Recruitment, growth and production of blue mussels in the Baltic Sea

Results from recruitment, growth and substrate-tests at six "Baltic Blue Growth" project farms 2016-2019

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About

Baltic Blue Growth is a three-year project financed by the European Regional Development Fund. The objective of the project is to remove nutrients from the Baltic Sea by farming and harvesting blue mussels. The farmed mussels will be used for the production of mussel meal, to be used in the feed industry. 18 partners from 7 countries are participating, with representatives from regional and national authorities, research institutions and private companies. The project is coordinated by Region Östergötland (Sweden) and has a total budget of 4,7 M€.

Partners

- *Region Östergötland (SE)*
- *County Administrative Board of Kalmar County (SE)*
- *East regional Aquaculture Centre VCO (SE)*
- *Kalmar municipality (SE)*
- *Kurzeme Planning Region (LV)*
- *Latvian Institute of Aquatic Ecology (LV)*
- *Maritime Institute in Gdańsk (PL)*
- *Ministry of Energy, Agriculture, Environment, Nature and Digitalization of Schleswig-Holstein (DE)*
- *Municipality of Borgholm (DK)*
- *SUBMARINER Network for Blue Growth EEIG (DE)*
- *Swedish University of Agricultural Sciences (SE)*
- *County Administrative Board of Östergötland (SE)*
- *University of Tartu Tartu (EE)*
- *Coastal Research and Management (DE)*
- *Orbicon Ltd. (DK)*
- *Musholm Inc (DK)*
- *Coastal Union Germany EUCC (DE)*
- *RISE Research institutes of Sweden (SE)*

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Picture 1. Production units with floating tubes and trawl nets for mussel farming in the Great Belt in Denmark.

1. Summary

The overall aim of this study was to demonstrate efficient production methods of farming under different conditions in the eastern and western Baltic Sea. Focus was on technical development of the demonstration farms, including optimization of mussel production by comparing growth and recruitment at different types of substrates being trawl nets with different mesh size, Smartfarm nets, Fuzzy rope, and Swedish bands.

At the musel farm at Musholm, in Denmark, the overall growth rates were low on all the different substrates and varied from 0.04-0.09 mm day^{-1} from 2016-2019. Because growth rates were based on the differences in the average length of mussels from one sampling period to the next, these rates may be affected negatively by the size-selective predation of eider ducks at this test site. Similarly, at Musholm the estimated biomass was low on all the substrates and the biomass varied considerably from 2016-2019 with highest increment in biomass in 2016. However, the biomass (kg m^{-1} headrope) on the substrates with the smallest mesh sizes (30 mm and 60 mm) was approximately twice as high as the biomass on Smartfarm nets (300 mm). Data on final biomass estimates on Swedish bands varied from 2-22 kg m^{-1} headrope with the highest increment in biomass in 2017/2018. Significant difference in mussel length and weight of biomass from different substrates was observed. However, since the negative impact of size-selective predation of eider ducks could not be differentiated from a possible effect of the substrate, these results are inconclusive.

At the mussel farm in Kiel, Germany, where substrates were not affected by predation or fouling, there was no difference in length of mussels from different nets or depths in 2017/2018. The mussels grown on Swedish bands were significantly larger than the ones grown on nets in 2017/2018. The results showed that mussels settled in August grew nearly as big as mussels settled in June when measuring the length in January 2018. During both growth seasons, there were results indicating a loss of large mussels over the summer period, where substrates deployed in June 2018 ended up having more biomass than substrates deployed in April. Overall, trawl nets carried more biomass than Swedish bands despite of the marginally higher growth rate found on the Swedish bands.

At the mussel farm in Kalmarsound, Sweden, the overall growth rates were low on all the different substrates and possibly affected by fouling from barnacles and thus, competition for space during mussel development. Despite this bias, the overall growth rates appeared to be similar between tested substrates, and the highest growth was measured on the net substrates in contrast to the Swedish Bands. Mussel growth at different depths was tested for 1 m, 3 m, 4 m, and 13 m, and the mussels from 13m was significantly smaller than the mussels from 1m. Similarly, the highest biomass estimate per kg m^2 substrate was on the net substrates, which was similar for all mesh sizes. There was comparatively low biomass on the Swedish Bands in 2017/2018 and no biomass at all in 2018/2019. The Smartfarm substrate carried considerably lower biomass than the trawl net with same mesh size, which indicates that the very robust Smartfarm nets may not be optimal for mussel production in areas with low growth rates.

At the mussel farm at the Coast of Kurzeme, Latvia, growth rates could not be estimated due to only one sampling every year. The biomass per meter headrope could however be calculated for 2018/2019 and was found to be low with a value of 0.08 kg m^{-1} headrope or 1.3-1.6 kg m^{-1} headrope in the growth and recruitment study. A low growth rate was expected for the Latvian farm due to low salinity and rough weather conditions.

In the growth and recruitment study, there was found a great variability in the biomass yield, abundance and length frequency distribution of mussels between different regions and sampling times. As expected largest mussels were found in the most saline regions of the Baltic Sea area. However, within the Baltic Proper area spatial differences in biomass, abundance and length frequency distribution did not clearly follow the salinity gradient, indicating that other factor as predation, temperature stress during summer, settling of other organisms, may influence the production.

There were some sporadic events resulting in seasonal losses of larger size classes. Although the reason of such losses is not yet fully understood it is likely that in more saline areas mussels grow large resulting in the intensification of density dependence processes (i.e. increased competition for space). When the mussel stands get crowded stronger winds are expected to significantly reduce the biomass of mussels in the growing ropes. In less saline areas, however, the smaller mussel sizes reduce substrate limitation (density dependence), and populations experience less loss from large individuals detaching.

From the growth and recruitment study, and from the substrate test study it is demonstrated, that the production potential in different areas of the Baltic Sea, does not only follow variation in salinity and food availability. It very much depends on the site-specific growth environment where e.g. predation on mussel farms can be an obstacle for any mussel growth at all. A thorough screening of a potential mussel farming area with respect to food availability, predation, weather conditions and competing species is therefore heavily emphasized before a possible mussel production is initiated in the Baltic Sea region. Alternatively, new mussel farms should start in a small scale, using some years to test and area, and develop a site-adapted husbandry optimizing the production before scaling up.

2. Introduction

In the coming years, blue bioeconomy initiatives will be on the political agenda and should be adequately supported by greater confidence and certainty for investors provided through maritime spatial planning and a knowledge platform about production, products and market. Mussel farming has been proposed as a mitigation tool to reduce the effects of eutrophication. In order to allocate marine space for the mussel farming, spatial planners have to beinformed about areas, which have environmental conditions supporting mussel production.

To date, such information does not exist for the Baltic Sea area and therefore. This document reports monitoring data on the settlement and growth of mussels in the Baltic Sea area, including growth of mussels on different substrate types. Standardized methodology was used at all focus farms in order to make a proper comparison among the functionally different regions of the Baltic Sea.

The Baltic Blue Growth interregional project aims to examine the potential of mussel farming in different regions of the Baltic Sea. To develop the best guidelines for doing so, six demonstration farms located in different areas of the Baltic Sea were chosen in order to compare growth and recruitment of mussels on different types of substrates. An overview of substrate tests from 2016 – 2018 is described in Table 1 for the six demonstration farms.

This report is aimed at present and future mussel farmers in the Baltic Sea region as well as policymakers and stakeholders related to the use of mussels as a mitigation tool to remove excess nutrients from the Baltic Sea. The report should then be readable for all persons, with limited knowledge to mussel farming.

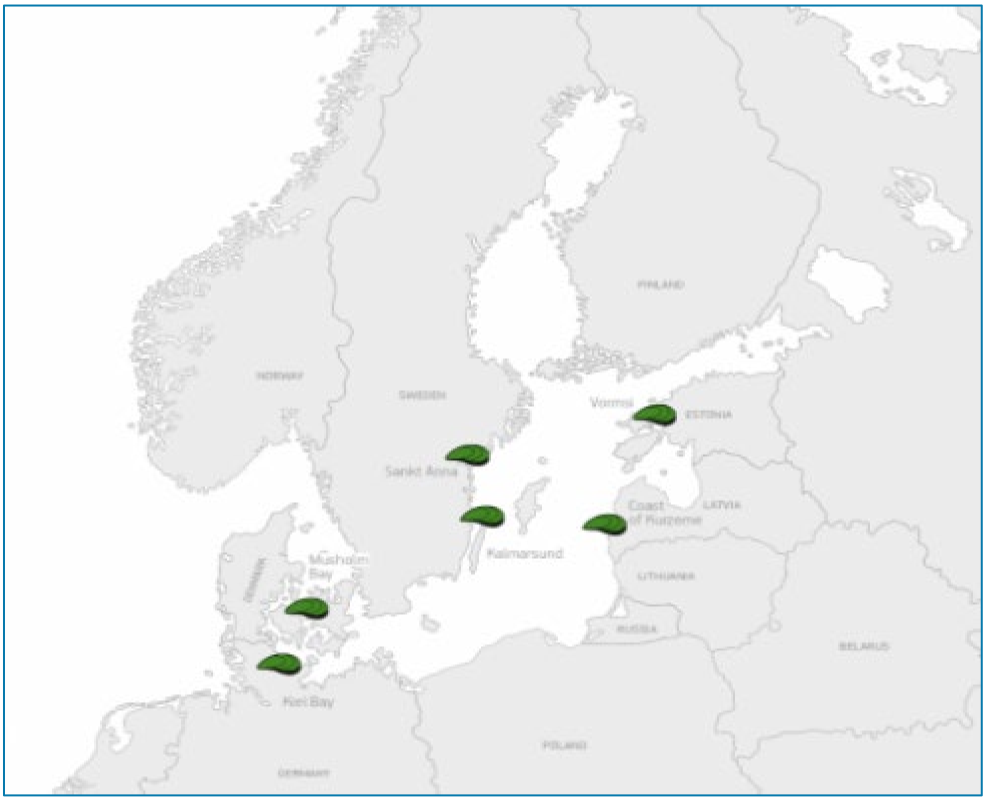


Figure 1. Map of demonstration mussel farms in the Baltic Blue Growth project.

Musholm Bay, Denmark: The farm in the Musholm Bay is run by an aquaculture company producing rainbow trout in open cages. Thus, the farm represents the "Danish model" of fish farms that compensate for nutrient discharge from their fish farm by growing and harvesting mussels. The conditions for farming mussels at the exposed site are generally variable winds, strong currents, fluctuating salinity and large swells during rough weather. At this stage, the Musholm farm has particular interest in maximizing nutrient uptake through increased mussel biomass. The potential of this was investigated by testing mussel biomass on different mesh-sizes of net substrate at different times of the year in order to increase the mussel production at harvest time. Since it is more efficient to harvest mussels at a smaller size if the aim is to gain a high biomass in a short time, the business potential of using small and thin-shelled mussels in animal feed is also of great interest to the Musholm farm.

Kiel Bay, Germany: The Ministry of Energy, Agriculture, Environment and Rural Areas Schleswig-Holstein (MELUR) has established a cultivation site in the Kiel Bay in Northern Germany with the aim of maximizing biomass production of small mussels. The farm area is at least 100 x 40 m and has three production units consisting of 100 m rope. The farm is next to a local farm with longlines taking up app. 0.6 ha. As a result of a public procurement, the private company "Kieler Meeresfarm" (www.kieler-meeresfarm.de) was selected as the operator of the farm by MELUR. The company is also running a small-scale, commercial mussel cultivation in the Kiel Fjord and is selling its mussels to both private and business customers for human consumption. The Baltic Blue Growth project farm will be an extension of the company's existing cultivation site.

Table 1. Overview of substrate test from 2016 - 2019 on each demonstration farm.

Demonstration farms	2016/2017	2017/2018	2018/2019
Musholm farm	Trawl nets with mesh size: 50 mm, 80 mm, 150 mm. Smartfarm: 300 mm	Trawl nets with mesh size: 30 mm, 60 mm. Smartfarm (mesh size 300 mm) Swedish Bands Fuzzy rope	Trawl nets with mesh size: 66 mm Swedish Bands
Kiel farm	No tests	Trawl nets with mesh size: 50 mm, 100 mm. Swedish Bands Fuzzy rope	Trawl nets with mesh size: 50 mm, 100 mm Swedish Bands
Kalmar farm	No tests	Trawl nets with mesh size: 50 mm, 80 mm, 150 mm. Smartfarm: 150 mm. Swedish Bands Fuzzy rope	Trawl nets with mesh size: 66 mm Swedish Bands
Sct. Anna farm	No tests	Fuzzy rope	No tests
Latvian farm	No tests	Preliminary growth test on single rope Fuzzy rope	Trawl nets with mesh size: 66 mm Swedish Bands Missed settling
Estonian farm	No tests	Fuzzy rope	Trawl nets with mesh size: 66 mm Swedish Bands Missed settling

Kalmarsund, Sweden: Placed in an exposed area at the northern inlet of the Kalmar Strait, this mussel farm uses a submerged net-farm production system, which is designed to withstand ice and offshore conditions. The area is chosen because of its good biological potential for mussel growth, with few conflicting uses and interests and with a proximity to two large harbors, making the farm easily accessible. The estimated harvest in 2018 was 50 tons, corresponding to a potential nutrient uptake of 500 kg nitrogen (N) and 50 kg phosphorous (P). The farm is owned and run by the company Bohus Havsbruk, in compliance with a contract with Kalmar municipality.

Coast of Kurzeme, Latvia: Off the port town of Pāvilosta on the Latvian coast, the Latvian Institute of Aquatic Ecology has established a test-cultivation mussel farm using long lines as a substrate. Located approximately five km offshore in the open sea, there are strong currents and rapid water circulation in the area. To protect the cultivation, the units were submerged to a depth of at least five m.

Skt Anna, Sweden: The Sankt Anna mussel farm is the first full-scale mussel farm with a long-line system on the Swedish East Coast. It is located in the sheltered archipelago of Östergötland. The primary goal of the project is to demonstrate the potential for an industry with a positive impact on the environment and the creation of jobs in the region. The position of the musselfarm is in a protected natural area and is therefore not affected by conflicts of land/water-ownership. The site has sufficient depth (~20 m), salinity and acceptable current and wind conditions. In addition, the area is not normally affected by ice movements during freezing or spring break-up. Based on a prior study, the potential harvest of this pilot farm will be approximately 21 tonnes. A harvest of that size will remove 231 kg of nitrogen (N) and 23 kg of phosphorous (P). The farm is owned and run by East Sweden Aquaculture Centre (ERAC), a non-profit organization aiming to facilitate the transfer of information between research and industry, and to educate and advise interested parties on aquaculture in East Sweden.

Vormsi Island, Estonia: Placed in the waters outside the island of Vormsi, this small-scale test farm is owned and run by the private company Vormsi Agar, which is cooperating with the University of Tartu. The small-scale test farm focus on blue-green business and rural development, and they have been experimenting with different products such as mussel-based consommé. The farm is very interesting from a business development perspective but also biologically, as it is the most eastern farm of the focus sites represented in BBG. This small-scale test farm is also operating with cultivations of the red algae (Furcellaria lumbricalis) and blue mussels (Mytilus trossulus) in the same area.

This report describes the mussel growth at six different mussel farms in the Baltic Sea: Musholm Bay (Denmark), Kiel Bay (Germany), Kalmarsund (Sweden), Vormsi, Estonia, Sct. Anna, Sweden, and Coast of Kurzeme (Latvia). The aim of the tests was to examine how well different substrate types for mussel production perform in the Baltic Sea region with respect to growth and recruitment.

3. Method and sampling

3.1. *Overview of sampling*

The study covers the time-period from May 2016 to February 2019, where sampling was conducted on four of the six demonstration farms and analyzed in the lab.

Table 2. Overview of sampling occasions on each demonstration farm from 2016-2019. The substrates at the Wormsi Island farm and Latvian farm in 2018 had no larvae settling due to a delayed deployment.

Farms 2016/2017	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Musholm				x		x	x			
Farms 2017/2018	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Musholm			x			x				x
Kiel	x		x					x		
Byxelkrok			x			x				
Kurzeme			x							
Farms 2018/2019	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Musholm			x		x				x	
Kiel	x	x		x		x				
Byxelkrok					x					
Kurzeme	x		x							

3.1.1 *Musholm (DEN): Setup for tests of different types of substrate*

In 2016/2017, the four different trawl test-nets, with mesh sizes of 50 mm, 80 mm, and 150 mm, were placed inside an empty fish pen. The nets were held just below the surface by a floating PVC pipe, which was visible on the surface (Picture 2). The depth of each test-net extended down to 3 m and the length of each test-net was 4 m. The full length of floating PE pipes, each with two test-nets, was 10 m long and 30 cm in diameter. Additionally, a standard full-length Smartfarm unit (120 m in length), holding the largest mesh size (mesh size: 300 mm) was placed next to the fish production area.

The Musholm farm tested five different substrates for mussel production in year **2017/2018**; two different trawl nets with mesh sizes of 30 mm (two units, 120 m), and 60 mm (four units 120 m) (see Picture 2), a Smartfarm net with mesh size 300 mm (one unit of 10 m), and two different spat collection substrates - fuzzy rope and Swedish bands. All substrates were placed in the Great Belt during the months from settling in May and June until October (16.10.2017). Hereafter, the units were moved north into the Kalundborg Fjord to the following destination: 55.39’816N, 11.04’480E to avoid predation from Eider ducks.

The nets were held just below the surface by a floating PE pipe, which was visible at the surface. The attachments of the nets to the PE pipes were designed to enclose the floating pipe in a way so that the pipes could rotate within the net (see Picture 3). The depth of each Smartfarm and trawl test-nets extended down to 3 m. The depth of fuzzy ropes and Swedish bands were 5-6 m.

Picture 2. **The test set up in 2016/2017, with two nets with different mesh sizes alongside each other, on a 10-meter PE tube.**

Picture 3. Musholm net with mesh size 60 x 60 mm in 2017/2018.

In 2018/2019, the Musholm farm tested two different substrates for mussel production: Trawl net with mesh sizes of 66 mm and Swedish bands. The experimental substrates were placed inside an empty fish cage (Picture 4) in the Great Belt during the months from settling in May and June until February the following year.

Picture 4. Empty fish cage with test substrates inside to prevent predation from eider ducks at Musholm.

3.1.2 *Kiel (DEU): Setup for tests of different types of substrate*

In 2017/2018 the Kiel farm had Swedish bands, nets with mesh size 50 x 50 mm and 100 x 100 mm (Picture 5, Picture 6, Picture 7) deployed in Kiel Bay at two different depths (2 and 5 m). The purpose was to test which substrate was optimal for settling and mussel growth to achieve a high mussel biomass.

The substrates were deployed on the 28th of April 2017 and sampling was carried out on the 27th of June, the 14th of August and on the 17th of January the following year. Additionally, three Swedish bands were deployed at 2 m and at 5 m on the 14th of August, to study the late summer settling. Except for the loss of three nets (100 x 100 mm) samples from 5 m depth between August 2017 and January 2018, deployment and sampling of mussels was carried out successfully.

In 2018/2019, the Kiel farm had Swedish bands, nets with mesh size 50 x 50 mm and nets with mesh size 100 x 100 mm (Picture 8, Picture 9, Picture 10) at 2 m depth in Kiel Bay. The purpose was to test and compare the same substrates in different areas in the Baltic Sea concerning optimal settling and high mussel biomass.

Some of the substrates were kept in water from the previous test where deployment was carried out on the 27th of April 2017. Other substrates were deployed the 4th of June 2018 (see Table 1). Sampling was carried out on the 4th of June, the 30th of July, the 17th of September and on the 5th of November 2018. Deployment and sampling of mussels was carried out successfully.

Orbicon carried out analysis of mussel samples. Method and procedures are described below.

Table 3. Overview of substrate samples from the Kiel farm.

Substrate deployment	Substrate	Depth (m)	Substrate samples
27th of April 2017	Swedish Bands	2	9
4th of June2018	Swedish Bands	2	9
27th of April 2017	Net 50 x 50 mm	2	12
4th of June2018	Net 50 x 50 mm	2	9
27th of April 2017	Net 100 x 100 mm	2	6
4th of June2018	Net 100 x 100 mm	2	9

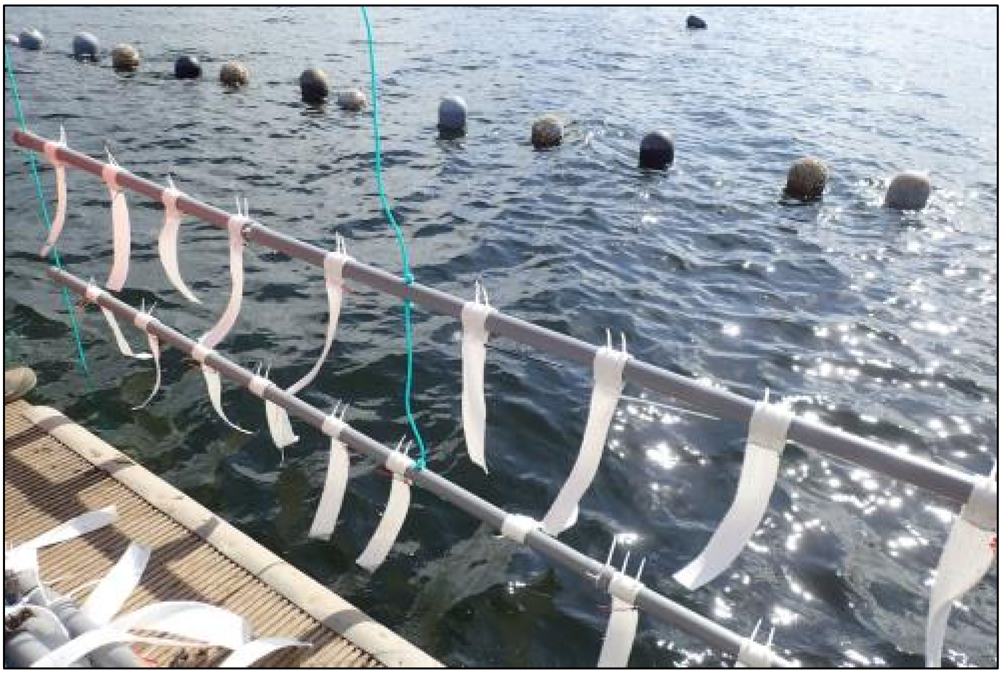
Picture 5. Test substrate with mesh size of 50 mm at Kiel Farm.

Picture 6. Test substrate with mesh size of 100 mm at Kiel Farm.

Picture 7. Experimental setup with Swedish bands at Kiel Farm.

Picture 8. Setup with 50 x 50 mm mesh net in 2018/2019. Deployment the 4th of June 2018.

Picture 9. Set up with 100 x 100 mm mesh size trawl net in 2018/2019. Deployment the 4th of June 2018.



Picture 10. Set up with Swedish bands in 2018/2019. Deployment the 4th of June 2018.

3.1.3 *Kalmarsund (SWE): Setup for tests of different types of substrate*

The substrate test in Kalmarsund included tests of six different substrates: Swedish Bands, Fuzzy rope, smartfarm net with mesh size 150 x 150 mm, and trawl nets with different mesh sizes (50 x 50 mm, 80 x 80 mm, 100 x 100 mm, and 150 x 150 mm). Additionally, a depth study was carried out to test if vertical differences in food availability had any effect on mussel growth.

Nets with mesh sizes from 50 x 50 mm to 150 x 150 mm were made from trawl nets, whereas the net with mesh size 300 x 300 mm was a Smartfarm net with thicker rope. The smartfarm net and underwater sampling can be seen in Picture 11 and Picture 12. The surface view of the Byxelkrok farm is depicted in Picture 13.

Picture 11. Depth study reaching down to 13 m depth with Smartfarm net (mesh size 150 x 150 mm).

Picture 12. Mussel sampling in Byxelkrok. Distribution of mussel coverage is very inhomogeneous.

Picture 13. The Byxelkrok farm in Kalmarsund.

3.1.4 Coast of Kurzeme (LVA): Setup for tests of different types of substrate

Despite the fact, that there was no planned tests in 2017, preliminary results based on mussel samples from a rope deployed in May 2017 was included.

The growth and recruitment study with fuzzy ropes planned for 2017-2018 with four samplings were unfortunately reduced to only one sampling in 2017 due to loss of ropes caused by rough weather.

In 2018, the substrates (Swedish bands, net with mesh size 100 x 100 mm) mm were deployed too late due to a combination of delayed substrates and rough weather conditions, and unfortunately, the data from sampling are poor.

3.2. Sampling of mussel production

The sampling followed a BBG sampling instruction manual developed by Orbicon (BBG_Instructions GoA 3.3_Experimental manual). The aim of the sampling instructions is to standardize methodology of measuring the growth and production of mussels, to ensure compatibility of demonstration farms. Therefore, the production data is presented as weight (biomass) per m^2 substrate from each trawl test-net and from the Smartfarm Units.

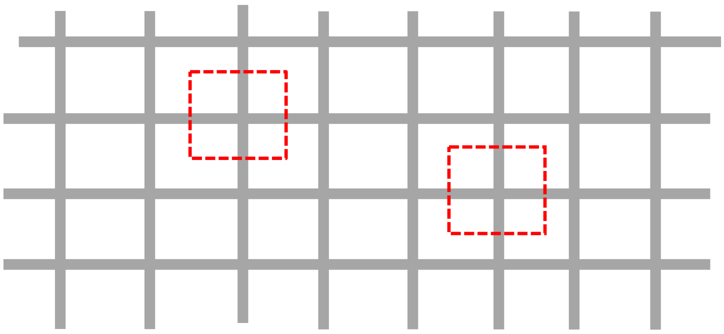


Figure 2. Schematic drawing of how the samples are removed (cut out) of the test nets. The squares measure 300 x 300 mm.

3.2.1 Sampling from Smartfarm- and trawl nets

The mussels were collected in 10 separate samples from six squares (quadrants) of 300x300 mm from random places on the substrate net (see Figure 3). No statistical difference between top- and bottom growth was found by the Musholm farm in 2016, and the sampling was therefore not specific to the depth. The sampling squares were marked with clothespins before sampling to indicate the area of sampling before mussel growth. Because mussels will have a greater density where the vertical and horizontal ropes intercept, the sampling square was located where it was not in contact with the edge of the sampled square. All mussels were carefully collected from the net. Alternatively, the squares was cut out and the mussels was collected in the laboratory. Because mussels lose water after sampling, the collected mussels were weighed just after sampling – the *fresh weight*. If the mussels were removed by cutting out the sampled section of the substrate, then the sampled mussels and net was weighed together and separately.

3.2.2 Sampling from Swedish bands

During each sampling procedure, one entire band of 4-6m or smaller pieces of bands was collected and depth, and the date and location was noted on the sample. Because mussels lose water after sampling, the collected Swedish bands with mussels were weighed just after sampling and again after separation of mussels from band, so that weight of mussels and band was noted separately.

For Swedish Bands, the weight per m^2 substrate is based on a standard production deployment of 2 bands per m^2, or 12 m per meter headrope i.e. biomass data is based on the weight measurements from Swedish Band substrates scaled up to biomass per m^2 or per meter headrope.

3.3. Growth and recruitment study

The growth and recruitment study was a part of an larger objective to provide a database of environmental quality in and around mussel farms to support a scientifically sound assessment of the environmental impacts of the existing operative mussel farms in the Baltic Sea. The study was carried out by the University of Utartu.

A standardized artificial substrate was used in key farms to experimentally evaluate the recruitment and growth of mussels in order to link broad patterns of oceanographic conditions to the net increment of mussel stock. When all these techniques are used interactively, the collated datasets enable placing the farm impacts into broader spatial and finer temporal scales and allow the PanBaltic assessment of farm potential and impacts. Here, the BBG monitoring data on the settlement and growth of mussels is reported for the Baltic Sea area.

Standardized methodology was used at all focus farms in order to make a proper comparison among the functionally different regions of the Baltic Sea. The experiment started in April 2017 (start of deployment) and finished in October 2018 (removal of last lines). Each experimental unit consisted of a 30 cm long fuzzy rope that was attached with two-three cable ties to a main line. The rope pieces were deployed at two depths: 2-3 m and 5-6 m (see Figure 2). Each depth level had three replicate rope pieces. In all areas, the main line had a reasonably strong anchor to keep the line on place. The other end had a small floater keeping the line in an upward position. Each farm had altogether four of these lines. The setup for the Musholm farm is depicted in Picture 14.

In each sampling occasion (altogether four sampling events), one line was taken in for analyses. Each rope piece was gently removed from the main line and packed separately into the plastic bag, and labelled with area, time, and depth level. The samples were kept at -20C.

Delivery of samples to UTARTU took place once a year. In the UTARTU laboratory, all mussels were individually counted, measured, and weighed. Based on this data, the total growth yield and the length frequency distribution of mussels were estimated.

Picture 14. Ropes with triplicate pieces of fuzzy rope at 2-3m and at 5-6m ready to deploy at the Musholm site. The ropes were stretched with large shackles in the bottom.

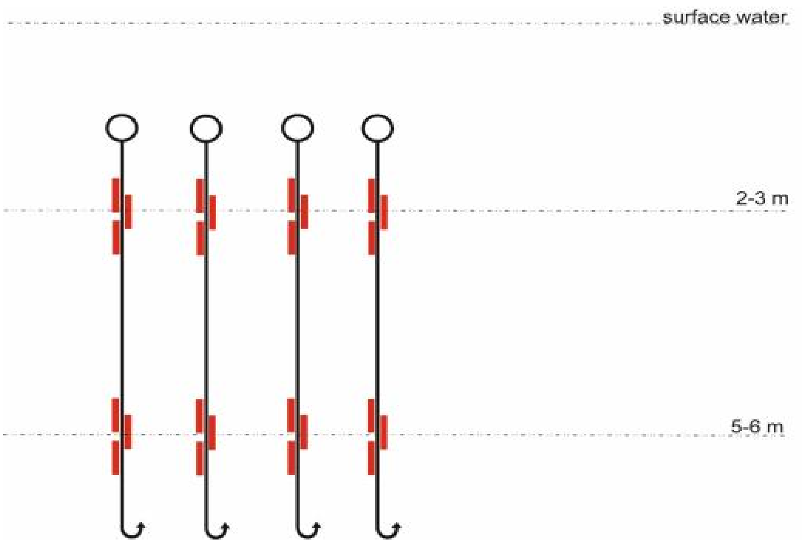


Figure 3. Schematic diagram of the experimental units.

3.4. *Procedures in the Laboratory*

The collected mussels were weighed just after sampling, and again after being frozen, to estimate the loss of water during the freezing/draining process, which amounted to approx. 30%. The weight of the mussels before freezing, the frozen weight, the drained weight of the mussels, and eventually the weight of the substrate separated from the mussels were noted for later calculations. The wet weight (WW) of the mussels is calculated as:

$$WW = WW_D + (WW_{FS} - WW_D - W_S)$$

WW_D represent the drained weight of mussels, WW_{FS} is weight of frozen sample including the substrate, and W_S is the weight of substrate. Furthermore, the size of the substrates was measured (see Picture 16) in order to estimate the biomass per area of substrate.

Picture 15. Substrates are weighed separately from mussels.

Picture 16. Substrates are measured in order to estimate the biomass per area.

The mussel lengths were measured from subsamples of 80 - 150 mussels using an electronic pair of calipers (0.1 mm precision). The shell length was measured as the maximum length from the umbo (see Figure 4). An example of the work in progress can be seen in Picture 17 and Picture 18.

The time spent on each sample, when the procedures were up and running was approx. 0.5 hours.

Figure 4. Showing the maximum length from the umbo.

Picture 17. An example of a sample of small mussels from Kalmar Strait.

Picture 18. Working process with an electronic caliper, measuring very small mussel lengths.

3.5. *Calculation procedures*

To estimate the biomass on the trawl nets per meter headrope, the biomass from the weight results excl. weight of substrate was calculated in g cm^{-2} of net substrate and scaled up to kg m^{-2} and finally into kg m^{-1} of headrope by multiplying by 3 m^2 for nets and by 12 m for Swedish bands and Fuzzy rope.

Example of calculation of biomass on nets:

In one sample with a substrate area of 637 cm^2 the mussels weighed 40.43 g. This equals 40.43g/637 cm^2 = 0.063 g cm^{-2}. This is scaled up to kg m^{-2} by multiplying by 10 000 cm^2 m^{-2} and dividing with 1000 g kg^{-1}. (0.063 g cm^{-2} x 10000 cm^2 m^{-2})/1000 g kg^{-1} = 0.63 kg m^{-2}. To get a value of kg per meter headrope, this was multiplied with 3 m^2 m^{-1} headrope for nets and 12 m m^{-1} headrope for Swedish bands and Fuzzy ropes. Biomass per meter of headrope: 0.63 kg m^{-2} * 3 m^2 = 1.90 kg m^{-1}.

The assumption of 12 meter of Swedish band per meter of headrope is based on experience from commercial production of mussels using Swedish bands with 2400 meter of bands for every 200 m of rope.

4. Results Musholm

Tests with different substrates were carried out in the Musholm area from 2016-2019. For every year, the results from mussel growth on different substrate types are described with respect to growth in length and weight. Finally, an estimate of the biomass production potential for a production unit of 120 m tube or 200 m head rope is estimated for every substrate and year.

4.1.1 Results Musholm 2016/2017

The following changes in relation to the original sampling plan for 2016 have been carried out; the sampling program began in September and ended in December. Due to very little biomass on substrates, the harvest planned for November was cancelled and all the Smartfarm nets and trawl nets were left in the water until spring 2017. One of the PE test pipes with two test nets (mesh size: 78 mm and 80 mm) was lost between November and December, and therefore, the sample measurements for December only include trawl nets with mesh sizes 50 mm and 150 mm. Because the mesh sizes 78 mm and 80 mm were so close to each other, they were both treated as mesh size 80 mm in the laboratory. By mid-February 2017, there were no more mussels on any of the trawl or Smartfarm nets, and it is assumed that they have been eaten by Eider ducks.

In September, the size of the mussels ranged from 1-8 mm, and mean lengths (approx. 3 mm) were similar on all tested nets (Figure 5). Overall, there was an increase in length from September to November. However, the largest increase in length happened between November and December (Figure 3). The average size of the mussels grown on Smartfarm nets only increased slightly from September to December, whereas the mussels grown on trawl nets with different mesh sizes increased their length by nearly a factor-two (on mesh size = 150 mm) between November and December.

The distribution of mussel length from September to December changed from a narrow peak with high frequency of mussels from 1-8 mm on both Trawl nets (smaller mesh sizes) and Smartfarm nets in September, to a broader size distribution in December peaking in the range of 12–19 mm for mussels grown on trawl nets, and 6-9 mm for mussels grown on Smartfarm nets. The size of mussels on both the trawl and Smartfarm substrates showed a greater increase in size from November to December, compared with the size increase from September to November (see Figure 4).

To compare the average length of mussels grown on trawl nets with mussels grown on Smartfarm nets, a T-test was carried out on average length values from the trawl nets and from SmartFarm nets. Results showed statistical difference between mean values for each group in September (T-test, $p < 0.05$, N=200), November (T-test: $p<0,001$, N=200) and December (T-test: $p<0,001$, N=200) (see Figure 5 and Figure 6).

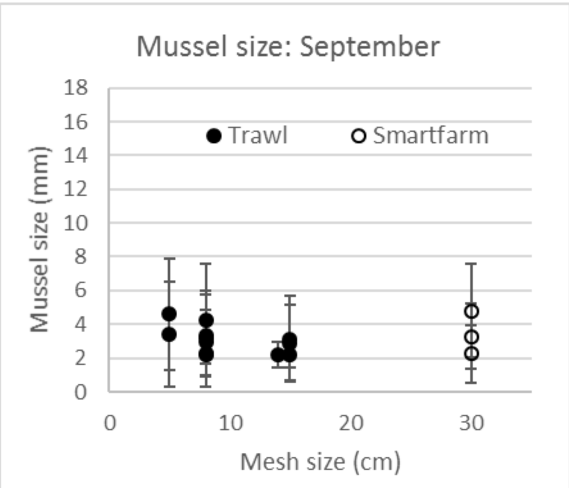
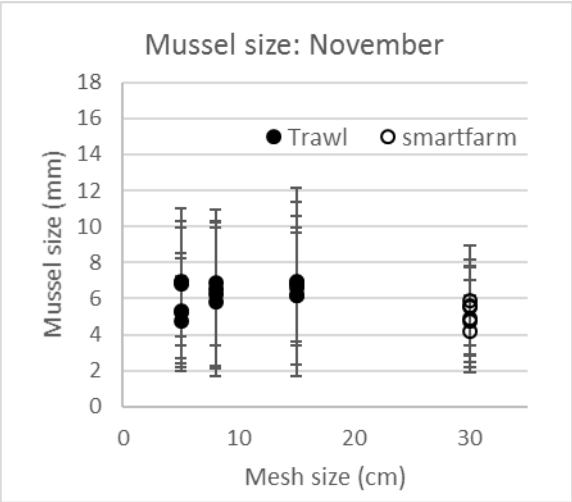


Figure 5.The graph shows average mussel length measured on 100 mussels from each sample. The overall number of mussels measured in September was 1500 mussels, November 2400 mussels and December 800. The error bars show ± standard deviations from average values.


Mussel size: November
Trawl
smartfarm
Mussel size (mm)
Mesh size (cm)
0
2
4
6
8
10
12
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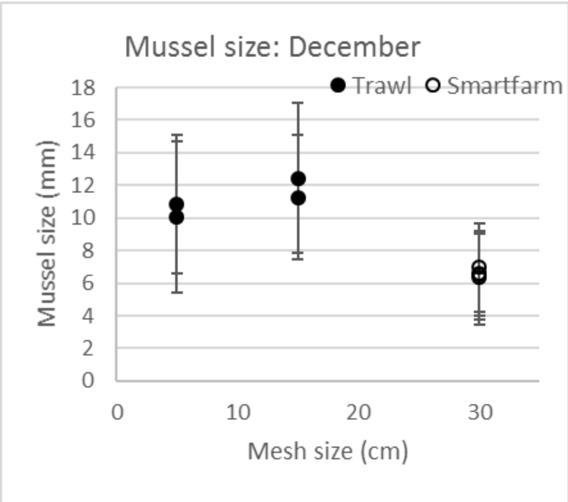
20
30


Mussel size: December
Trawl
Smartfarm
Mussel size (mm)
Mesh size (cm)
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2
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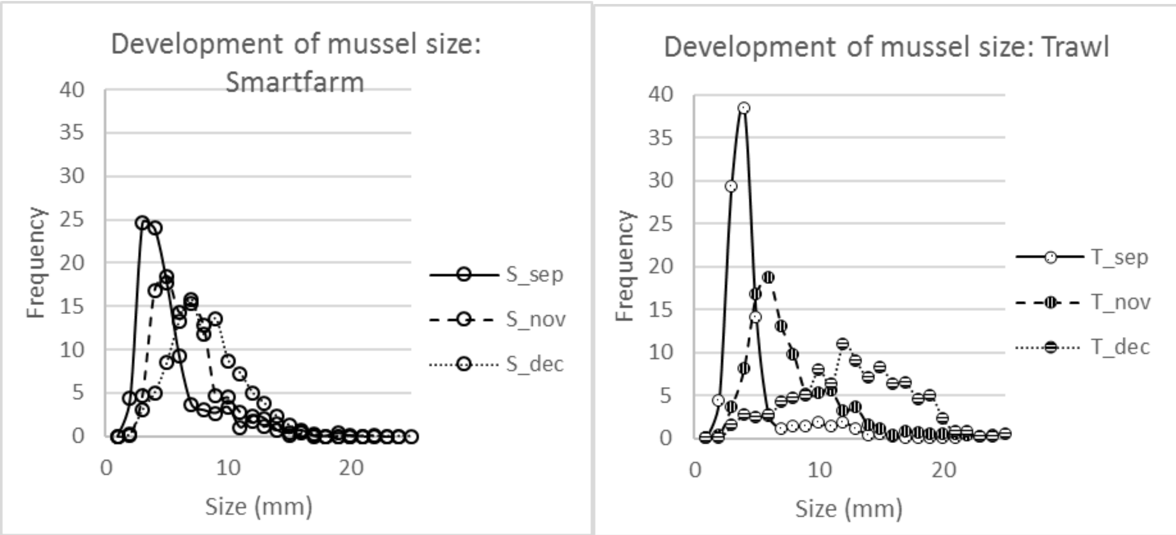

Figure 6. The graphs show the development and distribution of mussel size from September to December for mussels grown on Trawl nets (left graph) and for mussels grown on Smartfarm nets (right graph).

Overall, the average weight of the mussels on the Trawl and Smartfarm nets, measured by weighing a subsample of 100 mussels from each substrate, increased from September to December, and most noticeably during the last month (Figure 3). Mussels grown on trawl nets increased their average weight per month by a factor-three, whereas the mussels grown on Smartfarm nets only increased their average weight per month by approx. 60 % (see Figure 5). Overall, the total weight (biomass) of mussels on Smartfarm nets decreased from September to December (see Figure 6), whereas the overall biomass on trawl nets continued to increase during the study period (September-December) (see Figure 6).

Picture 19. Example of homogeneity in mussel size. The picture was taken in December 2016.

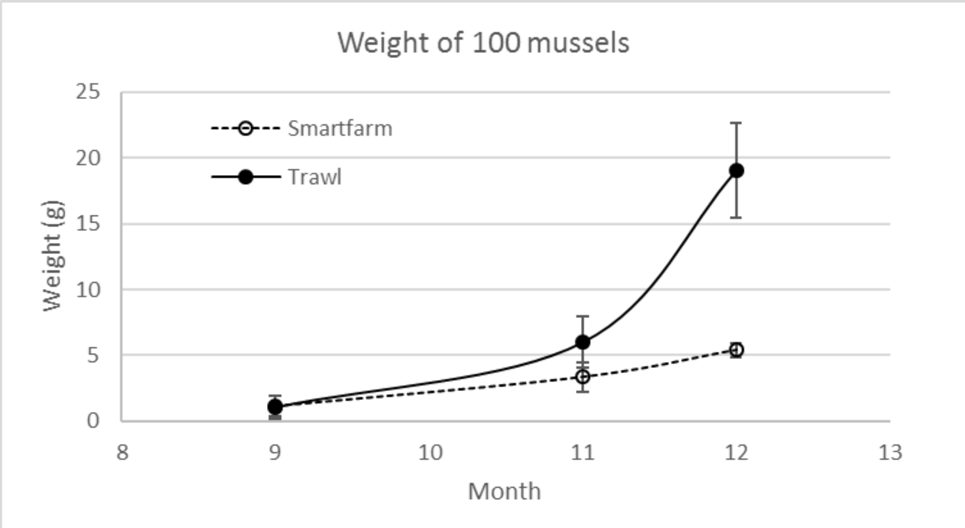

Figure 7. The graph shows the development of the average weight of 100 mussels on Trawl nets and Smartfarm nets from September to December. The vertical bars show ± standard deviations from average values.

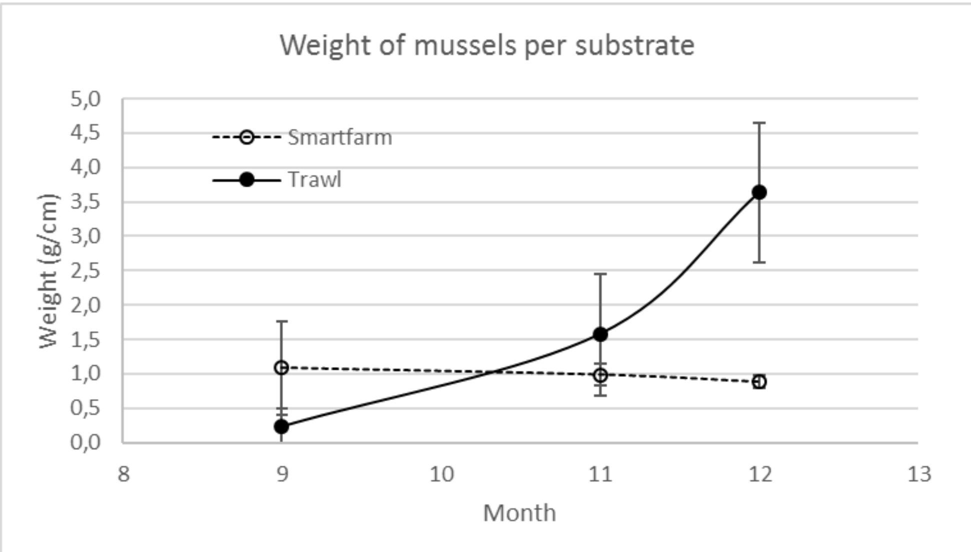

Figure 8. The graph shows the weight of mussels (g) standardized to weight of mussels per cm substrate line for mussels grown on Smartfarm nets and for mussels grown on trawl nets. The vertical bars represent the ± standard deviations from average values.

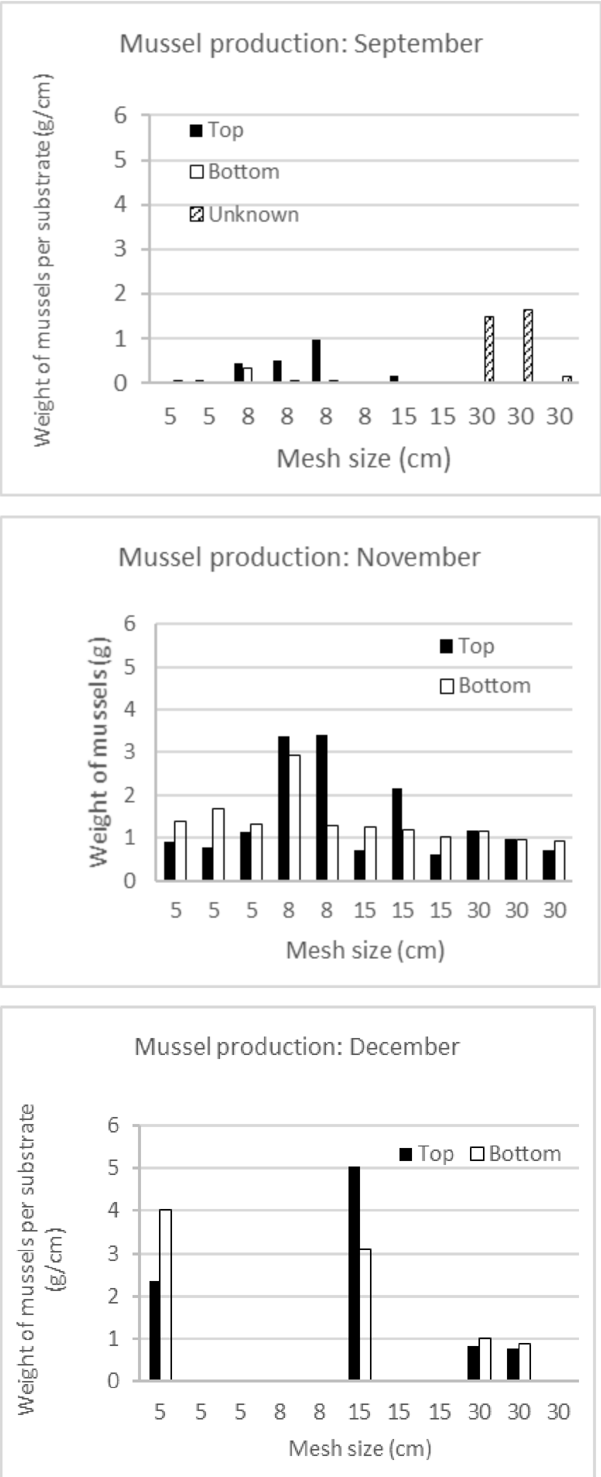

Figure 9. The graphs show production measured as weight of mussels per length (cm) of substrate from trawl nets with mesh sizes: 50, 80, 150 mm and the Smartfarm net with mesh size: 300 mm. Filled bars indicate samples taken from the top of nets and open bars indicate samples taken from the bottom of nets. Samples noted "unknown" means that it is unknown if samples are from the top or bottom. There is no significant statistical difference between the weight per length of substrate in samples taken from the top and bottom of the nets; T-test (P > 0.05, n=22) from November.

The highest biomass per length of substrate varied between different mesh sizes in different months. For September, Smartfarm nets (mesh size 300 mm) had the highest biomass indicating the largest settlement of mussel spat. In November, the highest biomass was found on Trawl nets with mesh size 80 mm, (see Figure 7). In December, Trawl nets with mesh size 150 mm showed the highest biomass. However, results from the mesh size 80 mm were not available and may have shown even higher biomass if earlier tendencies in biomass growth on this substrate continued.

Full-scale estimates of the production of mussels on all the substrates (mesh size 50 mm, 150 mm and 300 mm) in December, upscaled to production units that are 100 m long with 3 meter deep vertical panels, would result in a mussel production of approximately 3.7 tons (trawl - mesh size 150 mm), 1.95 tons (trawl - mesh size 50 mm), and 216 kg (Smartfarm – mesh size 300 mm) - see Table 1.

Table 4. Full scale estimates of the production (biomass) of mussels on all the substrates (mesh size 50 mm, 150 mm and 300 mm) in December 2016. The floating tubes were 100 m long with three meter deep vertical panels.

Mesh size	**Biomass December**
50 mm - trawl	1.95 t
80 mm - trawl	No data – damaged production units
150 mm - trawl	3.7 t
300 mm - Smartfarm	0.22 t

Comparisons of recruitment and growth on different Trawl nets with mesh sizes 50, 80, and 150 mm and Smartfarm net with mesh size 300 mm showed initially, that Smartfarm nets with a large mesh size had a slightly greater recruitment of small mussels than trawl nets with smaller mesh sizes. However, results over time indicated that both the average size of mussels and the biomass on the nets with smaller mesh sizes increased at a considerably better rate than the average size of mussels and biomass on the Smartfarm nets. In fact, the total biomass of mussels on the Smartfarm nets remained more or less the same from September to December, despite a five-fold increase in average mussel size, indicating a large decrease in the overall abundance of mussels on the Smartfarm nets.

4.1.2 Musholm 2017/2018

Changes of the original sampling plan for 2017 due to predation from eider:

After an initial period of testing offshore musselproduction near Musholm, the test units were moved north into the Kalundborg Fjord due to heavy predation by Eider ducks, which consumed most of the mussel biomass over two days in late August. During the transfer, mussels on the substrates were lost due to abrasive movements between the units contact to the seabed in shallow areas. However, because of mussel loss during the movement of units, estimations of the total biomass and production potential on each substrate was undertaken using growth parameters with the biomass estimates from August before the eider ducks foraged on the production systems.

The sampling program for 2017/2018 started in August 2017 and ended in March 2018, and included three sampling occasions.

The Smartfarm systems in Musholm were used to test, if the standard mesh sizes of these units are indeed optimal for a maximized biomass production. We therefore checked if smaller mesh sizes perform better with respect to increase in biomass of small mussels. Particularly as mussel growth at this site is relatively slow, smaller meshes provide more substrate for smaller mussels. Preliminary tests in 2016 were used to design substrate tests in 2017 and 2018.

The size distribution of mussel lengths from August 2017 to March 2018 changed from a small variation in shell length to a high variation in shell length as the mussels grow larger (Figure 10). In contrast, the size distribution of mussels from the Swedish Band already showed a broader pattern with more mussels of lengths up to 12 mm in August. The broad pattern continued in November 2017 and March 2018, where the peak in March represented a majority of mussels within the size range 24-27 mm, whereas the mussels from trawl nets and Smartfarm nets in March peaked within the size range 12-22 mm. This indicates, that the Swedish bands provided a substrate which resulted in larger mussels at the end of the growing season, as compared to the net substrates.

The size of mussels on both the trawl, Smartfarm, and Swedish band substrates showed a linear increase in size from August 2017 to March 2018 (Figure 11). By 272 days, the mussels from nets had increased their average lengths with a factor-three, and the mussels from the Swedish bands with a factor of more than four.

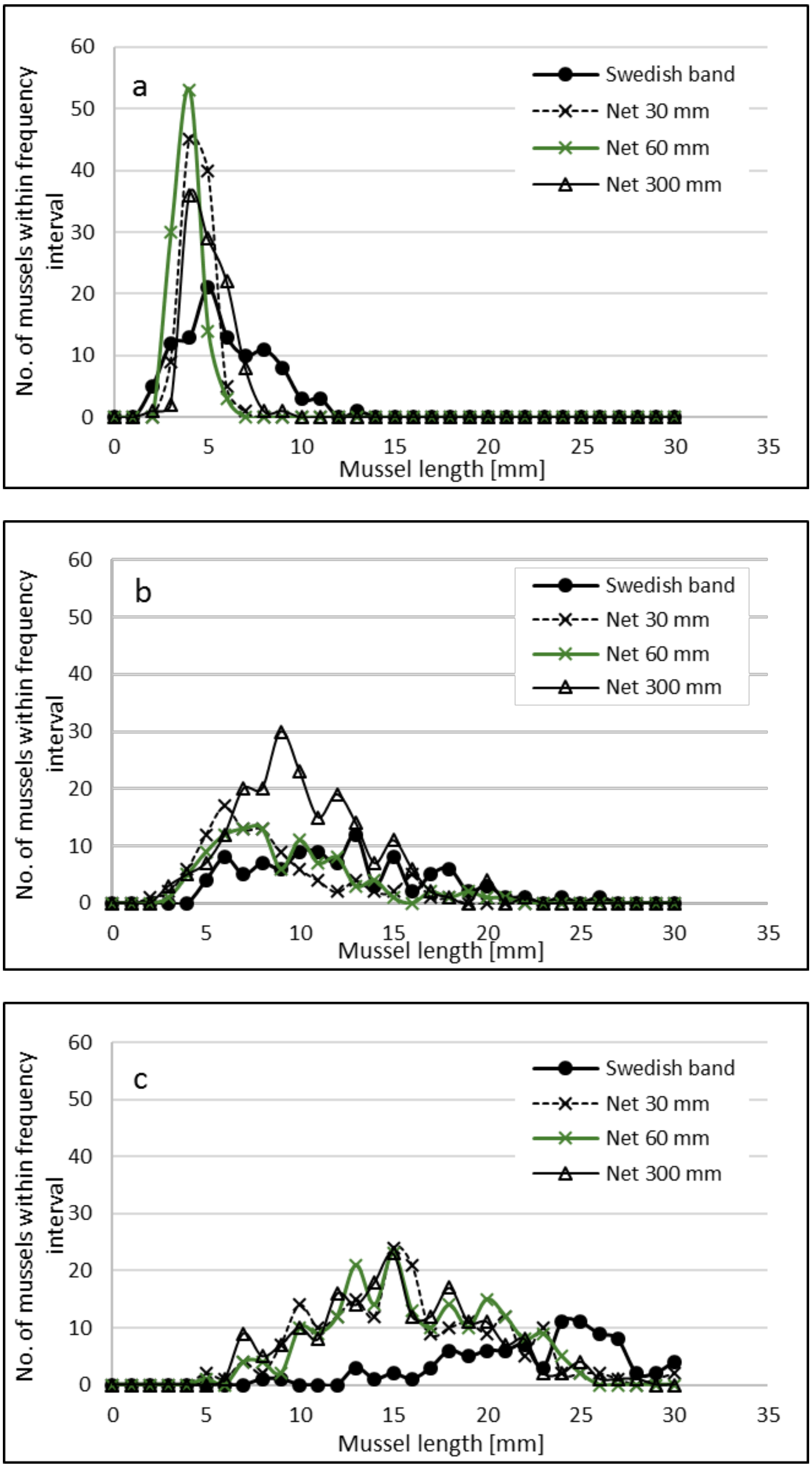

Figure 10. The graph shows size distribution of mussels from four different substrates from a) 22-08-2017, b) 08-11-2017, and c) 19-03-2018. The mussels have a small variation in shell-length in August, and the variation is increased as the mussels grow larger

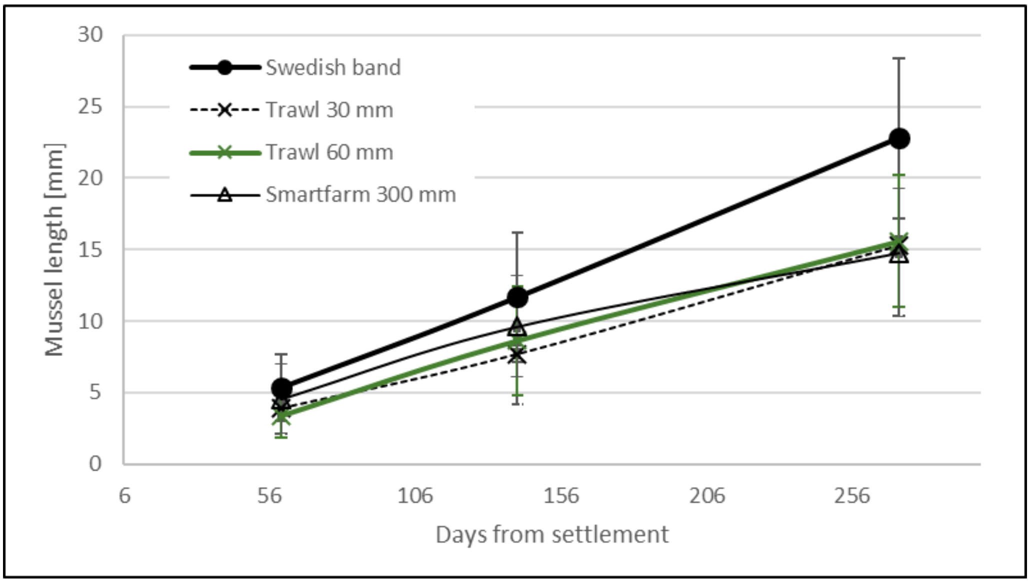

Figure 11. Growth in mussel length (mm) from August 2017 to March 2018 for mussels from four different substrates: Swedish band, trawl (30 mm), trawl 60 (mm) and Smartfarm (300 mm). Symbols show the average values calculated from sample sizes of 100-500 mussels for each substrate. Vertical bars show the ± standard deviation from average.

The length of mussels from the Swedish bands, collected 19th of March 2018, was on average 1.5 times longer than the mussels grown on nets. The difference in mussel size according to substrate was first tested using a one-way ANOVA. Results indicated that there was a significant difference between mussel size growing on different substrates ($F(3,396)=20.8$, $p<0.0001$). To examine where these differences were, a t-test was carried out using average length values for each triplicate between mussels from different substrates. Results showed that mussels grown on Swedish Bands were significantly larger than mussels grown on all the trawl and Smartfarm nets (Table 3.1.1 and Figure 11).

There was no significant difference in the size of mussels grown on nets with mesh size 30 x 30 mm and 60 x 60 mm. Mussels grown on Smartfarm nets with mesh size 300 x 300 mm were significantly larger than mussels grown on nets with mesh size 30 x 30 mm and 60 x 60 mm (Table 5).

Table 5. P-values from t-tests carried out to compare mussel sizes from different substrates. Highly significant values (<0.0001) are indicated by ** and significant values at 0.05 level is indicated by *.

Substrates	P value
Swedish Band versus 60 x 60 mm	< 0.0001**
Swedish Band versus 30 x 30 mm	< 0.0001**
Swedish Band versus 300 x 300 mm	<0.0001**
60 x 60 mm versus 30 x 30 mm	0,078
60 x 60 mm versus 300 x 300 mm	0,034*
30 x 30 mm versus 300 x 300 mm	< 0.0001**

The growth rate of mussels from different substrates is shown in Table 6. As mussel growth is only available during a season, the growth can be modelled as a linear growth. Growth rates were estimated from the linear growth pattern seen in Figure 11. Here, the growth rate of mussels from the Swedish band was noticeably higher (0.084 mm day^{-1}) than the growth rate of mussels from all net substrates (0.056 – 0.058 mm day^{-1}). Not only was the settling earlier on the Swedish bands, but the mussels also grew faster on this substrate.

In general, the larger mussels collected on Swedish bands appeared to be a result of a better support for the settling in June 2017 of mussel larvae. This presented an opportunity for the continual occurrence and growth of these larger mussels throughout the sampling period.

Table 6. Growth rate of mussels estimated derived from the relation between mussel length and days after settling. The period for growth was from the 22nd of August 2017 to the 19th of March 2018.

Type	Mesh size	Growth rate (mm day^{-1})	R^2
Swedish Bands	0	0.084	0.99
Trawl	30	0.056	0.99
Trawl	60	0.058	0.99
Smartfarm	300	0.058	0.92
Average		0.064	

Eider-predation of mussels had severe impact on the mussel production at Musholm in 2017. The Musholm Island, close to the area with mussel production, is frequently visited by eider ducks from August/September to February of each year, and the mussels are an important part of their diet.

Picture 20. Test unit on Musholm with resting eiders in the Great Belt in July 2017.

The biomass per area substrate was measured in August 2017, November 2017, and in March 2018. In August, biomass per m^2 substrate area ranged between 1.1-3.9 kg m^{-2} per substrate and was considerably higher on the net with the smallest mesh size (30 mm) in comparison with the nets with mesh sizes of 60 mm and 300 mm (Smartfarm net) and the Swedish Bands (1.2-1.9 kg m^{-2}) (see Table 7and Figure 12).

During the period from August to November, the biomass on all the substrates either remained the same or decreased slightly (biomass between 0.9-2.1 kg m^{-2}). This may be due to eider duck predation directly on the production systems.

To estimate what the biomass on each substrate might have been in November, a potential biomass was calculated by multiplying the measured biomass per area (kg m^{-2}) on each substrate with the average increase in weight of 500 mussels from August to November (weight gain factor = 11.59). This value may be an overestimation as there was few mussels and therefore very little food limitation. The value was derived by dividing the weight of a subsample of mussels in November by the weight of a subsample of mussels in August (Table 7). Results indicated that there would have been a biomass of between 4.8-10.7 kg m^{-2} on the different substrates in November, had the eider ducks not eaten nearly all the mussels.

An estimate of the biomass loss due to eider ducks was calculated by subtracting the actual biomass per area measured in November from the potential biomass estimated for November. The estimated biomass of mussels lost due to predation by eiders ranged from 90 to 96 % (Table 7).

Potential biomass values were based on the relation between the estimated biomass per area substrate (kg m^{-2}) and the average increase in weight of 500 mussels from August to November: Potential biomass in November = weight August (kg m^{-2}) * average weight gain factor (Aug-Nov). Biomass loss due to Eider ducks was calculated as the percentage difference between potential biomass and measured biomass in November. Biomass for Swedish Bands is based on a standard production deployment of 2 bands per m^{-2} i.e. biomass data is based on the weight measurements from Swedish Band substrates scaled up to a substrate 2 meters in length.

BIOMASS	Biomass 22-08-2017 (kg m^{-2})	Biomass 08-11-2017 (kg m^{-2})	Biomass 19-03-2018 (kg m^{-2})	Potential Biomass Nov. 2017 (kg m^{-2})	Biomass loss due to Eider ducks
***Swedish band**	1.50	1.67	-	16.8	90 %
Trawl 30 mm	3.79	2.09	10.68	43.88	95 %
Trawl 60 mm	1.19	0.94	9.77	13.84	93 %
Smartfarm 300 mm	1.92	0.96	4.76	22.19	96 %

Table 7. Mussel biomass and potential mussel biomass per substrate area (kg m^{-2}) measured for the different substrate types.

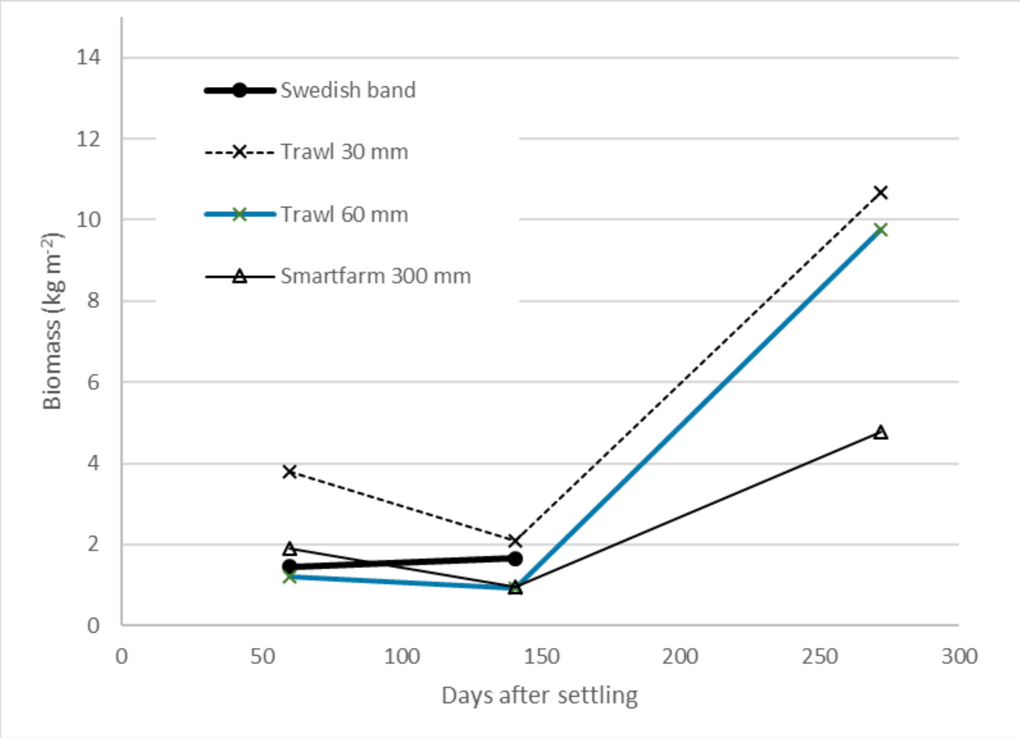

Figure 12. Biomass per area substrate (kg m-2) shown for Swedish band, trawl net with mesh size 30 x 30 mm, trawl net with mesh size 60 x 60 mm, and Smartfarm nets with mesh size 300 x 300 mm. The last sampling was 272 days after settling.

To avoid further eider duck predation, all the substrate units were moved north into the Kalundborg Fjord. Unfortunately, the movement of mussels from one location to another caused damage to the Swedish band that was sampled in March 2018, and mussels were only found on the metal shackle that was used to keep the substrate vertical in the water. Hence, no biomass per area for Swedish Bands could be measured in March 2018.

The estimated biomass on the net substrates in March 2017 showed the highest amount of biomass per m^2 on the nets with 30 mm mesh size (10.7 kg m^{-2}) and 60 mm mesh size (9.8 kg m^{-2}). The biomass on the Smartfarm net of 300 mm mesh size was 4.8 kg m^{-2}. Estimates of full-scale production of mussels on all the substrates (mesh size 30 mm, 60 mm and 300 mm) based on biomass estimates in March, upscaled to production units that are 126 m long with 3 meters deep vertical panels, resulted in a production of 4, 3.7, and 1.8 tons, respectively. The low biomass on substrates was due to eider duck predation on the mussels. An upscaling of the potential biomass would have been in the order of 17, 5 and 8 tons respectively.

The biomass for Swedish bands measured in November 2017 allowed the assessment that the Swedish band biomass was similar to the biomass on the nets. A full production system with 200 m rope and bands going 6 meter deep with 10 kg m^{-2}, would then amount to 12 tons.

4.1.3 *Musholm 2018/2019*

The size distribution of mussels in the Great Belt showed low variation with a narrow peak of 60 out of 100 mussels, with a length of 4 mm in August 2018 - see Figure 13. As is normal for a mussel size distribution, the variation increased with time. In February 2019, mussel sizes ranged from 5-17 mm with an average of 10 mm (Figure 13). The growth rate, estimated as the slope on the average development of mussel lengths over time based on the three samplings, results in 0.03 mm day^{-1} (Y=0.03x +b, R^2 = 0.93). There was a statistical significant difference in lengths of mussels with mussels from trawl nets being larger than mussels from Swedish bands sampled in February 2019 ($F(3,89)=4.02$, $p<0.05$), and the biomass values are therefore plotted for net and Swedish bands respectively

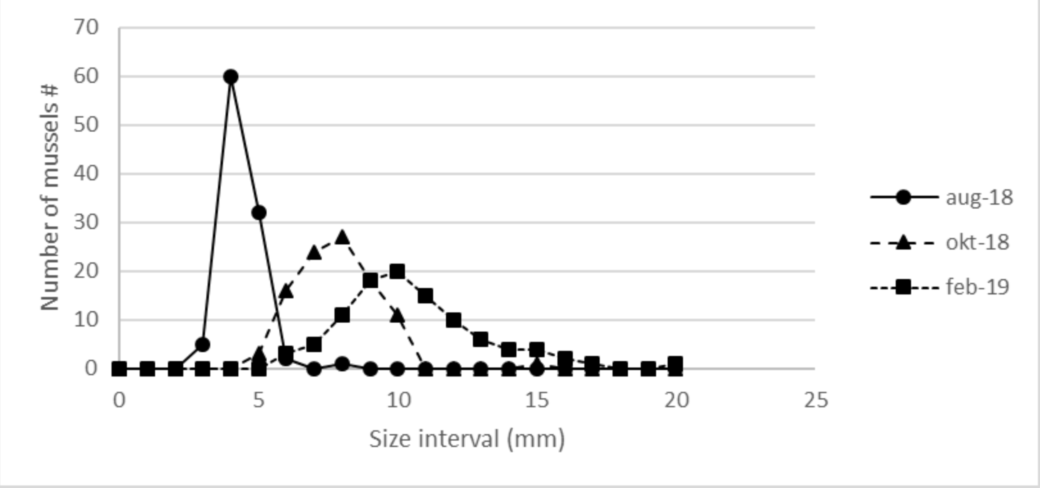

Figure 13 Development in mussel length from August 2018 to February 2019. Each size distribution represents an average of 200-1200 mussel lengths from different substrates.

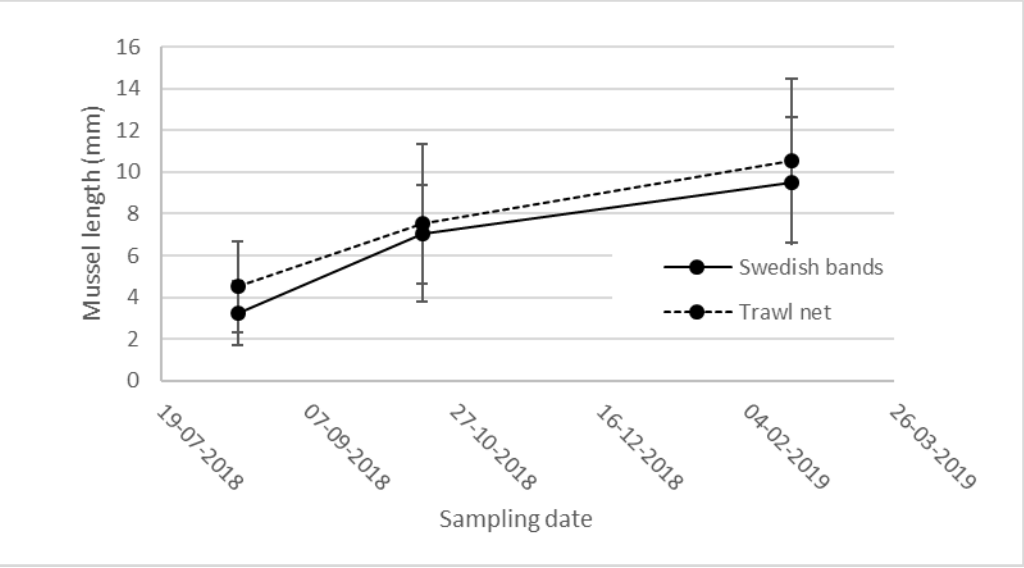

Figure 14. Development in mussel length on Swedish bands and nets from August 2018 to February 2019 in Musholm. The standard deviation is shown with vertical error bars, and show the variation within the entire mussel sample of 100-600 mussels.

The development of biomass on trawl net and on Swedish bands was calculated as the average weight of mussel biomass per meter of headrope. For each meter of headrope, this included 3 m^2 net and 12 m of Swedish bands. The biomass on the Swedish bands increased from August to October 2018 and decreased again to the initial amount of biomass from October 2018 to February 2019 (see Table 8 and Figure 15). Hence, there was no biomass gain from August 2018 to February 2019. However, the biomass on the trawl net increased during this period from 2-7 kg per meter head rope.

Scaling up the numbers to a full-scale farm unit, 126 m of net would equal 7 kg m^{-2} * 126 m = 882 kg after one growth season from June to February the following year. A farm with Swedish bands would equal: 2 kg m^{-1} * 200 m = 400 kg per production unit.

The settling on Swedish bands and trawl net was in general poor compared to other years, and there was, for some reason, a better settling on the ropes and structures on and connected to the fish cage (see Picture 21).

Table 8. Weight of mussel biomass per m^2 from nets and per m from Swedish bands and for every meter of headrope including 3 m^2 for nets and 12 m for Swedish bands.

Substrate type	Sampling date	Weight of mussels (kg) per m^2 or m	Weight (kg) per m headrope
Swedish bands (m)	14-08-2018	0.18 ± 0.02	2.20 ± 0.23
Trawl net (m^2)	14-08-2018	0.64 ± 0.64	1.91 ± 0.23
Swedish bands (m)	16-10-2018	0.33 ±	3.92 ±
Trawl net (m^2)	16-10-2018	1.87 ± 0.53	5.61 ± 1.59
Swedish bands (m)	19-02-2019	0.16 ± 0.09	1.96 ± 1.14
Trawl net (m^2)	19-02-2019	2.36 ± 0.76	7.07 ± 2.27

Picture 21. Mussels settled on the rope that holds the net instead of settling on the net. Musholm October 2018.

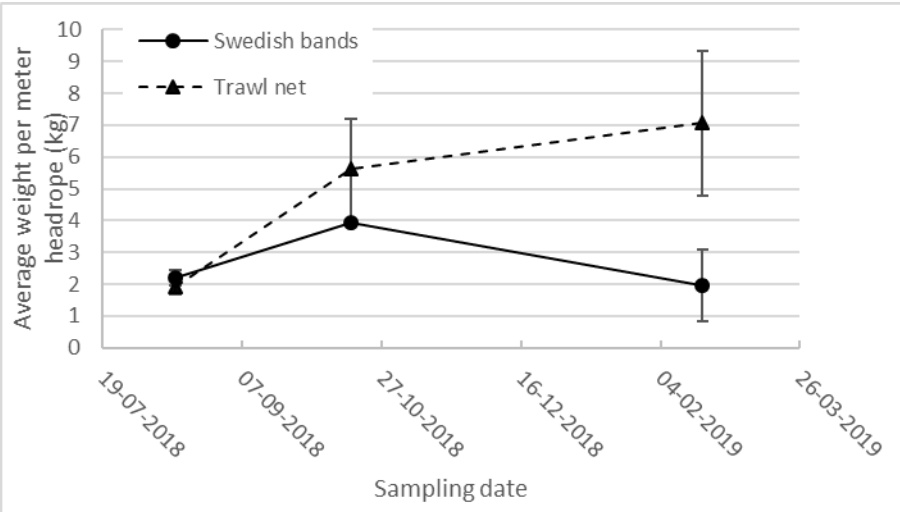

Figure 15. Development of biomass per meter of headrope for Swedish bands and for trawl net in Musholm. For net, each meter of headrope includes three m^2. For Swedish bands, each meter of headrope includes 12 m.

Comparison of mussel growth at Musholm with other Danish areas

The mussel growth in the Great Belt and Kalundborg is a factor 10 lower than mussel growth in the same area and other marine areas within Danish Waters in other investigations (see Table 9), despite the impressive settlement of small mussels (see Picture 22). The average mussel growth from August to November in this investigation was 0.064 mm day^{-1} (see Table 6), whereas growth rates of mussels in earlier studies from the Great Belt showed growth rates from 0.13 to 0.19 for juvenile mussels (see Table 9). The low estimated growth rates observed at the Musholm site is probably an artifact of size-selective predation by Eider ducks. Eiders are very common in the Great Belt area, and observed predation by eiders at the study site, also indicated by the considerable loss of mussels on the substrates, may have led to the low observed biomass. Because eiders prefer preying on the largest mussels, this would affect estimates of growth rates negatively, as the removal of the largest mussels decreases the average length of the remaining mussels, which is used to estimate the change in length per day (growth rate) of the mussel population over time. Consequently, predation by Eider ducks continuously taking the largest mussels from the substrates will result in a low biomass and low growth rate estimates.

Picture 22. Trawl net with mussels from August 22nd 2017 showing good settling of mussels in Musholm.

Table 9. Mussel growth measured in length per day (mm d^{-1}) for mussels grown in different Danish marine areas. Reference for the study is given under Location. Dark grey indicates mussel growth for larvae and spat and light grey indicates mussel growth for a whole season including winter.

Location	Production system	Growth in length (mm day^{-1})	Mussel length (mm)	Season of year	No. Of days with growth
As Vig (outer Horsens Fjord) (KOMBI 2015)	Smart Farm	0.10	Juveniles (1.1 – 10.7)	Jul-Oct (2012)	96
Sælkrogen (Horsens Fjord) (Information from Mads Van Deurs)	Smart Farm	0.138	Juveniles (1.2 – 13.8)	Jul-Okt (2012)	91
Great Belt – near Kerteminde (Information from Mads Van Deurs)	Smart Farm	0.131	Juveniles (4.4 – 14.4)	Sep-Nov (2010)	76
Great Belt – near Kerteminde (Daniel Pleissner et al. Poster presentation)	Linemussels in socks	0.138	Juveniles (22 - 32)	Aug-Oct (2010)	72
Great Belt – Stavreshoved - 1 (MarBioShell Project: Riisgaard et al. 2012)	Linemussels in ”net-bags”	0.16 (0.12-0.18)	Juveniles (18.6-29.2)	Sep-Oct (2009)	51
Great belt – Stavreshoved - 2 (MarBioShell Project: Riisgaard et al. 2012)	Linemussels in ”net-bags”	0.19 (0.13-0.26)	Juveniles (15.3-25.1)	May-Aug (2009)	69
Limfjorden (Daniel Pleissner et al. Poster presentation)	Linemussels in socks	0.22	Juveniles (22 - 34)	Aug-Sept (2010)	55
Limfjorden (Løgster Bredning) (MarBioShell Project: Riisgaard et al. 2012)	Linemussels in ”net-bags”	0.33 (0.3–0.38)	Juveniles (16.5-25.3)	Aug-Oct (2009)	22
Limfjorden (Skive Fjord) (MarBioShell Project: Riisgaard et al. 2012)	Linemussels in ”net-bags”	0.30 (0.27-0.31)	Yngel (16.5-25.3)	Aug-Oct (2009)	22

5. Results Kiel

5.1.1 2017/2018

The size distribution of mussel lengths from June 2017 to January 2018 changed from a narrow range of lengths (typically 0-1 mm on both nets and Swedish Bands) just after settling in late June, to a broader size distribution in August 2017 and January the following year (Figure 16).

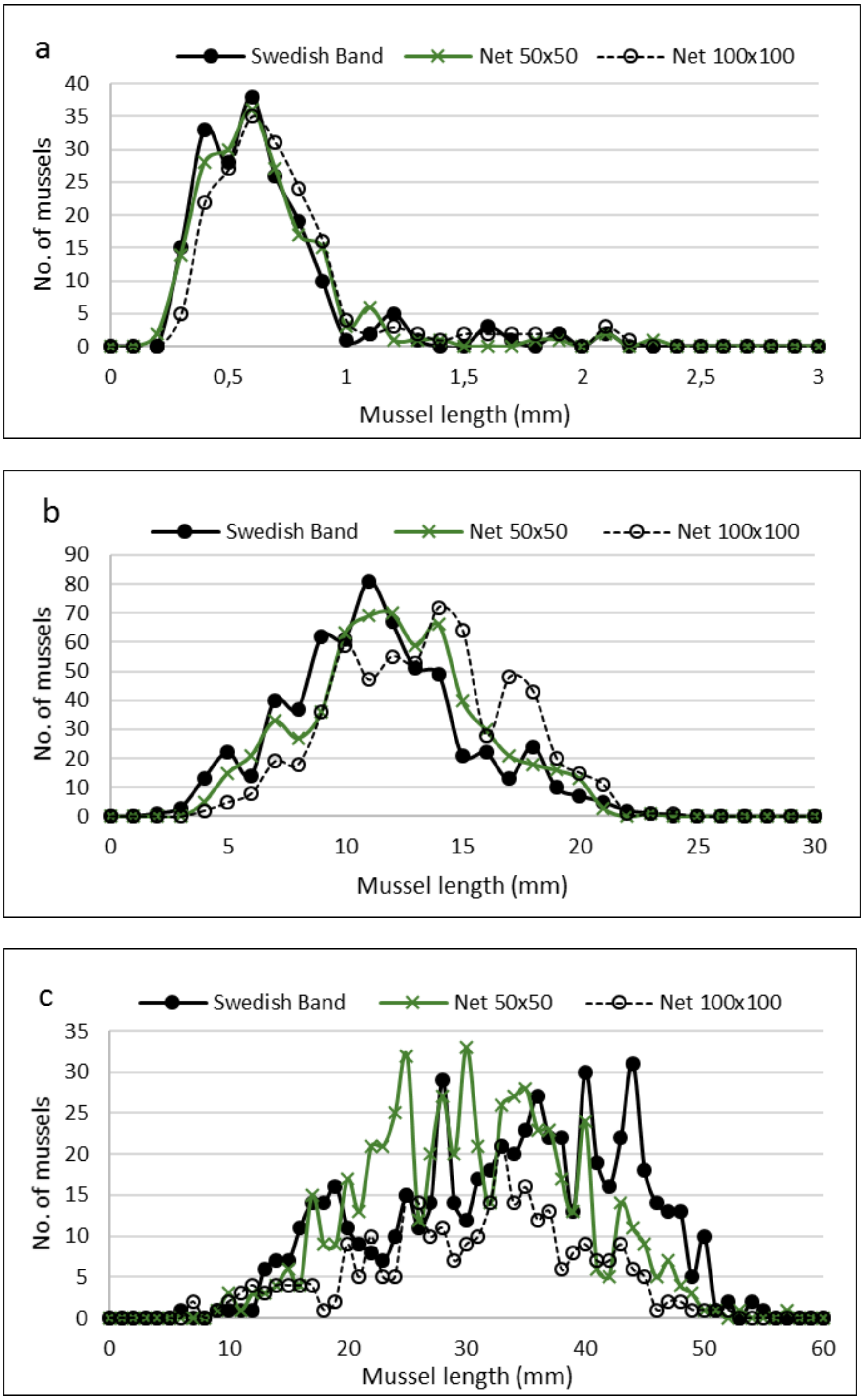

Figure 16. Size distribution for mussels on different substrates from three different sampling dates in Kiel Bay: a) 27.06.2017. b) 14.08.2017, c) 17.01.2018

The size of mussels on nets and Swedish Band substrates increased between the 26th of June and the 14th of August, whereas the increase was less in the time period between the 14th of August and the 17th of January the following year (see Figure 17). During the growth period from August to January (app. 157 days), the mussels had increased their lengths by a factor of three. Mean length values from the final sampling period in January were 34.3 mm for mussels from Swedish Bands, and 30 – 31.4 mm for mussels from the net substrates (Figure 17).

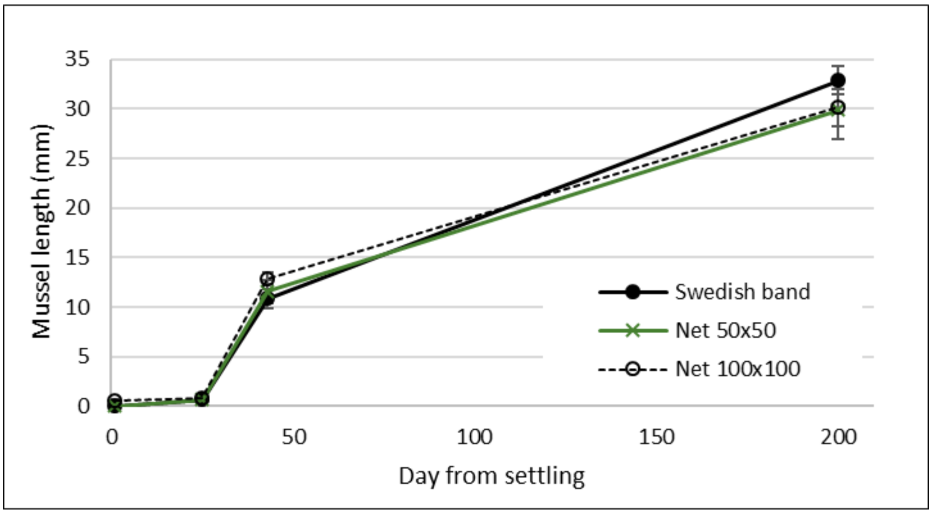

Figure 17. Average mussel lengths and standard deviation for Swedish bands, net with mesh size 50 mm x 50 mm, and net with mesh size 100 mm x 100 mm. Days of growth after settling were calculated from 27th of June, where spat (< 1mm) was observed on the substrates.

The growth rate for each substrate was calculated as the average growth in length per day over two periods (see Table 10) assuming a linear growth over winter which is unlikely. The purpose of the test was, however, to estimate the overall growth within a growth season, and the linear growth was therefore included. Results showed that the mussels from Swedish Bands and nets had similar growth rates both during the first period after settling and overall which amounted to 0.21-0.23 mm day^{-1} throughout the sampling period. Substrates were deployed at a depth of two and five meter to investigate if mussels had different growth rates due to vertical differences in food availability at different depths. T-tests were carried out on mussels sampled in January 2018 to test if there was any significant difference in the average length of mussels placed at 2 m depth and mussels placed at 5 m depth. Results indicated that there was no significant difference in the average length of mussels at 2 m and mussels at 5 m from the Swedish bands deployed in April 2017 ($p=0.55$, $n=300$) or on the net with mesh size 50 x 50 mm ($p=0.12$, $n=300$). The mussels growing on the Swedish band deployed in August were significantly larger at 2 m than at 5 m ($p<0.05$, $n=300$).

Table 10. Growth rate (mm day^{-1}) for Swedish bands, nets with mesh size 50 mm x 50 mm, and nets with mesh size 100 mm x 100 mm. The growth rate was based on the increase in mussel length during two growth periods from June to August and again from August to January the following year.

Growth (mm day^{-1})				
days after settling	Date	Swedish bands	Net 50x50	Net 100x100
43	14-08-2017	0.25	0.27	0.30
200	17-01-2018	0.16	0.15	0.15
Average		0.21	0.21	0.23

Since there was no difference in mussel lengths between depths - except for the Swedish Band deployed in August - a t-test was carried out on mussels from different substrates deployed in April and sampled in January, irrespective of depth. Mussel lengths on Swedish Bands were significantly larger than mussels grown on nets with mesh size 50 x 50 mm (t-test, p<0.0001, n=600) and for mussels grown on nets with mesh size 100 x 100 mm (t-test, p<0.0001, n=600). There was no significant difference of mussel lengths grown on nets with mesh size 50 x 50 mm and 100 x 100 mm (t-test, p=0.12, n=600), and therefore, the mussel length from these different net types are considered similar.

Settling of mussels happened in June and August. The mussels sampled in January 2018, grown on the Swedish band substrate deployed on the 28th of April, were only slightly larger, with an average length of 32.89 mm, than the mussels that were grown on the Swedish band deployed on the 14th of August (29.44 mm). This could be considered unusual as the Swedish band deployed in April included mussels settled in June and August, whereas the Swedish bands deployed in August only included mussels settled in August.

In Figure 18, the size distribution of the mussels from the Swedish Band deployed in April shows a broader length distribution pattern with more mussels above 40 mm than were found on the Swedish Band from 2 m deployed in August. Since there was a significant difference between the average mussel length from different depths (2 m and 5 m) on the Swedish band deployed in August, only mussels from 2 m were compared to mussels from the Swedish band deployed in April. Statistical evaluation showed that the mussels on the Swedish Band deployed in April were significantly larger than the mussels on the Swedish band deployed in August (p< 0.01, n=300).

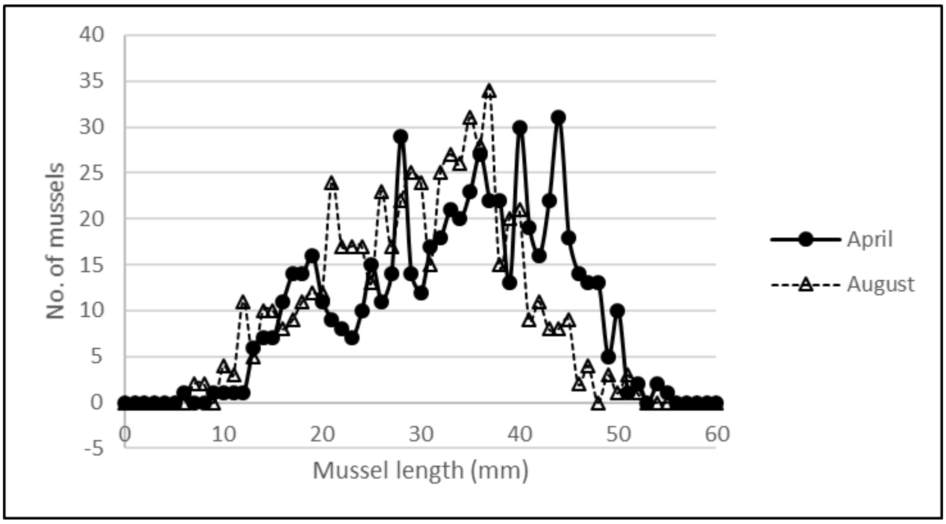

Figure 18. Size distribution of mussels from Swedish Bands at 2 m deployed in April and August in Kiel, and sampling was undertaken in January the following year (2018). Mussels on Swedish Bands deployed in April contained mussels settled from June - August. Mussels from Swedish Bands deployed in August only contain mussels settled in August.

Biomass per area substrate for each sampling period is given in Table 11. Biomass is based on weight measurements from samples on each substrate scaled up to an area of 1 m^{-2}. Biomass for Swedish Bands is based on a standard production deployment of 2 bands per m^{-2} i.e. all data are based on weight measurements from Swedish Band substrates scaled up to a substrate 2 meters in length.

Table 11. Biomass in kg m^{-2} for substrates *Swedish Bands, nets 50 x 50 mm and nets 100 x 100 mm deployed in Kiel Bay. *Biomass for Swedish Bands is based on a standard production deployment of two bands per m-2 i.e. all data is based on measurements from 2 meters Swedish Band substrate.

	Swedish Bands Average Weight (kg m^{-2})	50 mm Average Weight (kg m^{-2})	100 mm Average Weight (kg m^{-2})	Days of growth
27-06-2017	0.3 ± 0.02	1.4 ± 0.3	1.3 ± 0.4	25 ±
14-08-2017	2.3 ± 0.7	8 ± 2	6 ± 1	43 ±
17-01-2018	10.3 ± 1	13 ± 6	25 ± 4	200

Results show that net substrates typically had a greater estimated biomass per m^2 than a Swedish Band production unit m^{-2}. Initially, the biomass on nets with 50 mm mesh was slightly greater than the biomass on nets with 100 mm mesh. As the season progressed over 200 days, the biomass on nets with 100 mm mesh increased most and was an estimated 25 kg m^{-2}. Final biomass estimates per m^2 for 50 mm mesh size nets was 13 kg m^{-2}, and for Swedish Bands 10, 3 kg m^{-2}. However, biomass increased by a factor of 4.5 on Swedish Bands, 4.2 on nets with mesh size 100 mm and 1.6 on nets with the smallest mesh size 50 mm.

Estimates of full-scale production of mussels on both types of nets in January, upscaled to standard production units that are 126 m long, with 3 meters deep vertical panels, was calculated based on the growth results described above. The results were 4.9 tons for nets with mesh size 50 x 50 mm and 9.5 tons for nets with mesh size 100 x 100 mm after 200 days of growth. The average length of these mussels was approximately 31 mm.

For Swedish Bands, the normal production method is to have 2400 m of bands (5 cm wide) per 200 meter head rope (12 m Swedish Band per meter head rope) as each band extends down to 6 m in depth. Normal Swedish Band production methods use twice as much water depth than production units made of nets. The average length of mussels on all substrates after 200 days of growth ranged between 3.1-3.4 cm.

5.1.2 *Kiel 2018/2019*

The size of mussels from the substrates deployed the 27th of April 2017 averaged around 25 ± 1 mm in November 2018. The mussels from the substrates deployed the 4th of June 2018 averaged at 32 ± 1.4 mm in November 2018. Hence, the mussels grown on substrates deployed the same year grew bigger in Kiel Bay than the mussels from substrates deployed the year before.

The development in size distribution of mussels from the substrates deployed in the previous year, started from a broad pattern with mussels sizes from 10 mm and up to 56 mm in June 2018 and ended up with a more narrow pattern in November, with fewer large mussels. There is a small growth of length from June to July with an average mussel length of 27.2 mm to 34.5 mm. (Figure 19). Thereafter, a decrease in length is observed once again from July to November 2018 to 25 mm. This results in a negative growth rate of 0.02 mm day^{-1}. As can be seen on Figure 19, there is a loss of larger mussels during the period from April 2017 to November 2018, and this explains the negative growth rate.

A significant difference (one-way ANOVA) was found in mussel lengths from different substrates in November, for the ones deployed in June 2018 (($F(3.03)= 4.28$, $p<0.05$), however not for the ones deployed in April 2017 (($F(3.03)= 1.22$, $p=0.3$).

The development of size distribution of mussels on the substrates deployed the 4th of June 2018 showed a classic pattern with a very narrow peak of smaller mussels from 2-16 mm that grows into a wider pattern in November with sizes from 10-50 mm (Figure 20). The average mussel size increased from 8.3 mm in July to 31.8 mm in November 2018 (Figure 21) which indicates a growth rate of 0.24 mm day^{-1}.

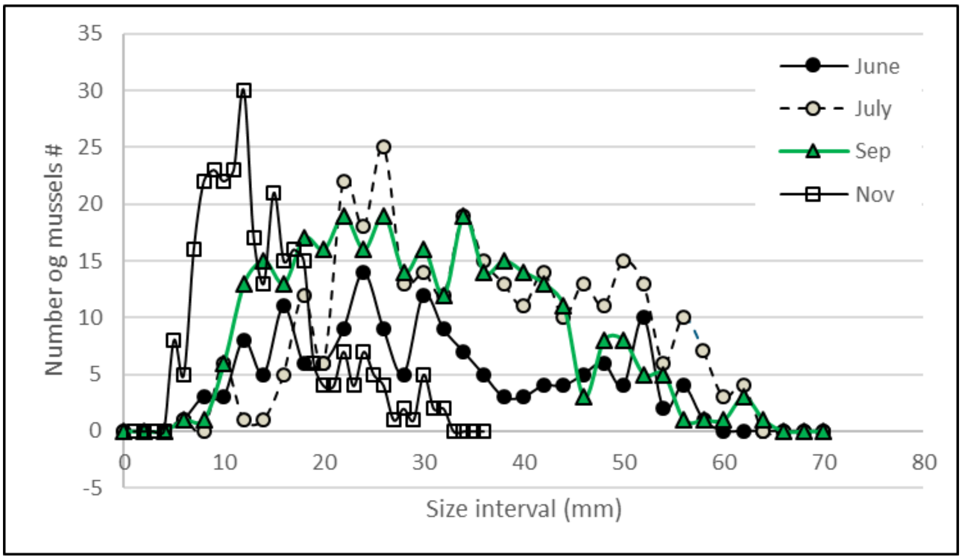

Figure 19. Size distribution of mussels in Kiel Bay from June to November 2018. The substrates were all deployed in April 2017 and sampling has been carried out in June, July, September and November 2018. Sample size is 300 mussels pooled from each substrate type.

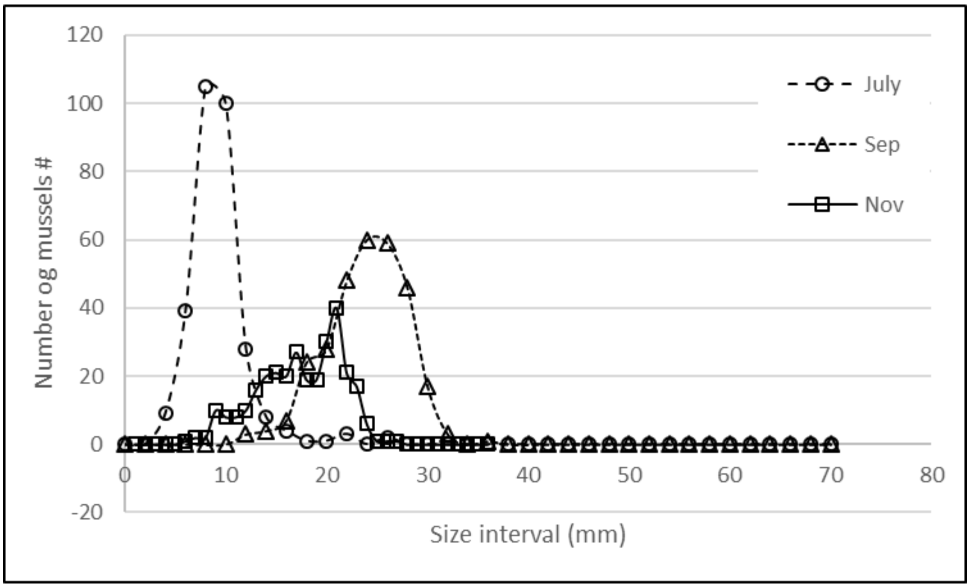

Figure 20. Size distribution of mussels in Kiel Bay from July to November 2018. The substrates were deployed in June 2018 and sampling has been carried out in July, September and November 2018. Sample size is 100 mussels from each substrate type.

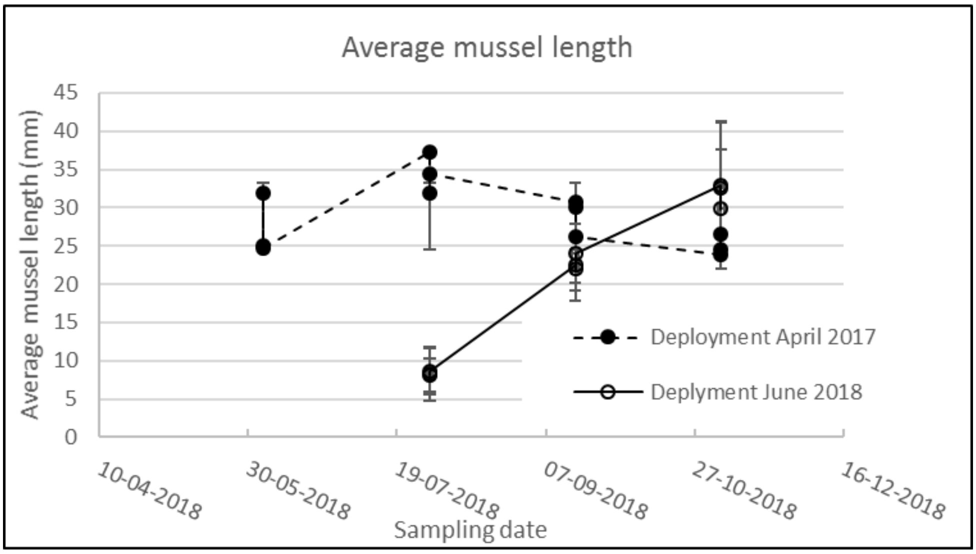

Figure 21. Average mussel size on the different substrate types from June to November 2018. The stippled line indicates mussels from substrates deployed the 27th of April 2017 and the full line mussels from substrates deployed the 4th of June 2018. The standard deviation shows the variation within each mussel sample representing 100 mussels. There is no differentiation between substrate types.

The mussel biomass per m^{-2} for nets and m^{-1} for Swedish bands was calculated from the measures of length of substrates and weight of mussels without substrate. Every weight measure shows an average of triplicate samples and the standard deviation (see Table 12). The mussel biomasses per meter head rope was calculated for nets and for Swedish bands (see Table 13 and Figure 22). Every meter of head rope includes 3 m^2 net and 5m of Swedish bands reflecting the actual depth conditions at the site. The net with 50 x 50 mm mesh size had on average 170 kg m^{-1} in November, and thereby contains the largest biomass of mussels compared to the other substrate types. The net with 50 mm mesh size deployed in June 2018 had a lower biomass (110 kg m^{-1}) in total compared to the 50 mm mesh size net deployed in April 2017 but the same amount as the net with 100 mm mesh size deployed the year before.

Table 12. Development of mussel biomass in Kiel Bay in kg m^{-2} for trawl nets and in kg m^{-1} for Swedish bands. The accumulated days shows how long the substrates have been in the water after deployment. Standard deviation is calculated from sample triplicates.

Deployment date	Sampling Date	Acc. Days	Net 50 x 50 (kg m^{-2})	Net 100 x 100 (kg m^{-2})	Swedish bands (kg m^{-1})
27-04-2017	04-06-2018	404	41 ± 4		
27-04-2017	30-07-2018	460	30 ± 10	27 ± 10	10 ± 0
27-04-2017	17-09-2018	511	27 ± 5	26 ± 4	7 ± 1
27-04-2017	05-11-2018	559	57 ± 7	35 ± 3	11 ± 2
04-06-2018	30-07-2018	57	5 ± 0	5 ± 0	1 ± 0
04-06-2018	17-09-2018	108	29 ± 3	28 ± 1	5± 1
04-06-2018	05-11-2018	156	37 ± 6	35 ± 3	8 ± 0

An overall increase in biomass on the substrates deployed in April 2017 from April 2017 to November 2018 (see Table 12 and Figure 22) was observed. However, a loss during the summer and fall of 2018 was also observed, which affected the overall outcome of the production test. The substrates deployed in June 2018 did not seem to lose any mussels indicated by a normal development in size distribution, and the development in biomass did therefore increase more. Hence, the results from this study showed that there was no efficient advantage in deploying the substrates a year before compared to the risk of impact on the equipment from ice and strong wind.

The different biomass outcomes can be increased to full production assuming 126 m headrope/tube per unit for the 3 m deep nets and 200 m headrope for the Swedish bands. The biomass from substrates deployed in April 2017 and sampled in November 2018 would then be (57 kg m^{-1} x 200m) 11.4 t for Swedish bands, (105 kg m^{-1} x 126m) 13.23 t for net with 100 mm mesh size and (170 kg m^{-1} x 126m) 21.4 t for nets with 50 mm mesh size. For the substrates deployed in June 2018 this equals (105 kg m^{-1} x 126m) 13.23 t for 50 mm mesh size nets and (38 kg m^{-1} x 200) 7.6 t for the Swedish bands.

Table 13. Development of mussel biomass in Kiel Bay in kg per meter head rope. For every meter of head rope, there is 3 m^2 net and 12 m of Swedish band. The accumulated days shows how long the substrates has been in the water after deployment. Standard deviation is calculated from sample triplicates.

Deployment date	Sampling Date	Acc. Days from substrate deployment	Net 50 x 50 (kg m^{-1} headrope)	Net 100 x 100 (kg m^{-1} headrope)	Swedish bands (kg m^{-1} headrope)
27-04-2017	04-06-2018	404	123 ± 11		
27-04-2017	30-07-2018	460	90 ± 30	81 ± 30	48 ± 1
27-04-2017	17-09-2018	511	80 ± 16	78 ± 13	34 ± 4
27-04-2017	05-11-2018	559	170 ± 21	105 ± 10	57 ± 12
04-06-2018	30-07-2018	57	14 ± 1	16 ± 1	4 ± 0
04-06-2018	17-09-2018	108	87 ± 8	83 ± 3	24 ± 3
04-06-2018	05-11-2018	156	110 ± 17	105 ± 10	38 ± 2

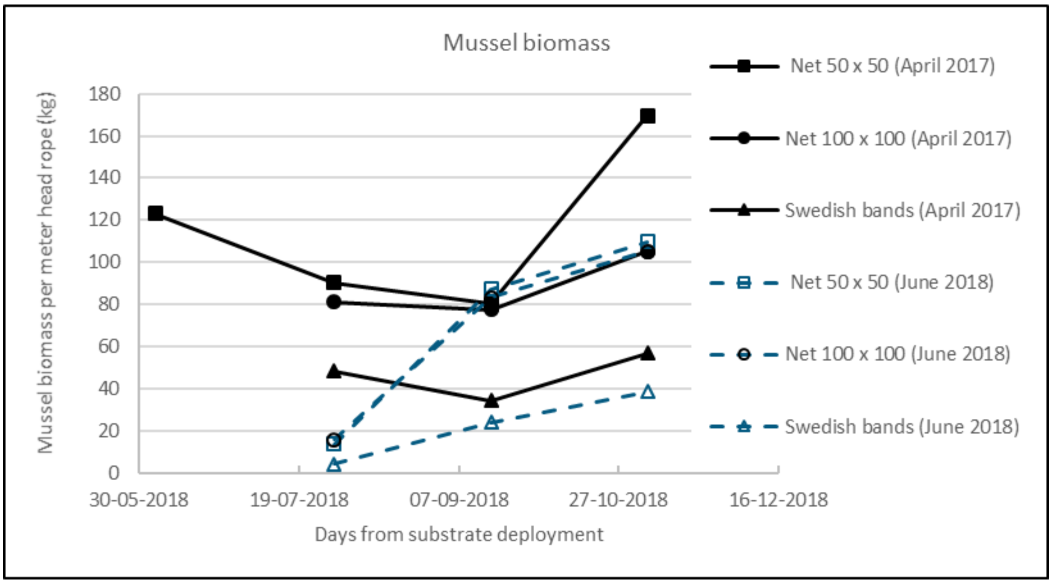

Figure 22. Development of mussel biomass per meter of head rope on different substrate types in Kiel Bay. The different substrate types were trawl net (50 x 50mm, and 100 x 100 mm), and Swedish bands. The substrates were deployed at two different dates; 27th of April 2017 (full line) and 4th of June 2018 (stippled line). They were all deployed at 2 m depth.

6. Results Kalmarsund

6.1.1 2017/2018

The study of mussel growth in Byxelkrok, Sweden, included five different types of mussel substrates: Swedish Band, and nets with mesh sizes 50 x 50 mm, 80 x 80 mm, 150 x 150 mm and smartfarm net 150 x 150 mm. Substrates were deployed in June and samples were taken on the 24th of August and on the 8th of November 2017.

Unfortunately, one of the Smartfarm nets detached from its anchoring and sank, and therefore, the Smartfarm substrates at 1 and 3 m could not be sampled in November 2017.

Swedish bands, Smartfarm nets and trawl nets all had high amounts of fouling by barnacles. This is shown on a Swedish Band in Picture 23.

The size distribution of mussels from Byxelkrok was similar on all five of the substrate types sampled in August 2017. The size range was from 0.5 – 3.5 mm with most mussels being 2 mm long (see Figure 23a). The size distribution observed in August indicates that there has been one concentrated settling on all the substrates in June.

In contrast to length measurements in August, the size distribution of mussels sampled in November 2017 showed a difference between mussels from Swedish Bands and the net substrates (see Figure 23b). Average mussel length from the Swedish band was 3.38 mm, which was less than the average length of mussels from the net substrates (range 5 – 5.7 mm). However, there may be a bias in the length results of the Swedish bands because they were only sampled once in August and once in November, whereas replicates were carried out for net samples. Therefore, there are some uncertainties related to the interpretation of results from the Swedish Bands.

Picture 23. Picture of fouling by barnacles on Swedish Band

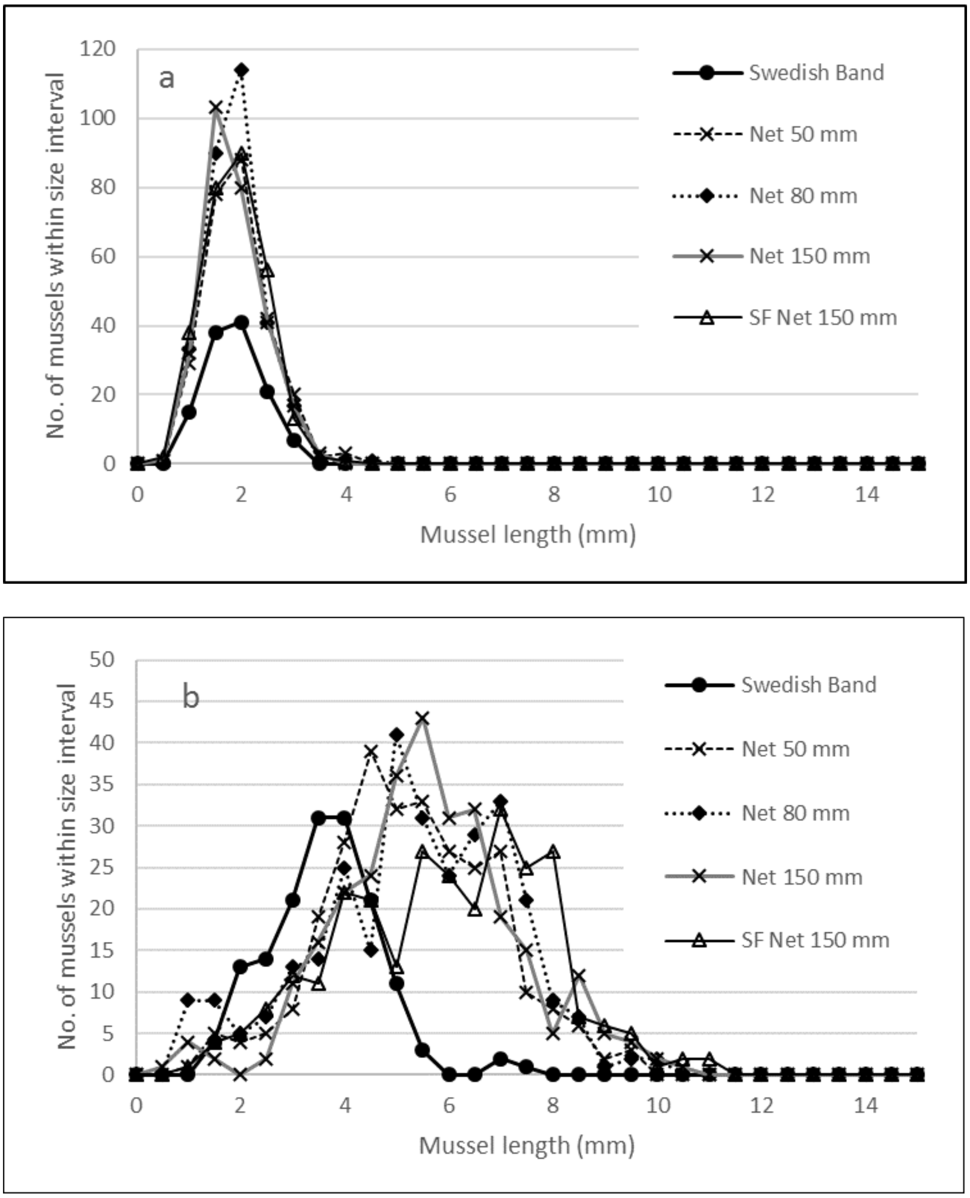

Figure 23. Size distribution of mussels sampled on 5 substrate types in a) August 2017 and b) November 2017.

There were concerns that length measurements of mussels, especially small mussels, have uncertainties. Therefore, this was tested as double measurements were carried out with the same standard method on two samples, one with 139 mussels and one with 132 mussels (lengths approximately 5 mm). The two samples that were re-measured were mussels from a Smartfarm net substrate at 1 m in August and mussels from a net with mesh size 50 x 50 mm at 3 m in November (Table 14). Samples were taken as replicates. The length differences between replicates were in most cases small or in the same size order as the values from counting the same sample twice, indicating primarily that there is uncertainties related to the counting/measuring method and secondly, that there is little difference in length between replicates. However, standard variation is useful to give an indication of the variation in lengths on the substrates and thus, help to interpret the average values by indicating overall size composition.

Table 14. Average of mussel lengths measured from 2 measurements (counts) of the same sample and for the replicate (different sample). Replicate samples were more similar than the average values from counting the same sample twice.

Mussel length (mm)	Average # 1	Average # 2	Replicate
August 2017	5.58	4.57	5.73
November 2017	5.04	5.30	5.1

There was a significant difference in size of mussels sampled in November from different depths; One-way ANOVA, ($F(2,783)=19.3$, $p<0.0001$). An unpaired student's t-test was used to examine between which groups there were a significant difference. The results from the t-test showed that mussels from 13 m were significantly smaller than mussels from 1 m ($p<0.0001$, $n=262$), but not significantly different from mussels growing at 4 m ($p=0.1$, $n=262$). Mussels grown at 1 m were significantly larger than mussels grown at 4 m ($p<0.0001$, $n=262$). The difference in size can be seen in Figure 24.

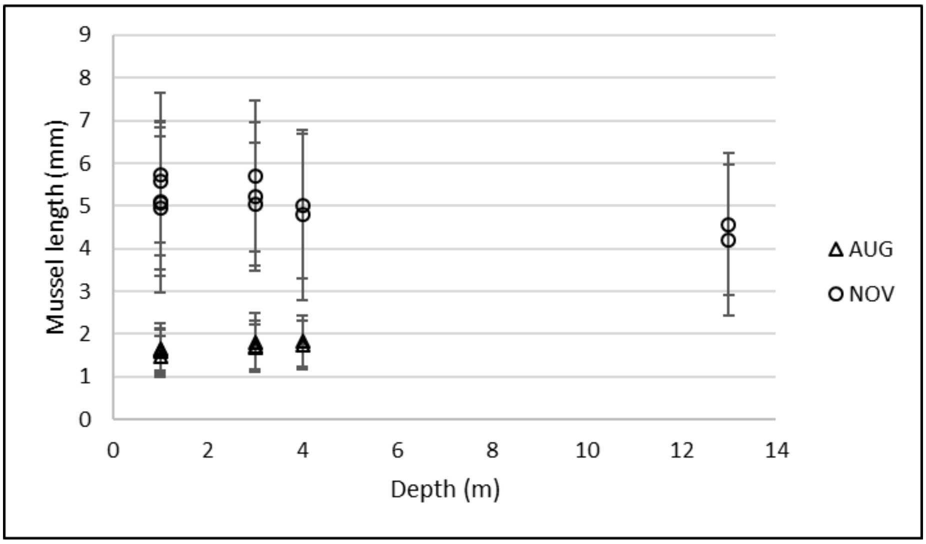

Figure 24. Mussel length (mm) in August and November from smartfarm nets at different depths. Mussels from 13 m were only sampled in November. Vertical bars indicate the standard variation from the average mussel length.

Growth of mussels from the 24th of August to the 8th of November 2017 is shown in Figure 25. The precise time of settling is not known but it is assumed to have happened in late June. Growth rates of mussels from different substrates were calculated from the increase in length and the days from the sampling in August to the sampling in November.

Growth rates were low, and the mussels would need more than 900 days or 2.5 years to reach consumption sizes of >4 cm if targeted for the fresh market.

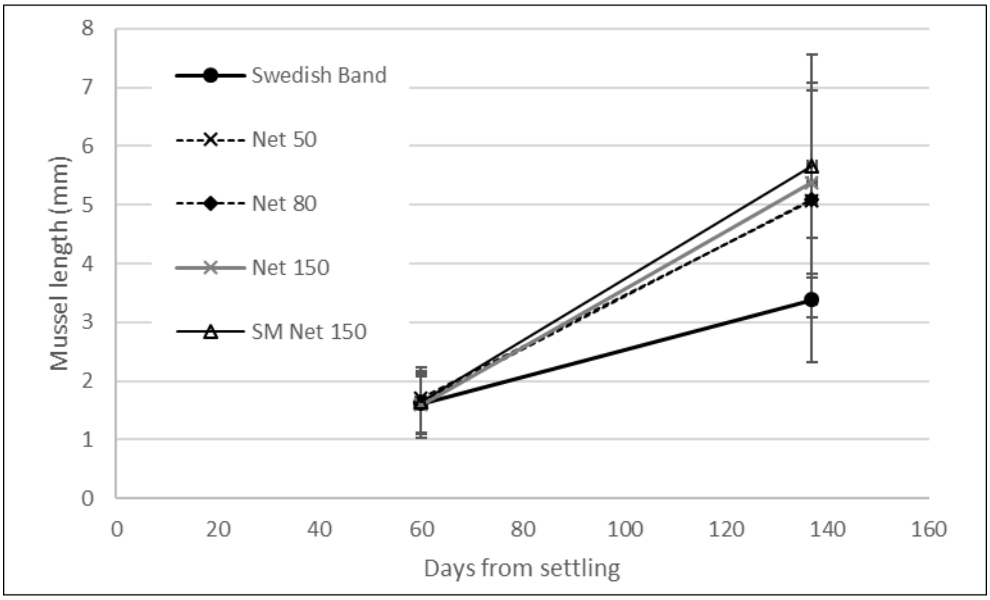

Figure 25. Growth of mussels from the 24th of August to the 8th of November 2017. Mussels from net substrates with mesh size 50 x 50 mm and 80 x 80 mm had the same growth and can therefore not be differentiated.

Table 15. Growth rates of mussels on five different substrates calculated from the increase in length from August to November 2017.

Growth rate (mm day^{-1})						
Time period	Days of growth	Swedish Band	Net 50	Net 80	Net 150	Net 300
24th of Aug – 8th of Nov	77	0.02	0.04	0.04	0.05	0.05

In August, biomass per area substrate was greatest for the trawl net substrates with the smallest mesh sizes (50 mm and 80 mm mesh sizes) (Figure 26). Whereas, the biomass per area substrate was the lowest on the trawl net substrate with the mesh size of 150 mm and comparatively low on the Smartfarm substrate, with mesh size 150 mm (Table 16 and Figure 26).

In November, biomass per area substrate was still the greatest for the trawl net substrate with 50 mm mesh size, and in general, considerably higher on all the trawl net substrates (50, 80 and 150 mm) compared to the low biomass on the Smartfarm substrate (150 mm mesh size), even though the mesh size was the same (Figure 26).

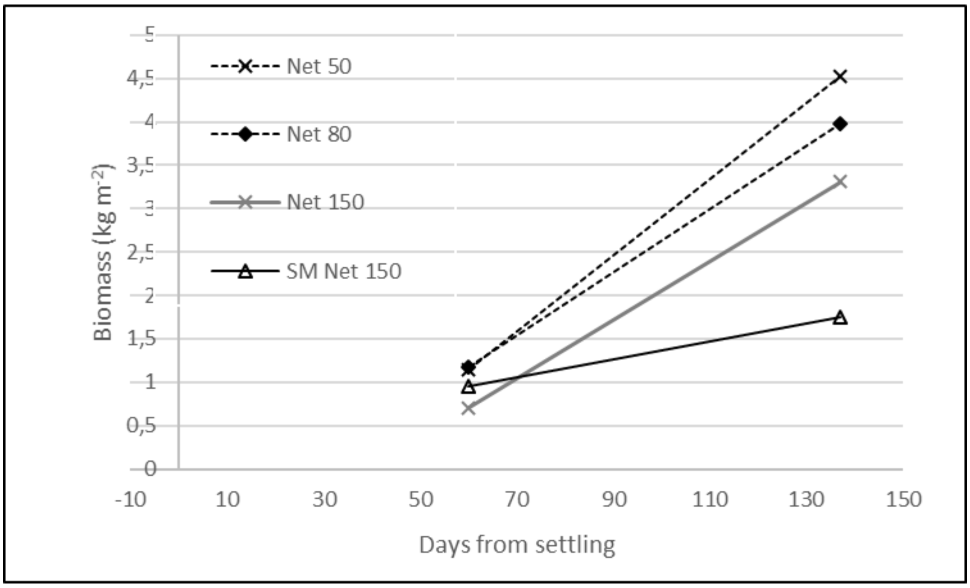

Figure 26. Biomass (kg m-2) estimates for four different substrates. SM net is Smartfarm net with mesh size 150 x 150 mm. *Biomass estimates for the Swedish Band substrate was not undertaken due to missing data for substrate area.

Full-scale production estimates of mussels on all types of trawl nets in November, upscaled to production units that are 126 m long with 3 meters vertical panels, resulted in an estimate of 1.7 tons for nets with mesh size 50 mm, 1.5 tons for mesh size 80 mm, and 1.3 tons for mesh size 150 after 137 days of growth. The full-scale production estimates of mussels on the Smartfarm substrate in November amounted to 0.6 tons after 137 days. Production estimates for Swedish Bands could not be undertaken due to missing data.

Table 16. Biomass in kg m^{-2} on four substrate types sampled in August and November 2017. *Biomass estimates for the Swedish Band substrate was not undertaken due to missing data for substrate.

	*Swedish Band	Net 50 mm	Net 80 mm	Net 150 mm	Smartfarm 150 mm
AUG	-	1.14	1.17	0.71	0.95
NOV	-	4.53	3.98	3.31	1.75

6.1.2 *Kalmarsound 2018/2019*

The mussels that settled in June 2018 grew into an average size of 3.6 ± 1 mm. in October 2018, with 33 % out of 552 mussels reaching a size of 5 mm or above. The mussels sampled in October showed one normal distribution in size intervals, which shows that there was only one cohort of mussels (Figure 27). The weight results from one Swedish band and six net samples from the 16th of October 2018 show varying biomass (Figure 28). No mussels were found on the Swedish band (not included in figure 23). On the nets, the biomass per m head rope varied from 0.16 – 5.78 kg with an average of 2.7 ± 2.2 kg. This would equal 324 ± 264 kg on each production unit 120 m long.

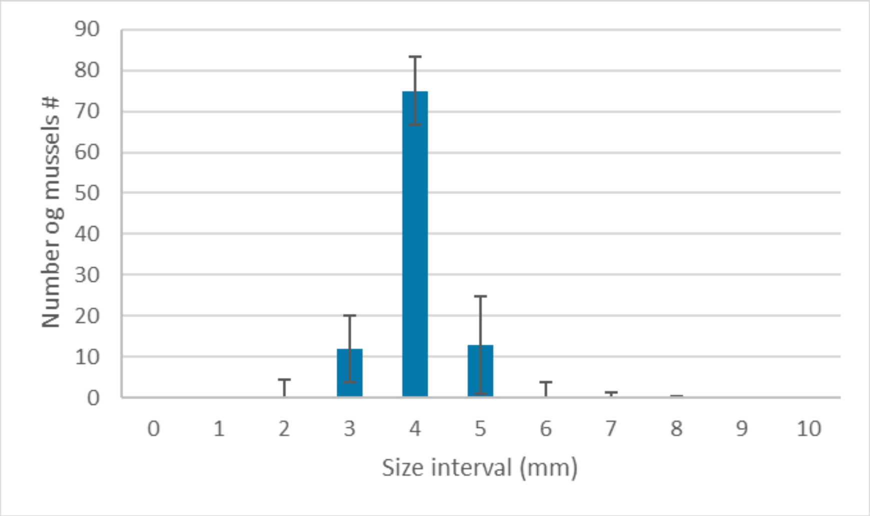

Figure 27. Size distribution of mussel length in mm. sample size of six samples with 100 mussels in five of them and 52 mussels in the last one. Settling occurred in June 2018 and sampling in October.

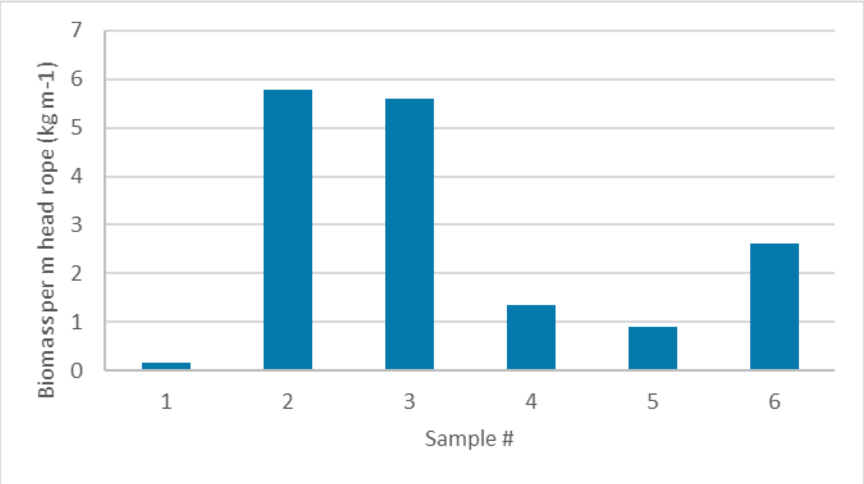

Figure 28. Mussel biomass measured on 6 net samples with mesh size 66 mm. The biomass per meter head rope is calculated from kg biomass per m^2.

7. Results Coast of Kurzeme

7.1.1 2017/2018

The mussel farm at the coast of Kurzeme is not yet a part of the substrate test. However, exploratory test results from sampling of ropes in August shows the timing of mussel settling and the size of mussels after approximately 2 months of growth. Despite the limited amount of data, these results are included in this report with the purpose of making preliminary comparisons with the other areas in the substrate study.

The settling of mussels occurred in late June and sampling took place on the 24th of August. The average length of mussels on each of the rope substrate samples was 1.3 mm (0.28-3.0 mm) and 2,0 mm (0.6-4.4 mm), respectively (Table 17).

Because sampling was sparse and samples were taken from a rope that was not similar to substrate types used in the other test areas, these results should only be considered as being exploratory and preliminary.

Table 17. Results from sampling of ropes on the 24th of August 2017. Average and maximum + minimum of mussel length from two samples.

No. of mussels measured	Days of growth	Min size, mm	Max size, mm	Average, mm
60	60	0.28	3.0	1.3
60	60	0.60	4.4	2.0

7.1.2 Coast of Kurzeme 2018/2019

Due to rough weather conditions, it was not possible to deploy nets (66 mm mesh size) and Swedish bands until late June in 2018, and the first settling was most likely lost. Therefore, the mussels found in the samples were from a later settling. The Swedish bands were not sampled, but the diver noted fewer mussels on these than what was found on the nets.

One sample was taken in October 2018. After approx. three months, the average mussel size was 1.2 mm with only 8 % reaching a size of 2.5 mm (see Figure 29). The weight was also measured to 0.63 g of fresh mussels. The sample size was 240 cm^2, which gives a small biomass of 0.08 kg per meter of head rope, including three m^2 of net. Knowing the large uncertainties related to very small values, this would equal an insignificant amount of 9.4 kg of mussel biomass on each production unit 120 m long.

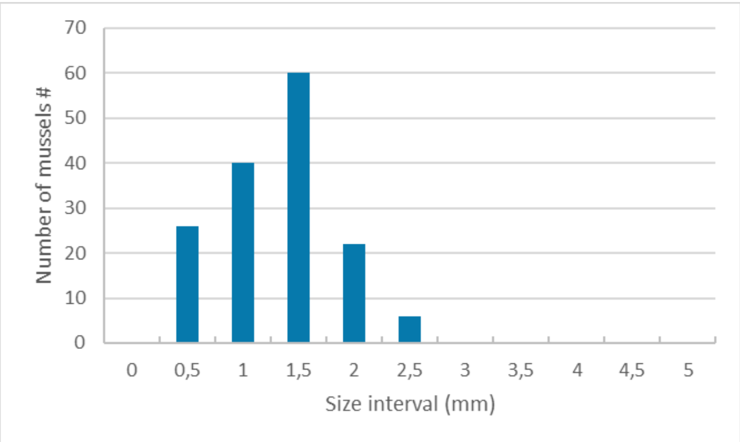

Figure 29. Size distribution in mussel length (mm) based on a sample size of 77 mussels. Period of growth was from mid-June 2018 to the 18th of October 2018.

8. Results from Growth and recruitment study

Due to harsh weather conditions, the experimental units were lost in the LIAE and Kalmar farms. In spite of this loss, an estimate of mussel recruitment and growth throughout the whole Baltic Sea salinity gradient was carried out.

A standardized artificial substrate was used in key farms to evaluate the recruitment and growth of mussels experimentally, in order to link broad patterns of oceanographic conditions to the net increment of mussel stock. When all these techniques (mentioned above) are used interactively, the collated datasets enable placing the farm impacts into broader spatial and finer temporal scales and allow the PanBaltic assessment of farm potential and impacts.

The data from monitoring of the settlement and growth of mussels in the Baltic Sea area is reported in the following. Standardized methodology was used at all focus farms in order to make a proper comparison among the functionally different regions of the Baltic Sea.

8.1.1 Regional differences in the mussel growth yields

The growth of mussel biomass follows the large-scale salinity patterns with highest growth observed at Kiel and Musholm farms. In these more saline regions, total biomass yield reaches maximum in the first year and then, due to an intensification of the competition for space (mussels grow bigger), significant declines in biomass were observed. In Kiel farm, the highest peak in biomass was observed in January 2018 and since then the values were significantly decreasing. By September 2018, there was only one quarter of the biomass left compared to the values recorded in January 2018. Throughout the Baltic Sea, the biomass growth of mussels at 2 m was higher, compared to measurements taken at 5 m (Figure 30). Only St Anna farm in November 2017 had higher values at 5 m but this is because we observed a proportionally larger loss of mussels from July to November 2017 in the shallower depth.

8.1.2 Regional differences in the mean and maximum size of mussels

There was a large variation in the abundance and length frequency distribution of mussels between different regions and sampling times. As expected, the largest mussels were found in the most saline regions of the Baltic Sea. For example, in the Kiel mussel farm, mussels above 60 mm can be found. However, within the Baltic area, the spatial differences in mussel abundance and length, frequency-distribution did not clearly follow the salinity gradient. Here, the most represented length classes in all the mussel farms remained between 0 and 20 mm. The highest abundance of mussels was recorded at LIAE (Pavilosta) farm, where the maximum count reached higher than 40 000 individuals. However, all were of very small sizes, around 2 mm of length.

Higher abundancies and larger mussels were mostly observed at 2 m compared to 5 m. At some farms, losses of individual mussel cohorts during different seasons were observed. In the Kiel farm, there were two distinct cohorts of 10 to 20 and 40 to 50 mm in January 2018. However, in June and September 2018 the length class of 40 to 50 mm had significantly decreased. At the St Anna farm, significant losses of 10 to 20 mm mussels were observed from July 2017 to November 2017.

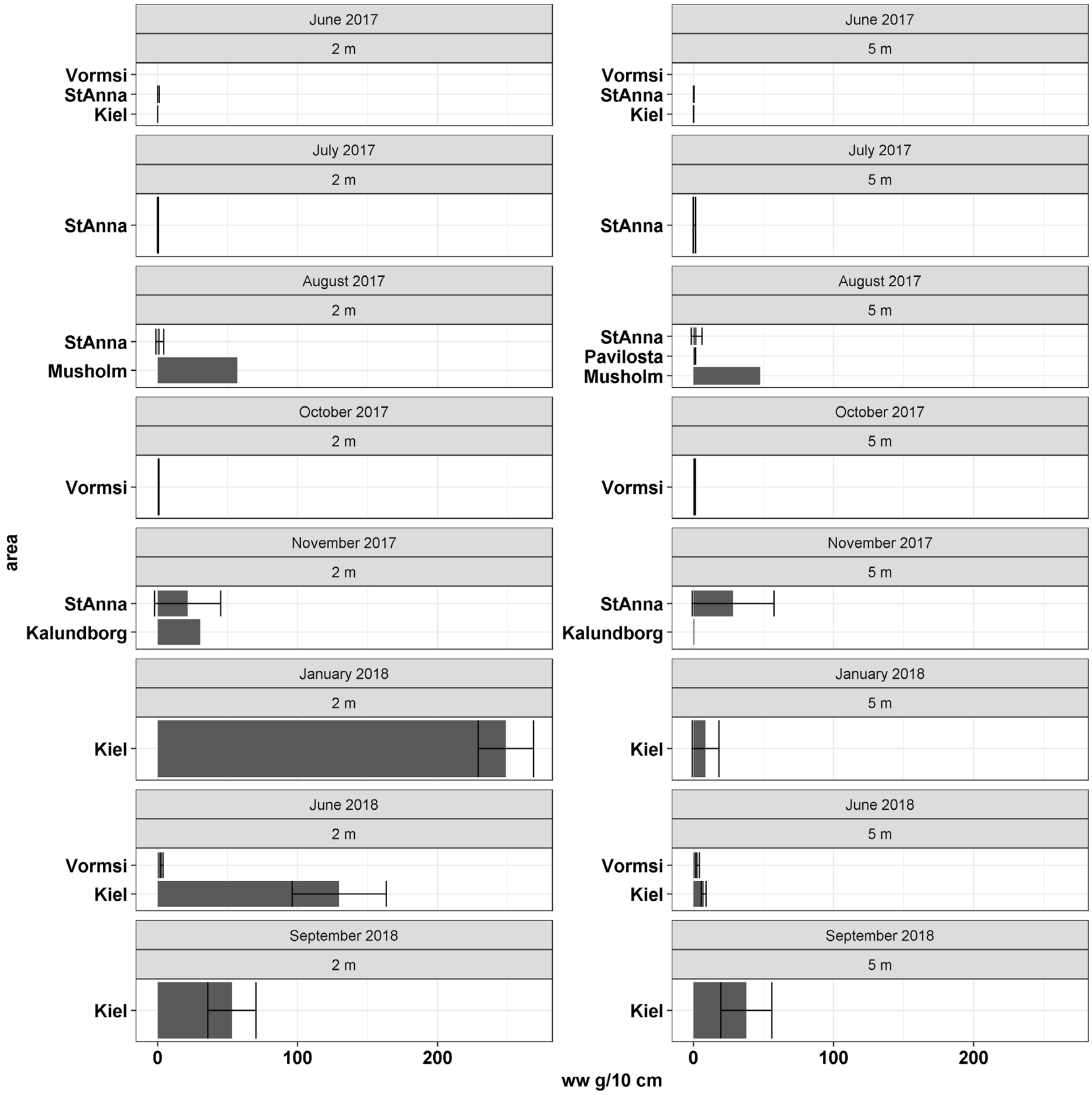

Figure 30. Mussel wet weight in g per 10 cm fuzzy rope at different mussel farms during various sampling events.

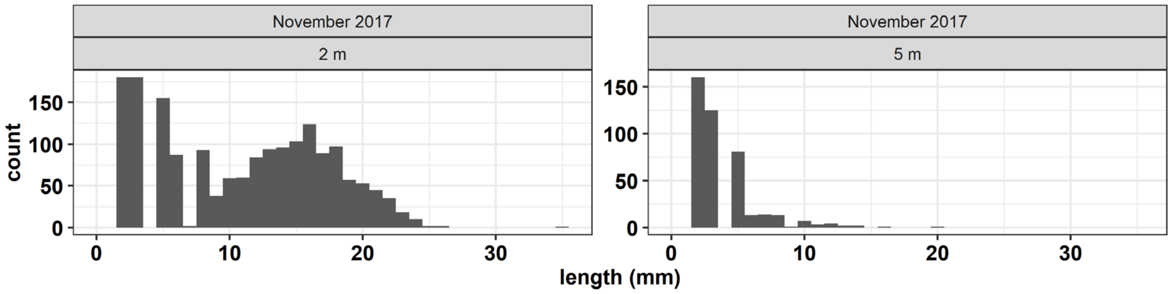

Figure 31. The abundances and length frequency distribution of mussels from Kalundborg, Denmark.

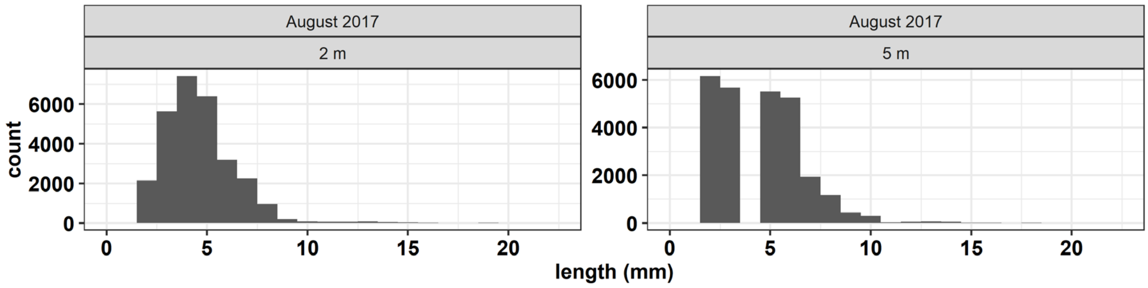

Figure 32. The abundances and length frequency distribution of mussels from Musholm, Denmark.

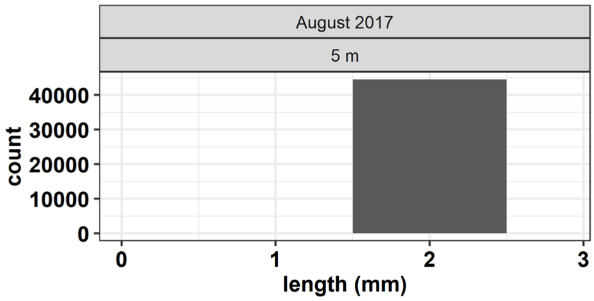

Figure 33. The abundances and length frequency distribution of mussels from Latvia.

There was a great variability in the biomass yield, abundance, and length frequency distribution of mussels between different regions and sampling times. As expected, the largest mussels were found in the most saline regions of the Baltic Sea area. However, within the Baltic Proper area, spatial differences in biomass, abundance, and length frequency distribution did not clearly follow the salinity gradient. One possible explanation could be that salinity variability in this sub-basin is not large enough to cause different amounts of energy diverted from growth to osmoregulation, and thereby cause differences in the reduction of mussel growth rate and ultimately their size. Instead, other variables such as food availability, which is determined by water currents and phytoplankton biomass, and loss to predation better describe the growth patterns of mussels.

There were some sporadic events resulting in seasonal losses of larger size classes. Although the reason of such losses is not yet fully understood it is likely that in more saline areas mussels grow large resulting in the intensification of density dependence processes (i.e. increased competition for space). When the mussel stands get crowded, stronger winds are expected to reduce the biomass of mussels in the growing ropes significantly. However, in less saline areas, the smaller mussel sizes reduce substrate limitation (density dependence), and populations experience less loss from large individuals detaching. Therefore, the loss of mussels in the St Anna farm cannot be attributed to storm effects. There are many other possible causes of such loss, e.g. bird and fish predation, competition between macroalgae and mussels, or heatwaves, but based on the observed dynamics of length frequency data none of these explanations seems plausible.

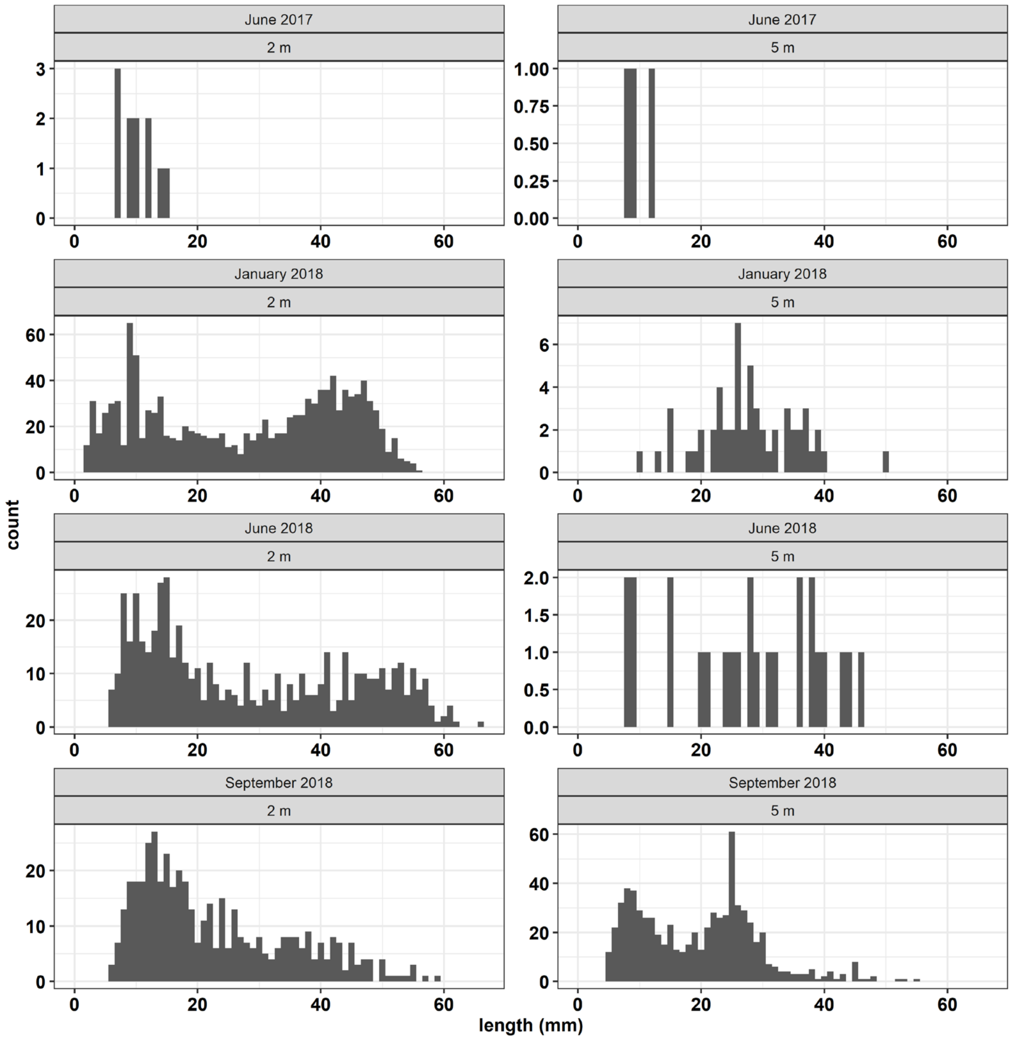

Figure 34. The abundances and length frequency distribution of mussels from Kiel, Germany.

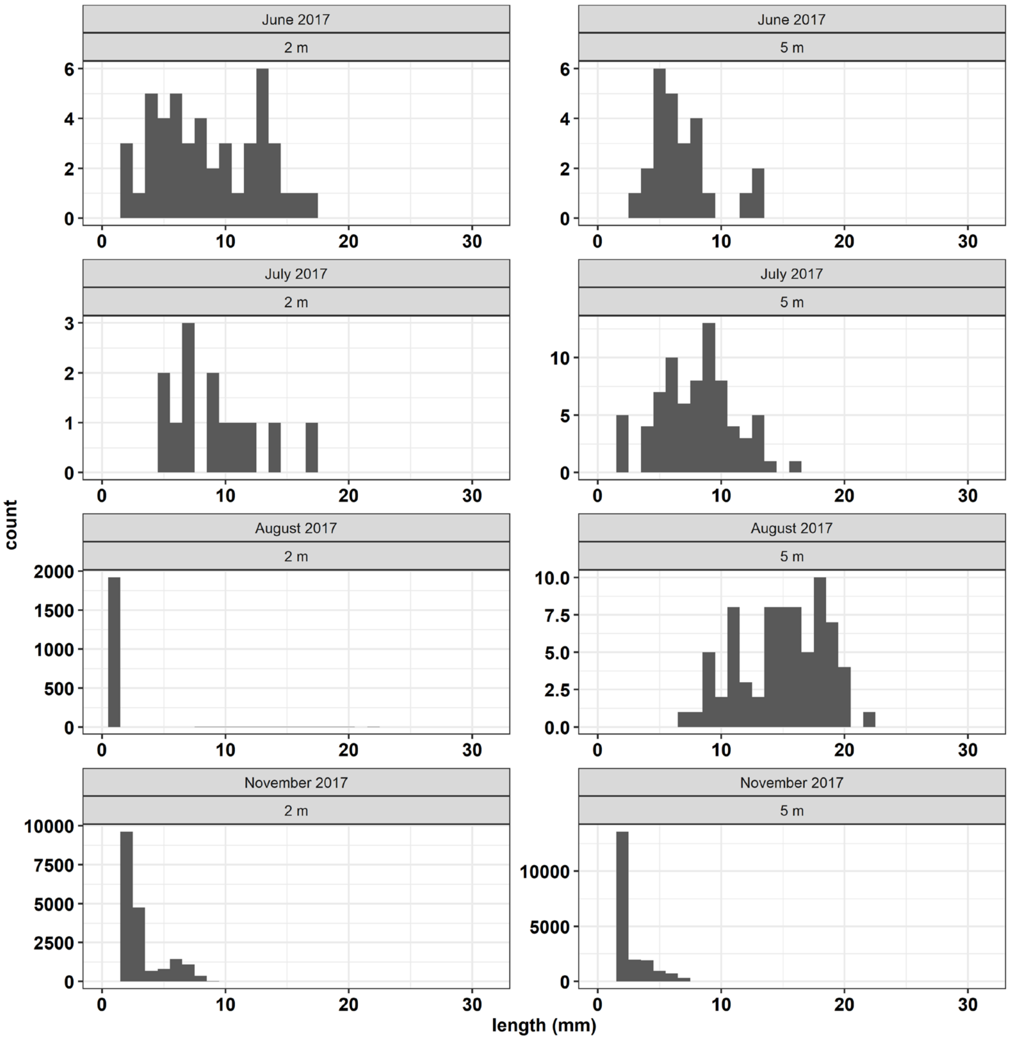

Figure 35. The abundances and length frequency distribution of mussels from St Anna, Sweden.

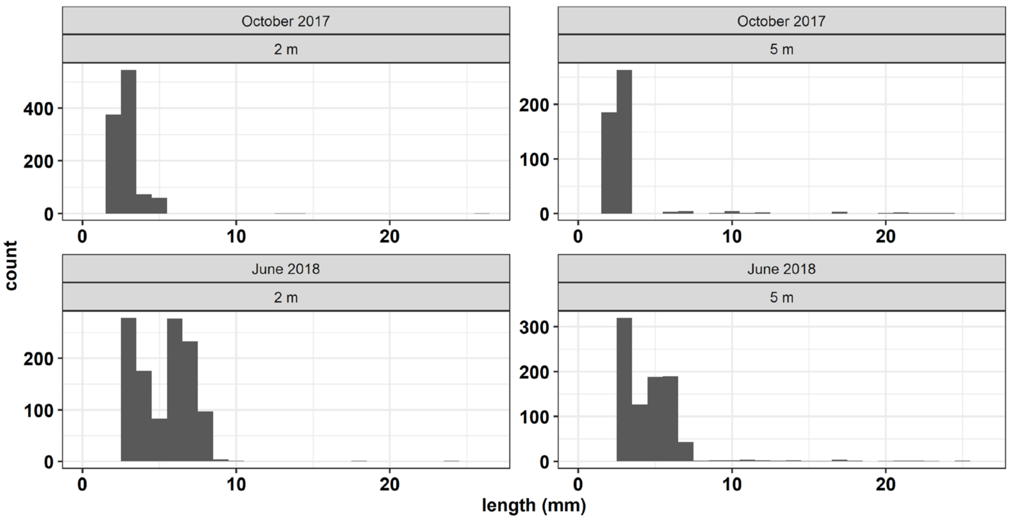

Figure 36. The abundances and length frequency distribution of mussels from Vormsi, Estonia.

9. Growth and biomass on nets and Swedish bands

The range in growth rates and biomass from Musholm, Kiel and Kalmarsound from 2016-2019 can be seen in Table 18, where growth and increment in biomass is highest in Kiel on trawl nets and Swedish bands. The different maximum and minimum growth rates from Musholm, Kiel and Kalmarsound can be seen in Figure 37.

For the purpose of comparison between farms, the standard meter of Swedish bands was set to 12 m per meter headrope. The depth at the Kiel farm does not allow the Swedish bands to reach 6 m depth, and therefore, the high biomass estimate does not correspond fully to the output on the farm, but gives information on the potential of mussel production in this area.

Average biomass estimates for different substrate types were plotted as a function of months from June, where the main settling happened. This was plotted for different farms and years (see Figure 38). A linear regression of growth months from June and biomass per meter headrope of nets on the different farms (not including Kiel), shows that there is a significant overall positive development of biomass on the nets with time in the Baltic sea ($p<0.05$, $R^2 = 0,63$, $n = 8$). This means that there is an overall positive development in biomass independent of types of nets or different growth rates. The exact time of settling was not known but noted as June for all years and farms, and the biomass estimates are therefore related with uncertainties as to exactly how many months of growth from when the settling happened.

Table 18. The growth rates of mussels and biomass per meter headrope on different substrates from 2016-2019 on the three primary test sites (Musholm, Kalmarsound and Kiel) and exploratory results from the Coast of Kurzeme. One meter of headrope includes 3 m^2 of net and 12 m of Swedish bands. The number of months of growth is different for the different farms and years.

Growth rates (mm day-1)				Biomass (kg m-1 headrope)		
	year	Time period	Overall range	Nets	Swedish bands	Fuzzy ropes
Musholm	2016	Sep-Dec	0.04-0.09	1.8-25.3		
Musholm	2017/2018	Aug-Mar	0.06	7.2-18	21.6	7.2 (Jun-Sep)
Musholm	2018/2019	Aug-Feb	0.03	4.8-9.3	1-3	
Kiel	2017/2018	Jun-Jan	0.21-0.23	39.9-76.4	123.6	30 (Jun-Jan) 6 (Jun-Sep)
Kiel	2018/2019	Jul-Nov	0.24	105-110	38	
Kalmarsound	2017/2018	Aug-Nov	0.04-0.05	5.25-13.5	_	
Kalmarsound	2018/2019	Oct (2018)	_	0.16-5.78	_	
Kurzeme	2017/2018	Aug (2017)	_	_	_	
Kurzeme	2018/2019	Oct (2018)	_	0.08	_	

The Swedish bands and Fuzzy ropes, overall, follows the performance of the other substrate types, except for the case with low biomass on the Fuzzy rope in Kiel after 16 months of growth where the larger mussels fell off and the high biomass on Swedish bands in Kiel after 8 months of growth. From the growth and recruitment study and from the substrate tests it was clear that the Kiel bay area was optimal for mussel production with higher biomass results and higher growth rates than was found in the other demonstration farms. The biomass estimates from there, should therefore be evaluated in its own line of development and as mussel production for human consumption.

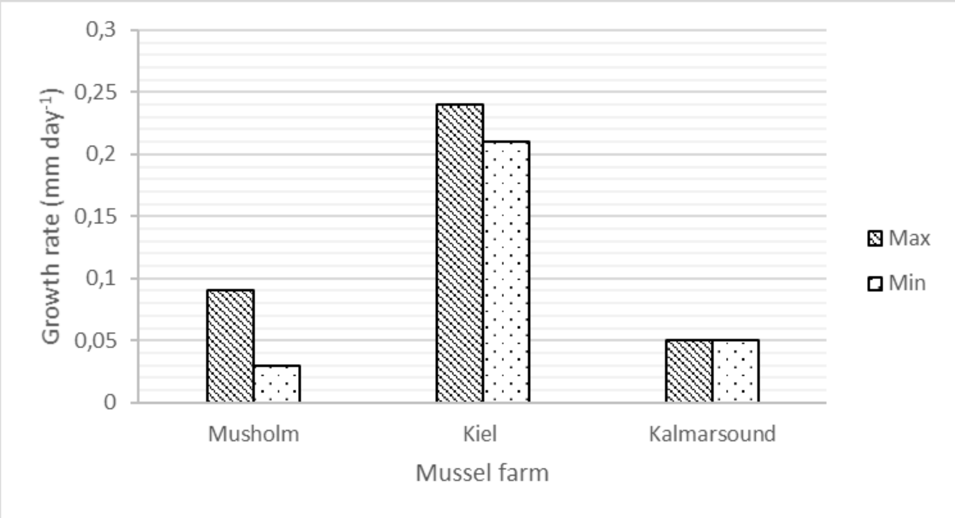

Figure 37. Maximum and minimum growth rates (mm day^{-1}) from different test sites (Musholm, Kalundborg, Kiel, and the Kalmarsound from 2016-2019. Growth rates are estimates from different time periods of the year.

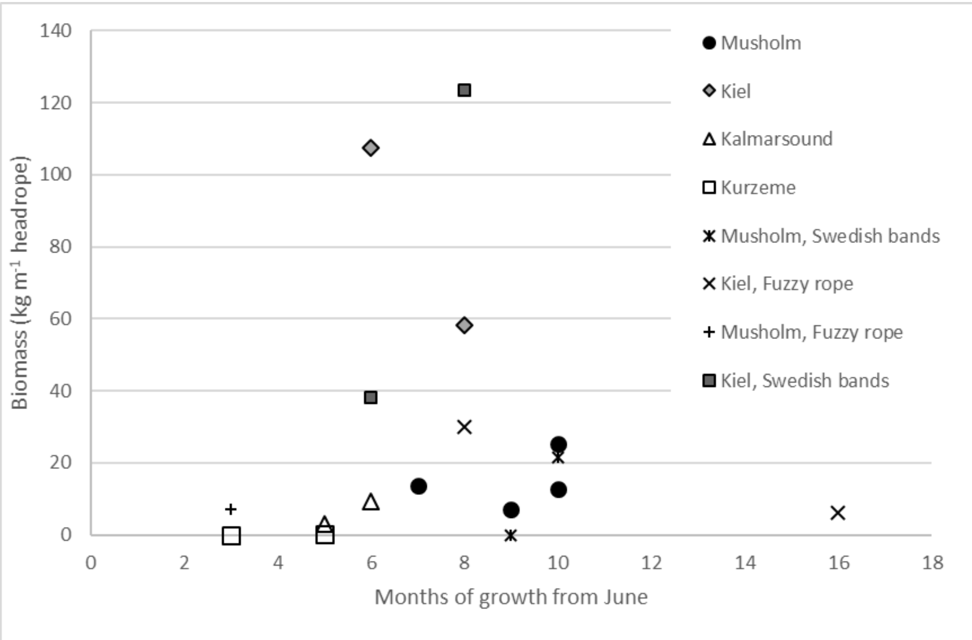

Figure 38. The average estimated biomass per meter headrope (kg m^{-1}) from five different test sites from 2016-2019. Biomass is a function of months of growth from June, where the main settling of mussel larvae occurs. Data is based on the average biomass from nets, Swedish bands and Fuzzy rope. The Swedish bands and Fuzzy rope are from Musholm and Kiel.

10. Discussion and Conclusion

Overall, the results indicate that trawl nets with small mesh size can be used to grow mussels in areas with low growth rate, where large mesh sizes, such as the smartfarm net, proved less optimal. The results from growth on Swedish bands were inconclusive, where some years gave good recruitment and growth and other years poor recruitment and growth in the same area. The results from the growth and recruitment study show similar biomass per meter headrope, as was seen for Swedish bands and trawl nets (see Figure 38). Hence, all substrates tested proved applicable for mussel production in Baltic waters, which allows the farmer to focus on cost price and how well the substrate performs with respect to weather and handling.

Swedish Bands

At the Musholm and Kiel test site, Swedish Bands appeared to provide the best substrate for settling larvae in 2017/2018. The settling of larvae was better supported by Swedish bands this year than by nets, with the result that Swedish Bands had a greater number of larger mussels than net substrates during the development of the mussels, as well as at the end of the experiment. The following year, a very low recruitment and growth was observed on the Swedish bands in the Musholm farm, which leads to inconclusive results from testing the performance of this substrate type. In the Kalmarsound, results on Swedish Bands showed that mussel growth rates and average lengths were lower than on all the nets after similar larvae settling patterns on all the substrates. In 2018/2019, no mussels settled at all on the Swedish bands in the Kalmarsound which indicates a poor performance of this substrate type in this area. In Kiel there was good settling and growth on the Swedish bands and the Swedish bands carried a biomass higher than what was found on any of the other substrate types. Commercial production with Swedish bands usually include 2400 m of Swedish bands for every 200 m rope, and the continuous loops go as deep as 6 m, which means that they are twice as deep as the nets. The biomass from a commercial unit with Swedish bands could therefore produce more biomass (124 kg m^{-1} headrope x 200m = 24.8 tons) than a commercial unit with nets (76 kg m^{-1} headrope x 120 m = 9.12 tons) based on results from the Kiel farm in 2017/2018. However, depth study from the Kalmarsound farm indicates that mussels growing deeper in the water column will have less growth, due to reduced food availability.

Unfortunately, growth rates have in general been low in the remaining demonstration farms within the Baltic Blue Growth project, and challenges that might come with large mussels on Swedish bands has therefore not been tested in this project. If the mussels are large and in high biomass on the Swedish Bands, they have a high risk of falling off. This is most likely what happened in Kiel in 2018, where most of the larger mussels disappeared from nets and bands. This can be prevented by thinning the mussels in high growth areas. This is an aspect that we have not yet tested on the remaining demonstration farms, and because of relatively low growth rate in the Baltic Sea region, this may never become a problem.

Net substrates. In general, there was no difference in the growth rates of mussels on the different mesh sizes of the net substrates at any of the test sites. This was in line with the assumption, that the growth rate was unaffected by differences in mesh size, when densities of mussels did not result in food limitation. Hence very small mesh sizes can potentially create an almost closed mussel net, that reduces the food availability.

With respect to biomass, there were significant differences between nets with different mesh sizes. The largest amount of biomass per meter headrope at the beginning of the production period was often on the net substrates with the smallest mesh sizes (30, 50 and 60 mm) in comparison to substrates with the largest mesh sizes (150 – trawl nets and 150 and 300 mm - Smartfarm nets). This tendency often continued as the production period progressed, as the estimated biomass was also greatest on the smaller and mid-range mesh sized substrates (30-100 mm) at the end of the sampling period. Here, the biomass on the small and medium mesh substrates was typically twice as high as the biomass on the net substrate with largest mesh size (300 mm – Smartfarm nets). Overall, the test of different mesh sizes and nets was influenced by other parameters such as the interannual variation in recruitment and growth, different deployments, rough weather conditions and loss to predation. Hence, the most important results from this study is the documentation of growth and recruitment on different types of substrates, that allows the farmer to focus on other important parameters in mussel production such as cost price, robustness of the production system and how easy the system is to work with.

Growth and biomass comparison at different salinities

Growth rates and biomass per area substrate was the greatest at Kiel where salinities were approximately 15 ppt. In comparison, observed growth rates and the first exploratory growth rates were considerably lower at Byxelkrok and at the Coast of Kurzeme where salinities were lower at 7 and 7.5 ppt. Growth rates at Byxelkrok may however, have been affected by completion by barnacles (fouling) on substrates at this test site. Similarly, at Musholm, where salinities were approximately 15 ppt, Growth rates were strongly affected by the biases created by the size-selective predation of mussels by Eider birds. Hence, this study shows that growth rates can be secondary to determine production potential in areas with other parameters affecting the mussel production.

Timing of substrate deployment

The larvae settlement was similar at the different places in the Baltic Sea, happening within the month of June in Sweden, Denmark, Latvia and Germany. The settlement of mussel larvae was unsuccessful in the Latvian and Estonian farm during the last substrate test in 2018/2019 which was due to a substrate deployment in late June, most likely after the main settlement had occurred.

Results from deployment of Swedish Bands in Kiel Bay at different times during the season (April or August) showed that the average length of mussels on Swedish Bands deployed in April before the early larvae settlement was only slightly larger than the average length of mussels on Swedish bands deployed in August. The following year samples were taken from the substrates deployed in April and from substrates deployed the year after in June. The results showed, that the new settling pushed off the larger mussels and the substrate deployed late ended up being the one gaining most biomass. Hence, the timing of substrate deployment is important and should be targeting the main settling of mussel larvae in June.

Biases

The biomass estimates were based on few samples compared to the length measurements that were based on more than a hundred mussels for each sample. In the Kalmarsound, as an example, there was only one weight result for the biomass on Swedish band from each of the two sampling occasions. Hence, the estimate of biomass on Swedish bands in Kalmarsound is not necessarily representative of a general picture of the performance of this substrate in the area. The sampling was optimized with regard to biomass estimates in the substrate study in 2018, where more samples were taken for weight measurements.

Also from the Kalmarsound, a study of uncertainties with regard to the length measuring method was carried out, where the same sample was measured twice. This study showed that despite of homogenized procedures in the lab, there are large uncertainties related to the measuring method, and that the results therefore should be read without decimal numbers, and not much interpretation should be put into minor size differences.

The results at Musholm were biased by Eider duck predation on mussels while the results at the Kalmarsound farm were potentially biased by fouling, rough weather and the large amount of barnacles that also settled on the substrates. The Latvian farm faced challenges from predation by the rounded goby, hence this study documents area specific challenges with regards to mussel farming and production.

Predation by Eider ducks at Musholm was enormous and reduced the amount of mussels on all the substrates to less than 10 % of what could be expected on the substrates under optimal conditions. The size-selective predation by Eider ducks, which select the largest mussels first, no doubt biased results, both by decreasing the estimated growth rates and by reducing the overall biomass on the substrates. Although there was clearly predation on all the substrates, it is difficult to determine how this effects the results from each substrate and the overall interpretations.

Similarly, fouling by the settling of barnacles on all the substrates in Kalmarsound may have also created an undeterminable bias of results from this test site. This could have an effect on both mussel growth rates and mussel biomass development as mussels would have to compete for both space on the substrates they share with barnacles and for food, as barnacles, like mussels, are also filter feeders.

The movement of mussels to the warmer waters in the Kalundborg channel did not appear to have an effect on mussels at this test site, as there was no apparent change in the growth rate as one might expect. However, moving the mussels appear to have solved the problem of predation by Eider birds as an increase in mussel biomass on the different substrates once again continued to increase after the move to the more protected area.

Conclusion and recommendations

The Baltic Blue Growth project focused on production of small mussels in high quantities as a blue biomass for the feed industry. All substrate types being trawl nets and smartfarm nets with different mesh sizes, Fuzzy ropes, and Swedish bands all proved applicable in biomass production of mussels in the Baltic Sea, though with a high inter annual production yield and a low performance of smartfarm nets. These results allow the mussel farmer additionally, to focus on cost price of the substrate, and how easy the production system and substrate type is to handle, instead of having a narrow assortment to choose from.

Settlement of mussel larvae appeared to happen in June throughout the Baltic Sea during the years from 2016 to 2018, and it is recommended, that substrates for mussel farming is deployed in May the latest.

Furthermore, as the study shows that there is no guarantee for more biomass on substrates deployed for several growth cycles in high productive areas such as the Kiel Bay, one should implement additional strategies for production such as thinning. On the contrary, several growth cycles may be optimal in areas such as the Vormsi farm in Estonia or the St. Anna farm in Sweden.

From the growth and recruitment study, and from the substrate test study it is clear, that the production potential in different areas of the Baltic Sea, does not only follow variation in salinity and food availability. It very much depends on the site-specific growth environment where e.g. predation on mussel farms can be an obstacle for any mussel growth at all. A thorough screening of a potential mussel farming area with respect to food availability, predation, weather conditions and competing species is therefore heavily emphasized before a possible mussel production is initiated in the Baltic Sea region.

Picture 24.Mussels on Musholm on trawl net. The picture was taken in November 2016.

11. Relevant literature, reports, and ongoing projects

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Relevant ongoing projects:

Bonus Optimus project: http://www.bonus-optimus.eu/

MuMiPro: http://www.mumipro.dk/