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Offshore aquaculture farming - Report from the initial feasibility study and market requirements for the innovations from the project

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Öryggi, umhverfi og erfðir

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Offshore Shellfish Ltd

Offshore aquaculture farming Report – Work package 1

Deliverable D1.1a: Report from the initial feasibility study & market requirements for the innovations from the project

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Skýrsluágrip Matís ohf
Icelandic Food and Biotech R&D
Report summary

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Titill / Title	**Offshore aquaculture farming. Report from the initial feasibility study and market requirements for the innovations from the project** / Kröfur og markaðsmöguleikar fyrir tæknilausnir í úthafseldi		
Höfundar / Authors	Ólafur Ögmundarson, John Holmyard, Gunnar Þórðarson, Friðrik Sigurðsson and Helga Gunnlaugsdóttir		
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Ágrip á íslensku:	Í þessari skýrslu er lagt mat á tæknilegar kröfur og markaðsmöguleika á legufærum sem gætu hentað við þróun á kræklingarækt í úthafi, við erfiðar aðstæður. Skoðuð var sú tækni sem notuð er við kræklingaræktun á heimsvísu, þar með talin ræktun innfjarða, úthafsræktun og að hluta til í óvörðu umhverfi. Mest af kræklingarækt heimsins fer fram í vörðu umhverfi, þar sem skjól er fyrir úthafsöldu og eru byggðar upp með yfirborðs flotholtum eða línu sem ekki stenst álag úthafsöldu. Þrátt fyrir það, þarf innfjarðarræktun á öflugum akkerum að halda sem gætu jafnframt dugað við úthafsræktun. Úthafsræktun á krækling er yfirleitt byggð á djúpsjávar eða hálf-marandi línum sem lagðar eru neðan við yfirborð sjávar, sem eru minna háðar úthafsöldu og þeim kröftum sem þeim fylgja, en hægt er að þjónusta frá yfirborði. Meirihluti úthafs ræktunar eru annaðhvort þegar stórræktun eða mun verða stórræktun með þúsundir akkera. Þjónusta og viðhald akkera við slíkar aðstæður kalla á vandamál og gera miklar kröfur um styrkleika og áreiðanleika. Slíkur búnaður kallar á hagkvæman og áreiðanlegan búnað, sem hægt er að staðsetja með mikilli nákvæmni og miklum fjölda og stærð sem hentar tiltölulega smáum þjónustubátum. Sá búnaður sem best stendur undir slíkum kröfum er skrúfakkeri sem hægt er að staðsetja með búnaði frá yfirborði án þess að nota kafara. Úthafsræktun á krækling hefur verið rekin í stórum stíl með góðum árangri í Kína, Frakklandi og Ítalíu, áratugum saman. Þessi ræktunaraðferð hefur einnig öðlast útbreiðslu, í smærra mæli þó, í Bretlandi, Þýskalandi, Írlandi, BNA, Búlgaríu og Nýja Sjálandi. Stórtækari ræktun er í undirbúningi í Nýja Sjálandi og Bretlandi, og reyndar í mörgum öðrum löndum, og verið að þróa hagkvæmni slíkrar ræktunar. Markaður í nánustu framtíð fyrir akkeri hönnuð fyrir úrhafsræktun á kræklingi mun að mestu verða drifin af markaðsþörf fyrir kræklinginn sjálfan, sem aftur ræðst af almennri efnahagsþróun í markaðsríkjum. Stefna Evrópusambandsins og einstakra ríkja innan þess í eldi sjávarafurða liggur í að kynna stórræktun á sameiginlegri ræktun kræklings og þangi, sem gæti leitt til mikilla markaðs möguleika fyrir búnað til slíkra ræktunar. Mikil áhersla er á endurnýjanlega nýtingu auðlinda sem gæti aukið úthafsræktun á krækling. Framtíðar eftirspurn fyrir búnað eins og skrúfakkeri gætu líka komið frá innfjarðarræktun, þar sem slíkur búnaður er ódýr og öruggur og einfaldur í notkun, og stenst vel samkeppni við eldri gerðir að búnaði sem hingað til hafa verið í notkun.		

Skýrsluágrip Matís ohf
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Report summary

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Summary in English:	This report consists of an appraisal of the technical requirements and market potential for a mooring system that will prove suitable for use by offshore mussel farming developments in high energy exposed locations. A review is carried out of the technology that is currently in use in mussel farming industries around the world, including those in inshore environments, offshore environments and partially exposed environments. Most mussel farms around the world are located in sheltered inshore waters and consist of surface rafts or long lines that are deemed unsuitable for high energy exposed locations. Despite this, inshore mussel farms often require high holding power mooring systems that will also be suitable for use at offshore locations. Offshore mussel farms generally consist of submerged or semi-submerged long lines of a variety of designs that are suitable for withstanding high energy conditions while still enabling access to the crop supported by the lines. The majority of offshore farms are either currently, or will soon become, large scale operations with numbers of moorings in the thousands. Inspection and maintenance of moorings in these circumstances is often problematic and absolute reliability is a high priority. This brings with it the requirement for a cost effective, reliable mooring that can be placed accurately and rapidly in large numbers by relatively small, standard mussel farm service vessels. The mooring system that best meets these requirements is the helical or screw-in anchor that can be placed remotely without the use of a dive team. Offshore mussel farming has been successfully carried out on a large scale in China, France and Italy for several decades. This form of aquaculture has also been adopted in smaller scale commercial and trial projects in the UK, Germany, Ireland, USA, Bulgaria and New Zealand. Large scale developments are scheduled for the near future in New Zealand and the UK and many other mussel producing countries are known to be considering trials pending the success of current projects and the development of suitable economic conditions. The near future market for offshore mussel farm mooring systems will largely be driven by the market for the mussels themselves which is dependent on the general economic climate. Aquaculture strategies at EU and individual state level which promote large scale integration of mussel and seaweed farming with offshore renewables could lead to a very large long term market potential for offshore mussel farm mooring systems, if these strategies are implemented. Further markets for these mooring systems could arise from their use by existing inshore finfish and shellfish aquaculture providing that they were cost effective in comparison to the systems currently in use.
English keywords:	Mussel farming, offshore farm, mooring system

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1. Introduction

The report is a part of an approved NORA project, *"Offshore aquaculture"*. The main project goal is to develop a new innovative technology and machinery, which allows for mussel aquaculture to be taken offshore. The proposed work of *"Offshore Aquaculture"* will provide innovative technological solutions that will create a new farming system that will enable submerged and semi submerged mussel aquaculture at exposed offshore deep-water culture sites. New exposed mussel culture sites generate various challenges that require innovative technological solutions which make it possible to grow and harvest mussels in rough open ocean conditions e.g. high waves, unstable weather and oceanic currents that exist in the open deep-water relatively far from the coast. This project sets out to develop new technologies that are suitable for submerged deep-water and offshore blue aquaculture that can also be used in costal culture sites.

The objective of this report is to create a detailed overview of the existing knowledge and in depth understanding of the specific requirements for submerged offshore aquaculture in different oceanic conditions and market potential. To achieve this following topics are addressed:

1. A patent review
2. A literature review
3. Information on offshore aquaculture/offshore mussel farming in the world
4. Market potential

A short evaluation will be provided to present and highlight the technical requirements and data regarding technical requirements with regards to differences in existing farming systems (e.g. rope type, thickness and shape, strength, use of weights etc.). This report also gives an overview on different farming strategy and the various farming strategies (surface, semi submerged, fully submerged). An overview of husbandry methods is also included in this report (seed collection, stocking densities, socking methods, thinning and grading practices) as well as market potential for technical solutions.

2. A patent review

A patent review was undertaken on the 14th and 15th of October 2010.
The following search engines were used:

United State Patent and Trademark Office

http://patft.uspto.gov/

www.espacenet.com

Search combinations:

- Anchor and aquaculture
- Drill and aquaculture
- Drill and seabed
- Mooring system

None of the patents rules out a patent for the drill and anchors which are being developed and prototypes produced by this project.

3. A literature review

The following table gives an overview over selected scientific and practical publications on open ocean aquaculture in the world.

Title	Author/Publishing	Keywords
Open Ocean Aquaculture	Harold F. Upton et al. Published 2010 http://ncseonline.org/nle/crs/detail.cfm?Category=Water	Open ocean aquaculture (defined), environment, operation, legal and regulatory environment
Offshore Aquaculture in the United States: *Economic Considerations, Implications & Opportunities*	U.S. Department of Commerce National Oceanic & Atmospheric Administration Silver Spring, Maryland http://aquaculture.noaa.gov/news/econ.html	Economic potential, technology, feeds, rules and legislation
First offshore aquaculture project as a multifunctional use of offshore wind farms	Buck et al. Website, dated 2006 http://www.awi.de/en/research/new_technologies/marine_aquaculture_maritime_technologies_and_iczm/projects/marine_aquaculture_projects/offshore_aquaculture/	Offshore wind farms, aquaculture, resource use
Open Ocean Aquaculture	Borgatti et al. Published 2004 http://ncseonline.org/nle/crsreports/04dec/RL32694.pdf	Appropriate species and culture techniques; start-up capital investment; designing and constructing social and economic impacts; and potential environmental impacts
Assessment of the Potential for Mussel Aquaculture in Northland	Andrew Jeffs Published: 2003 http://aquanic.org/species/shellfish/documents/northland-mussel.pdf	Expanding inshore mussel growing areas, expanding offshore mussel growing areas, developing wild spat catching

		enterprises ,developing artificial spat production, developing seed mussel production.
European mussel cultivation along the Atlantic coast: production status, problems and perspectives	A.C. Small in *Hydrobiologia* 484: 89–98, 2002. *O. Vadstein & Y. Olsen (eds), Sustainable Increase of Marine Harvesting: Fundamental Mechanisms and New Concepts.* © 2002 *Kluwer Academic Publishers. Printed in the Netherlands.*	*Mytilus edulis*, carrying capacity, culture methods, culture areas

Table 1 Table of literature review

A lot has been written about open ocean aquaculture/mooring. Pro´s and con´s have been brought to light, economic feasibility has been calculated and environmental impact of this kind of aquaculture/mooring has been considered. One of the conclusions coming from these studies is that offshore aquaculture/mooring is an option worth looking at. Still, there are threats. To name a few: How to fasten mooring systems in open oceans is not widely developed and tested. Also little is known about the environmental impact of this kind of aquaculture. The third thing mentioned here is that regulations and legislation of most countries does not consider open ocean aquaculture. That is vital to change, as the other.

4. Technical Requirements

Data on the technical requirements with regards to differences in existing farming systems (e.g. rope type, thickness and shape, strength, use of weights etc.).

This “Technical requirements” overview will highlight the different types of anchors and moorings commonly used in the shellfish industry, provide a visual image or photo of the component, and a short text to explain its use.

Definition of anchors and moorings

We generally associate anchors as being heavy objects, often made of concrete, or metal like those used to hold a ship in place. Wikipedia defines anchors within 2 classes:

1) Permanent
   a) permanent anchors[1]
   b) moorings[2]
2) temporary anchors

We often presume that currents are the largest forces an anchor must overcome, but vertical movement of waves can actually develop the largest loads on lines, especially when:

a) the mussel workboat is tethered to long lines or
b) there’s excessive floatation on the surface or submerged Long line

A temporary anchor is usually carried by the vessel, and hoisted aboard whenever the vessel is underway. There’s a range of grapnels, Danforth, Stingray, Manta-ray, DorMor, Bruce, spade, and various plough anchors to name a few. However, shellfish growers who seek stability and permanence tend to install long lines that use permanent anchors and moorings.

A variety of permanent anchors/moorings exist for shellfish culture and the selection of permanent mooring depends on the surrounding topography, whether there is easy access to nearby land or harbors, and the type of seabed available to keep the mooring stable, not to mention exposure of the site to weather, storms and drift ice.

Three types of permanent moorings are commonly used for anchoring long lines and rafts.

a) **deadweight moorings**, such as train wheels, concrete blocks, railway ties and drag anchors, such as heavy chains
b) **lightweight moorings** such as spiral or helix anchors, and hydraulically driven expansion anchors
c) **hold-fast moorings**, such as steel bolts

Comment: The larger the mass or the longer the deadweight (rail tracks), the more dangerous and cumbersome they can be to handle and adjust after they shift. While old steel deadweight’s may be compact compared to concrete, they can easily roll and are not designed to support long line structures in the long-term, even if embedded in very soft bottoms. Short term savings tend to result in long-term expenses due to maintenance.

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[1] A permanent anchor is often called a mooring and is rarely moved

[2] Moorings work by resisting the movement force of the long line that´s attached to it. There are two primary ways to do this – via „raw mass“, or by „hooking“ into the seabed to use its gripping potential.

a) Deadweight permanent anchors/moorings

General overview of anchors and moorings

Deadweight moorings, such as train wheels, concrete blocks, railway ties and drag anchors, are associated with permanent anchoring of long lines and mussel rafts. The key is matching the deadweight mass with the load on the lines and the bottom substrate material.

Component & material	Anchor type/name	Image/Photo
Deadweight permanent moorings	**Concrete blocks**	
	Train wheels **Old railway tracks**	
	Drag anchors Danforth	
	Salmon cage type	
	Stingray drag anchor	

Installation logistics related to anchoring dead-weights for mooring

Deploying many heavy concrete anchors can be dangerous, especially for rapid deployment. A ship can be hired, but logistic preparation of land-based transport of the blocks to small harbor docks is necessary. It is also possible to outfit small aquaculture workboats to transport heavy concrete moorings to mussel sites, if they are not too far, or when it occurs on very calm days.

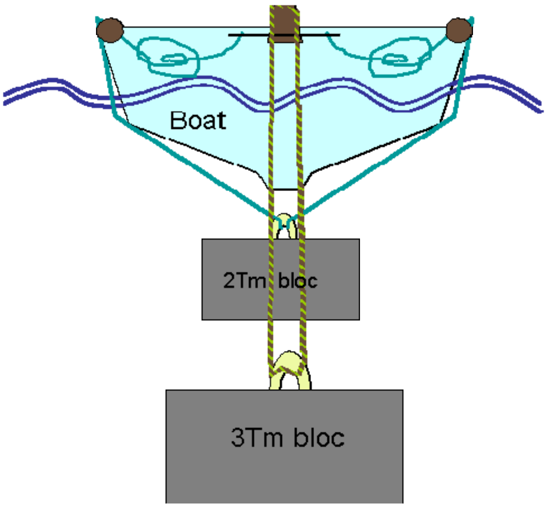
Logistics of large scale installation	Anchor type/name	Image/Photo
Need large ship and crane with trained crew	Concrete blocks with large ship	
Need large ship and crane with trained crew	Train wheels and heavy chains with large ship	
Outfitting of small aquaculture workboat to transport heavy concrete moorings	Transport of heavy concrete blocks using small inshore craft	

Table 2 Deadweight permanent anchors/moorings

b) Lightweight anchors and moorings require more logistic planning

Lightweight embedded moorings, such as spiral screw or helix anchors, and hydraulically-driven expansion anchors can require greater planning, however they are extremely reliable and leave very little footprint above the seafloor. It is essential to use a platform that is stable while drilling, to maintain its position in windy conditions, and allow the mooring to embed vertically down.

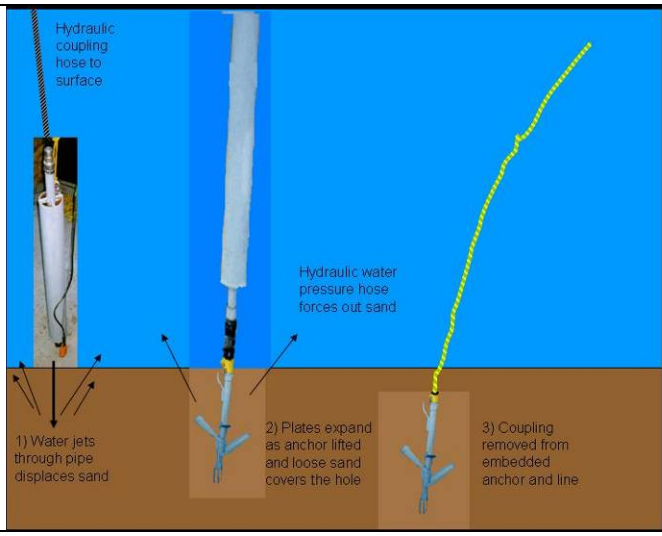
<table>
<tr><td colspan="3">Lightweight permanent anchors come in 2 common forms. They require different logistic set-up to become proper mooring systems:
a) the spiral screw anchors o helical screw anchors
b) the hydraulically driven expansion anchors</td></tr>
<tr><td>Spiral screw anchors also called; ‘round shaft anchors’</td><td>The thickness and mass of the plate depends on the required holding power and the diameter of the plate that will be welded onto the steel shaft</td><td>
</td></tr>
<tr><td>Lightweight helical screw anchors</td><td>Helical mooring systems resemble spiral screw anchors, but usually include double, triple or more leads depending on substrate type</td><td></td></tr>
<tr><td>Hydraulic expansion anchors</td><td>Expansion anchors consist of flukes hinged to a hollow shaft, which is driven into the seabed by a powerful hydraulic water jet that blows the surrounding hard loose substrate outward from the nose</td><td>
</td></tr>
</table>

Table 3 Lightweight anchors and moorings

c) Hold fast moorings

Different topographic situations require their own adapted solution. The ideal situation is when the steel bolt anchor can be installed below low water tide levels, to avoid visual contact, yet optimize accessibility. The work boat to hug the shore and move between long lines, and the chained ropes can reduce damage by winter ice or ultraviolet radiation.

Hold-fast moorings	Steel bolt anchored to granite shoreline with shackle	
Alternative lightweight moorings	Wooden posts in a dike enclosure allow a hundred plus surface long lines to be solidly anchored to huge wooden posts planted along the dike.	

Table 4 Hold fast moorings

5. Farming Strategy

Biophysical conditions that determine farming strategy

Different biophysical and environmental conditions, associated with the individual biology of the culture species in production impose specific grow-out strategies for shellfish. Some examples are provided below to set the context.

Mussel spat is collected in the surface layer, thus mussel collector lines need to be near-surface in most situations, but may be deeper as well if the water is well mixed, or if the surface layer is mostly fresh water overlaying saltier brackish or oceanic water. However grow out may take place at or near surface if the site is sheltered, and lines can be submerged in more exposed environments, as the mussels will grow as long as there is sufficient food available.

Scallop spat are collected above bottom in deeper coastal water, and the lines must not be exposed to wave action or shaken in any manner. This calmness must be maintained for growing out scallops as well.

Oyster culture on long lines can also be near surface or submerged, depending on exposure, but the spat need to be supplied by hatcheries or collected in brackish water environments near shore.

Type of long lines

There are different types of long line designs and each one uses flotation differently to maintain tension. The key parameter for successful shellfish culture is maintaining long line tension in all environmental and working conditions, so the shellfish do not flop vertically in waves or sway horizontally on the long line in currents or during maintenance.

Three (3) types of long lines can be distinguished in practical grow-out terms: a) surface long lines, b) semi-submerged, and c) fully submerged lines. Each type has different structural characteristics and limitations.

Surface long lines models can be single, double, or rigs with multiple lines attached within a rig.

Structural characteristics

Surface long lines (static structures)

Surface rafts have been found to be highly unsuitable as they are badly affected by poor weather conditions. Strong wave motion causes damage to the raft structures and leads to violent movement of the suspended ropes which then lose most of the attached mussels. Those mussels not dislodged become so strongly attached by excessive byssus production that the mussels are often fatally stressed when removed from the ropes for harvest.

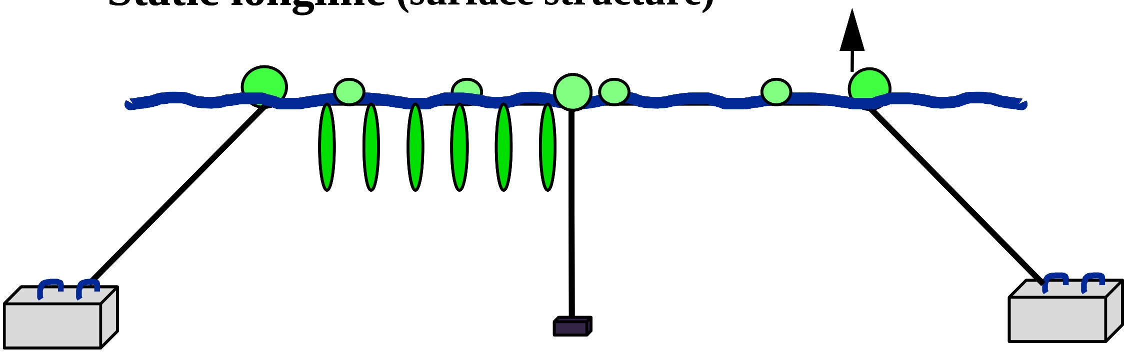
Submersible and adjustable buoyancy rafts have been developed but have either proved too expensive to be commercially viable or have been unreliable in operation.

These surface structures characteristically maintain tension and stability by using the surface buoyancy of the floats in constant tension with the anchors. The geometric design is not always critical to its stability and maintenance. Depending on the long line length and the local currents, some growers add intermediate anchors weights and floats to reduce lateral motion.

The fully floating system is rarely used offshore as it suffers from the same problems as surface rafts. Fully floated long lines in semi-exposed water in Bulgaria and Cornwall UK have been successfully used for a few years but long term survival seems unlikely and high maintenance is required. In New Zealand the farms in Wilsons Bay, Coromandel, North Island, use fully floated surface farms on the inside of the Bay where the waves are diminished by the farms outside them. The outer farms are often surface floated in the summer and submerged in the winter. They do this by removing some of the surface floats normally tied direct to the long lines and reattach the long lines to vertical floats with a long bridle or float line.
http://musselrope.co.nz/

Surface headlines usually consist of 2 parallel backbones with 200-400l floats lashed between them. Standard headline rope size is usually 32mm diameter or greater. Long line length is usually 150-300 m. It is believed that the planned, large scale fully offshore farms will not be surface long lines but will be a combination of submerged and semi-submerged.

Static longline (surface structure)



These lines are static in that they do not require extensive design; however they do require stronger anchor stability due to exposure to wind and surface currents.

Semi-submerged long lines

Picture 1 Long line Farm, Sangou Bay, China

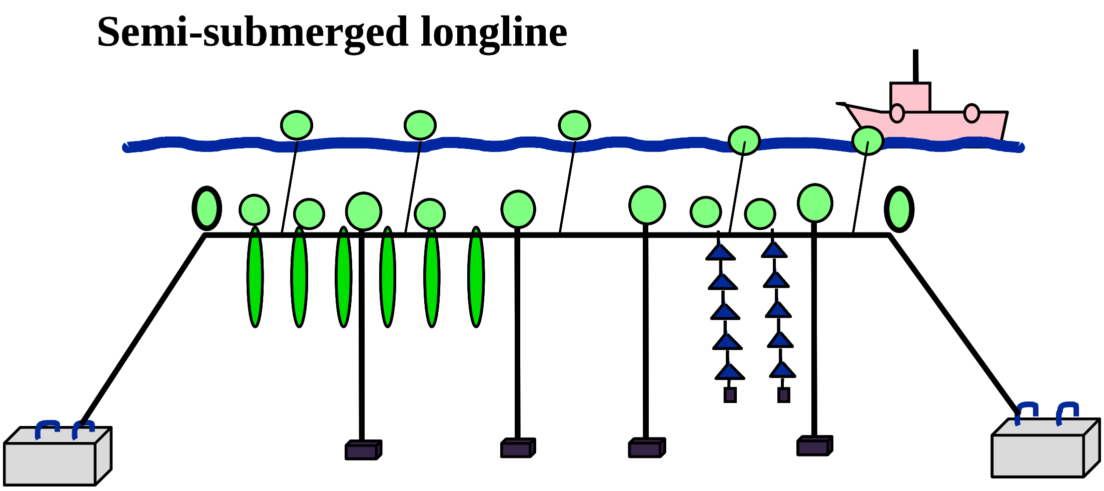
These semi-submerged structures characteristically maintain tension either by adjusting the buoyancy forces from the surface and allowing these floats to support the mainline buoyancy at specific depth from the surface, or by using submerged floats that are tensioned with counter weights on the bottom. As the line gets heavier, the counterweights strike bottom, thus adding extra buoyancy to the structure below water. The surface floats act to identify the line and to add extra safety so the line does not sink.

Picture 2 Long line farm, Pertuis Antioch, France

The stability is greater if well maintained, but the tension of the line can vary greater if not designed properly.

This system is not suitable for exposed locations, which may also risk damage from winter drift ice.
Semi-submerged long lines are used in the Chinese industry, the Atlantic coast of France, Adriatic coast of Italy, New Zealand, UK, PEI Canada and elsewhere.

In China the lines are usually 100m long, the headline ropes are varied but usually 20mm diameter, and the headlines are set about 1-2 meters below the surface. The floats used are usually spherical buoys of around 20-50 liters. Although these farms are in the open sea they are usually part of very large scale polyculture farms of 10-100 square km that include seaweed long lines. The effect of the seaweed farms, which are usually set to the seaward side of the mussel farms, is that much of the wave energy is reduced before it reaches the mussel lines. This allows for the lightweight equipment that is used.



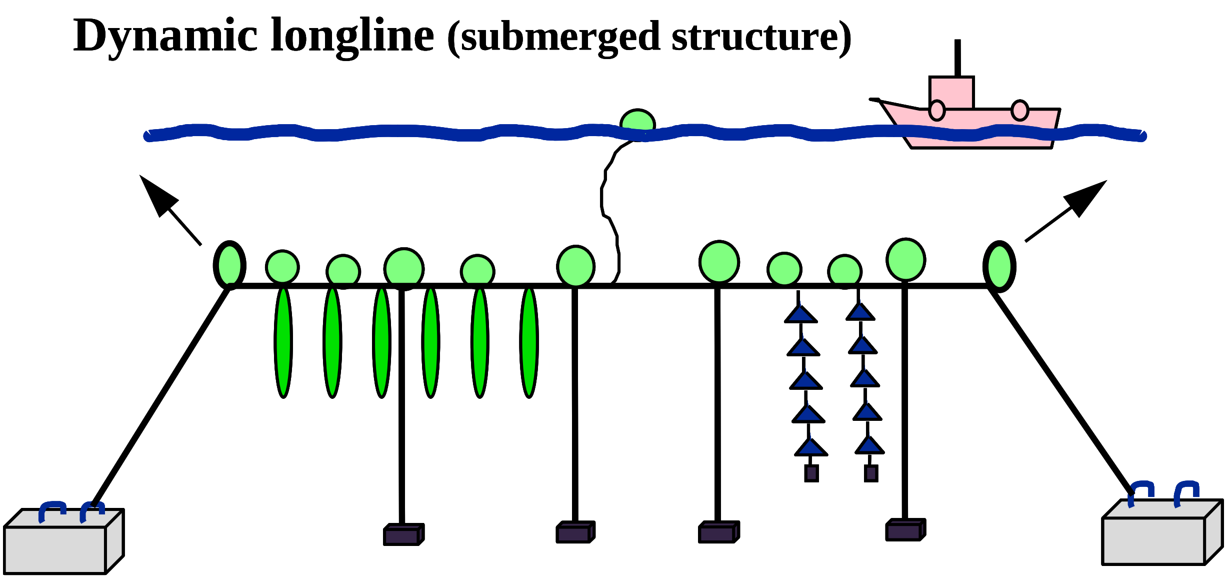
In France and Italy the semi-submerged lines are approximately 200m long and are anchored by a combination of concrete blocks and embedding anchors. The headline ropes used can vary a lot and may be very large diameter (50mm+) second-hand ship hawsers or 32mm polypropylene, they use a combination of spherical submerged floats (20-50l) coupled closely to the long lines and taller floats (150l+) that penetrate the surface and are attached to the headline by a float rope of 1-2m . The small floats look like large trawl floats and the tall floats are purpose built and could be cylinders 1-2m long, or long thin diamond shaped floats.

Fully submerged long lines:

Fully submerged long lines are used in France on the Mediterranean coast and are described in Danioux et al http://ressources.ciheam.org/om/pdf/b30/0 0600655.pdf.
They are also used in the trials in the USA and are widely used in Eastern Canada. They tend to be single backbone lines and rely on their geometry and the stretch and slack in the system to allow them to be hauled to the surface. The advantage of submerged systems is that they can be placed below the damaging effects of the weather. The disadvantages include the difficulty of carrying out regular inspections and maintaining the correct floatation to keep droppers off the bottom. They can also become slack and cause tangling without this being easily noticed. Development of multibeam side scan sonar has helped with the inspection problem.

A further problem with fully submerged lines is that the position of the mussels in the water column is fixed in relation to the sea bed, not the surface, so that in regions with a large tidal range there can be a significant change in water height above the lines. This can cause the mussels to be at a non optimal depth for mussel growth as the surface waters are often the most productive. Depth changes also causes changes in pressure on the floatation. This does not matter much in regions with a small tidal range such as the Mediterranean but would matter more where tidal range is large.

Submerged long lines use a specific geometric shape to remain dynamically accessible for maintenance by boat, to maintain optimal tension and to be independent of surface floatation. The key factor is the tension provided by larger corner buoys, solid anchoring and regular husbandry. Counterweights are usually added to compensation floats in offshore exposed sites to stabilize the line depth over the production cycle. Depth is easily verified with a depth sounder.



There is an unusable segment at each end of the mainline, which depends on the submerged depth from the surface. Planning is required to design and install this effective system.

Surface long line models

There are many variants of surface and sub-surface long lines, and these production units are mentioned briefly in order to cover the range of existing possibilities for growers. The selection of one model over another depends on the investment willingness of the grower; on the type of boat and equipment planned, on the exposure of the site, and seasonal weather conditions like hurricanes and ice.

In every case the water depth, food availability, boat size and current patterns will impose a choice on the distance between lines, whether they are single, double or rigs with multiple lines. Some examples are provided below.

Picture 3 Single lines in Norway Fjord

Picture 4 Double long lines

Picture 5 Rig with 10m stainless steel tube frame each end with 4 lines 120m long

http://www.cocci.org.uk/dettagliolavorazionemolluschi.aspx?id=96

In Canada the lines vary according to location but can be up to 200m long. Floats can be purpose made spherical floats of up to 50-60l or can be reused 25l containers. In areas where winter ice is a problem the majority of the floats are removed in the autumn allowing the ropes to sink until the droppers rest on the bottom which then supports some of the weight.

The semi-submerged headlines used offshore in the UK are both double and single headlines. The length of headline is usually about 200m and they are submerged to a depth of 1-2m. Floats used so far are either reused plastic barrels of 200 l. or standard surface headline floats of 300-400l attached at one end, by a float rope to the headline. Headline rope is usually 32-40mm diameter.

Picture 6 Submerged long line with plastic barrels floats

Partly exposed offshore farm, UK using second hand drums as floats

The farm of Offshore Shellfish Ltd at Lyme Bay South Coast of England will use 150m long headlines supported by vertical cylindrical floats. The floats will be attached to the headlines by 1-2m long float ropes. The headline ropes are likely to be 32mm diameter.

Moorings:

Moorings are always decided by a combination of several factors including, the nature of the ground they are deployed in, the weight of the farm attached to them, the severity of the weather, the speed of the current, the boats available to lay them and the budget of the operator.

Moorings in New Zealand are typically either large shaped concrete blocks of 10-20 tones, or they are drilled screw anchors.
http://fieldermarine.com/index.htm, http://www.n-viro.com/index.htm.

The size and depth of the screw anchors will vary with the consistency of the sediment and the size of the headline attached. They can be flat plate or helical. Chain is rarely used in these moorings and tension is maintained by regular retensioning of the lines after each harvest cycle, together with the use of buffer floats on the submerged anchor warps.

Fielder Marine and N-Viro have both developed their systems to be operated from a relatively small vessel, typical of that found on a mussel farm. The mooring systems that they use are designed for soft and cohesive sediments. Fielder Marine is also in the process of designing a system that will allow moorings to be placed in hard rock sea bed. This will work on the basis of a “lost drill bit” which is permanently fixed in the seabed with epoxy grouts.

The moorings used on the French Mediterranean farms are usually concrete blocks of less than 1tonne at the end of the long lines with subsidiary weights at intervals along the lines. Seabed pins are sometimes used to reinforce the holding power of the anchors. Headlines are usually 200-300m long. Movement of the blocks does happen occasionally during storms resulting in loss of tension and tangles in the headline. Headlines are retensioned by dragging the blocks back into position.

Moorings in the UK tend to be single fluke Sampson type anchors of 250-500kg or concrete block of 2-4 tones used in conjunction with 10-30m of 32mm chain. This approach is cost effective for farms with small numbers of moorings but not viable for the larger offshore farms being planned with ‘000’s of moorings.

Picture 7 Chinese Missile

The Lyme Bay Offshore shellfish Ltd farm will have 1,600 moorings and will use sea bed screws with no chain.

The Chinese farms use long wooden stakes that are driven into the sea bed by attaching them to the nose of 1tonne steel “missile” which is then dropped vertically over the side of the boat. The “missile” is retrieved leaving the stake embedded deep in the sea bed.

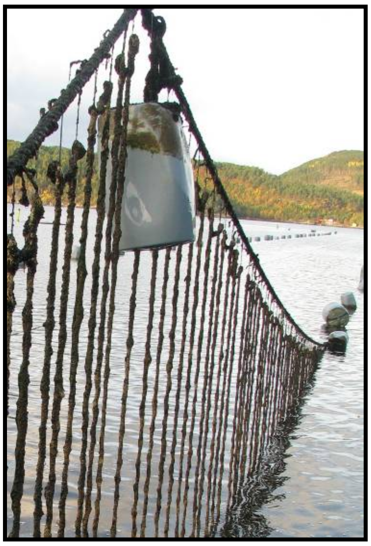
Chinese mooring “missile”

Duck-bill anchors which are driven into the seabed by percussion and then open out to give good pull out resistance are also used in the same way.

Husbandry

There is a huge variety of methods and materials used within the grow-out of mussels and other bivalves reared in suspension, from seed collection to harvest. The materials and techniques are intimately linked to the bio-physical conditions of the site, the level of mechanization, the length of the production cycle and the scale of the farm, not to mention the direct production costs associated with local labor laws, production depth, and seasonal weather and ice variations.

This review covers seed collection, thinning and grading, stocking densities and practices.
A brief overview is provided for mussel culture in offshore environments, because certain principles apply in order to succeed, the most important being that 1) seed collection is not limiting, and 2) grow-out is feasible with above average meat content and growth rates.



Picture 8 Unsuccessful spat set 2008

Seed collection, stocking densities, thinning and grading practices vary according to site specific conditions. Some practices seem to be the result of tradition rather than rational development, some are the result of particular economic influences such as labor costs and some have been developed in a rational and scientific manner. Most of the practices are directly comparable to those used at inshore mussel farms.

Seed collection

Access to abundant mussel spat is essential. Spat collection does not necessarily have to occur offshore, but proximal to the harbor from which the crew will travel to their offshore lease where grow-out will occur. Exceptionally, seed may be purchased from suppliers, but this is hard to establish during start-up of offshore culture.

Picture 9 Successful 2009 spat set full +4m

Seed collection cannot be taken for granted. Annual and seasonal variations are par for the course and difficult to predict. Successful offshore sites usually have more than one seed collection site.

Coastal spat collection usually occurs within the first 2-6m depth, and offshore sites can have unlimited spat with depth. Spat collection substrates vary with location and the success may or may not be related to the spat collection ropes. Small farms may use old crab fishing ropes from 12-18mm with added weights, while others use Canadian ‘fuzzy’ rope, plastic mesh, Swedish flat bands, Norwegian stone rope, or the NZ xmas-tree (leaded or not) or power loop ropes specially designed for seed collection. Mussels attach to most surfaces, but harvesting efficiency is the key.

The type of material, its strength and thickness depend on whether the collectors are vertical single droppers, or continuous ropes more often associated with intensive mechanized stripping and declumping, before reseeding (re-socking). Effective decisions are site specific and financial.

The size at reseeding will depend on the grower, on seasonal growth rates and specific fouling issues associated with the location. Some growers can collect seed in any of the four seasons.

Seed can be obtained from hanging collectors on the farming site, hanging collectors at a specific seed collection site, natural sub tidal seed beds, natural intertidal seed beds and hatchery production.

Successful collection of mussel seed on hanging collectors will depend on deploying ropes in the water where and when there are plenty of mussel larvae. The number of mussel larvae present in the water tends to reduce with increasing distance from the shore. Larval numbers will also vary with depth and the degree of stratification in the water column.

Where the numbers of rope settled seed are large it is usual to grow the seed up to a size of around 20mm on the collectors then to strip them off and reseed on to the grow out ropes at an optimum density using biodegradable cotton socking or plastic pergolari tubing. The optimum density will depend on a number of factors, but principally it depends on what weight of crop/meter of dropper is expected to be successfully reared on the ropes.

The weight of mussel crop that can be successfully reared on a rope will obviously vary from site to site so it is not useful to generalize but it is linked to the productivity and temperature of the water as well a number of other factors. As a rough guide Blue mussels are expected to yield around 5-8kg/m of dropper.

Growers producing for the French market, which prefers a smallish mussel of around 80-100 pieces/kg, will reseed at rates of 600-1000 seed/meter. Growers targeting the Belgium or Spanish market, which prefer a larger mussel of 50-90 pieces/kg, will reseed at 350-700 seed/meter.

In most of NW Europe there are usually sufficient larvae in the water column for collection on hanging collectors on the farming site to be practical, although some places are obviously better than others.

For many years the Irish rope mussel industry relied heavily on seed collected from rocks, which was then reseeded on to the ropes.

Some farms occasionally use seed that has been dredged from the seabed and is then reseeded onto the grow out ropes. Where the seed has been obtained from a high energy, hard substrate seabed then this strategy can be successful. Where the seed has been obtained from a low energy, soft sediment seabed, there are often problems experienced in the lack of byssus production by the reseeded mussels.

The Chinese industry rears a number of different species of mussel, Blue, Green and Brown. A large portion of the seed used comes from hatchery production, particularly for newly introduced species.

The New Zealand industry relies heavily on seed collected intertidally that is attached to seaweed washed up on one specific beach in North Island. Some seed is also collected on ropes grown out sites and efforts are being made to develop a good supply of hatchery reared seed.

In Washington State, USA, Mytilus trossulus seed is collected from the wild and Mytilus galloprovincialis seed is hatchery reared.

In many areas, the small mussels that are separated out during the grading process of market ready crops are an important resource for restocking the ropes. This is particularly true where a heavy over settlement happens with juvenile mussels from one year class settling on the adult mussels from a previous year. This is most likely to happen in regions of slow growth.

The practice in many inshore farms is to allow the ropes of collectors to self thin. This is where the original spat settlement is left alone, and as they grow, many of the excess mussels will fall off. This is wasteful of mussel seed and reduces the rate of growth but it also greatly reduces the amount of labor required. Following this practice is not reliable in offshore farms as the higher energy experienced at these sites can shake all the mussels off which tend to be only loosely attached to the ropes if left at a high density.

Stocking densities:

Stocking densities in offshore farms will be determined by the productivity of the water, the speed of the current, the size of the farm site and the design and layout of the long lines within the farm.

As there are so few offshore farms and they are each very different to each other it is difficult to assign an average density. However they would typically be stocked at a lower density than those in inshore waters. This is not because they are intrinsically less productive, but because as they tend to be bigger, they need greater spacing between the ropes in order to allow water flow to be maintained through the farm.

Typical spacing between headlines in an inshore farm may be as little as 10m while on an offshore farm the spacing between lines would be typically 50m. Inshore farms will tend to use double or even treble backbone headlines, whereas offshore farms would usually use single backbone headlines. This means that offshore farms might only be stocked at 10-20% of the density of an inshore farm.

The lower density of lines/ha, the lower seeding density of mussels/m of dropper and the better water flow through the farms mean that offshore farms often have a better growth rates and shorter production cycles.

6. Status of mussels farming in various countries

Spain:

Spain is the largest producer of rope cultured mussels in Europe with a production of around 250,000 tons per annum. The great majority is produced in the sheltered Rias of Galicia on rafts known as Bateas. The available space and plankton resources within the Rias are now at or near maximum levels of exploitation and for further expansion there would need to be a move into more exposed offshore waters.

Research into rafts suitable for offshore use has produced prototypes but they have not been taken up at a significant commercial level for technical and economic reasons. Long line culture has been used for offshore production with recently installed farms near Gibraltar and elsewhere. This could expand significantly in the future. Technical details are not known although it is believed that these farms are fully submerged.

Portugal:

There is a recently installed offshore long line farm in Southern Portugal. It is believed that this is fully submerged.

France:

The majority of French production uses the bouchot method but expansion is constrained by lack of available space. Long line production is used offshore in the Med and the Atlantic coasts. The Mediterranean farms have been in use since the late 1970s and are all fully submerged and produce up to 10,000 tones/year, although this has decreased in recent years due to predation and water quality. The techniques and equipment are fully described by, Ch. Danioux, X. Bompais, C. Loste and Ph. Paquotte
http://ressources.ciheam.org/om/pdf/b30/00600655.pdf

Offshore long lines have been used for more than 15 years on the Atlantic, Charentais coast, in the Pertuis Breton and the Pertuis Antioch. It is believed that there are several hundred lines in this region. Production is around 5,000 tons from offshore long lines. Expansion will depend on access to new space and improvement in techniques. New long line farms are currently in development in Northern France off the Brittany and Normandy coasts. It is believed that these are semi-submersible lines and will total less than 100 lines.

Italy:

Offshore long line mussel production has been in place in the Adriatic for some years and plays an increasingly significant part of production. It is described by Danioux et al.
http://ressources.ciheam.org/om/pdf/b30/0 0600655.pdf.

There has been an increase in production since this guide was written. The lines used are semi-submersible and the floats used are vertical cylinders or similar.
http://www.cocci.org.uk/dettagliolavorazionemolluschi.aspx?id=96

Croatia, Greece:

Croatia has a small long line mussel industry which seems to be restricted to inshore waters and uses rafts or standard surface long lines.

Greece has a semi-protected offshore long line mussel industry which consistently produces 20-25,000 tones. It seems to be restricted to deltaic regions with higher productivity. Expansion into other offshore areas would seem unlikely due to the extreme depths and the low productivity of the waters.

Turkey:

Turkey has had some mussel production in the Black sea for some time. There is information that this is likely to expand significantly with the improvement in water quality. Successful trials have been carried out using surface long lines. It is likely that if there were a large expansion it would be offshore.

Bulgaria:

An offshore mussel farm has been successfully established over the last few years. It is a joint Bulgarian/Irish company using surface double long lines of the standard NZ model. The floats used are made by an Irish company JFC http://www.jfcmarine.com/ which are said to support greater mussel growth than standard floats. This is claimed to be due to the shape of the floats reducing the amount of drop off of mussels rather than the volume of the floats, otherwise this would bring Archimedes principle into question!!
http://www.thefishsite.com/fishnews/10460/from-the-black-sea-comes-eus-largest-mussel-farm

Expansion of this farm is planned and if successful is likely to be copied in the area.

Romania:

The Romanian Black Sea coast has less shelter than its neighbor Bulgaria and is known to be considering mussel culture on a large scale. Partly as a source of food and income but also as bioremediation to help tackle the problems of eutrophication caused by nutrient input to the Black Sea via the Danube.

Georgia, Russia:

Both Georgia and Russia had some mussel culture in the Black Sea in the Soviet era. The current status is not known.

Netherlands:

The Dutch mussel industry has traditionally been dominated by bottom culture of mussels in the Oosterschelde and the Waddenzee. This relied on collecting and redistributing, naturally settled seed from the Waddenzee. For a number of reasons this resource is now much reduced and there has been a rapid increase in long line production of mussels. This is largely for the production of seed mussels which are then re-laid on the bottom although there is also a lot of interest in offshore long line production of market size mussels. The long lines currently used for seed production are mostly of the Smartfarm type with a surface floating pipe supporting a net to collect the seed. http://www.smartfarm.no/

Belgium:

Belgium has not had a mussel industry of its own, despite it being one of the largest consumers of mussels. There have been trials of large buoy-like structures that have been technically successful but there is little space on the short Belgian coastline. There may be interest in offshore long lines in the future.

Germany:

Germany has shown a lot of interest in developing an offshore long line mussel industry based on sharing the space used by offshore wind farms.

Buck, B.H., 2007. Experimental trials on the feasibility of offshore seed production of the mussel Mytilus edulis in the German Bight: installation, technical requirements and environmental conditions. Helgol. Mar. Res. 61, 87–101.
Trials carried out so far have proved the technical feasibility but there would need to be refinement of the equipment used in order to make the industry economic and practical. This includes the floats and moorings.

Denmark, Sweden:

Denmark has a dredge fishery for mussels and also a long line production industry. This is inshore at present and may expand into the offshore zone.
In common with the other southern Baltic countries there is interest in the use of large scale mussel farms and possibly seaweed farms, for the purpose of bio-remediation and excess nutrient removal. This has already been successfully trialed in Southern Sweden.
http://www.ncbi.nlm.nih.gov/pubmed/15865310
http://www.ncbi.nlm.nih.gov/pubmed/15865313

It is assumed that if this idea is progressed then there will be a significant use of large scale coastal mussel farms.

Norway:

Norway has a long line mussel industry that takes place in the sheltered fjords. The industry has frequently been hampered by algal toxin events. It may be possible that the Norwegian industry will move offshore to avoid the toxins in the fjords.

UK:

The UK long line mussel industry occurs mostly in sheltered waters in Scotland and the south west of England. Until recently there has been no offshore development, but there are now 3 smallish farms in exposed coastal waters in SW England with a total of approximately 30 x 200m headlines between them. Offshore Shellfish Ltd is developing a fully exposed farm in Lyme Bay, Devon, which will begin deployment in 2011 and will total 790 x 150m headlines.
Personal communications suggest that there is interest in developing a large scale offshore farm in Scotland, probably Shetland. There is also interest in Wales in combining mussel farms with Wind Farms.

Ireland:

Ireland has long line farms in sheltered, semi-sheltered and exposed waters. They are known to want to develop offshore systems so that they can expand production away from the crowded inshore waters such as Bantry Bay where carrying capacity may be being exceeded. They have trialed the Smartfarm system offshore but found problems with the mooring systems and the surface pipes buckled in large seas.

USA:

Long line farms have been successfully trialed in New Hampshire waters and these are now run on a commercial basis. http://ooa.unh.edu/shellfish/shellfish_about.html

A trial offshore farm of 4 lines in Maine waters produced its first crop in 2010 using the same technology as UNH. This is likely to expand over the next few years.

Further expansion of offshore mussel farming in the USA seems likely as the market is growing and currently most mussels are imported from Canada and Chile. However there will need to be a change in current legislation if farms are to be developed in Federal waters and existing farms are all within individual state jurisdiction waters.

Canada:

Long line farming takes place in PEI, Quebec, BC and New Brunswick waters. Most of this is in sheltered waters and expansion will require some movement into offshore waters. On the Eastern seaboard where there is a problem with winter ice, systems need to be fully submersible to cope with this.

Chile:

There is a large and growing long line mussel industry in Chile that is mostly in sheltered waters. It seems unlikely that there will be a big move to offshore waters as there is still a large space resource in sheltered waters. The increase of the current industry is likely to affect the market for frozen mussels in many other countries and may therefore affect plans for offshore development in those countries.

Brazil:

There is a growing brown mussel (Perna perna) industry in Brazil (circa 17,000 tones) which at the moment appears to be artisanal. This may change and move offshore if the forecast large scale expansion is to take place. ftp://ftp.fao.org/docrep/fao/011/i0444s/i0444s16.pdf
The New Zealand system has been trialed and this seems the method likely to be used for expansion.

South Africa:

There is an inshore mussel industry which is based on raft production. There may be a future need to move offshore. Namibia is also said to be examining the possibility of farming mussels offshore.

Australia:

There are long line farms for mussel in sheltered waters in Western Australia, Victoria and New South Wales. In Tasmania there is at least one offshore mussel farm with a large lease and room to expand. http://www.springbayseafoods.com.au/

New Zealand:

The large scale (90,000 tones) long line mussel industry is mostly based within the sheltered waters of the Marlborough Sounds with some semi exposed farms in Golden Bay and Wilsons Bay.
Applications for several very large, fully exposed offshore farms in the North and South Islands have been made that could total another 100,000 tones of production if they were all permitted and built. Offshore trials have been successfully carried out and expansion is dependent on market conditions and currency exchange rates.

China:

China has the world's largest mussel farming industry with most of it taking place in exposed or semi-exposed areas. These farms are often part of much larger integrated aquaculture operations with seaweeds, fish and other shellfish all being farmed in the same area.

Thailand, Philippines, Malaysia, Singapore, Taiwan and Vietnam:

These countries all have large and expanding mussel farming industries and there is a high probability that these will start to move offshore as pressure for inshore space increases.

7. Market potential

The market for offshore mussel long line equipment will be almost entirely dependent on the future market for mussels themselves. Moving production into exposed areas will result in higher capital costs and higher operational costs, while the mussels sold are unlikely to attract a price premium over and above the current inshore production. Therefore for there to be a significant growth in offshore production there will need to be significant market drivers. This may come about from an increased per capita consumption and therefore a greater total market or there may be a continued reduction in the availability of existing inshore production.

Europe:

The current shortage of mussels in Europe largely results from the reduction over the last 10 years in Dutch supplies by 70-80,000 tones. Part of that shortfall has been made up by increase in production in other European countries and part has been made up by imports of frozen mussels from Chile.

It seems likely that the market potential for offshore equipment will be for farms built to replace the remainder of this shortfall. That shortfall is approximately 50,000 tones.

A 150m long line might produce an average of around 8-10 tones/year therefore in Europe there is a potential need for around 5-6,000 long lines. Each long line will need 2 moorings and approximately 2000l of buoyancy or 20 x 100l floats.

Therefore there is a potential market for 10-12,000 moorings and 100-120,000 floats in Europe.

USA and Canada:

There is a large potential for expansion into offshore long line mussel farming in USA. However this will only be able to happen if there is a change in legislation which would allow farming in Federal waters. Any increase in production in USA would also be likely to displace the mussels currently imported into USA from Canada and Chile. These mussels would then possibly be redirected to Europe. This may therefore result in no net increase in the need for farm equipment.

New Zealand:

There is likely to be a very large expansion of production in New Zealand, if and when the value of the NZ$ decreases and makes exporting mussels more profitable. If this production increase were to happen then it is likely that the NZ industry would use its own locally produced equipment rather than importing.

Bioremediation:

The use of mussel farms and seaweed farms for bioremediation purposes has been frequently suggested in a range of governmental and NGO strategies. It has been successfully trialed in Southern Sweden and if this were to be adopted on a large scale then there would be a very substantial market for offshore long line equipment. This strategy is also being considered in Romania and has been suggested for eutrophic waters such as Chesapeake Bay in the US.

Wind Farm/ Mussel/Seaweed developments:

It has been proposed in the EU aquaculture strategy that the space resource within the boundaries of wind farms should be considered for utilization by large scale mussel/seaweed farms. This would require the development of novel markets for the products which could include, poultry feed, fish aquaculture feed, biomass for energy production, fertilizers.

This market for offshore long line equipment would be potentially extremely large as hundreds of thousands of hectares could become available. However the economics of this are largely unexplored and this should be considered as a long term possibility.

8. Conclusion

There are two main types of anchors and moorings; permanent and temporary. A temporary anchor is usually carried by the vessel and hoisted aboard whenever the vessel is underway but permanent moorings are more used by shellfish growers who seek stability and permanence tend to install long lines that use permanent anchors and moorings. A permanent anchor is generally a heavy object made of concrete or metal, or moorings such as spiral or helix anchors, hydraulically drive expansion anchors.

Lightweight embedded moorings, such as spiral screw or helix anchors, and hydraulically-driven expansion anchors can require greater planning, however they are extremely reliable and leave very little footprint above the seafloor. It is essential to use a platform that is stable while drilling, to maintain its position in windy conditions, and allow the mooring to embed vertically down.

Lightweight permanent anchors come in two common forms and require different logistic set-up to become proper mooring systems:

a) the spiral screw anchors o helical screw anchors
b) the hydraulically driven expansion anchor

There are different types of long line designs and each one uses flotation differently to maintain tension. The key parameter for successful shellfish culture is maintaining long line tension in all environmental and working conditions, so the shellfish do not flop vertically in waves or sway horizontally on the long line in currents or during maintenance.

Three (3) types of long lines can be distinguished in practical grow-out terms: a) surface long lines, b) semi-submerged, and c) fully submerged lines. Each type has different structural characteristics and limitations but all of them require permanent, high holding power moorings if they are to be used offshore.

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This market for offshore long line equipment would be potentially extremely large as hundreds of thousands of hectares could become available. However the economics of this are largely unexplored and this should be considered as a long term possibility.

Status of offshore mussel farming in 32 countries is introduced in this report.