhead Lifting?	Material
	Grade 30	Proof Coil	A413	X	Low-Strength Carbon Steel
	Grade 43	High Test	A413	X	Carbon Steel
	Grade 70	Transport	A413	X	Carbon Steel
	Grade 80	Alloy	A391	✓	Alloy Steel
	Grade 100	Alloy	A973	✓	Alloy Steel
	Grade 120	Winner Pro	n/a	✓	High Strenth Alloy Steel

Figure 1.13: Example chain sizes and materials from US Cargo Control, a chain manufacturer in the U.S.[24]

CONNECTORS

FUNCTION

Connectors are used in joining, reinforcing, and securing various aquaculture gear components, thereby providing structural integrity to the overall system. Connectors in aquaculture systems include shackles, thimbles, corner plates, and steel rings. The size and type of connector depends most importantly on expected loads. Connectors usually include attachment mechanisms (e.g., pins or bolts) to function properly.

MATERIALS

Like chains, connectors are usually made from either galvanized, stainless, or polyethylene-coated steel.

SHACKLES

Shackles connect multiple components (e.g., mooring ropes, chains, and anchors) in an aquaculture system. Connecting multiple components to a single point can enhance the structural integrity of the system, preventing deformation and damage. Shackles are rated by holding capacity, and come in a variety of shapes and sizes. They are essential for mooring and anchoring systems, ensuring secure connections that withstand environmental forces and loads. Shackles also provide versatility when connecting and

[24] U.S. Cargo Control-Industrial Chain. [Available at https://www.uscargocontrol.com/collections/chain]

adjusting multiple components as needed. Omega-shaped shackles (also called bow shackles) are the most common because they can accommodate a greater number of connections and can take loads from many different directions. Piling shackles have a narrower, elongated, shape, making them more suitable for lifting, and D-shackles (also called chain shackles) are suitable for straight load lifting, as they may bend under side loads (Figure 1.14). Once the components are attached to a shackle, the threaded shackle bolt is usually secured by a cotter pin, zip tie, or steel wire (i.e., "mousing" a shackle), to ensure the components do not become disconnected by vibrating loose.

Figure 1.14: Examples of shackles: Omega (left); Piling (center); D-Shackle (right)[25]

THIMBLES

Thimbles are used to reinforce a rope splice loop (Figure 1.15) when the rope needs to be connected to a metal component such as a shackle or ring. Thimbles protect ropes from wear and abrasion, particularly in high-stress areas such as connection points to anchors or buoys. Additionally, thimbles prevent kinking and fraying of the rope splice loop and maintain the rope's splice loop integrity. Thimble types used for mooring lines are either closed (tube-type) or open (Figure 1.15). Tube-type thimbles reduce the possibility of the splice becoming undone over time and provide more protection to the spliced rope. However, they are heavier and more expensive than open-type thimbles due to the additional steel and labor involved in making them.

[25]Safety lifting gear: Different kinds of shackles. [Available at https://www.safetyliftingear.com/news/post/types-of-shackles]

Figure 1.15: Open thimble inside of a rope splice loop (left), open thimble with no attachments (center)[26], and closed or tube type thimble (right)[27]

CORNER PLATES

Corner plates provide a single location for the connection of multiple components (e.g., lines, buoys, and chains). The connection of multiple components to a single location can enhance the structural integrity of the system, preventing deformation and damage. Corner plates are usually square-shaped and are designed with multiple insertion points for all of the required connections. The insertion points in the corner plates are where, for example, the threaded bolts of the corresponding shackles are inserted (Figure 1.16).

Figure 1.16: Corner plate with multiple shackles connected at various insertion points[28]

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[26]Thimble images [Available at http://E-rigging.com] (right) and https://www.boatus.com/expert-advice/expert-advice-archive/2017/october/thimble-splice](left)

[27]Closed or tube type thimble. [Available at http://E-rigging.com]

[28]Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. *FAO Fisheries and Aquaculture Technical Paper No. 593*. Rome, FAO. 152 p.

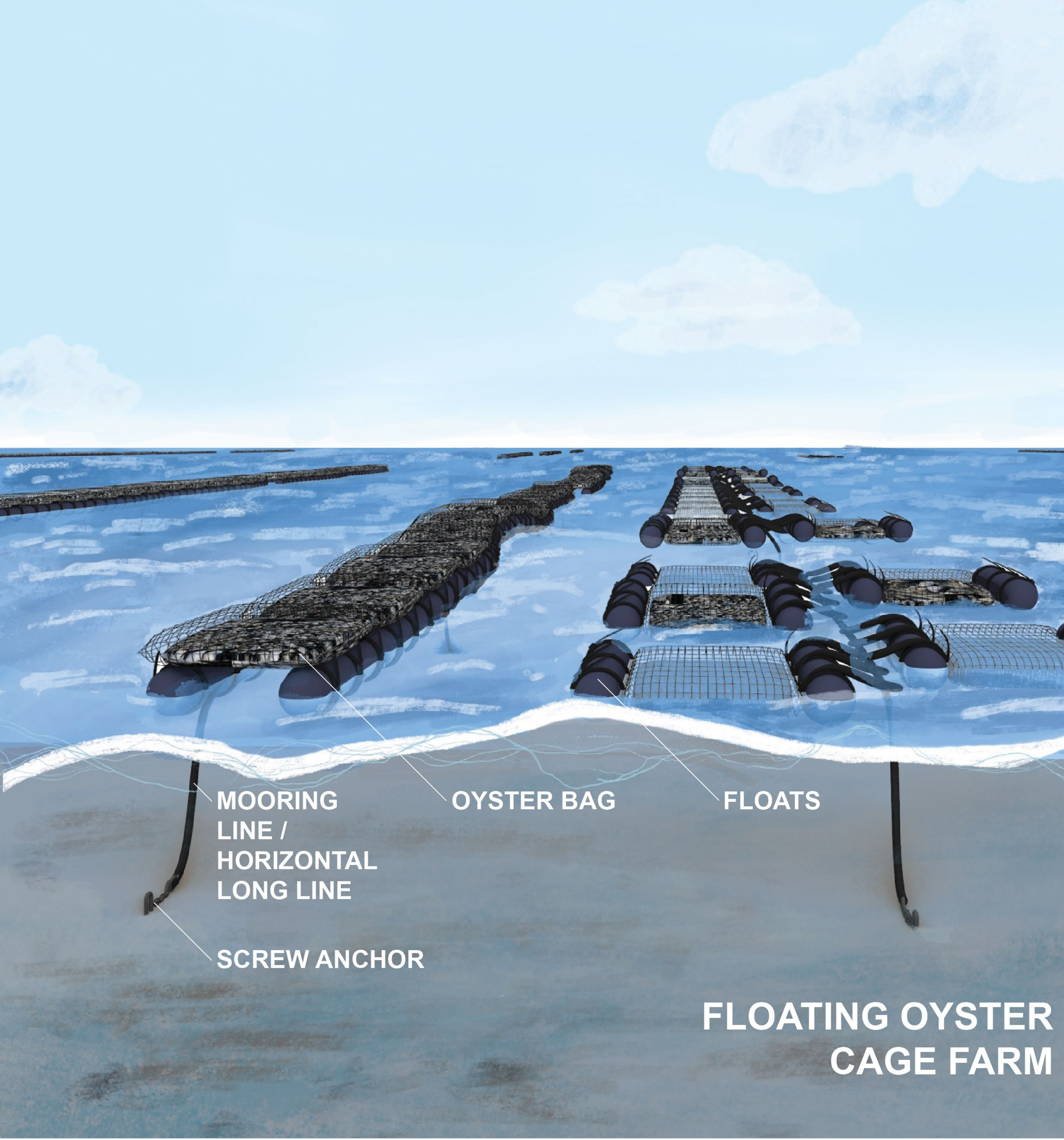
STEEL RINGS

Steel rings can be substituted for corner plates as they also provide a single location for the connection of multiple components (e.g.., lines, buoys, and chains). Steel rings provide a strong, reliable connection point and are particularly useful for attaching netting to support structures. Because of their simple design, steel rings are less expensive than corner plates and are more versatile; however, they have less carrying capacity for components and less holding strength. Round-shaped rings are often used as a point of intersection for different types of lines (e.g., ropes connected to chains). Shackles from chains connect to the ring using cotter pins. Oval-shaped (or elliptical) rings are often inserted into steel thimbles to avoid using larger more expensive components when connecting elements of similar breaking loads (Figure 1.17).

Figure 1.17: Round steel ring with multiple shackles connected (left) and connection of two open thimbles (with eye splice ropes) with round (silver) and oval (red) steel rings using a pair of shackles (right)[29]

[29]Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. *FAO Fisheries and Aquaculture Technical Paper No. 593*. Rome, FAO. 152 p.

CHAPTER 2


MOORING LINE / HORIZONTAL LONG LINE
OYSTER BAG
FLOATS
SCREW ANCHOR
FLOATING OYSTER CAGE FARM

CHAPTER 2 : SHELLFISH AQUACULTURE

INTRODUCTION

This chapter will focus on the most commonly aquacultured shellfish types within the U.S.: oysters, clams, mussels, geoducks, and scallops, and describe cultivation systems and strategies for shellfish aquaculture in inshore and offshore marine environments, their component technologies, and general operations. While land-based hatchery and nursery operations comprise important infrastructure to support shellfish cultivation, these systems and facilities are outside the scope of this guide, which is focused on shellfish aquaculture gear in the marine environment.

Farming of marine bivalves, known as shellfish aquaculture, has occurred throughout the world for centuries. Today, all U.S. coastal regions engage in shellfish aquaculture[30], with farms predominantly sited in inshore environments (e.g., bays and estuaries). Shellfish aquaculture gear systems can be placed in or on the bottom substrate, off-bottom, suspended in the water column, or floated/suspended at the surface (Table 2.1). Shellfish that are not cultured directly in or on the bottom are often cultured using a primary containment structure that's optimized for the specific environment.

There are a wide variety of containment designs for shellfish aquaculture, with containers varying in dimension, material, and mesh size based on the species and age class they're designed to hold. Although shellfish can be cultivated without containers (e.g., oyster aquaculture in Willapa Bay, Washington and indigenous clam gardens in the U.S. Pacific Northwest), they are technically considered "gearless". Therefore, the aquaculture systems described in this chapter are those designed with the use of manmade containment systems.

The specific system components selected by shellfish farmers depend on many factors, including availability, cost, maintenance requirements, harvest strategy, environmental conditions, and market specifications for a particular species and location. The specific culture method used will depend primarily on the species being cultured and local environmental conditions. On-bottom shellfish aquaculture is prone to more biofouling and benthic predation, than shellfish grown in off-bottom systems. Off-bottom shellfish aquaculture typically has increased growth rates and reduced predation by benthic predators; however, it can be labor intensive.

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[30] NOAA Fisheries. (2025). Understanding Shellfish Aquaculture. [Available at https://www.fisheries.noaa.gov/insight/understanding-shellfish-aquaculture#what-are-the-major-concerns-with-respect-to-aquaculture-and-the-environment]

Table 2.1: Comparison of shellfish aquaculture gear systems

-	On Bottom/In Bottom	Off-bottom	Suspended Longline	Floating Gear	Rafts
Examples	Bags, Mesh or PVC Tubes	Stacked racks, rack and bag	Tumble gear, pearl nets, lantern nets, suspended bags/cages	Floating bags or cages	Wooden rafts
Description	Shellfish seed placed on the seafloor or in containers that are anchored to or in the seafloor	Gear sits on the seafloor, but keeps shellfish suspended in the water column	Horizontal longline strung parallel to the seafloor between posts driven into the substrate with lines, bags, or cages suspended vertically from the longline	Bags or cages with floats that can be strung together in a row along a horizontal longline	Wooden raft from which lines, bags or cages are suspended vertically
Advantages	Low cost compared to other gear	Increased water flow	Avoids benthic predation	Avoids benthic predation	Avoids benthic predation
-	Vessel is not often required	Delivery of suspended nutrients	More control of biofouling than off-bottom gear	More control of biofouling than off-bottom gear	More control of biofouling than off-bottom gear
Challenges	Predation due to easy access by benthic predators	Cost of gear	Cost of gear	Cost of gear	Cost of gear
-	-	Increased labor to install, maintain, and harvest over on-bottom gear	Have to sink during storms	Have to sink during storms	More labor required than off-bottom gear

SHELLFISH GEAR COMPONENTS GLOSSARY

ANCHORS AND MOORING SYSTEMS

Shellfish aquaculture systems use anchors that are appropriate for holding in intertidal and nearshore environments. Shellfish anchor systems vary greatly but can include drag, deadweight, and direct embedment anchors (see Chapter 1 for more information). Direct embedment anchors such as toggle anchors (e.g., Platipus™ anchors; Figure 2.1) and auger (also known as helical) anchors are common in shellfish systems. Auger anchors are widely used for floating systems as they are low cost and readily available. Toggle anchors can be easily installed by hand or from a vessel and can be tensioned after installation. They consist of an anchor, wire tension rod, and top accessory. Shellfish aquaculture mooring systems consist of a line or chain link that attaches to a line that extends from the anchor to the surface. The use of chain and the chain size selected is dependent on depth, size of the gear, and required holding capacity (general chain information can be found in Chapter 1).

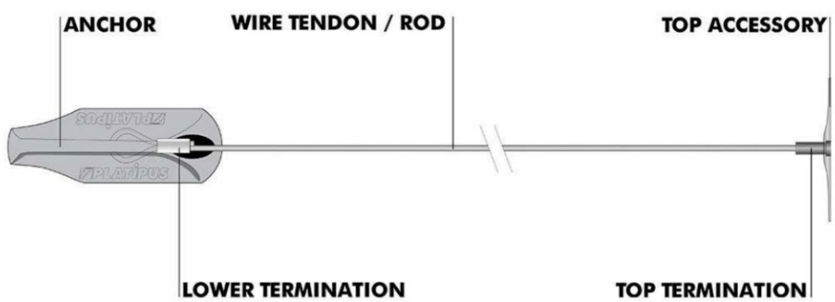

Figure 2.1: Platipus™ anchor system labeled with individual components[31]

GROUNDLINES

Groundlines are lines that hold on-bottom oyster bags in place by anchoring them at either end to the sea floor. Groundlines are typically made of metal braided line.

BUOYS

Buoys for shellfish aquaculture systems are sized for intertidal and subtidal nearshore environments and low wave energy environments. They can be used as farm markers or to

[31] Platipus Earth Anchor Systems. Anchor Designs. [Available at https://platipus.us/learn-more/about-the-platipus-earth-anchors/]

provide buoyancy to suspended longline systems to maintain the gear at a particular depth. More information on buoys can be found in the Buoy Section of Chapter 1.

HORIZONTAL LONGLINE/BACKBONE

Horizontal longlines, also known as backbones, are lines from which floating containment bags, cages, or vertical dropper lines are hung in suspended longline aquaculture. These lines connect bags and/or cages together or provides substrate for cultivated species to grow on. Horizontal longlines are typically some form of polyester/polyethylene blend rope and line diameter is dictated by design loading and availability.

BAGS, CAGES, TRAYS

Shellfish can be grown in containment systems, which can be either bags, cages, or trays made from metal or plastic (see Oyster section below for more information).

PVC/MESH TUBES

PVC and mesh tubes are used as predator deterrence for geoduck farms in the early stages of growth. The tubes are removed as the geoduck increases in size and then are reused for newly planted animals.

PREDATOR NETTING

Predator netting is used in shellfish aquaculture to prevent predators from feeding on the shellfish being cultivated. In shellfish farms, predator netting is used predominantly in clam aquaculture over on-bottom clam aquaculture or over tubes in geoduck aquaculture. Geoduck tubes are often covered with wire netting for predator control (see geoduck section below). The types of netting used in shellfish aquaculture operations varies, but netting generally is described in more detail in Chapter 1.

PILINGS AND POLES

Pilings are used in shellfish aquaculture for farm navigation markers and to construct farm systems. Farm pilings are often used to hang horizontal longlines/backbones in oyster, mussel, and scallop aquaculture systems (Figure 2.2). Pilings can be made from wood or PVC and may range from 6-18 in (15-45 cm). Farm markers are discussed in Chapter 1.

Figure 2.2: Off-bottom oyster aquaculture gear system showing cages hanging from a horizontal longline where each longline is attached to a pile, which keeps the longlines from sagging due to the weight of the bags[32]

SAND BAGS

Sand bags are plastic mesh bags filled with either rock or sand that are used to hold down predator netting on clam farms.

OYSTER AQUACULTURE

The main oyster species currently cultivated in the U.S. are the American (or Eastern) oyster (*Crassostrea virginica*) and the Pacific oyster (*Magallana gigas*). Other oyster species such as the Kumamoto oyster (*Crassostrea sikamea*), European flat oyster (*Ostrea edulis*), and Olympia oyster (*Ostrea lurida*) are cultivated on a smaller scale for boutique markets. Oyster aquaculture gear selection depends on factors such as desired growth rate,

[32]NOAA Fisheries. Aquaculture in the Southeast Region. [Available at https://www.fisheries.noaa.gov/southeast/aquaculture/marine-aquaculture-noaa-fisheries-southeast-region]

salinity preference, phytoplankton biomass consumption rate, and local predators, which all vary depending on the species and environment.[33,34]

The most common containment systems of most oyster aquaculture are oyster bags, cages, and baskets (Figure 2.3).

* **Oyster Bags** are made of a stabilized plastic mesh that is flexible, but stiff enough to maintain some degree of structure. Oyster bags are available in a range of mesh sizes that can be used to accommodate different size classes while allowing for the exchange of seawater through the bag.

* **Cages** are structures used to house multiple oyster bags. Cages are made of rigid materials such as hard plastic, steel wire, or aluminum, and have hatches that can be opened and closed to insert and remove oyster bags.

* **Baskets** (and trays) are rigid, injection-molded plastic containers that come in a variety of designs to hold oysters with integrated, articulating features such as opening hatches and clips that attach directly to lines.

Figure 2.3: Oyster bags from OysterGro®(left), Oyster cages from Flow and Grow™(center), and Oyster baskets from Hexcyl systems (right)[35]

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[33]Walton, W. C., Davis, J. E., Chaplin, G. I., Rikard, F. S., Hanson, T. R., Waters, P. J., & Swann, D. L. (2012). Off-bottom oyster farming. *Agriculture and Natural Resources Timely Information: Fisheries and Aquaculture Series. Alabama Cooperative Extension System. 8pp*.

[34]Yang, H., Sturmer, L.N. & Baker, S.M. (2016). Molluscan Shellfish Aquaculture and Production. UF/IFAS Extension: Program in Fisheries and Aquatic Sciences of the School of Forest Resources and Conservation-#FA191. pp.8.

[35]OysterGro Bags (left). [Available at http://OysterGro.com]; Ketcham SupplyFLOW N GROW™ bay floating oyster cage (center) [Available https://ketchamsupply.com/product/low-pro-deluxe/]; Hexcyl oyster baskets (right) [Available at https://hexcylsystems.com.au/].

ON-BOTTOM GEAR

On-bottom oyster aquaculture gear is characterized by containers that are anchored to the seafloor in the intertidal zone. Containers may consist of individual bags or cages that can hold multiple bags. Individual bags can be anchored to the seafloor using metal stakes (Figure 2.4). Alternatively, individual bags can be strung together with groundlines and then anchored to the seafloor at the end of each groundline. Cages containing multiple bags of oysters can also be placed on the seafloor, which may be heavy enough to not require an anchoring system (Figure 2.5).

On-bottom oyster cultivation can be less costly than off-bottom culture, since less gear may be required.[36] However, on-bottom oyster cultivation is more prone to fouling of gear, predation, and siltation impacts/effects. Siltation in on-bottom oyster aquaculture has been found to lower survival rates, as spat gets smothered in sediment. On-bottom oysters also have a higher potential for clumping together, which can inhibit individual growth.

Figure 2.4: On-bottom bags for oyster aquaculture

[36]Petrolia, D. R., Walton, W. C., & Cebrian, J. (2022). Oyster economics: Simulated costs, market returns, and nonmarket ecosystem benefits of harvested and non-harvested reefs, off-bottom aquaculture, and living shorelines. *Marine Resource Economics*, *37*(3), 325-347.

Figure 2.5: On-bottom six-compartment cage for up to 6 grow-out bags (Photo courtesy of Zachary Gordon, NOAA Fisheries)

OFF-BOTTOM GEAR

Off-bottom oyster aquaculture is defined as gear that sits on the seafloor, but keeps shellfish suspended in the water column. The definition of off-bottom may vary based on specific U.S. state aquaculture permit requirements. U.S. states aquaculture agencies often offer either a bottom-only, water-column only, or combined aquaculture lease. They may define off-bottom as any gear that is not directly sitting on the bottom, or gear that is a defined height off of the bottom. Either way, off-bottom gear differs from on-bottom aquaculture in that the oysters are in the water column, exposing them to increased water flow and delivery of suspended nutrients. This leads to decreased predation from benthic predators, leading to increased growth rates and improved overall yields.[37]

Culturing oysters using off-bottom gear allows the farmer to take advantage of areas with soft substrates that are not normally conducive to on-bottom oyster growth (e.g., mud mix). However, off-bottom gear requires significantly more initial investment due to the cost of the gear[38], can require a larger area, and requires greater labor to install and

[37]Walton, W.C., Davis, J.E. & Supan, J.E., (2013). Off-bottom culture of oysters in the Gulf of Mexico. *SRAC Publication No. 4308*.

[38]Engle, C., van Senten, J., Parker, M., Webster, D., & Clark, C. (2021). Economic tradeoffs and risk between traditional bottom and container culture of oysters on Maryland farms. *Aquaculture Economics & Management*, *25*(4), 472-503.

maintain.[39] Off-bottom oyster aquaculture gear is growing in popularity compared to the more traditional on-bottom gear on the U.S. East Coast, due in part to research indicating off-bottom gear has the potential to increase growth rates by 50-percent because of increased water flow and decreased mortality from benthic predation.[40]Along the U.S. West Coast, similar improved growth and survival has been demonstrated[41] and market demand for half shell oysters has driven the transition from on-bottom to off-bottom culture. The Pacific oyster's elevation off the seafloor provided innovation opportunities and the creation of a deep-cupped Pacific oyster that mimics the highly sought after Kumamoto oyster for the half shell trade (Teri King, NOAA Fisheries, personal communication).

As stated in the introduction, there is immense variation among aquaculture systems, and the aquaculture gear used in off-bottom oyster cultivation throughout the U.S. is no exception. In this section, we have attempted to provide as many representative examples of off-bottom oyster aquaculture gear as possible.

RACK AND BAG

Rack and bag aquaculture gear is a type of off-bottom gear, preferred by farmers in areas of unsuitable substrate for on-bottom culture and with a shallow tidal range (Figure 2.6). The rack component is a rigid table-like frame, typically made of galvanized rebar that is placed directly on the seafloor, with the legs driven into the sea floor for stability.[42] An oyster bag, typically constructed of a stiff plastic mesh, is filled with oyster seed and secured on top of the rack with zip ties, plastic clips, or bungee cords. The rack structure keeps the bags off the bottom, minimizing predation from benthic predators. Rack and bag units are normally laid out in rows and separated by lanes or alleys to allow for access by the farmer.

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[39]Davis, J.E., B. Walton, G. Chaplin, F.S. Rikard, D.L. Swann & T. Hanson. (2012). Gulf Coast Off-Bottom Oyster Farming Gear Types: Adjustable Long-line System. Mississippi-Alabama Sea Grant Consortium Publication

[40] Paynter, K. T., & DiMichele, L. (1990). Growth of tray-cultured oysters (Carssostrea virginica) in Chesapeake Bay. *Aquaculture*, *87*(3-4), 289-297.

[41] Ruesink, J. L., Houle, K., Beck, E., Boardman, F. C., Suhrbier, A., & Hudson, B. (2023). Intertidal Grow-Out Technique, Not Eelgrass (Zostera marina), Influences Performance of Pacific Oysters (Magallana gigas). *Aquaculture Research*, *2023*(1), 6621043.

[42]Davis, J.E., B. Walton, G. Chaplin, F.S. Rikard, D.L. Swann & T. Hanson. (2012). Gulf Coast Off-Bottom Oyster Farming Gear Types: Adjustable Long-line System. Mississippi-Alabama Sea Grant Consortium Publication #12-013-01. 2 pp. [Available at https://shellfish.ifas.ufl.edu/wp-content/uploads/Off-Bottom-Culture-of-Oysters-in-the-GoM-SRAC-4308.pdf]

Figure 2.6: Oyster farmers working on rack and bag gear[43]

STACKED RACK AND BAG

Stacked rack and bag gear is an enhancement of the single rack and bag system described above. Multiple rigid racks, usually constructed of galvanized rebar, are placed atop of one another forming a single, vertical unit of multiple racks. This entire multi-rack structure is then placed on the seafloor. Oyster bags are filled with seed and then secured to each of the individual racks of the multi-rack unit (Figure 2.7). As with the single bag and rack gear, the stacked bag and rack gear keeps the bags off the bottom. This stacked rack methodology consolidates more oyster bags in a given space, thereby reducing the total farm footprint.

Figure 2.7: Oyster rack and bag system exposed to air during low tide [44](left) and multi-tiered oyster rack and bag system [45](right)

[43]The different methods of Growing Oysters. [Available at https://www.pangeashellfish.com]

[44]Getchis, T. L. (2014). Northeastern U.S. Aquaculture Management Guide: A manual for the identification and management of aquaculture production hazards. Northeastern Regional Aquaculture Center and US Department of Agriculture.

[45]Sturmer, L. (2013). Introduction to intensive oyster aquaculture: Overview of U.S. East Coast oyster culture operations and Florida's experiences. Carabelle and Cedar Key Workshop Presentations. September 26-27, 2013.

SUSPENDED GEAR

Suspended aquaculture gear, also known as adjustable longline gear, consists of a main horizontal longline strung parallel to the seafloor between wooden, PVC, or metal piles driven into the substrate. The diameter of these piles varies depending on the depth of water, substrate type, exposure to prevailing winds and wind-driven adverse weather events, maximum expected tidal and flood-driven currents, and the shape of the lease area. Oysters are grown in bags or cages that are suspended from the horizontal longlines using lines or clips (Figure 2.8).[46] The oyster seed is loaded into the containers before deployment and the entire system is oriented perpendicular to the wind and waves, when possible. The lines used to hang the bags or cages are usually the same diameter as the horizontal longline but can vary in diameter depending on the distance between the posts, the number of bags or cages to be hung, and farmer's preference. Adjustment of the individual lines connected to the bags or cages allows the containers to be raised and lowered in the water column to maximize oyster feeding duration, control exposure to the air to address biofouling, and maintain access to the cages for maintenance or harvest.

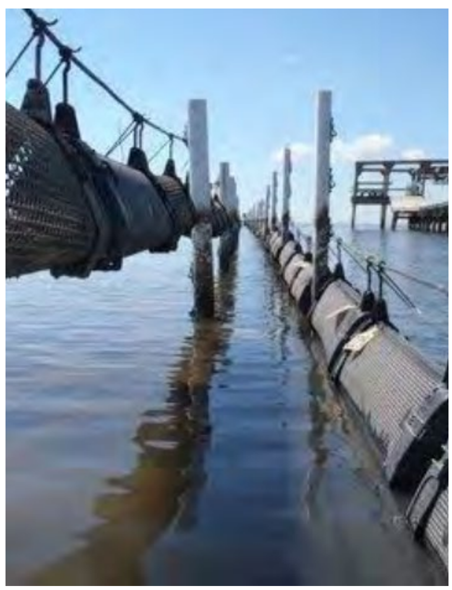

Figure 2.8: Suspended longline gear hanging above the air-water interface[43,47]

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[46]Davis, J.E., B. Walton, G. Chaplin, F.S. Rikard, D.L. Swann & T. Hanson. (2012). Gulf Coast Off-Bottom Oyster Farming Gear Types: Adjustable Long-line System. Mississippi-Alabama Sea Grant Consortium Publication #12-013-01. 2 pp. [Available at https://shellfish.ifas.ufl.edu/wp-content/uploads/Off-Bottom-Culture-of-Oysters-in-the-GoM-SRAC-4308.pdf]

[47]Davis, J.E., B. Walton, G. Chaplin, F.S. Rikard, D.L. Swann & T. Hanson. (2012). Gulf Coast Off-Bottom Oyster Farming Gear Types: Adjustable Long-line System. Mississippi-Alabama Sea Grant Consortium Publication

However, this can be labor intensive and expensive due to pile installation and extensive maintenance during the growing season[48] as the lines require frequent and intermittent fine-tuning based on intertidal water level changes.[49]

INTERTIDAL TUMBLE OYSTER SYSTEMS

Intertidal tumble oyster systems (also called “flip-bag” oyster culture) use tumble bags that rotate around a line or pole, which allows for shearing of the fluted edges of the oyster, forcing growth into the depths of the oyster versus the length (Figure 2.9). A variety of tumbling techniques have been developed by U.S. West Coast producers, and innovation continues to perfect the gear used to create the oyster shape desired by the farmer and the consumer. Some tumble bags require floats that are attached to individual bags so that, as the tide comes in, the bags rotate around their pole or line by 180 degrees to sit above the longline. As the tide recedes, the bag flips over, the oysters gently tumble to the other end of the bag or container and if a float is attached, it rests just off the seafloor. Some tumbled oysters are grown in cylindrical containers that rotate around a pole with tidal action to produce a continually tumbled oyster versus a tidally-influenced tumbled oyster. This method harnesses the power of flood and ebb tides to tumble the oysters, which reduces the handling needs required to achieve an oyster optimized for the half shell market.[50]

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[48] Southern Regional Aquaculture Center. 2013. Off Bottom Culture of Oysters in the Gulf of Mexico. SRAC Publication No. 4308. 2 pp. [Available at https://shellfish.ifas.ufl.edu/wp-content/uploads/Off-Bottom-Culture-of-Oysters-in-the-GoM-SRAC-4308.pdf]

[49] Doiron, S. (2008). Reference Manual for Oyster Aquaculturists. New Brunswick Department of Agriculture, Fisheries and Aquaculture.

[50] Leavitt, D., Griffin, M., & Adams-Cook, T. (2017). Does a Flip-Bag System Produce a Better Eastern Oyster? East Coast Shellfish Growers Association Newsletter, Issue 4, December 2017. [Available at https://ecsga.org/wp-content/uploads/2017/12/ECSGA_NL_v4-17.pdf]

Figure 2.9: Tumble oyster bags, also known as flip bags, that flip over the horizontal line in the tide (Photo courtesy of Bobbi Hudson, Pacific Shellfish Institute)

INTERTIDAL LONGLINE CULTURE

In the U.S. North Pacific region, oyster shells pre-seeded with spat in onshore tanks are sewn into longlines, which are then suspended in the intertidal zone in what's called intertidal longline culture.[51] The longlines are suspended off the bottom in the intertidal zone to minimize predation and allow the clusters of oysters to grow more effectively (Figure 2.10).

Figure 2.10: Intertidal longline culture in coastal Washington (Photo courtesy of Bobbi Hudson, Pacific Shellfish Institute)

[51] Intertidal longline culture. (2024.) Penn Cove Shellfish, LLC. [Available at https://www.penncoveshellfish.com/intertidal-longline]

SURFACE GEAR

Surface oyster gear systems are used in subtidal environments and use floatation devices to maintain cultured species at or below the surface of the water, whereas the previously described on- and off-bottom gear types are used in intertidal environments (with the exception of on-bottom cages) and are connected to the seafloor. There are multiple types of surface gear for oyster cultivation, including surface longlines, suspended stacked trays, intertidal longlines, rafts, and lantern and pearl nets, which are described below.

SURFACE LONGLINES

Surface longline culture systems for oysters consist of containers, which are either bags or cages made of a plastic or a coated metal mesh that float on the water's surface and maintain their buoyancy by the attachment of floats or buoys. Each container can be loaded with oyster seed prior to deployment along the longline. There are multiple float configurations possible, depending on the environment and the preference of the farmer. In one example, buoys are attached on the sides of an oyster bag, allowing the bag to float at the air/water interface with the bottom portion submerged and the top portion exposed to the air (Figure 2.11). Alternatively, farmers may attach floats to the bottom of an oyster cage to provide the buoyancy necessary for the entire cage to be floated completely out of the water (Figure 2.12) or on the top such that the cage is completely submerged in the water column (Figure 2.13).

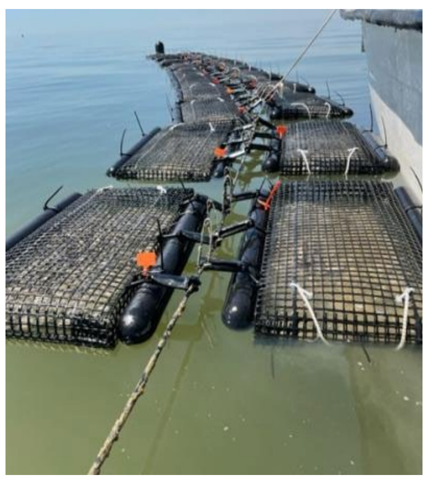

Figure 2.11: Floating bags, with floats attached to the sides, attached to a horizontal longline at Barrier Beauties aquaculture farm in Galveston Bay, TX[52]

[52]NOAA Fisheries. (2022). Tide to Table Profile: Barrier Beauties Aquaculture Farm in Galveston Bay, TX. NOAA Fisheries Office of Aquaculture News Story. Published September 23, 2022 [Available at https://www.fisheries.noaa.gov/feature-story/tide-table-profile-barrier-beauties]

Figure 2.12: Floating oyster growing cages, with floats on the bottom, at a demonstration project at the Horn Point Laboratory[53]

Surface gear is typically connected in a series tied or clipped to horizontal longlines (also called backbones), to form a "run" (Figure 2.13; Figure 2.14). Each end of the horizontal longline is attached to a mooring line and anchor. Once the horizontal longlines and mooring lines are attached to the anchors, farmers will adjust the lines of the run by tightening them to allow the containers to move with the current. This provides support and control of the run's location. The length of a run is variable and is predominantly dependent on the size of the container used, depth of water, dimensions of the farm, expected production levels, and the ability of the farmer to access individual runs via foot or vessel.

Figure 2.13: Multiple runs of floating oyster cages with the floats on top of the cages[54]

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[53]Maryland Sea Grant. (2017). New Study to Reduce Fouling on Oyster Aquaculture Equipment. Published October 31, 2017 [Available https://www.mdsg.umd.edu/news/new-study-reduce-fouling-oyster-aquaculture-equipment]

[54]Floating Bag Oyster Aquaculture Gear. (2024). Go Deep Shellfish Aqua. [Available at https://tidalmarine.com/]

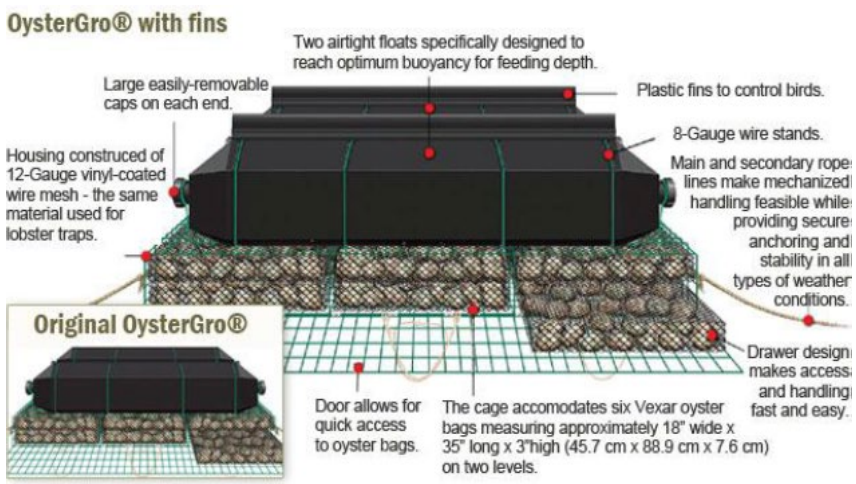

Figure 2.14: Illustration showing the side view of a typical OysterGro® unit used for floating oyster aquaculture systems[55]

LANTERN AND PEARL NETS

Lantern and pearl nets are made of mesh and can be used to cultivate oysters in the water column similar to suspended stacked trays described below. While lantern and pearl nets are used in oyster aquaculture, they are more commonly used in scallop production, and will be discussed in detail in the scallop cultivation section.

SUSPENDED STACKED TRAYS

Suspended stacked trays (also known as hanging stacked baskets) are used for cultivating oysters on the U.S. East Coast and in Alaska. They are designed to withstand high energy environments that aren't typically experienced in the intertidal zone (Figure 2.15). Suspended stacked wire-mesh trays are the primary method of oyster aquaculture in Alaska (Figure 2.16). These trays are suspended from either horizontal longlines or rafts and tend to be more productive for growing oyster over traditional monofilament mesh lantern nets. Sea otter depredation is one of the main factors for farmers in Alaska when choosing oyster gear, along with high-water surface currents and potential surface freezing. Due to these concerns, the majority of oyster aquaculture farmers in Alaska use stacked trays suspended under rafts, as they are less accessible by sea otters than bottom gear or off-bottom gear described above. On the U.S. East Coast, stacked trays are predominantly hung vertically on horizontal longlines, but may be suspended under rafts. Suspended stacked trays for oyster aquaculture are very similar to suspension cages used for scallop aquaculture, which are discussed later in this document.

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[55] OysterGro: OysterGro Aquafarming. (2024). [Available at http://oystergro.com/en/page/oystergro]

Figure 2.15: Suspended stacked trays being hauled in from a vessel in Rhode Island at American Mussel Harvesters oyster farm (Photo courtesy of Zachary Gordon, NOAA Fisheries)

Figure 2.16: Suspended stacked trays used for oyster aquaculture in Alaska (Photo courtesy of Bobbi Hudson, Pacific Shellfish Institute)

RAFT CULTURE

Raft aquaculture gear is primarily used to grow mussels, however, it is occasionally used in the U.S. West Coast region to grow oysters, as described above for suspended stacked trays. Lantern nets, pearl nets, or suspended stacked trays are filled with oyster seed and hung from rafts that float on the surface. Raft culture gear is discussed in more detail in the mussel aquaculture section below.

CLAM AQUACULTURE

Clams burrow into seafloor sediments using their muscular foot but remain close enough to the sediment-water interface so their siphons can extend into the water column for feeding and excretion, making clams ideal for on-bottom (also called in-bottom) culture methodologies. Clams cultivated in the U.S. include the Manila clam (*Ruditapes philippinarum*), Pacific littleneck clam (*Leukoma staminea*), soft-shelled clam (*Mya arenaria*), northern quahog (or hard clam; *Mercenaria mercenaria*), and Atlantic surf clam (*Spisula solidissima*). Other clam species such as the sunray Venus clam (*Macrocallista nimbosa*), and southern hard clam (*Mercenaria campechiensis*) are also cultivated in the southeastern U.S. on a small scale.[56]

DIRECT ON-BOTTOM/IN-BOTTOM CULTURE

For on-bottom clam culture, clam seeds are distributed across a confined area of the seafloor at the farm site.[57] The clam seed bury themselves in the sediment of the seafloor to the point where their siphons can extend into the water. As the clams eventually bury themselves in the sediment, on-bottom clam aquaculture is also referred to as in-bottom aquaculture. In this type of culture, there is no gear per se, but clam seed is often covered by predator netting to inhibit predation. Clam seed might be planted before or after placing predator netting, depending on operator preference.[55] Predator netting commonly consists of a woven flexible mesh netting or a woven wire covering, depending on the level of predation. The netting is anchored to the seafloor using rebar, heavy weighted ropes, sand bags, or other materials. Aside from deterring predation by bottom predators such as crabs, rays, fish, and invertebrates, the netting can also delineate the area in which the clam seed has been planted or distributed, and may also deter poaching. On farms where predation may be less intense and netting is not used, markers are used to delineate the farm boundary instead.

ON-BOTTOM BAGS

There are two types of on-bottom clam culture methods, one using soft bags (Figure 2.17), which dominate clam culture techniques on the U.S. East and Gulf coasts, and another using hard mesh grow-out bags, which is primarily used on the U.S. West Coast.

[56] United States Department of Agriculture. (2017). Census of Aquaculture Volume 3. Special Studies. Part 2

[57] Whetstone, J. M., Sturmer, L. N., & Oesterling, M. J. (2005). Biology and culture of the hard clam. *Southern Regional Aquaculture Center*, *433*, 1-6.

In the soft bag method, clam seed is placed inside woven polyester mesh grow-out bags (Figure 2.17). These clam bags differ from rigid oyster bags in that they include a spout on one end of the bag for ease of access. Chemical net coatings are often applied to clam bags either by the production company or the farmer to stiffen the fabric to deter benthic predators. The clam bags contain clam seed in a limited space, and like oyster bags, the bag mesh size allows for seawater to flow over the clam seed. As the clams grow, some farmers may choose to change to larger mesh bags to accommodate the size of the growing clams and to increase water flow. Similar to oyster bags, clam bags are aligned with the tidal flow at specific operating depths to maximize filtration by the clams.

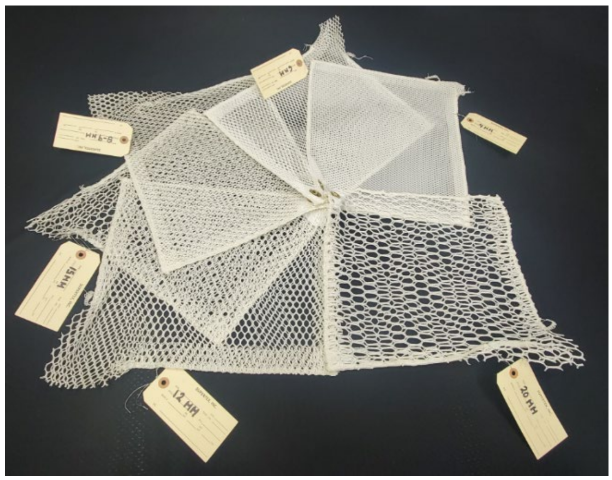

Figure 2.17: Clam bags of assorted mesh sizes

Similar to direct on-bottom clam aquaculture described above, farmers may use predator netting to cover the clam bags (the red netting in Figure 2.18); even when the clams are placed in bags, they are covered with predator netting and naturally bury themselves in the substrate over time. Farmers use markers such as sand bags, lines, or rebar stakes to hold down the clam bags and predator netting, and to identify where the farm is located, as the bags may become covered with bottom sediment over time.

Figure 2.18: An array of planted clam bags, some covered with red predator netting[58]

On the U.S. West Coast, hard-mesh clam bags are utilized in some Manila clam farming operations. Farmers dig a divot the size of a clam bag and place a bag full of seed in the substrate. Over time, the tide helps the surrounding sediment to fill in and around the bag. Unlike soft-bag culture, the hard-mesh bags are filled once with seed and harvested based on market demands; the seed is not transferred to larger mesh bags as the clams grow. Clams raised in this fashion are generally in low-energy environments and don't require staking or securing to the seafloor (Figure 2.19).

Figure 2.19: Manila clam bag aquaculture (Photo courtesy of Teri King)

[58]FL Department of Agriculture and Consumer Services (FDACS). (2020). Information and Regulations for Clam Aquaculture-Net Coatings. *FL Department of Agriculture Technical Bulletin #3*. DACS-P-00069

GEODUCK AQUACULTURE

The Pacific geoduck (*Panopea generosa*), an infaunal clam native to Washington state that is naturally found in low intertidal to subtidal waters, has been farmed intertidally in Washington since 1991.[59] Geoduck are long-lived and deep-digging clams that can be planted in both intertidal and subtidal areas. A variety of techniques are used to protect the delicate geoduck seed from infaunal predators until it reaches a depth of 10 to 12 in. in the substrate. The original technique for geoduck cultivation, still commonly used but being slowly phased out, used 4 or 6 in. diameter PVC pipe placed with the center of each pipe one foot apart (Teri King, personal communication). New industry techniques use a 3to 6 in. diameter, 10 in. long hard mesh tube or a soft high density polyethylene (HDPE) mesh tube which is placed into the substrate using an auger or a water pump, and then planted with the appropriate number of geoduck seeds (Figure 2.20; Bill Dewey, Taylor Shellfish Farms, personal communication). The center of each adjacent pipe is highly variable among farms, but all tubes are planted with between 1-3 geoduck seeds. Planting is commonly done on a rising tide or when the tubes are covered with seawater. This ensures a higher survivorship of the seed clams. Hog rings (metal rings that are open on the side), or other weights, are added to each tube to prevent dislocation due to buoyancy issues of the mesh tubes (Teri King, NOAA Fisheries, personal communication).

Geoduck pipes or tubes may be covered with individual mesh nets that are secured with bands, or blanket predator netting over all of the tubes, secured to the seafloor with stakes. Mesh tubes and netting may occasionally be dislodged during winter storms, and farms require frequent inspection and maintenance by operators. Well embedded mesh tubes are not dislodged as easily as PVC tubes, however, and also offer superior water circulation.

In Washington, tubes and nets used in geoduck culture are marked with the company name either burned into each piece of gear or marked with a zip tie containing the company information. With rigid tubes, after the geoduck has dug down below the tube length, the tubes are retrieved, cleaned, and stored for future deployment. The length of time a tube is deployed in the substrate is based on how long it takes the juvenile geoducks to reach the depth of the tube, which is often a year or longer (Teri King, NOAA Fisheries, personal communication).

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[59]Washington Sea Grant. (2013). Final Report: Geoduck aquaculture research program. Report to the Washington State Legislature. *Washington Sea Grant Technical Report WSG-TR 13-03*, 122 pp.

Figure 2.20: Polyethylene plastic UV stabilized mesh tubes used in geoduck farming to protect against predation, which are removed when the geoduck is fully embedded in the sediment and large enough to avoid predation (Photo courtesy of Bobbi Hudson, Pacific Shellfish Institute)

MUSSEL AQUACULTURE

Mussel species cultivated in the U.S. include the blue mussel (*Mytilus edulis* and/or *Mytilus trossulus*), California mussel (*Mytilus californianus),* and the Mediterranean mussel (*Mytilus galloprovincialis*). Mussel larvae produce byssal threads that are flexible strands of protein filaments, which allow the larvae to attach to solid surfaces. Similarly to oysters and clams, mussels can be grown on- or off-bottom. On-bottom mussel cultivation is similar to oyster and clam on-bottom culture, but requires wild seed collection. Mussel seed is collected and then planted directly on the bottom or in on-bottom bags, just like oysters and clams. Off-bottom culture includes suspended longlines and raft gear as described below. While suspended longline culture is suitable for inshore and offshore environments, raft culture is more suited for inshore low energy environments. Recent research on offshore shellfish aquaculture has focused on adapting inshore suspended longline culture methods to meet the requirements for mooring, maintaining, and harvesting mussels in offshore, high-energy ocean environments.

SUSPENDED LONGLINE CULTIVATION

Farmers take advantage of the byssal threads' ability to attach to structure, by encouraging the settlement of mussel larvae on vertical dropper lines either in situ or in land based grow-out tanks. Once the mussels are attached to the vertical dropper lines, they are transferred to the grow-out location to complete process. On the U.S. East Coast, mussel suspended longline gear consists of a main horizontal longline or backbone, with buoys at prescribed lengths along the backbone, to maintain flotation. This horizontal longline is moored by anchors and attached mooring lines at each end, which keep the horizontal longline at tension and enhance system stability (Figure 2.21). Anchors used in mussel longline systems are usually either a screw-type, dead weight, or drag embedment anchor (as described in Chapter 1).

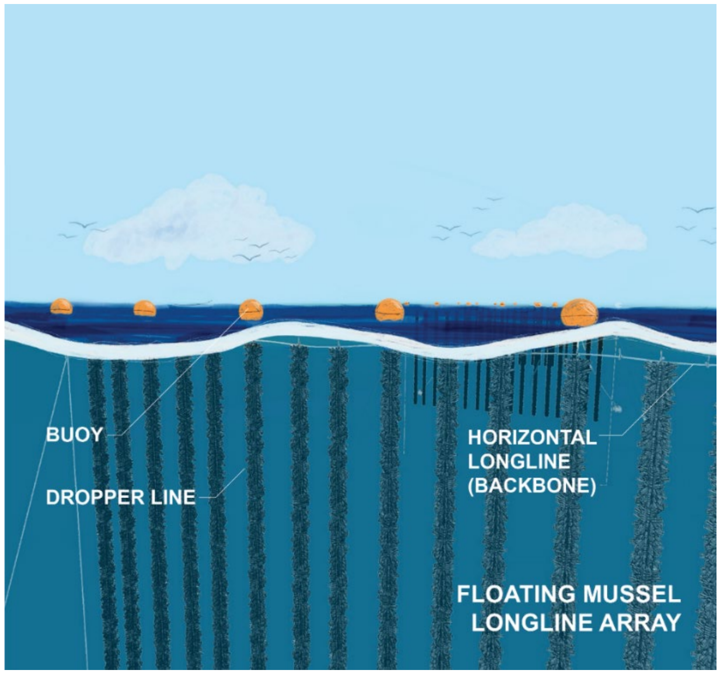

Figure 2.21: Illustration of a mussel horizontal longline array (Illustration courtesy of Zoe Lee and Louis Hand)

On the U.S. East Coast, vertical dropper lines are hung in the water column to collect naturally occurring mussel spat from the surrounding water column (Figure 2.22). Once the mussels reach a desired size, they are typically harvested and transferred to another line at a chosen density (i.e., number of mussels per foot length of rope) to optimize productivity. Mussels can be grown on dropper lines that are socked or not-socked. Socked dropper lines are lines sleeved with a cotton bag, called a sock that is pre-seeded with mussel spat (Figure 2.23). When dropper lines are socked, the cotton material of the sock biodegrades within months; during that period, the mussels will attach themselves to the dropper lines. The socking material usually covers the entire length of the dropper line but the total length of the socking material can also depend on the depth of the water and the skills of the farmer. A new sock can be sleeved at regular intervals over the existing dropper line. This continuous replacement of socking material allows for increased production of an individual dropper line. When mussel lines are used as spat collectors, the farmer does not have to invest in mussel seed to pre-seed the dropper lines. However, the total volume of mussels that can be cultured is limited by the total amount of mussel larvae in the water column at the farm site and, to a greater extent, how much mussel spat is actually collected by the mussel lines.

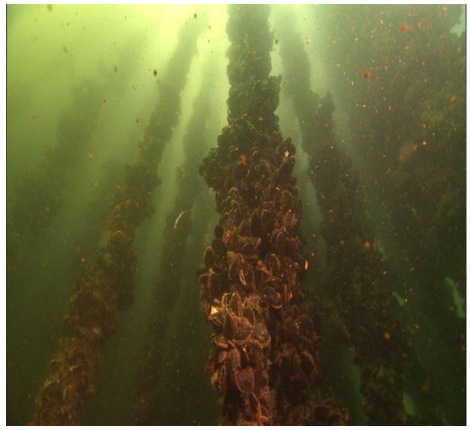

Figure 2.22: Underwater view of mussel dropper lines at Taylor Shellfish in Washington (Photo Courtesy of NOAA Fisheries)

Figure 2.23: Mussel sock filled with mussel seed ready for deployment[60]

With both pre-seeded and naturally-seeded mussel dropper lines, the dropper lines are attached to the main horizontal longline at regular intervals and hung vertically in the water column (Figure 2.22, Figure 2.24). The spacing between dropper lines is site-specific and is dependent on the farmer's preference and local environmental considerations.[61] Dropper lines may be hung individually or using various configurations along the backbone, such as "continuous looping" (Figure 2.24, Figure 2.25). The total vertical length of the dropper line depends on the depth of the water column, temperature at depth, and

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[60]Go Deep Shellfish Aqua. (2024). GDI Mussel Sock-Cotton Bisect. [Available at https://tidalmarine.com/]

[61]Drapeau, A., Comeau, L. A., Landry, T., Stryhn, H., & Davidson, J. (2006). Association between longline design and mussel productivity in Prince Edward Island, Canada. *Aquaculture*, *261*(3), 879-889.

nutrient availability. However, productivity tends to decrease the deeper the mussels are in the water column.[62] Biofouling by sponges, barnacles, algae, tunicates, and polychaete worms leads to decreased productivity. As a result, farmers spend significant time and effort controlling biofouling organisms.[63]

In commercial mussel farms, multiple horizontal longlines are moored in an array similar to Figure 2.21 where the number of lines are limited depending on the acreage of a farm site and expected production levels. Suspended longline systems for mussels are easily adaptable for deeper waters and rough ocean conditions. Therefore, they are the most likely type of system to be used in the development of offshore mussel aquaculture. However, complexity of mooring systems may be a limiting factor in the development of offshore operations, as they can be more difficult to deploy due to the size of the mooring components and the need for large work vessels with specialized deployment and harvesting gear.

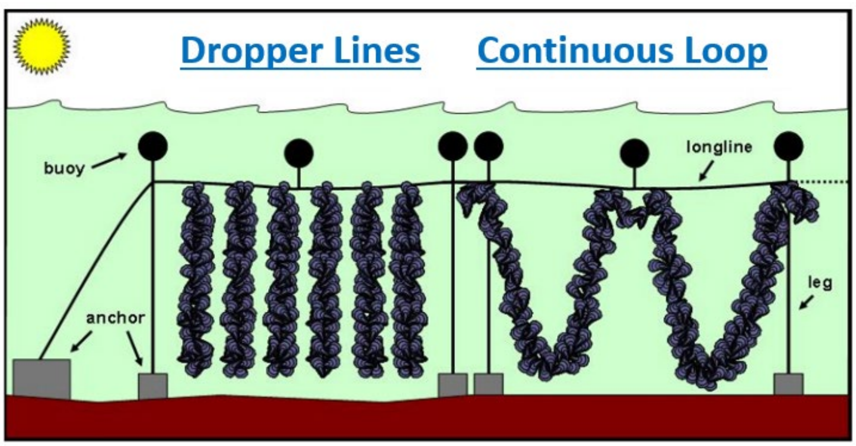

Figure 2.24: Depiction of a longline system with individual dropper lines vs. a continuous loop grow line[64]

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[62]Fuentes, J., Gregorio, V., Giráldez, R., & Molares, J. (2000). Within-raft variability of the growth rate of mussels, Mytilus galloprovincialis, cultivated in the Rıa de Arousa (NW Spain). *Aquaculture*, *189*(1-2), 39-52.

[63]Watts, A. M., Goldstien, S. J., & Hopkins, G. A. (2015). Characterizing biofouling communities on mussel farms along an environmental gradient: a step towards improved risk management. *Aquaculture Environment Interactions*, *8*, 15-30.

[64]McKindsey, C. W., Anderson, M. R., Barnes, P., Courtenay, S., Landry, T., & Skinner, M. (2006). *Effects of shellfish aquaculture on fish habitat* (p. 84). Fisheries and Oceans.

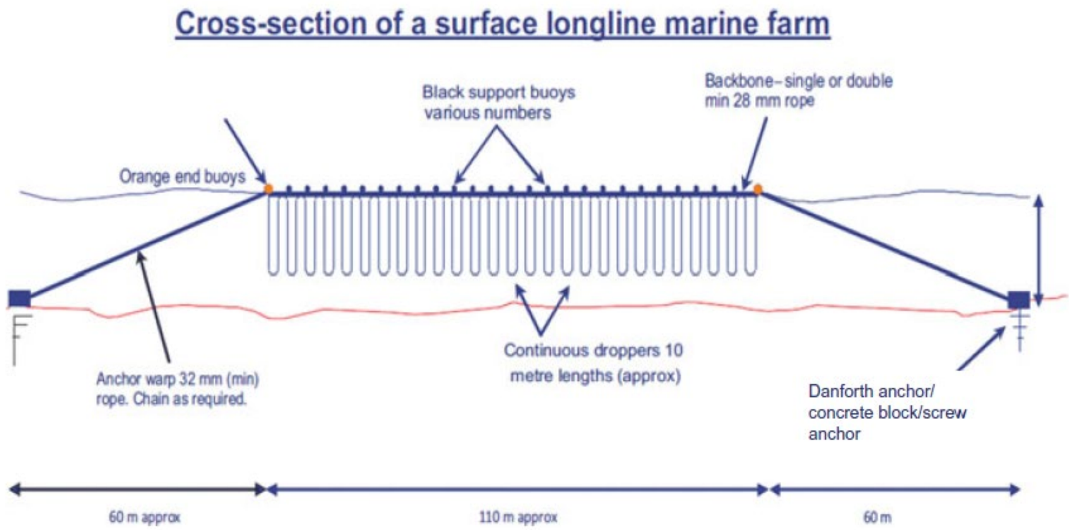

Figure 2.25: Surface New Zealand style (continuous loop) mussel longline system used to culture mussels in a commercial setting, but can be modified to culture other types of shellfish (e.g., replacing mussel line with lantern nets for culturing oysters)[65]

LANTERN NETS

Lantern nets, similar to those described in the scallop section below, are also used to cultivate mussels in Washington and Alaska. Lantern nets are made from mesh and are hung from suspended horizontal longlines with large drums as buoys at the surface (Bobbi Hudson, Pacific Shellfish Institute, personal communication). Lantern net gear systems are discussed further in the scallop cultivation section below.

RAFT CULTURE

Mussel rafts are platforms used for mussel cultivation that are constructed with steel I-beam main frames and wooden cross members, which are supported by large polyethylene floats (Figure 2.26). On the U.S. West Coast, mussel farmers primarily use rafts for mussel aquaculture instead of suspended horizontal longlines (Figure 2.27). Rafts are also used on the U.S. East Coast, but are less common. Mussel rafts are often anchored to the seafloor with large concrete deadweight anchors. Farmers may operate a single raft or multiple

[65]Goseberg, N., Chambers, M. D., Heasman, K., Fredriksson, D., Fredheim, A., & Schlurmann, T. (2017). *Technological approaches to longline-and cage-based aquaculture in open ocean environments* (pp. 71-95). Springer International Publishing.

rafts simultaneously, depending on their production goals. Securing multiple rafts together provides greater stability and is accomplished using chains and additional concrete deadweight anchors. The distances between rafts secured together is site-specific.

Dropper lines are hung vertically into the water column from the raft and can be in one of three phases of grow-out: seed/spat collecting droppers, droppers with mussels in the grow-out phase, and droppers with mussels that have reached marketable size. On the U.S. West Coast, natural recruitment of mussels on dropper lines is not reliable, therefore nearly all mussel seed is produced in a hatchery.

Figure 2.26: U.S. East Coast mussel raft with some dropper lines visible under the platform along with predator netting to minimize predation from diving ducks[66]

On the U.S. West Coast, dropper lines that are not socked have mussel discs spaced periodically down the dropper line to prevent the sloughing of mussels off of the line as the weight of the mussels growing on the line increases (Figure 2.28). These discs are marked with the company name and may be required by regulation depending on the state (Teri King, NOAA Fisheries, personal communication). Mussel rafts may also support socked mussel lines, where the socks, rather than the discs, prevent the mussels from sloughing off the lines as they grow. Mussel rafts provide a stable working platform and consolidate dropper and sock lines in a confined area for ease of access. Mussel rafts, however, require

[66]Morse, D. L., & Rice, M. A. (2010). *Mussel aquaculture in the northeast* (pp. 1-10). Northeastern Regional Aquaculture Center.

mooring in locations less susceptible to high energy storm conditions, require more capital outlay to maintain, and this form of cultivation may be subject to profit limitation, since small sized rafts may limit growth rates by packing these filter feeding animals into a confined portion of the water column. In some instances, predator netting is used on the outer edges of the raft to prevent predation by diving ducks, otters, and other marine predators.

Figure 2.27: Floating Mussel raft in Puget Sound, Washington (Photo courtesy of Teri King, NOAA Fisheries)

Figure 2.28: Disc-net mussel dropper lines with mussels attached to the line and the disc[67]

[67]Penn Cove Shellfish: Mussel Discs and Disc net line system. (2024).[Available at https://www.penncoveshellfish.com/mussel-discs-disc-net-line-system]

SCALLOP AQUACULTURE

Scallop species cultivated in the U.S. include the rock scallop (*Crassadoma gigantea*), Atlantic sea scallop (*Placopecten magellanicus*), and bay scallop (*Argopecten irradians*). Unlike other shellfish, scallops are active swimmers, especially when small, and can move more than 2 m (6.6 ft.) during a single swimming event.[68] Unlike mussel aquaculture, where farmers use the same gear to collect and grow the spat or seed, scallop aquaculture involves collecting spat on collection gear and then transferring that to other gear for grow out.[69]

SCALLOP SPAT COLLECTION

Scallop aquaculture seed can be collected from the natural environment or purchased from nurseries or hatcheries. Wild scallop spat collection requires a suitable substrate hanging in the water column to provide a point of attachment. Scallop collection gear is placed in areas where scallop larvae are expected to be present and in waters with low turbidity when feasible, as silty waters can impede spat attachment. The gear used in scallop spat collection has two principal parts: (1) the spat bag (Figure 2.29), and (2) the spat settlement substrate or "stuffing" placed inside the spat bag.[70] The spat bag is made of a polyethylene mesh in a range of colors, but blue bags are often preferred as research indicates that the color blue seems to attract the most spat.[71] The stuffing can be a polyethylene mesh that is highly resistant to UV light and abrasion and is often reusable, or may be composed of recycled monofilament gill net material.[72]

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[68]Dadswell, M. J., & Weihs, D. (1990). Size-related hydrodynamic characteristics of the giant scallop, *Placopecten magellanicus* (Bivalvia: Pectinidae). *Canadian Journal of Zoology*, *68*(4), 778-785.

[69]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). [Available at https://repository.library.noaa.gov/view/noaa/38586]

[70]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (Placopecten magellanicus).

[71]Davidson, and Dadswell, M. & Parsons, G.J. (2018). Sea Scallop (Placopecten magellanicus) Culture in Northeastern North America Background.

[72]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). [Available at https://repository.library.noaa.gov/view/noaa/38586]

Figure 2.29: Scallop spat bag[73]

Each spat bag is secured above the seafloor, as high spat loss can occur due to abrasion and fouling if the bags scrape the seafloor. The bags are most often suspended vertically from a single suspension line (also called the up-and-down line; Figure 2.30). Each spat bag has a drawstring that is tied to the up-and-down line. Spat bags hang in the water column at a predetermined depth, based on depth at the farm site, ease of manipulation by the farmer, and total number of bags to be hung. A hard plastic toggle buoy is attached above the topmost bag on an up-and-down line, which keeps the bags oriented vertically.[74] Additional surface buoys and anchors are utilized to keep the spat bag in place.

Once the collected spat grows to a suitable size[75]; they are collected either by lifting individual spat bags out of the water manually or using a block and hauler system. The scallop spat are then placed in grow-out systems (discussed below). Although less common, spat bags attached to a vertical dropper line may also be attached to suspended horizontal longlines similarly to mussel spat lines discussed above.

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[73]Ketchum Supply Spat Bags. (2024). [Available at https://ketchamsupply.com/product/spat-bags/]

[74]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus).* [Available at https://repository.library.noaa.gov/view/noaa/38586]

[75]Papa, L., Prato, E., Biandolino, F., Parlapiano, I., & Fanelli, G. (2021). Strategies for successful scallops spat collection on artificial collectors in the Taranto Gulf (Mediterranean Sea). *Water*, *13*(4), 462.

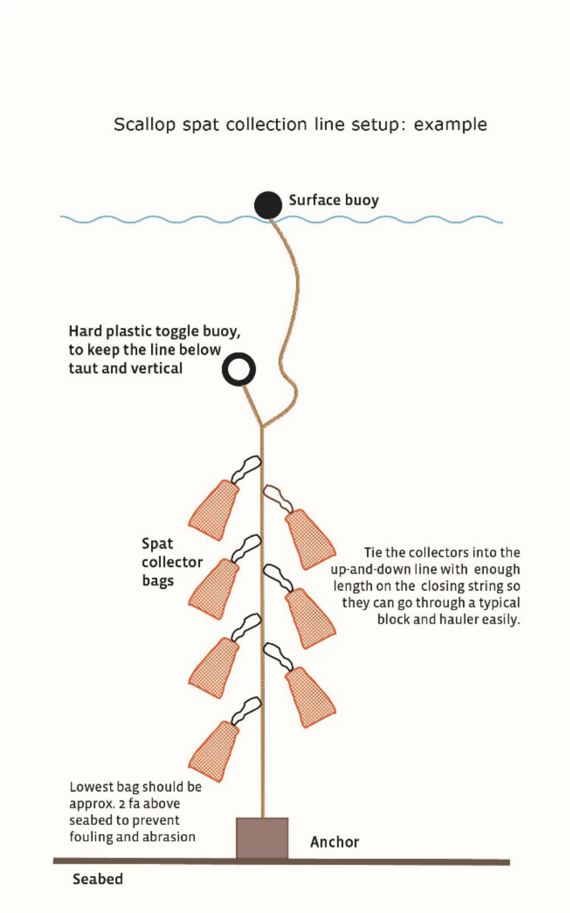

Figure 2.30: Representation of common scallop spat collection gear deployment[76]

SCALLOP GROW-OUT SYSTEMS

The grow-out systems for scallops depend on the market size required and grower preference. Low-density culture of scallops is preferred[77], because when scallops are grown too close together, scallops tend to clamp down on one another's shells, which can damage both the shell and the mantle of the scallop. Additionally, low-density culture of scallops is preferred because scallops possess relatively thin shells, requiring careful handling. The appropriate stocking density is dependent on the size of the gear, and

[76]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). [Available at https://repository.library.noaa.gov/view/noaa/38586]

[77]Parsons, G. J., & Dadswell, M. J. (1992). Effect of stocking density on growth, production, and survival of the giant scallop, *Placopecten magellanicus*, held in intermediate suspension culture in Passamaquoddy Bay, New Brunswick. *Aquaculture*, *103*(3-4), 291-309.

research has found that scallop density should be no more than the number that can line up side by side on the side wall of the net or cage facing the current for maximum productivity.[78]

PEARL NETS

Pearl nets consist of a series of vertically aligned conical-shaped nets consisting of a taut mesh made of nylon, metal, or similar material (Figure 2.31). The conical-shaped nets are supported by a square frame base. The mesh size of the netting depends on the size of the scallops being cultivated. Similar to mussel dropper lines, pearl nets are hung vertically in the water column from a suspended horizontal longline and weights are connected to the bottom of each pearl net to maintain rigidity of the pearl net structure. Pearl nets are often deployed as a string or series of nets along each suspended horizontal longline (Figure 2.32).

Figure 2.31: Pearl net being removed from the water[79]

[78]Davidson, Dadswell, M. & Parsons, G.J. (2018). Sea Scallop (*Placopecten magellanicus*) Culture in Northeastern North America Background.

[79]Morse, D. L., Cowperthwaite, H. S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). [Available at https://repository.library.noaa.gov/view/noaa/38586]

Figure 2.32: A string of pearl nets used for scallop aquaculture[80]

LANTERN NETS

Lantern nets are rigid structures consisting of a series of galvanized wire hoops, which may be plastic-coated to reduce corrosion. The hoops are covered with a taut mesh netting made of nylon or metal, creating a series of vertically-aligned tiers (Figure 2.33). Each tier has an opening that can be closed using Velcro, zippers, or, more commonly, sewn shut. Lantern nets come in a variety of mesh sizes, heights, number of tiers, and shapes, with round being the most common. Mesh size depends on the size of the scallop spat being placed within the compartments, with larger mesh for larger scallops and increased water flow.[81]

Lantern nets are hung vertically from a suspended horizontal longline, which is moored to the seafloor and with mid-water adjustment buoys and surface buoys attached along the line to provide additional support. Like pearl nets, weights are connected to the bottom of the lantern net arrays to maintain rigidity of the structure and to keep it oriented vertically in the water column. Horizontal spacing between the lantern nets is site-specific.

Some scallop farmers prefer using pearl nets to stock scallop spat at lower densities. Other scallop farmers prefer lantern nets because they tend to have larger mesh sizes than pearl nets, which allows for greater water movement for feeding and may, in turn, lead to faster growth rates. Farmers may use both types of cultivation gear simultaneously. Like oysters

[80]Clear Ocean Aquaculture: Scallop 101; Catching Techniques. [Available at https://clearocean.ca/scallop-101/331-catching-techniques]

[81]Ketchum Supply Spat Bags. (2024).[Available at https://ketchamsupply.com/products/spat-bags-1]

and clams, scallops must be periodically sorted and culled by size during the grow-out process. When using both lantern and pearl nets, farmers often sort smaller scallops into pearl nets and the larger-sized scallops into lantern nets. This strategy of using a combination of lantern and pearl nets has been shown to grow scallops to market size more quickly and improve profitability.[82]

Figure 2.33: Hugh Cowperthwaite, CEI Senior Program Director for Fisheries and Aquaculture, holds up a lantern net (Photo courtesy of NOAA Fisheries)[83]

BOTTOM CAGES

Bottom cages (Figure 2.34) are also used for sea scallop cultivation. The bottom cages for scallops are similar to the rack and bag gear used to cultivate oysters, in that they consist of multiple trays that hold the scallops and are slightly elevated above the seafloor. Bottom cages for scallop aquaculture are used less often than pearl and lantern nets, due to the limitations in capacity because scallops don't grow as well when stocked in higher densities.[84]

[82]Davidson, Dadswell, M. & Parsons, G.J. (2018). Sea Scallop (*Placopecten magellanicus*) Culture in Northeastern North America Background.

[83]NOAA Fisheries. (2022). Farming Sea Scallops in Maine, NOAA Fisheries Feature Story. Published December 29, 2022. [Available at https://www.fisheries.noaa.gov/feature-story/farming-sea-scallops-maine]

[84]The Maine Aquaculturist: Learn the Gear. [Available at https://www.themaineaquaculturist.org/essential-start-guide-maine-aquaculture/learn-gear/]

Figure 2.34: Example of a bottom cage for scallop production using Aqua Trays[85]

SUSPENSION CAGES

Suspension cages, also called rigid cages, are very similar to the suspended stacked trays described for oyster aquaculture. They can be placed on the seafloor or suspended from a horizontal longline like pearl and lantern nets. Similar to other culture methods for scallops, suspension cages are compartmentalized and their rigid nature contributes to their stability (Figure 2.35). Suspension cages are more expensive than lantern or pearl nets and require stronger lines for support, but they are easier to handle than lantern nets, pearl nets, or bottom cages.

[85]Morse, D. L., Cowperthwaite, H.S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). Maine Sea Grant. [Available at https://repository.library.noaa.gov/view/noaa/38586]

Figure 2.35. Suspension cage (Max-Flow trays™), being manipulated by a farmer[86]

SHELLFISH AQUACULTURE OPERATIONAL CONSIDERATIONS

This chapter highlights a wide variety of shellfish aquaculture gear and farming methods, but it is impossible to include all possible types of shellfish aquaculture gear. Farmers select shellfish aquaculture gear depending on cost, production, capacity, handling, fouling control methods, predation, environment, and potential exposure to storm events. It is imperative to consider all aspects of an aquaculture operation during the project review process (e.g., Section 7 consultation), including specialized gear that may be used for operational purposes. This section describes shellfish aquaculture operations and the gear used during those operations including seed collection and growth, deployment, maintenance, and harvesting.

GEAR DEPLOYMENT

Delineation of the farm site is done using wood or PVC posts which are placed at the corners of the farm. Similar posts are also used for the farm itself, to hang horizontal longlines, etc. The size and diameter of the posts varies greatly depending on the location and substrate of the farm site. PVC posts are often driven into the substrate by hand or

[86]Morse, D. L., Cowperthwaite, H.S., Perry, N., & Britsch, M. (2020). Methods and Materials for Aquaculture Production of Sea Scallops (*Placopecten magellanicus*). Maine Sea Grant [Available at https://repository.library.noaa.gov/view/noaa/38586]

water–jetting using a submersible pump with a high-pressure hose, whereas wooden pilings are often driven into the substrate using an impact pile driver.

Small vessels are used to transport the shellfish aquaculture gear to and from the farm. Deployment of gear is done by hand or by using a block and tackle or davit crane. Block and tackle is a system of two or more pulleys with a rope or cable threaded between them (Figure 2.36). A davit crane is a mechanism consisting of a cantilevered boom arm fixed to a pivoting, vertical mast, which utilizes a winch to lift an object to and from the vessel (Figure 2.37). Such cranes can vary in size, but are often used on larger vessels. Davit crane winches can be either motorized or manually operated depending on the size of the crane and weight of the gear.

Figure 2.36: Harvest of oyster cage from a small vessel using a block and tackle system[87]

[87]Sturmer, L. (2013). Introduction to intensive oyster aquaculture: Overview of U.S. East Coast oyster culture operations and Florida's experiences. Carabelle and Cedar Key Workshop Presentations. September 26-27, 2013.

Figure 2.37: Harvesting vessel for a surface New Zealand style mussel longline farm with a davit crane system[88]

SHELLFISH FLOATING UPWELLER SYSTEMS (FLUPSY)

Shellfish growers can purchase seed that is large enough to be out-planted directly into grow-out gear or they can buy smaller seed and add a nursery component to their farm. A Floating Upweller System (FLUPSY) is a type of nursey system which consists of a container that houses and protects shellfish seed and through which ambient marine water is pumped. The increased water flow supplies the shellfish seed with a constant supply of nutrients, thereby increasing growth rate. Once the shellfish seed in the FLUPSY reaches the preferred grow-out size, they are moved to the grow-out gear at the farm site. FLUPSYs can hang from piers or docks, or be enclosed in rafts, where they float in the water close to shore. FLUPSYs are often sited close to shore due to the need to be close to a power supply.

MAINTENANCE

Gear maintenance is a regular and necessary part of all shellfish operations. Farm workers perform maintenance of shellfish gear by inspecting the gear at regular intervals. Ropes are inspected for fraying, abrasion, or biofouling. Surface buoys are inspected as a collective unit, to ensure proper buoyancy of the system, as well as individually, for cracks, biofouling, and rope degradation. Predator netting is assessed for holes, wear, and

[88]Baird Maritime. (2020). Vessel Review: Vanguard-New mussel harvester for New Zealand is packed full of innovations. [Available at https://www.bairdmaritime.com/fishing-boat-world/aquaculture-world/vessel-review-vanguard-new-mussel-harvester-for-new-zealand-is-packed-full-of-innovations/]

abrasion. Anchors are assessed to ensure they are properly embedded and that the mooring lines are not frayed, abraded or worn.

Biofouling typically occurs regardless of the gear selected. The density and type of biofouling depends on local conditions (e.g., temperature, salinity) and species present in the water column that can attach to the gear. Biofouling removal is required at regular intervals during the life of the gear as it makes an aquaculture structure heavier, which causes further stress on the lines. Additionally, biofouling decreases the water exchange inside cages or bags, affects the overall balance of an aquaculture cultivation system, and adds drag. Desiccation, the exposure of gear to air and sunlight, is the primary method used to remove biofouling. Desiccation can occur for floating gear when farmers flip their floating bags or cages, changing their orientation at the air-water interface, so that the different sides of the cage are exposed to the air. Additionally, farmers may choose to cycle or rotate gear to control biofouling. Other biofouling control techniques include brushing, power washing, chemical application such as acid treatment, or hot water dipping.[89]

CULLING AND HARVEST

During all phases of cultivation, shellfish periodically need to be cleaned and sorted by size (i.e., culled).[90] Shellfish farmers thoroughly observe the varying size classes and modify the required gear, if appropriate (e.g., increase mesh size of gear), replant shellfish until they reach market size, or split them into containers to continue grow out in lower densities.[91] Additionally, farmers may choose to agitate the shellfish using sorters and tumblers in order to remove fouling organisms, prevent shellfish from adhering to one another, which slows growth, and promote a consistent shape and size (Figure 2.38). Tumblers agitate, wash, and can even sort the shellfish, all of which promotes a consistent shellfish shape and size. A large tumbler is usually land-based; however, small manually-operated tumblers can be attached to the deck of a vessel. Barge- or raft-based tumblers are common on deeper water farms (e.g., in Alaska). For on-bottom and in-bottom shellfish grown in the U.S. West coast, harvested shellfish are sometimes re-planted in intertidal areas for final

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[89]Bannister, J., Sievers, M., Bush, F., & Bloecher, N. (2019). Biofouling in marine aquaculture: a review of recent research and developments. *Biofouling*, *35*(6), 631-648.

[90]Getchis, T. L. (2014). Northeastern U.S. Aquaculture Management Guide: A manual for the identification and management of aquaculture production hazards. Northeastern Regional Aquaculture Center and US Department of Agriculture.

[91]Doiron, S. (2008). The Reference Manual for Oyster Aquaculturists. New Brunswick Department of Agriculture and Aquaculture.

grow-out. The natural scouring that occurs in the intertidal region both agitates and cleans the shellfish preparing them for sale.

Figure 2.38: Oyster tumbler used to sort oysters by size and agitate the oysters to remove biofouling and smooth the shells for market[92]

Harvesting shellfish is labor intensive, especially if gear is pulled by hand.[93] Market size shellfish are harvested by a wide variety of methods depending on the type of gear used, the type of shellfish, and bottom environment. For example, clams grown on the bottom can be harvested by hand or by specially designed rakes with a basket attached, called a bull rake. Mechanized harvest of clams also occurs in some regions, typically on large plots when the bottom substrate is adequately firm and flat to accommodate the harvesting equipment. On-bottom gear can also be brought to the surface by hand, block and tackle, or davit crane. Alternatively, a dredge can be used for harvesting shellfish, as shown for on-bottom oysters (Figure 2.39). Geoduck culture employs a unique harvesting method, using a hose to jet water from an offshore barge.[94]

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[92]Hoopers Island Oyster Co. Tumbler, Sorter and Washer. 2024. [Available at: https://hoopersisland.com/equipment-item/tumbler-sorter-washer/]

[93]Novaes, A. L. T., de Andrade, G. J. P. O., dos Santos Alonço, A., & Magalhães, A. R. M. (2017). Ergonomics applied to aquaculture: a case study of postural risk analysis in the manual harvesting of cultivated mussels. *Aquacultural Engineering*, *77*, 112-124.

[94]Vanblaricom, G. R., Eccles, J. L., Olden, J. D., & Mcdonald, P. S. (2015). Ecological effects of the harvest phase of geoduck (Panopea generosa Gould, 1850) aquaculture on infaunal communities in southern Puget Sound, Washington. *Journal of Shellfish Research*, *34*(1), 171-187.

Figure 2.39: On-bottom oyster dredge in Washington (Photo courtesy of Bobbi Hudson, Pacific Shellfish Institute)

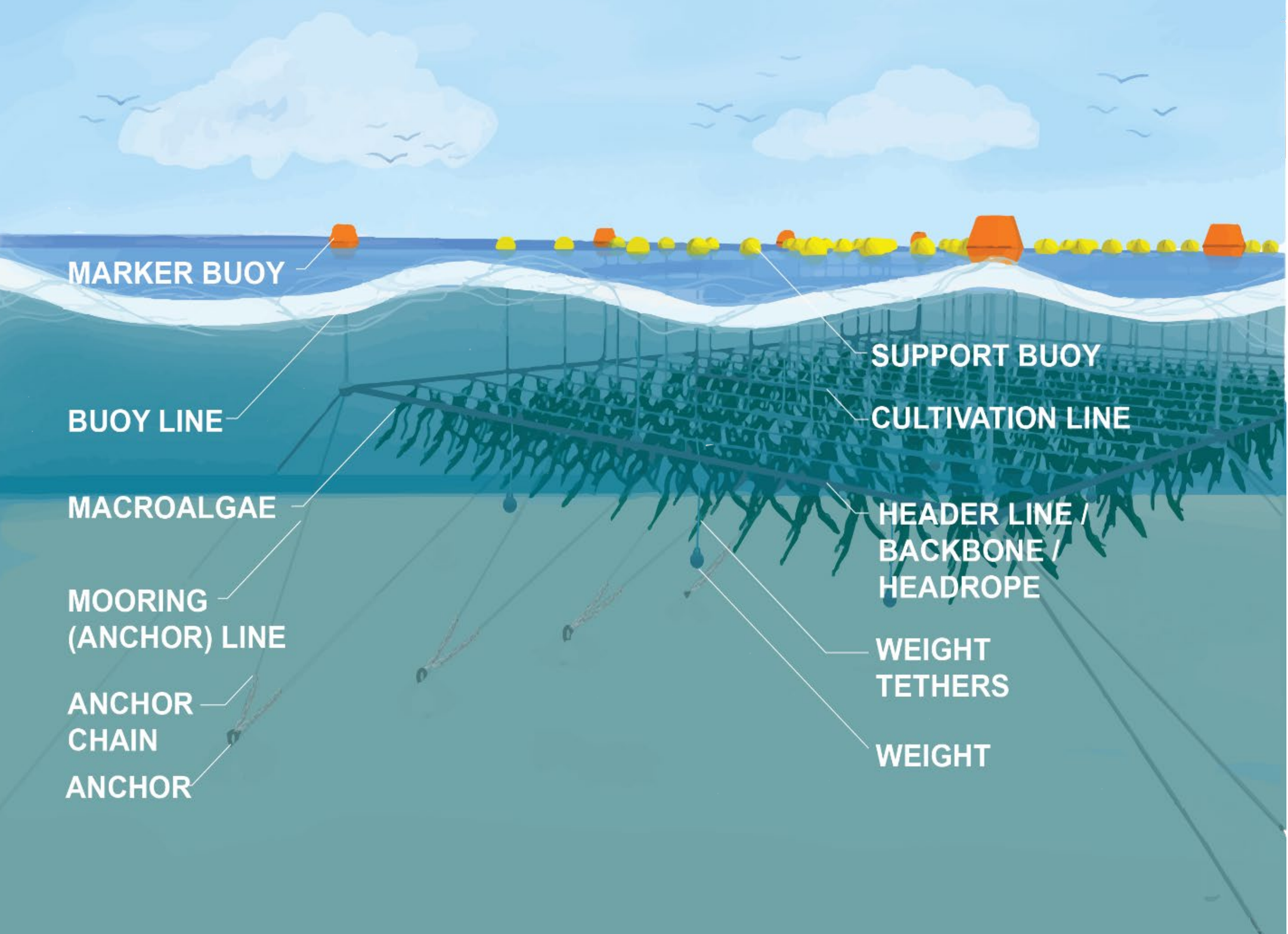
Figure 2.40: Manila clams in Samish Bay, Washington being harvested mechanically with a modified tulip bulb harvester (Photo courtesy of Bill Dewey, Taylor Shellfish Farm)

Floating gear is hauled on board a vessel or onto a specially built frame secured to the vessel, either by hand or with a small hoist system. The hoist system lifts the gear onto the vessel for culling, sorting, or harvesting. Some floating gear are designed to remain on the longline through the growing and harvest cycle. With these systems, crop maintenance is managed by moving the shellfish, rather than removing the gear from the longline system. Recent innovations in floating shellfish gear include the reduction of labor associated with maintenance and harvesting through the use of a conveyor belt type system on board the farm vessel used for Flip Farm gear (Figure 2.41). Farm workers sort through shellfish either by hand or using tumblers and graders from the vessel; or motor back to the land base of operations to sort and categorize the product for sale.

Figure 2.41: Flip Farm Gear used for oyster aquaculture[95]

[95]Flip Farm Aquaculture Gear. [Available at https://www.flipfarm.co.nz/].

CHAPTER 3



HORIZONTAL LONGLINE MACROALGAE ARRAY

CHAPTER 3 : MACROALGAE (SEAWEED) AQUACULTURE GEAR

INTRODUCTION

Marine macroalgae (seaweed) aquaculture is a growing global industry. Macroalgae production increased by over 4% from 2021 to 2022 and makes up over 17% of world aquaculture production.[96] China, Indonesia, Korea, and the Philippines have typically dominated the macroalgae aquaculture industry. U.S. macroalgae production, by comparison, is far behind, although interest in the industry is increasing.

Gear used for macroalgae production varies worldwide, depending on the species cultured, scale of operations, environmental conditions, cost, maintenance requirements, and harvest strategy. Production can be as small as a single line or as complex as hundreds of lines in an industrial longline production system. Macroalgae are cultivated close to the surface where there is adequate sunlight for photosynthesis (Figure 3.1).[97] Successful macroalgae production also requires adequate current flow and nutrient availability that is specific to the species grown.[98] Like all types of aquaculture, there are limitations associated with locating farms close to land, due to competing human uses such as ocean development, tourism, water pollution, fishing, and increasing water temperatures due to climate change. Due to these challenges, there has been interest in moving macroalgae aquaculture systems further offshore. It has been estimated that only 10% of the world's oceans have appropriate ecological conditions for potential offshore macroalgae production, which includes specific salinity, temperature, nutrients, solar input, and depth.[99] However, the future of macroalgae aquaculture growth will predominantly depend on increasing the market for algae products, development of technology for all stages of growth and harvest, processing, and funding.

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[96]FAO. (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome.

[97]Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M. & Yuan, X. (2021). Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development. *FAO Fisheries and Aquaculture Circular No. 1229*. Rome, FAO.

[98]García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J.C., Pereira, L., & Gonçalves, A.M.M. (2020). The Evolution Road of Seaweed Aquaculture: Cultivation Technologies and the Industry 4.0. *Int. J. Environ. Res. Public Health 17*:6528.

[99]Lehahn, Y., Ingle, K.N. & Golberg, A. (2016). Global potential of offshore and shallow waters macroalgal bio refineries to provide for food, chemicals and energy: feasibility and sustainability. *Algal Research, 17*: 150–160.

Figure 3.1: Kelp line at Copps Island Oysters, CT (Photo courtesy of Megan Ewald, NOAA Fisheries)

MACROALGAE GEAR COMPONENTS GLOSSARY

ANCHORS AND MOORING SYSTEM

Anchors used for macroalgae aquaculture systems are primarily drag embedment anchors, but can also be direct embedment anchors depending on the holding capacity requirements of the farm (see Chapter 1 for details on anchors). Macroalgae aquaculture mooring systems consist of a line or chain link that attaches to a line that extends from the anchor to the surface. The use of chain and the chain size selected is dependent on depth, size of the gear, and required holding capacity (general line and chain information can be found in Chapter 1).

HEADER LINE (AKA BACKBONE OR HEADROPE)

The header line, also known as a backbone or headrope, in a macroalgae system provides a point or points of connection for other lines, such as cultivation lines, mooring lines, buoy lines, etc. Header lines distribute the loading on the system (e.g., from cultivation lines) to the mooring lines. They are typically some form of rope and the diameter is dictated by design loading and availability.

CULTIVATION/GROW LINE

Cultivation lines, or grow lines, are the lines that are used to grow macroalgae in the marine environment. Cultivation lines are either populated with seeded twine that is wrapped around the line or by directly planting the macroalgae in the line by hand (see the Macroalgae operational consideration section below for more information). Cultivation lines are made of various materials such as polypropylene or 3-strand rope (see Chapter 1 for rope information). Some macroalgae species are grown more successfully on netting or ribbon cultivation lines that are flat instead of round, although there is some evidence that flat lines are subject to increased biofouling.

CATENARY LINE

Catenary lines are used in macroalgae aquaculture systems to provide mooring stability to a macroalgae array. They distribute loads and minimize concentrated forces during dynamic loadings, as well absorb shock and dynamic forces caused by wave action or sudden movements. Catenary lines provide adaptability to water level changes, reduce surface interaction, and prevent vertical movement of the system. The use of catenary lines reduces the number of anchors necessary in a macroalgae array, as there does not need to be an anchor at each end of every cultivation line. Catenary lines are attached to the outer frame lines of the array and are added to the system as modules. Smaller systems may only have one catenary and larger systems may have several.

SPREADER BARS

Spreader bars are a horizontal bar or beam connecting two or more attachment points. They are used to distribute loads evenly across their length, preventing concentrated forces on specific points and consequent structural failures. The spreader bar maintains a specific separation between attachment points, serving varied purposes in different applications. It also contributes to the stability of structures by helping prevent swinging or tilting of the lifted load. Spreader bars are utilized in construction, lifting operations, and offshore macroalgae aquaculture. They are used to construct arrays consisting of multiple lines attached to the spreader bars and help keep cultivation lines equidistant from each other using a fixed attachment point for each line. They are designed to be easily handled and attached to different types of equipment, such as cranes and hoists, but can introduce difficulty during harvesting operations without specialized equipment.

BUOYS AND WEIGHTS

Macroalgae aquaculture systems consist of multiple buoys and weights in order to keep the system at the required depth for maximum growth potential. Support buoys provide buoyancy to keep the macroalgae at a prescribed depth, the size and spacing of which are determined by the system design (e.g., greater spacing will require larger buoys). Each buoy is attached to a buoy line which connect buoys to the header or other line in the system. The buoy line can be short or long sections of rope depending on desired location of buoy. Weights are also used to keep the macroalgae at a prescribed depth. Similar to buoys, weights are connected to the header lines by weight tethers, which are a piece of line, the length variable depending on depth.

DEADEYE TENSIONER

Deadeye tensioners are blocks that allow multiple lines to run through, which allow for self-tensioning of the aquaculture system under changing loads. They are not used in all macroalgae gear systems, but are helpful for controlling tension in changing ocean conditions and as the weight of the algae increases with growth.

CULTURED SPECIES

While there are more than 10,000 different types of macroalgae, only 27 species were cultivated in aquaculture systems globally in 2019[100] and only 8 of those were harvested in large volumes and sold commercially.[101] The three phyla of macroalgae are commonly referred to as brown, red, and green algae, and their specific characteristics and culturing systems are presented below in Table 3.1. In Hawaii, the term "limu" is all encompassing for brown, red, and green types of edible macroalgae.

[100]Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A. & Lucente, D., (2021). Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development. *FAO Fisheries and Aquaculture Circular*.

[101]Grandorf Bak, U. (2019). Seaweed cultivation in the Faroe Islands: An investigation of the biochemical composition of selected macroalgal species, optimized seeding techniques, and open-ocean cultivation methods from a commercial perspective. Kgs. Lyngby, Denmark: Technical University of Denmark.

Table 3.1: Comparison of macroalgae phyla and the method used for cultivation in aquaculture systems.

Species/Species Group	Species Characteristics	Aquaculture Gear System
Brown algae (commonly referred to as kelp)	Long and thick fronds; significantly increase in weight throughout the growing season; winter (cold weather) growth cycle	Longline; grid/array; Integrated Multi-Trophic Aquaculture (IMTA)
Red algae	Small in size at full harvest; do not increase significantly in weight throughout the growing season; bushy with thin fronds; warm waters; can be grown year round	Raft culture; longline (horizontal only); cages; direct planting on bottom
Green algae	Flat in shape with ruffled edges; can be grown in a wide variety of temperatures but grows fastest in warm waters; can be grown year round; high growth rate[102]	Longline; grid/array; IMTA

BROWN MACROALGAE (PHYLUM OCHROPHYTA)

Brown macroalgae (often referred to as kelp) includes species such as sugar kelp (*Saccharina latissima*) (Figure 3.2), bull kelp (*Nereocystis luetkeana*), ribbon kelp (*Alaria marginata*), winged kelp (*Alaria esculenta*), skinny kelp (*Saccharina angustissima*), Japanese kombu (*Saccharina japonica*), wakame (*Undaria pinnatifida)*, oarweed (*Laminaria digitata*), and *Sargassum spp*. Brown macroalgae are typically grown on a seasonal cycle in

[102]Mohamed, R. A. (2023). Ulva species usage in aquaculture-Current status and future prospective. *Biomedical Journal of Scientific & Technical Research*, *51*(4), 42985-43009.

temperate water regions such as China, Japan, Korea, and northern Europe. Brown macroalgae species dominate the U.S. commercial macroalgae market, particularly sugar and winged/ribbon kelp grown in Washington, Alaska, and the New England region.[103] Kelp in the U.S. is grown during the winter months (September - May) and is harvested before water temperatures exceed 15-20 degrees Celsius (59-68 degrees Fahrenheit), as warmer waters tend to inhibit development, induce reproduction, and promote biofouling, which all reduce the market potential of the product.[104]

Figure 3.2: Sugar kelp (*Saccharina latissima*) being harvested off the coast of Connecticut[105]

RED MACROALGAE (PHYLUM RHODOPHYTA)

Red macroalgae species grown commercially include dulse (*Palmaria palmata*), *Gracilaria* spp., *Kappaphycus/Euchema* spp., and nori (*Poryphyra* spp.). Red macroalgae species are grown primarily in the warmer waters of Indonesia, the Philippines, Malaysia, Tanzania, and Zanzibar. Research has shown that *Gracilaria spp*. appears to have the greatest potential for aquaculture in warm water regions of the U.S. and Caribbean (Ken Riley, personal communication). Red macroalgae (Figure 3.3), is small, thin, and bushy, and, therefore, may be grown on different types of gear used for cultivating long strands of kelp.

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[103]Grebe, G.S., Byron, C.J., Gelais, A.S., Kotowicz, D.M. & Olson, T.K., (2019). An ecosystem approach to kelp aquaculture in the Americas and Europe. *Aquaculture Reports*, *15*, p.100215.

[104]Fredriksson, D.W. & Beck-Stimpert, J., (2019). Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico. NOAA Tech. Memo. NMFS-SER-9. 27 p.

[105]NOAA Fisheries (2023). Milford Lab Takes on Sugar Kelp Cultivation. NOAA Feature story. [Available at https://www.fisheries.noaa.gov/feature-story/milford-lab-takes-sugar-kelp-cultivation]

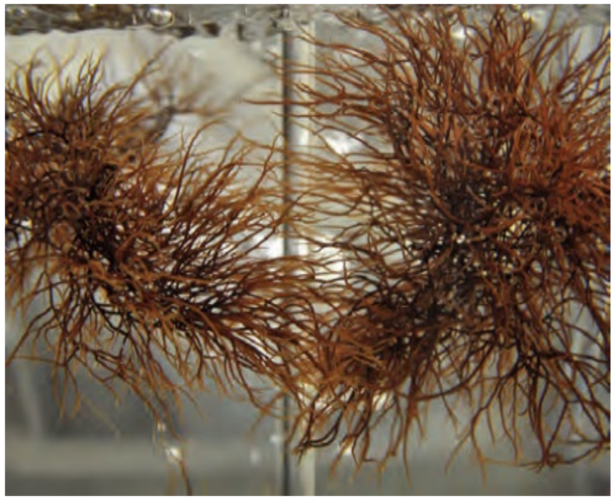

Figure 3.3: Gracilaria seaweed[106]

GREEN MACROALGAE (PHYLUM CHLOROPHYTA)

Green macroalgae species produced in aquaculture systems include *Caulerpa* spp., *Monostroma nitidum*, *Ulva* spp. (Figure 3.4), *Capsosiphon fulvescens*, and *Codium fragile.* Green macroalgae aquaculture is the smallest sector of the macroalgae industry, and over the last 30 years production has decreased and primarily been replaced by brown and red macroalgae aquaculture.[107] However, there has been renewed interest in green macroalgae due to their nutritional profiles and uses in different applications.[108] For example, green algae in the genus *Monostroma* is not cultivated in large quantities but is used as a food product that is added to soups, salads, and jams. *Capsosiphon fulvescens* is used medicinally in Korea to treat stomach ailments, and occasionally used in food products.

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[106]Redmond, S., Green, L., Yarish, C., Kim, J. and Neefus, C., (2014). New England seaweed culture handbook: nursery systems. [Available at https://repository.library.noaa.gov/view/noaa/44208]

[107]García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J.C., Pereira, L. & Gonçalves, A.M. (2020). The evolution road of seaweed aquaculture: cultivation technologies and the industry 4.0. *International Journal of Environmental Research and Public Health, 17*:18, p.6528.

[108]Moreira, A., S. Cruz, R. Marques, & P. Cartaxana. (2021). The underexplored potential of green macroalgae in aquaculture*. Rev. Aquac. 14:5-26*

Figure 3.4: Large-scale cultivation of the Northern Hemisphere Sea Lettuce (*Ulva fenestrata*) in Sweden[109]

MACROALGAE SYSTEM DESIGNS

Like shellfish aquaculture, macroalgae gear systems are selected based on the species grown and the marine environment where the gear will be utilized. Table 3.2 describes the primary gear systems used to cultivate macroalgae aquaculture, which are then discussed in more detail below

[109]Steinhagen, S., Enge, S., Larsson, K., Olsson, J., Nylund, G.M., Albers, E., Pavia, H., Undeland, I. & Toth, G.B., (2021). Sustainable large-scale aquaculture of the northern hemisphere sea lettuce, *Ulva fenestrata*, in an off-shore seafarm. *Journal of Marine Science and Engineering, 9:*6, pp.615.

Table 3.2: Comparison of macroalgae gear systems

Gear System	Description	Advantages	Challenges
Longline Systems	Submerged, anchored or suspended lines supporting macroalgae growth.	Can be easy to deploy, maintain, and harvest and withstand open ocean conditions.	Vulnerable to strong currents and storms; can be navigational hazards and may take up large swaths of ocean space.
Grid Array Systems	Arrays of frames or grids used for high-density farming.	Good for high-density farming.	Complex installation and maintenance.
Raft net systems	Floating structures with nets suspended beneath for various species.	Utilizes surface area effectively.	Susceptible to wave and wind impacts.
Catenary array systems	Suspended structures in a catenary shape, often used for filamentous algae.	Allows for even exposure to sunlight.	Requires careful tension control.
Spreader bar systems	Spreader bars used to maintain a macroalgae array.	Spreader bars are used to maintain cultivation lines at an equal distance from each other.	Difficult to harvest without specialized equipment.
Other novel systems	Innovations like underwater cages, submersible systems, or hybrid designs.	Potential for addressing specific challenges.	Limited operational history and data.

LONGLINE CULTURE

Longline macroalgae systems consist of horizontal lines anchored to the sea floor using a mooring system similar to the suspended longline gear method described in the shellfish chapter. These horizontal lines are supported by vertical buoys that maintain the location of the horizontal line below the surface, where macroalgae growth is at its maximum potential. The simplest of these systems consists of one long horizontal headrope (also known as a header line or backbone) along which buoys are attached intermittently to increase stability. Commonly, macroalgae seed lines are wrapped around the headrope, transforming the headrope into the cultivation line (Figure 3.5). Throughout the growing season, additional buoys and weights are attached intermittently along the headrope and are adjusted to maintain tension on the line, as the weight of the macroalgae increases as it grows.

Macroalgae can also be grown on vertical dropper lines. Each vertical dropper line is a cultivation line, similar to a mussel dropper line (see Shellfish Chapter). The dropper lines are hung from the horizontal headrope and are held in place in the water column by small weights and buoys (Figure 3.6). Growing macroalgae on vertical dropper lines may be advantageous compared to horizontal longlines due to the ease of individual line tensioning and harvest. However, growth rates of the macroalgae on these vertical dropper lines may vary with depth so they may be less favorable for maintaining consistency and maximizing production. Vertical dropper lines can be tied underneath (Figure 3.5) or above the headrope (Figure 3.6).[4]

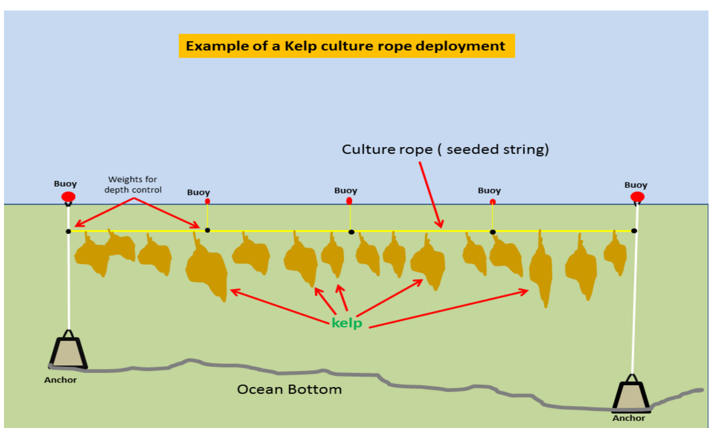

Figure 3.5: A simple longline system where macroalgae is grown vertically on a single headrope or cultivation line[110]

[110] Freitag, A. (2017). Seaweed Farming in Alaska. Alaska Sea Grant Marine Advisory Program-ASG-63.

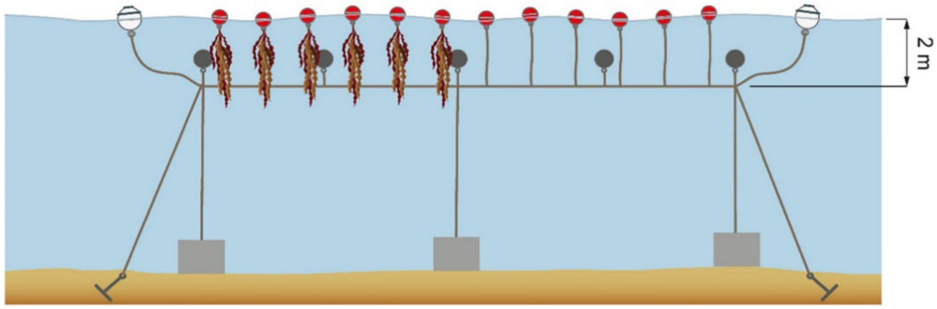

Figure 3.6: Schematic drawing of longlines with dropper lines, with gray buoys used for suspending the longline and a marker buoy on each end of the longline[111]

GRID AND ARRAY SYSTEMS

Grid and array systems are where multiple macroalgae longlines are laid out in a grid pattern or attached together in a single array. These systems can include horizontal or vertical cultivation lines, in a multitude of configurations, but primarily consist of two main headrope lines anchored to the seafloor with cultivation lines strung between them (Figure 3.7). In grid and array systems, the headropes do not double as cultivation lines, but instead function to support the grid or array.

Headropes in these systems consist of lines or bars made of metal, PVC, or fiberglass that support the entire array, providing tension with changing ocean conditions. The headropes are moored to the seafloor and a buoy line is attached to the point where the anchor line meets the headrope. The buoy functions to keep the headrope at a particular depth under tension so it doesn't sag in the water column. Some arrays may also include a series of smaller buoys and anchors intermittently attached along the headropes for the same purpose. These anchors and buoys must be continuously adjusted throughout the growing season, since macroalgae increases in weight as it grows and causes the lines to sag and lose tension.

A grid/array system can be significantly larger than a system of multiple single longlines and, as such, are often semi-permanent, remaining in place for a longer period of time than

[111]Boderskov, T., Nielsen, M. M., Rasmussen, M. B., Balsby, T. J. S., Macleod, A., Holdt, S. L., Sloth, J.J. & Bruhn, A. (2021). Effects of seeding method, timing and site selection on the production and quality of sugar kelp, Saccharina latissima: A Danish case study. *Algal Research*, *53*, 102160.

a single longline (Figure 3.7).[112] The size of an array will vary, but an array can cover many acres of ocean space and consist of hundreds of cultivation lines. Cultivation lines in a grid/array system are often spaced closer together than longline systems and, therefore, farmers may have more difficulty accessing the interior cultivation lines to manage biofouling, monitor growth, and harvest the macroalgae.[113] In addition, having the lines closer together can lead to lines crossing, getting tangled, and breakage of the cultivated macroalgae.[114,115] Arrays have been successful throughout the world[116] and their use is expanding throughout the U.S.[117]

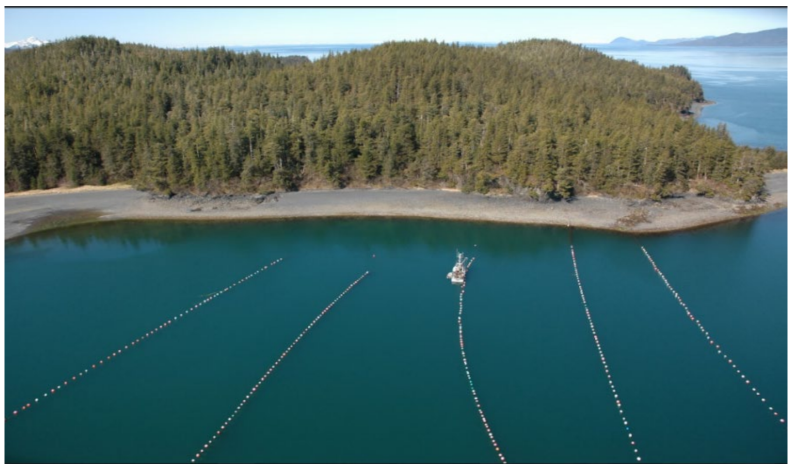

Figure 3.7: Aerial view of a macroalgae farm in Prince William Sound, AK, with submerged longlines for ribbon and sugar kelp (Photo Courtesy of NOAA Fisheries)

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[112]Stopha, M. (2020). Alaska Kelp Farming: The Blue Revolution. [Available at https://www.adfg.alaska.gov/index.cfm?adfg=wildlifenews.view_article&articles_id=949]

[113]Rolin, C., Inkster, R., Laing, J & McEvoy, L. (2017). Regrowth and biofouling in two species of cultivated kelp in the Shetland Islands, UK. *Journal of Applied Phycology, 29,* pp.2351-2361.

[114]Redmond, S., L. Green, C. Yarish, J. Kim, & C. Neefus. (2014). New England Seaweed Culture Handbook-Nursery Systems. Connecticut Sea Grant CTSG-14-01. 92 pp.

[115]Flavin, K., Falvin, N. & Fahive, B. (2013). Kelp Farming Manual A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. Ocean Approved, LLC.

[116]Bak, U. G., Gregersen, Ó., & Infante, J. (2020). Technical challenges for offshore cultivation of kelp species: lessons learned and future directions. *Botanica marina*, *63*(4), 341-353.

[117]NMFS Pacific Islands Regional Office. (2019). Letter of Concurrence for Kampachi Farms Blue Fields Macroalgae Aquaculture Research Project, Kona, Island of Hawaii, Hawaii. August 27, 2019.

CATENARY ARRAY SYSTEMS

Innovations in macroalgae aquaculture, especially in deeper waters, have focused on reducing the number of anchors and buoys while keeping the system at tension and able to withstand rough ocean conditions. Catenary arrays are a type of grid/array system that use curved catenary lines or spreader bars (Figure 3.8) made of polyethylene or HDPE at either end of the structure to keep the entire system at a consistent tension to prevent line crossing and chafing.[118] This can be accomplished due to the curved and flexible nature of the catenary line or bar. These features allow the catenary line or bar to connect the two outer headropes and allow for additional attachment points for the inner horizontal cultivation lines. Catenary lines use the same anchors and buoys as the headrope lines, thereby eliminating the need for additional anchors and buoys, while also increasing stability of the entire system (Figure 3.9). To remain at tension, the horizontal cultivation lines must differ in length and spacing, with the longer, and wider spaced lines on the outside closer to the backbones, and the shorter, more tightly spaced lines in the center of the system. As a result, a catenary system can typically use fewer anchors and buoys to moor it to the sea floor, and the mooring components allow the system to self-adjust in ever changing ocean conditions.[119] Catenary arrays may prevent lines from crossing and reduce the total number of lines, anchors, and buoys associated with the system, and therefore the overall cost. However, maintenance and harvest remain challenging for this system as it is difficult to access the interior lines of the catenary array. Commercial scale operations may require spacing between horizontal cultivation lines to allow vessel access, for maintenance and harvest, and to support kelp growth as kelp has a higher growth rate when given sufficient space.

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[118]Goudey. (2019). United States Patent. Patent No.: US10, 257,990 B1. April, 16, 2019.

[119]NMFS Pacific Islands Regional Office. (2019). Letter of Concurrence for Kampachi Farms Blue Fields Macroalgae Aquaculture Research Project, Kona, Island of Hawaii, Hawaii. August 27, 2019.

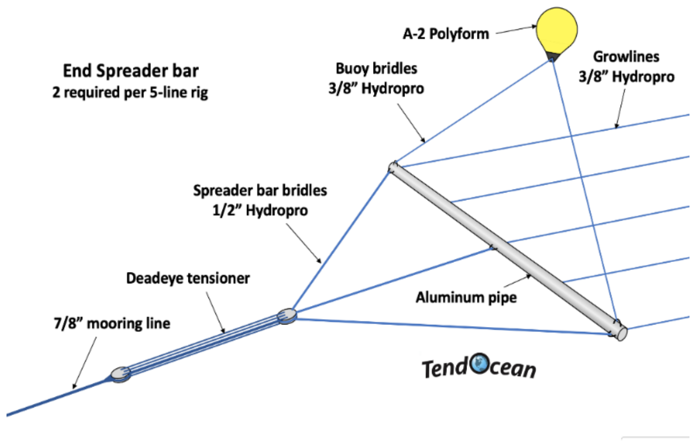

Figure 3.8: An example of a macroalgae array system using a spreader bar for tensioning (Photo courtesy of Clifford Goudey)

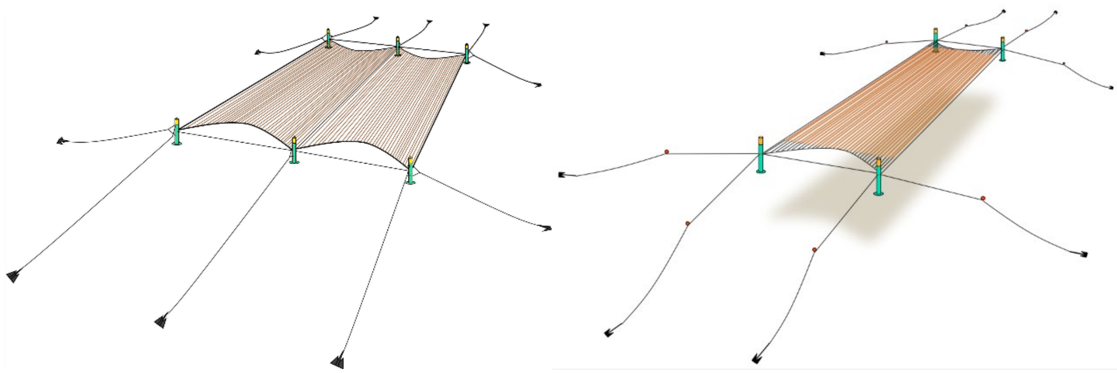

Figure 3.9: A two module (left) and one module (right) catenary array designed for kelp farming in Puerto Rico and Alaska respectively (Photo courtesy of Clifford Goudey)

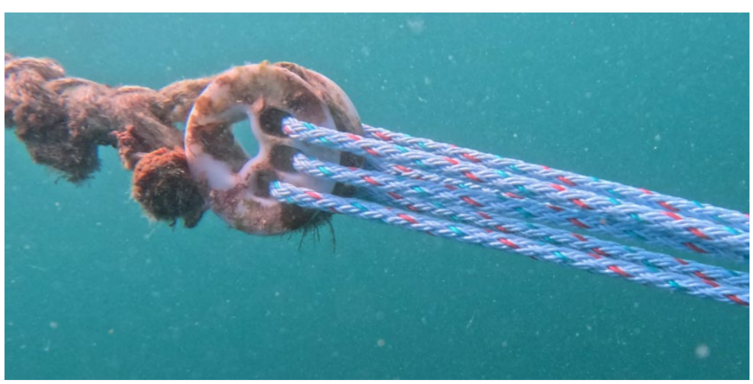

Figure 3.10: A deadeye tensioner used in a macroalgae catenary array system to maintain constant tension (Photo courtesy of Clifford Goudey)

RAFT OR NET SYSTEMS

Red and green algae species such as *Euchema* spp., *Gracilaria* spp., and *Porphyra* spp. that are short and bushy, rather than long and thin, can be grown on raft-like aquaculture systems (Figure 3.11).[120] In Asia, these raft systems are constructed of a small-mesh netting or webbing, attached to a floating bamboo frame. Raft systems are anchored to the bottom with mooring lines and if a non-floating, alternate material is used for the raft frame, buoys are used to provide buoyancy. A raft's production efficiency differs by material type, which is often dictated by supply and biofouling. In some instances, plastic rope produces greater macroalgae growths than nylon or jute rope, and square mesh netting results in higher production than straight line rafts.[121]

Raft systems are easier to deploy than longline systems or grid/array systems, as they require fewer anchors, lines, and buoys. They are also easier to harvest from, as the entire raft or net system can be lifted by hand or brought aboard a vessel using a crane, depending on its size. However, the raft systems may be less likely to withstand rough ocean conditions, and based on size, the center of the raft may be difficult to access for maintenance or biofouling removal.

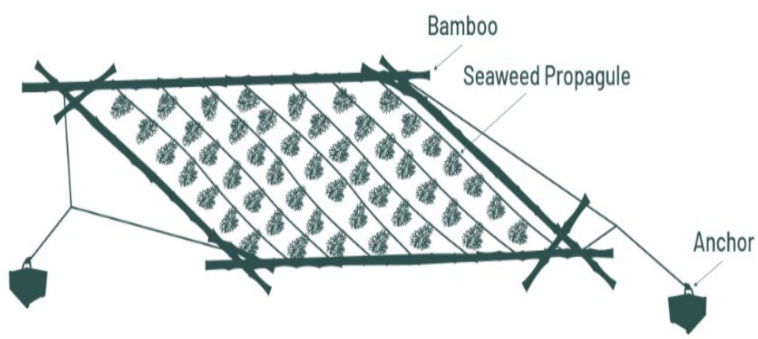

Figure 3.11: Raft gear used for growing red algae[122]

MACROALGAE CAGES

[120]Chopin, T. & Sawhney, M. (2009). In book: The Encyclopedia of Ocean Sciences (pp.4477-4487) Chapter: Seaweeds and their Mariculture. Publisher: Elsevier, Oxford Editors: J.H. Steele, S.A. Thorpe, K.K. Turekian.

[121]Sobuj, M.K.A., Mostofa, M.G., Islam, Z., Rabby, A.F., Rahman, T., Sonia, S.S., Hasan, S.J. and Rahman, S. (2023). Floating raft culture of *Gracilariopsis longissima* for optimum biomass yield performance on the coast of Cox's Bazar, Bangladesh. Scientific Reports, 13:1, p.2308.

[122]Seaweed Insights: Farm Design- Eucheumatoids. [Available at https://seaweedinsights.com/farm-design-eucheumatoids/]

Red macroalgae, particularly *Gracilaria spp*., can also be grown in cages, such as those used for cultivating shellfish due to its bushy nature, and are described above in Chapter 2.

NOVEL MACROALGAE GEAR SYSTEMS

While longline systems are the most common macroalgae systems in the U.S., researchers in other parts of the world have experimented with novel approaches to increase productivity, efficiency, and ease of operations. One such design is a system that consists of an inner and outer steel cable ring, with ropes strung in a cobweb-like pattern in between the two rings (Figure 3.12). The ring design allows for the cultivation lines to be contained within a steel structure, which makes them less susceptible to rough weather conditions. In addition, the ring is easier to set up and harvest from compared to multiple individual longlines or an array system, because the whole system can be deployed and retrieved using a shipboard crane. Other novel macroalgae aquaculture systems include grids utilizing a steel frame, anchored to the seafloor, serves as an outer grid and multiple culture lines serve as the inner grid. The cultivation lines can be strung straight across, in a zigzag pattern (Figure 3.13), or in a variety of other patterns. Patterns for cultivation lines are based on the farmer's preference, since certain patterns may be easier to access for harvesting and maintenance. Additional designs, such as 3-D rings and framed buoy systems, have been tested in experimental settings, but haven't been able to withstand ocean conditions, and have either collapsed, sunk, or fell apart during testing.[123]

The SPOKe (Standardized Production of Kelp) system (Figure 3.14)[124] also consists of an outer and inner ring, but with cultivation lines wrapped from the inner ring to the outer ring in a variety of potential patterns including outward, slanted, or in a spiral. The SPOKe system was designed so that harvest could be completely automated.

Co-locating macroalgae farms with other aquaculture systems, such as shellfish and/or finfish, is being explored in multi-trophic aquaculture systems described in Chapter 5. Researchers are also exploring co-locating macroalgae farms with offshore wind turbines.[125] Ultimately, additional novel offshore macroalgae aquaculture systems are still being developed and tested to determine the best technology that leads to maximum

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[123] Bak, U. G., Gregersen, Ó., & Infante, J. (2020). Technical challenges for offshore cultivation of kelp species: lessons learned and future directions. *Botanica marina*, *63*(4), 341-353.

[124] Solvang, T., Bale, E.S., Broch, O.J., Handa, A., & Alver, M.O... (2021). Automation concepts for industrial scale production of seaweed*. Frontiers in Marine Science 8*:613093

[125] Tullberg, R.M., Nguyen, H.P. & Wang, C.M. (2022). Review of the Status and Developments in Seaweed Farming Infrastructure*. Journal of Marine Science and Engineering, 10(10),* p.1447.

productivity and minimal environmental impact. New offshore systems for commercial use will need to ramp up technological innovations to be successful, taking into account biological, mechanical, and chemical engineering expertise.[126]

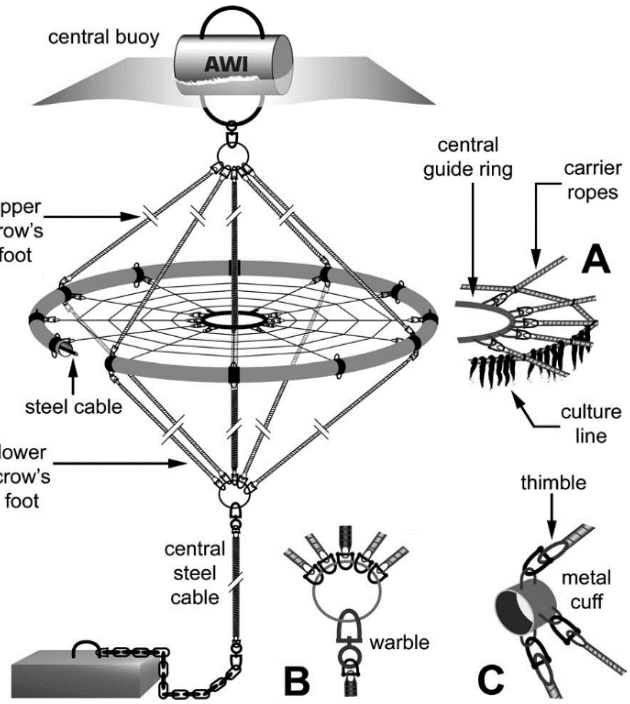

Figure 3.12: A novel concentric ring system for the culture of *Laminaria* at offshore locations. (A) central guide ring with attached carrier rope and culture line, (B) the transition between central steel cable of the mooring and that of the lower crow's foot, (C) metal cuffs, to which the crow's feet and the carrier ropes are attached[127]

[126]García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J.C., Pereira, L. & Gonçalves, A.M. (2020). The evolution road of seaweed aquaculture: cultivation technologies and the industry 4.0. *International Journal of Environmental Research and Public Health, 17*:18, p.6528.

[127]Buck, B. H., & Buchholz, C. M. (2004). The offshore-ring: a new system design for the open ocean aquaculture of macroalgae. *Journal of Applied Phycology, 16(5),* 355-368.

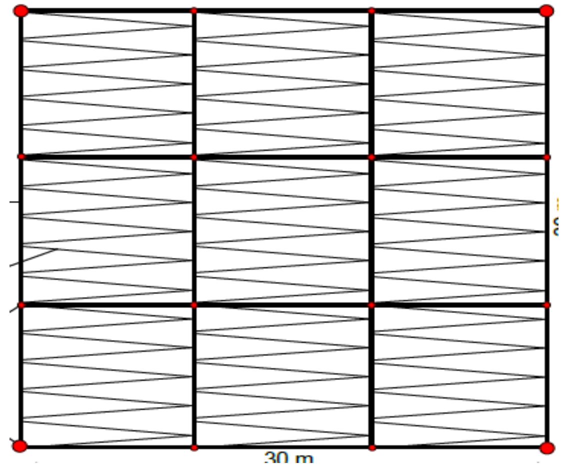

Figure 3.13: A zig-zag horizontal array macroalgae system[128]

Figure 3.14: A prototype of only 90 degrees of the SPOKe macroalgae grow system[129]

[128]Edwards, M. & Watson, L. (2011). Aquaculture explained. *Aquaculture, 26*, pp.1-71.

[129]Solvang, T., Bale, E.S., Broch, O.J., Handå, A. & Alver, M.O. (2021). Automation concepts for industrial-scale production of seaweed. *Frontiers in Marine Science, 8*, p.613093.

MACROALGAE AQUACULTURE OPERATIONAL CONSIDERATIONS

SYSTEM SELECTION

The type of macroalgae aquaculture system depends on the species being grown, production goals, and local environmental conditions. For example, production systems for kelp in the cold and high intensity waters of the North Sea will vary greatly from the warm, calm waters of Tanzania for *Gracilaria*. The information in this chapter provides an overview of species and different systems that may be selected for commercial production.

DEPLOYMENT

Macroalgae operations usually start in an on-shore facility, such as a hatchery, where macroalgae spores are grown into seedlings. In many regions there are limitations on where macroalgae growers can source seed in order to ensure only native species are cultured. These seedlings are later transferred to one of the aquaculture systems described above. In longline systems, growers attach the seedlings to cultivation lines using seed string or direct transplantation, although direct seeding is more time consuming.[130] Seed string is created when growers wrap twine onto spools, which are then sprayed or dipped with the microscopic macroalgae seeds so that the seedlings can grow directly on the string. To deploy the seedlings onto the gear, the seed string is tied and spliced into the cultivation line or the seed string is wrapped tightly around the cultivation line (Figure 3.15).[131] Seedlings are also transferred via direct seeding, when sporophytes or gametophytes are applied by hand directly into to cultivation lines without a binder such as a seed line, but is less common as it is more difficult to produce consistent macroalgae yields (Figure 3.16).[132]

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[130]García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J.C., Pereira, L. & Gonçalves, A.M. (2020). The evolution road of seaweed aquaculture: cultivation technologies and the industry 4.0. *International Journal of Environmental Research and Public Health, 17(18),* p.6528.

[131]Rolin, C., Inkster, R., Laing, J., Hedges, J. & McEvoy, L. (2016). Seaweed cultivation manual. Shetland Seaweed Growers Project 2014, 16.

[132]Wilding, C., Tillin, H. M., Corrigan, S. E., Stuart, E., Ashton, I. A., Felstead, P., Lubelski, A., Burrows, M. & Smale, D. (2021). Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management. Natural England Commissioned Reports. Natural England Report NECR378.

Figure 3.15: Seed string covered with macroalgae being wrapped around cultivation lines at sea[133]

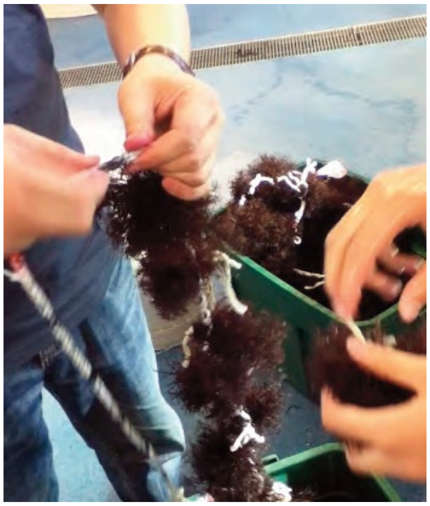

Figure 3.16: Direct, hand inserting of *Gracilaria* macroalgae into cultivation lines to be deployed[134]

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[133]Edwards, M. & Watson, L. (2011). Aquaculture explained. *Aquaculture, 26*, pp.1-71.

[134]Redmond, S., Green, L., Yarish, C., Kim, J. & Neefus, C. (2014). New England seaweed culture handbook: nursery systems. [Available at https://repository.library.noaa.gov/view/noaa/44208]

MAINTENANCE

Once deployed, the cultivation lines must be monitored on a regular basis for line entanglement and biofouling (Figure 3.17).[135,136] Maintenance of the production system includes removing biofouling organisms, usually by hand or power-washing gear, as needed, throughout the growing season. Biofouling on macroalgae is usually removed after harvesting, as farmers tend to harvest the crop prior to significant biofouling to preserve the quality of the macroalgae product.

Figure 3.17: Scientists check a longline of sugar kelp at an experimental site near Coghlan Island, Alaska[137]

HARVEST

Macroalgae can be harvested manually by pulling the longlines to the surface and removing the macroalgae by hand or with a knife. This is often time consuming and laborious due to the weight of the harvestable macroalgae on the line. Innovations in harvest technologies have allowed macroalgae operations to scale up their operations. Macroalgae can also be harvested using a winch or crane to pull the longlines to the surface, followed by cutting the macroalgae from the line.[138] Alternatively, longlines can be passed through a ring,

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[135]Visch, W., Nylund, G. M., & Pavia, H. (2020). Growth and biofouling in kelp aquaculture (Saccharina latissima): the effect of location and wave exposure. *Journal of Applied Phycology*, *32*, 3199-3209.

[136]Flavin, K., Flavin, N., & Flahive, B. (2013). Kelp farming manual: a guide to the processes, techniques, and equipment for farming kelp in New England waters. *Ocean Approved LLC, Saco*.

[137]NMFS (2020). Seaweed Aquaculture Seaweed farming, the fastest-growing aquaculture sector, can benefit farmers, communities, and the environment. [Available at https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture]

[138]Kirkman, H., & Kendrick, G. A. (1997). Ecological significance and commercial harvesting of drifting and beach-cast macro-algae and seagrasses in Australia: a review. *Journal of Applied Phycology*, *9*, 311-326.

shackle, or other device, which strips the macroalgae from the line. The macroalgae removed from the line then falls into a crate or bucket.[139] Other mechanical harvesting options include cutter boats or mowers[140], such as a harvesting machine developed in Alaska for harvesting kelp grown on horizontal longlines (Figure 3.18).[141] In 2021, Ocean Rainforest, in conjunction with the World Wildlife Fund, developed a seaweed harvesting vessel specially designed for deploying, seeding, maintaining, and harvesting macroalgae in the Faroe Islands (Figure 3.19). As the cultivation of macroalgae expands, the use of large vessels for harvesting may become more common.

Figure 3.18: Specialized seaweed harvesting vessel built by Alf Pryor for Alaska Ocean Farms (Photo courtesy of James Currie, NOAA Alaska Regional Office)

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[139]Lona, E., Endresen, P.C., Skjermo, J., Tsarau, A., Stefanakos, C. and Broch, O.J. (2020). AkvaLab–Project Summary Report-Evaluation of seaweed cultivation technology for weather exposed locations. *SINTEF Rapport*.

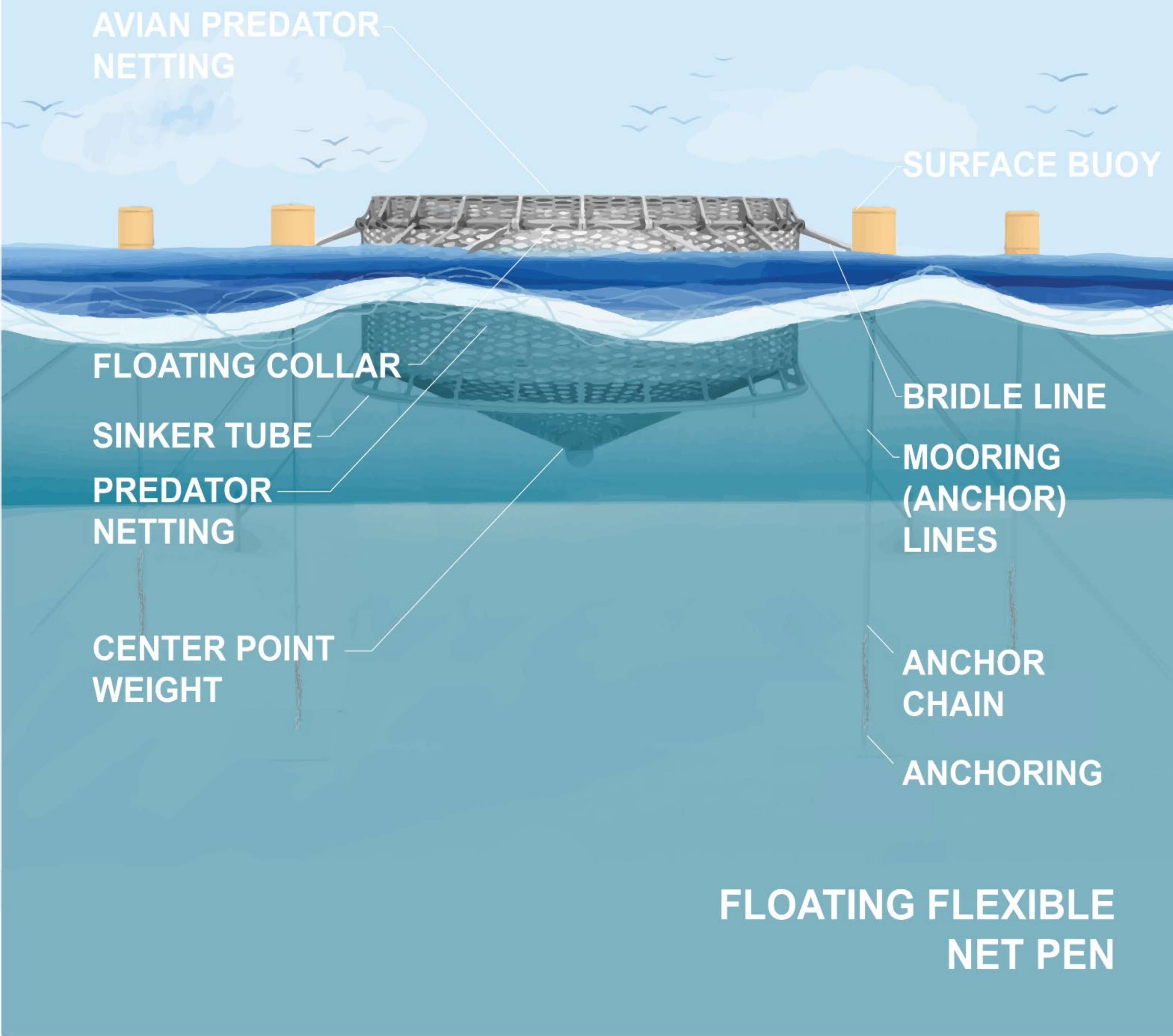
[140]Wilding, C., Tillin, H.M., Corrigan, S.E., Stuart, E., Ashton, I.A., Felstead, P., Lubelski, A., Burrows, M. and Smale, D.A. (2021). Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management.

[141]Zhang et al. (2017). Harvesting machine for kelp culture in floating raft. *Aquaculture Engineering 78*: 173-179.

Figure 3.19: Specialized kelp harvesting vessel used by Ocean Rainforest[142]

[142]Ocean Rainforest: First Specialized Multi-Purpose Seaweed Vessel. [Available at https://www.oceanrainforest.com/blog-en/2021/9/7/first-specialized-multi-purpose-seaweed-vesselnbspnbsp]

CHAPTER 4


AVIAN PREDATOR NETTING
SURFACE BUOY
FLOATING COLLAR
BRIDLE LINE
SINKER TUBE
MOORING (ANCHOR) LINES
PREDATOR NETTING
CENTER POINT WEIGHT
ANCHOR CHAIN
ANCHORING
FLOATING FLEXIBLE NET PEN

CHAPTER 4 : MARINE FINFISH AQUACULTURE GEAR

INTRODUCTION

Marine finfish aquaculture in the U.S. is in the early stages of development, however, based on advancing technologies and its perceived potential, marine finfish aquaculture could become a larger component of the nation's array of aquaculture options. Marine finfish are cultivated in the marine environment using containment structures called net pens, where juvenile fish (known as fingerlings) are stocked and grown out to a harvestable size.

The type of net pens used depend on environmental and oceanographic conditions, and the species to be grown. Ultimately, farmers must also consider cost, maintenance requirements, harvest strategy, and market factors in choosing their production gear and species. There are multiple production systems for finfish, and this chapter will only provide a general overview of the five primary systems most likely to be proposed for use in waters of the U.S., including descriptions of component technologies and operations.[143]

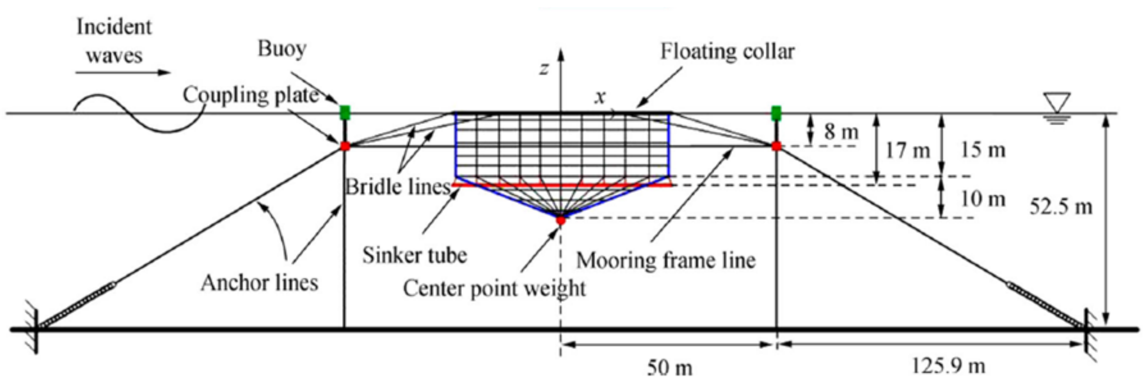


Figure 4.1: Experimental setup of finfish floating net pen with full-scale dimensions (side view).[144]

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[143] Chu, Y.I., Wang, C.M., Zhang, H., Abdussamie, N., Karampour, H., Jeng, D.S., Baumeister, J. & Aland, P.A. (2023). Offshore fish farms: a review of standards and guidelines for design and analysis. *Journal of Marine Science and Engineering, 11(4)*, p.762.

[144] Faltinsen, O.M. & Shen, Y. (2018). Wave and Current Effects on Floating Fish Farms: Keynote Contribution for the International Workshop on Wave Loads and Motions of Ships and Offshore Structures, Harbin, China, 5-7 November, 2017. *Journal of Marine Science and Application, 17(3),* pp.284-296.

FINFISH AQUACULTURE COMPONENTS GLOSSARY

ANCHORS

Anchors used for net pen aquaculture systems are predominantly large, heavy, direct embedment or drag embedment anchors and vary based on system requirements (see Chapter 1 for more information on anchors).

BUOYS AND BUOY LINES

Buoys provide buoyancy to keep the net pen structure at a prescribed depth and provide stability for the net pen (see Chapter 1 for more information on buoys). Buoy lines are used to attach the buoy to the net pen structure or mooring lines.

SPARS

Spars are rigid tubes in the center of semi-submersible net pens that give the pen structure and variable ballast. They are used to raise and lower the net pen in the water column by pumping the spar with air or water.

SPAR BUOY

Spar buoys support the corners of a net pen. They can be filled with air to float the net pen or as ballast or with water to increase stability or sink due to adverse conditions. Vertical spar buoys consist of multiple air chambers where one or multiple air chambers within each spar can be filled or purged of air to raise or lower the net pen.

BRIDLE LINES

A bridle line is a line that is used to attach buoys to the net pen. It also connects the pen(s) to the mooring grid system. Bridle lines are important when raising and lowering the net pen in the water, as they provide stability depending on their length and at different depths. These lines are often not at tension when the net pen is at the surface.

MOORING GRID LINES

A system whereby one or more pens are secured to a grid which is usually made of rope, which is held in position through mooring lines. The grid lines give floating net pens additional stability by linking the pens to one another.

BALLASTING SYSTEM

Ballasting systems are tank(s) that can be filled with water to sink the net pen or filled with air to raise the net pen to the surface. They provide variable buoyancy which allows the operator to change the net pen's depth. Ballasting systems can also include weights for stability of the system.

NET PEN STRUCTURE

The net pen structure provides stability for all the components of the entire structure, keeps the containment netting in place, and holds the shape of the netting. It is usually circular or polygonal in varying sizes and is constructed from materials with strength, durability, and non-toxic composition, e.g., HDPE, and aluminum, steel. It also provides flotation and structural integrity to maintain shape.

FLOATABLE PIPE COLLAR RINGS

Pipes are used to create floating collar rings in flexible floating net pens. The floatable pipes are joined together to create collar rings on which the containment netting is strung. They provide the overall structure for the containment netting for flexible floating net pens and are predominantly made of HDPE.

CONTAINMENT NETTING

Containment netting is the primary net that keeps the fish contained within a specific volume of seawater. It is constructed from materials with high durability, breaking strength, resistance to abrasion, as well as ease of handling, and the ability to maintain its shape, (e.g., synthetic fibers such as nylon and polyester, copper-alloy-coated, marine-grade stainless-steel, or polyethylene terephthalate monofilament [known as Kikkonet™]) (see Chapter 1 on netting for more information).

PREDATOR NETTING

Predator netting is a layer of netting surrounding the containment net above and below the waterline. It usually has a larger stretch mesh than the primary containment netting. It is used to prevent predators from feeding on the cultured fish and can also act as a secondary containment net, preventing escapes in the case of primary net breakage.

JUMP NET

Jump nets are the upper portion of the net in the pen that is between the water line and the handrail.

TARPS

Net pens may include tarps that protect fish from harmful algal blooms and sea lice, and to provide containment for therapeutic baths. Tarps are made of polyester, canvas, polyethylene, or polypropylene, and are rolled down inside of the net pen to act as a protective layer between the fish and the outside environment.

LEAD LINE

Lead lines are weighted line or a length of another weighted material permanently attached to the netting. They join the side wall of the netting and the base of the netting.

LIFTING ROPE

Lifting ropes are a down rope on a net which can be used to lift the net that allows for manipulation of the nettings orientation.

SINKER TUBE

Sinker tubes are a weighted ring suspended from the net pen by ropes attached directly to the ring or led through blocks attached to the ring. They provide stability for the net pen and netting.

STANCHION

Stanchions are used as a vertical support for the handrail and are also the point at which the net down ropes are attached. Stanchions provide support and structural integrity to floating net pens.

SINGLE POINT MOORING

Single point moorings are a type of mooring system where the net pen or other associated vessels with the aquaculture operation are connected to the sea floor through the use of a single line mooring system. This allows the net pen structure or other equipment to swing free in the water column, mitigating the effects of current and wind.

WEIGHTING SYSTEM

The weighting system in a finfish net pen is used to maintain the desired shape and tension of the net using a combination of individual weights, sinker tubes, and rope and blocks.

FINFISH SPECIES

The species cultivated may influence the type of net pen employed. Atlantic salmon (*Salmo salar)* and steelhead salmon (*Oncorhynchus mykiss*) are the most widely recognized marine finfish raised in the U.S. and globally. At present, almaco jack (*Seriola rivoliana*) is the only other species currently being commercially farmed in U.S. marine waters. Additional species being considered for U.S. marine net pen cultivation include red drum (*Sciaenops ocellatus*), Atlantic striped bass (*Morone saxatilis*), moi (*Polydactylus sexfilis*), California yellowtail (*Seriola lalandi*), black sea bass (*Centropristis striata*), pompano (*Trachinotus carolinus*), sablefish (*Anoplopoma fimbria*), tripletail (*Lobotes surinamensis*), red snapper (*Lutjanus campechanus*), mahi (*Coryphaena hippurus*), cobia (*Rachycentron canadum*), and some species of tuna.[145]

NET PEN SYSTEMS

GENERAL DESCRIPTION

A marine finfish net pen, also referred to as a marine cage,[146] has two primary components: a frame (the cage structure) and netting. The frame keeps the netting in place, holds the shape of the netting, and provides stability against forces acting upon the entire structure. The netting is important to the overall system because it is responsible for fish containment and control while allowing seawater circulation through the enclosed environment (Figure 4.2).

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[145]Weirich, C.R., Riley, K.L., Riche, M., Main, K.L., Wills, P.S., Illán, G., Cerino, D.S. and Pfeiffer, T.J. (2021). The status of Florida pompano, Trachinotus carolinus, as a commercially ready species for US marine aquaculture. *Journal of the World Aquaculture Society, 52(3),* pp.731-763.

[146]Price, C.S., Morris, J.A., Keane, E.P., Morin, D.M., Vaccaro, C. & Bean, D.W.W. (2017). Protected species and marine aquaculture interactions.[Available at http://doi.org/10.7289/V5/TM-NOS-NCCOS-211]

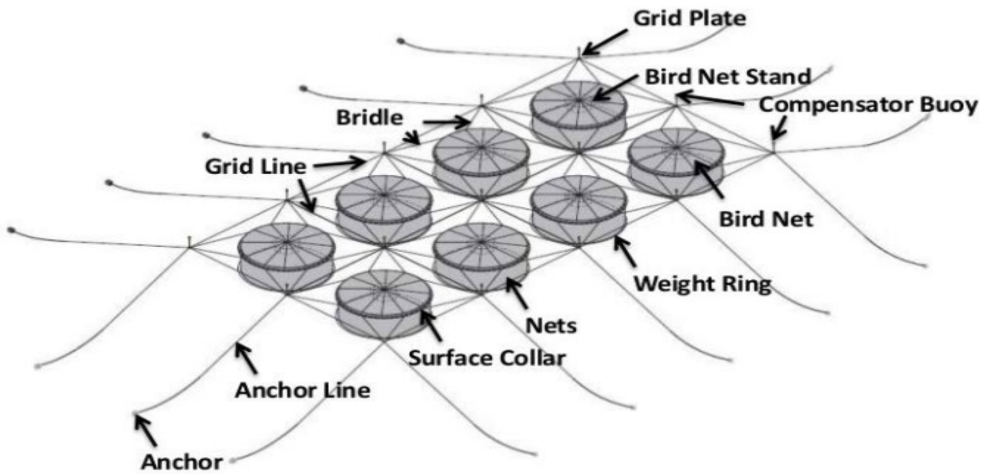

Figure 4.2: Line drawing of a finfish net pen array, moored in a grid pattern.[147]

Net pen structures and moorings constantly have physical, chemical, and biological forces at play against them. Physical forces include waves, wind, currents, and storms while chemical forces include oxidation and chemical degradation of the net pen framework and components. Biological forces include colonization of marine organisms on the net pen system via biofouling organisms as well as gear depredation from predators (e.g., sharks, seals, etc.) biting and wearing on nets. To counteract these forces, a variety of materials that have the common characteristics of strength, durability, and non-toxic composition are used in net pen construction. The criteria for selecting materials for the net pen framework, the shape, size, and volume of the net pen include material strength, resistance to corrosion, costs of repair and maintenance, the marine environment at the farm location and the species being cultivated. Net pen engineering requires structural analysis of the mooring system(s) that depends on the structural capacity of the net pen selected. These analyses consider static-state and the life cycle of components that the operator may need to replace on a given schedule. While small aquaculture farms may not require engineering analysis, due to the complexity of any offshore aquaculture system, including net pens, most net pen aquaculture farm proposals will be accompanied by detailed design drawings and engineering specification information. There are three predominant categories of finfish net pens: floating flexible, semi-submersible, and rigid (Table 4.1).

[147]Bridger, C.J., Fredriksson, D.W., & Jensen, Ø. (2015). Physical containment approaches to mitigate potential escape of European-origin Atlantic salmon in south coast Newfoundland aquaculture operations. DFO Can. *Sci. Advis. Sec. Res. Doc. 2015*/072. 54 p.

Table 4.1: The three main finfish net pen designs[148]

Net Pen Type	Structural property	Advantages	Disadvantages
Floating Flexible	Rely on buoyancy and weight to keep shape and volume	Can be moved more easily; adaptable to various environments; ease of workability and ability to access the net pen from above without entering the water	Vulnerable to surface ocean conditions
Semi-submersible	Rely on tension and compression to keep shape and volume	Reduced impact from surface weather and avian predators; less vulnerability to extreme weather events	Higher setup and maintenance costs; Higher technical complexity for submersion
Rigid	Rely on rigid construction to keep shape and volume	Less vulnerability to extreme weather events; potentially less direct environmental impact	Very high initial costs, higher maintenance and operations costs

SYSTEM SELECTION

The structural capacity of a proposed finfish net pen must correspond with the offshore conditions in which it will be deployed. The finfish net pens currently available globally have different structural properties for different uses and environments (Table 4.2).

[148] Chu, Y.I., Wang, C.M., Zhang, H., Abdussamie, N., Karampour, H., Jeng, D.S., Baumeister, J. & Aland, P.A. (2023). Offshore fish farms: a review of standards and guidelines for design and analysis. *Journal of Marine Science and Engineering, 11(4),* p.762.

Table 4.2: General material, shape, size, and volume of finfish net pen systems in use globally.

Net pen Type (Example)	Material	Shape	Typical Size	Typical Volume (m^3)
Floating Flexible (Polar Cirkel™)	Flexible HDPE pipe	Circle	13-83 m diameter	1150-300,000
Floating Rigid (Havfarm™)	Steel	Hexagon or square	47 x 47 m	69,000
Semi-Submersible rigid (StormSafe Cage™)	Steel	Hexagonal	31.4 m diameter	9,000
Semi-Submersible flexible (SeaProtean™ by Innovasea)	Flexible HDPE	Cylinder	23-26m diameter	6,400-14,500

FLOATING FLEXIBLE NET PENS

Floating flexible net pens or more commonly, HDPE net pens, were invented in the 1970s. They are currently used throughout the world, most notably in Norway, Chile, Canada, Japan, New Zealand, and the Mediterranean. This type of net pen is used most often in shallow bays or other semi-protected water bodies. The HDPE pipes used in floating flexible net pen construction are durable, flexible, shockproof, resistant to UV light, and require relatively little maintenance. HDPE pipe has low corrosive properties, can be fabricated in a variety of diameters and pipe wall thicknesses depending on the application. HPDE has elasticity and is flexible, which allows for movement in the waves and easy molding into different shapes. To construct a single floating flexible net pen, a single HDPE pipe is held together in a circular shape with brackets and stanchions to form a net pen collar that floats at the surface (black ring on the surface in Figure 4.3). The diameter of the net pen collar determines the buoyancy of the net pen system; the larger the diameter, the greater the buoyancy.

Figure 4.3: HDPE fish net pen examples (Left: Tyrrhenian Sea, Italy; Right: Aegean Sea)[149]

Containment netting is then hung from the floating net pen collar to the desired depth and cinched together at the bottom of the netting using weights to provide closure of the system and tensioning.[150] The netting can vary in material, size, shape, and thickness relative to the net pen design and the size of fish being cultivated. Floating flexible net pens can be moored as stand-alone systems or multiple floating net pens can be affixed to one another in a grid mooring system (Figure 4.4, Figure 4.5). A grid mooring system of multiple floating flexible net pens is designed to dampen the overall forces generated by waves and currents. However, the flexibility of the HDPE pipe makes these net pens more prone to deformation when exposed to strong waves and currents. This deformation can also adversely affects the netting of the structure and subsequently stress the fish being cultivated.

[149]Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. FAO Fisheries and Aquaculture Technical Paper No. 593. Rome, FAO. 152 pp.

[150]Chu, Y.I., Wang, C.M., Zhang, H., Abdussamie, N., Karampour, H., Jeng, D.S., Baumeister, J. & Aland, P.A., (2023). Offshore fish farms: a review of standards and guidelines for design and analysis. *Journal of Marine Science and Engineering, 11(4)*, p.762.

Figure 4.4: Floating salmon net pen off the coast of Maine with green avian predator netting supported in the middle with an HDPE floating support (Photo courtesy of David Bean, NOAA Fisheries).

Figure 4.5: Floating net pen (Polar Cirkel™) (Photo courtesy of David Bean, NOAA Fisheries).

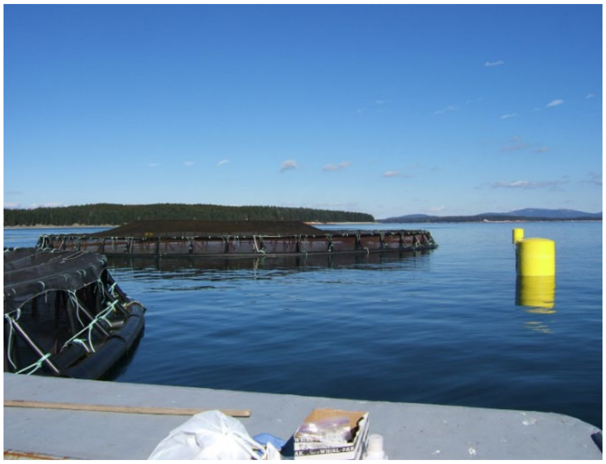

Figure 4.6: Circular net pens with avian predator netting; yellow compensator buoy (on right) (Photo courtesy of David Bean, NOAA Fisheries).

FLOATING RIGID NET PENS

Floating rigid net pens are large, framed structures, designed for maximum strength, stiffness, stability, and buoyancy, to neutralize the wave and current action in an offshore open ocean setting. They are often massive systems made from steel and concrete, and are either anchored to the seafloor or can be designed to include engines that allow for them to be movable to different locations or for returning to port. Due to their size and structure, these floating rigid net pens provide a stable working platform for all husbandry and management operations including feeding, harvesting, and maintenance (Figure 4.7). Some floating rigid net pen systems even include live-aboard quarters for staff. These types of finfish aquaculture systems can be constructed and maintained in conventional shipyards and have the potential to grow large volumes of finfish, however, they also require high capital investment and operating costs and utilize large, heavy mooring systems.

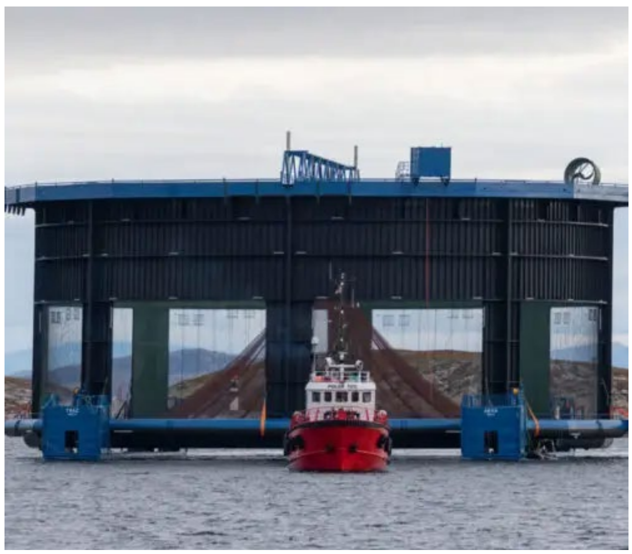

Figure 4.7: Aquatraz™ salmon net pen in Norway[151]

SEMI-SUBMERSIBLE NET PENS

Semi-submersible net pens differ from floating net pens in that they can be characterized by their capacity to be submerged below the higher energy, surface waters, for specific periods of time. Once submerged, movement or motion stress is reduced, which could potentially reduce damage to fish stocks. Submerging net pens also allows operators to reduce the potential for damage to the gear in rough ocean conditions due to extreme weather events. The deployment of these systems at the surface and submerged, needs to

[151] SeaFarming Systems: Aquatraz. [Available at https://seafarmingsystems.com/category/aquatraz/]

be controlled effectively and at the right times, which adds potential complexity and risk. Like floating net pens, there are two structural classes of semi-submersible net pens: rigid and flexible. These pens are not currently used in the U.S. at the time of publication of this guide.

SEMI-SUBMERSIBLE RIGID NET PENS

Unlike flexible net pens, semi-submersible rigid net pens are designed with rigid framework elements that create a large mass with a low center of gravity, and the framework can be adjusted to different vertical positions in the water column. The ability to submerge these net pens in the water column allows the net pen to withstand rough offshore surface conditions and also restricts vertical movement (or volume change), which keeps the fish being cultured in place. Additionally, this type of net pen can be raised above the water line for feeding, maintenance, and harvesting purposes. The overall rigidity of this net pen type also allows for the installation of feeding systems, harvesting cranes, or surveillance system attachments directly on the frame itself.

The size and diameter of the mooring and bridle ropes for these systems are large; similar to those used for traditional large ocean structures such as oil rigs. High-capacity drag embedment anchors (described in Chapter 1) are used because of large uplift that can occur at depth. The vertical holding capacity must be very large to mitigate the risk of structural failure of these pens during extreme storms. Semi-submersible rigid net pen systems have a long service life, however, there are high capital costs associated with these types of systems, including a thorough design and engineering analysis prior to deployment.

The StormSafe ® Submersible Rigid Net Pen, developed for use in the Great Lakes region, is an example of a semi-submersible rigid net pen that has been proposed for use for a commercial marine finfish operation (Figure 4.8). In other parts of the world, where commercial offshore finfish aquaculture operations are more prevalent, larger, more robust semi-submersible rigid systems, such as the Ocean Farm 1, by SalMar (Figure 4.9), are being developed and tested.

Figure 4.8: StormSafe ® Submersible Rigid Net Pen[152]

Figure 4.9: Ocean Farm 1™ structure being towed for deployment in Norway[153]

SEMI-SUBMERSIBLE FLEXIBLE NET PENS

Like floating flexible net pens, semi-submersible flexible net pens also utilize a floating collar system to maintain buoyancy, however in semi-submersible system it is a double-ring system. The two (upper and lower) collars (Figure 4.10), consist of chambers that can be filled with air to float or filled with water to submerge the net pen. Containment netting

[152]Aquaculture North America. (2016). Submersible net cage system comes a long way. Published October 5, 2016. [Available at https://www.aquaculturenorthamerica.com/submersible-net-cage-system-comes-a-long-way-1486/]

[153]Fish Farming Expert. (2023). Ocean Farm 1 cost owner NOK 100m last year. Published June 26, 2023. [Available at https://www.fishfarmingexpert.com/ocean-farm-1-salmar-aker-ocean-as/ocean-farm-1-cost-owner-nok-100m-last-year/1537677]

is then attached between the two floating collars to form the entire structure. Semi-submersible flexible net pens are designed to expand and contract with the effects of wind and waves allowing them to dissipate wave, wind and current energy. Semi-submersible flexible net pen systems by Innovasea Systems, Inc. have been used by Blue Ocean Mariculture in Kona, Hawaii since 2009 to grow almaco jack (*Seriola rivoliana*) (Figure 4.11, Figure 4.12). Blue Ocean Mariculture submerges the pens each night for a variety of reasons such as allowing the fish more space to swim within the net pen, reducing wave action, etc. They raise the pens each morning for maintenance, allowing the sun to dry much of the biofouling and feeding. Innovasea Systems, Inc. has a variety of semi-submersible flexible cages that they sell to aquaculture operations around the world, which vary in design for different marine environments and species.[154]

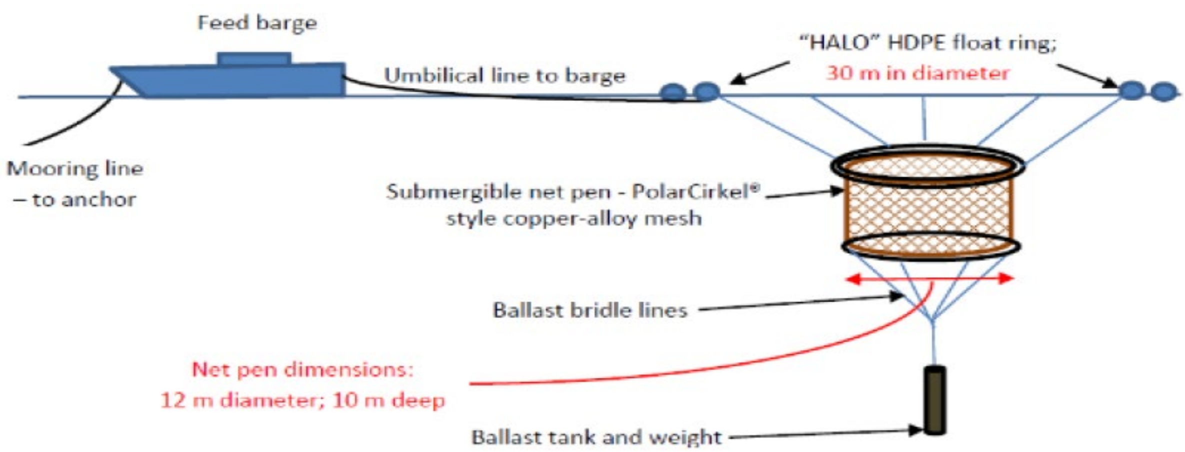

Figure 4.10: Side View Schematic of a typical flexible net pen (including feed barge) designed by PolarCirkel[155]

[154]Innovasea Open Ocean Aquaculture. [Available at https://www.innovasea.com/]

[155]Nichols, D., Tosatto, M.D., Brown, M., Van Fossen, L., & Wunderlich, M. (2016). Issuance of a Permit to Authorize the Use of a Net Pen and Feed Barge Moored in Federal Waters West of the Island of Hawaii to Fish for a Coral Reef Ecosystem Management Unit Species, *Seriola rivoliana*. Environmental Assessment. [Available at https://repository.library.noaa.gov/view/noaa/14791]

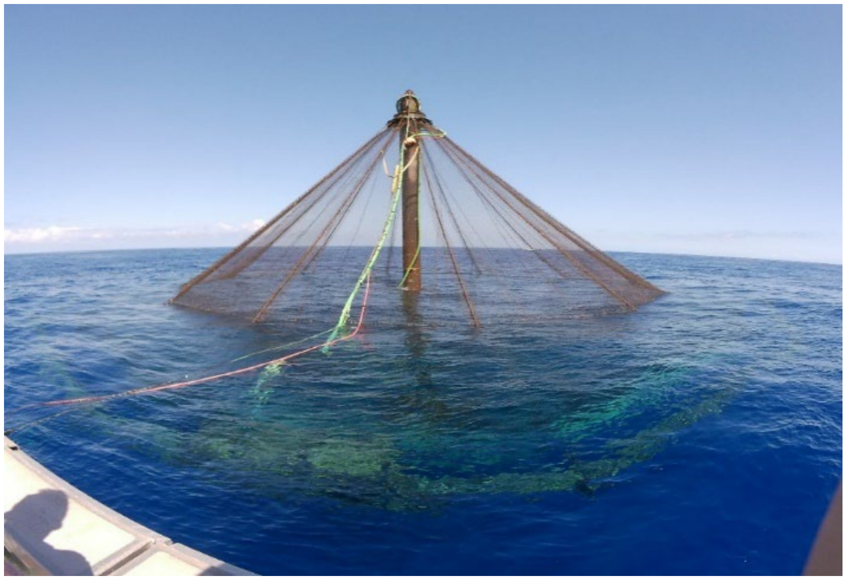

Figure 4.11: An Innovasea Sea Station™ cage raised to the surface at Blue Ocean Mariculture in Kona, Hawaii (Photo courtesy of Kirsten Ieong for NOAA Fisheries)[156]

Figure 4.12: Divers service an Innovasea Sea Station™ cage at Blue Ocean Mariculture in Kona, Hawaii (Photo courtesy of Blue Ocean Mariculture)

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[156]Innovasea (2020). Innovasea Helps Open Blue Become the Largest Open Ocean Fish Farm in the World. [Available at: https://www.innovasea.com/case-study/open-blue-largest-open-ocean-fish-farm/]

NOVEL FINFISH GEAR SYSTEMS

SHIP BASED CONTAINMENT SYSTEMS

Floating rigid net pens can be standalone pens or based on ships such as the Havfarm in Norway (Figure 4.13) by the company Nordlaks. Ship based aquaculture systems have the rigid net pen frame or structure contained within the ship itself. Depending on the size of the ship, the number, size, and capacity of each pen is variable.

Figure 4.13: Havfarm floating rigid salmon aquaculture net pen in Norway[157]

CLOSED FLOATING NET PENS

Closed finfish net pen technology is a recent development which uses a closed semi-submersible system that provides continuous flow within the system, minimizes the water and effluent exchange with the surrounding marine environment, and is thought to prevent exposure to predators and pests. The marine donut (Figure 4.14) is made of HDPE in a closed containment system that pumps filtered water into the donut where the fish are contained, and collects effluent such as excess feed and fecal matter so that is not released into the marine environment.[158] The first closed finfish pen, the marine donut is in trials in Norway as of 2024.

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[157]Guneriussen, M. (2022). Analysis of the Havfarm concept for extreme environmental loads. Master's thesis in Marine Technology. Supervisor: Jørgen Amdahl. Co-Supervisor: Martin Slagstad. Norwegian University of Science and Technology.

[158]Blue Green Group Fact sheet: Marine Donut. [Available at https://bluegreengroup.no/assets/fact-sheet-marine-donut.pdf]

Figure 4.14. The Marine Donut, the donut shaped floating closed containment fish farm operated by the same operators as Ocean 1; SalMar in Norway[159]

FINFISH AQUACULTURE OPERATIONAL CONSIDERATIONS:

CONSTRUCTION AND DEPLOYMENT

Finfish net pens can be constructed inshore or offshore depending on the size and complexity of the net pen. Once the net pen frame is constructed and on-site, the netting is attached and the entire structure can be deployed (Figure 4.15). Deployment depends primarily on the buoyancy of the system. For structures that are negatively buoyant, such as submerged rigid systems, it is common for the mooring system to be deployed first, then the net pen. For floating structures, it is common for the net pen to be deployed first since it can be manipulated at the surface.

[159] Thousands of salmon now swimming in the 'Marine Donut'. [Available at https://www.salmonbusiness.com/thousands-of-salmon-now-swimming-in-the-marine-donut/]

Figure 4.15: Flat deck work barge with netting aboard (Photo courtesy of David Bean, NOAA Fisheries)

The construction of marine net pens can also include the installation of predator netting, which is a secondary, coarser net, usually composed of polyethylene (see Chapter 1 for more information on netting). Predator netting provides an extra barrier against potential marine predators such as diving avian species, sharks, predatory fish, and/or marine mammals. The predator netting surrounds the entire net pen structure and is hung or supported vertically, from the top buoyancy collar, at a specific distance from the containment netting. Predator netting can alternatively be attached to the bottom collar or a weighted ring at depth. The bottom collar or weighted ring acts to maintain the shape of the predator netting and prevent deflection from the currents.

Aerial netting prevents access to a net pen by predatory birds (e.g., osprey, eagles, herons, and gulls). It is usually composed of polyester due to its UV resistance, and is attached along the outer surface of a net pen along the floating support structure. It can also be hung from a stand located in the middle of the net pen (called tenting) (Figure 4.16 and Figure 4.17). This aerial netting covers the entire diameter of the net pen located above the waterline (Figure 4.17).

In addition to the predator netting, net panels or jump fences may be installed above the water line and secured to the hand rails or collar around the cage, to prevent fish from jumping out of the cage (Figure 4.16). This type of predator netting can also act as an additional protective layer to prevent pinnipeds from getting into the cage in environments where they are present. Usually, the net panels and jump fences are fastened together for extra protection to avoid escapement and predation.

The addition of predator netting requires an understanding of how currents, wave conditions, and wind will affect the overall system, as what as what species inhabit the local environment. Sufficient tensioning of the predator netting is required for not only functionality, but also balance of the entire net pen system.

Figure 4.16: Three ring floating net pen with jump fence (reddish-brown) and avian predator netting attached (Photo courtesy of David Bean, NOAA Fisheries)

Figure 4.17: A HDPE support structure is used to support the avian predator net as well as provide a secure place for the feed spreader (middle)[160]

[160]Cage Farming Aquaculture. AKVA Group. Aquaculture Catalog. [Available at https://pdf.nauticexpo.com/pdf/akva-group-asa/cage-farming-aquaculture/44708-113379-_2.html]

MAINTENANCE

Maintenance includes routine monitoring of all net pen components for structural integrity and correct positioning. This includes checking both the containment netting and all predator nettings for tears or holes, regular cleaning and biofouling control. Biofouling organisms (e.g., ascidians, algae, mollusks and cnidarians[161,162]) can weigh down and stress the system, decrease the water exchange, affect the overall balance of the system, affect the coefficient of drag, and cause abrasions to the fish. The removal of biofouling organisms can be done at the surface by exposing biofouled gear to the air, or net pens can be cleaned below the surface using divers or remotely operated vehicles. Growers may also control biofouling by using copper alloy mesh, or other materials, in the construction of the containment netting. The use of copper alloy mesh or copper coatings not only reduces biofouling, but reduces parasitic eggs that settle on biofouling that can spread to the fish being cultured. Using copper alloy mesh therefore, also reduces parasites on the fish product and reduces the need for parasite treatment during operations.

FEEDING

The two main components required for finfish feeding are the holding/storage unit (silo) of the feed pellets and the delivery system. The feeding of finfish can occur either at the surface or at depth.

For surface feeding, the most basic way to deliver fish feed is by hand, however, this form of feeding is only practical at small aquaculture operations or nursery systems. For larger commercial finfish cultivation operations, a common feed delivery system used at the surface is a rotary feed spreader. Rotary feeder systems usually consist of piping and a blower system (Figure 4.18). Blowers aboard a vessel supply compressed air which propels the feed "pellets" along the piping to a feed spreader located in an individual net pen. The SeaFeed spreader is one such example, in which compressed air forced into the piping

[161]Dürr, S. & Watson, D.I. (2010). Biofouling and antifouling in aquaculture. Biofouling, 12, pp.267-287.

[162]Fitridge, I., Dempster, T., Guenther, J. & De Nys, R. (2012). The impact and control of biofouling in marine aquaculture: a review. *Biofouling*, *28*(7), pp.649-669.

causes the spreader to rotate in a circular motion, equally distributing the feed across the surface layer of the cage (Figure 4.19).[163, 164]

Figure 4.18: Airborne rotary feeder in the center of a fish net pen[165]

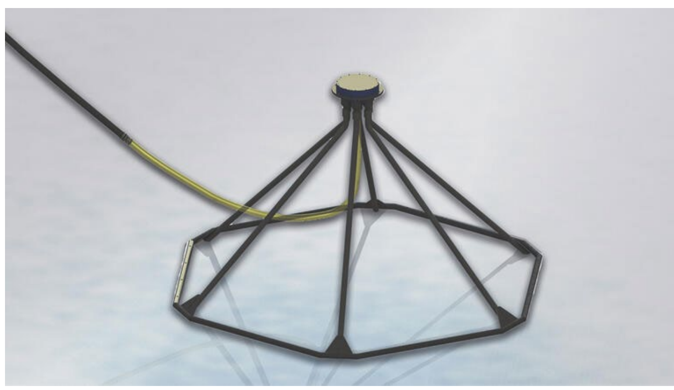

Figure 4.19: AKVA Underwater spreader for feed delivery directly into the net pen[166]

Feed pellets can also be delivered to an underwater spreader using water pumps (Figure 4.20). Underwater spreaders operate in the same way as surface spreaders but pump feed

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[163]Liena, A.M., Schellewalda, C., Stahlib, A., Franka, K., Skøienb, K.R., & Tjølsend, J.I. (2019). Determining spatial feed distribution in sea cage aquaculture using an aerial camera platform. *Aquacultural Engineering, 87,* 102018.

[164]Skoien, K.R., & Alfredsen, J.A. (2014). Feeding of large-scale fish farms: Motion characterization of a pneumatic rotor feed spreader. 2014 Oceans - St. John's, 1-7.

[165]AKVA Airborne rotary feeder in the center of a fish net pen. [Available at https://www.akvagroup.com/sea-based/precision-feeding/feed-systems/airborne-feeding]

[166]AKVA Underwater spreader for feed delivery in aquaculture net pens. [Available at https://www.akvagroup.com/sea-based/precision-feeding/feed-systems/waterborne-feeding]

directly under the water, delivering feed pellets directly into the water column from either the top or the bottom of the net pen. This allows the finfish to feed deeper in the water column, which is a more natural feeding behavior.

Large finfish operations may use feed barges, self-contained vessels designed to safely withstand waves, currents, and storm events while providing a reliable feed system. The basic equipment aboard a feed barge includes an automatic feed system, feed storage compartment (silo), generator(s), control room, living quarters, and safety equipment (Figure 4.21).

New and innovative fish feeding technology is being developed at a rapid pace to increase efficiency in feed operations for offshore aquaculture. Unmanned robotic systems are being developed with cameras and sensor systems to deliver a specified amount of feed, monitor consumption rates, and ensure fish are fed optimally.

Figure 4.20: (Left) Feed Barge (with feed hoses deployed) and (Right) feed hoses from a feed barge extending out to fish net pens[167]

[167]Cage Farming Aquaculture. AKVA Group. Aquaculture Catalog. [Available at https://pdf.nauticexpo.com/pdf/akva-group-asa/cage-farming-aquaculture/44708-113379-_2.html]

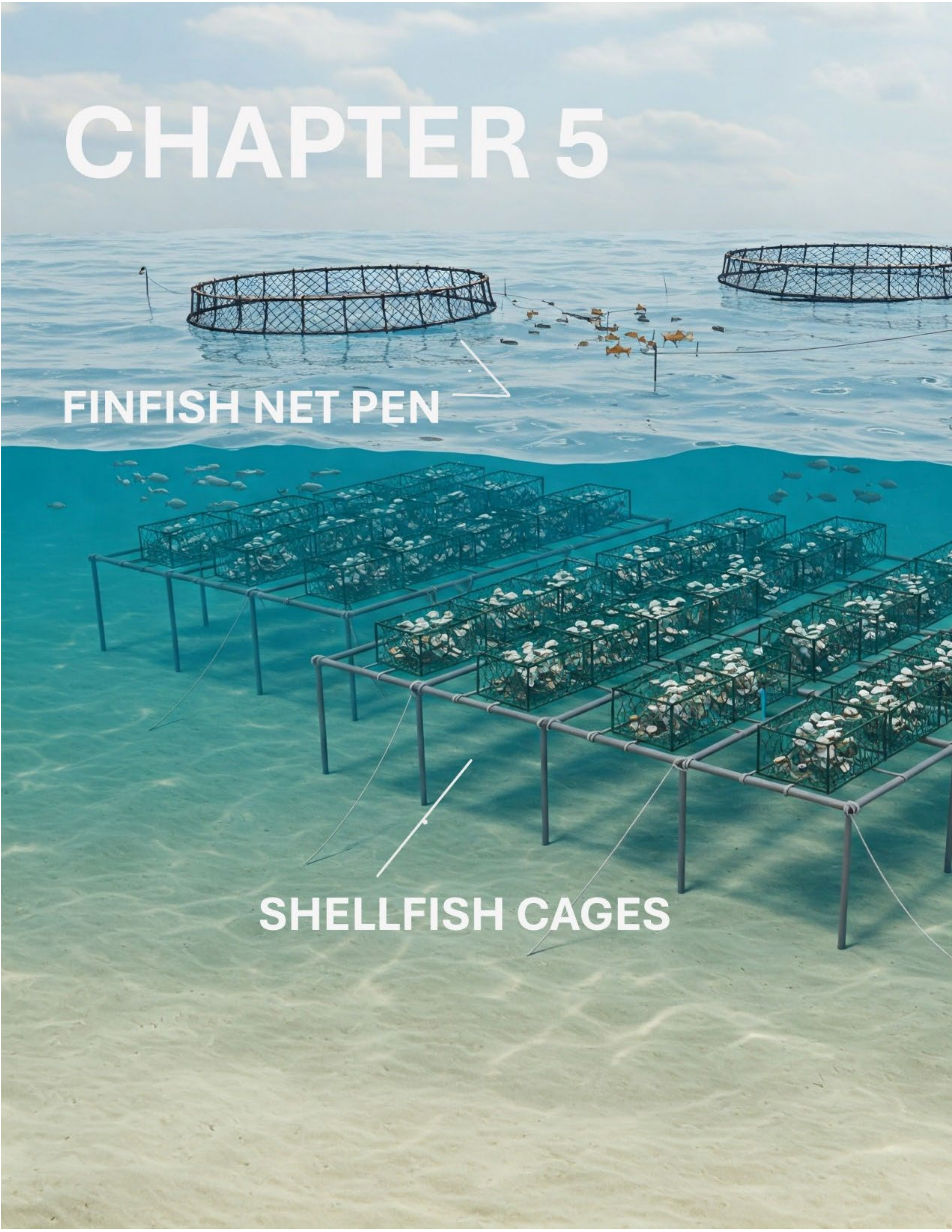
Figure 4.21: Feed barge (top left corner) with white feed pipe and circular bird net frame with a rotary spreader in the center of the net frame[168]

HARVESTING

Cultured finfish are harvested once they have reached the desired market size. Harvesting finfish from net pen aquaculture systems is a highly specialized task and may require trained personnel working both above and below the waterline. Harvest is completed either manually by staff using nets to bring fish aboard a support vessel; by the use of a net connected to a large boom on the support vessel, which is lowered to the deck for capture and processing; or mechanically using a specialized fish transfer pump. Harvest pumps consist of large diameter hoses, lowered into the net pen which sucks the fish up through the hose and subsequently to a hold in a support vessel.

[168]Lien, A. M., Schellewald, C., Stahl, A., Frank, K., Skøien, K. R., & Tjølsen, J. I. (2019). Determining spatial feed distribution in sea cage aquaculture using an aerial camera platform. *Aquacultural Engineering, 87*, 102018.

CHAPTER 5



CHAPTER 5 : THE FUTURE OF AQUACULTURE GEAR SYSTEMS

INTRODUCTION

In the 1980s, China and Japan developed multi-species aquaculture systems in an attempt to address their declining independent production of shellfish and macroalgae due to disease, biofouling, and lack of sufficient nutrients in the environment.[169] In Sanggou Bay, China, they found that the cultivation of multiple species on a single farm both improved the surrounding ecological environment and improved the economy in the region.[170] Culturing multiple species together is now common in bays and estuaries throughout China, and pilot systems have been developed in the U.S., Canada, Chile, South Africa, and Europe.[171] The term IMTA, or Integrated Multi-Trophic Aquaculture, was coined in the 1990s by Thierry Chopin of the University of New Brunswick, following his development of the AquaNet project, which cultured kelp and Atlantic salmon together in a mutually positive integrated system.[172] The term IMTA has also been used synonymously with other more modern terms such as 3D Ocean Farming, blue economy aquaculture, or regenerative farming (Figure 5.1).[173]

IMTA specifically describes the culturing of marine species of different trophic levels to take advantage of nutrient cycling. These systems typically couple fed species (i.e., finfish) with species that can extract nutrients from the water column and benthos (e.g., shellfish,

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[169]Watanabe, S., Minakawa, M., Ishihi, Y., Hasegawa, N., & Sakami, T. (2022). IMTA as a possible countermeasure for reduced aquaculture productivity in Japan. In J. P. Altamirano, R. Nambu, N. D. Salayo, & M. Kodama (Eds.), Understanding current challenges and future prospects in Integrated Multi-trophic Aquaculture (IMTA) research. Proceedings of the JIRCAS-SEAFDEC/AQD Joint Workshop on IMTA research held at SEAFDEC/AQD, Tigbauan Main Station, Iloilo, Philippines on 6-8 August 2019 (pp. 26–33). Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center.

[170]Fang, J., Zhang, J., Xiao, T., Huang, D., & Liu, S. (2016). Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. *Aquaculture Environment Interactions, 8,* 201-205.

[171]Alexander, K.A., Potts, T.P., Freeman, S., Israel, D., Johansen, J., Kletou, D., Meland, M., Pecorino, D., Rebours, C., Shorten, M. and Angel, D.L. (2015). The implications of aquaculture policy and regulation for the development of integrated multi-trophic aquaculture in Europe. *Aquaculture, 443*, pp.16-23.

[172]Chopin, T., Robinson, S., Sawhney, M., Bastarache, S., Belyea, E., Shea, R., Armstrong, W., Stewart, I., & Fitzgerald, P. (2004). The AquaNet integrated multi-trophic aquaculture project: rationale of the project and development of kelp cultivation as the inorganic extractive component of the system. *Bulletin of the Aquaculture Association of Canada 104,* 11–18.

[173] Bennett, M., March, A. and Failler, P. (2023). Blue farming potentials: Sustainable ocean farming strategies in the light of climate change adaptation and mitigation. *Green and Low-Carbon Economy*.

macroalgae, and sea cucumbers).[174,175,176] Fish farm discharges, including waste and excess feed, can impact the surrounding environment through increased sedimentation under the farm and nutrient loading of excess nitrogen and phosphorus into the surrounding environment.[177,178] These systems reduce the amount of inorganic and suspended organic matter discharged into the environment by finfish farms through the proximal culture of extractive species that absorb and feed on that matter.[179] Additionally, these systems have the potential to reduce the environmental footprint of an aquaculture farm by combining multiple systems in one space, improve the social license for finfish aquaculture, and provide economic benefits to farmers through crop diversification and seasonal predictability.[180]

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[174]Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H., & Fang, J. G. (2009). Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture, 297(1-4),* 1-9.

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

[176]Buck, B.H., Troell, M.F., Krause, G., Angel, D.L., Grote, B. and Chopin, T. (2018). State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Frontiers in Marine Science, 5,* p.165.

[177]Hargrave, B. T., Holmer, M., & Newcombe, C. P. (2008). Towards a classification of organic enrichment in marine sediments based on biogeochemical indicators. *Marine Pollution Bulletin, 56(5)*, 810-824.

[178]Holmer, M. (2010). Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. *Aquaculture Environment Interactions, 1(1),* 57-70.

[179]Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A. H., Kautsky, N., & Yarish, C. (2003). Integrated mariculture: asking the right questions. *Aquaculture, 226(1-4),* 69-90.

[180]Knowler, D., Chopin, T., Martínez-Espiñeira, R., Neori, A., Nobre, A., Noce, A. and Reid, G., 2020. The economics of integrated multi-trophic aquaculture: where are we now and where do we need to go? *Reviews in Aquaculture, 12(3),* pp.1579-1594.

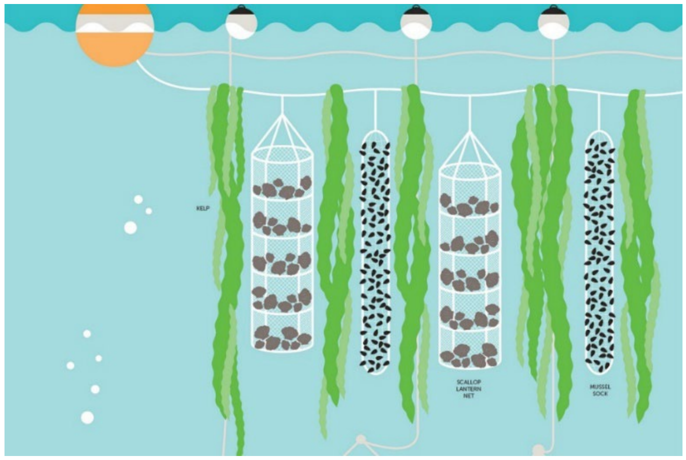

Figure 5.1: IMTA, also known as 3D Ocean farming, illustration by Agritecture that shows kelp, scallops, and mussels grown together in one system[181]

SINGLE STRUCTURE IMTA SYSTEMS

Experimental systems have tested the feasibility of growing multiple species in a single structure. The Aquafort, is one such system, developed by the University of New Hampshire, which has been used to grown steelhead trout alongside macroalgae and mussels (Figure 5.2). The Aquafort has the potential to be replicated in other locations with different species, however, the size of the system precludes it from being used for a large commercial operation unless it is expanded. There are a multitude of research papers touting the possibilities of single structure IMTA systems, but thus far, there are not any single structure IMTA systems being used for commercial purposes at the time of this publication.

[181]Agritecture. 3D Ocean Farming. [Available at https://www.agritecture.com/blog/2018/5/3/3d-ocean-farming]

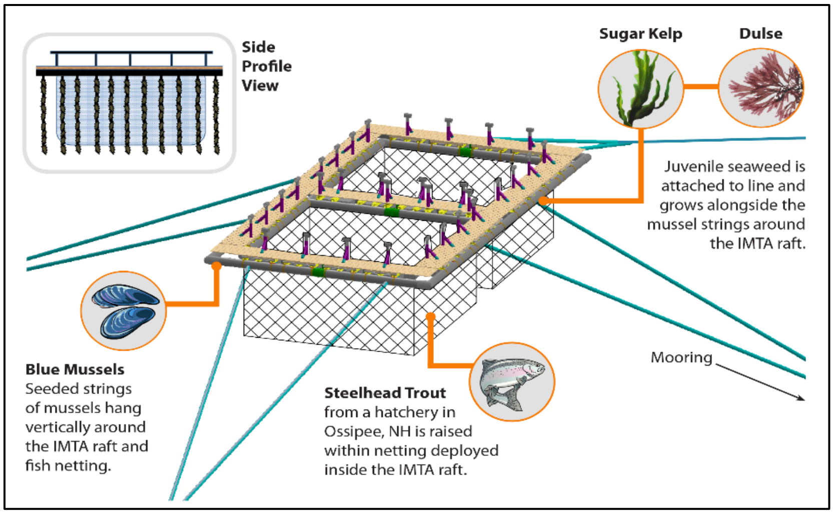

Figure 5.2: Schematic of the Aquafort structure[182]

MULTI-GEAR OCEAN FARMING POLYCULTURE

More common than single structure IMTA systems is the use of bay-wide multi-gear IMTA polyculture, such as in China, Canada, Norway, Japan, and Chile, all of which vary greatly in their designs. Experimental projects use well-established gear technologies and species that have been grown successfully in the same region. For the most part, these projects consist of multiple gear types grouped within a single area (such as a bay) such that they interact oceanographically (Figure 5.3). For example, two seafood production companies (Folla Alger and Cermaq) in Norway, are testing the production of sugar kelp alongside salmon farms. Their aquaculture project site consists of 24 cages with gear for kelp production in the middle cages and salmon in the outermost cages.[183] In Sanggou Bay, China, in the Yellow Sea, an area, 100 km^2 in size, has been devoted to IMTA. Over half of this area is devoted to the cultivation of more than 30 different species including kelp, scallops, oysters, abalone, and sea cucumbers. These species are all grown together in the intertidal zone using longlines, cages, fish net pens, bottom racks, and on-bottom culture (Figure 5.4).[184] There is also a multi-gear IMTA project being developed in Hawaiian waters

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[182]Sea Grant New Hampshire. (2021). Aquafort Info Sheet. [Available at https://seagrant.unh.edu/sites/default/files/media/2021-05/nhsg-aquafort-info-sheet.pdf]

[183]Folla Alger and Cermaq are testing a new combined sea site for salmon and kelp: will contribute to the green shift. [Available at https://www.cermaq.com/news/folla-alger-and-cermaq-are-testing-a-new-combined-sea-site-for-salmon-and-kelp-will-contribute-to-the-green-shift]

[184]Shi, H., Zheng, W., Zhang, X., Zhu, M. and Ding, D. (2013). Ecological–economic assessment of monoculture and integrated multi-trophic aquaculture in Sanggou Bay of China. *Aquaculture, 410*, pp.172-178.

for fish and macroalgae (limu) using both semi-submersible net pens and horizontal longline gear as described above.[185]

Figure 5.3: Culture of mussels within a salmon finfish net pen alongside pens stocked with salmon in the Bay of Fundy, Canada[186]

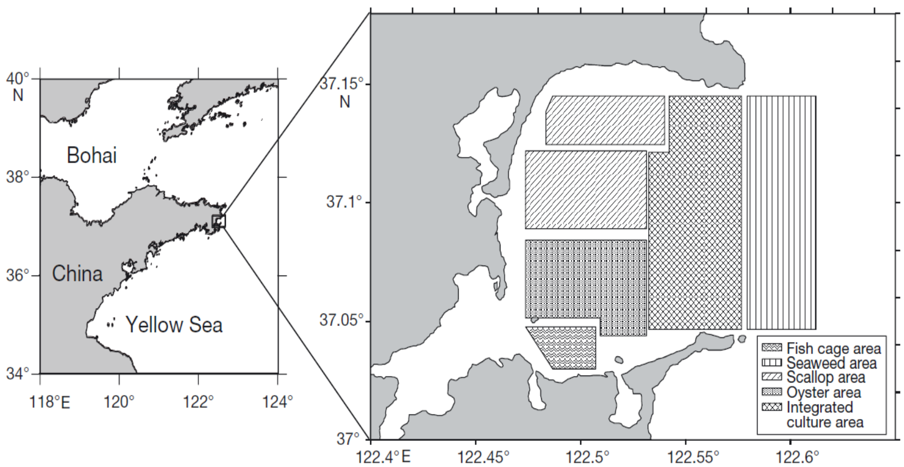

Figure 5.4: Aquaculture in Sanggou Bay, China[187]

[185]Ocean Era (2023). Draft Environmental Assessment for an Ocean Era Offshore Farm of 'EWA Beach, Oahu, Hawai'i. Prepared by Ocean Era, Inc. June 6. 2023

[186]Strand, Ø. Jansen, H.M., Jiang, Z., & Robinson, S.M.C. (2019). Perspectives on Bivalves Providing Regulating Services in Integrated Multi-Trophic Aquaculture. In: Smaal, A., Ferreira, J., Grant, J., Petersen, J., Strand, Ø. (eds) Goods and Services of Marine Bivalves. Springer, Cham.

[187]Fang, J., Zhang, J., Xiao, T., Huang, D., & Liu, S. (2016). Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. *Aquaculture Environment Interactions, 8,* 201-205.

ON-DEMAND/ROPELESS GEAR

Future aquaculture farms may take advantage of recent developments in on-demand fishing gear, which uses less rope than traditional fishing gear and is generally thought to reduce the potential environmental impact of the gear in the water. On-demand system research is currently taking place in trap/pot fisheries at the time of publication, as a potential method to minimize ropes used in those fisheries that have a high risk of entanglement for large whales[188]. On-demand gear uses some type of inflatable lift buoy that is deflated and attached to a coil of line on the trap. When a signal is sent from the fishing boat, the spool of line unravels, the buoy inflates, and comes to the surface, so the gear can be retrieved[189]. While this type of gear is still in the research phase, it may be applicable to shellfish gear systems in the future. Researchers are starting to think about the applicability of on-demand gear to other types of fishing and aquaculture gear. As some shellfish gear uses cages, the technology may be adaptable to aquaculture gear systems in the future.

Figure 5.5: On-Demand fishing gear built by Lift Labs and installed on a lobster trap (Photo courtesy of Megan Amico, Northeast Fisheries Science Center, NOAA Fisheries)

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[188]Myers, H.J., Moore, M.J., Baumgartner, M.F., Brillant, S.W., Katona, S.K., Knowlton, A.R., Morissette, L., Pettis, H.M., Shester, G. & Werner, T.B. (2019). Ropeless fishing to prevent large whale entanglements: Ropeless Consortium report. *Marine Policy*, *107*, p.103587.

[189]NOAA Fisheries. Developing Viable On-Demand Gear Systems-On-demand gear development continues to evolve with the help of industry [Available at https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-mammal-protection/developing-viable-demand-gear-systems]

AQUACULTURE GEAR CO-LOCATION

Co-location is the combination of aquaculture gear systems and other marine structures, particularly renewable energy facilities in the marine environment. These marine structures can include those for oil and gas, wind, or regenerative wave energy. Research on co-location has been focused on shellfish and macroalgae, rather than finfish, likely due to the size of the gear needed in finfish aquaculture in the marine environment.[190] It is unknown what aquaculture gear systems for co-location would look like, however, it is likely that gear will be adapted from current technologies presented in this guide.

AQUACULTURE GEAR INNOVATIONS

Aquaculture gear technology is innovating at a rapid pace, and it is impossible to cover all gear technologies that may become commonplace in aquaculture gear in the future. However, there is some research, particularly research that is being conducted in the U.S., which may be applicable sooner than others. Researchers at the University of New Hampshire have done research on using fiberglass rods instead of ropes to grow macroalgae, with some success.[191] The fiberglass rods are more stiff and rigid than traditional ropes used in horizontal longline macroalgae aquaculture, and may mitigate the risk of marine animal entanglement. In Washington, Blue Dot Sea Farms is working with Composites Recycling Technology Center testing the use of recycled carbon fiber for macroalgae aquaculture cultivation "lines". There is also a lot of research into more sustainable aquaculture gear, including minimizing plastics and the potential for marine debris for aquaculture gear.[192] Gear innovations to reduce plastics in aquaculture practices include gear made from natural biodegradable materials, such as biodegradable socks for mussel culture or predator netting for clam aquaculture.

Other gear technologies include sensors, cameras, and GPS trackers for monitoring aquaculture gear. Technology is rapidly expanding to include unmanned systems for aquaculture operations including feeding, water quality monitoring, inspection, and

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[190]Gonzales, C.M., Chen, S. and Froehlich, H.E. (2024). Synthesis of multinational marine aquaculture and clean energy co-location. *Frontiers in Aquaculture*, *3*, p.1427839.

[191]Moscicki, Z., Swift, M.R., Dewhurst, T., MacNicoll, M., Chambers, M., Tsukrov, I., Fredriksson, D.W., Lynn, P., Landon, M.E., Zotter, B. & MacAdam, N. (2024). Design, deployment, and operation of an experimental offshore seaweed cultivation structure. *Aquacultural Engineering*, *105*, p.102413.

[192]Skirtun, M., Sandra, M., Strietman, W.J., van den Burg, S.W., De Raedemaecker, F. & Devriese, L.I. (2022). Plastic pollution pathways from marine aquaculture practices and potential solutions for the North-East Atlantic region. *Marine pollution bulletin*, *174*, p.113178.

more.[193] Operations are transitioning to underwater robotic systems and cameras with advanced imaging processing. It remains to be seen what additional aquaculture gear system technologies will be invented in the future.

[193]Wu, Y., Duan, Y., Wei, Y., An, D. & Liu, J. (2022). Application of intelligent and unmanned equipment in aquaculture: A review. *Computers and Electronics in Agriculture*, *199*, p.107201.