Baltic Blue Growth

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Ecological impacts at the small-scale commercial mussel farms in the Baltic Sea

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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 Center VCO (SE)*
- *Kalmar municipality (SE)*
- *Kurzeme Planning Region (LV)*
- *Maritime Institute in Gdańsk (PL)*
- *Ministry of Energy, Agriculture, Environment and Rural Areas (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)*
- *Swedish Institute of Agricultural and Environmental Engineering JTI (SE)*

Executive summary

Worldwide, the aquaculture, including mussel production, has been fastest growing sector of the food industry since 1970-ties (McKindsey et al. 2011). The increase in production has generated also increase of concerns related to impacts of the activities on local environments. Although, initially concerns were directed at fish farming the localized increase of biodeposition generated by farmed bivalves has been an issue of interest for several decades as well (e.g., Mattsson and Lindén 1983; Kaiser et al., 1998; Mirto et al., 2000; Fabi et al., 2009; Wilding and Nickell 2013).

More recently mussel farming has been considered also as a measure to mitigate N and P in coastal waters of the Baltic Sea. The Baltic Sea Action Plan (HELCOM, 2007) has identified country specific targets for nutrient reduction. Consequently, the countries have been devising and implementing plans to comply with these targets. So far, the main focus has been on terrestrial reduction measures. However, none of them so far has been sufficient to reduce nutrient loading and eutrophication (Petersen et al., 2012) and it has been argued that costs of further possible mitigation measures if they approach their technological limits might exceed those of mussel farming (Rose et al., 2012). Furthermore, it has been stressed that mussel farms can be very effective at mitigation on a local scale since the mussel effect is immediate in contrary to land based measures where effects often have large time lags. On the other hand, there has been expressed concern that sedimentation of organic material can lead to enhanced oxygen consumption below mussel farm resulting in hypoxic or even anoxic conditions that will negatively alter nutrient release from sediments (Stadmark and Conley 2011) so arguing that nutrient removal by this method is substantially offset by altered environmental conditions. However, it should be stressed that effect of enhanced biodeposition under mussel farms is local and highly site specific from limited impact of farm on benthic environment in sheltered already hypoxic area (Holmer et al., 2015) to increase in biomass and species richness (e.g., Kraufvelin and Diaz 2015; Ysebaert et al., 2009) in well oxygenated coastal areas. There have been few cases when negative impact of mussel farms on benthic communities was demonstrated (e.g., Christensen et al., 2003), however, none of them was in the Baltic Sea.

Nevertheless, there have been only few studies on actual impact of mussel farm on environment. Therefore, in order to supplement knowledge base on mussel farm environmental impacts we present environmental impact study results from mussel farms deployed at six different areas of the Baltic Sea (Figure 1). All farms, except one (Pavilosta mussel farm at Kurzeme coast) are located at more or less sheltered areas. The most sheltered was Sankt Anna mussel farm. It was also located in comparatively deep area (20 m) as was Pavilosta mussel farm. Other farms were located in comparatively shallow (8-10 m) areas. Consequently, relatively dynamic water exchange conditions in near-bottom water were observed during study. Thus, generally near-bottom water was relatively well oxygenated at both mussel farm and reference sites. At the same time, at almost all areas temporal thermocline or halocline could be observed during summer, although, during most of the time the water column was quite well mixed. Especially pronounced water stratification was during summer months of 2018 when at Sankt Anna mussel farm oxygen in near-bottom layer was completely depleted in August. It should be stressed, however, that this event was completely natural as evidenced by data since oxygen was depleted at both mussel farm and reference sites. Furthermore, data from June 2018 suggest that oxygen depletion occured more rapidly at reference site than at mussel farm site most likely due to slight differences in near-bottom water hydrology.

Similarly to oxygen also nutrient concentrations at all farm and their respective reference areas exhibited natural patterns. As observations were mainly focused on productive season, when most severe impacts of mussel farm could be expected, the nutrients were mostly bound in organic (living organisms and detritus) fraction. The nitrogen limitation, characteristic for areas of the Baltic Sea where mussel farms were located, has been clearly evidenced since inorganic phosphorus formed substantially larger proportion from total phosphorus than inorganic nitrogen from total nitrogen. There could be observed nutrient concentration buildup in near-bottom water during summer months, however, the level of this buildup was dependent on the level of vertical water stratification and so no influence of mussel farm could be detected.

As in case of nutrients and oxygen, the species composition and abundance of phytoplankton as well as its proxy chlorophyll *a* did not manifest any clearly distinguishable impact of mussel farms. The observed changes in species composition and biomass was most likely the result of inter-annual variability of environmental factors. Therefore, it can be assumed that variability generated by natural factors substantially exceed any effect created by small-scale mussel farms.

It could have been expected that in relatively shallow and hydrologically dynamic areas enhanced sedimentation of organic particles caused by mussel farm would leave limited impact on such factors as near-bottom water oxygen and nutrient concentrations. Therefore, particular attention was given to community of benthic organisms inhabiting sediments just below the mussel farms. By comparing data from benthos monitoring stations just below mussel farms with those at reference site at none of sites negative impact of mussel farm could be identified. Rather the opposite since at most mussel farms (Sankt Anna, Kalmarsund, Musholm, Kiel) the species richness (number of encountered species) was higher than at respective reference areas. The differences in biomass for those species that are encountered both in mussel farm and reference area are less pronounced since for some species biomass is larger in mussel farm area but for other species in reference site. Furthermore, it is not uncommon when the relative biomass ratio (mussel farm/reference site) is shifting from one year to another. The benthic community in Pavilosta mussel farm area also differ very substantially from reference area mainly due to large number of juvenile mussel *Mytilus trossulus* that are encountered in mussel farm area and are not encountered at reference site. However, since the difference was observed already in 2017 when mussel farm was just recently established and could not have had any impact on environment it seems more plausible that other factors have been more important. The most probable explanation is that the mussel farm has been established in area where coastal fishery is very active in contrary to reference site where coastal fishery is not as active. So, the round goby population could be substantially suppressed due to fishery and that in turn decreases predation pressure that round goby otherwise would impose on mussel population.

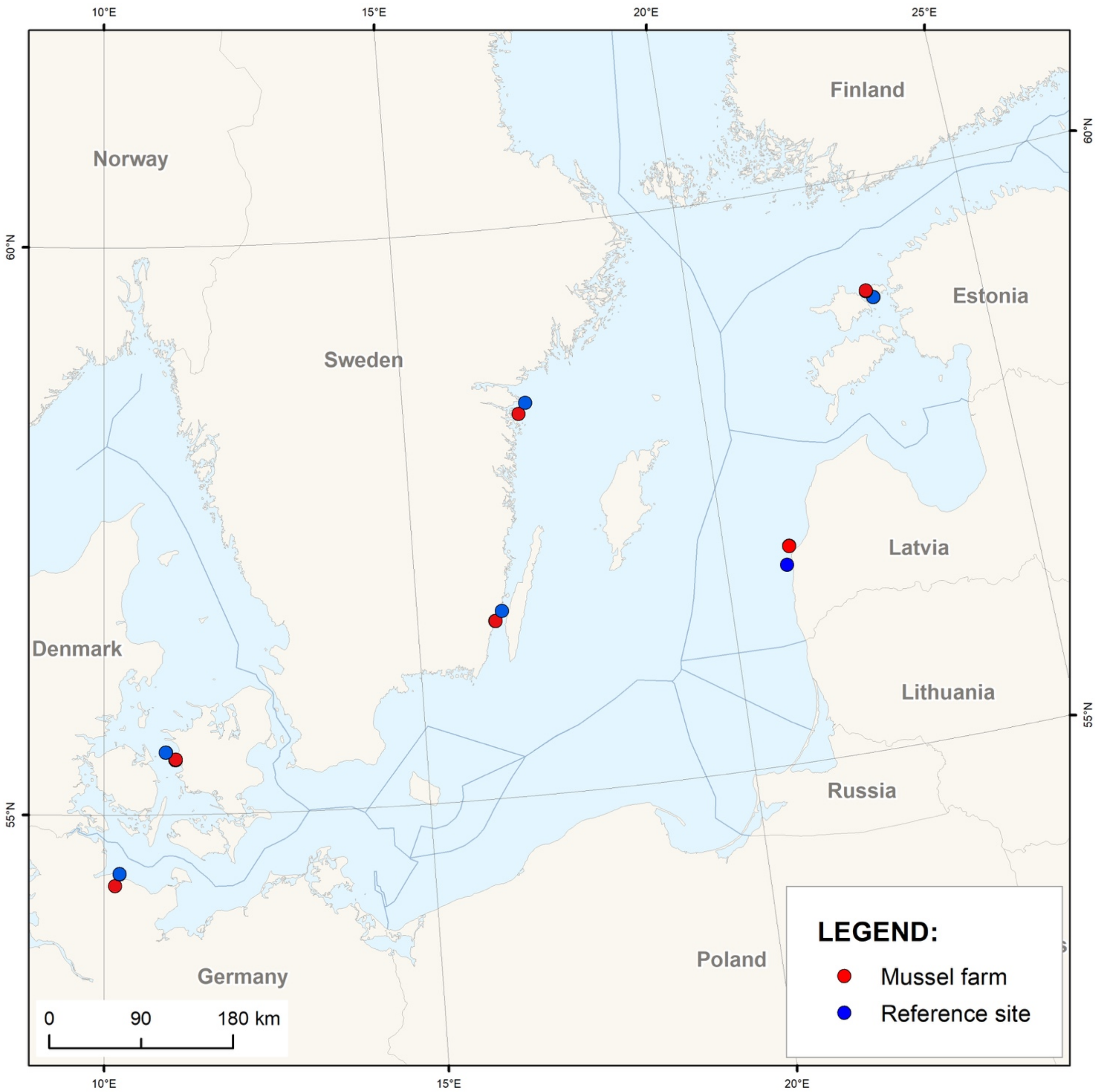


Figure 1: Locations of mussel farms and reference sites

1. Site description

1.1. Sankt Anna mussel farm

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 very sheltered archipelago of Östergötland (Figure 1.1) just east of the island Inre Kärrö (58° 21,22’ N; 56° 56,14’E). The area of the farm is part of protected natural area. The water depth at the farm area is approximately 20 m and water salinity varies between 6 and 7 g kg^{-1}. During summer temporal vertical stratification can be observed in the area. The farm area is 0,5 ha and mussel growth depth is 2-12 m.

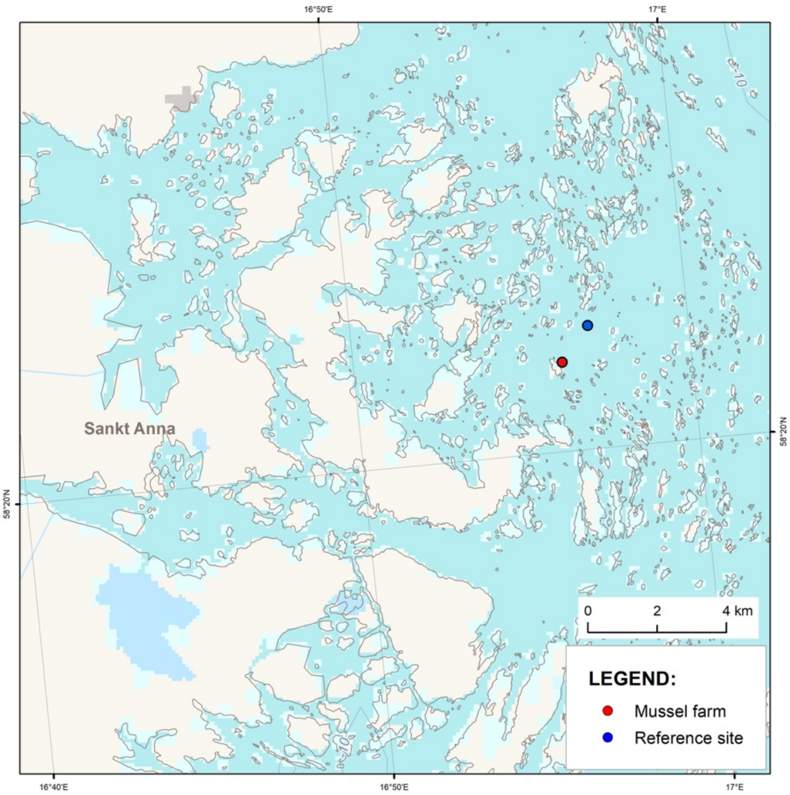


Figure 1. 1: Location of Sankt Anna mussel farm and reference site

The soft sediments under the farm as well as at reference area is characterized by relatively high carbon, nitrogen and phosphorus concentrations (Table 1.1). No distinct differences between mussel farm and reference areas could be identified. The observed differences most likely are due to local spatial variability.

Table 1. 1: Concentrations of carbon, nitrogen and phosphorus in sediments under the Sankt Anna mussel farm and at the reference site in June 2018

Site	Mussel farm (n=5)			Reference (n=5)		
	TC (% dw)	TN (% dw)	TP (µg/kg dw)	TC (% dw)	TN (% dw)	TP (µg/kg dw)
Sankt Anna	8,15 (7,85-8,55)	1,06 (1,04-1,10)	573 (560-590)	7,90 (7,77-8,05)	1,08 (1,07-1,09)	595 (560-645)

1.2. Kalmarsund mussel farm

The Kalmarsund mussel farm is placed in an exposed area at the northern inlet of the Kalmarsound (Figure 1.2) between the Swedish East Coast and Öland island. The farm uses a submerged net-farm

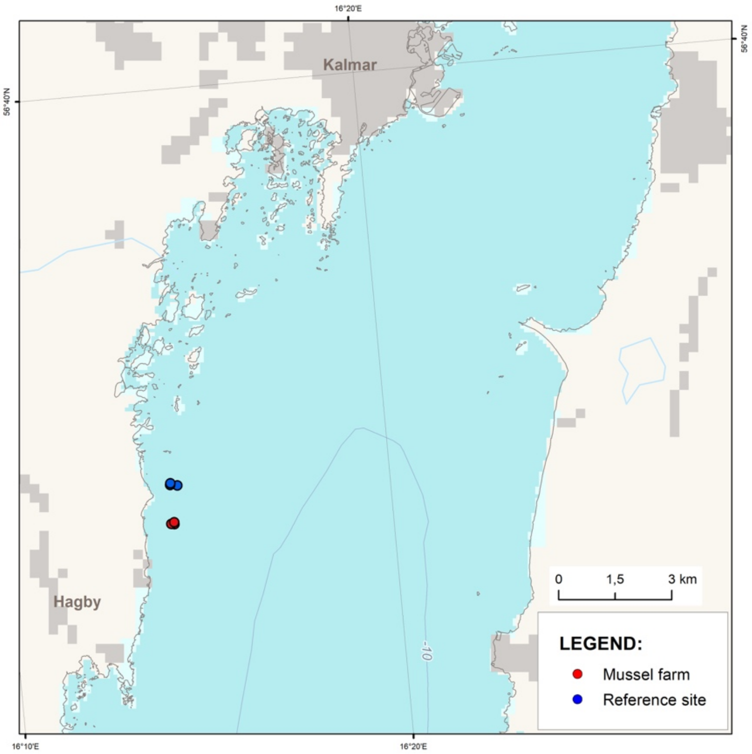


Figure 1. 2: Location of Kalmarsund mussel farm and reference site

production system (growth depth is 3-6 m) which has been designed to withstand ice and offshore conditions.

The soft sediments under the farm as well as at reference area is characterized by relatively moderate carbon, nitrogen and phosphorus concentrations (Table 1.2). No distinct differences between mussel farm and reference areas could be identified, except for phosphorus, where substantially higher concentrations were observed at reference site. The observed differences in carbon and nitrogen concentrations most likely are due to local spatial variability. The phosphorus concentrations are rather low at both areas as could be expected in exposed coastal area and it is quite likely that observed differences in phosphorus concentrations between mussel farm area and reference site are due to natural variability.

Table 1. 2: Concentrations of carbon, nitrogen and phosphorus in sediments under the Kalmarsund mussel farm and at the reference site in June 2018

Site	Mussel farm (n=5)			Reference (n=5)		
	TC (% dw)	TN (% dw)	TP (µg/kg dw)	TC (% dw)	TN (% dw)	TP (µg/kg dw)
Kalmarsund	2,23 (1,22-3,35)	0,31 (0,16-0,46)	131 (122-138)	2,19 (1,70-2,43)	0,31 (0,24-0,34)	219 (202-229)

1.3. Musholm bay mussel farm

The Musholm bay mussel farm is placed in relatively shallow and exposed area (Figure 1.3) with general strong currents, shifting salinity and rough weather. Although, the water depth at mussel farm is only around 8 m temporal events of halocline can be observed. The mussel growth depth was 0-4,5 m.

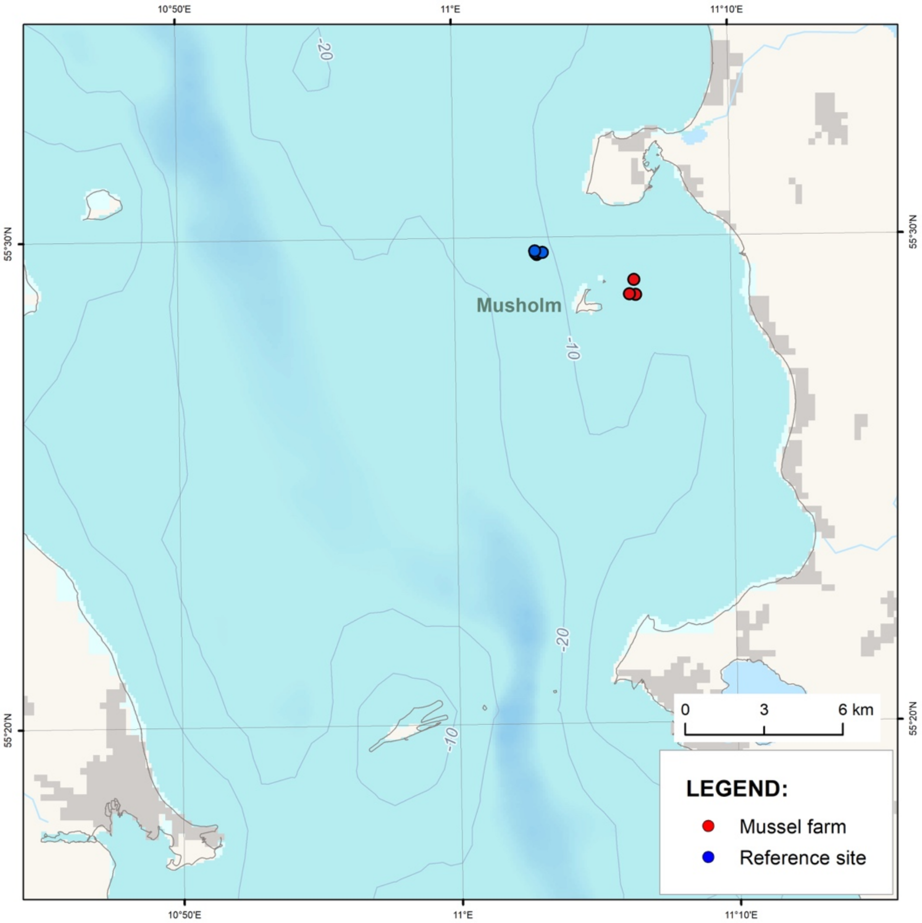


Figure 1. 3: Location of Musholm bay mussel farm and reference site

The soft sediments under the farm as well as at reference area is characterized by relatively low carbon, nitrogen and phosphorus concentrations (Table 1.3). The reference site exhibit relatively higher concentrations of carbon and nitrogen at reference site, while no distinct differences between mussel farm and reference areas could be identified for phosphorus. The observed differences in carbon and nitrogen concentrations most likely are due to local spatial variability.

Table 1. 3: Concentrations of carbon, nitrogen and phosphorus in sediments under the Musholm bay mussel farm and at the reference site in June 2018

Site	Mussel farm (n=5)			Reference (n=5)		
	TC (% dw)	TN (% dw)	TP (µg/kg dw)	TC (% dw)	TN (% dw)	TP (µg/kg dw)
Musholm bay	0,59 (0,54-0,66)	0,05 (0,04-0,06)	242 (223-253)	1,22 (0,95-1,54)	0,12 (0,11-0,15)	253 (210-267)

1.4. Kiel bay mussel farm

The Kiel bay mussel farm is placed in a shallow and sheltered area (Figure 1.4). The mussel growth depth is ……… m. The water depth at mussel farm is around 9 m and the salinity varies between 15 and 16 g kg^{-1}. The water column is fairly well mixed vertically, however, slight salinity and temperature differences between surface and bottom water layers can be observed.

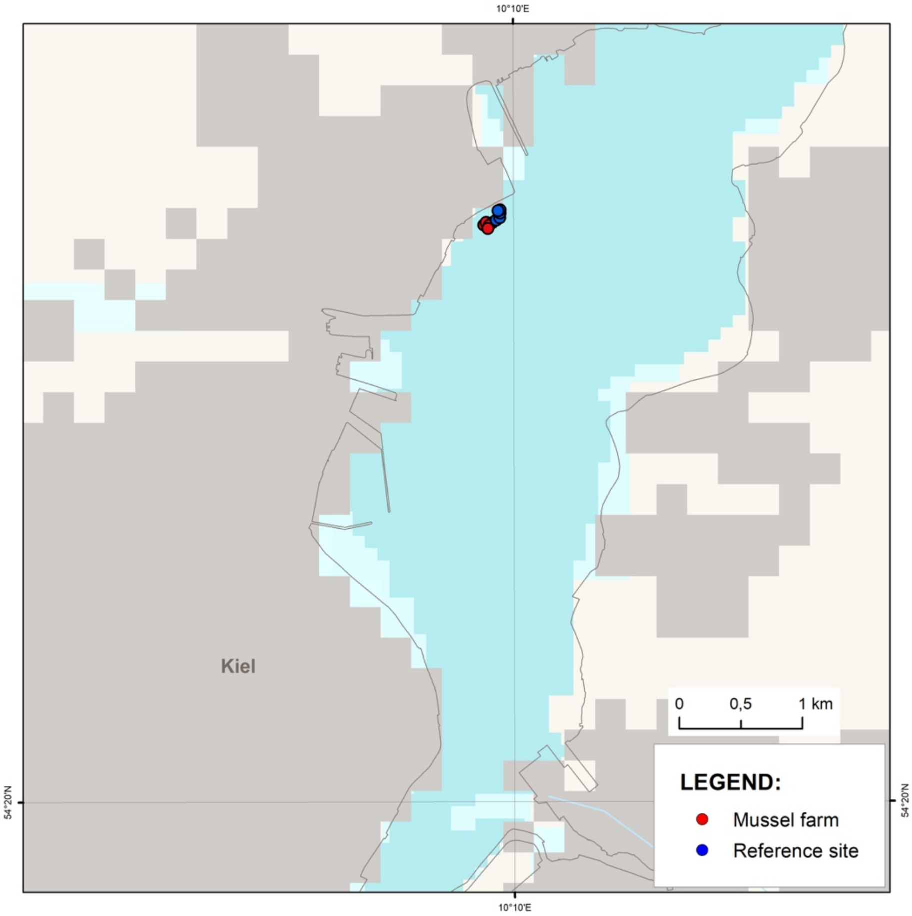


Figure 1. 4: Location of Kiel bay mussel farm and reference site

The soft sediments under the farm as well as at reference area is characterized by relatively high carbon, nitrogen and phosphorus concentrations (Table 1.4). The reference site exhibit relatively lower concentrations of carbon and nitrogen at reference site, while phosphorus concentrations at reference site are slightly higher than at mussel farm site.

Table 1. 4: Concentrations of carbon, nitrogen and phosphorus in sediments under the Kiel bay mussel farm and at the reference site in June 2018

Site	Mussel farm (n=5)			Reference (n=5)		
	TC (% dw)	TN (% dw)	TP (µg/kg dw)	TC (% dw)	TN (% dw)	TP (µg/kg dw)
Kiel bay	6,86 (6,15-7,56)	0,7 (0,58-0,82)	477 (451-496)	5,96 (5,04-6,88)	0,55 (0,45-0,68)	493 (469-532)

1.5. Pavilosta (Coast of Kurzeme) mussel farm

The Coast of Kurzeme mussel farm is placed in a very exposed area (Figure 1.5) some 5 km off the shore. The area is exposed to strong wind and high waves that ensures rapid water circulation in the area. The water depth in the mussel farm and reference site is approximately 19 m. The water salinity is around 7 g kg^{-1}. The water temperature increased from around 4 °C in spring to around 22 °C in summer of 2018 and development of temporal thermocline can be observed during summer. The bottom substrate is consisting mostly of stones with small patches of hard moraine and sand. Therefore, measurements of carbon, nitrogen and phosphorus content of sediments was not possible. To protect the cultivation units, the mussel farm was completely submerged to 5 m depth (growth depth 5-8 m) in 2017 and to 10 m depth (growth depth 10-14 m) in 2018.

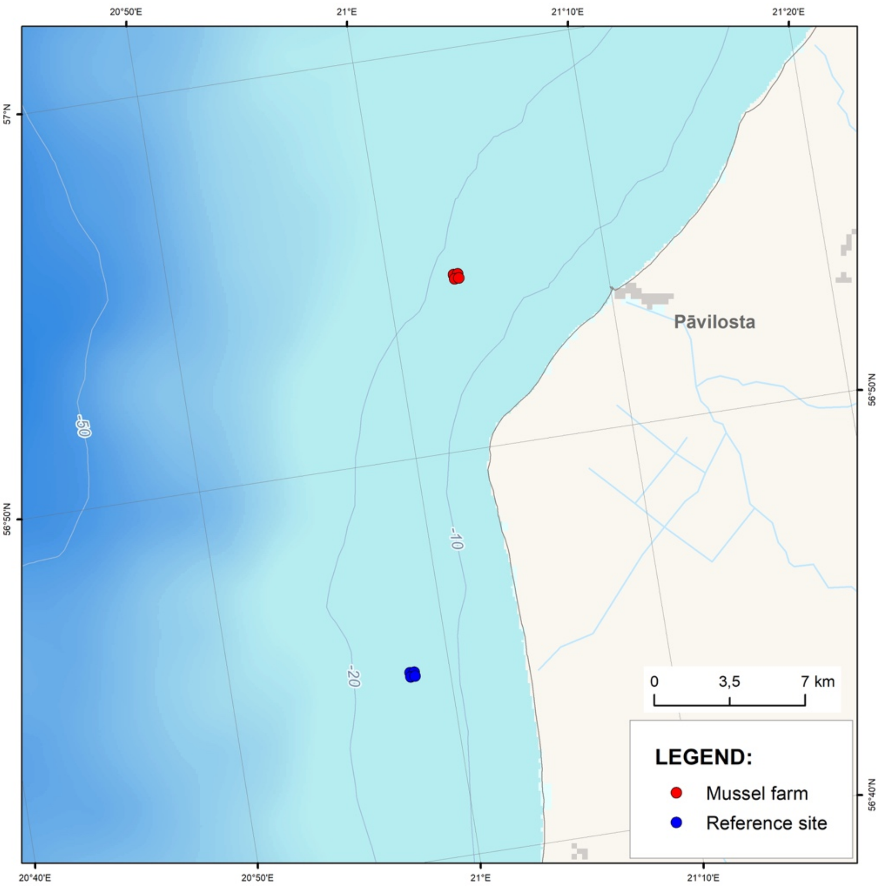


Figure 1. 5: Location of Coast of Kurzeme mussel farm and reference site

1.6. Vormsi island mussel farm

The Vormsi island mussel farm is placed in a sheltered area (Figure 1.6) outside the island of Vormsi. The water depth is around 8 m and water column is mostly well mixed. However, formation of temporal thermocline can be observed during summer. The salinity is fluctuating between 6,5 and 6,8 g kg^{-1}. The mussel growth depth is 0-3,5 m.

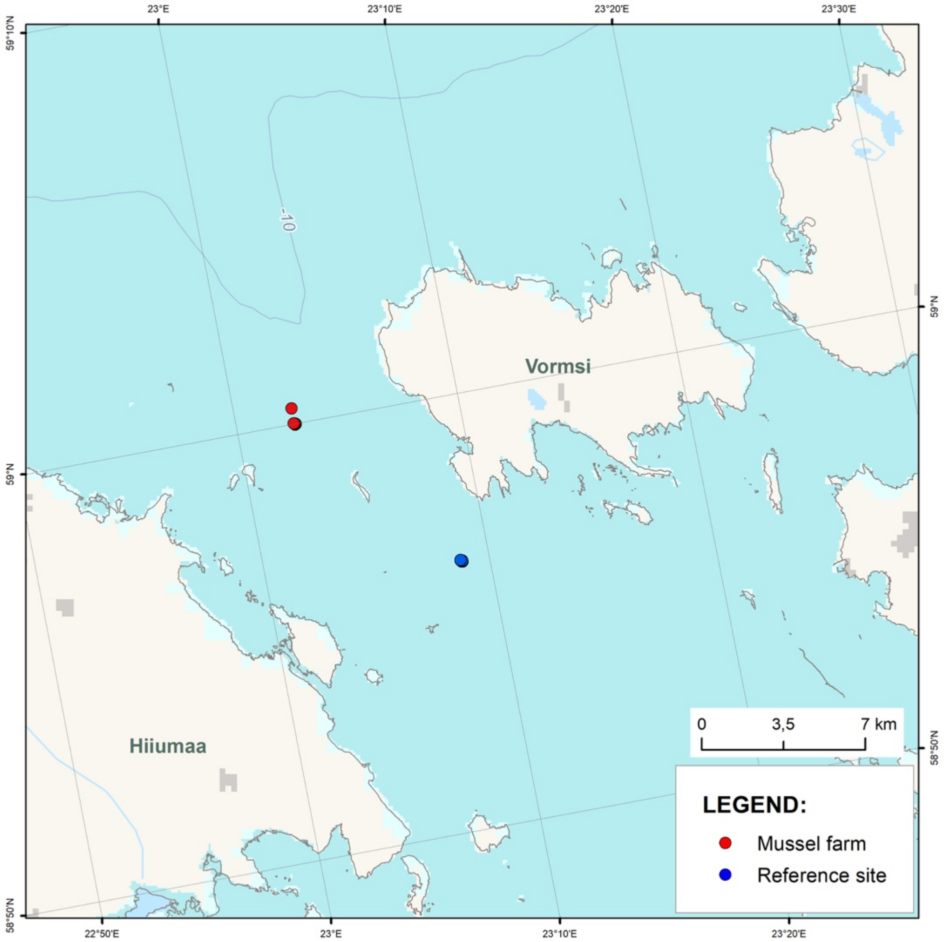


Figure 1. 6: Location of Vormsi island mussel farm and reference site

The soft sediments under the farm as well as at reference area is characterized by relatively low carbon, nitrogen and phosphorus concentrations (Table 1.5). The reference site exhibit relatively higher concentrations of carbon and nitrogen at reference site, while phosphorus concentrations at reference site are slightly higher than at mussel farm site. The observed differences in concentrations most likely are due to local spatial variability.

Table 1. 5: Concentrations of carbon, nitrogen and phosphorus in sediments under the Vormsi island mussel farm and at the reference site in June 2018

Site	Mussel farm (n=5)			Reference (n=5)		
	TC (% dw)	TN (% dw)	TP (µg/kg dw)	TC (% dw)	TN (% dw)	TP (µg/kg dw)
Vormsi	1,87 (1,71-2,32)	0,09 (0,07-0,15)	154 (110-189)	2,97 (2,00-3,89)	0,17 (0,1-0,2)	272 (201-326

2. Mussel farm monitoring results

2.1. Salinity, temperature and dissolved oxygen

2.1.1. Sankt Anna mussel farm

In June 2017, salinity was homogenous throughout the whole water column (Figure 2.1) in mussel farm (6.8 g/kg) and reference location (6.9 g/kg). While temperature (around 13.0 ºC) and oxygen (7.3 ml/l) in reference location was also homogenous in the whole water column it was not the case in the mussel farm. In mussel farm, there was observed gradual temperature (from 12.7 to 10.3 ºC) and oxygen decrease (from 7.3 to 6.5 ml/l) starting from 10 m depth till the bottom.

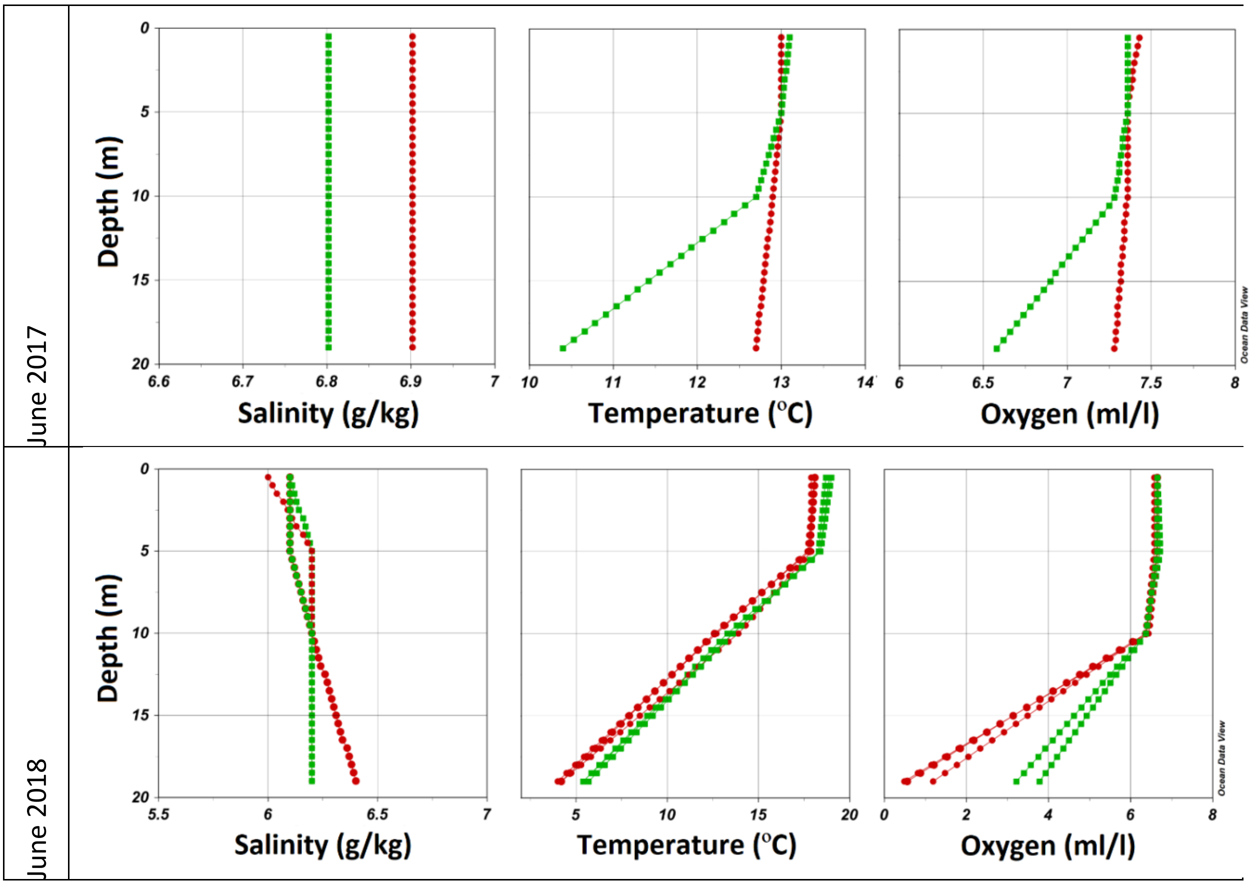


Figure 2. 1: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in June

In June 2018, salinity, temperature and oxygen was similar in mussel farm and reference location (Figure 2.1). Salinity varied between 6.0-6.5 g/kg which was lower than observed in June 2017 and salinity was not as homogenous as in June 2017. Temperature had distinct gradient in both locations with increased temperatures in the upper layer (around 18.0 ºC) and further gradual decrease of temperature till the bottom layers. This gradual decrease of temperature was evident also in reference location as opposed to June 2017. Similar situation as with temperature was observed also regarding oxygen dynamics. However, oxygen concentration in bottom layer was higher (by about 3.0 ml/l) in mussel farm.

In August 2017, salinity data was equal in mussel farm and reference location (Figure 2.2) and it was the same as observed (6.8 g/kg, also homogenous throughout the water column) in June 2017. Temperature in the reference location was not homogenous (as it was in June 2017) anymore and upper layers were approximately 3.0 ºC warmer than bottom layers. In mussel farm this difference between layers was not so pronounced (around 1.5 ºC). Oxygen decreased gradually from approximately 5 m depth in both locations, although the decrease was more prominent in reference location (from 6.0 to 2.0 ml/l). Upper layer oxygen in August 2017 was more than 1.0 ml/l lower than in June 2017 and this difference only increased closer to the bottom layers.

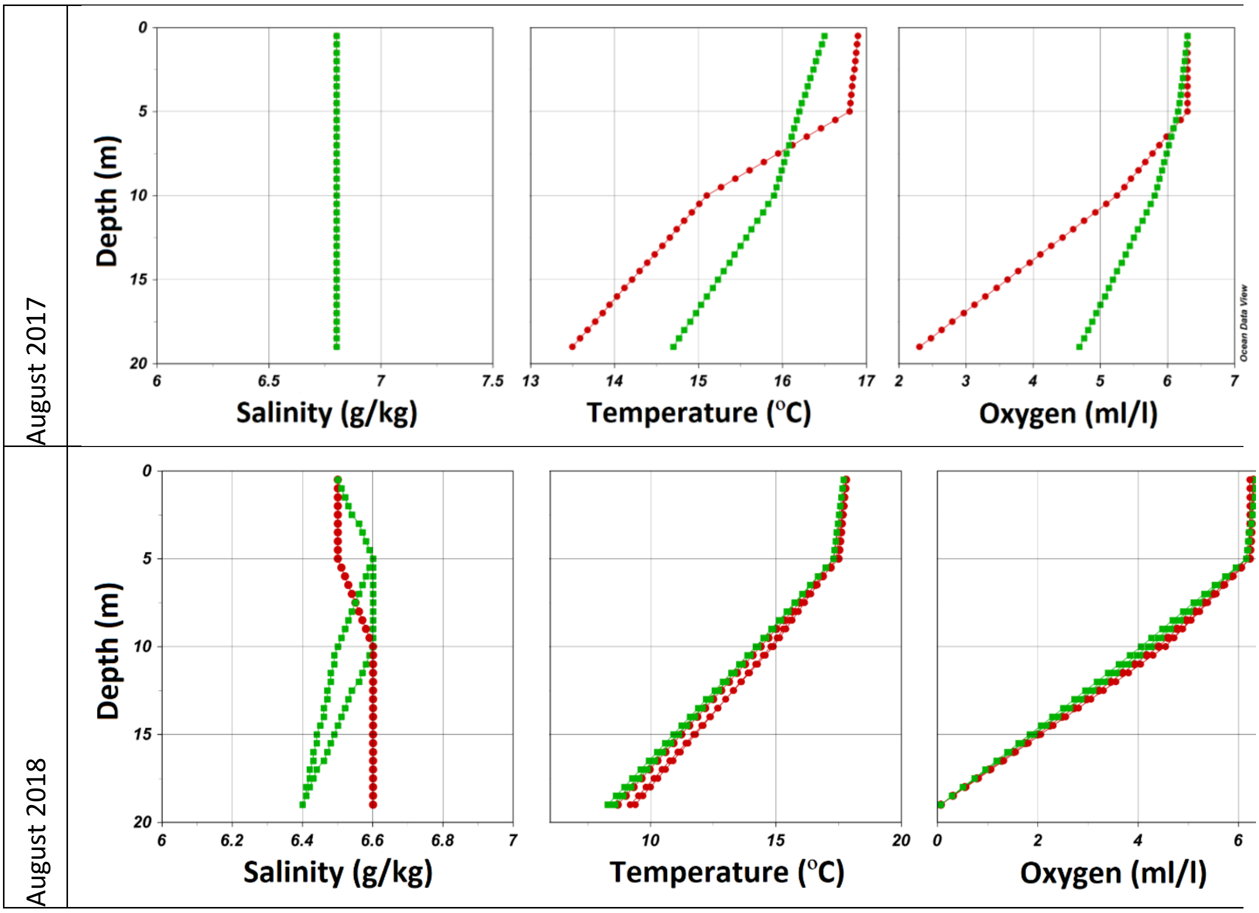


Figure 2. 2: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in August

In August 2018, temperature and oxygen in mussel farm and reference location was almost identical (Figure 2.2). In bottom layer, there was no oxygen in both locations as opposed to August 2017 where oxygen was still evident (low concentrations, though) in bottom layers.

In October 2017, all parameters were pretty much homogenous again throughout the whole water column due to the convective mixing (Figure 2.3). Salinity in mussel farm (6.6 g/kg) and reference location was about 0.2 g/kg lower than in June and August 2017. Temperature and oxygen was quite similar in both locations – temperature varied between 11.7-11.8 ºC and oxygen was around 7.1 ml/l in both locations.

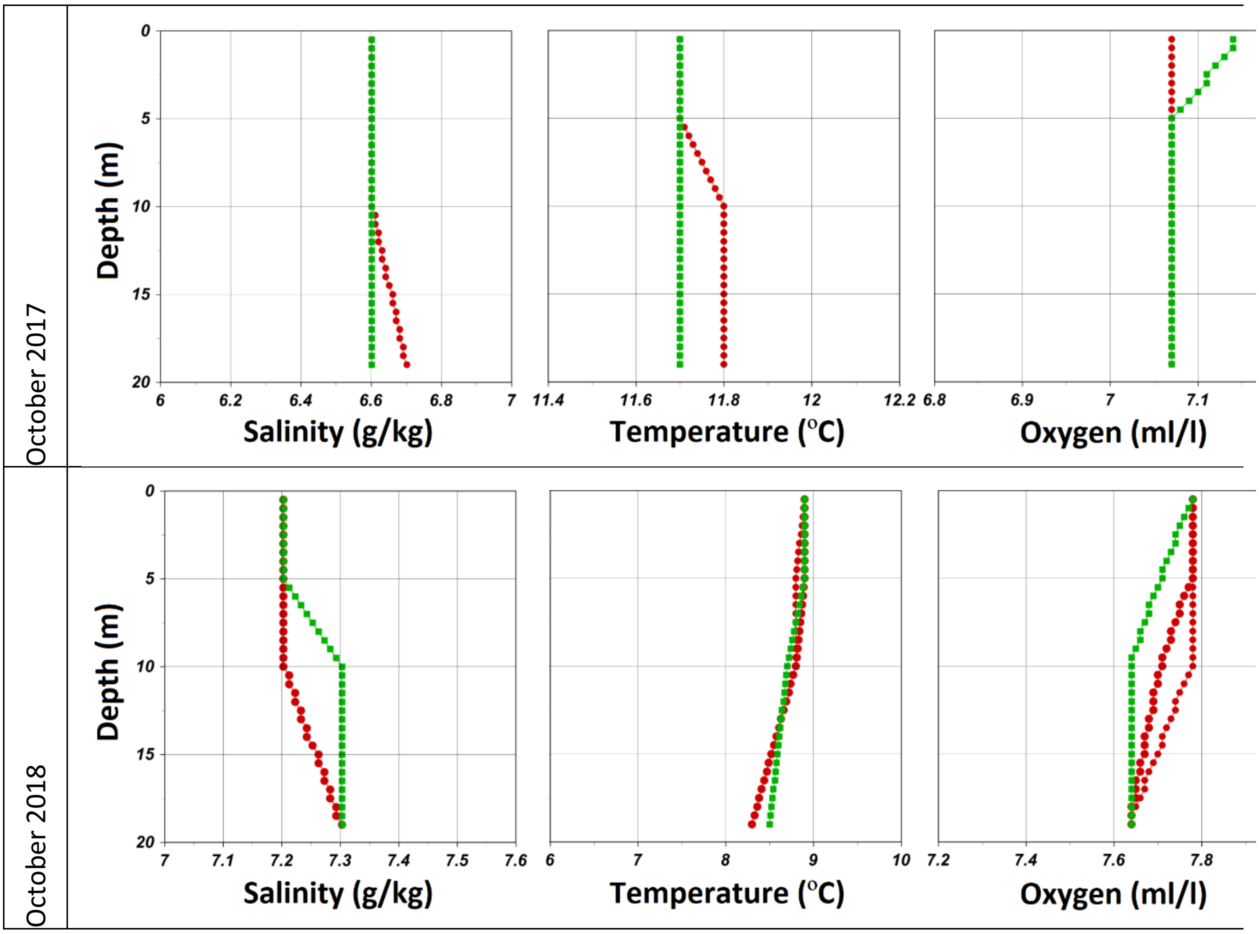


Figure 2. 3: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in October

In October 2018, the vertical difference and mutual difference between parameters in mussel farm and reference location was minor similarly as it was observed in October 2017 (Figure 2.3). Salinity was between 7.2-7.3 g/kg in both locations and that was higher (by about 0.4 g/kg) than the values observed in October 2017. Temperature stayed between 8.0-9.0 ºC in both locations which was cooler than observed in 2017, whereas oxygen varied between 7.6-7.8 ml/l which was more than 0.5 ml/l higher than in October 2017.

The continuous measurements of oceanographic parameters (available on ODSS portal) in water layer just above seafloor covered period from autumn 2016 till summer 2017. The oxygen concentrations (Figure 2.4) generally were inverse of temperature with highest values during winter when water temperature was low and lowest during summer when temperature was at its maximum. At the same time, short term sharp oxygen concentration increase events were observed during summer. The corresponding increase in temperature suggest that the observed increase in oxygen concentration most likely was due to inflow of warmer and relatively oxygen rich surface water into near-bottom water layer.

Figure 2. 4: Oxygen dynamics in the bottom layers at the Sankt Anna mussel farm in 2016-2017 (Source: ODSS)

2.1.2. Kalmarsund mussel farm

In June 2018, there were seemingly 2 ensembles of data with mussel farm and reference location (Figure 2.5). First ensemble of data showed temperature between 15.7-15.9 ºC throughout the water column in both locations (farm and reference). The second ensemble of data comprises mussel farm with 18.1 ºC temperature and reference location with 18.5 ºC temperature throughout the water column. In September 2018 temperature data only about mussel farm was available (Figure 2.5). It showed temperatures between 15.7-15.9 ºC in mussel farm throughout the water column.

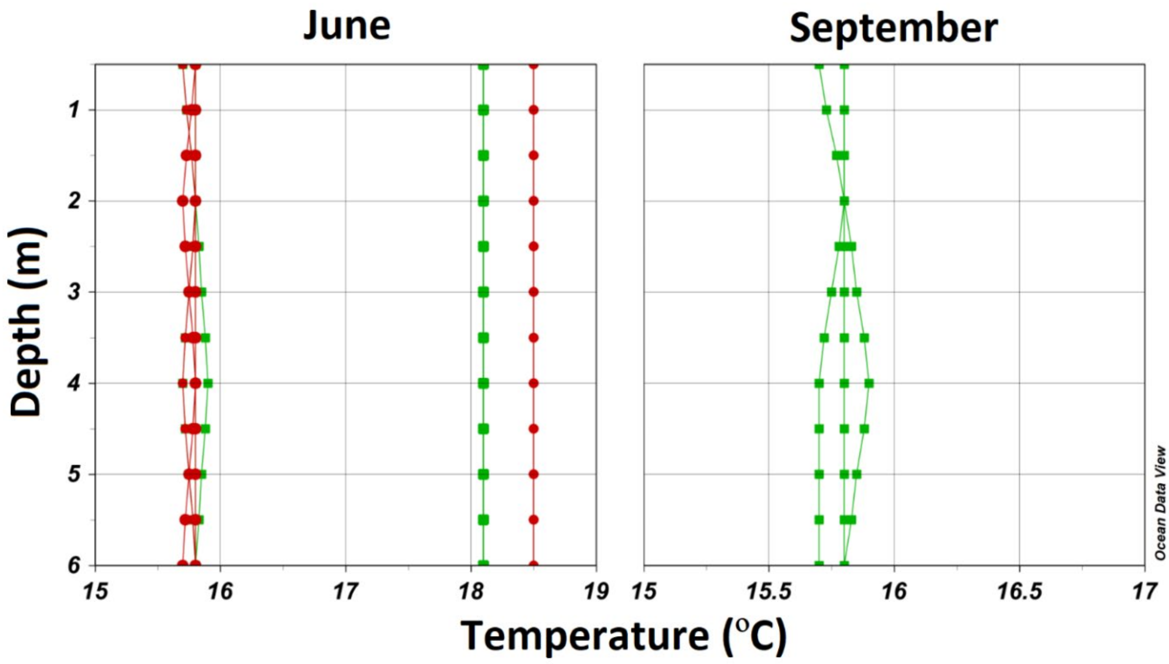


Figure 2. 5: Vertical distribution of temperature in mussel farm (green line) and reference location (red line) in June and September 2018

The continuous measurements of oceanographic parameters (available on ODSS portal) in water layer just above seafloor covered period from autumn 2016 till summer 2017 and from autumn 2018 till summer 2018. The oxygen concentrations (Figure 2.6) generally were inverse of temperature with highest values during winter when water temperature was low and lowest during summer when temperature was at its maximum. The short-term fluctuations of oxygen concentration reflect near-bottom water layer dynamic. And the relatively lower values of oxygen concentration in summer 2018 in comparison of summer 2017 indicates development of stronger thermal stratification in 2018.

Figure 2. 6: Oxygen dynamics in the bottom layers at the Kalmarsund mussel farm in 2016-2018. (Source: ODSS portal)

2.1.3. Musholm bay mussel farm

In June 2018, there was a disparity between different salinity, temperature and oxygen vertical profiles in mussel farm as well as reference location (Figure 2.7). Temperature and oxygen in the mussel farm was homogenous in the whole water column and it varied around 16.7 ºC and 6 ml/l, respectively. The reference location was apparently deeper and temperature and oxygen in it were higher than the ones observed in mussel farm, although, this applies only to 1 reference location profile which has substantially higher temperature (around 2.0 ºC) and oxygen (0.5 ml/l). The other profile has rather similar vertical dynamics as observed in the mussel farm. In the reference location below 10 m depth temperature decreased, whereas salinity and oxygen increased (Figure 2.7). Salinity in the mussel farm again strongly varied between 2 vertical profiles (more than 3.0 g/kg), although, salinity of approximately 21.0 g/kg seems unlikely taking into account that such salinity amount was not observed in August 2018 or October 2018.

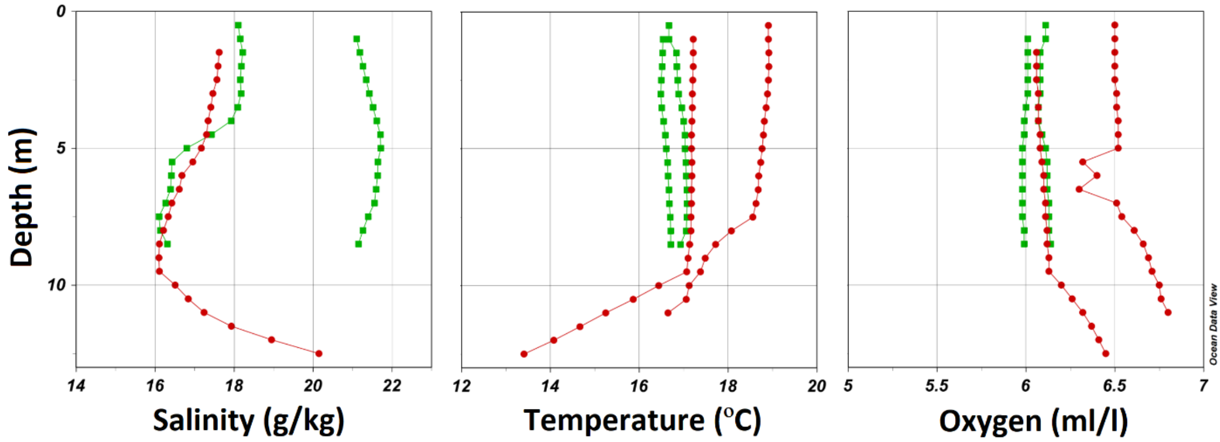


Figure 2. 7: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in June 2018

In August 2018 oxygen was mainly homogenous (except of bottom layers of reference location) and it mainly varied between 5.5-5.8 ml/l in mussel farm as well as reference location (Figure 2.8). Oxygen was lower than the one observed in June 2018 by about 0.2-0.3 ml/l, most probably, due to the more intense oxygen consumption by biota in summer. Salinity in August 2018 was higher than in June 2018 in both locations with salinity in reference location (about 20.0 g/kg) exceeding the one observed in the mussel farm (about 18.0 g/kg). Temperature in August 2018 was higher in whole water column if compared to June 2018 and temperature in the mussel farm (about 20.0 ºC) exceeded that observed in the reference location (about 19.5 ºC). Such a difference might be explained by the fact that the mussel farm is situated in the shallower waters than the reference location. Similarly, as in June 2018, also in August 2018 one can observe salinity and oxygen increase (also temperature decrease) in the bottom layers of the reference location. This might be explained by the fact that more saline and oxygen rich waters from the North Sea are penetrating inside the Baltic Sea through the bottom layers.

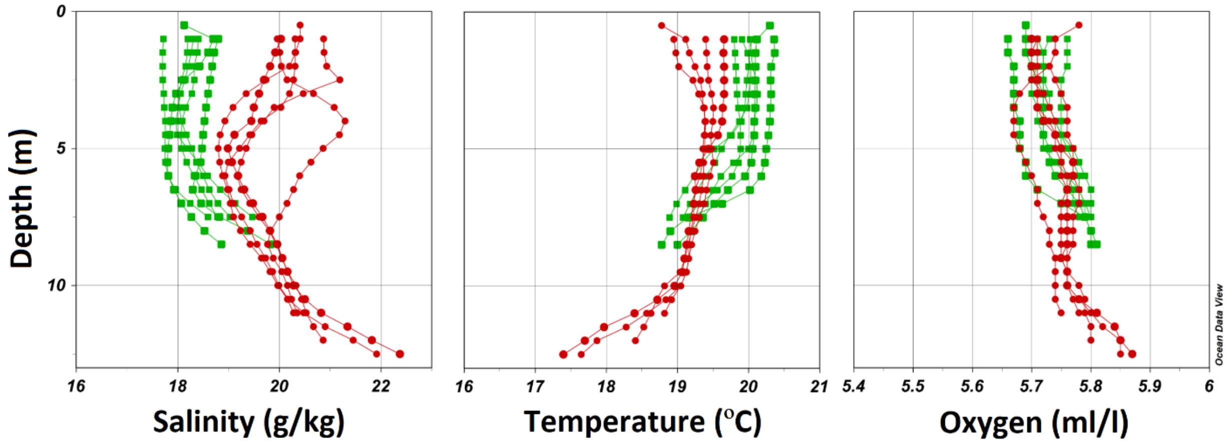


Figure 2. 8: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in August 2018

In October 2018, salinity, temperature and oxygen dynamics in mussel farm only slightly differed from reference location (Figure 2.9). Temperature in the upper layer was a bit (by about 0.5 ºC) higher in the reference location than in the mussel farm, whereas the oxygen was slightly lower in the reference location. Oxygen in October 2018 is higher (mainly between 6.6-6.8 ml/l) than the ones observed in June and August 2018. The different dynamics of bottom layers of reference location (salinity increased, temperature and oxygen slightly decreased) were seen as well in October 2018.

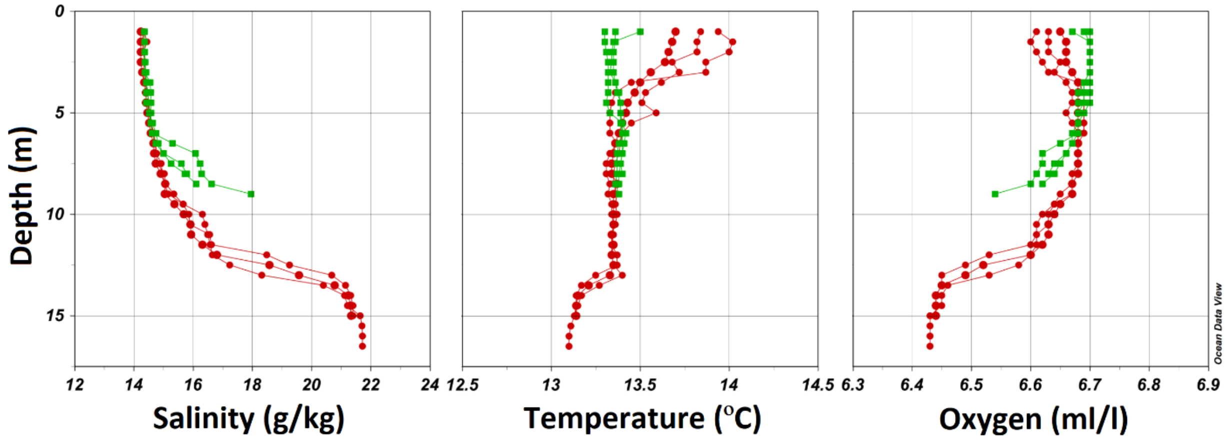


Figure 2. 9: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in October 2018

The continuous measurements of oceanographic parameters (available on ODSS portal) in water layer just above seafloor covered period from spring till autumn 2017. The oxygen concentrations (Figure 2.10) generally were inverse of temperature with highest values during winter when water temperature was low and lowest during summer when temperature was at its maximum. However, in contrary to other areas the oxygen concentration remained comparatively high throughout summer period mostly fluctuating at the 75-90 % saturation level suggesting rapid near-bottom water layer exchange. At the same time, exceptionally low oxygen levels could be observed as well. The minimum values were observed in July 25 (3.2 mg/l), September 23 (3.8 mg/l) and in August 11 (4.5 mg/l). The dynamic of water column and very short duration of oxygen minimum suggest that the observed phenomenon is most likely caused by introduction of water with low oxygen concentration from adjacent deeper areas.

Figure 2. 10: Oxygen dynamics in the bottom layers at the Musholm mussel farm in 2017. (Source: ODSS portal)

2.1.4. Kiel bay mussel farm

In June 2017, salinity, temperature and oxygen in mussel farm and reference location were very similar (Figure 2.11). Salinity and oxygen were a fraction higher in the reference location, whereas temperature in both locations were approximately 1.5 ºC higher in the upper layer (around 18.0 ºC) if compared to the deep layer (around 16.5 ºC).

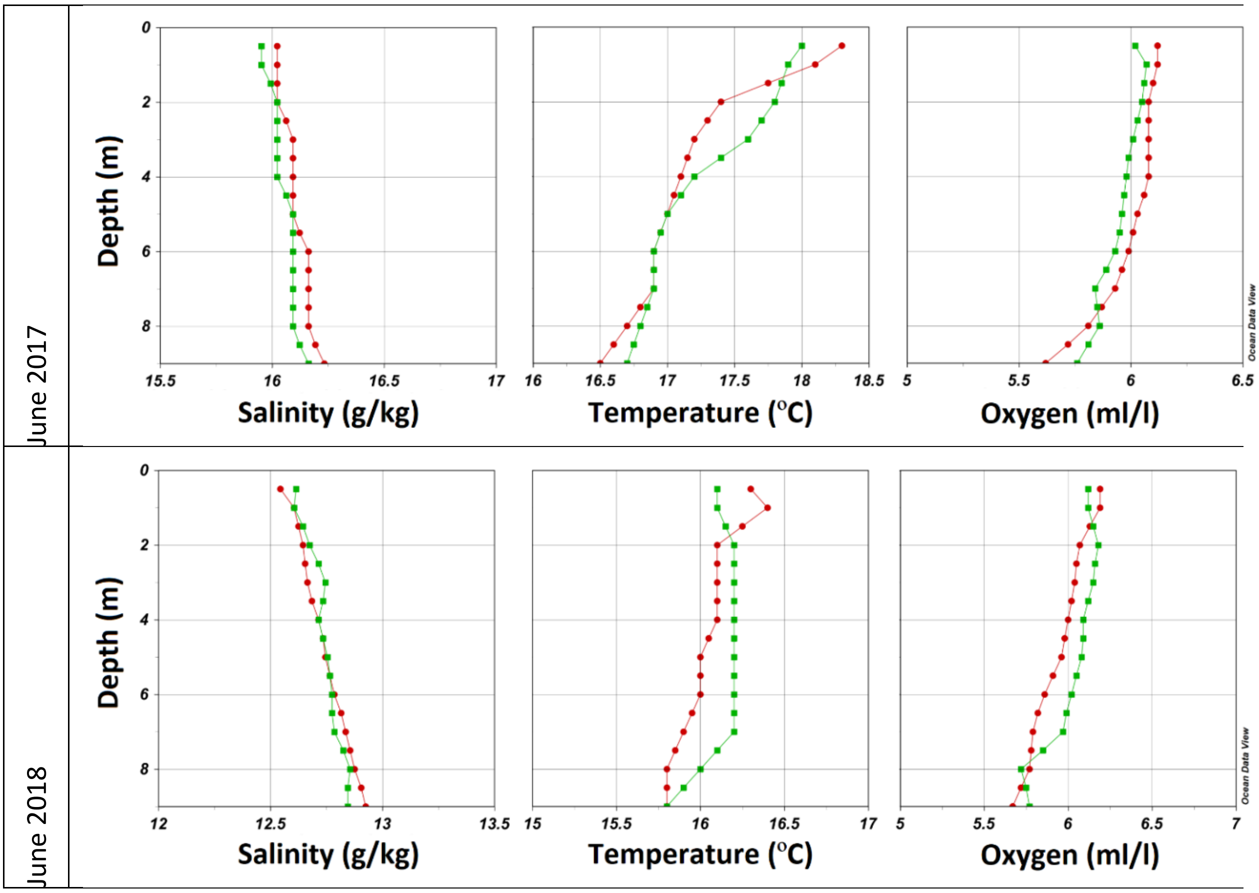


Figure 2. 11: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in June

In June 2018, salinity, temperature and oxygen dynamics (Figure 2.11) between mussel farm and reference location still remained close as it was observed in June 2017. Salinity in June 2018 was almost identical in both locations and varied between 12.5-13.0 g/kg, although the salinity in June 2018 was considerably lower (by about 3.5 g/kg) than observed in June 2017. Temperature in mussel farm and reference location was almost homogenous (varied mainly between 15.8-16.2 ºC) and there were only small differences between upper and bottom layers (in June 2017 differences were more pronounced). Oxygen in June 2018 had, in principle, the same range of values as in June 2017 and only difference was that in 2018 oxygen was slightly higher in the mussel farm as opposed to reference location.

In September 2017, the close resemblance of all the parameters from mussel farm and reference location was still existent (Figure 2.12). Salinity in September 2017 was substantially lower (on average 0.6 g/kg) when compared to the June 2017, temperature of the water column higher and oxygen was also a fraction higher than in June 2017.

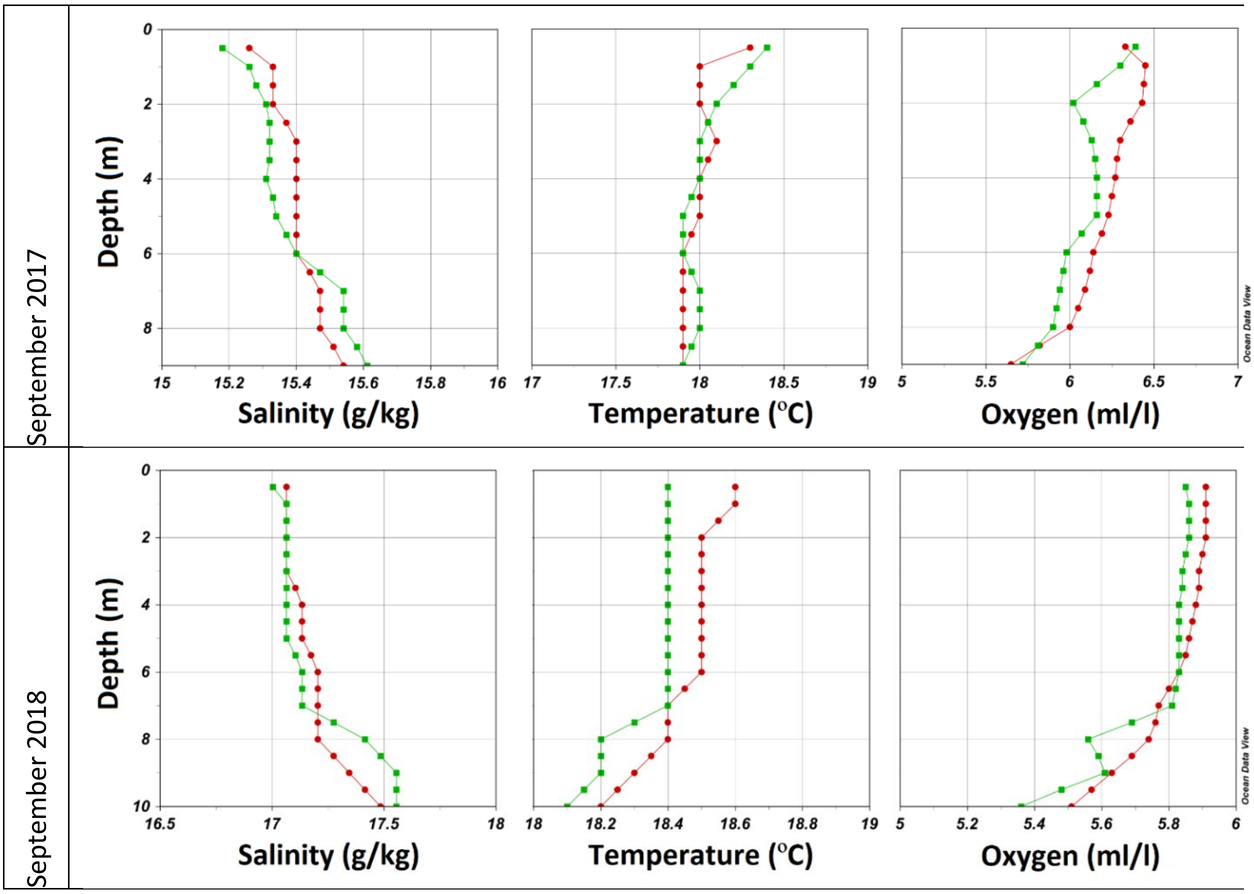


Figure 2. 12: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in September

In September 2018, the parameters in mussel farm and reference location still had similar tendencies (Figure 2.12), although year 2018 differed from 2017. Salinity in September 2018 was considerably higher (by about 4.5 g/kg) than in June 2018 and salinity also exceeded (by about 2.0 g/kg) those values observed in September 2017. Temperature was slightly higher in the reference location (by 0.1 ºC) and in both locations temperature decreased slightly in the bottom layers. If compared to September 2017 temperature was also slightly higher (mainly between 18.2-18.6 ºC) at both locations in September 2018. Oxygen in September 2018 was lower than in 2017 (at least by 0.5 ml/l) and also slightly lower than in June 2018.

In November 2017, still the difference between parameters in the mussel farm and reference location were negligible (Figure 2.13). Salinity mainly varied around 17.0 g/kg in both locations, temperature was decreasing starting from the upper layers (varied between 10.5-11.5 ºC in whole water column) and oxygen was pretty much similar to what was observed in September 2017 (between 5.5-6.5 ml/l).

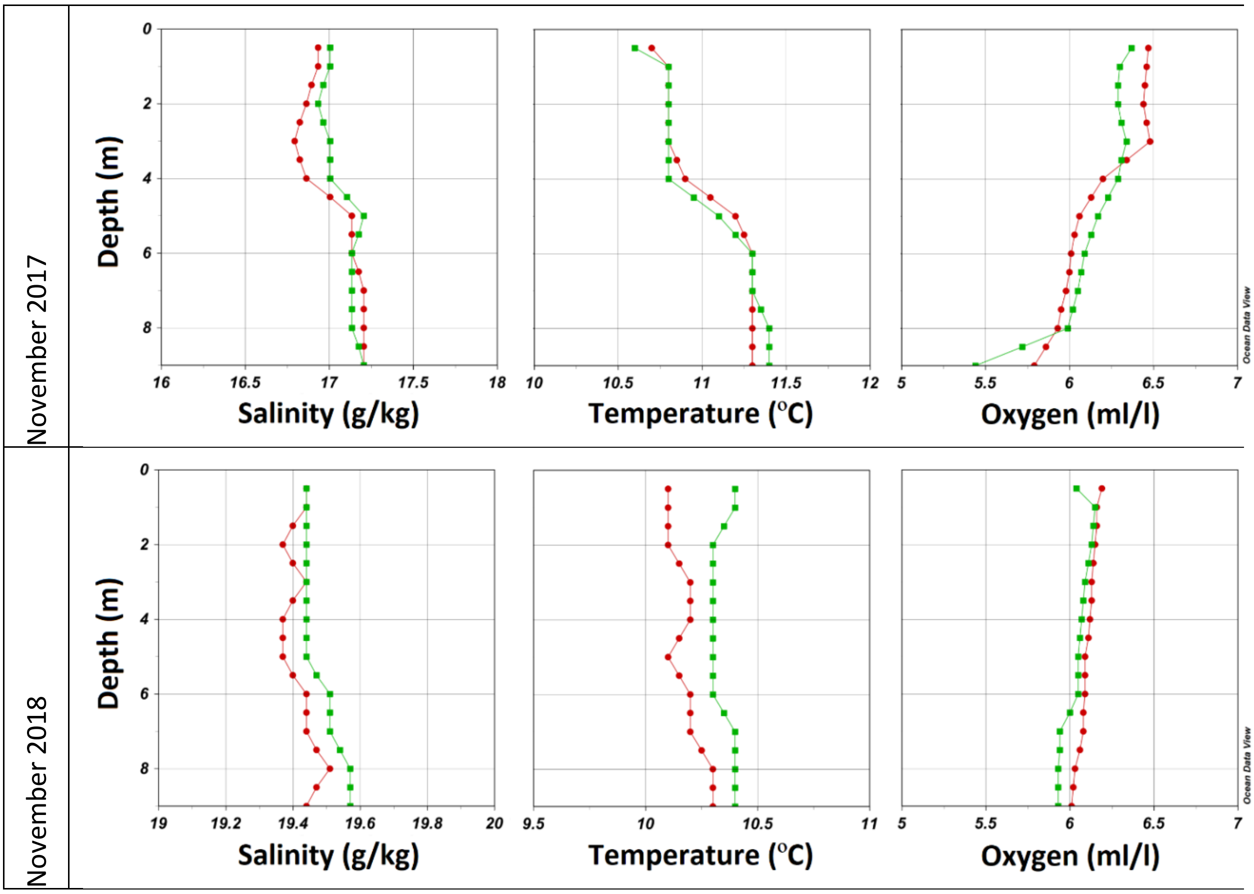


Figure 2. 13: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in November

As in previous months, November 2018 had higher salinity than in November 2017 – salinity mainly varied between 19.4-19.6 g/kg and it was more than 2.0 g/kg higher than year before (Figure 2.13). Temperature was rather homogenous from top to bottom of the water column (10.0-10.5 ºC) as opposed to November 2017 when slightly higher difference between upper and bottom layers was observed. Oxygen in November 2018 was almost identical and homogenous in mussel farm and reference location (about 6.0 ml/l) in contrast to November 2017 when there were more differences between upper and bottom layers.

The continuous measurements of oceanographic parameters (available on ODSS portal) in water layer just above seafloor covered period from September 2017 till July 2018. The oxygen concentrations (Figure 2.14) generally were inverse of temperature with highest values during winter when water temperature was low and lowest during late summer – autumn when temperature was high. Mostly, water saturation level with oxygen remained above 30 % with occasional short term concentration drops. The period of lowest oxygen concentration was observed between September 10-12 when almost no oxygen was detected. The very fast decrease from 60 % oxygen saturation in September 1 to 1 % saturation in September 11 with subsequent recovery to 30 % saturation in just 2 days suggest external inflow of organic rich water (like from sewage treatment plant) into water layer below mussel farm which was subsequently replaced or diluted by more oxygenated water masses.

Figure 2. 14: Oxygen dynamics in the bottom layers at the Kiel mussel farm in 2017-2018. (Source: ODSS portal)

2.1.5. Pavilosta (Coast of Kurzeme) mussel farm

In May 2017 salinity, temperature and dissolved oxygen concentration (from here on referred simply as oxygen) was rather similar in mussel farm and reference location (Figure 2.15). Salinity varied mainly between 7.4-7.5 g/kg, temperature between 5-7 ºC and oxygen between 7.6-8.0 ml/l with salinity and oxygen being slightly higher in the mussel farm, whereas temperature being slightly higher in the reference location. Difference between upper and lower layers was also negligible as in May the water column usually is still well mixed following the convective mixing from winter.

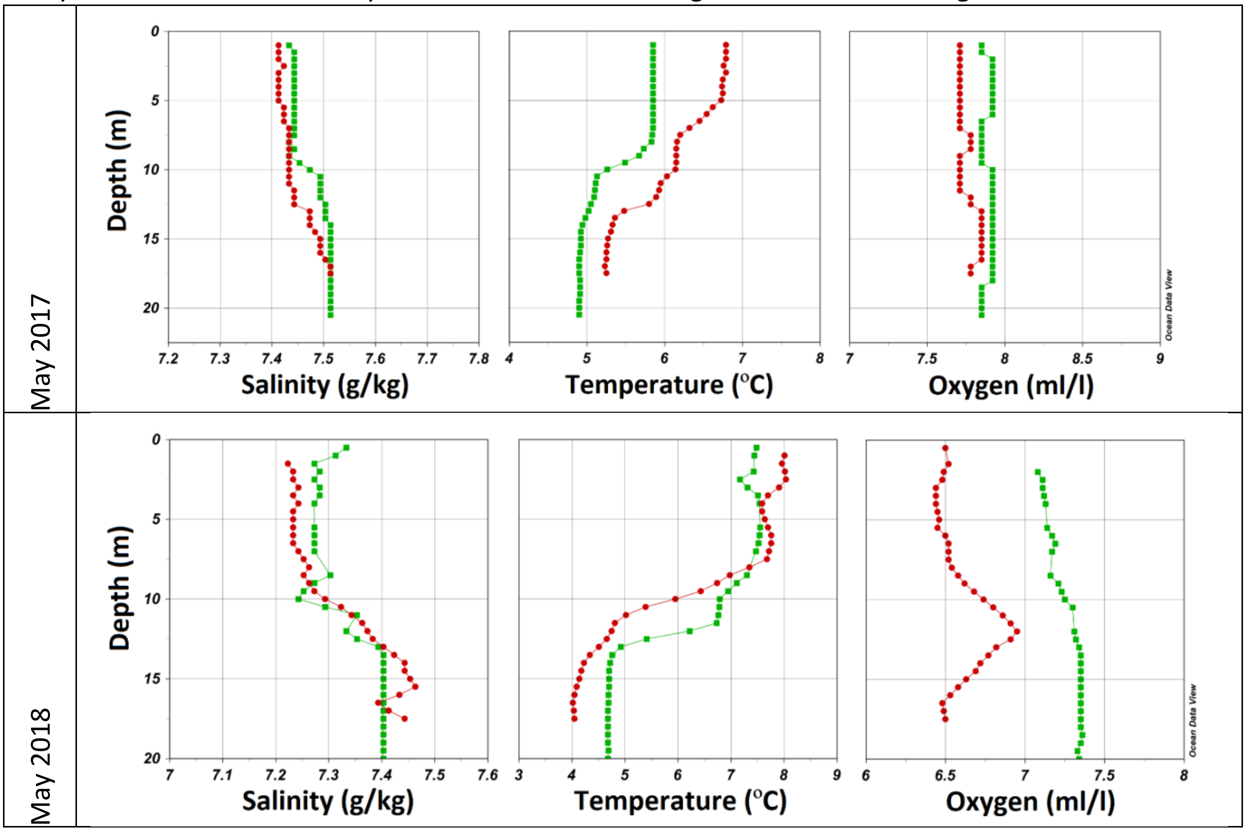


Figure 2. 15: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line)

In May 2018, the difference between upper and bottom layers as well as difference between oxygen in mussel farm and reference location was more substantial (Figure 2.15) than the one observed in May 2017. The temperature in upper layers of mussel farm and reference location were mainly between 7.0-8.0 ºC (at least by 1.0 ºC higher than in May 2017), whereas the temperature in bottom layers varied between 4.0-5.0 ºC (lower than in May 2017). The difference in salinity between upper and bottom layers was also more pronounced in May 2018 than in May 2017 despite the fact that water column was more saline in May 2017. Altogether, in May 2018 one might acknowledge a small (compared to August) thermocline already developed where temperature decreases by about 3.0 ºC in mussel farm and 4.0 ºC in reference location. Oxygen in the mussel farm was mainly homogenous and varied between 7.1-7.4 ml/l, whereas in reference location oxygen was lower (around 6.5 ml/l) with slight increase (from 8-12 m depth) coinciding with the start of thermocline and further decrease back to 6.5 ml/l.

In July 2017, the difference between salinity in mussel farm and reference location is still small (around 0.1 g/kg) although salinity itself is much lower (approx. 0.5 g/kg) than in May mainly due to the freshwater from the Curonian lagoon (Figure 2.16). Temperature in July 2017 is higher and oxygen is lower than in May but there are substantial differences in vertical distribution of the oxygen if compared to May (Figure 2.15), especially regarding the mussel farm. In May, the oxygen was just below 8.0 ml/l throughout the whole water column, whereas in July the oxygen was around 6.5 ml/l in the 0-10 m layer and then started to decrease reaching values below 5.5 ml/l in the bottom layers. Oxygen decrease coincides rather well with the small temperature drop (around 0.5 ml/l) starting from around 12 m depth till the bottom. At the same time temperature (around 16.5 ºC) and oxygen (around 6.2 g/kg) in the reference location stayed homogenous throughout the whole water column.

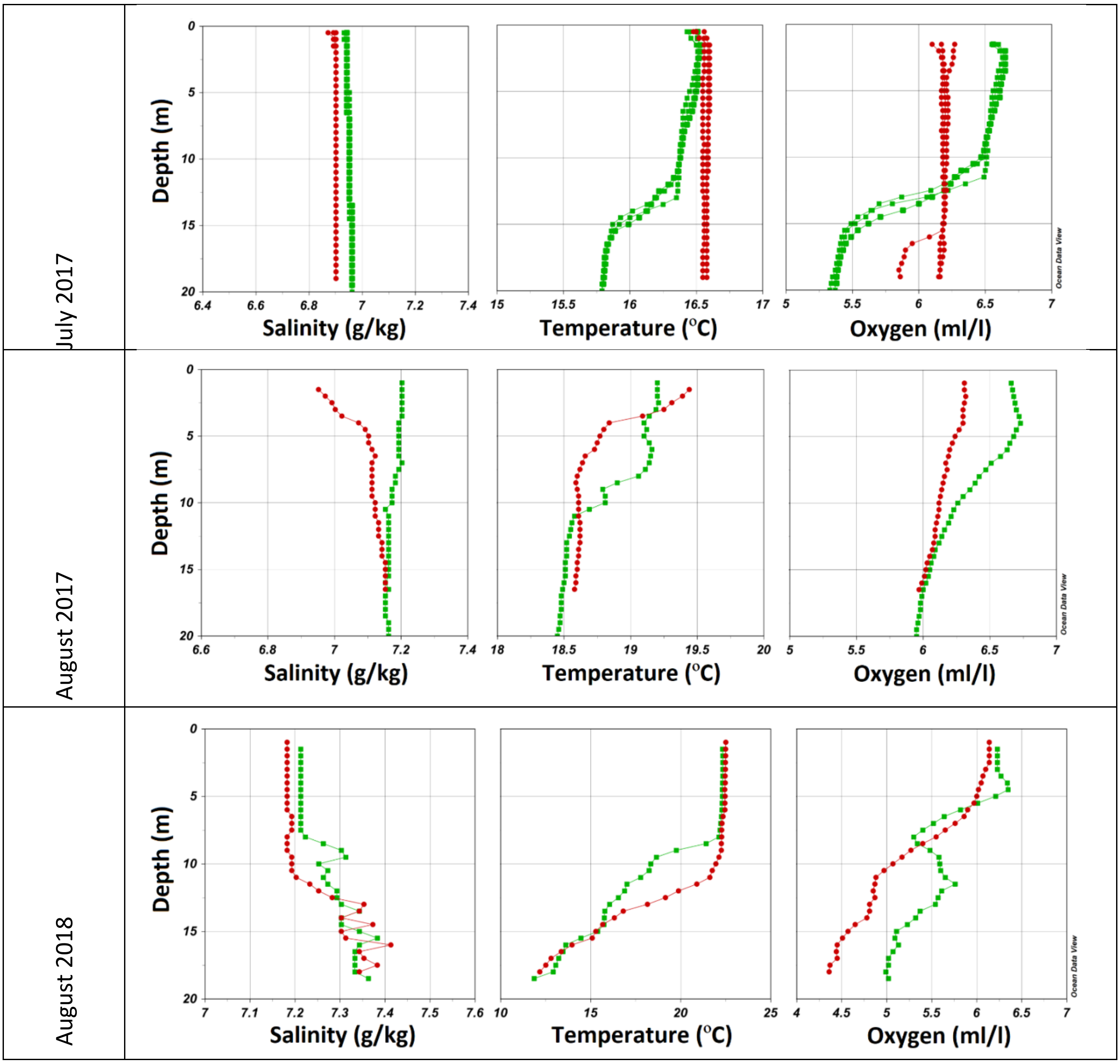


Figure 2. 16: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line)

In August 2017, the water column continued to warm up starting from the upper layers and temperature exceeded 19.0 ºC in upper layers of both mussel farm and reference location (Figure 2). The oxygen decrease in the mussel farm was not so pronounced (around 0.6 ml/l difference between upper and bottom layers) as in July 2017. The temperature difference between upper and bottom layers also was not very distinct as one should expect in August which implies that in August 2017 there was not strong stratification evident in the region. Nevertheless, salinity and temperature of the upper layer in reference location differed from layers below (as well as from July 2017 and mussel farm) with water being fresher and warmer and most probably explained by the horizontal advection of the water masses.

In August 2018, the stratification was more pronounced (temperature decreasing by about 10.0 ºC during the thermocline) than in 2018 May which is typical situation for the region (Figure 2.16). Salinity dynamics in August 2018 were rather similar between mussel farm and reference location with salinity varying mainly between 7.2-7.4 g/kg (by around 0.2 g/kg higher than in August 2017) with salinity being slightly higher in mussel farm (due to the more northward location). Similarly, as with temperature, the difference between upper and bottom layer salinity in August 2018 was more pronounced than in August 2017. Subsequently, due to the stratification and reduced vertical mixing oxygen in the whole water column in August 2018 was substantially lower (decreasing from 6.0-6.5 ml/l in upper layers to 4.5-5.0 ml/l in bottom layers) than the one observed in August 2017 (mainly 6.0-6.5 ml/l in whole water column). Below 10 m depth the oxygen in mussel farm was by about 0.5 ml/l higher than in the reference location.

In November 2017, the vertical distribution of all parameters in the mussel farm and reference location was mainly homogenous again (Figure 2.17). Salinity and temperature was a bit higher in the mussel farm (about 0.1 g/kg and 0.4 ºC, respectively), whereas the oxygen was a bit higher (by about 0.1 ml/l) in the reference location.
In November 2018, the differences between upper and bottom layer salinity and temperature were still evident (as opposed to November 2017) in mussel farm as well as reference location due to the strong stratification in August 2018 (Figure 2.17). Salinity and temperature in the upper layer was slightly higher in the mussel farm, whereas in the deep layers the reference location had higher salinity and temperature. Salinity and temperature in mussel farm and reference location varied between 6.9-7.1 g/kg and 9.3-10.0 ºC (mussel farm) and 6.8-7.2 g/kg and 8.9-10.4 ºC (reference location), respectively. Despite the still existing differences in November 2018 between upper and bottom layers the oxygen in November 2018 was considerably higher (mainly between 7.5-8.0 ml/l) in the whole water column if compared to November 2017 (mainly between 6.2-6.4 ml/l).

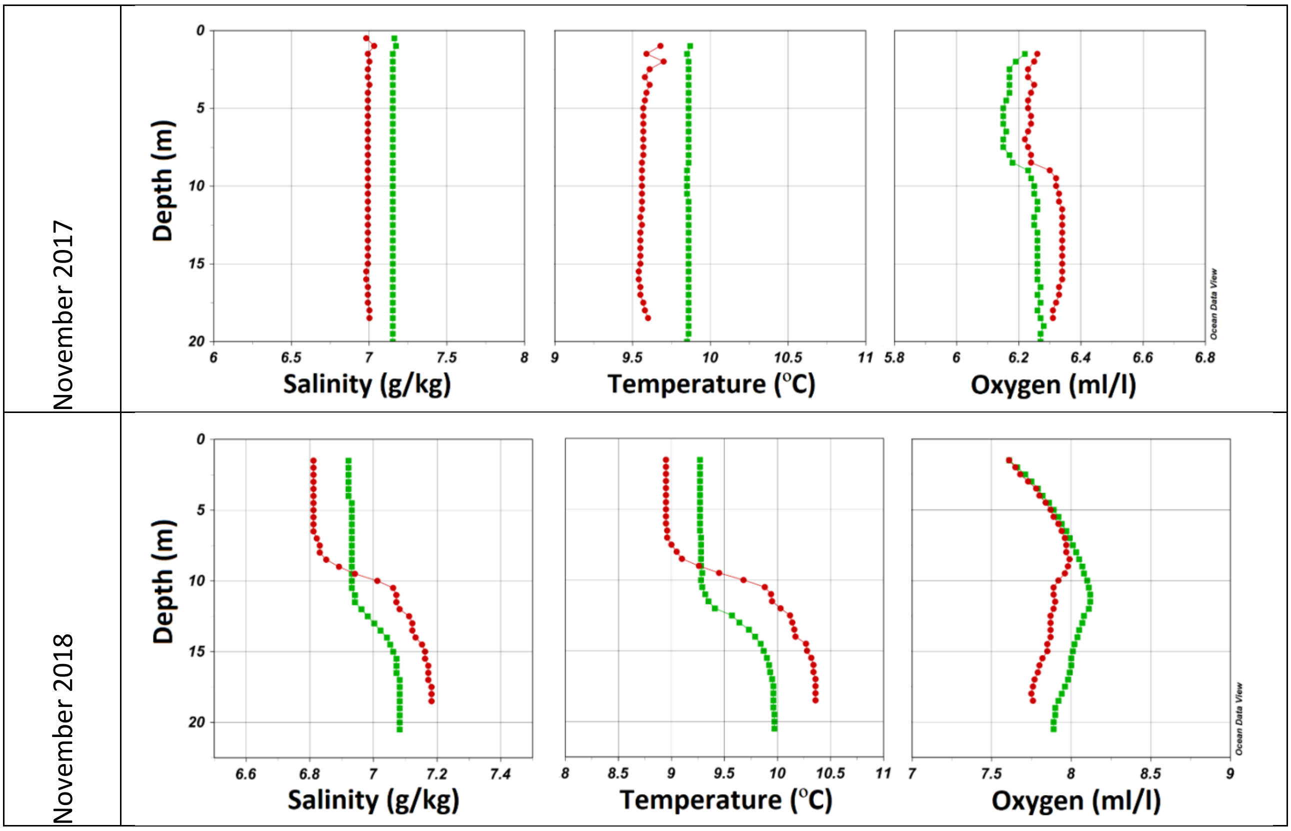


Figure 2. 17: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line)

2.1.6. Vormsi island mussel farm

In April 2017, there was only slight difference between vertical distribution of salinity, temperature and oxygen in the mussel farm and reference location (Figure 2.18). Water column was well mixed as it always is in early spring. Salinity was almost identical in both places and was around 6.8 g/kg, temperature was slightly higher (by about 0.2 ºC) in the reference location, whereas oxygen through whole water column was a bit higher (by about 0.5 ml/l) in the mussel farm.

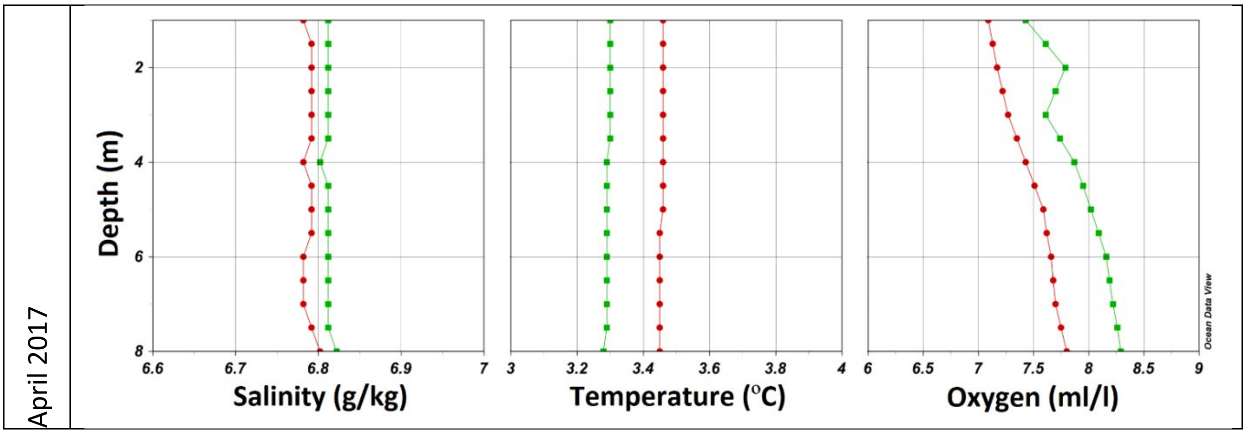


Figure 2. 18: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in April

In June 2017 (Figure 2.19), the difference between mussel farm and reference location was quite similar as in April 2017 (Figure 2.18). Salinity was still similar and around 6.6 g/kg in both places (although it was 0.2 g/kg lower than in April 2017), temperature was higher in whole water column if compared to April 2017 and in June 2017 reference location had slightly warmer temperatures in the deep layers, whereas oxygen was lower (most probably due to the increase of the oxygen consumption by the biota) in mussel farm and reference location when compared to the April 2017 values. In June 2017 oxygen was higher in the mussel farm than reference location by about 0.1-0.5 ml/l depending of the depth (Figure 2.19).

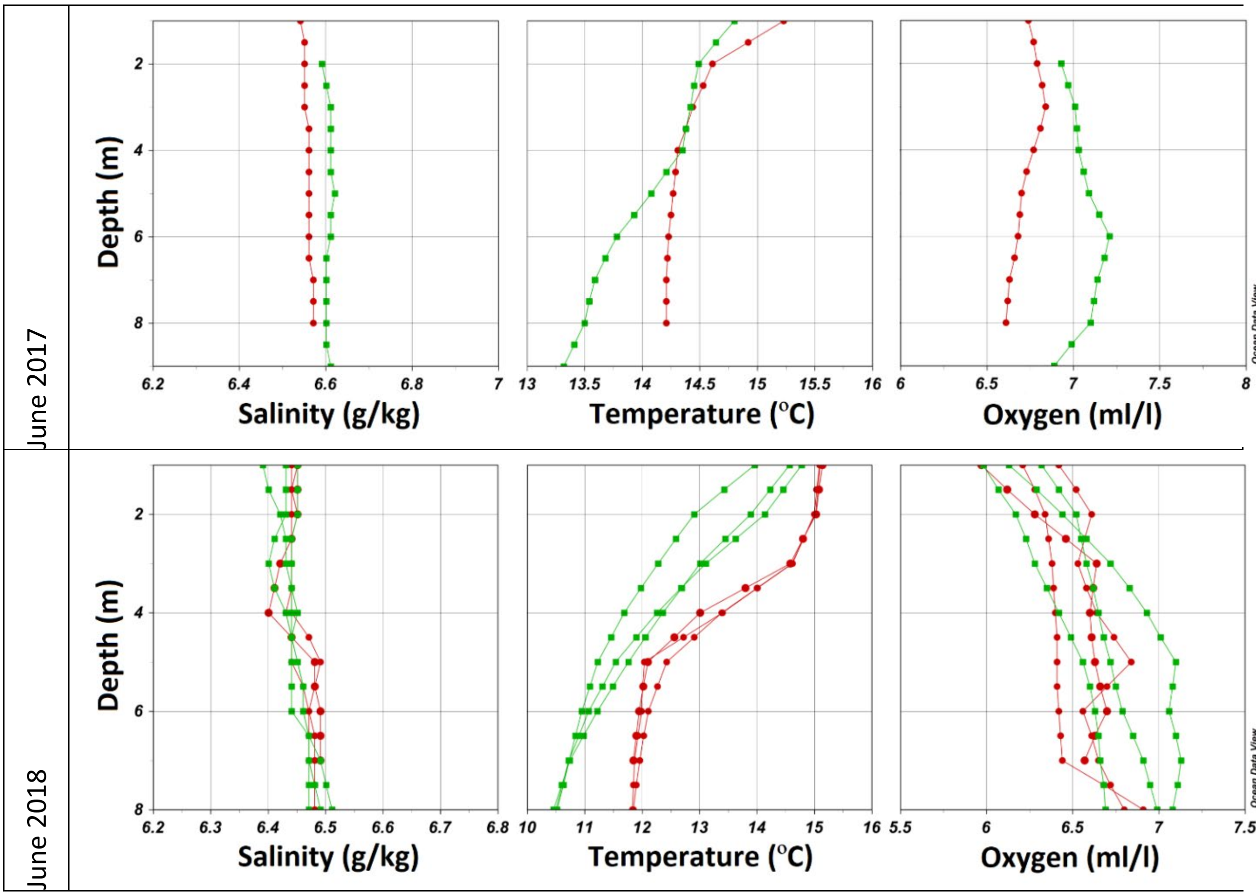


Figure 2. 19: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in June

In June 2018, the results from salinity, temperature and oxygen showed similar tendencies between mussel farm and reference location (Figure 2.19). Salinity mainly varied between 6.4-6.5 g/kg through whole water column in both locations and was slightly (by about 0.1 g/kg) lower than one observed in June 2017. In June 2018 temperature had bigger differences between upper and bottom layers as opposed to June 2017 and temperature in the reference location slightly exceeded (by about 1.0 ºC) that observed in the mussel farm throughout the whole water column. Oxygen in mussel farm and reference location had pretty similar dynamics and oxygen varied mainly between 6.0-7.0 ml/l throughout the whole water column. The oxygen values were also quite similar to those observed in June 2017 with oxygen being slightly lower in the upper layers (June 2018).

In August 2017, the vertical distribution of salinity, temperature and oxygen was still quite homogenous (Figure 2.20). However, there were distinct differences between sites. The biggest difference between mussel farm and reference location was observed for salinity – salinity in the reference location was more than 1.0 g/kg lower than in the mussel farm which might be explained by some local horizontal advection of water masses. Temperature as well as salinity was lower (around 17.5 ºC) in the reference location than in the mussel farm (between 18.2-18.5 ºC). Oxygen was pretty similar in both locations (between 5.8-6.0 ml/l) which was substantially lower from the values observed in April and June 2017 (Figure 2.20).

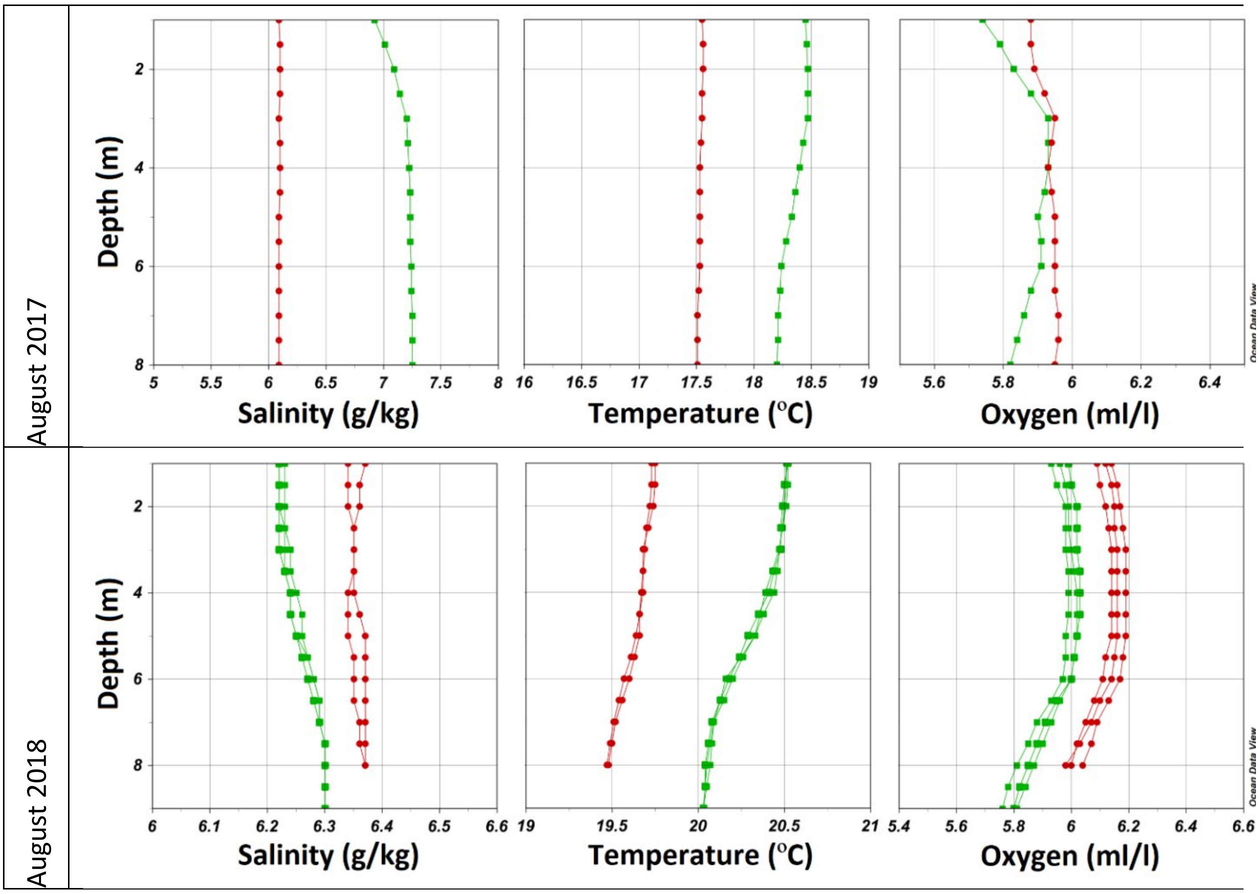


Figure 2. 20: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in August

In August 2018 salinity, temperature and oxygen values varied negligibly between mussel farm and reference location (Figure 2.20). Salinity difference was about 0.1 g/kg between two locations and mainly varied between 6.2-6.4 g/kg which is a lot closer than salinities observed in August 2017 between the mussel farm and reference location. In August 2018 reference location had slightly higher salinity but lower temperatures (by about 0.5-0.8 ºC), whereas oxygen was by about 0.2 ml/l higher in the reference location than in mussel farm and oxygen values in reference location (6.0-6.2 ml/l) were also a bit higher than the ones observed in the August 2017.

In October 2017, there were more pronounced differences between the upper and bottom layer salinity and temperature than in previous months. Salinity difference between upper and bottom layers was more pronounced in the mussel farm where salinity increased from around 6.2 g/kg in the upper layer till almost 7.0 g/kg in the bottom layer (Figure 2.21). In the reference location salinity increased from 6.2 g/kg to almost 6.6 g/kg in the bottom layer. Temperature started to decrease again from the upper layers in both locations as it is common with the convective mixing starting from Autumn. The vertical characteristics of oxygen were similar in both locations with oxygen being slightly higher in whole water column of mussel farm than reference location. The oxygen values in October 2017 exceeded those observed in August 2017 by approximately 1.0 ml/l.

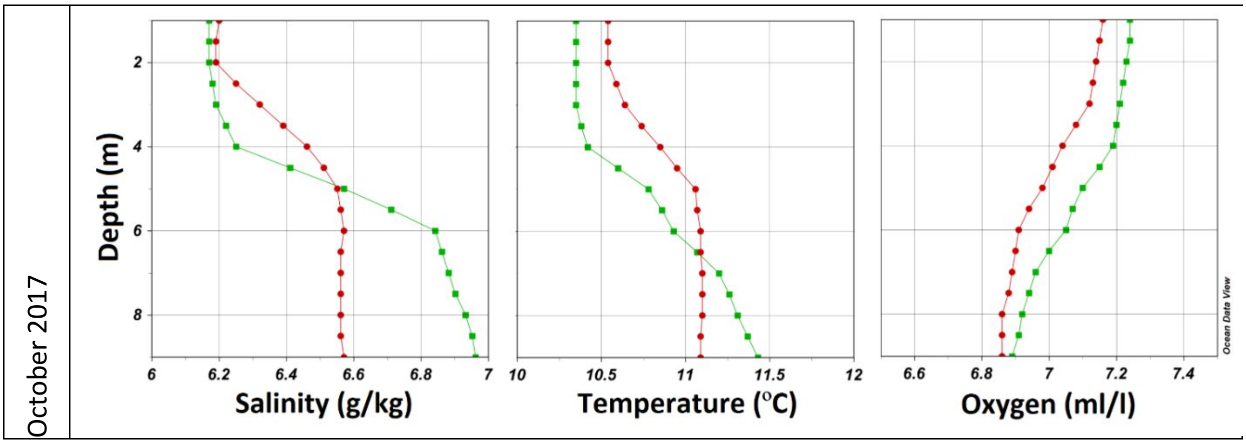


Figure 2. 21: Vertical distribution of salinity, temperature and dissolved oxygen in mussel farm (green line) and reference location (red line) in October 2017

In the Vormsi mussel farm the continuous measurements were carried out from August 22, 2016 till April 17, 2017 (Figure 2.22). As the period covered mostly the cold part (autumn-spring) of the year the observed oxygen concentrations were rather high – from middle of the November till the middle of April the oxygen varied mainly between 12.0-14.0 mg/l. Lowest oxygen was observed at the end of August till the beginning of the October (usually at the end of summer and the start of autumn the stratification is at its maximum) when oxygen was considerably lower (varied between 7.0-9.0 mg/l) than in other period. Nevertheless, similar as it was in Musholm mussel farm the oxygen changes at the bottom layers were quite dynamic from day to day which, most probably, is due to the rather shallow depth (around 9.0 m) of the mussel farm and the season when measurements were taken (autumn and winter has on average the highest wind speed, thus, the highest influence on the water mixing between upper and bottom layers).

Figure 2. 22: Oxygen dynamics in the bottom layers at the Vormsi Agar mussel farm in 2016-2017

2.2. Nutrient concentrations

2.2.1. Sankt Anna mussel farm

The concentrations of inorganic fractions of nitrogen, especially nitrate and nitrite, were mostly very low (Table 2.1) comprising on average only around 2 % of total nitrogen, indicating rapid uptake of inorganic nitrogen by phytoplankton even in October. The exception was August 2018 when obvious water vertical stratification event created situation favorable for nutrient accumulation in near-bottom water layer. As a result, increased concentrations of ammonia (Figure 2.23) were observed in near-bottom layer reaching around 17 % of total nitrogen. The concentration increase was observed at both mussel farm and reference sites, indicating that the observed concentration increase is attributable to natural factors rather than to influence of mussel farm.

Similarly to nitrogen, the concentrations of inorganic phosphorus were also fairly low (Table 2.1) in June 2018 comprising from on average 10 % in surface layer to 40 % in near-bottom layer. The relative part of inorganic phosphorus increased to on average 55 % in August 2018 and 72 % in October 2018 in surface layer while in near-bottom layer inorganic phosphorus comprised on average 77 % of total phosphorus in both August 2018 and October 2018. The inorganic phosphorus fraction was relatively smallest in surface layer and biggest in deeper water layers. Similarly to nitrogen, substantial increase in inorganic and total phosphorus concentration in near-bottom water layer could be observed in August 2018 (Figure 2.23). In 2017, inorganic phosphorus accumulation was less pronounced and varied on average from 10 % in August 2017 to 42 % in June 2017.

Similarly to nitrogen, there was no detectable difference between mussel farm stations and reference area stations. Therefore, it is highly unlikely that increased sedimentation of organic material caused by mollusks at mussel farm was creating accumulation of inorganic phosphorus in deeper layers of the water column in summer of 2018.

Table 2. 1: Average concentrations of nutrients in Sankt Anna mussel farm and reference area in 2017 and 2018

Parameter	2017			2018		
	June	August	October	June	August	October
NH_4	0	0,59	0,66	0,56	5,4	0,4
NO_{23}	0,12	0,04	0,38	0	0,69	0,12
TN	19,29	19,64	20,71	22,5	24,4	17,11
PO_4	0,31	0,12	0,28	0,29	1,44	0,71
TP	0,73	1,1	0,93	0,94	1,84	0,96

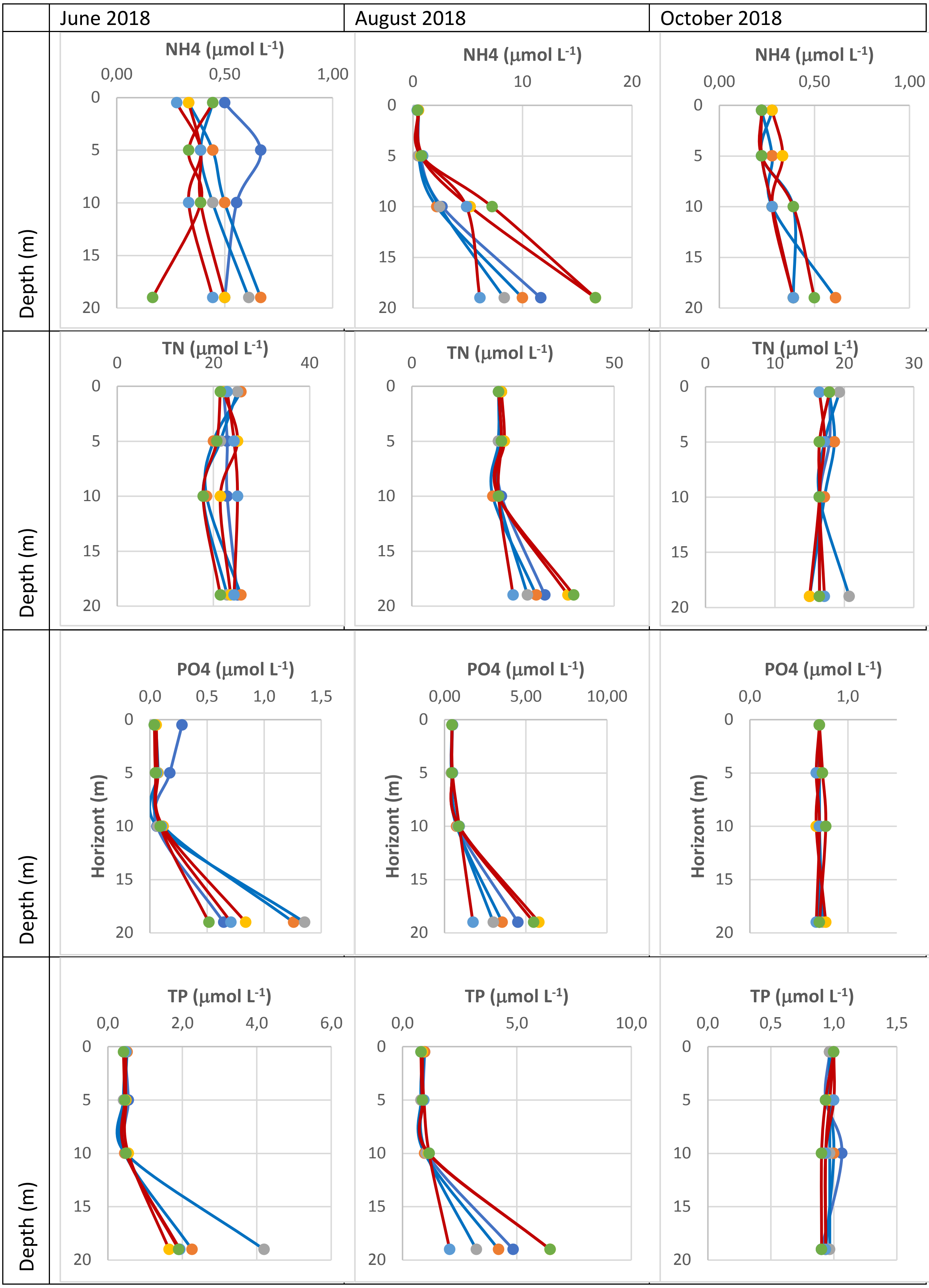


Figure 2. 23: Vertical profiles of nutrients in Sankt Anna mussel farm (red lines) and reference site (blue lines) in 2018

2.2.2. Kalmarsund mussel farm

The average concentrations of inorganic fractions of nitrogen were low during all sampling events (Table 2.2). Comparatively highest concentrations of ammonia were observed in June during both years. Nevertheless, the inorganic nitrogen formed very small fraction of total nitrogen, less than 2 % of total nitrogen in surface layer and less than 1 % in bottom layer. The observed concentrations generally did not indicate any differences due to vertical stratification of water column except in June 2018 when slightly higher concentrations of ammonia were recorded in near-bottom water at both mussel farm and reference areas (Figure 2.24). This might be the result of massive sedimentation of spring phytoplankton bloom earlier in the year.

The total nitrogen exhibited very similar average concentration values in June 2017 and 2018, as well as in August 2017 and 2018. At the same time, the total nitrogen pool was substantially depleted in October 2018 while no such depletion event could be observed in October 2017. Generally, there were no detectable differences in vertical distribution of total nitrogen concentrations during any sampling event (Figure 2.24).

Table 2. 2: Average concentrations of nutrients in Kalmarsund mussel farm and reference area in 2017 and 2018

Parameter	2017			2018		
	June	August	October	June	August	October
NH4	0,36	0,21	0,09	0,72	0,09	0,03
NO23	0,1	0,04	0,17	0,01	0,04	0,04
TN	23,9	27,4	26,1	23,6	27,2	19
PO4	0,5	0,46	0,48	0,14	0,26	0,45
TP	1,04	1,2	1,12	0,59	0,93	0,83

The average concentrations of inorganic phosphorus demonstrated different patterns in 2017 and 2018. In 2017 the average concentrations were fairly similar at all sampling events (Table 2.2). At the same time, in 2018 the average concentrations clearly indicated phosphorus pool accumulation over the year with lowest concentration in June and highest in October. Nevertheless, the inorganic phosphorus constituted on average around 26 % of total phosphorus during June and August, and around 50 % in October, indicating strong nitrogen limitation. At the same time, the average total phosphorus concentrations exhibited increase only from June 2018 to August 2018 (Table 2.2). There was no detectable vertical pattern of inorganic and total phosphorus concentrations (Figure 2.24).

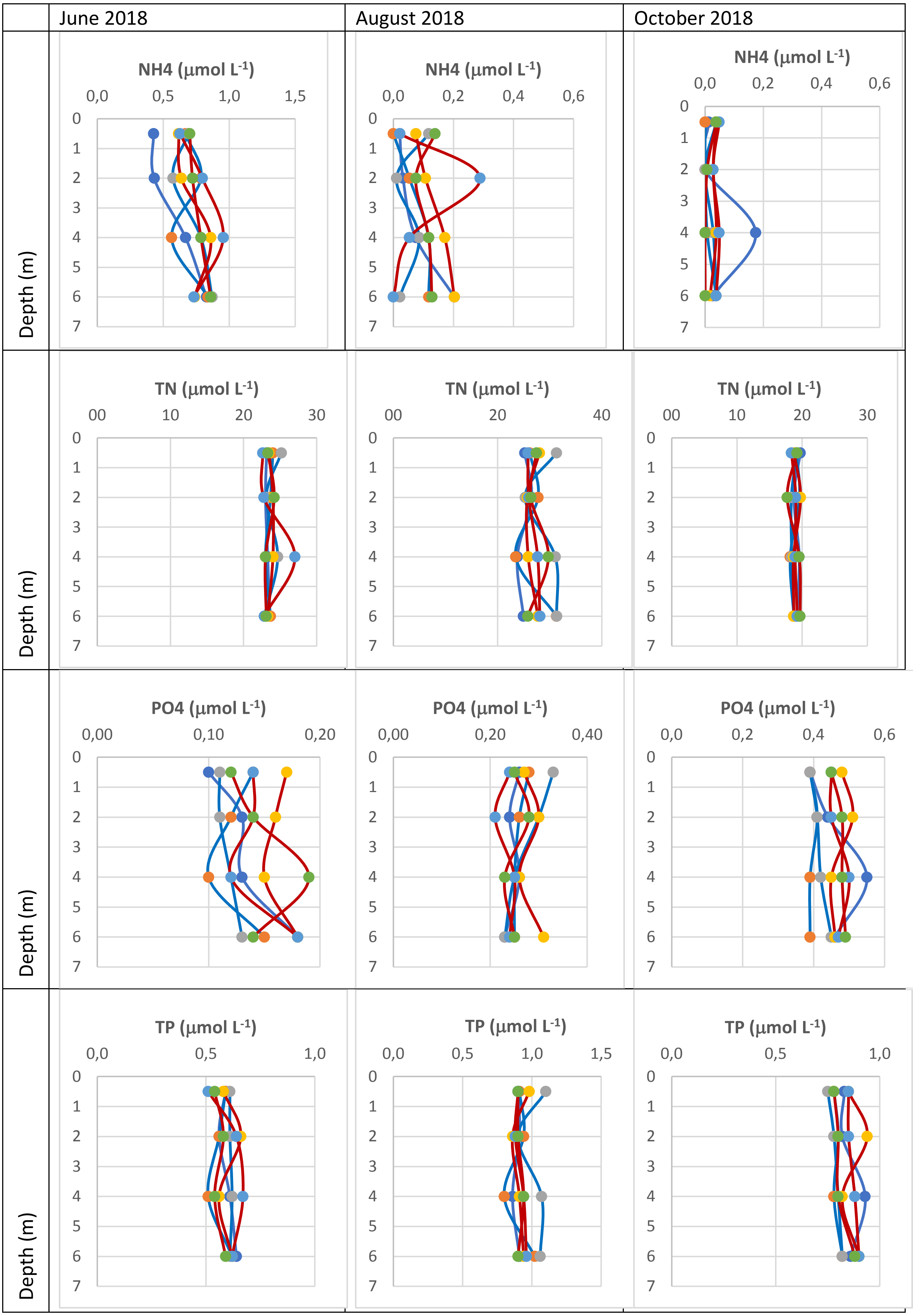


Figure 2. 24: Vertical profiles of nutrients in Kalmarsund mussel farm (red lines) and reference site (blue lines) in 2018

2.2.3. Musholm bay mussel farm

The concentrations of inorganic nitrogen relative to total nitrogen were low (Table 2.3) during all sampling events comprising around 4 % of total nitrogen. The lowest concentrations were observed in June and thereafter concentration increase could be observed. The concentration of total nitrogen was similar during all sampling events. The concentrations of inorganic nitrogen substantially varied vertically (Figure 2.25) demonstrating slight increase towards near-bottom layer. However, it should be noted that concentration variations were mostly within limits of analytical dispersion and or natural variability. The concentrations of total nitrogen exhibited quite even vertical distribution at all sampling events.

As in other areas of the Baltic Sea the substantial part of total phosphorus is in inorganic form during all sampling events (Table 2.3). During June and August, the concentrations of inorganic phosphorus in surface layer are lower (comprising on average 17 % from total phosphorus) than in near-bottom water layer (comprising on average 34 % from total phosphorus (Figure 2.26). The slight increase of total phosphorus concentration in near-bottom water layer is mostly due to increase of inorganic fraction.

Table 2. 3: Average concentrations of nutrients in Musholm bay mussel farm and reference area in 2018

Parameter	2018		
	June	August	October
NH_4	0,05	0,6	0,57
NO_{23}	0,2	0,34	0,65
TN	22,5	21,7	24,1
PO_4	0,15	0,21	0,32
TP	0,77	0,73	0,98

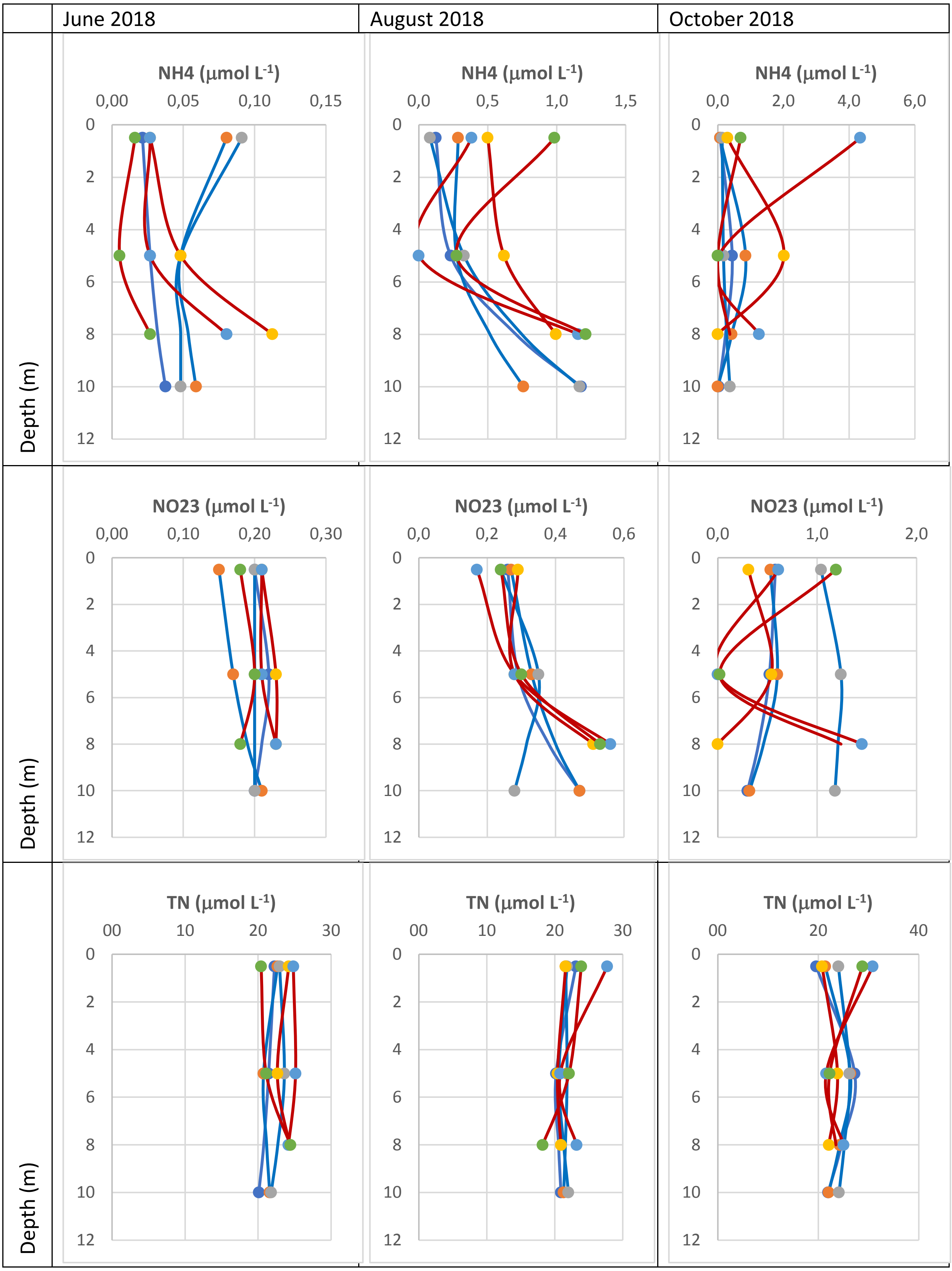


Figure 2. 25: Vertical profiles of nutrients in Musholm bay mussel farm (red lines) and reference site (blue lines) in 2018

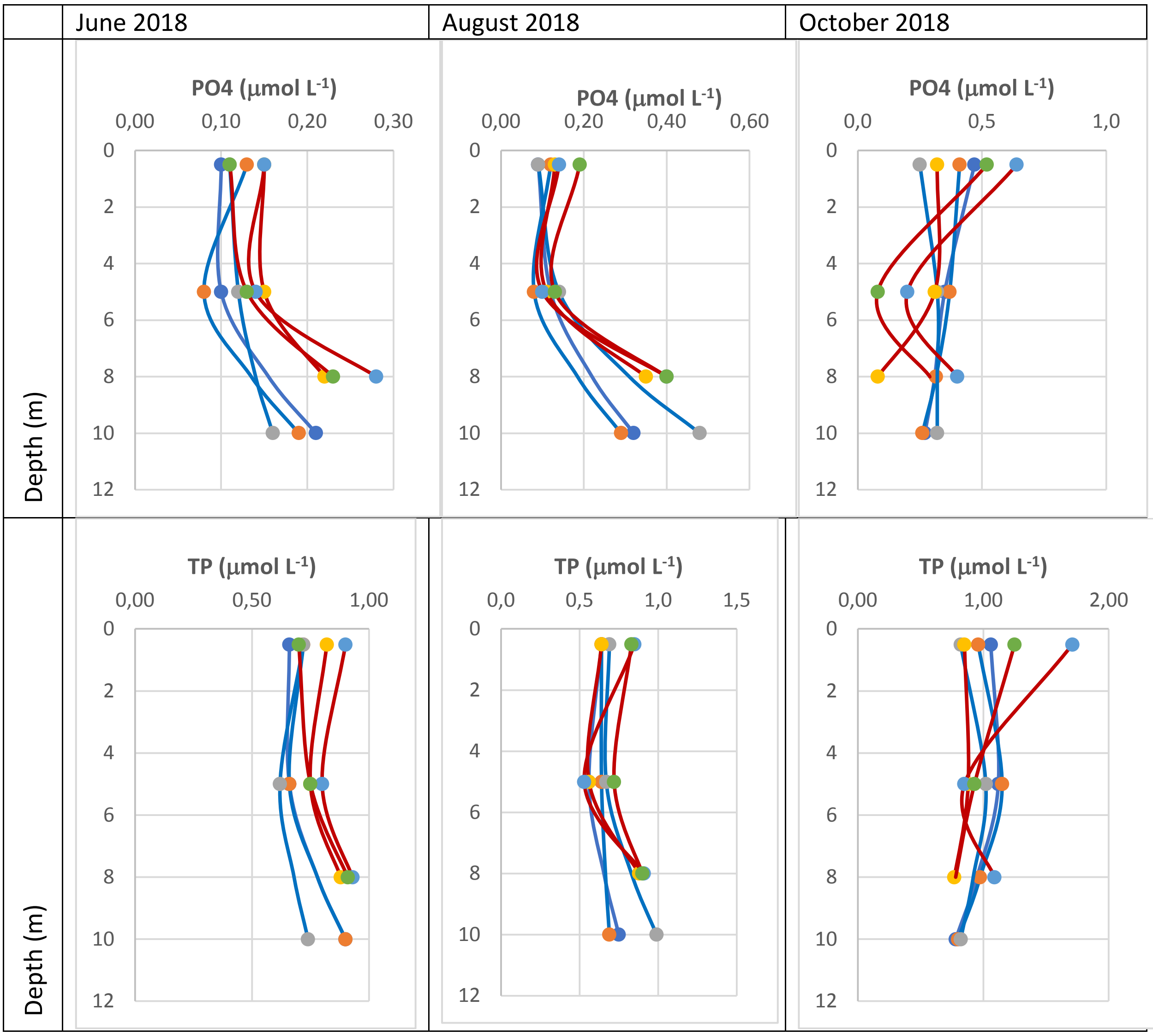


Figure 2. 26: Vertical profiles of nutrients in Musholm bay mussel farm (red lines) and reference site (blue lines) in 2018

2.2.4. Kiel bay mussel farm

Similarly to other regions of the Baltic Sea, the concentrations of inorganic nitrogen (NH4 and NO23) form minor part of the total nitrogen pool (Table 2.4). The common pattern during both years is that pool of inorganic nitrogen substantially increase during autumn (November) indicating end of productive season when nitrogen is starting to shift from organic to inorganic pool. The total nitrogen concentrations, except in November 2017 (see text below), do not demonstrate discernible concentration increase in autumn. Generally no vertical concentration gradient could be observed for inorganic and total nitrogen (Figure 2.27) indicating that water column is well mixed. At the same time occasional concentration increase, e.g., ammonia in near-bottom water layer in June and August at one station, and in surface layer in November, as well as total nitrogen in surface layer in November suggest that there are occasional inputs of nutrients in area that temporarily create very local nutrient enrichment. This was even more visible in November 2017 when extremely high ammonia (16 µmol L^{-1}) and total nitrogen (160 µmol L^{-1}) concentrations were observed in reference station at depth of 5 m. It is highly likely that since mussel farm and correspondingly also reference stations are located in fairly enclosed area and close to shoreline the impacts of adjacent terrestrial area are more visible than the impacts generated by mussel farm.

Unlike nitrogen, the phosphorus pool (total phosphorus) was substantially bigger in autumn (November) than during summer months (Table 2.4). The observed increase was mostly due to buildup of inorganic phosphorus pool. Since no vertical gradient was observed (Figure 2.28) and increase in phosphorus pool was not balanced by corresponding increase in nitrogen pool it is not possible to speculate about possible causes of such concentration increase. Anyhow, since concentration increase was occurring at both areas, e.g., mussel farm and reference, it is highly likely that the cause of concentration increase is external possibly originating on land.

Table 2. 4: Average concentrations of nutrients (µmol L^{-1}) in Kiel bay mussel farm and reference area in 2017 and 2018

Parameter	2017			2018		
	June	September	November	June	September	November
NH4	0,28	0,35	2,77	0,19	0,08	1,98
NO23	0,02	0,03	4,64	0,1	0,03	1,44
TN	23,79	21,76	41,04	25,1	21,22	25,09
PO4	0,12	0,34	0,88	0,34	0,32	0,97
TP	0,76	0,87	1,53	1,11	1,01	1,82

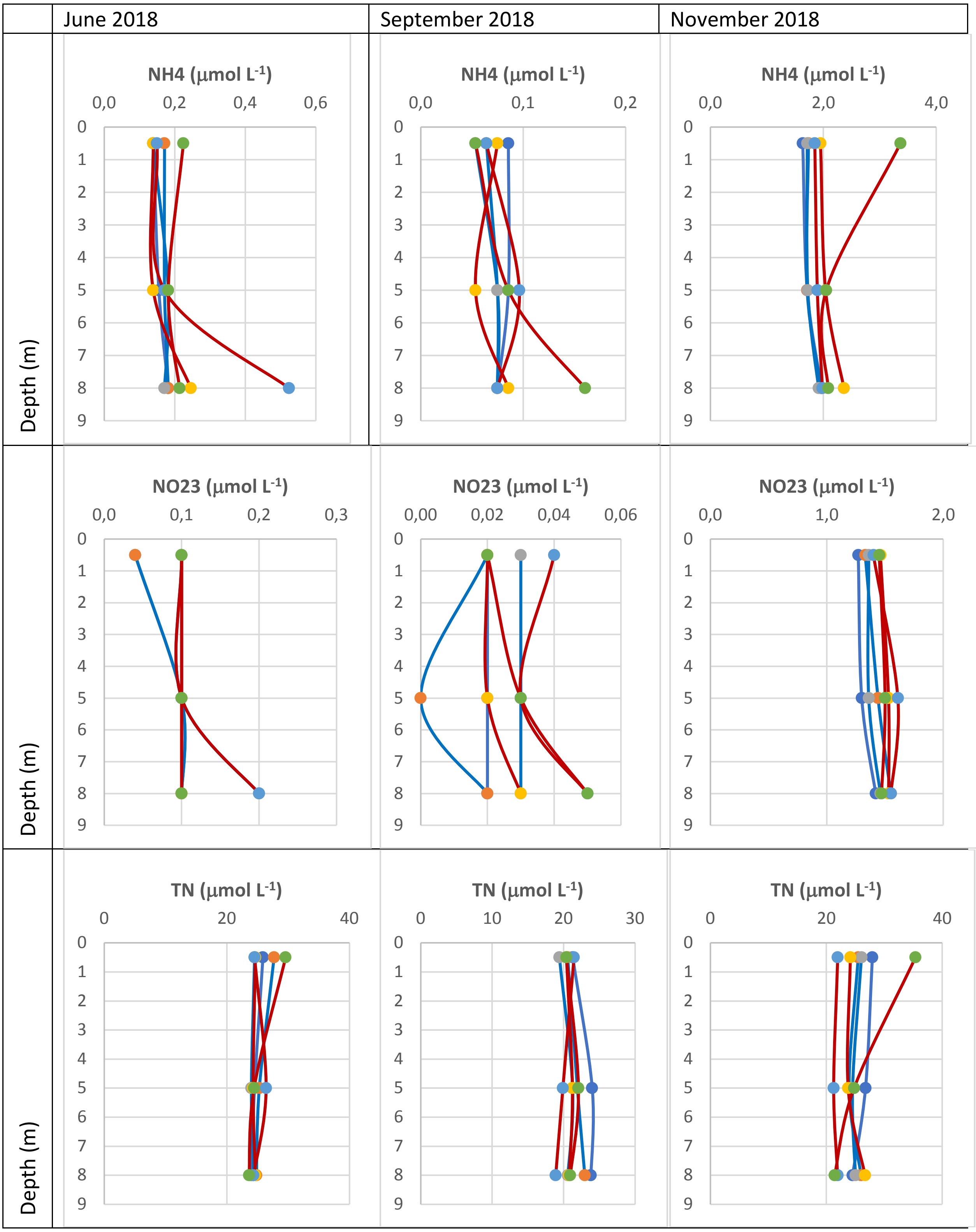


Figure 2. 27: Vertical profiles of nutrients in Kiel bay mussel farm (red lines) and reference site (blue lines) in 2018

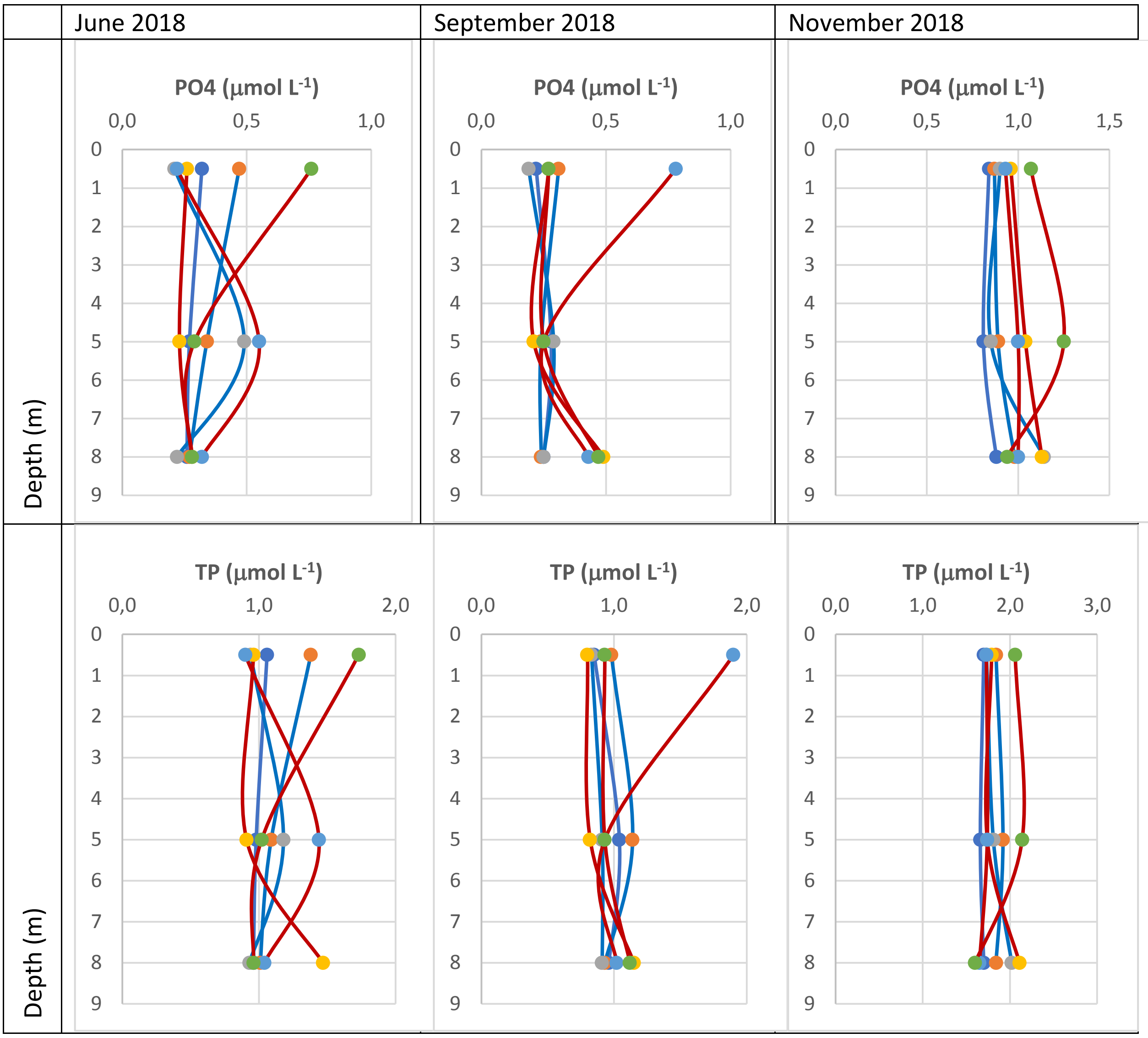


Figure 2. 28: Vertical profiles of nutrients in Kiel bay mussel farm (red lines) and reference site (blue lines) in 2018

2.2.5. Pavilosta (Coast of Kurzeme) mussel farm

The concentrations of nutrients observed at mussel farm and reference stations (Table 2.5) demonstrate classical seasonal pattern with lowest concentrations in spring (May) when pat of winter pool is removed from water column by spring bloom sedimentation and highest concentrations in autumn (November) when nutrient pool is partly replenished by input of nutrients from land and by assimilation of atmospheric nitrogen (cyanobacteria). Similarly to other areas of the Baltic sea the nitrogen inorganic compounds constitute minor fraction of the total. The relative share of inorganic compounds is increasing in autumn when biological activity is decreasing and shift from organic pool to inorganic is beginning. Similarly, inorganic phosphorus relative share is increasing in autumn as well.

The mussel farm and reference areas are located at comparatively to most other farm sites deep area and similarly to Sankt Anna mussel farm experience temporal thermic stratification. As a result, enhanced accumulation of ammonia, nitrate+nitrite and phosphate could be observed during summer months (Figure 2.29; 2.30). No such accumulation could be observed for total nitrogen and very minor for total phosphorus indicating that observed accumulation of inorganic forms of nutrients is rather a result of dissolution of particles occurring in water column that in near-bottom water is not balanced by instant uptake by phytoplankton cells due to light limitation than release of nutrients from sediments. More so since sea bottom in area of interest is mostly stones and morena, and therefore do not contain previously accumulated nutrients that could be released back into water column.

Table 2. 5: Average concentrations of nutrients (µmol L^{-1}) in Coast of Kurzeme mussel farm and reference area in 2017 and 2018

Parameter	2017			2018		
	May	July/August	November	May	July/August	November
NH4	0,07	0,16	2,31	0,13	0,5	0,13
NO23	0,07	0,07	5,55	0,09	0,16	6,82
TN	23,86	28,66	29,98	20,59	23,85	32,38
PO4	0,16	0,06	0,71	0,04	0,27	0,54
TP	0,52	0,89	1,34	0,55	0,73	1,02

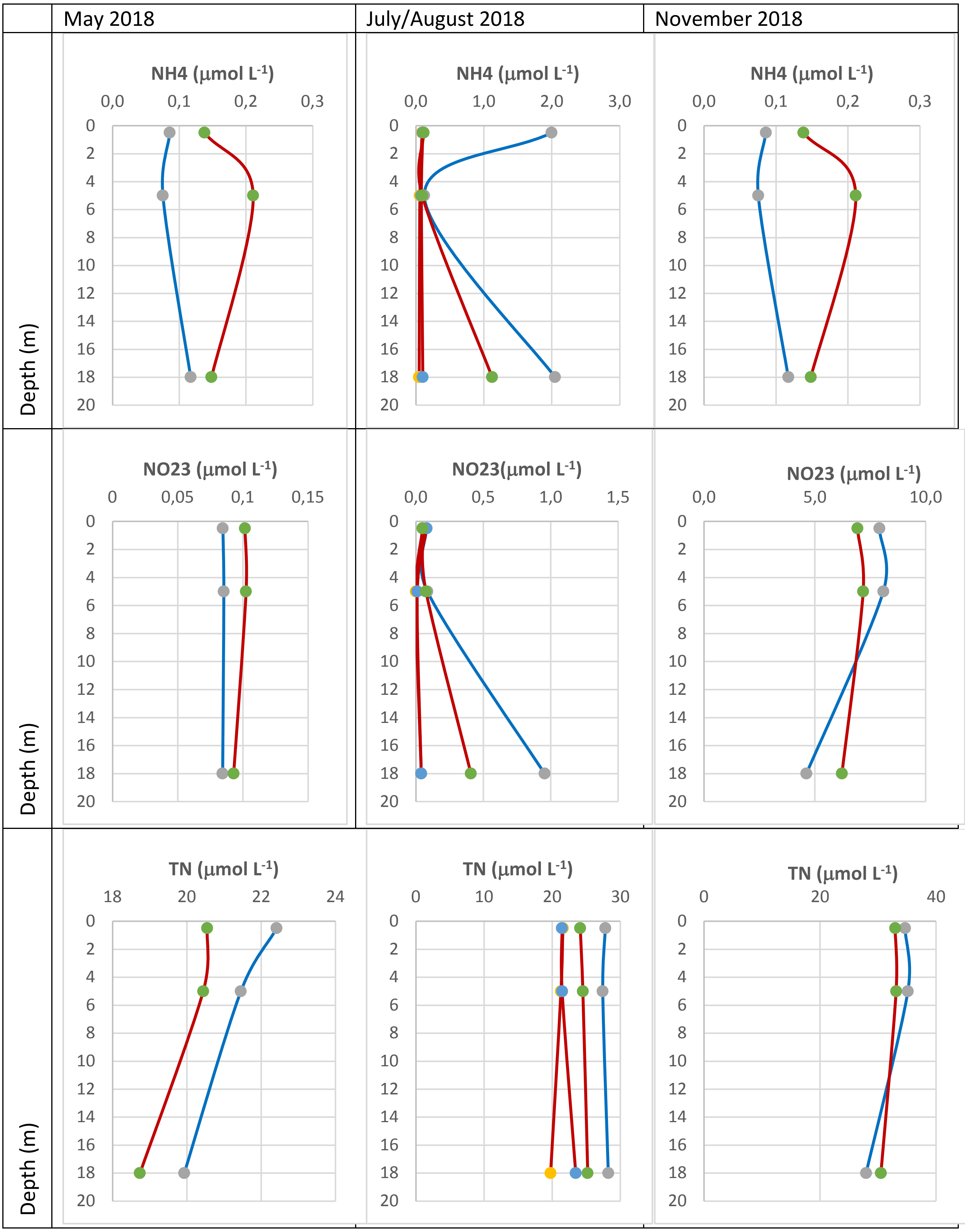


Figure 2. 29: Vertical profiles of nutrients in Coast of Kurzeme mussel farm (red lines) and reference site (blue lines) in 2018

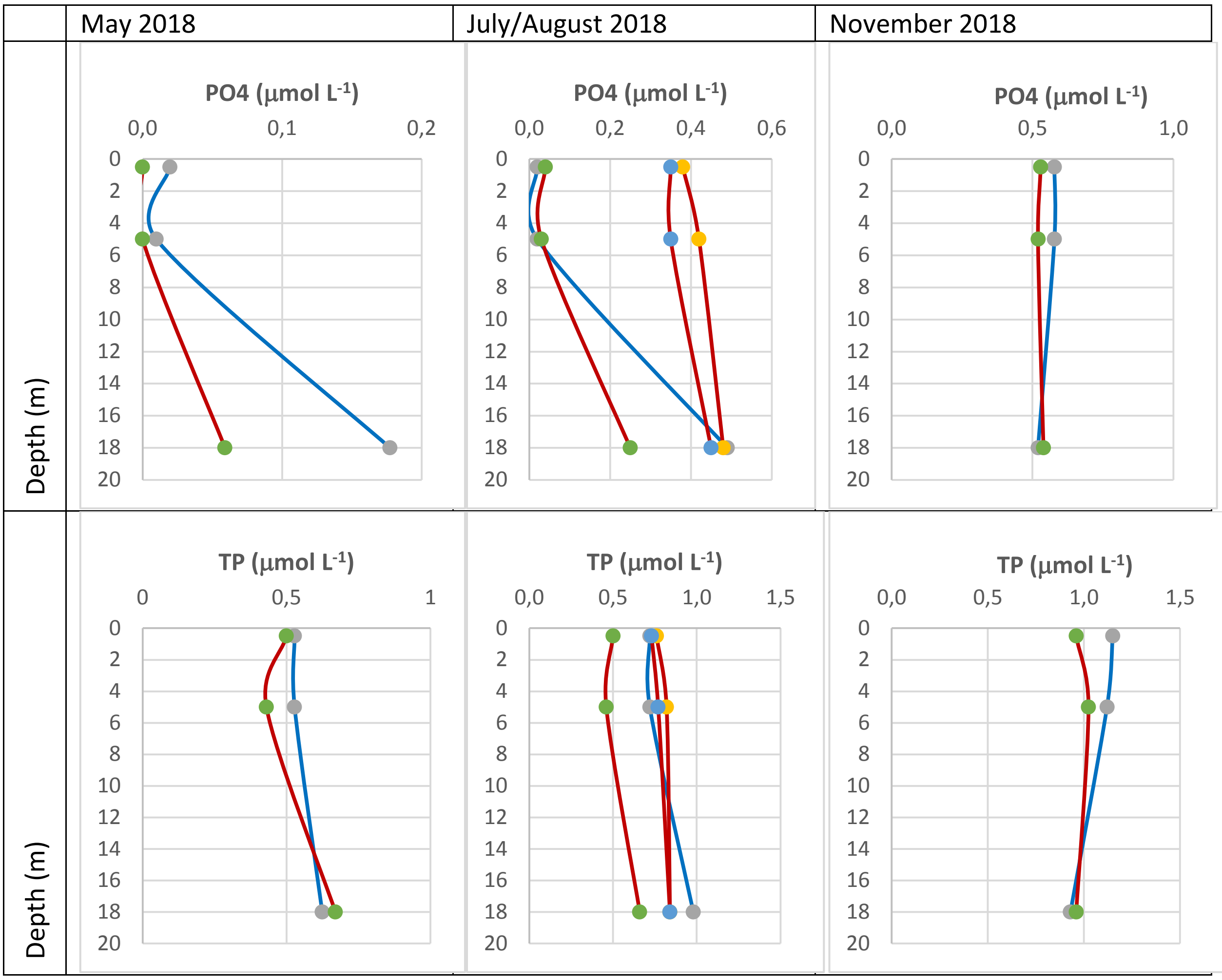


Figure 2. 30: Vertical profiles of nutrients in Coast of Kurzeme mussel farm (red lines) and reference site (blue lines) in 2018

2.2.6. Vormsi island mussel farm

The nitrogen (inorganic and total) exhibited classical pattern with lowest concentrations in June, as a result of nutrient removal from water column by spring phytoplankton bloom sedimentation, and highest in autumn when nutrient pool is partly replenished in 2017 (Table 2.6). In 2018, however, the lowest concentrations of total nitrogen and total phosphorus could be observed in August suggesting recent inflow of nutrient relatively poor water inflow into the area just prior the sampling event. Similarly to other areas of the Baltic Sea the inorganic compounds constitute minor fraction of the total nitrogen. At the same time, the share of inorganic phosphorus from total is substantially bigger constituting on average 20-40 %.
Despite relative shallowness of the area, the concentration profiles of inorganic nutrients (both nitrogen and phosphorus) indicate certain level of water column vertical stratification (Figure 2.31; 2.32). Since neither total nitrogen nor total phosphorus concentrations in June and August exhibit increased values in near-bottom layer it is highly likely that increased levels of inorganic nutrients rather indicate their lower assimilation rate in near-bottom water than in surface water layer by phytoplankton than nutrient excess release from sediments.

Table 2. 6: Average concentrations of nutrients (µmol L^{-1}) in Vormsi mussel farm and reference area in 2017 and 2018

Parameter	2017			2018		
	June	August	October	June	August	October
NH4	0,12	0,25	1,3	0,25	0,57	0,57
NO23	0,12	0,39	1,73	0,12	0,15	2,67
TN	28,37	34,81	41,2	30,95	18,59	33,62
PO4	0,44	0,29	0,54	0,33	0,18	0,55
TP	1,19	1,06	1,32	1	0,57	1,37

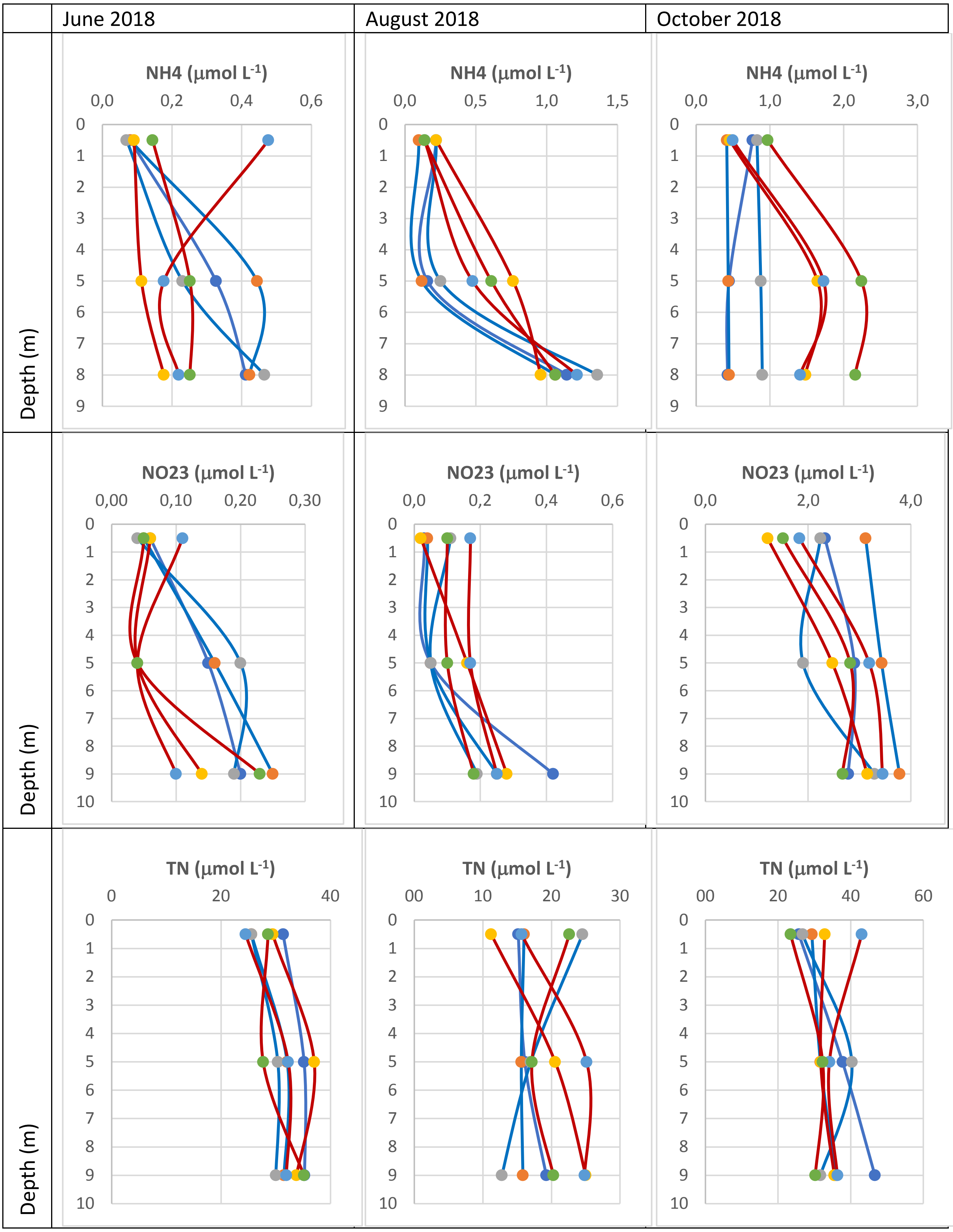


Figure 2. 31: Vertical profiles of nutrients in Vormsi mussel farm (red lines) and reference site (blue lines) in 2018

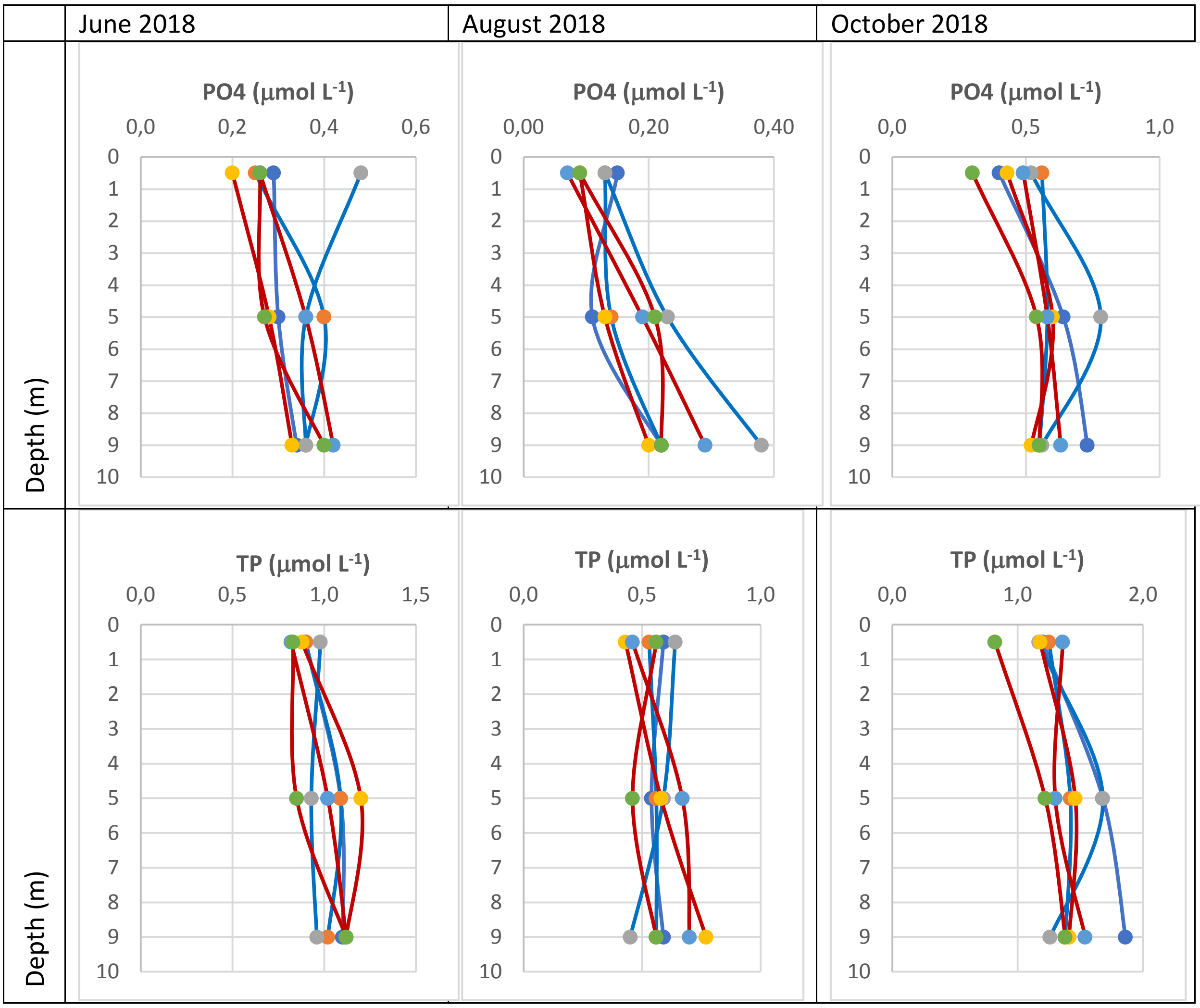


Figure 2. 32: Vertical profiles of nutrients in Vormsi mussel farm (red lines) and reference site (blue lines) in 2018

2.3. Phytoplankton and Chlorophyll *a*

2.3.1. *Sankt Anna mussel farm*

The total phytoplankton biomass in the mussel farm in June, August and October 2018 was similar and varied between 407 and 430 mg m^{-3} (Figure 2.33). Phytoplankton succession in June was characterized by mix of all functional groups. The diatoms (*Diatomophyceae*), mostly big cell size *Coscinodiscus granii*, were dominating (62% of total phytoplankton biomass) in August and mixotrophic ciliate (*Litostomatea*) *Mesodinium rubrum* was dominant (56%) in October (Figure 2.33). Total phytoplankton biomass in reference site was lower (30% in average) comparing with mussel farm and did not exceed 262 in June, October and 356 mg m^{-3} in August. The taxonomical composition in reference area was similar with that in mussel farm in June and August while mixture of four groups (20-25%) was more pronounced in October (Figure 2.33).
The average chlorophyll *a* concentrations in farm and reference site in all sampled months were fairly low, e.g., below 2 mg m^{-3} (Figure 2.39).

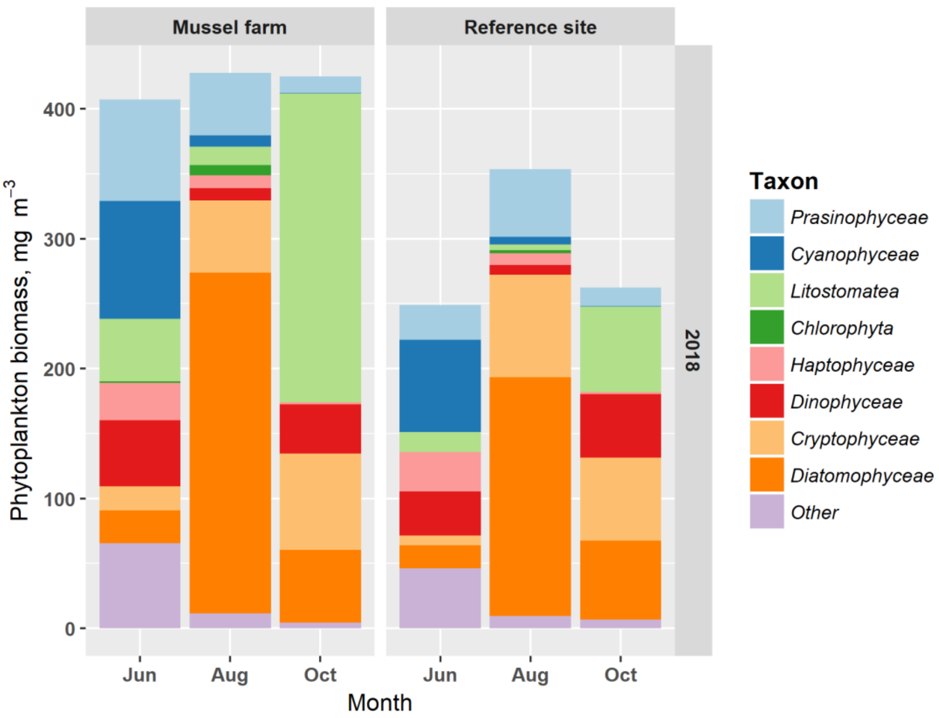


Figure 2. 33: The phytoplankton biomass by taxonomical groups in the Sankt Anna mussel farm and at the reference site

2.3.2. *Kalmarsund mussel farm*

The total phytoplankton biomass in farm in July, August, and October 2017 was from 109 to 219 mg/m3 with a mixture of different taxonomical groups (Figure 2.34). The cryptophytes (*Cryptophyceae*), mainly *Plagioselmis prolonga*, were most abundant in July, diatoms - *Cyclotella choctawhatcheeana*, cyanobacteria (*Cyanophyceae*) – *Aphanizomenon flosaquae* in August and *Mesodinium rubrum* in October (Figure 2.34). The total phytoplankton biomass in reference site was higher (29% in average) and the distribution of taxonomical groups were similar to that observed in mussel farm. Diatoms *C. choctawhatcheeana* and *Coscinodiscus granii* were more common (>50%) in July and August (Figure 2.34).

Total phytoplankton biomass in mussel farm (463 mg m^{-3}) and reference site (517 mg m^{-3}) in June 2018 was 54 – 86% higher than in September and October. The cyanobacteria *A. flosaquae* was the most dominant (58%) specie in the phytoplankton succession. (Figure 2.34 lower panel). Diatom *C. granii*, dinoflagellate (*Dinophyceae*) *Heterocapsa triquetra* was dominating in mussel farm and *H. triquetra* in reference site in September. Phytoplankton biomass in October was dominated by *M. rubrum* (65%) in mussel farm while in reference site different taxonomical groups exhibited rather equal share of the total (Figure 2.34 lower panel).
The average chlorophyll *a* concentration was 2 mg m^{-3} in 2017 exhibiting highest values in October and 1 mg m^{-3} in 2018 with highest concentrations in June (Figure 2.39).

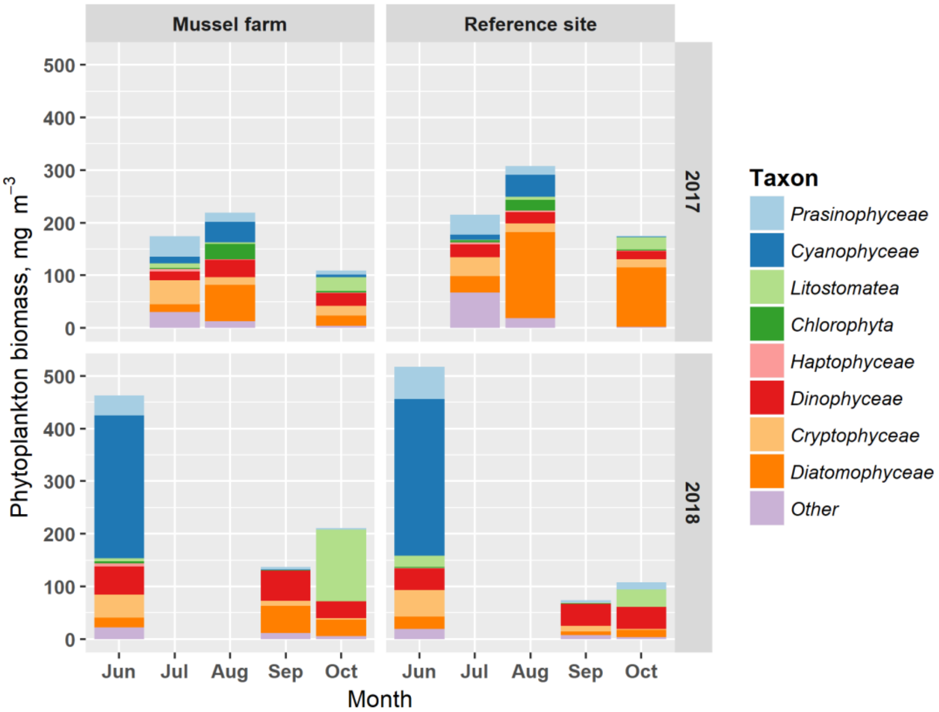


Figure 2. 34: The phytoplankton biomass of taxonomical groups in the Kalmarsund mussel farm and at the reference site

2.3.3. Musholm bay mussel farm

The highest total phytoplankton biomass (734 and 762 mg m^{-3}, respectively) was observed in the mussel farm in August and in the reference site in October (Figure 2.35). The lowest (155 and 41 mg m^{-3}, respectively) biomass values were observed in Jun at bought sites (Figure 2.35). The distribution of taxonomical groups in both sites and in all months was similar. The dinoflagellates was dominating (54 – 90%) group during all sampling events. However, dominating species varied between sampling events, e.g., *Gymnodnium* spp. in mussel farm and *Dinophysis norvegica* as well as *Heterocapsa* spp. in reference site were most abundant in June. The *Polykrikos schwartzii*, *Ceratium tripos*, *Prorocentrum micans* in mussel farm and *Polykrikos schwartzii* in reference site were most abundant in August. The *Karenia mikimotoi* (synonyms *Gymnodinium mikimotoi*, *G. nagasakiense*) in both sites were most abundant in October (Figure 2.35). This specie is widely distributed and has formed blooms in Australia, Denmark, Ireland, North Sea, Norway, Ireland, Scotland, southwest coast of England, China, New Zealand, Hong Kong, Florida and Texas, Gulf of Mexico, Arabian Sea and western India (Hallegraeff 2003). *K. mikimotoi* produce toxins responsible for fish death. It makes the red to dark-brown discoloring waters when the density reaches over one million cells/L. Effects on marine fauna are measurable above a few million cells/L (Gentien, 1998). Widespread mortality events of

wild fishes and benthic invertebrates were observed along the English south coast since 1978 and off the southwest Ireland in 1976 and 1978 (review of Jones et al. 1982). The economic consequences of fish death due to red tides can be significant, e.g. fish farms in Scottish lochs in September 1980 (review of Jones et al. 1982), 3,546 tons of caged fish were killed in Hong-Kong Bay in 1998 (Hodgkiss and Yang, 2001; Yang and Hodgkiss, 2001). In 1985, the occurrence of a bloom at 800,000 cells/L of K. mikimotoi in the Bay of Brest caused a loss of 4,000,000 individuals in scalop nurseries and culture trays (Erard-Le Denn et al., 2001). Along the French Atlantic coast, a mortality of 800-900 tons of the mussel *Mytilus edulis* (Gentien, 1998) and many fish in 1995 coincided with an exceptional bloom of 48 million cells/L (Arzul et al., 1995). In Musholm bay mussel farm the abundance and biomass of *K. mikimotoi* were 77,7826 cell/L and 281 mg/m3 (42% of total phytoplankton biomass) in farm and 134,946 cell/L 487 mg/m^3 (36% of total phytoplankton biomass) in reference site.
The average chlorophyll *a* concentration was 2 mg m^{-3} in mussel farm and 3 mg m^{-3} in reference site with comparatively higher concentrations in October in both sites (Figure 2.39).

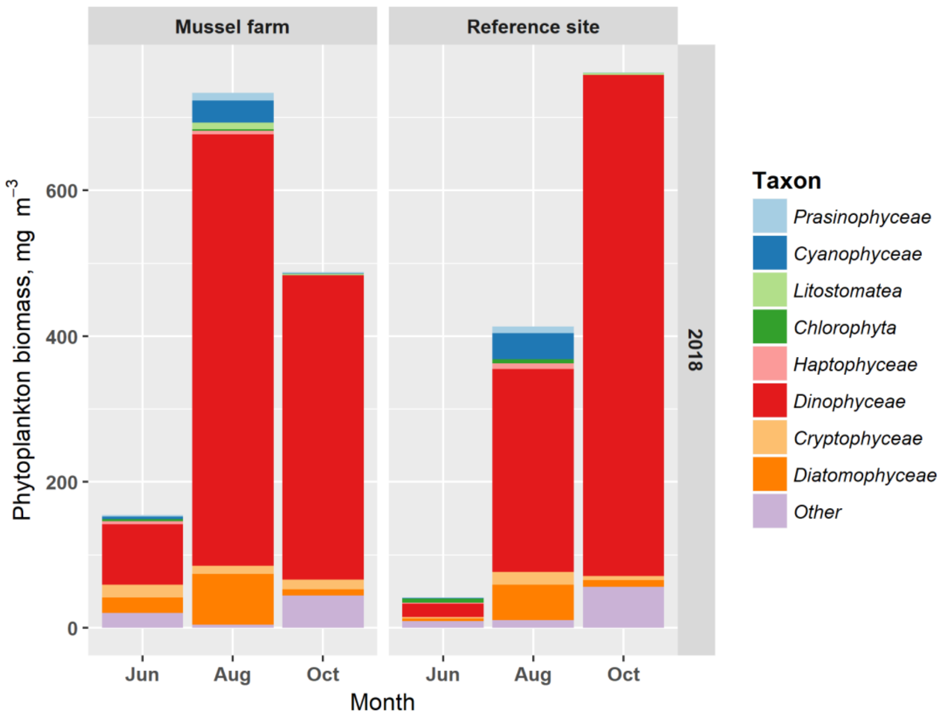


Figure 2. 35: The phytoplankton biomass of taxonomical groups in the Musholm bay mussel farm and at the reference site

2.3.4. Kiel bay mussel farm

The total phytoplankton biomass in 2017 was substantially higher in mussel farm in November than during other sampling events. In reference site, the phytoplankton biomass increased from June to November never reaching values observed in mussel farm (Figure 2.36). The distribution of taxonomical groups in mussel farm in June was similar to reference site. In both areas diatoms (>90%), mainly *Coscinodiscud granii* in mussel farm and *C. granii, Cerataulina pelagica*, in reference site, dominated. At the same time, in September (87% in both areas) and November (97 and 64% in mussel farm and reference site, respectively) dinoflagellates (*Ceratium tripos* and *Ceratium fusus*) were most abundant (Figure 2.36).

The total phytoplankton biomass in 2018 was more even among sampling events than in 2017 (Figure 2.36). The division of taxonomical groups in 2018 was similar to that observed in 2017, e.g., dinoflagellates dominated (64 – 87%) during all sampling events. The most abundant dinoflagellates were *Oblea rotunda* and *Ceratium tripos* in June, *Polykrikos schwartzii* and *Pyrophacus horologium* in September, and *Ceratium lineatum* and *Gymnodinium* spp. in November (Figure 2.36 lower panel).
The average chlorophyll *a* concentration in 2017 was around 2 mg m^{-3} (Figure 2.39). The chlorophyll *a* concentration substantially increased in November in mussel farm while no such increase was observed in reference site. The average chlorophyll *a* concentration (4 mg m^{-3}) in 2018 was two times higher than in 2017 due to differences in species composition (Figure 2.39).

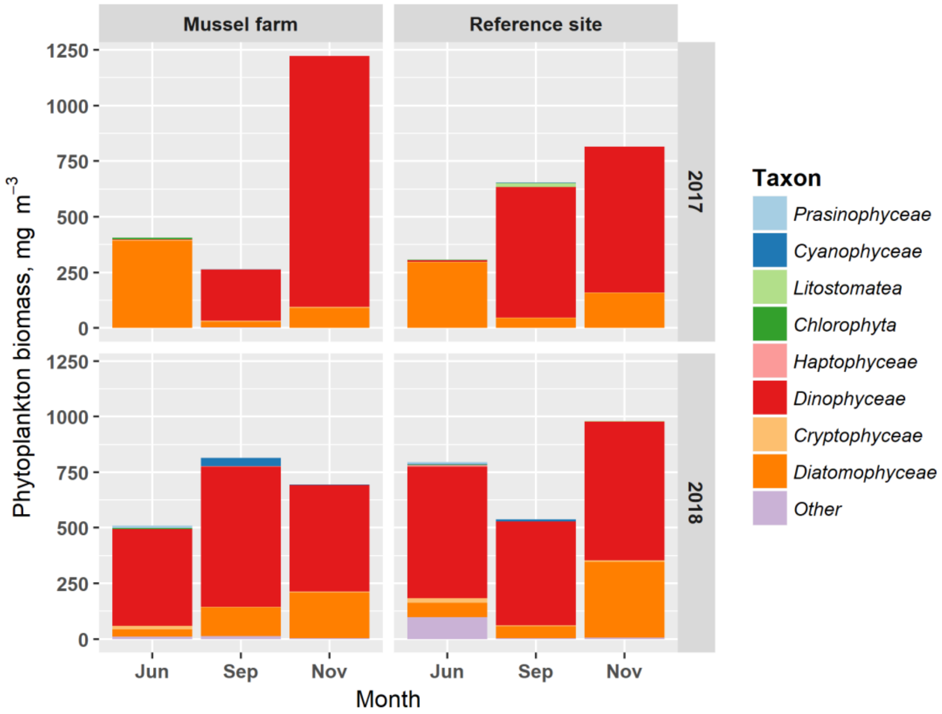


Figure 2. 36: The phytoplankton biomass of taxonomical groups in the Kiel bay mussel farm and at the reference site

2.3.5. Pavilosta (Coast of Kurzeme) mussel farm

The highest total phytoplankton biomass was in summer 2017, while the smallest lowest was in autumn (Figure 2.37). The biomass in respective months was higher in mussel farm area than in reference site. The diazitrophic filamentous cyanobacteria *Aphanizomenon flosaquae* was clearly dominating in July in mussel farm area and cconstitute substantial part of total biomass during other summer months. The rest of biomass were made of different taxonomical groups most of them chlorophytes (*Chlorophyta*) and cryptophytes as it is characteristic for summer period (Figure 2.37).
The highest total phytoplankton biomass in 2018 was in August both in mussel farm and reference site (Figure 2.37). The lowest biomass was in mussel farm in November. At the same time, second highest biomass was observed in November at the reference site. The total phytoplankton biomass in May and July mostly was composed of dinoflagellates *Heterocapsa* spp. (around 50%) and ciliate *Mesodinim rubrum* (20-30%). Cyanobacteria (40%) *A. flosaquae* and dinoflagellates (35%)

Heterocapsa spp. were most abundant in both sites in August. And small centric (7-12µm) diatoms were dominant (97%) in November in reference site.

The chlorophyll *a* concentrations in 2017 varied considerably over months with high values during summer and low during autumn. Average chlorophyll a concentration in 2018 was generally lower than during 2017. In both years highest values were observed in August when cyanobacteria and dinoflagellates dominated (Figure 2.39).

Figure 2. 37: The phytoplankton biomass of taxonomical groups in the Coast of Kurzeme mussel farm and at the reference site

2.3.6. *Vormsi island mussel farm*

The total phytoplankton biomass in 2017 was highest in June in both sites. Thereafter sharp biomass decrease was observed in August with subsequent slight increase in October (Figure 2.38). The relative proportion of taxonomical groups varied between mussel farm and reference site. In mussel farm, half of biomass was made by ciliate *M. rubrum* and the rest mostly of dinoflagellates *Peridinium* spp., *Dinophysis acuminata* and cyanobacteria *Aphanizomenon flosaquae* in June. At the same time, in June phytoplankton community was substantially more (70%) dominated by *M. rubrum* in the reference site. In August, no clear dominant specie was identified at both sites. At the same time, in October the *M. rubrum* was dominating (64%) again in mussel farm while second most abundant specie (*A. flosaque*) constituted 27% of total biomass. In the reference area no such clearly dominating specie was identified. Most of was made by tree groups: ciliate *M. rubrum*, dinoflagellates *Gymnodinium* spp. and cryptophytes *Plagioselmis prolonga* (Figure 2.38).

Similarly to 2017 also in 2018 the highest phytoplankton biomass was observed in June followed by sharp biomass decrease in following months. Ciliate *M. rubrum* (53%), dinoflagellates (25%) *Oblea rotundata*, *Protoperidinium* spp. and *A. flosaquae* (13%) were most abundant in mussel farm in June.

At the same time, only three species (*M. rubrum*, *A. flosaquae* and diatom *Actinoptychus octonarius*) was abundant in reference site.
The average chlorophyll *a* concentration in 2017 and in 2018 was fairly low, e.g., around 2 mg m^{-3} (Figure 2.39).

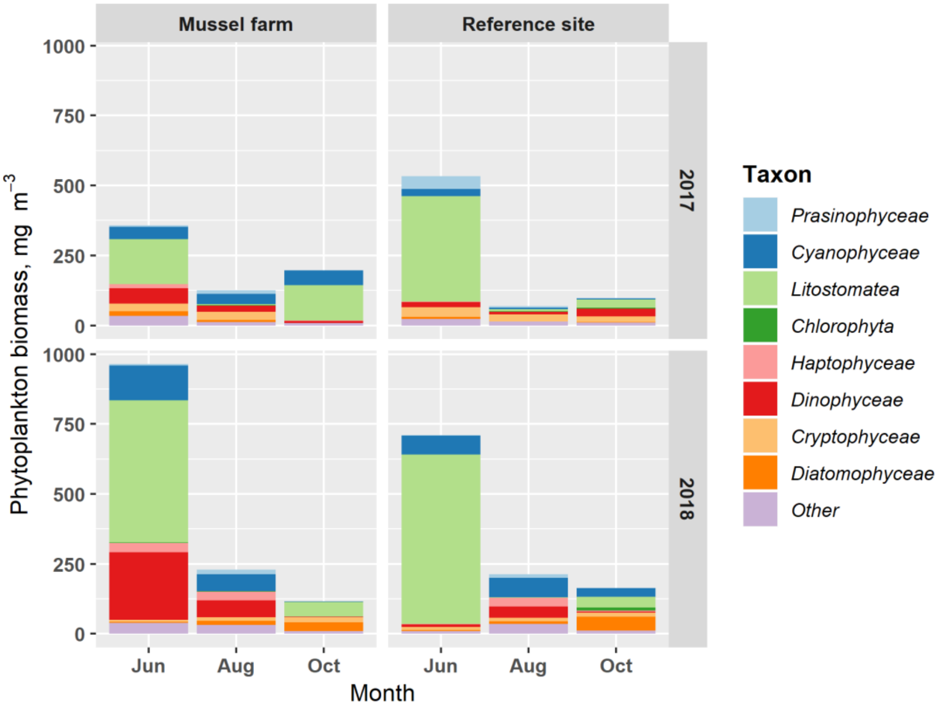


Figure 2. 38: The phytoplankton biomass of taxonomical groups in the Vormsi island mussel farm and at the reference site

Figure 2. 39: The Chlorophyll *a* concentrations in the all mussel farms and at the reference sites

2.4. Benthic habitats

2.4.1. Sankt Anna mussel farm

Samples of benthic organisms from St. Anna Archipelago (Sweden**)** were collected in June 2017 and May 2018. Overall, in both mussel farm and reference stations, a small number of taxa and organisms were detected. In mussel farm stations (June 2017) only 4 Taxagroups (Figure 2.40) were found (*Bivalvia* (62%), *Crustacea* (18%), *Diptera* (also 18%) and - *Priapulida* (2%)) represented by only 7 species. The most commonly observed was *Limecola balthica* (average count of 300 ind/1m^2) while the rarest ones were *Sadura entomon* and *Mytilus trossulus* - average count of 2 ind/1m^2.

At the same time, only two taxa groups - *Crustacea* (67%) and *Diptera* (33%) were identified in the reference stations. The identified taxa groups were represented by only two species - *Monoporeia affinis* (average count of 28 ind/1m^2) and *Chironomidae* (average count of 14 ind/1m^2).

Results from samples collected in May 2018 presented slightly greater variety of taxa in mussel farm stations as also *Gastropoda* and *Oligochaeta* organisms were found, but the overall percentage was small and the dominant taxon also at this period was *Bivalvia* (Figure 2.40). However, identified taxons were represented by just 6 species. Similarly, to results in 2017, *Limecola balthica* was the most common in farm station (average count of 216 ind/1m^2). The second most abundant was *Chironomidae* (average count of 48 ind/1m^2), but *Potamopyrgus antipodarum* was most rarely encountered (average count of 2 ind/1m^2).

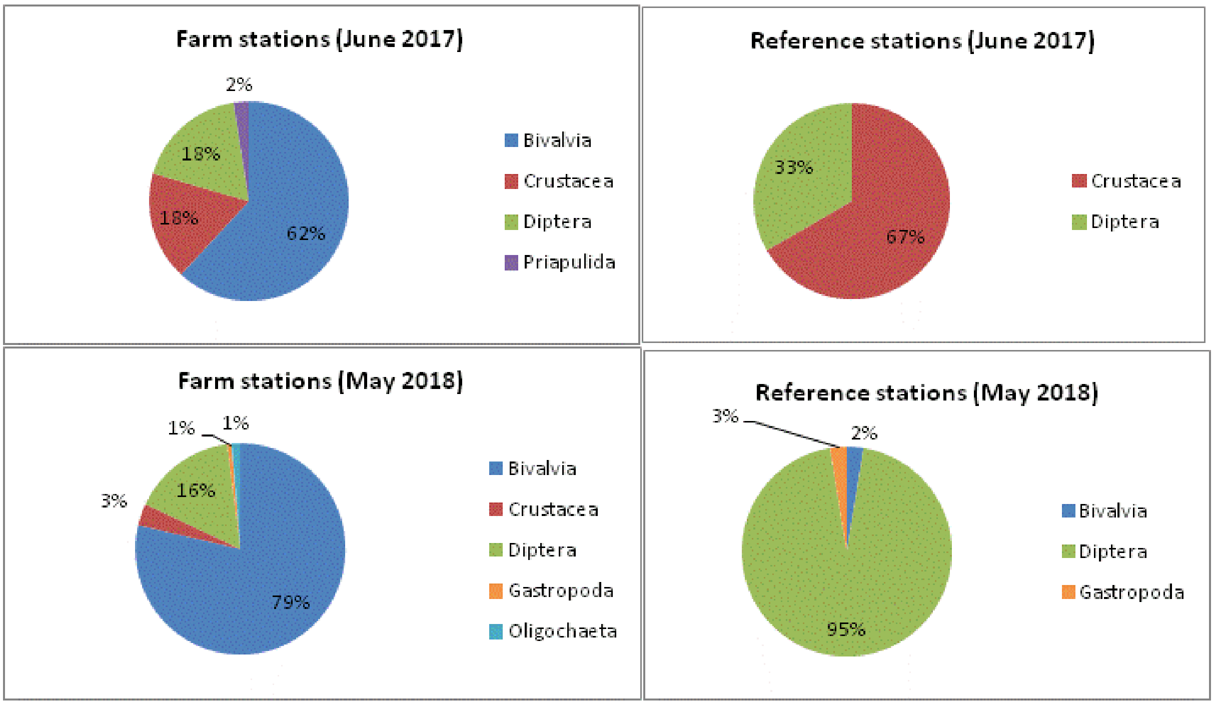


Figure 2. 40: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations (in St.Anna Archipelago) (by count)

In reference stations (May 2018) *Diptera* organisms dominated, while proportion of other 2 taxa found (*Bivalvia* and *Gastropoda*) was low (Figure 2.40). Similarly to 2017 also in 2018, reference stations had a very small variety of species, e.g., only 3 species found in the samples - *Limecola balthica*, *Chironomidae* and *Potamopyrgus antipodarum*.

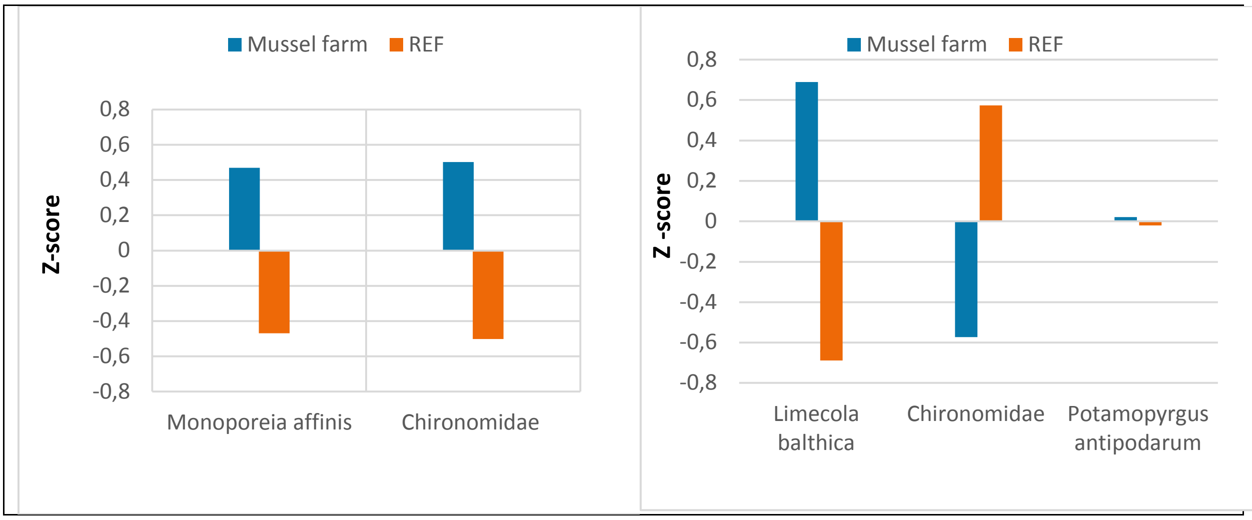


Figure 2. 41: Z-scores for dry biomass distribution among species identified in both Mussel farms and reference farms in St. Anna Archipelago, left – 2017 and right – 2018. Z-scores - shows the number of standard deviations that the particular score is above (positive) or below (negative) the average value in the sample

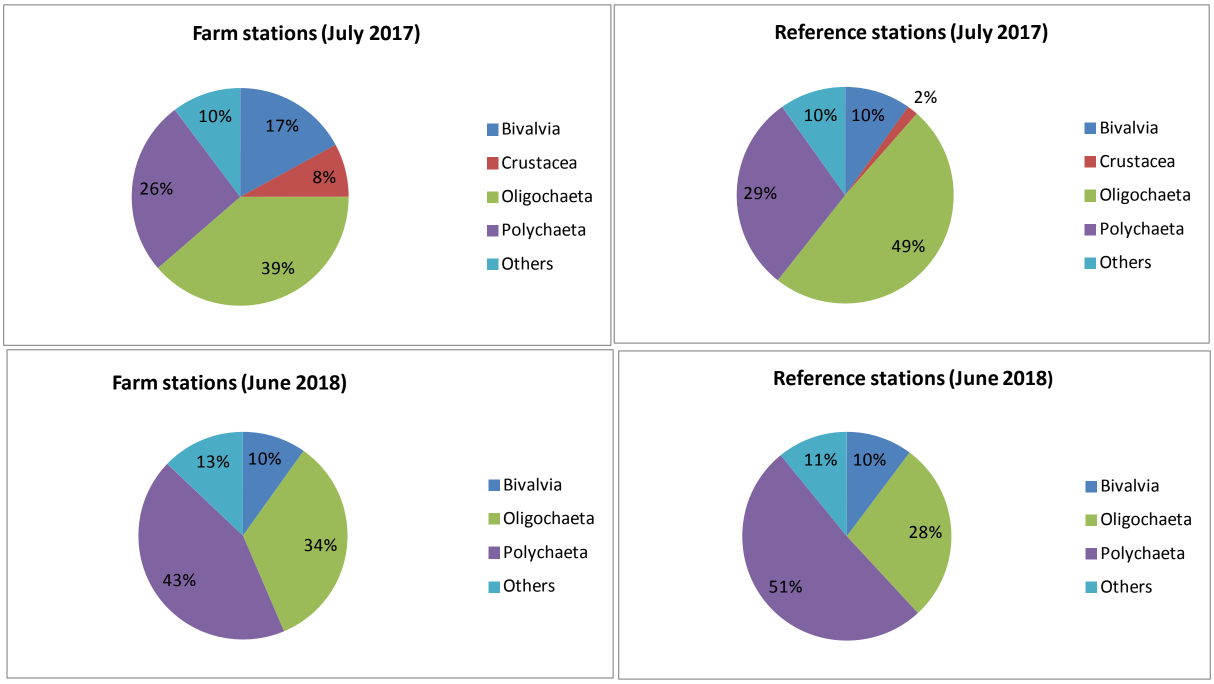
The biomass of the two species (*Monoporeia affinis* and *Chironomidae*), that were identified in both sites in 2017, on average was higher in mussel farm stations than in the reference area stations. However, in May 2018 only one specie had a higher biomass in mussel farm stations than in reference farms – *Limecola balthica*, while another specie (*Chironomidae*) had a higher biomass in reference stations. *Potamopyrgus antipodarum* had very close average biomass detected between the two sites, but *Oligochaeta* was the one the species that had a too small and thus unmeasurable weight and was thus excluded from the graph(Figure 2.41).

2.4.2. Kalmarsund mussel farm

Samples from Kalmarsund (Sweden) were collected in July 2017 and June 2018. At both sampling sites, the taxa groups by count were quite similar, but their proportions differed (Figure 2.42). The *Oligochaeta* organisms dominated both in mussel farm and reference areas in 2017 while in 2018 *Polychaeta* dominated.

In mussel farm identified taxons were represented by 11 species in 2017. However, the absolute count of the specimens was relatively small. The most common taxon (*Oligochaeta*) organisms reached on average count of 68 ind/1m^2, while other species were with the individual count of 20 or less per 1m^2. The molluscs found in the samples (*Limecola balthica*, *Mytilus trossulus*, *Cerastoderma* *edule* and *Mya arenaria*) were identified as juvenile and very small in size. Ten different species of organisms were detected in reference stations in July 2017. However, their abundance was slightly higher than in mussel farm stations. The most abundant were *Oligochaeta* (average count of 120 ind/1m^2), *Hediste diversicolor* (average count of 60 ind/1m^2) and *Limecola balthica* (average count of 16ind/1m^2).

In June 2018 12 species were identified at mussel farm stations. Of these, most were *Oligochaeta* organisms (average abundance of 710 ind/1m^2), *Hediste diversicolor* (average abundance of 604 ind/1m^2) and *Marenzelleria* sp. (average abundance of 308 ind/1m^2). At reference stations 10 species were identified and the most dominant were *Oligochaeta* organisms (average abundance of 256 ind/1m^2) and *Hediste diversicolor (*average abundance of 312 ind/1m^2).



*Other taxa in farm station (July 2017): *Diptera*, *Nematoda*;
Other taxa in reference station (July 2017):*Diptera*, *Nematoda*;
Other taxa in farm stations (June 2018): *Crustacea*, *Diptera*, Nematoda*;*
Other taxa in reference station (June 2018): *Crustacea*, *Diptera*, Nematoda*.*

Figure 2. 42: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations in Sweden, Kalmarsund (by count)

There is no clear difference in biomass for the species encountered in both sampling sites (mussel farm and reference sites) both in July 2017 and June 2018 (Figure 2.43) since although for some species relative biomass is higher at mussel farm for other species the biomass is higher at reference site. Furthermore, as can be seen, several species have higher biomass in mussel farm area in 2018 while lower in 2017. At the same time, for some species such shift in relative biomass ration could not be observed. Therefore, it is most likely that observed differences of species composition, abundance and biomass between mussel farm area and reference site is due to natural variability rather than manifestation of mussel farm influence.

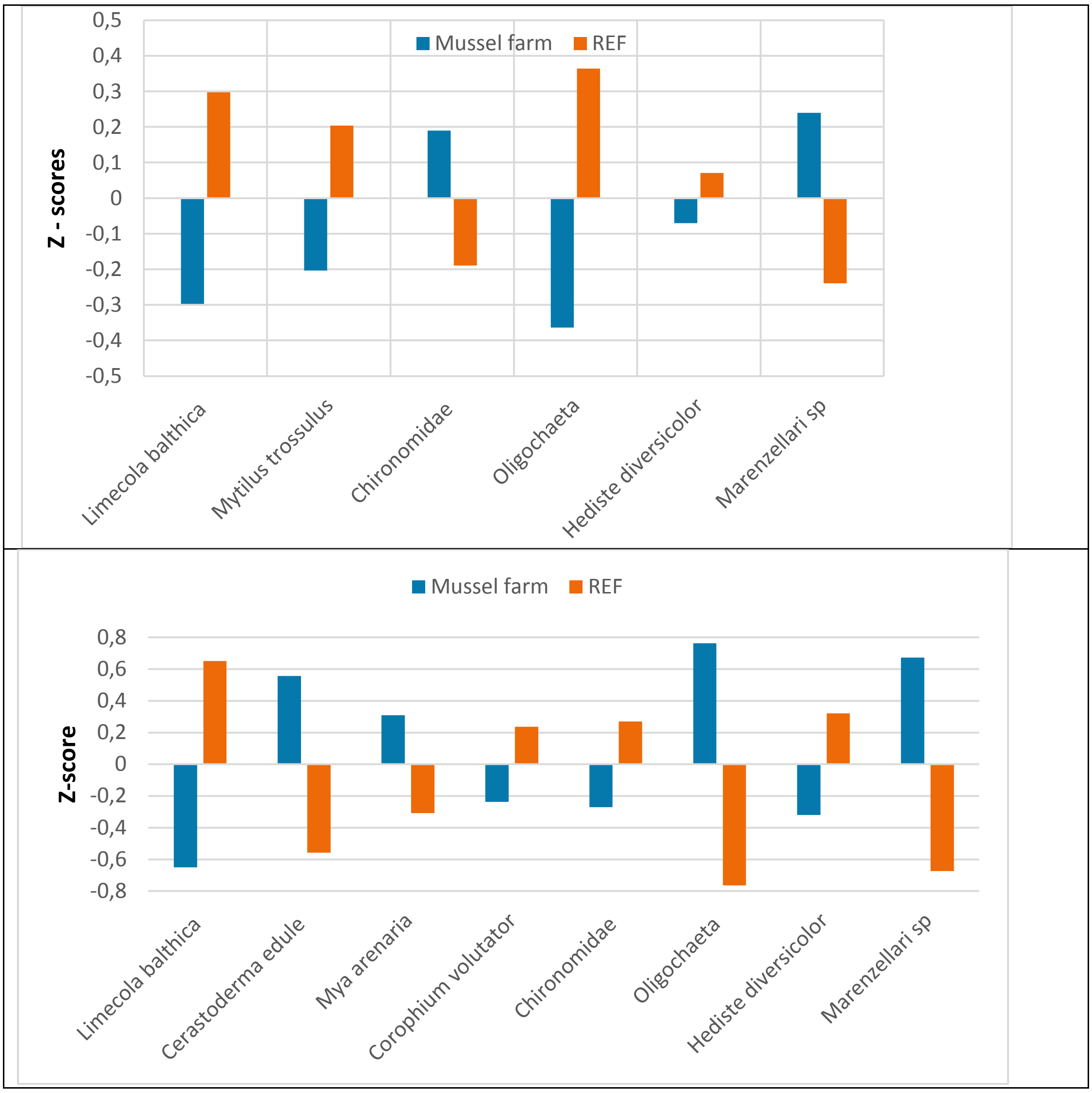
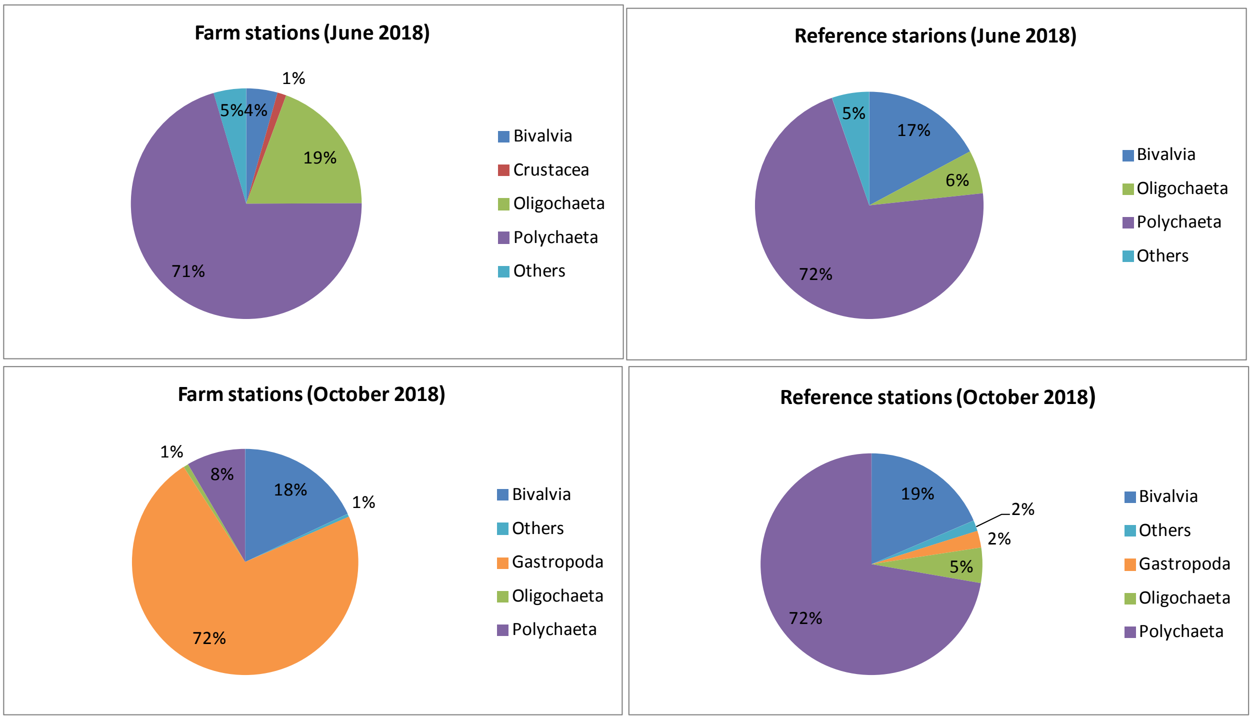


Figure 2. 43: Z-scores for dry biomass distribution among species identified in both mussel farm and reference area in Kalmarsund, upper panel – 2017, lower panel – 2018

2.4.3. *Musholm bay mussel farm*

Samples of benthic organisms from Musholm farm in 2018 were collected twice: on June and October. In June 2018, the dominant taxa was *Polychaeta* both in mussel farm and reference area stations (Figure 2.44). The next most representative taxa group in mussel farm area was *Oligochaeta* (19%), while *Bivalvia*, *Crustacea* and taxa group "Others" (which includes *Nemetoda*) made up a small percentage of the total. At the same time, the next most abundant taxa was *Bivalvi*a in reference stations, while *Oligochaeta* and "Other" taxa which includes *Nemetoda* and *Echinodermat*, had substantially lower share. In mussel farm stations identified taxonomic groups were represented by 11 different species. Numerically most abundant of the *Polychaeta* taxon were *Scoloplos armiger* (average abundance of 352 ind/1m^2), *Pygospio elegans* (average abundance of 158 ind/1m^2) and *Hediste diversicolor* (average abundance of 150 ind/1m^2). Slightly smaller number of species (10 different species) were observed in reference stations, of which *Scoloplos armiger* (average abundance of 522 ind/1m^2) was dominant, similarly to mussel farm stations. From other species abundance of only *Manayunkia aestuarina* and *Limecola balthica* exceeded 100 individuals per one square meter, while other species were below.



*Others taxa in farm stations (June 2018) – *Nematoda*;
Others taxa in reference stations (June 2018) – *Nematode*, *Echinodermata;*
Others taxa in farm stations (October 2018) – *Diptera*, *Hydrachnidae*, *Nemetoda*, *Crustacea*;
Others taxa in reference stations (October 2018) – *Priapulidae*, *Echinodermata*, *Nemetoda*, *Crustacea*.

Figure 2. 44: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations in Musholm (by count)

In October 2018 similar situation of taxonomic group distribution was observed only in reference stations (Figure 2.44). In mussel farm stations, major changes in taxonomic group relative distribution could be observed. There the *Gastopoda* substituted *Polychaeta* as the dominant taxon. It should be also noted, that *Gastopoda* was not detected in the Mussel farm stations in June (Figure 2.44). Furthermore, at Mussel farm stations species richness substantially increased in October compared to June, accounting for 25 different species, most of them snails and mussels. The highest prevalence was encountered for two species - *Hydrobia sp.* (average abundance 6598 ind/1m^2) and *Mya spp.* (average abundance 962 ind/1m^2). Similarly, the species richness increased also at the reference sampling sites, accounting for 19 species, with the largest share having *Scoloplos armiger* (average abundance 546 ind/1m^2) and *Corbula sp.* (average abundance 100 ind/1m^2). *Hydrobia sp* which had high abundance in mussel farm stations, had a relatively low abundance in the reference sampling sites, with only 14 individuals per one square meter.

There were six common species identified in farm and reference stations in samples from June 2018. Two of those, namely *Limecola balthica* and *Oligochaeta* were with a higher average biomass in reference stations, while *Mya arenaria* and *Bylgides sarsi* had higher biomass in reference stations. For two species (*Hediste diversicolor* and *Scoloplos armiger*), the difference in biomass was too small to establish notable difference between both areas. In samples from October 2018, however, there was already more diverse selection of species with total of 12. Seven of those were with a higher average biomass in mussel farm, while only three in reference area. The two remaining species (*Hediste diversicolor*, *Nephtys hombergii*) didn't have a notable difference between the sampling sites (Figure 2.45).

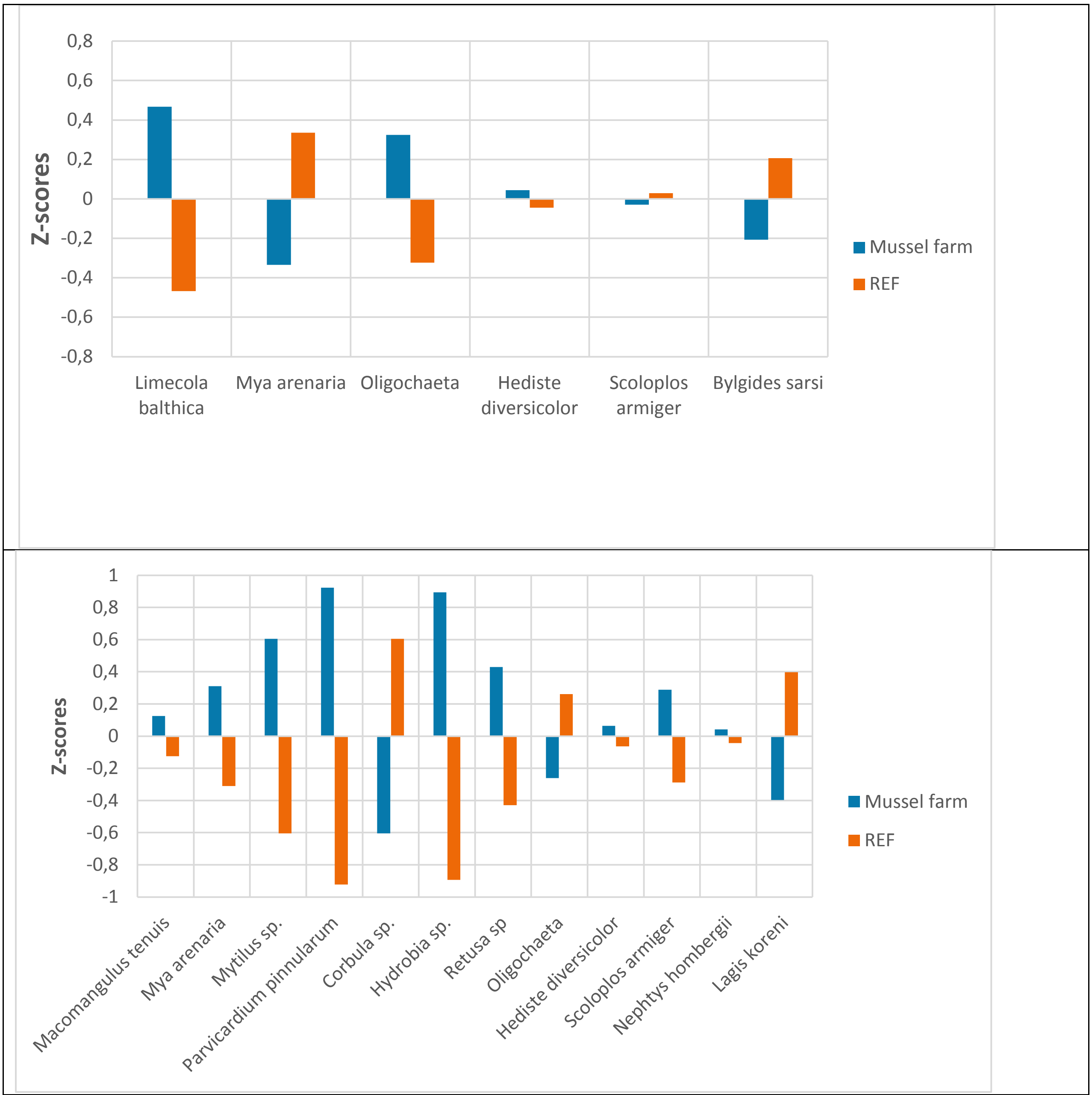
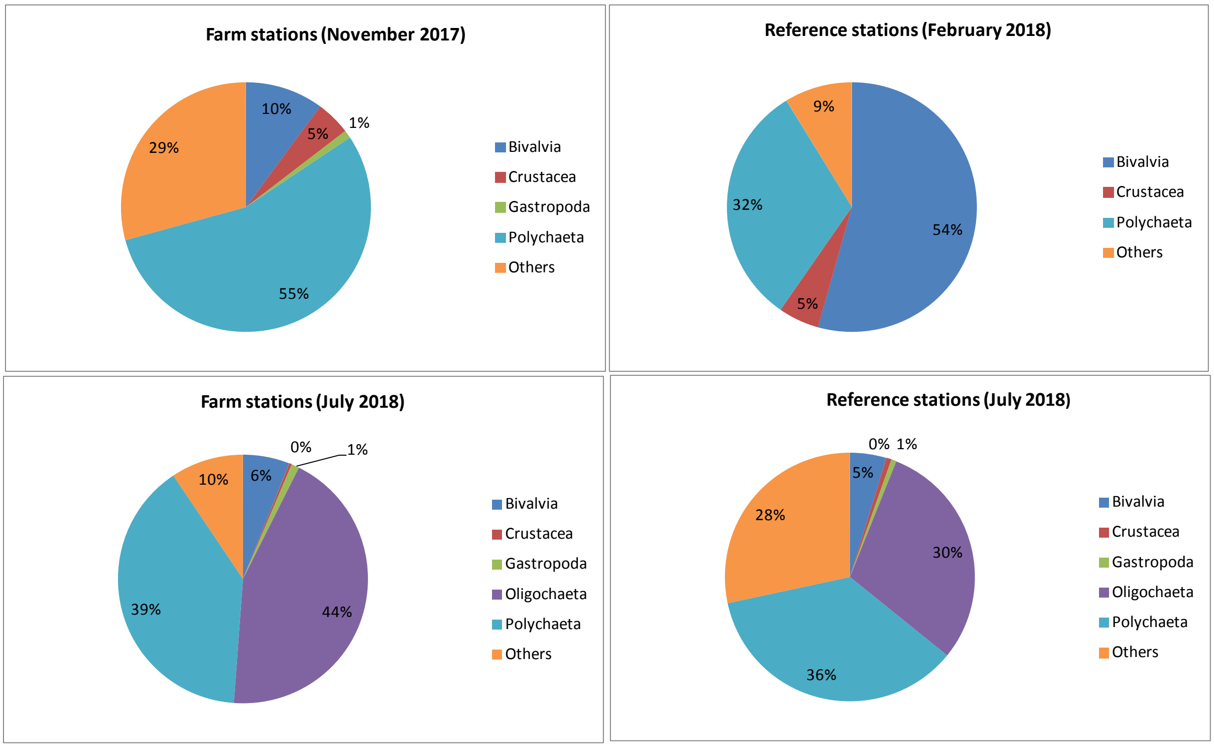


Figure 2. 45: Z-scores for dry biomass distribution among species identified in both Mussel farms and reference site in Musholm, upper panel - June 2018, lower panel – October 2018

2.4.4. *Kiel bay mussel farm*

Samples of benthic organisms from Kiel (Germany) were collected on November 2017, February 2018 and July 2018. In mussel farm stations (November 2017) *Polychaeta* group was the most dominant, accounting for more than half of the organisms found in the samples (Figure 2.46). The second most abundant group was composed of representatives of the several taxonomic groups: *Nematoda*, *Nemertea* and *Plathelminthes* (included in the taxa group "Others"), while *Bivalvia*, *Crustacea* and *Gastropoda* made up a smaller percentage in mussel farm stations. The identified taxonomic groups were represented by 29 species. The specie *Nemetoda* (average count of 11740 ind/1m^2) was found in large quantities in mussel farm stations. From other species most abundant were *Capitella capitata* with an average count of 7896 individuals per 1m^2, *Heteromastus filiformis* (average count of 5922 ind/1m^2), *Polydora ciliate* (average count of 3065 ind/1m^2) and *Paradoneis lyra* (average count of 2460 ind/1m^2).

In reference stations (February 2018) most of the organisms were found in taxonomic group *Bivalvia*, less in *Polychaeta* and *Crustacea*, while *Gastropod*a organisms were not detected in reference stations at all (Figure 2.46). The species diversity was lower in reference stations than in mussel farm stations totalling 17 different species, most of which were mussels *Kurtiella bidentata* (average count of 468 ind/1m^2) and *Corbula gibba* (average count of 987 ind/1m^2). *Capitella capitate*, that had high prevalence in Mussel farm, had a relatively low abundance in the reference farms with only 52 individuals per one square meter.



*Other taxa in farm station (November 2017): *Nemetoda*, *Nemertea*, *Plathelminthes*;
Other taxa in reference station (February 2018): *Nemertea*, *Cnidaria;*
Other taxa in farm stations (July 2018): *Nematoda*, *Nemertea*, *Priapulida*;
Other taxa reference stations (July 2018): *Hydrachnidia*, *Nematoda*, *Nemertea*, *Priapulida.*

Figure 2. 46: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations (in Kiel) (by count)

Results from samples collected in July 2018 presented similar number of taxonomic groups at both - mussel farm and reference area stations. At the mussel farm and reference site stations most abundant were *Oligochaeta* and *Polychaeta*, while taxa groups such as crustaceans (*Crustacea*), mollusks (*Bivalvia*) and snails (*Gastropoda*) accounted for less than 10% of the total taxa groups found (Figure 2.46). The species/groups like *Nematoda*, nemertine worms and *Priapulida* also didn't exceed the 10% margin. The identified taxonomic groups were represented by 19 species at mussel farm stations. The most abundant were the oligochaetes (average abundance 6752 ind/m^2), *Mareznzelleria* sp. (average abundance 4155 ind/m^2), *Nemetoda* (average abundance 883 ind/m^2) and *Scoloplos armiger* (average abundance 727 ind/m^2). In mussel farm stations, also mollusk *Mytillus* spp. and crustacean *Microdeutopus gryllotalpa* were detected. In comparison, only 16 species were identified at the reference site, of which most abundant were oligochaetes (average abundance 2285 ind/m^2), *Hediste diversocolor* (average abundance 831 ind/m^2) and *Marenzellaria* sp. (average abundance 725 ind/m^2).

The biomass of observed species (12 in total) in both sampling locations was mostly higher in mussel farm stations than in reference area stations in July 2018 (Figure 2.47). Only three of the species – *Nemetoda*, *Hediste diversicolor* and *Scoloplos armiger* had a higher average biomass in reference stations, while the 9 remaining species showed a higher biomass in mussel farms

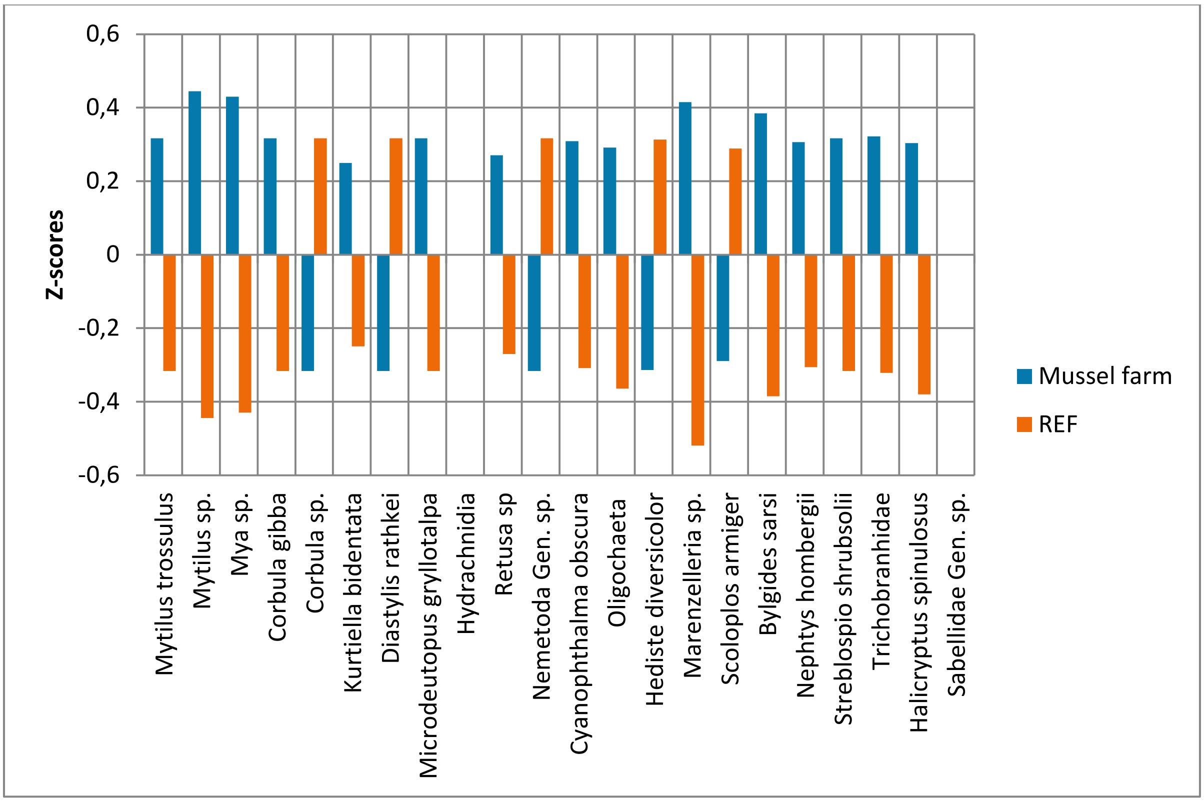


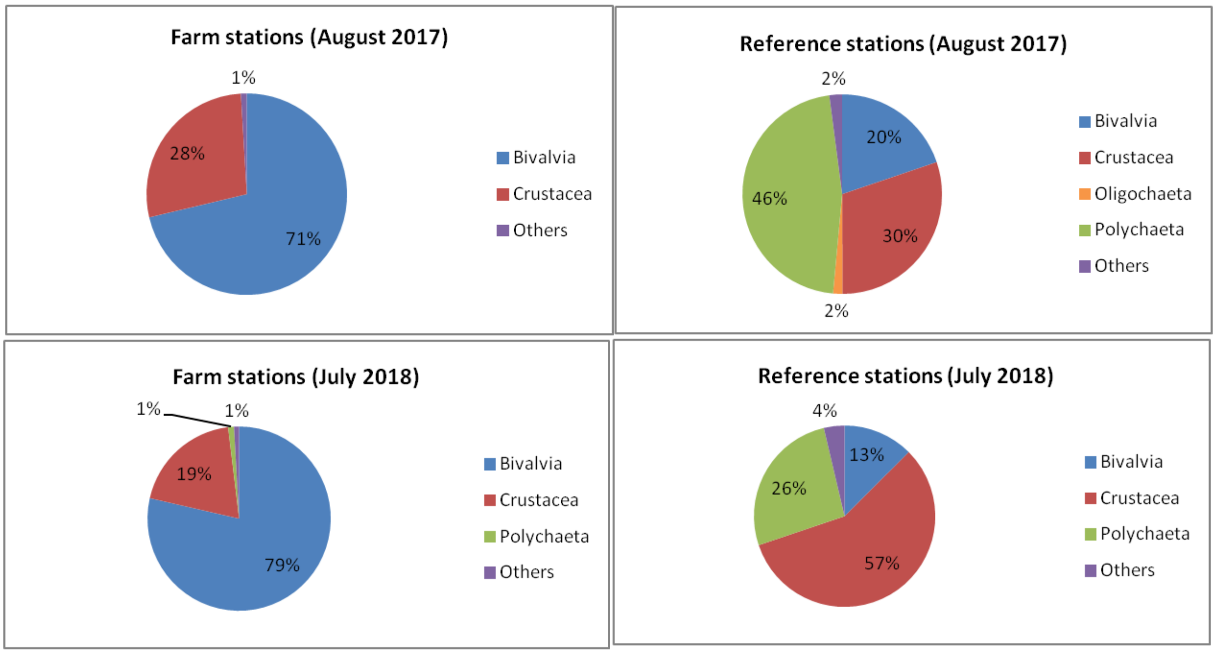
Figure 2. 47: Z-scores for dry biomass distribution among species identified in both Mussel farm and reference site in Kiel in July 2018

2.4.5. Pavilosta (Coast of Kurzeme) mussel farm

Samples from Pavilosta (Latvia) were collected on August 2017 and July 2018. In both sampling periods, there was quite similar taxa group distribution in the mussel farm stations. During both years, *Bivalvia* was the dominant taxa and approximately one third were *Crustacea* organisms (Figure 2.48). Other taxa groups like *Polychaeta*, *Diptera*, *Nemetoda*, *Oligochaeta* and *Hydrachnidia* (included in taxa group "Others") accounted for just a small share. The identified taxonomical groups were represented by 17 different species. Mussel *Mytilus trossulus* was the most abundant specie (average abundance 10367 ind/m^2 in August 2017 and 16058 ind/m^2 in July 2018) from 1mm to 4cm in length in mussel farm stations. The second most abundant specie was crustacean *Amphibalanus improvisus* (average abundance 2504 ind/m^2 in August 2017 and 1065 ind/m^2 in July 2018). In addition, various species of amphipod, for example, *Gammarus salinus*, *Gammarus zaddachi* and others were identified, although, their relative share was very low.

In reference stations (both years) there was a greater fragmentation of taxa. In samples taken in August 2017, *Polychaeta* was dominating, while *Crustacea* and *Bivalvia* taxa were detected in similar proportions with other taxons weakly represented (Figure 2.48). In samples from July 2018, more than half of the individuals were *Crustacea* organisms, while *Polychaeta* was second most abundant taxa (Figure 2.48).

The identified taxonomic groups were represented by 14 different species in August 2017, of which the most common species were *Manayunkia aestuarina* (average abundance 2129 ind/m^2) and *Amphibalanus improvisus* (average abundance 1362 ind/m^2). Although less frequently (average abundance 190 ind/m^2), the *Mytilus trossulus* was observed as well. At the same time, in July 2018 only 12 species were identified in reference are stations. Furthermore, in July 2018 most abundant was *Amphibalanus improvisus* (average abundance 2366 ind/m^2).

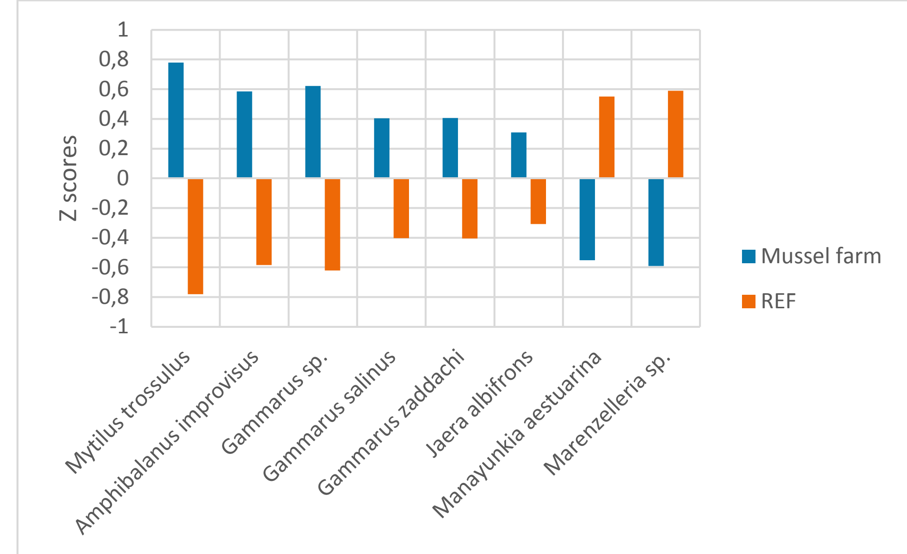


*Other taxa in farm station (August 2017): *Diptera*, *Hydrachnidia*, *Oligochaeta*, *Polychaeta*;
Other taxa in reference station (August 2017): *Diptera*, *Hydrachnidia*;
Other taxa in farm stations (July 2018): *Diptera*, *Hydrachnidia*, *Oligochaeta, Nematoda;*
Other taxa in reference station (July 2018): *Diptera*, *Hydrachnidia*, *Nematoda.*

Figure 2. 48: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations in Latvia (by count)

In 2017 for all species except two the biomass was bigger in mussel farm stations (Figure 2.49) compared to reference area stations. It should be noted that organisms like *Corophium volutator*, *Mysis mixta*, *Hydrachnidia*, *Oligochaeta*, *Hediste diversicolor* were also detected in the samples, but their abundance was too low to obtain their weight and so they are not used in comparison. The specie *Amphibalanus improvises* demonstrated higher biomass in mussel farm stations in comparison to reference area stations in 2017, while in 2018 higher biomass could be observed in reference stations. Other species in 2018 demonstrated the same biomass pattern as in 2017.

The species composition and biomass clearly indicated that in reference area macrozoobenthos community was substantially influenced by deposition of soft sediments on the otherwise stony surface of the marine bottom. As a result, share of species affiliated to soft sediments was much higher there. The observed effect was obviously due to much lover abundance of filtering organisms in reference area compared to mussel farm area.



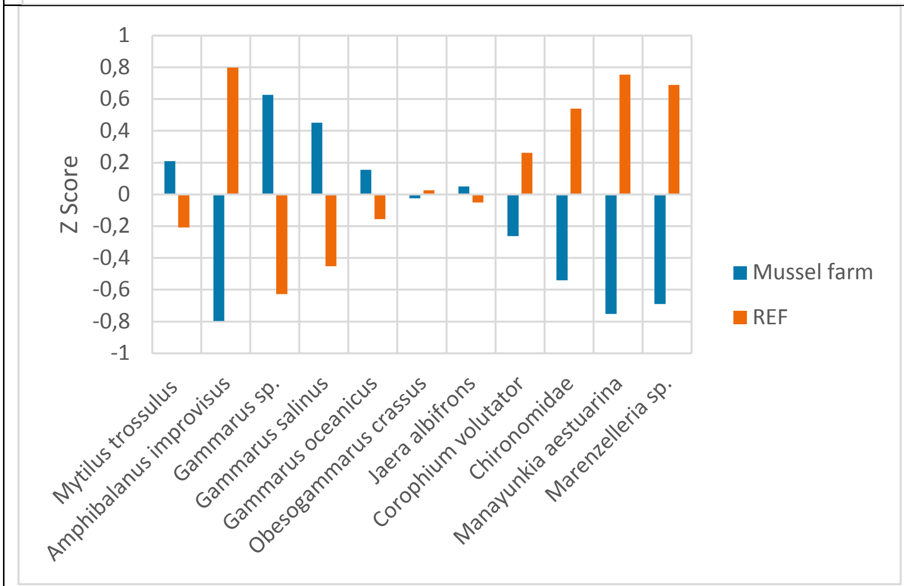


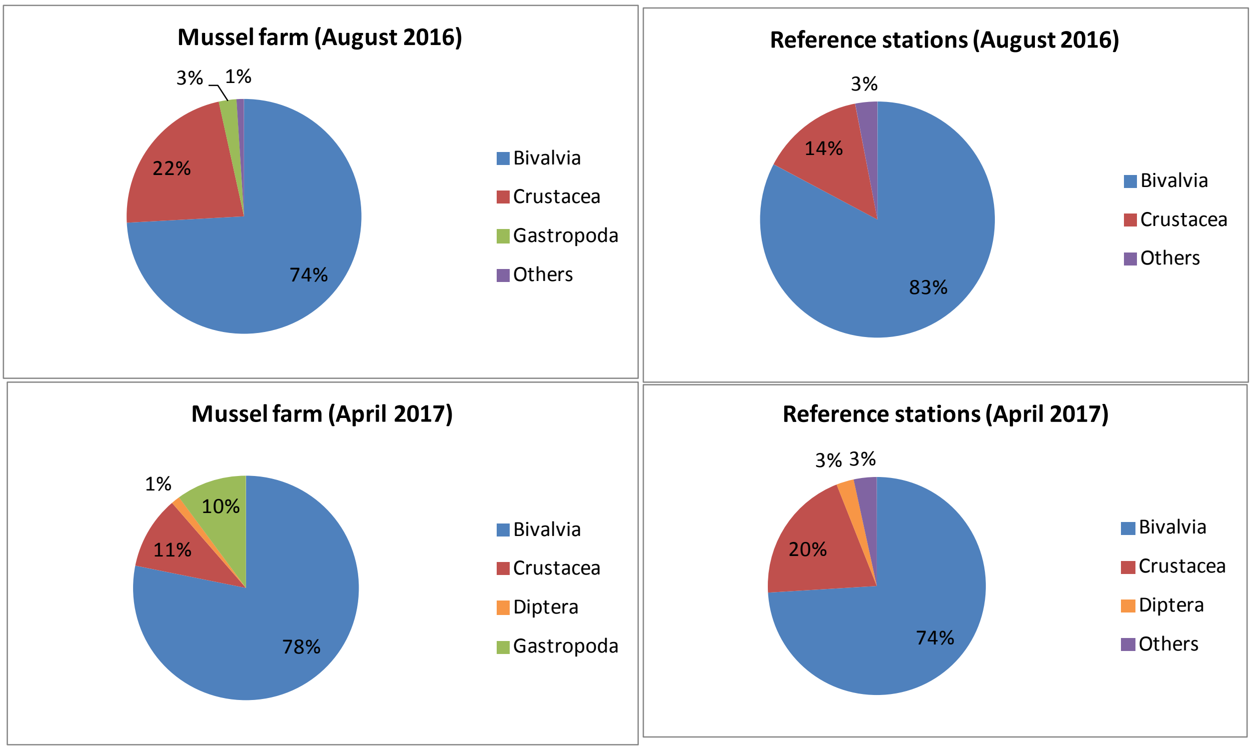
Figure 2. 49: Z-scores for dry biomass distribution among species identified in both Mussel farm and reference site in Pavilosta, upper panel – 2017, lower panel – 2018

2.4.6. Vormsi island mussel farm

Samples from Vormsi were collected on August 2016 and April 2017. Both the Mussel farm stations and the reference stations form a very similar taxon distribution in both years (Figure 2.50) with the *Bivalvia* taxon as most frequently encountered and *Crustacea* taxon as second most abundant. Other taxa represented a relatively small percentage except *Gastropoda* in 2017 in mussel farm area (Figure 2.50).

The identified taxonomical groups were represented by 14 different species in mussel farm stations in August 2016, most of which were mussels. The most abundant were *Mytilus trossulus* (average count of 4816 ind/1m^2), *Limecola balthica* (average count of 301 ind/1m^2) and *Cerastoderma glaucum* (average count of 72 ind/1m^2). The highest share of *Crustacea* taxon was made by two organisms - *Corophium volutator* (average count of 1333 ind/1m^2) and *Gammarus salinus* (average count of 158 ind/1m^2). In reference site, higher proportion of mussels was observed. Mussels like *Mytilus trossulus* (average count of 8543 ind/1m^2), *Limecola balthica* (average count of 487 ind/1m^2), *Mya arenaria* (average count of 530 ind/1m^2) and also *Cerastoderma glaucum* (average count of 229 ind/1m^2) were the most abundant ones. Like in Mussel farm stations, the dominant crustaceans were *Corophium volutator* (average count of 1290 ind/1m^2) and *Gammarus salinus* (average count of 258 ind/1m^2). 3% share was attributable to *Polycheta* taxon that mainly consisted of organism *Hediste diversicolor* (average count of 244 ind/1m^2).

In April 2017, similarly to the results of the previous year, 14 different species were identified in mussel farm stations. There was still a relatively high share of mussels found, however less than in the year before: *Mytilus trossulus* (average count of 1892 ind/1m^2) and *Limecola balthica* (average count of 181 ind/1m^2). The highest share of *Crustacea* was made by *Jaera albifrons* (average count of 136 ind/1m^2). The snail *Peringia ulvae* (average count of 267 ind/1m^2) also stands out, because of the high average number. In reference stations, most frequently detected organisms were *Mytilus trossulus* (average count of 3879 ind/1m^2), *Corophium volutator* (average count of 1075 ind/1m^2) and *Mya arenaria* (average count of 318 ind/1m^2).



*Other taxa in farm station (August 2016): *Oligochaeta*, *Polychaeta*;
Other taxa in reference station (August 2016):*Diptera*, *Oligochaeta*, *Polychaeta*, *Gastropoda*;
Other taxa in reference station (April 2017): *Gastropoda*, *Oligochaeta*, *Polychaeta.*

Figure 2. 50: Distribution of taxonomic groups of benthic invertebrates in Mussel farm stations and reference stations in Estonia (by count)

In samples from 2016 there were 13 species identified in both sites with 8 of those having higher average biomass in reference sites. In 2017 samples the distribution was even more in favor of reference sites – out of 14 species observed, 12 were with a higher average biomass in reference site (Figure 2.51).

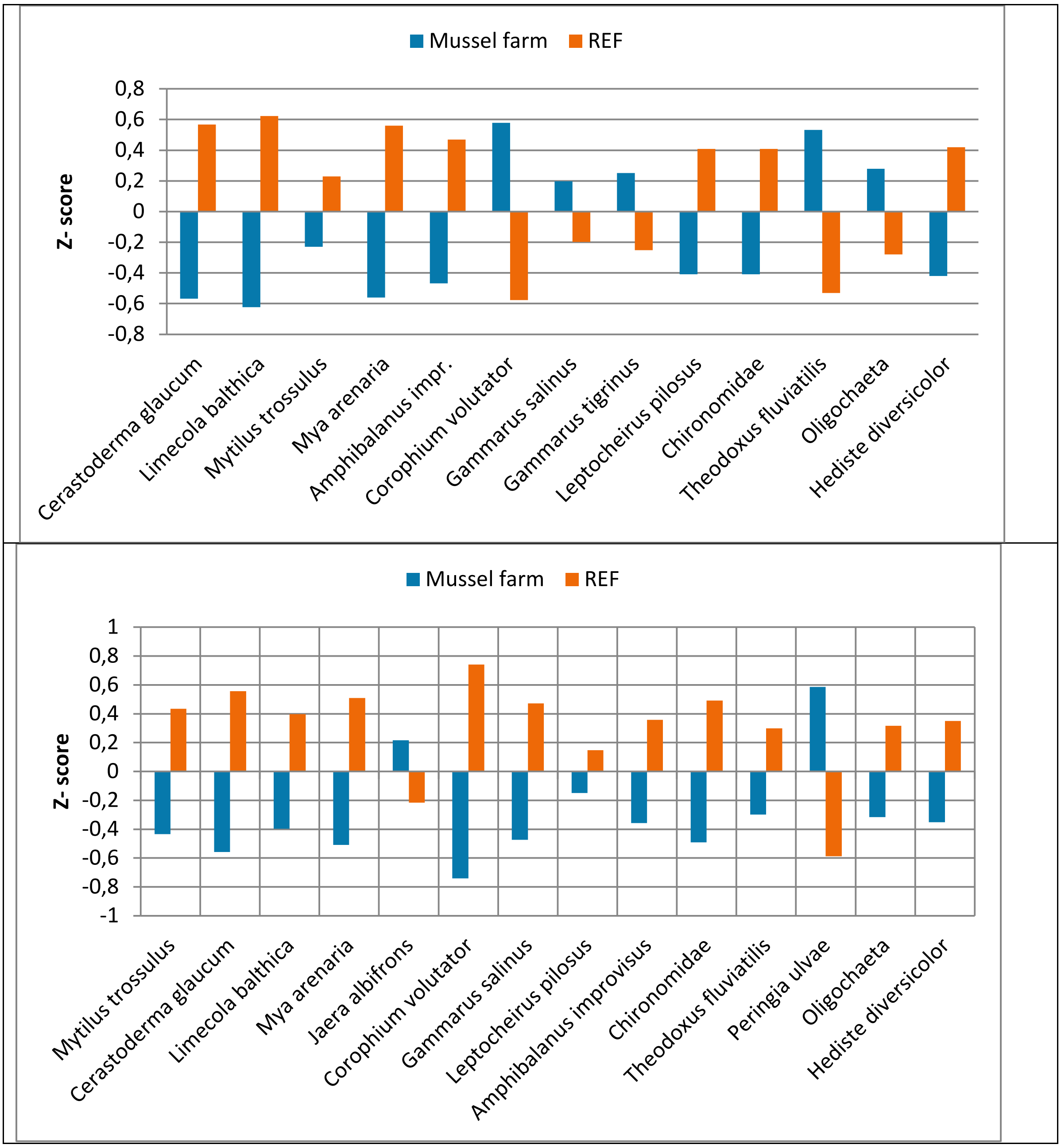


Figure 2. 51: Z-scores for dry biomass distribution among mussel farm and reference site in Vormsi, upper pane – 2016, lower panel – 2017

2.5. Description of zooplankton community at BBG mussel farms

Mesozooplankton samples were collected in one location per site (reference and farm) at each mussel farm during two consecutive years (2017-2018). Sampling was conducted during productive period of the year, usually once in each season: spring, summer and autumn. Table 2.7 show the main differences and similarities in species composition among mussel farms. Copepoda and meroplankton were the most frequently occurring groups of the mesozooplankton in all farms, yet the differences in species occurrence followed typical salinity gradient of the Baltic Sea, with marine species appearing in Musholm and Kiel farms, whereas presence of more brackish- tolerant species and freshwater species increasing in mussel farms located more eastward.

In Musholm and Kiel farms marine copepods *Oithona* sp., *Pseudo/Paracalanus* sp. and euryhaline copepods *Temora longicornis*, *Acartia* sp. and *Centropages* sp. together with cladoceran *Evadne nordmanni* and meroplanktonic (*Amphibalanus*, Bivalvia, Bryozoa, Gastropoda, Polychaeta) larvae were present almost at all sampling events. Also, marine appendicularians *Oikopleura dioica* was found in all samples collected in Musholm farm and in 50% of samples collected in Kiel farm (Table 2.7). Mesozooplankton biomass showed similar patterns and no evident differences were observed between farm and reference sites in Musholm and Kiel farms. The highest zooplankton biomass was observed in June 2018 for both farms, 410.02 and 488.08 mg m^{-3}, and 344.72 and 301.38 mg m^{-3}, for farm site and reference site at Musholm and at Kiel farm, respectively (Figure 2.52). However, the dominant taxa were different.

In average, mesozooplankton biomass at the Musholm farm was dominated by copepods (*Acartia* sp., *Centropages* sp. and *Oithona* sp.) and cladocerans. *Evadne nordmanni* composed 17 and 32% of mesozooplankton biomass during June 2018 at farm and reference sites, respectively, and 26 and 49% at the time of autumn sampling, whereas *Penilia avirostris* constituted 10 and 50% during August 2018. Bivalvia larvae were in the highest numbers and biomass during June 2018 at the farm station (9683 ind m^{-3}, 33.33 mg m^{-3}).

Mesozooplankton community of the Kiel farm showed inter-annual variability (Figure 2.52). In year 2017 reference site was characteristic with higher mesozooplankton biomass during summer (212.95±112.21 mg m^{-3}) than the farm site (52.08±8.27 mg m^{-3}), however both of them were dominated by copepods. *Oithona* sp. and *Acartia* sp. together formed 45-66% of mesozooplankton biomass, and they were abundant throughout all studied period. Copepods *Centropages* sp. constituted 16 and 22% of biomass during June 2017 at farm site and reference site, respectively, whereas *Pseudo/Paracalanus* formed up to 19 and 44% during late summer. Mesozooplankton biomass during autumn was low, but still copepod-dominated. In contrast, mesozooplankton biomass showed similar tendencies at both sites during year 2018. The highest biomass was observed during June, and it was dominated by Bivalvia larvae (33002 ind m^{-3}, 330.02 mg m^{-3} at farm site; 24446 ind m^{-3}; 244.46 mg m^{-3} at reference site). Successive sampling events in year 2018 showed copepod-dominated mesozooplankton community that was low in biomass.

Swedish farms (Kalmarsund and St. Anna farms) were characteristic with dominance of estuarine species. Copepods *Acartia* sp. and *Eurytemora affinis* together with euryhaline cladocerans *Bosmina coregoni*, *Pleopsis polyphemoides* and rotifers were the most frequently occurring taxa in these farms. Meroplankton was represented mainly by Bivalvia and Gastropoda larvae (Table 2.7). As both of Swedish farms were surveyed using non-standard sampling method, the results cannot be analysed quantitatively, subsequently they are not included in further analysis.

Table 2. 7: Frequencies (in percentage) of species occurrences at each location. N – number of samples during studied period; F – farm site; R – reference site

	Denmark		Germany		Sweden				Latvia		Estonia	
	Musholm		Kiel		Kalmarsund		StAnna		Pavilosta		Vormsi Agar	
	F	R	F	R	F	R	F	R	F	R	F	R
N	3	3	6	6	6	6	6	6	8	8	6	6
Cladocera												
Bosmina coregoni	0	0	17	0	50	83	83	83	63	63	83	33
Bosmina longispina	0	0	0	0	0	0	17	33	0	0	0	0
Cercopagis pengoi	0	0	0	0	0	0	0	0	13	13	17	50
Chydorus sphaericus	0	0	0	0	0	0	0	0	0	0	17	0
Daphnia sp	0	0	0	0	0	0	0	17	0	0	0	0
Evadne anonyx	0	0	0	0	0	0	0	0	0	0	17	33
Evadne nordmanni	100	100	33	67	33	50	83	83	38	38	50	33
Penilia avirostris	33	67	0	17	0	0	0	0	0	0	0	0
Pleopsis polyphemoides	0	33	0	33	83	50	83	67	38	25	33	83
Podon intermedius	0	0	17	33	0	0	0	0	0	0	17	17
Podon leuckarti	67	33	0	0	0	0	0	0	0	13	0	0
Podon/Pleopsis	0	0	0	0	17	17	33	17	0	13	0	0
Other Sididae	0	0	0	0	0	17	0	0	0	0	0	0
Copepoda												
Acartia sp	100	100	100	100	100	100	100	100	100	100	100	100
Acartia bifilosa adults	100	67	50	50	83	83	67	67	100	100	83	100
Acartia longiremis adults	33	33	0	17	0	0	0	0	75	100	0	0
Acartia tonsa adults	67	33	0	33	67	67	67	50	50	38	0	0
Centropages sp	67	67	67	67	17	0	33	17	88	25	33	50

Cyclopoida	67	67	17	17	17	17	83	83	0	13	17	33
Eurytemora affinis	0	0	0	0	100	100	83	83	75	88	100	100
Harpacticoida	33	0	33	50	0	33	67	33	25	13	17	0
*nauplii sp											100	100
Oithona sp	100	100	100	100	0	0	17	0	0	0	0	0
Pseudo/Paracalanus	100	100	100	83	0	17	0	17	63	38	0	33
Temora longicornis	100	100	83	50	100	83	67	100	100	100	67	83
Rotifera												
Bdelloidea	0	0	0	0	17	0	0	0	0	0	0	0
Brachionus sp	0	0	0	0	17	0	0	0	0	0	0	0
Kellicotia sp	0	0	0	33	0	33	0	0	0	0	0	0
Keratella cochlearis	0	0	17	0	83	83	100	100	25	25	17	50
Keratella cruciformis	0	0	0	0	67	67	83	50	50	38	17	17
Keratella quadrata	67	0	17	17	83	83	100	100	75	100	67	83
Lecane sp	0	0	0	0	0	0	0	17	0	0	0	0
Lepadellidae	0	0	0	17	0	0	0	0	0	0	0	0
Notholca acuminata	0	0	0	0	17	0	33	0	0	0	0	0
Notholca caudata	0	0	0	0	0	0	17	17	0	0	0	0
Polyarthra sp	0	0	0	17	17	17	0	0	0	0	0	0
Synchaeta baltica	67	33	33	0	100	100	83	83	100	100	100	83
Synchaeta curvata	0	0	0	0	0	0	0	0	0	0	50	33
Synchaeta fennica	0	0	0	0	33	17	50	50	13	25	0	0
Synchaeta monopus	0	0	17	0	67	50	67	83	50	38	50	50
Synchaeta sp	0	0	50	67	17	33	33	33	13	13	0	0
Trichocerca sp	0	0	17	17	0	33	17	17	0	0	0	0

* - Copepoda nauplii were lumped together for the Vormsi Agar farm. In all other farms they were distinguished to genus/species level (except for Cyclopoida) and incorporated in their descriptions.

Table 2.7 (cont.): Frequencies (in percentage) of species occurrences at each location. N – amount of samples during studied period; F – farm site; R – reference site

	Denmark		Germany		Sweden				Latvia		Estonia	
	Musholm		Kiel		Kalmarsund		StAnna		Pavilosta		Vormsi Agar	
	F	R	F	R	F	R	F	R	F	R	F	R
N	3	3	6	6	6	6	6	6	8	8	6	6
Meroplankton												
Amphibalanus cypris	33	0	0	0	0	0	0	0	0	0	0	0
Amphibalanus nauplii	67	100	67	67	67	83	17	33	75	88	83	100
Bivalvia larvae	100	67	100	100	83	67	100	100	88	75	67	83
Bryozoa larvae	33	33	17	17	17	17	0	0	0	0	0	0
Gastropoda larvae	100	67	50	67	50	100	100	67	0	13	50	67
Polychaeta larvae	67	67	100	100	33	0	0	0	50	75	17	50
trochophore larvae	0	0	17	17	0	0	0	0	0	0	0	0
Varia												
Arachnida larvae	0	0	0	0	0	0	0	0	0	13	0	0
Aurelia aurita	0	0	0	0	0	0	0	0	13	13	33	17
Cnidaria larvae	0	0	0	0	17	0	0	0	0	0	0	0
Fritillaria borealis	33	0	17	17	0	0	0	0	25	25	0	0
Mysidae	0	0	0	0	0	0	0	0	0	13	0	0
Nematoda	0	0	0	0	0	17	0	0	0	0	0	0
Noctiluca scintillans	0	0	0	17	0	0	0	0	0	0	0	0
Oikopleura dioica	100	100	50	50	17	0	0	0	0	13	0	0
Radiospermum corbiferum	0	0	0	0	0	0	0	0	13	25	0	0
Sagitta sp	33	0	0	0	0	0	0	0	0	0	0	0
Tintinnina	33	33	17	17	0	0	33	17	0	0	0	0

Pavilosta farm was dominated by euryhaline copepods *Acartia* sp. and *Temora longicornis*, as well as rotiferans from genera *Synchaeta* and *Keratella*. *Amphibalanus* nauplii, Bivalvia and Polychaeta larvae were the most occurring meroplanktonic taxa (Table 2.7). Furthermore, *Aurelia aurita* medusae were observed at both sampling sites in August 2017. However, the biomass of mesozooplankton was low in the Pavilosta farm, except for May 2018, when a typical spring peak of rotiferan *Synchaeta baltica* was observed (Figure 2.52). Summer mesozooplankton community in Pavilosta farm was characteristic with co-domination of copepods, *Amphibalanus* larvae and rotifers from *Keratella* genus, whereas autumn biomass is compiled mainly by copepods. Bivalvia larvae, overall, were low in abundance, and the highest values were reached during May (1689 ind m^{-3} at farm site; 775 ind m^{-3} at reference site) and August 2018 (333 ind m^{-3} at farm site; 1294 ind m^{-3} at reference site).

Estonian **Vormsi Agar farm** showed similar tendencies of mesozooplankton species composition to Pavilosta farm, with copepods *Acartia* sp. and *Temora longicornis*, cladocerans *Bosmina coregoni* and *Pleopsis polyphemoides*, as well as rotifers being the most frequently found organisms. Besides the mentioned, also estuarine copepod *Eurytemora affinis* was found in all of the samples collected in Vormsi Agar farm (Table 2.7). And likewise, *Aurelia aurita* medusae were present at the sampling locations in both - June and August 2017. Biomass values showed inter-annual and seasonal changes. Spring was dominated by rotifer *Synchaeta baltica*, whereas August and October was copepod-dominated. Noteworthy that *Acartia bifilosa* compiled 62% of total mesozooplankon biomass at the farm station, but *Eurytemora affinis* formed half of mesozooplankton biomass at the reference site during August 2018. Similar tendencies were also observed during year 2017, when *Acartia bifilosa* composed 67% of mesozooplankton biomass at the farm station, yet the biomass at the reference site was co-dominated by *Bosmina coregoni*, *Eurytemora affinis* and *Keratella quadrata,* together forming 62% of the biomass. Bivalvia larvae occurred almost in all studied seasons, but in low abundances, reaching the highest value of 1900 ind m^{-3} at the farm site during June 2017.

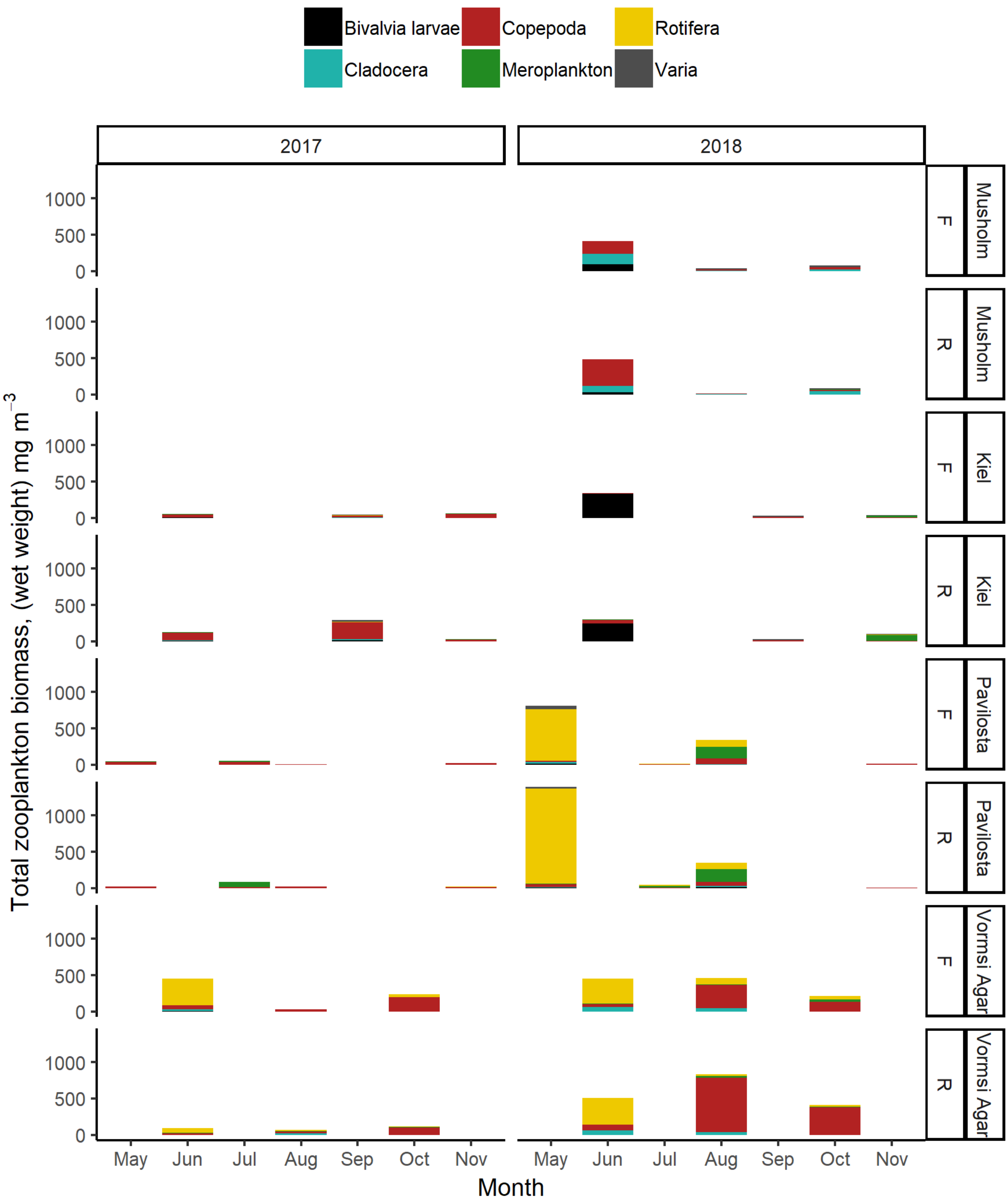


Figure 2. 52: Total mesozooplankton biomass (wet weight) at each sampling site in every mussel farm. F – farm site; R – reference site

Despite the observed characteristics and differences between sampling sites in every mussel farm described previously, no statistically significant differences in total mesozooplankton biomass were detected (Figure 2.53a). Also, dynamics of Bivalvia larvae biomass where similar between farm and reference sites (Figure 2.53b). Still, noteworthy that Bivalvia larvae showed higher variability in biomass at reference sites in Mussholm and Kiel farms, but almost no difference was evident between sites for Pavilosta and Vormsi Agar farms.

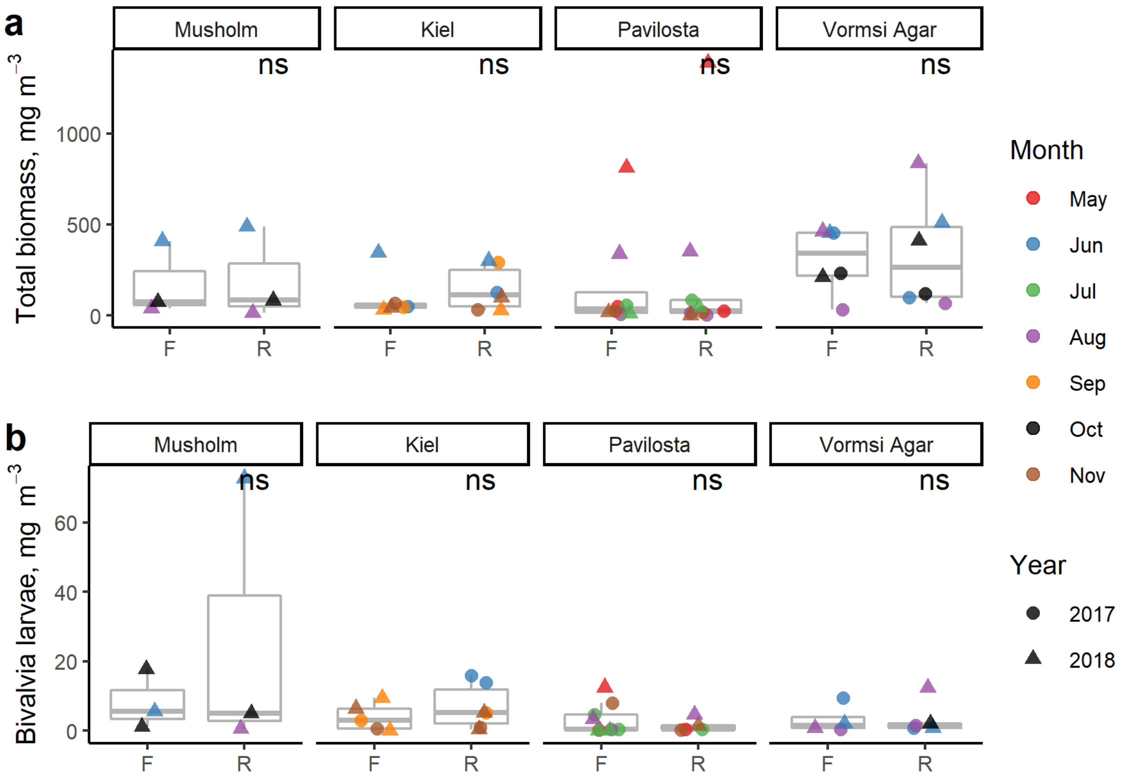


Figure 2. 53: A comparison (using Wilcoxon test) of biomass (wet weight) formed by a) total mesozooplankton and b) Bivalvia larvae between farm (F) and reference (R) sites at every mussel farm

To analyse differences of biodiversity between farm and reference sites in each farm, three diversity indices were calculated. The first one, *species richness* represents total number of species, *Shannon's diversity index* parametrizes the diversity of mesozooplankton community taking into account species richness, abundance of every species and proportions between them. *Pielou's evenness index* (ranges from 0 to 1) describes how evenly distributed in environment are all of the species, with value 1 representing completely even distribution (abundance) among species. All of these indices are abundance-based.

Diversity indices (Figure 2.54) of mesozooplankton community did not show statistically significant differences between farm and reference sites for every mussel farm, but they demonstrated slight differences among farms. Mesozooplankton community of the Musholm farm showed the highest values of all three applied indices. It was represented with the highest species amount (species richness), thus the highest overall species diversity (Shannon's index). And also mesozooplakton community of the Musholm farm was not dominated by one or several species, thereby it showed high Pielou's evenness rank. Median values of diversity indices for all the other farms did not vary much, however they displayed inter-annual and seasonal changes in mesozooplankton diversity. For example, mesozooplankton community of the Vormsi Agar farm show the lowest diversity during June, while early summer period is variable in Pavilosta farm, with high diversity during May 2017, but low diversity during May 2018 (due to pronounced dominance of *Synchaeta baltica*).

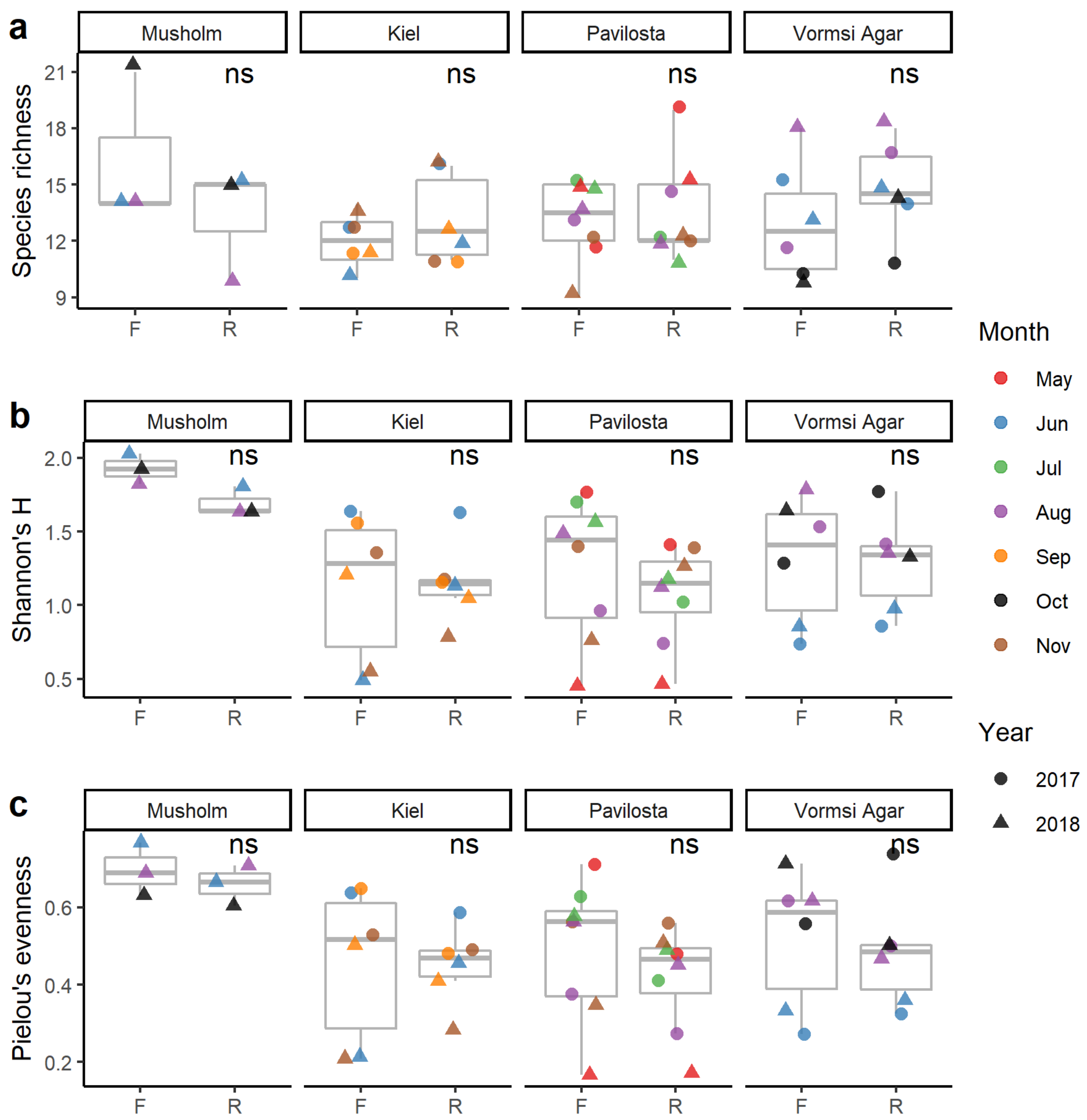


Figure 2. 54: Diversity measurements (abundance-based) of mesozooplankton community at each sampling site in every mussel farm. a) species richness – number of species found in the mesozooplankton community; b) Shannon's diversity index (H) – representing increase in species diversity with increasing value; c) Pielou's evenness index – ranging from 0-1, with 1 representing completely even distribution among species. F – farm site; R – reference site; ns – non-significant difference (according to Wilcoxon test)

3. Particulate organic matter sedimentation and deposition

Over the course of June and August 2018 research, revealing the influence of particulate organic matter deriving from the blue mussel farm in the Kieler Förde, has been carried out. The cultivation of blue mussels increases the sedimentation of particulate organic matter (POM) as well as the deposition of POM on a seafloor area, as compared to natural conditions absent of mussel farming.

The mean basic sedimentation rate shows consistently higher sedimentation of POM at the site of the blue mussel farm, than at the adjacent reference location. It varies between a surplus of $BSR = 4.8749\ g * m^{-2} * d^{-1}$ from June 4 to June 6 and $BSR = 3.5020\ g * m^{-2} * d^{-1}$ from July 23 to July 25, compared to the reference location. The quota of excess sedimentation at the standard location of the blue mussel farm reflects this trend, as it shows sedimentation being 1.74 to 3.74 higher than at the uninfluenced reference location. Thus, a positive correlation between the cultivation of blue mussels and increased POM sedimentation can be seen. This validates results from several other studies. However, the effects observed at the mussel farm in the Kieler Förde seem to be of smaller magnitude than elsewhere (Dahlbäck & Gunnarsson, 1981; Hatcher, Grant & Schofield, 1994; Hartstein & Stevens, 2005). The organic content of sediments beneath the blue mussel farm is also higher than at the reference area. With a particulate organic matter content of $OC = 0.0371\ kg(POM) * kg(Sediment)^{-1}$ it exceeds samples from the reference location by 1.25 times. Therefore, it can be assumed, that the presence of the Kieler Meeresfarm indeed increases the POM deposition, as compared to natural conditions absent of mussel farming. This effect has been documented for several other sites (Carlsson *et al.*, 2012; Martinez-Garcia *et al.*, 2015). However, the surplus of sedimentation is not reflected by the surplus of deposition. Quotas of sedimentation suggest at least 1.74 times more accumulation of POM to the seafloor, whereas values attained for the actual deposition only show 1.25 times as much POM compared to the unaffected reference area. Assuming, that sedimentation and deposition correlate directly, this phenomenon may be attributed to effects of bioturbation. The findings suggest that organic enrichment provides for an enhanced food supply, rather than it being a limiting factor related to oxygen depletion (Chen & Orlob, 1972). This results in the presence of deeper burrowing organisms, such as *Polydora* and *Bivalvia,* and deeper oxygenated sediments (Rumohr, 2005). Furthermore, as illustrated in Figures 6 and 7, the depth of oxygenated sediment under the blue mussel farm exceeds the depth at the reference location and can be very likely ascribed to effects of bioturbation. Due to increased oxygen availability and porosity of the sediment, organic matter mineralization and nutrient recycling is enhanced (Pearson, 2001; Martinez-Garcia *et al.*, 2015). This has been proven for sediments in the Baltic Sea (Morys, Powilleit & Forster, 2017) and seems to explain the disparity in the quotas for sedimentation and deposition of POM.

3.1. Particulate organic enrichment of sea bottoms

The functioning of a community is largely affected by trophic interactions and the disturbance of these (Gray *et al.*, 2014), namely excess organic matter, which can cause changes to the structure of benthic food webs by reducing diversity and reorganizing generalist and specialist consumers and ultimately shifting the regime of the trophic network (Grassle & Grassle, 1974; O'Gorman, Fitch & Crowe, 2012). This advocates the further examination of organic enrichment as it provides quick insight to the ecological state of ecosystems. A considerable amount of organic deposition, not directly deriving from nutrient enrichment, can also be identified as faeces excretion from cultivated organisms of higher trophic levels (Hargrave *et al.*, 2008; McKindsey *et al.*, 2011; Bannister *et al.*, 2014). According to Germanys´ Water Framework Directive (WFD), these effects need to be avoided to avert a potential degradation of the environment (Wasserrahmenrichtline, 2001). An effective tool to evaluate perturbations is the examination of the benthos (the community of organisms living at and within a marine sediment) (Hargrave *et al.*, 1997; Nordström & Bonsdorff, 2017). Numerous studies have addressed this subject matter and the establishment of indicators for biotic and environmental conditions within these systems is prevailing (Ansari, Ingole & Abidi, 2014). The conceptual model of Pearson and Rosenberg (Pearson & Rosenberg, 1978) indicates that abundance and biomass of macro-faunal species changes in variable degree to fluctuating organic enrichment. A high degree of organic deposition however, may super impose its influence on the ecosystem. Hypoxia (generally considered as a concentration of dissolved oxygen (DO) below 2 $ml * L^{-1}$ (Conley *et al.*, 2011)) as a consequence of high organic input modifies the networks energy transfer in the form of lower secondary production (Gray, Wu & Or, 2002). Further, a state of anoxia (DO below 0.5 $ml * L^{-1}$ (Conley *et al.*, 2011)) leads exclusively to microbial processes and the formation of hydrogen sulphide (H_2S) (Diaz & Rosenberg, 2008) which is highly toxic for most metazoic organisms. Summed up, organic enrichment causes physiological stress bringing along a shift from e.g. suspension feeders to predominantly deposit feeders and the trophic network is degraded (Rhoads, 1974; Magni, 2003; Rumohr, 2005).

3.1.1. Blue mussel farming as a source for organic discharges

Mussel farming is widely perceived as a tool for combating eutrophication. However, potentially detrimental impacts of bio-deposits from faeces and pseudo-faeces, of which mussels assemble substantial amounts (Smaal *et al.*, 1986), has to date been largely neglected. It has been stated that mitigating effects may be diminished due to blue mussels´ accumulating feeding behaviour, changing biogeochemical cycling of nutrients (Stadmark & Conley, 2011). However, the extent of organic accumulation is determined by the rate of decay, redistribution of the bio-deposits via erosion, the range of dispersal and the overall production of bio-deposits (Giles *et al.*, 2009). Although the overall production and settlement rates differ significantly between species, diet and mussel size (Weise *et al.*, 2009), it is apparent, that organic enrichment by blue mussel farming is considerable. Several studies have displayed an increased benthic loading with organic carbon being 3 to 5.5 times higher than in the adjacent reference areas (Dahlbäck *et al.*, 1981; Hatcher *et al.*, 1994; Hartstein *et al.*, 2005).

3.2. Methods and material

3.2.1. Sampling locations

Figure 3.1 shows the sampling locations at which the deployment of sediment traps took place. The supposedly unaffected reference location (Ref.) lies approximately 30 *m* upstream of the farms´ facilities. The standard location (Std.) lies within the farm area, approximately 15 *m* southeast of the center of the farm. This station was chosen on the assumption, that a net transport of sedimenting material lies downstream of the main current direction. Previous current measurements showed a mean velocity of 2 $cm * s^{-1}$ in a southwards direction (CRM; *unpublished*). On the base of preliminary settling velocity measurements, a lateral translocation of 15 *m* was anticipated. In 15 *m* intervals downstream of the standard location reside two further deployment locations, Std.15 and Std.30.

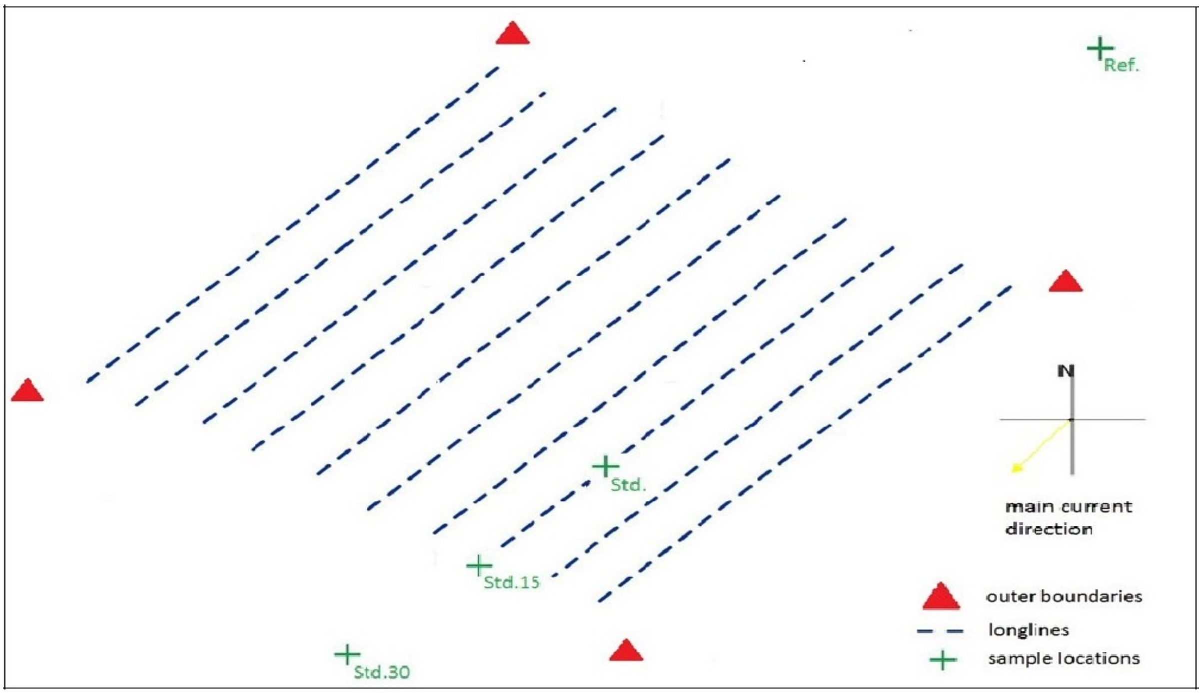


Figure 3. 1: Sampling locations Ref., Std., Std.15, Std.30 within the constellation of the blue mussel farm; positions based on preliminary calculations

3.2.2. Sediment traps

With the objective to quantify the sedimentation and dispersal of faeces from the mussel farm, particulate matter released from the site was sampled by sediment traps. Sediment traps were deployed at the reference and standard location in a depth of 7 *m* on two occasions each in June and July 2018. Furthermore, a transect of three sediment traps placed in 15 *m* intervals in main current direction from the standard location were deployed in the same depth (7 *m*) during two occasions each in June and July 2018. The traps consisted of 4 identical polyvinylchloride (PVC) tubes each, 5.6 *cm* in diameter and 70 *cm* in length, with detachable particle collectors at the lower end and aligned vertically at the ends of a cross-shaped frame. Deployment time was restricted to 48 *h* or a maximum of 100 *h* respectively to minimize microbial decomposition. No fixatives were used.

The loss of organic matter during deployment is considered to be low and tolerable. In the laboratory, the individual samples were concentrated by decanting excess water after dispersed particles had sedimented. Thereafter, the samples were homogenized and corresponding aliquots were dried (110*°C*, 24 *h*). Organic matter was determined by loss on ignition (LOI, weight loss of the dried samples was measured after 24 *h* in a 500*°C* furnace), which provides relative values of organic enrichment beneath the mussel farm. Due to pyrolysis of carbonates (Palandri, Gilot & Prado, 1993) and release of crystal water from possible sediment particles (Sun *et al.*, 2009), this method is likely to overestimate organic matter content. It was chosen nevertheless, as the sediments in Kiel Fjord are low in carbonates (Schwarzer & Themann, 2003) and the method allows a large quantity of sample analysis at low operating costs.

3.2.3. Sampling of sediments

To measure organic content of the sediment, samples were taken with acrylic tubes (7 *cm* diameter, 40 *cm* length, approx. 18 – 28 *cm* sampling depth) and collected by divers in July 2018. Sediment core samples (3 replicates each) were taken at the reference and standard location. In the laboratory, the sediment was carefully removed from the acrylic tubing in order to maintain the sediment´s profile. A significant change in colour was visible in a sampling depth of at least 2 *cm* (Figure 3.6 and 3.7), indicating a shift in the redox conditions to an anoxic state in the deeper parts of the sediment. A black colour signals iron sulphide (*FeS*) (Kohlus & Küpper, 1998). All samples were cut vertically at this depth, aiming for the lowest variance within replicates and between sampling locations. The sediment slices were weighed, homogenized and aliquots were dried (110*°C*, 24 *h*). LOI was carried out as described above.

3.3. Results

3.3.1. Sediment traps

Sediment traps have been deployed in two separate campaigns. The first took place from June 4, 2018 to June 15, 2018 and the second from July 23, 2018 to Aug. 2, 2018. For both campaigns there have been two separate approaches. On the one hand to determine the basic sedimentation rate of POM and on the other the decrease of sedimenting POM in a transect (display of results excluded; serve as validation for the dispersal model (Chapter 3.3.3)). However, it must be said, that one sediment trap went missing between July 25 and July 27, thus results during the second campaign are impaired.

After LOI, residual salt was subtracted by the average salinity from 1 to 7 *m* depth and particulate organic matter was calculated with the according factors for aliquots. Values obtained were then put into relation with the collecting area of the individual tube from the sediment trap and deployment time. To pool values of the four individual tubes from the sediment trap, the arithmetic mean (mean) is applied. Figures 3.2 to 3.4 show the relation of sedimenting POM for the reference and standard location between June 4 to June 8 and between July 23 and July 25.

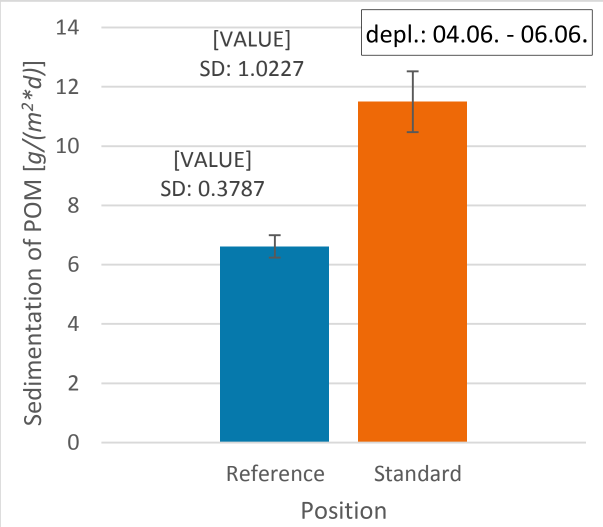


Figure 3. 2: Sedimentation rates between 04.06. and 06.06.; obtained by LOI after decanting excess water in the particle collectors

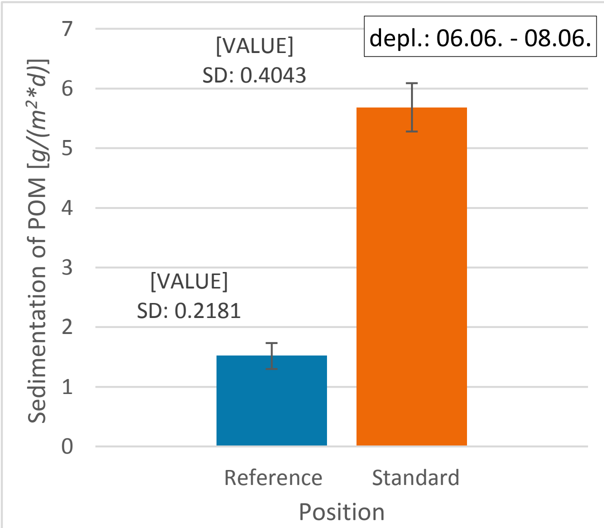


Figure 3. 3: Sedimentation rates between 06.06. and 08.06.; obtained by LOI after decanting excess water in the particle collectors

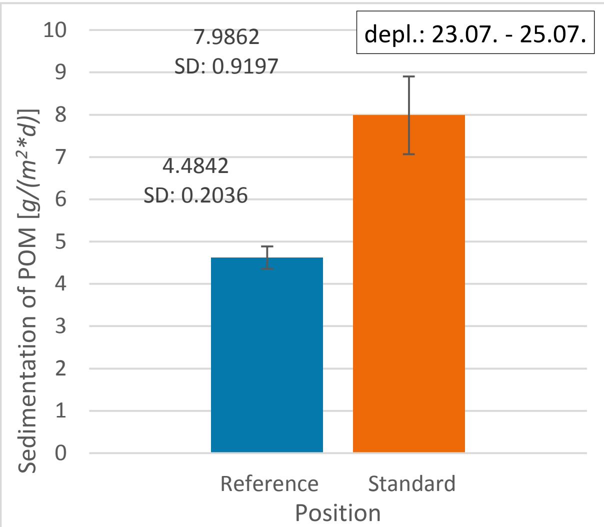


Figure 3. 4: Sedimentation rates between 23.07. and 25.07.; otained by LOI after decanting excess water in the particle collectors

It is apparent, that the sedimentation at the standard is consistently higher than at the reference location. Maximum values were detected between June 4 and 6 with $POM = 11.4927\ g * m^{-2} * d^{-1}$ at the standard and respectively $POM = 6.6223\ g * m^{-2} * d^{-1}$ at the reference location (Fig. 4). The lowest overall sedimentation can be seen between June 6 and 8, where $POM = 1.5184\ g * m^{-2} * d^{-1}$ is found at the reference. The lowest difference can be seen between July 23 and 25, where $\Delta POM = 3.502\ g * m^{-2} * d^{-1}$. For all occasions, the standard deviation at the reference is lower. Figures 2 to 4 never display an overlap of standard deviations from reference and standard locations and suggest a statistically significant difference in these. Thereafter, values of the reference are appreciated as blank values and, in order to determine the mean basic sedimentation rate (BSR) at the standard location, corresponding POM values are subtracted thereof. Further, to attain the quota of surplus sedimentation at the standard location values of sedimentation are put into relation (rSED).

Results are shown in Table 3.1:

Table 3. 1: Basic sedimentation rates and surplus in June and July

Deployment	04.06.-06.06.	06.06.-08.06	23.07.-25.07.
Mean BSR [$g*m^{-2}*d^{-1}$]	4.8749	4.1647	3.5020
SD	0.7711	0.3248	0.6661
rSED	**1.7361**	**3.7428**	**1.7810**

The highest basic sedimentation rate and likewise standard deviation, can be seen on the first occasion with $BSR = 4.8749\ g * m^{-2} * d^{-1}$. The minimum of $BSR = 3.5020\ g * m^{-2} * d^{-1}$ is distinguished between July 23 and 25. Values of deployment between June 6 and 8 reside in the middle, however the relative sedimentation rate is $rSED = 3.7428$ and exceeds others by more than double. This coheres with the overall low sedimentation of POM at the reference station during this interval. As the standard deviations overlap, the BSR are averaged for further calculations and results in $\overline{BSR} = 4.1805\ g * m^{-2} * d^{-1}$.

3.3.2. Sampling of sediments

Originally planned on the same date, the sampling of sediments at standard and reference location was performed on two different days, due to unforeseen circumstances concerning the divers. Nevertheless, the samples attained are appreciated as valid, as alterations in the sediment are assumed to take place over longer terms, i.e. months and years.

Sediment cores have been taken on July 16 and 20 at the reference and standard location. With the intention to obtain the organic content of sediments, LOI values from aliquots of the acrylic tubes have been set into relation to the amount of sampled sediment obtained from the upper 2 *cm* of the sediment core. The top layer has been chosen, as it is considered to correlate closely to the deposition of POM.

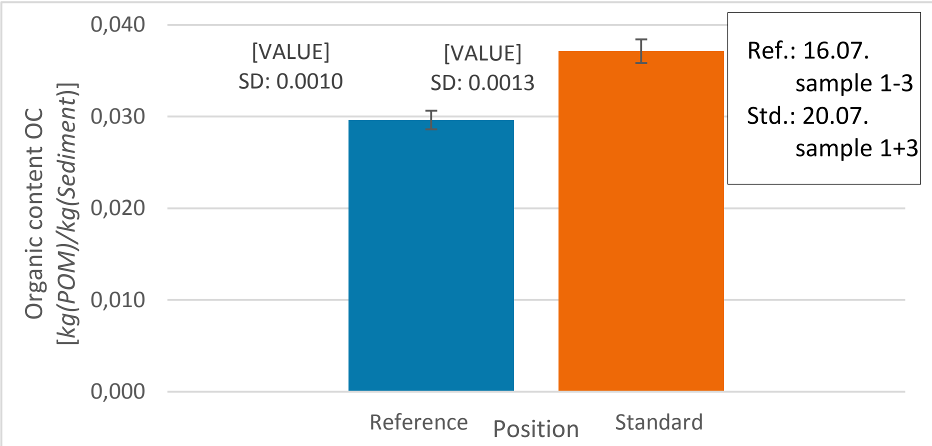


Figure 3. 5: Sampling of sediments on 16.07. (Reference) and 20.07. (Standard); obtained by LOI from the upper 2 cm of sediment in acrylic tubing

The organic content of sediment at the standard location outweighs the reference. With a mean of $\overline{OC} = 0.0371\ kg(POM) * kg(Sed)^{-1}$ it is $\Delta OC = 0.0075\ kg(POM) * kg(Sed)^{-1}$ higher. It must be said, that the exact sampling of 2 cm was difficult, especially for samples from the standard location, as they showed high water content and porosity and therefore parts of them unavoidably ran down the outer tubing instead of the petri dish. Furthermore, a large blue mussel was found in sample no. 2 of the standard location, enhancing this problem, to an extent of non-liable results. The homogenization of the aliquots, which proved difficult, raises doubts to the replicability. Obtained absolute results should be treated with caution, however they still allow setting them in to ratio. Results are displayed in Table 3.2:

Table 3. 2: Organic content and surplus of deposition in July

Position	Reference	Standard
Date	16.07.	20.07.
Sample No.	1 - 3	1 + 3
Mean OC [*kg(POM)*kg(Sed)*$^{-1}$]	0.0296	0.0371
SD	0.0010	0.0013
rOC	**1.2528**	

With a difference of $\Delta OC = 0.0075\ kg(POM) * kg(Sed)^{-1}$, the deposition at the standard is 25.28 % higher than at the reference location. Further, a visual analysis of the depth of oxygenated sediment for reference and standard samples is conducted. The depth of oxygenated sediment for each tubing was acquired by viewing with a tape measure (Figure 3.6). A change in colour from brown to black indicates a shift to anoxic conditions.

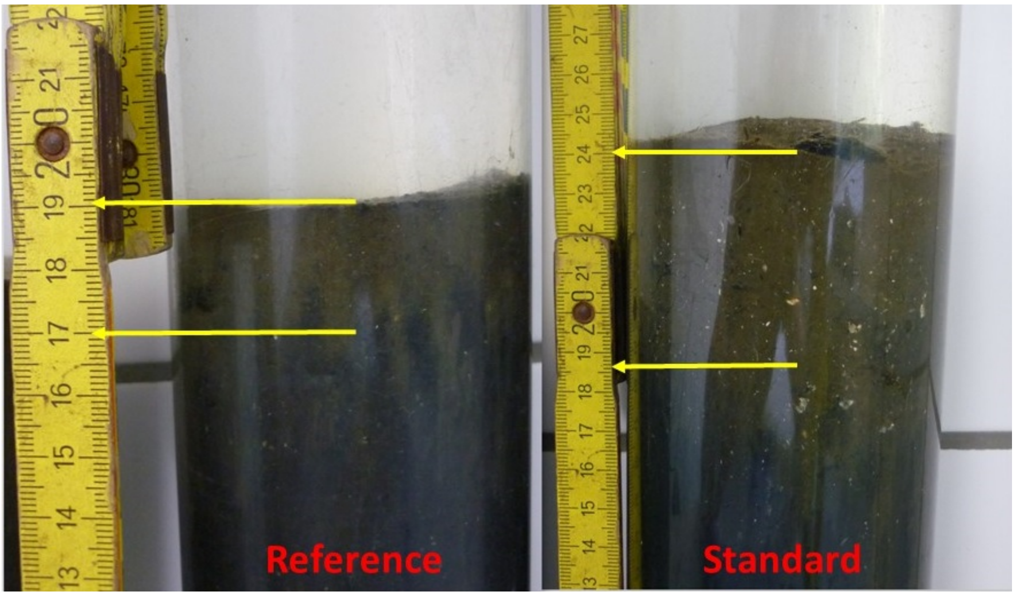


Figure 3. 6: Acquiring depth of oxygenated sediment; left reference sample no. 1; right standard sample no. 3; a change from brown to black signals a shift to anoxic conditions; note: tape measure (cm) shows unequal scale

Results are shown in Table 3.3:

Table 3. 3: Depth of oxygenated layer for sediment cores at the reference and standard location

Location	Reference			Standard		
Sample No.	1	2	3	1	2	3
Depth L [cm]	2	1.5	2.8	2.5	4	5.5
Mean Depth L [cm]	**2.10**			**4.00**		
SD	**0.66**			**1.22**		

The mean depth of oxygenated sediment at the standard location exceeds the reference, though in one case, the reference shows a shift of redox conditions in greater depth, than at the standard location (Sample No. 3, 1). The standard deviations suggest a statistical difference.

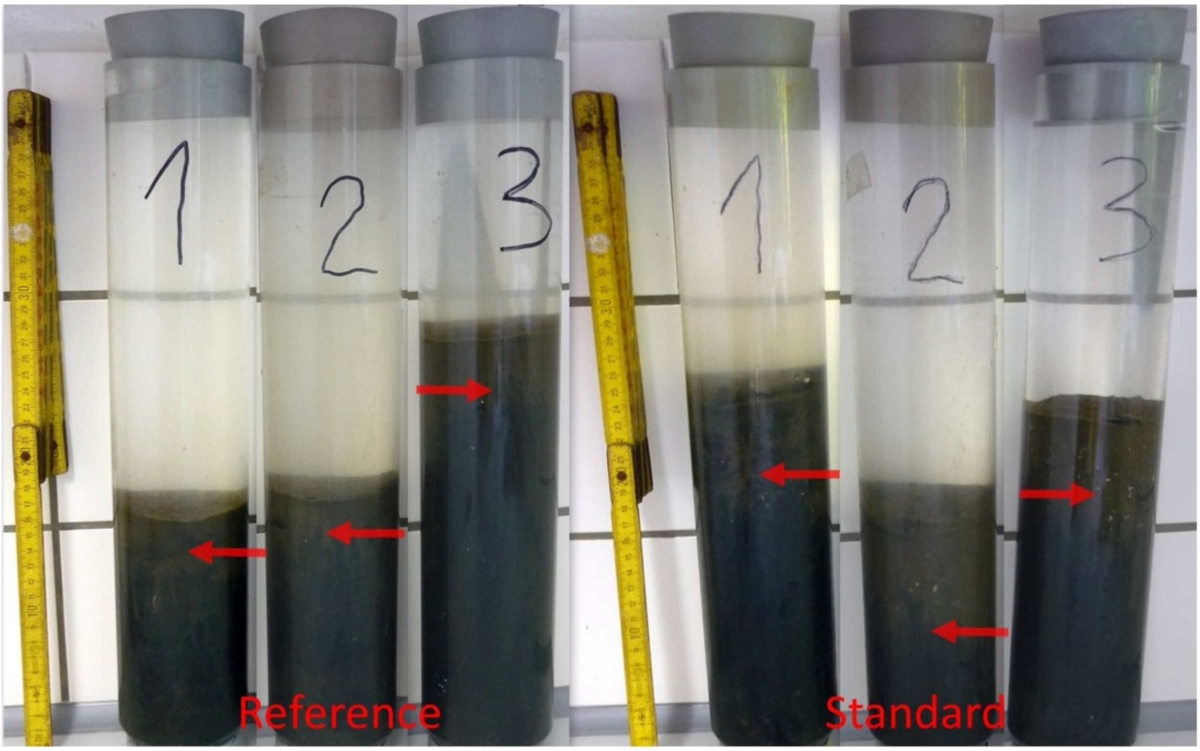


Figure 3. 7: Sediment samples in acrylic tubing; red arrows indicate shifts in colour and redox conditions; note: tape measure (cm) shows unequal scale

Taking into consideration the results displayed in Table 3.2 however, this does not directly correlate with the organic content of the sediment. The shift to anoxic conditions at the standard location takes place at almost twice the depth compared to the reference location, whereas the organic content only is 1.25 times higher.

3.3.3. Dispersal of particulate organic matter

Based on sinking velocities and mean water current velocities, the implementation of a model for the dispersal of POM at the facilities of the Kieler Meeresfarm is attempted. As calculated in Chapter 3.3.2, the mean value for POM sedimentation is applied to the relative spread of particles. The resolution of this model amounts to $RES = 5 * 5\ m$. The model shows the dispersal of POM in eight main cardinal directions over the course of time. Several assumptions have been made, including the discontinuous distribution of faecal sinking and water current velocities, as they are averaged and further separated into three categories or respectively eight cardinal directions. Furthermore, the occurrence of stagnant water was not assumed and water depth was considered to be $10\ m$ throughout the entire area of the model. Figure 8 shows varying deposition rates within the areal of the farm, based on dispersal rates obtained by faecal sinking and water current velocities and respective days.

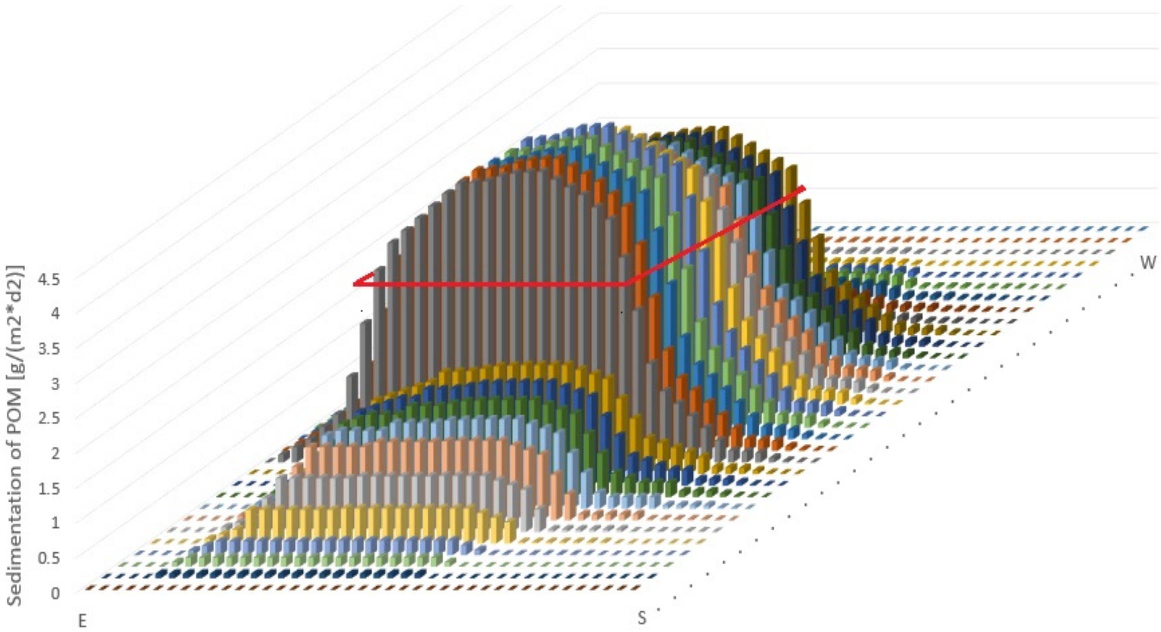


Figure 3. 8: Dispersal model for POM sedimentation over time of the Kieler Meeresfarm; red: indicating farm boundaries

Looking from the south, a strong dispersal of POM across the boundaries of the Kieler Meeresfarm, is visible. The decrease in sedimentation levels out rather slowly in the cardinal direction of south-west. However, a view from the north side, reveals a steep decrease, as the water current velocities and respective number of days would suggest. Highest sedimentation rates found within the farms boundaries are, due to the overall slow water current velocity, spread relatively evenly throughout the area. Unfortunately, due to a lack of sediment samples, definite conclusions on the deposition of dispersed POM cannot be drawn. However, assuming that low water current velocities and comparatively high faecal sinking velocities result in a close correlation between sedimentation and deposition (Krost, P., *personal communication* 16.08.2018), estimations can be made. It clearly illustrates enhanced sedimentation within the farm area. Looking northwards of the farm, or rather closer to the reference location, sedimentation decreases significantly and goes along with the previous conclusion that sedimentation positively correlates with deposition. Thus, it can be assumed, that the deposition across the farms areal fluctuates with the amount of sedimentation. Keeping in mind the lack of ground truth, this cannot be verified with certainty.

3.4. Conclusion

Mussel farming is widely perceived as a tool for mitigating eutrophication effects. However, potentially detrimental impacts of bio-deposits, amongst other particulate organic matter, of which mussels assemble substantial amounts, remains to date a subject of research. The accumulating feeding behaviour of blue mussels changes the biogeochemical cycling of nutrients. The extent of organic enrichment is determined by the rate of decay, redistribution of the bio-deposits via remineralisation, the range of dispersal and the overall production. Nevertheless, it is apparent, that organic enrichment by blue mussel farming is considerable. In the present work, an assessment of particulate organic matter sedimentation and deposition, as well as resulting ecological consequences, namely due to oxygen depletion, is carried out. Research has been performed over the course of June and August 2018, revealing the influence of the blue mussel farm in the Kieler Förde to its surrounding ecosystem. A significant amount and dispersal of particulate organic matter sedimentation has been determined and deserves notice. However, the associated oxygen depletion only takes place to small extent. The ecological footprint of the Kieler Meeresfarm can be evaluated as little and a prolonged operation of this facility is considered to be unproblematic.

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