Hydrographical and chemical observations in a coastal area with mussel farming, western Sweden.

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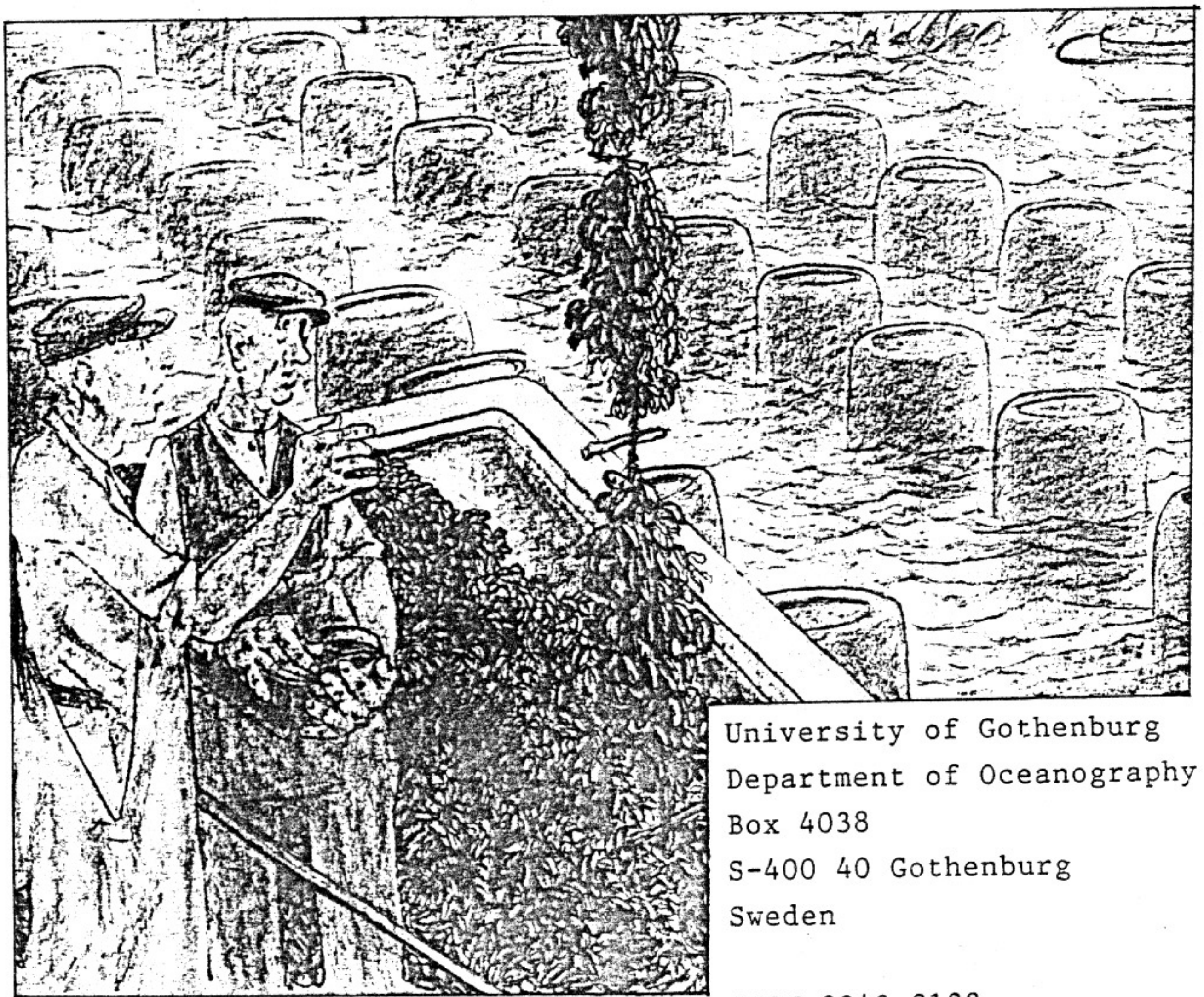
Report No 46 1984



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Contents

1 Abstract

Water currents through a blue-mussel culture have been studied together with measurements of inorganic dissolved nutrients, oxygen, salinity and temperature. A hanging long-line culture of *Mytilus edulis L.* was followed from June 1978 to March 1980. There were considerable changes in all parameters during the farming period. The nitrate-nitrogen varied from 0 to 36 μM and the phosphate-phosphorus varied from 0 to 1 μM. These changes were to some extent due to the seasonal cycle. However, still greater and more rapid changes in concentrations of the nutrients were caused by changes of watermasses in the area. On the whole, the conclusions are that in this case the mussel culture did not give rise to any measurable effects of the water quality in the area in consideration of inorganic nutrients and oxygen. Nevertheless special sections through the culture showed that the nutrient excretion from the mussels could be measured in situ at some occasions, especially by warm water and low current velocity. By this occasions the concentration of ammonium-nitrogen was doubled and the concentration of phosphate-phosphorus was fourfolded in a watermass by passing through the culture.

Phosphorus quantities of different items concerning with the culture are discussed.

A mean current velocity of 2-6 cm/s is suggested as the most convenient for mussel farms with the technique used today along the Swedish west coast.

2 Preface and acknowledgements.

This work is a part of an integrated project dealing with the ecology of mussel cultures on the Swedish west coast. The project was initiated in 1978 and includes the study of the developement of the *Mytilus* community, in relation to, e.g. currents, nutrients, phytoplankton, bacteria and sedimentation (Loo and Rosenberg (1983), Romare et al (1982), Wiigh-Mäsak (1982), Lännergren (1982), Hagström and Larsson (1982), Dahlbäck and Gunnarsson (1981)). An overall model for the energy flow in the mussel culture has been presented by Rosenberg and Loo (1983).

The project was sponsored by The Bank of Sweden Tercentenary Foundation. During the period of the projct I have had a scholarship from the Nordic College for Physical Oceanography and grants from the Carl Tryggers Foundation.

This part of the project has been possible to accomplish thanks to the cooperation of Mr Per-Ingvar Sehlstedt. I also wish to express my thanks to Dr Rutger Rosenberg, who was the leader of the project.

3 Introduction

Along the Swedish northwest coast, with its large area inside the belt of skerries and with in general unpolluted salty water, there are exellent conditions for cultivating the blue mussel, *Mytilus edulis*. Notwithstanding the establishment of mussel cultivations did not start until 1971, but ever since then the cultivating has been expanded. 1981 the harvest was 1000 tonnes and 1983 a production of 3000 tonnes is expected. As the potential for culturing is considerably higher we can look forward to a further increase.

This expected expansion of aquacultures has caused a debate about eventual enviromental effects on the marine ecosystems. In order to use a marine area for intense mussel farming one has to know the preconditions for the best localisation and the optimal size of the cultures. The aim is to obtain a maximum of harvest at the same time as the environmental influences are at a minimum.

Two of this eventual effects on the environment are increased nutrient concentrations and decreased oxygen content. Several papers discuss the nutrient excretion from *Mytilus* or the oxygen consumption by the mussels in laboratory experiments. In Bayne et al (1976) is given a review. Kautsky and Wallentinus (1980) have studied the in situ excretion of nitrogen and phosphorus from a benthic *Mytilus* system confined in plastic bags in the Baltic. Tenore and Gonzales (1975) investigated the role of nutrient intrusion in an area with intense mussel culture in Spain.

The aim of this part of the project was, on the one hand to describe the nature of water movements in a culture area together with an estimate of the current influence of the growth rate of the mussles. On the other hand, we wanted to investigate and quantify the in situ magnitude of nutrient intrusion and oxygen consumption in a full scale threedimensional mussel culture.

A *Mytilus* culture was followed from the settlement in June 1978 to the harvest in March 1980. The following parameters were measured: dissolved inorganic nutrients, total nitrogen and phosphorus and oxygen. In addition currents, salinity and temperature were measured.

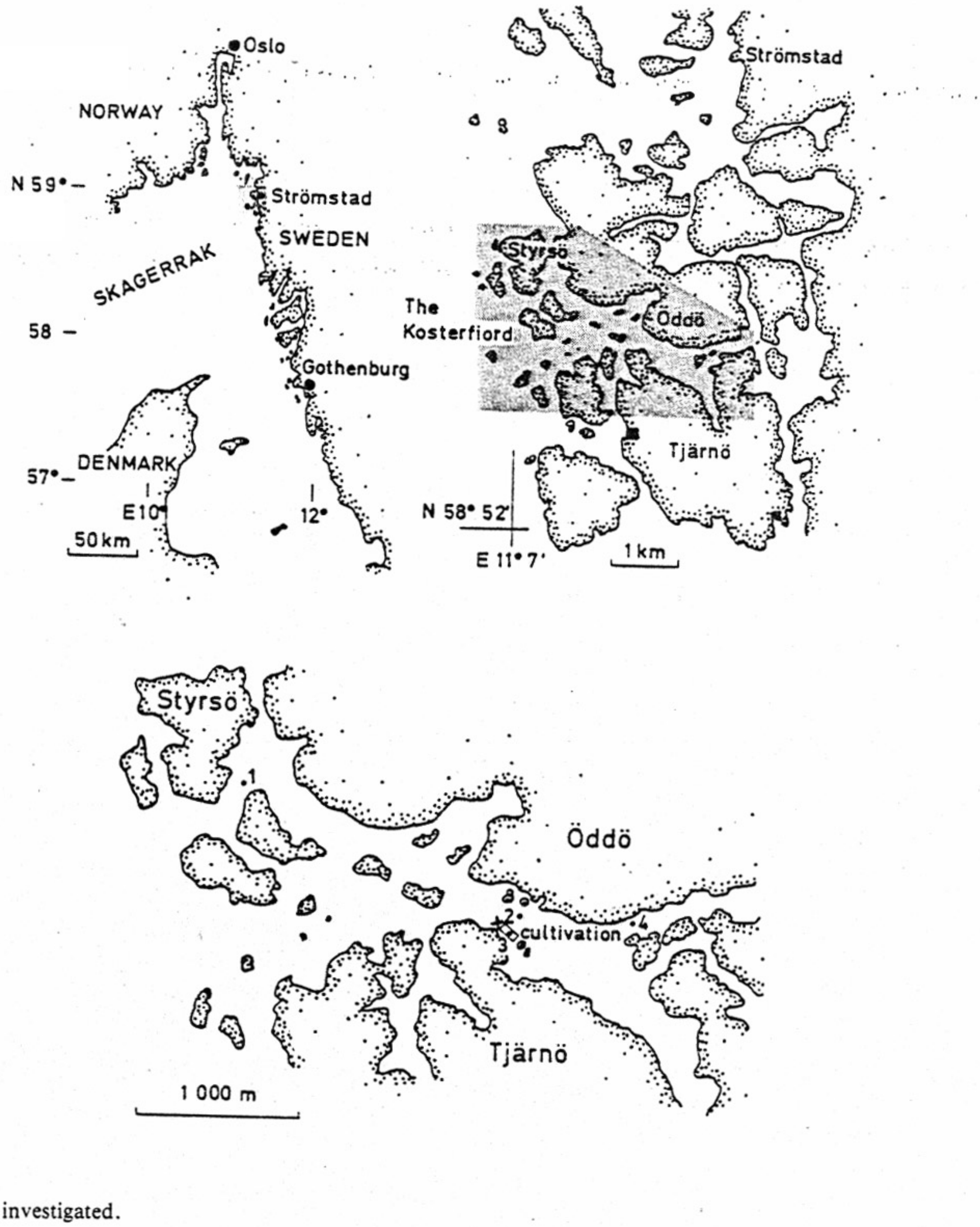

Figure 1. Area investigated.

Points 1-4 indicate sampling stations. The cross (x) outside the cultivation indicates position of current meters. Tjärnö Marine Biological Laboratory is marked with a square (■).

4 Investigation area.

The studied mussel culture is situated outside the island of Tjärnö in the northern part of the Swedish west coast (fig 1).The area is like a channel approximately in the east-west direction. The channel is about 3 km long with many small islands. Outside the channel the deep Kosterfjord at the boarder of Skagerrak is situated. On the inside of the narrow passage in the inner end of the channel is a shallow-water area. The water depth in the culture area is 10 to 18 m.

The culture was built by 14 horizontal, 180 m long lines moored near the sea surface and anchored to the bottom. The extension of the lines was in the same direction as the channel with a small island at one end. From the long-lines 6 m bands of polypropylene were attached. The culture covered an area of 4500 sqm. The mussels had grown to a size of about 6 cm after 20 months from the settlement. This size was found at depths of 0-2 m.

The culture gave a total harvest after 20 months of 12 metric tons of mussel-meat (dryweight),that is about 160 metric tons wetweight with shells.

The primary production in the area during 1979 was 222 g $C/m^2 \cdot year$ (Lännergren, 1983). The sedimentation rate just under the mussel culture (3 g $C/m^2 \cdot d$) was nearly three times higher than at a nearby station (Dahlbäck and Gunnarsson, 1981).

5 Materials and methods

5.1 Current measurements.

Three different methods for measuring the speed and the direction of the water current have been used. To estimate the variations in time three continously registrating current meters (Aanderaa) were placed next to the culture at 3, 6 and 10 m depth (Fig. 1). These were registrating the speed and the direction of the currents, temperature and salinity every 10th minute during different periods. Data given by the Aanderaa meters have been analyzed by computer. To estimate the variations of currents in different places in the area of investigation, especially at the same time as the chemical analysis were performed, a smaller current meter (Gyttre) was used. To estimate very low current velocities inside the culture the water was marked with a dye (Rodhamine B). The drift of the dye was observed either from a boat with a water field-glass or by a diver.

Complementary laboratory experiments with dye have also been carried out. The aim was to study which way through a culture the water will chose and how the speed of the water is influenced for different designs of the culture (Kolmberger, 1982).

5.2 Chemical analysis.

Samples were taken with a plexiglass water sampler. The water was stored in dark bottles. Analysis were performed in laboratoy as soon as possible or within less than some hours. Salinity was measured with an inductive laboratory salinometer (Plessey). Dissolved oxygen was determined by the Winkler titration method, modified by Carritt and Carpenter (1966). Analysis for the dissolved inorganic nutrients (ammonium, nitrate, nitrite, phosphate and silicate) were performed according to the Baltic Manual (Carlberg 1972).The total amounts of nitrogen and phosphorus were simultaneously analysed by the method of Koroleff (1972).

5.3 Observations.

Measurements were performed during the period of cultivation about every second month in a section from the outer part of the channel to the inner end of the channel. The stations 1-4 are marked on the chart in Fig. 1. All together this makes about 200 samples for chemical analysis together with current measurements at the sampling points. Besides special investigations have been worked out to study daily variations inside the cultivation and to study small scale variations of nutrients and oxygen inside the cultivation. Oxygen concentrations near the bottom in cultivations of different ages have also been measured.

Measurements of the currents by the continously registrating meters were performed at three depths during three different periods, each extended over at least two weeks.

6 Results

6.1 Water movements

The water currents in the area are caused by,
- ☐ changes in water level due to tidal forces,
- ☐ local winds,
- ☐ river discharge,
- ☐ differences in the atmospheric pressure.

Water level registrations at Kungsvik outside Strömstad and at the Tjärnö Marine Biological Laboratory (see Fig. 1) have given the period and the amplitude of the tides. The period is nearly 12.4 hours (M2). The mean amplitude at Kungsvik is 11.6 cm and corresponds approximatively to the amplitude at Tjärnö. If the change of the water level between high and low water is 20 cm, the current through the area will be of the magnitude of 2 cm s (Larsson and Lempert, 1978). The currents in our channel are often dominated by the contribution of these tidal currents. Consequently the main current will change its magnitude and direction every sixth hour in accordance with the water level changes. These water movements displace the water approximatively 400 m back and forth through the cultivation area. Due to the tidal currents the water is always moving through the cultivation. However, the tidal currents will not be sufficient for causing any noticeable intrusion of new water into the channel, neither from the inner shallow water area nor from the outer Skagerrak area.

Registrations of currents, water level, wind direction and wind speed during one week at 3 and 10 m depths are shown in fig 2. After visual inspection of all continously measurements this weak was chosen as a representative one. By week winds the currents at all depths are almost fully dominated by tidal currents. The winds are highly variable, however, and this can rapidly change the circulation pattern.

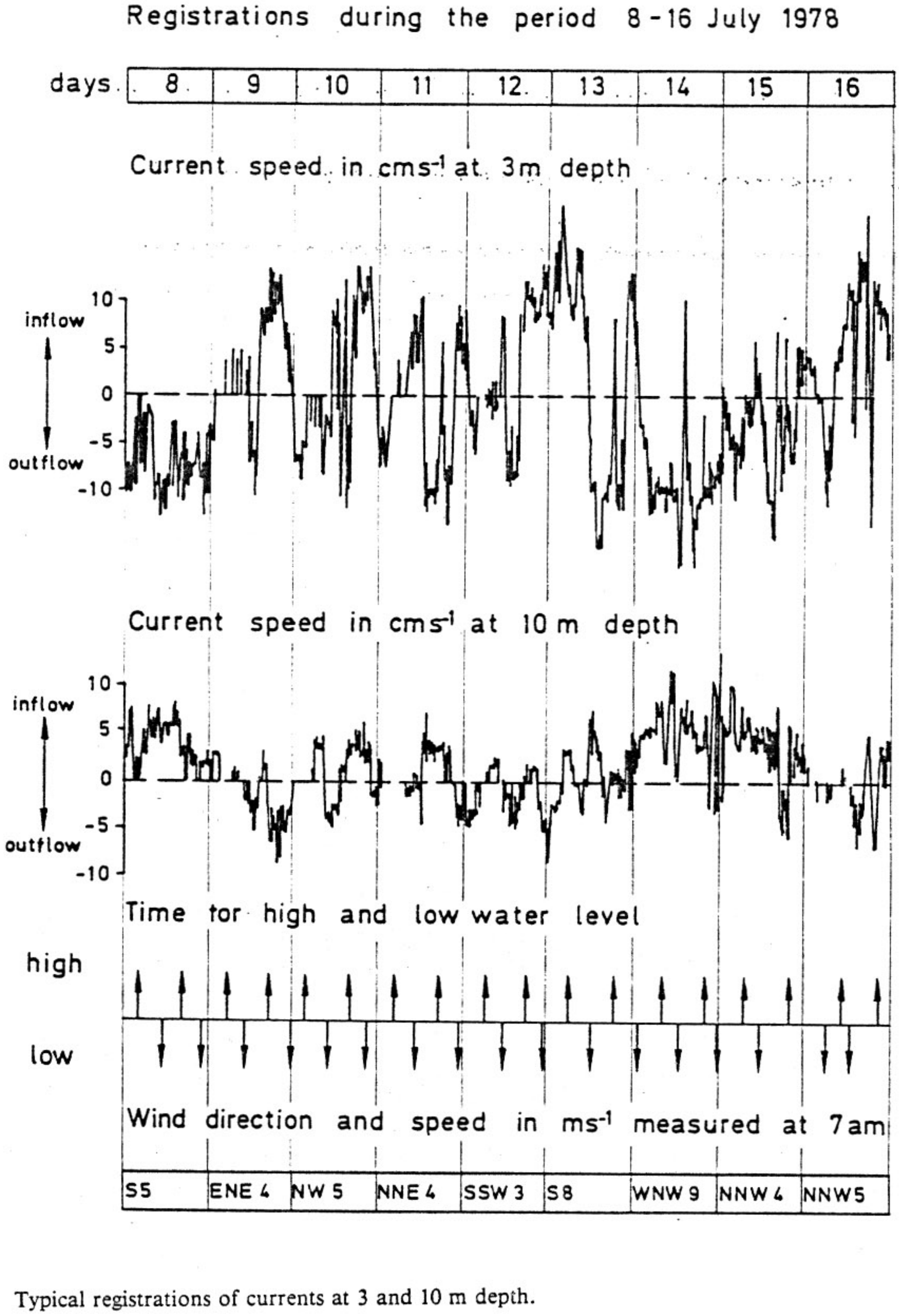

Figure 2. Typical registrations of currents at 3 and 10 m depth.

The registrations are made during the period 8-16 July 1978. The current components in the direction of the channel are calculated. Positve is inward flow (117°). Negative is seaward flow (297°). Below the current registrations are shown the times for high and low water level and the winds. Notice that wind observations are made only at 7 am.

The observed current are caused by the earlier mentioned different factors. These factors are in themselves highly fluctuateing and thus it is difficult, or in fact impossible to make a picture of the typical current pattern. However, one way to describe the measurements in different angels of approach is shown in Fig.3-5. The measurements were made just outside the investigated culture at 3, 6 and 10 m depth. The mean current velocities in cm s in different directions during August and September 1978 are given in Fig. 3. In Fig. 4 the numbers of registrations in different directions for the same depths and the same period of registration are shown. Finally, the numbers of these registrations for different current velocities are given in Fig. 5.

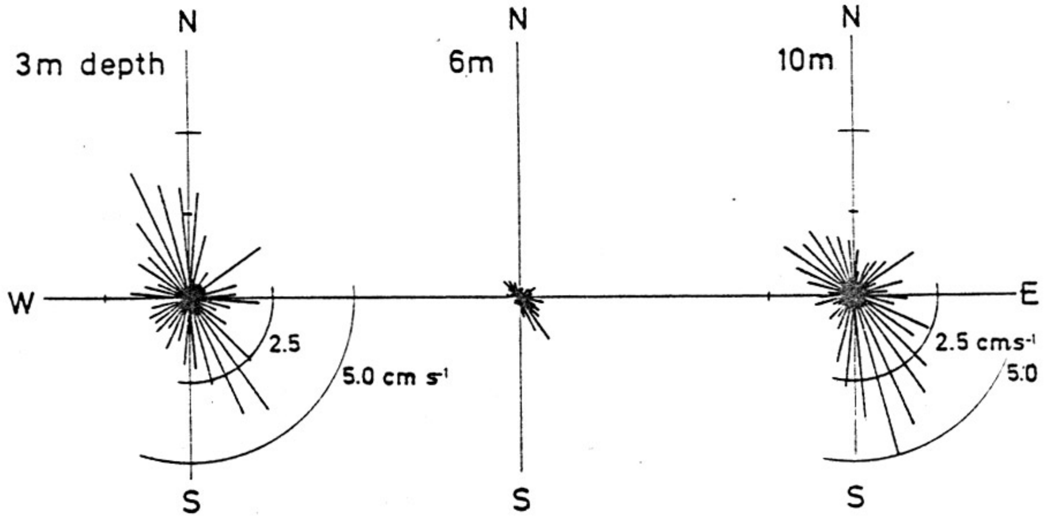

Figure 3. Mean current velocity.

Mean current velocity in cm/s in every 10°-section at 3, 6 and 10 m depth. Registrations from the Aanderaa meters during August and September 1978.

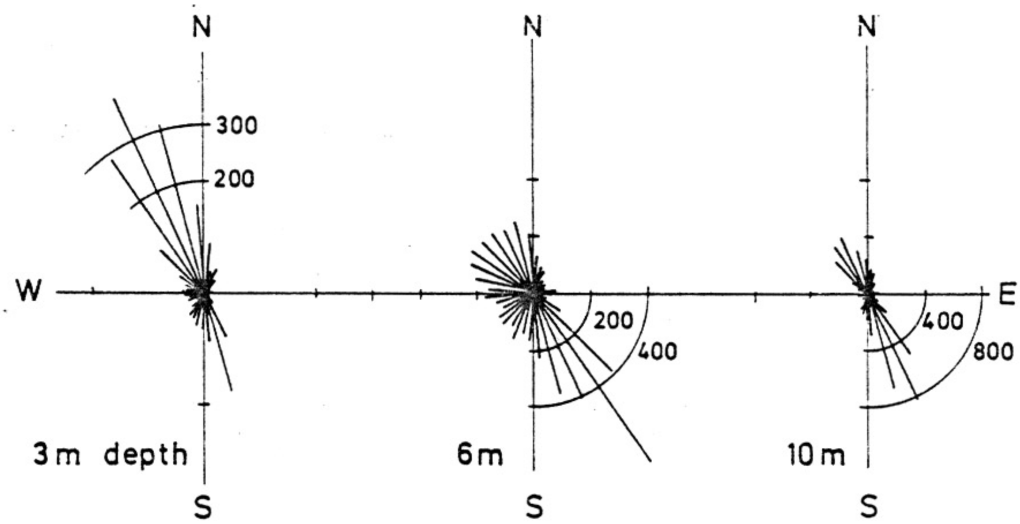

Figure 4. Current directions

Numbers of current registration in every 5°-section at 3, 6 and 10 m depth. Registrations from the Aanderaa meters during August and September 1978.

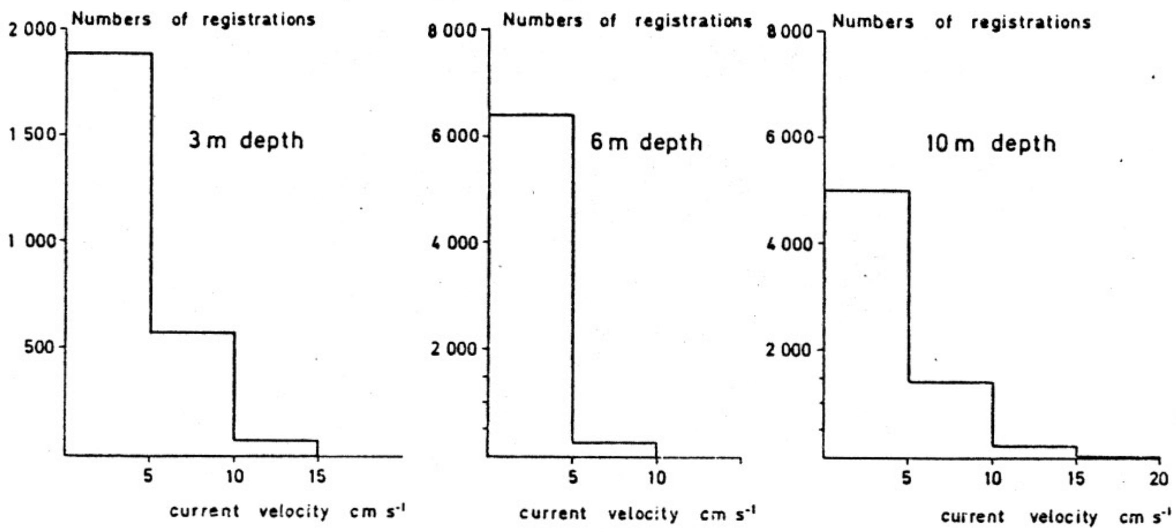

Figure 5. Numbers of registrations for different current velocities.

Registrations from the Aanderaa meters during August and September 1978, in velocity intervals of 0-5, 5-10 and 10-15 cm s .Notice the difference in scale for the numbers of registrations.

From Fig. 2-5 we can draw the conclusion that the current can take any direction at all depths. However, the predominant current directions are out of the channel (297°) or in to the channel (= 117°). The speed is generally highest at 3 m depth. Often the speed is higher at 10 m depth than at 6 m. This is a result of the *main* circulation in the channel which is a two-layer flow. There is an inflow or outflow in the surface layer and a flow in the opposite direction at lower layer. Between these layers there is a layer with low or no motion.

As previously mentioned the mean tidal current velocity is of the magnitude of 2 cm/s . Though, in Fig. 2 and 5 we observe that the velocities sometimes are considerably higher. The highest observed speed of the surface current during our measurements was 30 cm/s . These higher speeds are caused by the additional effcts of the local winds and of the differences in the atmospheric pressure. The river discharge is usually too small to effect the currents.

An attempt to analyze the changes in circulation due to the winds is made by separating the current registrations into four groups.[1] In Fig. 6 the numbers of registrations in different directions at 3 and 10 m depth are shown for two of the »wind-groups».

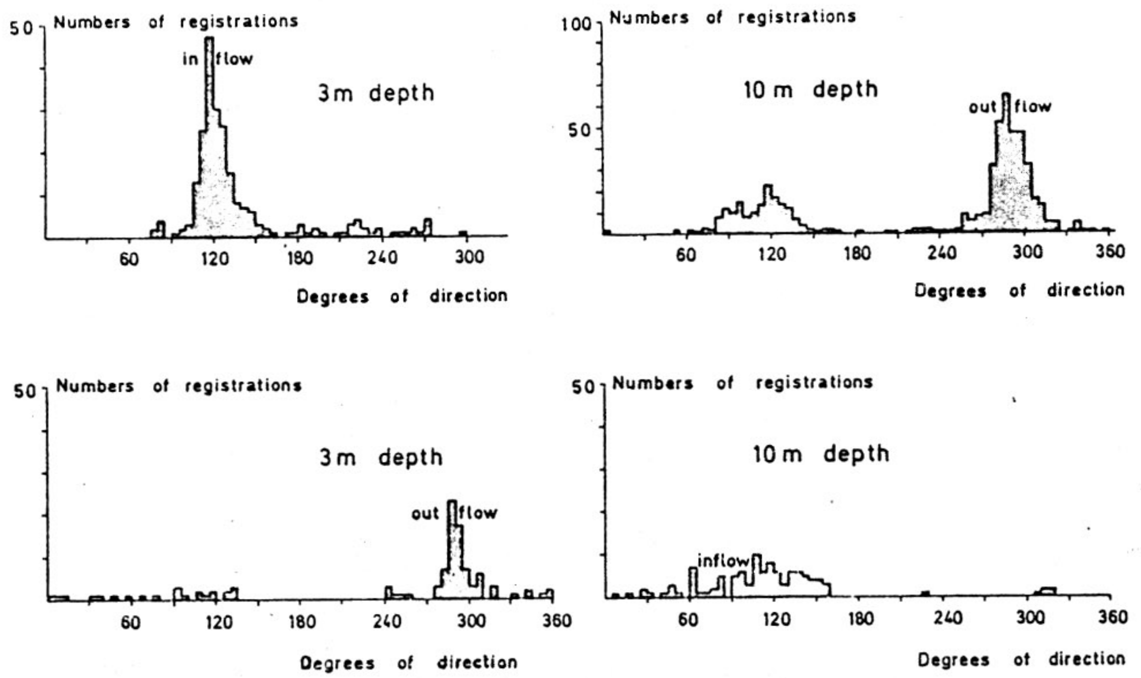

Figure 6. Current patterns for different winds.

Numbers of current registrations in different directions at 3 and 10 m depth.[2]
a/ winds from SSW to W
b/ winds from WNW to N

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1) The four groups are including measurements when the winds were blowing from: NNE to ENE, E to SSE, SSW to W and WNW to N.

2) Flow out of channel is in the direction 297°. Inflow is towards 117°.

These figures for all groups give the following main features:

- ☐ Winds from NE to SE, and also winds from SW to W, usually cause a surface flow into the channel and a seaward flow at deeper water (see Fig. 6a).

- ☐ When the wind is blowing from N and NW the surface water flows out of the channel. The measurements show a corresponding inflow at 10 m depth (see Fig. 6b). This is also the case at S-winds and strong SW-winds.

Because of the complex pattern of the currents we can not calculate the actual amount of water which have passed through the cultivation. However, typical mean movements of the water -apart from direction- are given as 2.8 cm/s at 3 and 10 m depth and 1.7 cm/s at 6 m depth. If the speed component in the direction of the channel is taken into account this gives a net inflow at 3 m of 1.2 cm s and a net outflow at 6 and 10 m of 0.7 cm/s . This is calculated from the measurements during August 1978.

The laboratory experiments show that higher current speeds cause more turbulence around the mussel bands. However, the distance between the bands must be very small if the culture will be able to effect the current to any greater extent (Kolmberger, 1981).

6.2 Temperature and salinity.

The temperature in the cultivation area was quite homogenous at all depths. A thermocline was developed just in a few times at seasons for heating or cooling the water. In the winter the whole water column was cooled down to -1.0 C. Ice covered the cultivation from January to the beginning of April in 1979 and during January and February in 1980. In the summer the temperature was at least 12°C at all depths. The temperature of the surface water was somewhat higher than that near the bottom.

Changes in temperature of the order of 0.1°C followed the changes in salinity. This means that the temperature of the water will not be influenced by the culture in this range.

The salinity values vary due to the total effect of currents, precipitation and river runoff. We have already seen that the currents are highly variable and undependent of season. Due to the currents the salinity at all depths can change rapidly. This is easy to observe when there is an outflow in the surface layer and an inflow of salty water in the bottom layer. *Mytilus edulis* tolerates an extremely wide range of salinities. The mechanisms of the adaption are poorly understood, but one knows that it takes a long time and requires energy supply (Bayne, 1976). However, we can establish that repeated rapid changes of the salinity reduce the growth rate.

As an example of rapid changes in temperature and salinity the continiously measurements at 3 and 10 m depth just outside the culture are shown in Fig. 7. The time of registration is the same as in Fig. 2. Just in a few hours the surface salinity increases from 25‰ to 30‰ due to the inflow of saltier bottom water. At the same time the temperature is decreased.

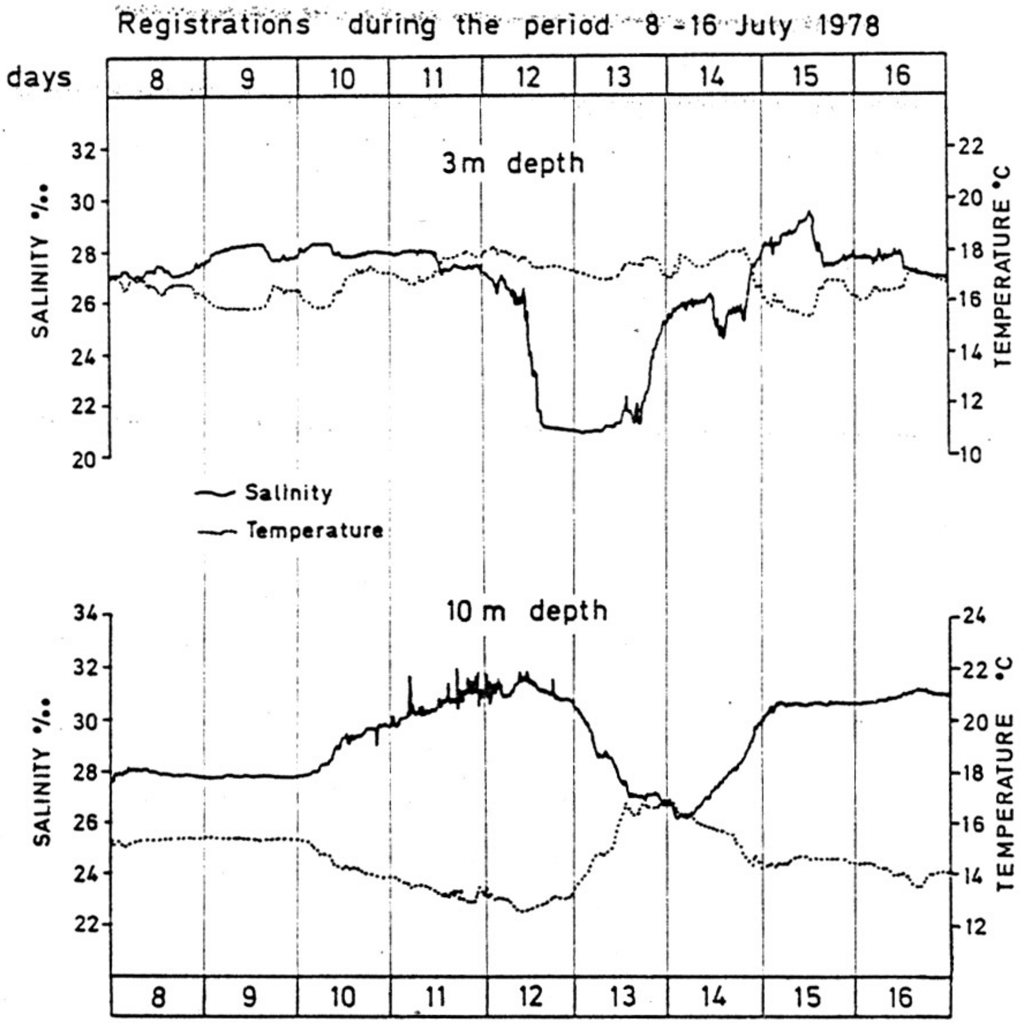


Figure 7. Changes in temperature and salinity.

Changes in temperature and salinity at 3 and 10 m depth during the period 8-16 July 1978. Currents for the same period are given in Fig. 2.

The amount of river discharge has an impact on the salinity just during early spring when ice and snow are melting. This causes a spring halocline at the depth of 1-3 m. This surface halocline can also develope in autumn after heavy rains.

In order to get an overview of temperatures and salinities during the period of cultivation all measurements are plotted against each other in Fig. 8. Overall the most frequent salinities were between 20 and 30‰ . This water either originates from the Kattegat or is a result of mixing processes in the inner part of the estuarium between less saline surface water and saltier deep water. Surface water with lower salinity occurred in the spring both years and on one occation during the second summer. The lowest salinity measured was 14‰ under the ice in March 1979. Fig. 8 also shows that intrusions by saltier water from the Skagerrak can occur. In January, March and June 1979 cold Skagerrak water was found at larger depths. In July and October 1979 warm Skagerrak water appeared in the area. The highest salinity value we found inside the cultivation was 32.2‰ in October 1979.

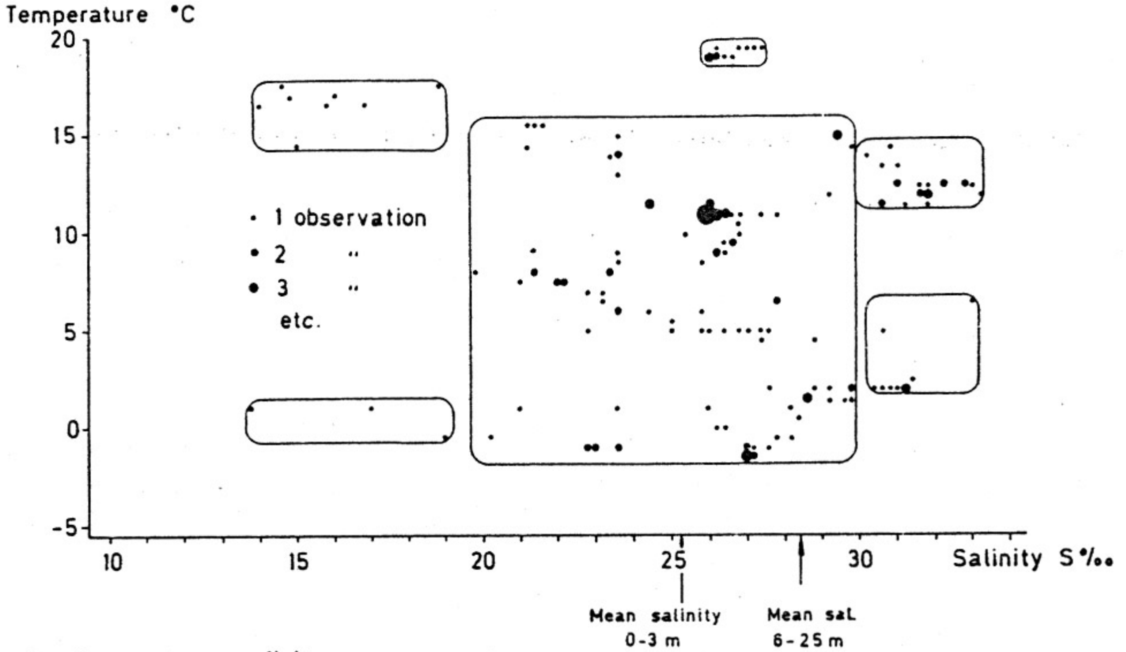


Figure 8. Temperature vs salinity.

Temperature and salinity values during the period of cultivation. All 200 observations at stations 1-4 in Fig. 1 are plotted. Surface values are not excluded.

6.3 Nutrients

The distribution of dissolved inorganic nutrients in estuarine waters is controlled by the nature of the estuarine circulation, mixing and other physical processes, together with biological, chemical and sedimentological effects. The nutrients are required for the production of organic matter. They are released back into solution by organisms, either direct as excretion or later when they die and decompose. Some dead organic matter are trapped in sediments or decompose later on the bottom.

Typical for the amounts of inorganic nutrients in our costal waters are high values in winter and low values after the spring bloom and during the summer. These variations were also recorded in our investigation area. However, in addition to this »normal» seasonal variation there was another variation due to the intrusion of water from land or from deeper nutrient rich water.

In order to give an overview of how the nutrients varied during the period of cultivation the results for nitrate-nitrogen are reported. Together with ammonium - nitrogen, nitrate represents the greatest amount of soluble inorganic combined nitrogen in the water. According to bag experiments by Lännergren (1983) the phytoplankton growth was limited due to shortage of phosphorus and nitrogen in combination. As mentioned before all inorganic forms of nitrogen together with the total amount of nitrogen were mesured. Figure 9 shows the variations of the nitrate concentration at different depths in the water surrounding the culture from settlement to harvest.

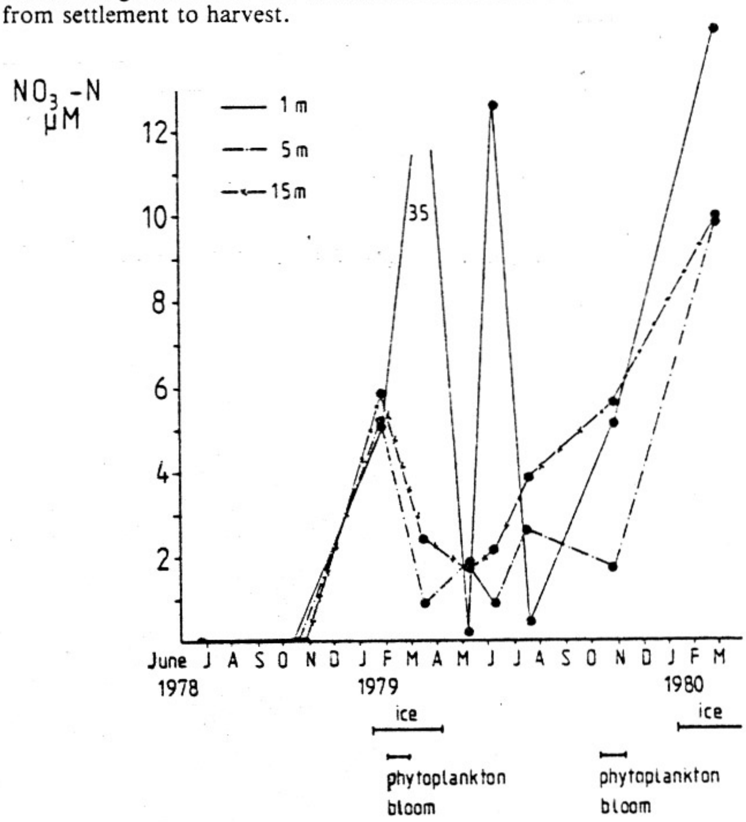


Figure 9. Nitrate concentrations.

The nitrate concentrations at 1, 5 and 10 m depth inside the culture during the period of cultivation. The point for the highest value (35 µM) lies much above the diagram.

During the »settling» summer 1978, the concentrations at all depths were low or near zero. They were increasing in November to January 1979 due to convection and low algal production. The spring bloom occurred under the ice in February 1979. The nitrate was depleted at all depths, except just near the surface. Here low salinity water with high amounts of nitrate instead caused higher concentrations. During the summer of 1979 the nitrate concentrations were comparatively low but never near zero. In June there was a considerable intrusion of saltier water, which caused salinity changes at all depths. In the surface water the salinity changed from 16‰ to nearly 30‰. This was accomplished by mixing processes and an equalization of the concentrations of the nutrients. The amounts at 1 m depth were decreasing, at the same time as the amounts at 5 and 15 m were increasing. This in spite of high production of organic matter (Lännergren, 1980). The winter values of nitrate - nitrogen in 1980 were higher than those in 1979, likely due to intrusion of low saline water. On the whole, a comparison with the equivalent diagram for the salinity variations gives that variations in nitrate concentrations followed the variations of the salinity. To get a better picture of this observation all nitrate measurements in the cultivation area are plotted against the corresponding salinity value in Fig. 10.

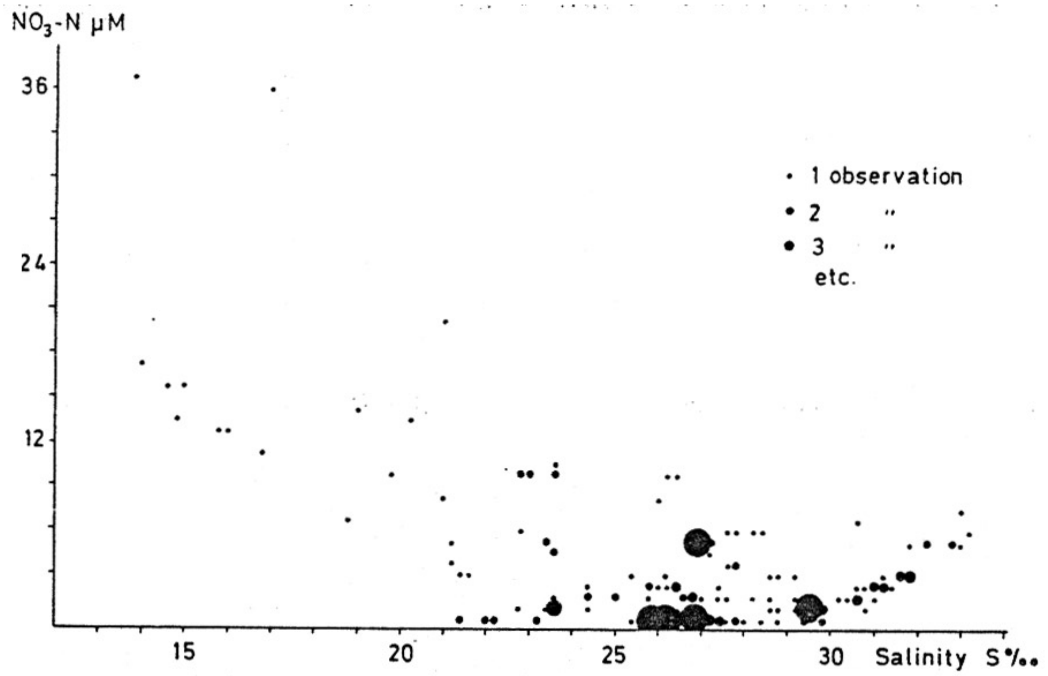


Figure 10. Nitrate as a function of salinity.

Concentrations of nitrate in µM as a function of salinity. All values in the area measured during the period of cultivation (200 values).

This diagram shows that the highest concentrations of nitrate occurs by low salinities. Maximum value was 36 µM NO_3-N in a water with the salinity of 13.8‰. In the medium saline water of the Kattegatt (20-30‰) the nitrate values were higher in winter and lower in summer (or they are completely determined by the extent of mixing). In the high salinity water from the Skagerrak the concentrations of nitrates were higher than those of the medium saline waters.

The same features of distribution and variations in concentrations as for nitrate were in general also valid for the other dissolved inorganic nutrients. The variations between two times of sampling during the same season can be much greater than the variations due to seasonal changes.

However, there were some differences for the dissolved phosphate and silica. According to phosphorus, the cocentrations in an estuary are in addition to physical and biological processes also regulated by a buffering effect of the sediments (Butler and Tibbits, 1972). In our area of investigation this is easily seen as there were no high phosphorus values corresponding to the high nitrate values at low salinities. The highest phosphorus values were instead found at high and medium salinities during the winter season.Therefore the variations in phosphorus cocentrations were not so connected to salinity and followed the »normal» seasonal changes more closely. This is shown i Fig. 11.

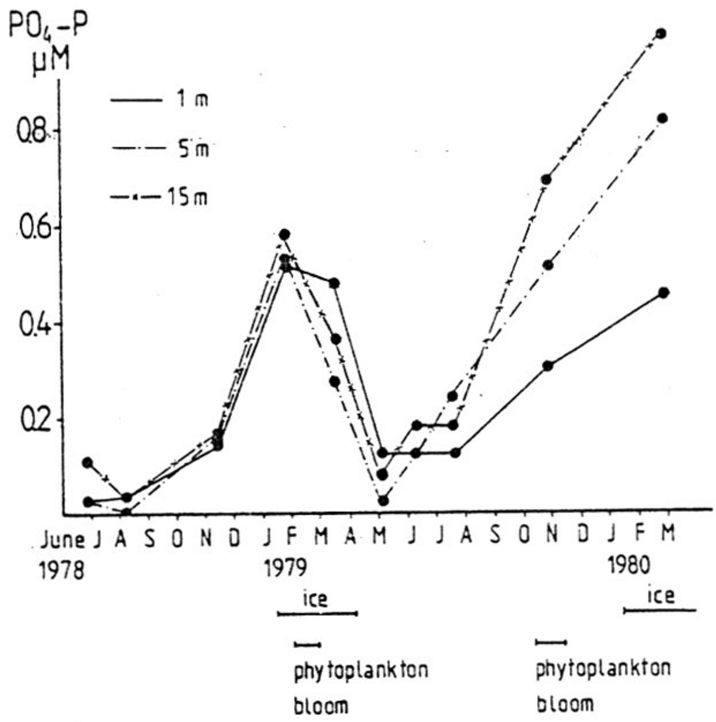


Figure 11. Phosphorus concentrations.

The phosphorus cocentrations at 1, 5 and 15 m depths inside the culture during the period of cultivation.

The dissolved silica is supplied to the oceans by rivers. In the estuarine water silica is primarily utilized by diatoms (phytoplankton). Besides, there is supposed to be a non-biological removal of dissolved silica by precipitation during estuarine mixing (Aston, 1980). In the Tjärnö area this precipitation was not significant. The variations of silica concentrations were instead similar to those of nitrate. That is, the variations depend on the biological removal together with salinity changes. Low salinities gave rise to the highest amounts of silica (15-40 µM). Higher salinities were connected with lower silica values (0.5-6 µM).

6.4 Oxygen.

The surface waters will normally be completely saturated with oxygen dissolved from the atmosphere. A water with low temperature and low salinity is able to dissolve a greater amount of oxygen than a warmer water with higher salinity. The dissolved oxygen is then consumed by breathing of organisms and by oxidation processes of organic and inorganic material. The consumption of oxygen in coastal waters is greatest in the bottom water. Therefore the amounts of oxygen just near the bottom in connection with the culture have been of certain interest. Here the amounts of organic matter, which consume oxygen during decomposition, are great. In Fig. 12 the variations of the oxygen saturation values are shown. The variations are shown during the period of cultivation and just near the bottom under the culture. By comparing this curve with the variations of the oxygen contents at a station not at all influenced by the culture, we can see that the variations were quite similar in time as well as in magnitude. The samples were taken from the same depth. Notice that the distances to the bottom were different.

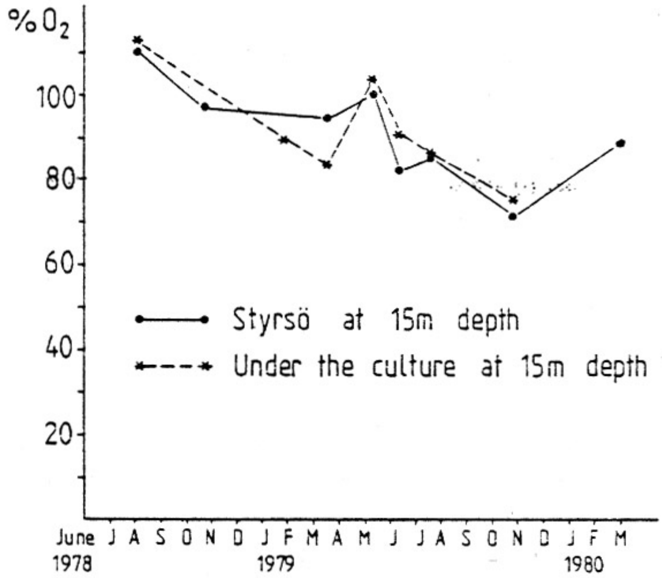


Figure 12. Oxygen saturation values.

Oxygen saturation values in the bottom water during the period of cultivation.
---- :samples at 15 m depth, 0.5 m above the bottom under the culture.
●----● :samples at 15 m depth, 10 m above the bottom at a reference station.

Both stations showed decreasing values of oxygen saturation during the period of cultivation. Was this due to the mussels or not? Again, one way to answer this, is to design a diagram to study the variations in oxygen content compared with the variations in salinity values. This is done in Fig. 13.

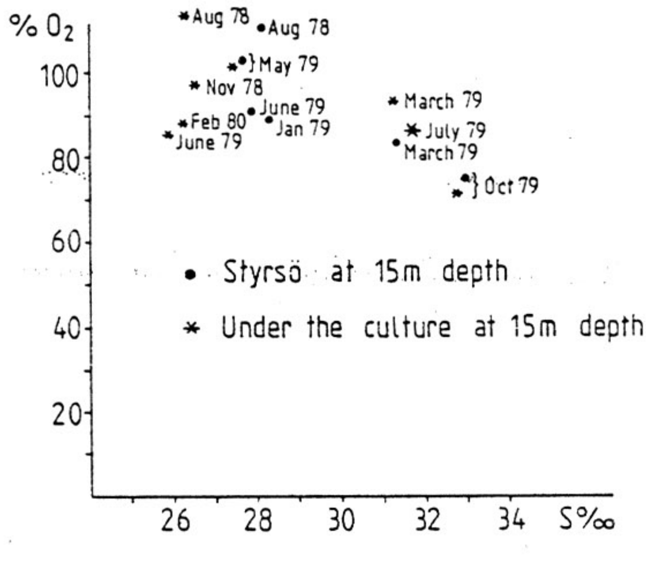


Figure 13. Oxygen saturation values vs salinity.

Oxygen saturation values plotted against the salinity.
*- :samples at 15 m depth, 0.5 m above the bottom under the culture.
•- :samples at 15 m depth, 10 m above the bottom at a reference station.
To the right of the * or • the dates of the sampling are noted.

In this figure it is obvious that the oxygen values above all changed according to the salinity values. Lower oxygen content was connected to water with higher salinity. Thus the lowest oxygen saturation values in October 1979 were due to intrusion of water with high salinity.

6.5 Sections under scrutiny.

The variations in dissolved inorganic nutrients and in oxygen concentrations during the whole period of cultivation gives the conclusion that there were no measurable effects due to the *Mytilus* cultivation. However, laboratory experiments have shown an increase of nutrients and a decrease of oxygen as the water is passing through a mussel (Bayne, 1976). Bayne (1973) has also reported that *Mytilus* excrete nitrogen mainly in the form of ammonium, to a varying degree as amino acids, and a few percentages as urea. The atomic ratio of inorganic nitrogen to inorganic phosphorus of the excretion products is about 7, (Kautsky and Wallentinus 1980). Regeneration of silica has not been investigated before.

In order to study this under scrutiny in situ under natural conditions we have followed a marked watermass on it's way through the culture. These experiments were performed on three occations,
- ☐ in the summer 1979, by warm water and low current speed,
- ☐ in the autumn 1979, by warm water and higher current speed,
- ☐ in the winter 1980, under the ice, by cold water and low current speed.

To ensure that the samples were taken from the very same watermass the water was dyed with Rodhamine. The coloured water was followed by a diver who also took the samples. Beside one station outside the culture there were three stations inside the culture. The sampling points and the current picture for the different occasions are drawn in the upper part of Fig. 14.

According to the dissolved inorganic nutrients the sections through the culture showed most considerable changes in the amounts of phosphate and ammonium. The changes of nitrate, nitrite and silica were smaller than the analytical errors. Therefore only phosphate, ammonium and oxygen are considered further on. These changes of concentrations can be real and due to the fact that there was a mussel culture. They can also be a consequence of mixing when the water passed through the culture. The mussel bands caused some turbulent effects, which may be observed through the movements of the dye or through measurements of the salinity and the temperature. Through the mixing effects saltier water with higher nutrient concentrations was penetrating to higher levels in the water column. Diagrams in Fig. 14 show the changes of the amounts of phosphate, ammonium, oxygen and salinity at 5 m depth. The 5 m samples are chosen as they represent the greatest differences.

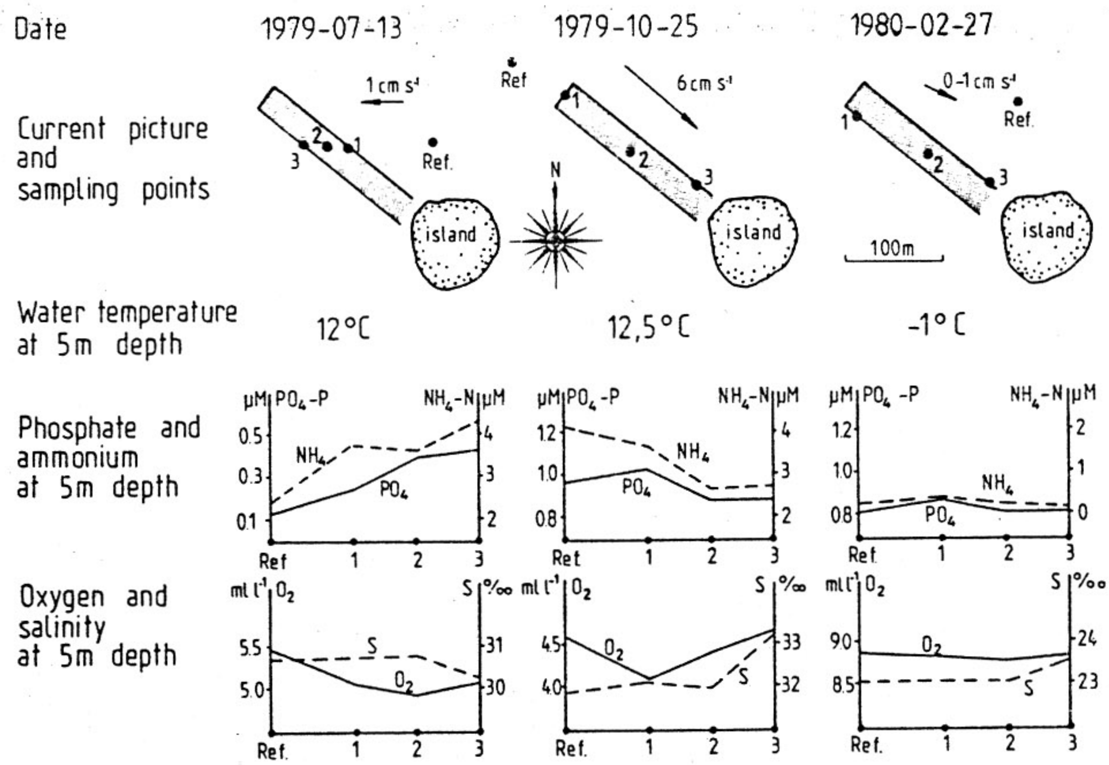


Figure 14. Sections under scrutiny.

Sections through the mussel culture at three occations.
In the upper part: date of sampling, sampling points (reference and stations nr 1-3), current pictures and temperatures of the water.
In the lower part: phosphate, ammonium, oxygen and salinity at the four stations and at 5 m depth.

In June 1979 with warm water, gradual increase in salinity from surface to bottom and low current speed, it is obvious that the amount of phosphate and ammonium at 5 m depth were increased due to nutrient release in the culture. At the same time oxygen was consumed and thus the oxygen concentrations were decreased. These changes were valid for all sampling depths. At 5 m depth the phosphate concentration was fourfolded from 0.1 µM to 0.4 µM when the water was passing through the culture. At the same time the concentration of ammonium was doubled from 2.4 µM to 4.2 µM. The mussels consumed about 50% of the available food referring to the chlorophyll *a* content of particles <200 µm. The phytoplankton population was changed from larger to smaller species as the water passed through the culture (Lännergren 1983). The larger ones were eaten by the mussels and the smaller ones were favoured as a resulting effect of the nutrient excretion.

In October 1979 salinity profiles showed a narrow halocline at 3-5 m depth at stations 1 and 2. The halocline was moving upwards towards station 3 due to changes in the bottom topography. Thus, this time the changes of concentrations of phosphate, ammonium and oxygen at 5 m depth were caused by intrusion of water with different concentrations of these parameters. Above the halocline the changes of concentrations showed the same pattern as in June 1979. However the percentual changes were smaller. The changes at the other occations were much smaller or of the same magnitude as the analytical errors.

The atomic ratios of ammonium-increase to phosphorus-increase in June at 5 m depth and in October at 3 m depth were 6. According to Kautsky and Wallentinus (1980) this is close to the ratio of the *Mytilus* excretion products.

In summary, the nutrient release from the mussel culture were measurable just when the water temperature was high in summer and autumn and especially when current velocity at the same time was low.

7 DISCUSSION

This investigation of water movements, inorganic nutrients and dissolved oxygen in a natural culture of the blue mussel *Mytilus edulis* indicates the difficulties to study an in situ ecosystem. The variability is considerable and complex. Besides, when discussing the influences of physical, biological and chemical processes on nutrients and dissolved gases it is important to remember that two coastal areas are never alike with respect to these influences. In spite of this, some calculations and conclusions will be done.

7.1 Nutrients.

A rough »budget» of phosphorus in the mussel culture and its surroundings has been performed (Fig. 15). It is not a complete budget. The aim is just to give a know-how about the magnitude of phosphorus content in some parts of the system. There are some complications to find the proper values for calculation. Some references are only given for laboratory experiments. Also the variable physiological condition of the individual mussel, which e.g. vary with size, temperature and salinity, can be of great influence when dealing with nutrients and oxygen (Bayne, 1975). None of these complications are taken into consideration here.

Kuenzler (1961) gives the excretion rates of phosphate-phosphorus for the mussels to 0.5-3.6 g per hour and g shell-free dry weight. Kautsky and Wallentinus (1980) give a somewhat higher excretion rate for the small-sized *Mytilus* of the Baltic. At harvest our musselfarm, designed for 200 metric tons wet weight, held 12 metric tons of mussel meat (shell-free dry weight). This gives the total amount of the excretion during 20 months to 100-600 kg phosphorous. To check if this value can be true also in our in situ investigation the measurements from the section in July 1979 (descibed under 6.5) are used as a comparison. An increase of 0.3 µM PO_4-P in the water passing the mussels, with a speed of 1 cm/s , certainly denotes a high rate of excretion. The total phosphorus release during 20 months was calculated on the basis of this to 800 kg. This is in line with the highest value of Kuenzler. Using the C:N:P ratios of 106:16:1 in planctonic material given by Redfield et al (1963), the phosphorus content of the harvested mussel meat is 100 kg. Roughly, I assume that the same ratio is valid for the seston (=the mussel food). This gives that the amount of phosphorus in particulate material transported through the culture during the whole period of cultivation is 1000 kg. Some of this is eaten by the mussels, some is just passing the culture. The energy content of the mean seston concentration is 10 kJ/m^3(Lännergren, 1983). A mean water transport through the culture is calculated to be 4 m/s at 1-6 m depth. Together with the seston this water also transports dissolved nutrients. As already seen the concentrations of dissolved inorganic phosphate-phosphorus vary to a great extent from 0 to 1.1 µM. If 0.3 µM is chosen as a representative value of the incoming Skagerrak water (Larsson and Rodhe, 1979), this gives an intrusion of 2000 kg phosphorus to the area of cultivation during 20 months. This should be compared to the contribution from the river discharge. Unfortunately, this is not known. Instead the input from the sewage-treatment from the Strömstad city is given as a comparison (S. Adolfsson, personal communication). They have a very high capacity of purification why the discharge only contained 600 kg phosphorus during the same period. The sedimetation rate under the mussel culture is three times higher than at a reference station or 2-3 g C/m^2·d (Dahlbäck and Gunnarsson, 1981). This gives a total sedimentation of 150-200 kg phosphorus during the period of cultivation.

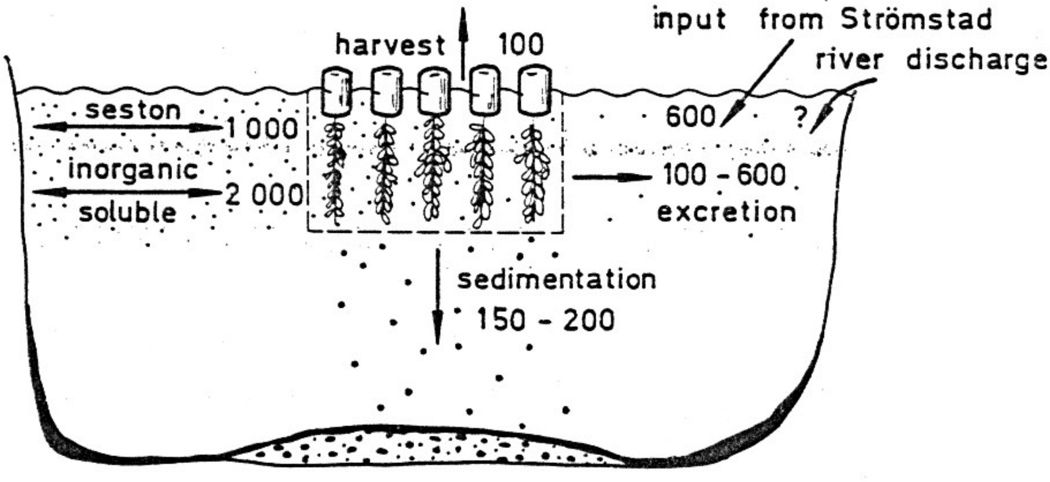


Figure 15. Phosphorus »budget».

Phosphorus in the mussel culture designed for 200 metric tons and its surroundings. Numbers indicate total quantities of phosphorus in kilogram during the period of cultivation (20 months). The calculations are explained in the text.

Interesting is that the phosphorus input from the city of Strömstad is just six times higher than the amount of phosphorus which is taken out by harvesting the mussel farm. Thus, anyhow as an intellectual experiment, it should be quite possible to absorb the sewage disposal by mussel farming. In this area a relatively small part is covered by cultures and the water renewal is good. Consequently we normally do not have any measurable effects of the nutrient excretion, which is small compared to the »natural» amounts. But, Fig. 15 indicates that, if the area will be more intense exploited, or if the water circulation will be poorer, then one has to take the question under reconsideration.

7.2 Water movements.

The inorganic nutrients of the incoming water as well as the nutrients from excretion are likely to be consumed by the phytoplankton during periods when radiation is enough. The total transport of soluble inorganic phosphorus by water movements is about ten times higher than the amount released by excretion. It is therefore reasonable to suppose that the intrusion and mixing by water from the other area or the effects of upwelling is of importance for the production of organic material in the area.

The water movements in the area, together with the food concentration are the most important factors limiting the size and the growth of a mussel culture. A typical speed of the water movements is given as 2.8 cm/s at 3 m depth. This is a weak current, and the mussels might have grown better by a higher water speed. Incze et al (1981) have offered a model for calculations of the energy need of a cultivated population. From this model the current velocity for different size of the culture and different seston concentrations can be calculated. Rosenberg and Loo (1983) discuss this for different seston concentrations and different current velocities. In our case with fourteen long-lines and the mean energy content in seston of 10 kJ/m^3, the current have to be 1 cm/s if the mussels should be able to maintain their metabolism.

Considerable differences in the production rate of the mussels in different areas of cultivation have been observed. The cultivation at Tjärnö have been compared to a similar cultivation further south (Wiight-Mäsak, 1982). Here the rate of growth is about twice that of the Tjärnö area during the same period. It is suggested that this is due to differences in current velocities beeing at least 2-3 times higher.

However, experiences by hard winds and by harvesting have shown that the falling off is much greater from the culture with higher production. Consequently it is suggested that a moderat typical mean current velocity of 2-6 cm/s is the most convenient for mussel farms with the technique used at the moment along the Swedish west coast.

7.3 Oxygen.

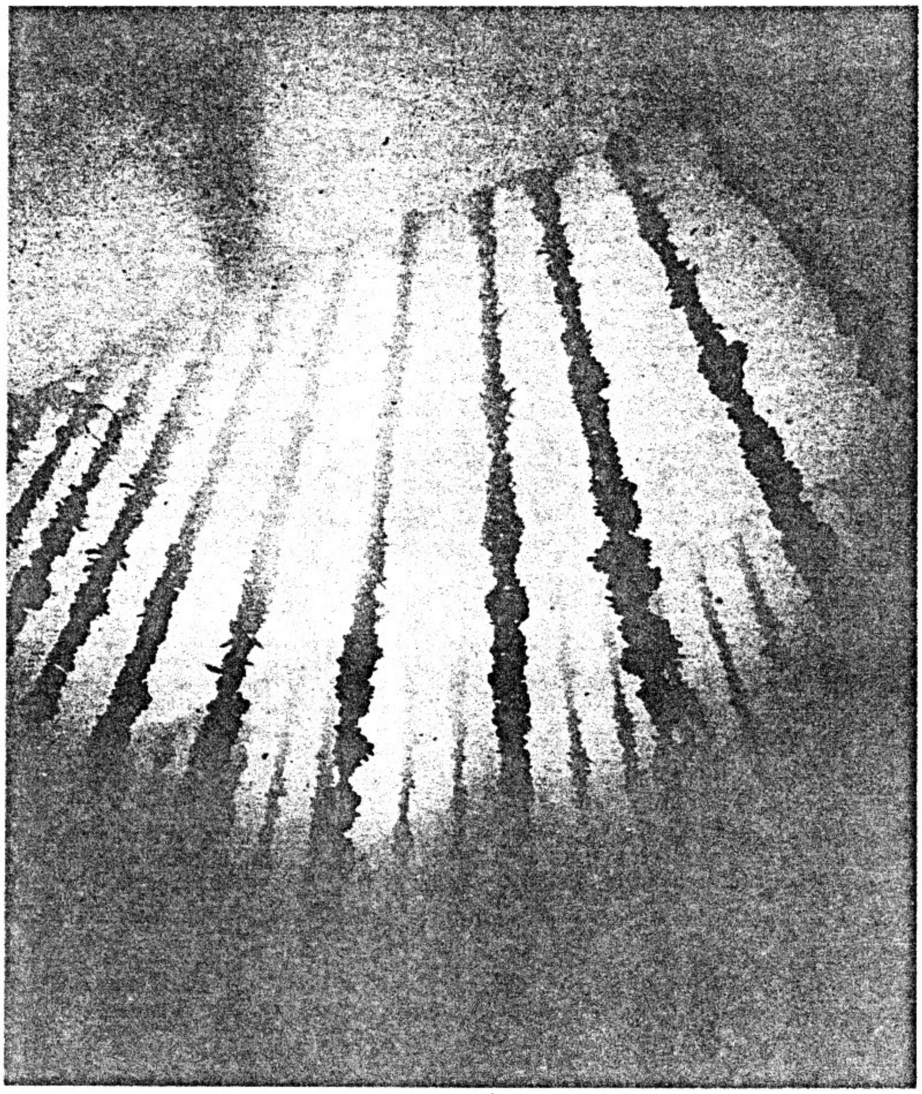
The increased rate of sedimentation under the mussel culture can, during some periods, cause anoxic conditions in the sediments (Dahlbäck and Gunnarsson, 1981) which will deteriorate the benthic fauna (Mattsson and Linden, 1983). This increased sedimentation of organic material does not give rise to anoxic conditions in the bottom water. Provided that there is no evidence for this in the undisturbed system, as for instance if the culture is located in surroundings with submarine holes. Our determination of the oxygen content in the water just above the sediment surface showed at least 65% saturation value. This in spite of anoxic sediments!

Besides the oxygen consumption by the mussel sediment the mussels also consume oxygen through respiration. The amount of respiration depends on the physiological status of the mussels and have a marked seasonal change. The reported ranges of consumption differ a lot, but oxygen consumption of 0.5 ml per hour for a grown-up mussel seems to be a high value (Bayne, 1976). At harvest there were 400 individes per meter band (Loo, Rosenberg 1982). In this culture with a volyme of $27 \cdot 10^6$ l and 30 000 m band there was an oxygen demand of 0.2 ml O_2/l h . The concentration of dissolved oxygen in the water was normally about 7 ml O_2/l. If the water is completly stagnant the oxygen content inside the culture will be sufficient for respiration of the mussels during 35 hours. When the water have the velocity of 1 cm s it will pass the culture in three hours. That is, new water is always transported to the culture fast enough not to deplete the oxygen concentration. There were no measurable differences of the oxygen between the water inside the culture and the outside water.

8 CONCLUDED REMARKS

The total amounts of phosphorus and nitrogen are decreased in the surface water of an area with mussel farms. At the harvest of the mussels phosphorus and nitrogen are taken out from the ecosystem. Also the increased sedimentation causes a removal or a delay of the recirculation of phosphorus and nitrogen. The mussels have a high efficiency of assimilation. This means that the particular material quickly will be decomposed and part of the nutrients will be transported back to the primary producers. Therefore mussel cultures act as a trap for phosphorus and nitrogen. This will increase the turnover time for nutrients, as these faster will be available for the primary producers. At the same time organic matter and thus phosphorus and nitrogen are withdrawn from the sea. The whole culture can be regarded as a large filtering system cleaning up the water followed by transportation to human food. Any local effects on inorganic nutrients and dissolved oxygen are highly determined by the nature of the water exchange in the area and by the extent of exploitation compared to the total water mass.

The sum up of the characteristics of a mussel culture, which has been given account for in this paper, must be that they cause positive ecological effects. In fact, they offer an unique opportunity to act against the eutrophication of the sea. Provided that they are of the proper dimensions and on the right locality. This optimum must be decided on in each specific case.



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