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Effect of reduced salinity on the great scallop (*Pecten maximus*) spat at two rearing temperatures

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Abstract

The effects of reduced salinity on scallop, *Pecten maximus*, spat of 1.7 mm shell height and 31.5 μg ash free dry weight were studied at 15 and 18 °C. Mortality, growth, byssus attachment, activity behaviour and clearance rate were studied at salinities of 30, 25 and 20 for a period of 25 days. The mortality of scallops held in salinities of 30 and 25 at 18 °C was 8%, which was significantly lower than for the spat kept at the other salinity–temperature combinations. Mean final mortalities at 15 °C were 59% for spat held at salinity of 20 and 25% for spat held at 25 and 30. At 18 °C and salinity of 20 final mortality was 26%. At salinity of 20, the increase in mortality rate commenced 1–2 weeks earlier at 15 °C than at 18 °C. Higher growth rates at temperature of 18 °C than at 15 °C were observed at salinities of 25 and 30. The shell of spat held in salinity of 20 became very thin and damaged easily, resulting in negative shell growth, while ash free dry weight growth was positive. No byssal attachments were observed in salinity of 20, and about 20% attachment occurred in 25. In salinity of 30 at 15 °C, the attachment rate decreased from 100% to 55%, while at 18 °C the attachment remained 83–97%. The general activity level was affected by low salinity as the foot movements decreased, the mantel retracted from the shell margin and gaping increased. Cultivation of scallop spat at sites influenced by brackish water (e.g., Norwegian polls) may result in high mortality when exposed to salinity lower than 25 and retarded growth may occur below 30. Locations exposed to salinities below 25 for an extended period should be avoided for nursery growth of *P. maximus* spat.

Keywords: *Pecten maximus*; Scallop spat, Growth; Mortality; Behaviour; Salinity; Temperature

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1. Introduction

Variations in salinity and temperature affect growth, survival and activity of marine species (Kinne, 1964). Oceanic organisms tend to be stenohaline compared to organisms living in coastal and estuarine habitats exposed to brackish water or aerial exposure. Pectinids in general, are less adapted to large environmental variations compared to bivalves like oysters, clams and mussels. The great scallop (*Pecten maximus*) is commonly found in sub-littoral areas on the eastern coast of the North Atlantic Ocean, where salinity and temperature are relatively constant. In farming situations scallops are often held at shallower depths and in more protected sites compared to natural conditions on the seabed, taking advantage of higher temperature and food availability. Cultivation sites at shallow depths in coastal waters, in landlocked basins or lagoons may occasionally be severely influenced by brackish water.

The tolerance to changes in salinity is affected by the ontogenetic and physiological stage of the scallop and further by environmental factors such as temperature (Paul, 1980a,b; Brand, 1991; Strand et al., 1993; Navarro and Gonzalez, 1998; O'Connor and Heasman, 1998). Byssus formation in pectinids appears to be extremely sensitive to environmental conditions (Brand, 1991), specifically to low salinity (Castagna and Chanley, 1973; Paul, 1980a; O'Connor and Heasman, 1998). The attachment rate therefore, has been suggested as a useful indicator of growth conditions for scallop spat (Paul, 1980a). Strand et al. (1993) studied the salinity tolerance of juvenile *P. maximus* (shell height, 30 mm) at 5 and 9 °C, and recommended scallop farming to be located in areas where the salinity seldom drops below 29. The tolerance to low salinity of post-larvae or early stage spat is, however, poorly known.

Optimisation of bivalve spat production is highly site and growth system-dependent (Claus et al., 1981). The great scallop (*P. maximus*) spat produced in a hatchery may be transferred to either a sea or land based nursery at a size of approximately 2-mm shell height for further growth. The period for successful transfer to the sea in temperate waters is limited by low temperature. In Norway transfer of *P. maximus* spat <2.6 mm to sea temperatures below 7 °C is shown to be fatal (Christophersen and Magnesen, 2001). The growth period in the sea is restricted to the months of higher temperature, and scallop spat need to be transferred in the period from June to August for the spat to reach a big enough size to survive the following winter in culture conditions.

One strategy to extend the spat production period is to use a landlocked heliothermic marine basin or "poll" as water supply and food production system for a land based nursery (Strand, 1996), allowing a 1- to 2-month earlier transfer of spat from the hatchery. In such an environment lower salinity and considerable higher temperatures, compared to sea conditions, are likely to occur (Gaarder and Bjerkan, 1934; Strand, 1996). Renewal of the poll water normally occurs during winter as saline and denser water from the fjord outside is allowed into the poll (Gaarder and Bjerkan, 1934). Due to mixing of the water from the fjord, typically holding a salinity of 33, and the poll water, a salinity of 30 is commonly found during spring (Gaarder and Spärck, 1932; Gaarder and Bjerkan, 1934; Strand, 1993). Runoff water and heavy rainfall may cause reduction in the salinity level during summer months (Strand, 1993). Exposure to low salinity may be of long-term duration and therefore knowledge about how reduced

salinity affect spat growth and survival at high temperatures is important for efficient management.

The objective of the present work was to investigate how growth, mortality and behaviour of small *P. maximus* spat are affected by nursery rearing conditions of low salinity and high temperature, which is likely to occur in shallow and landlocked coastal areas.

2. Materials and methods

The scallop (*P. maximus*) spat were obtained from hatchery production (Scalpro AS) at an age of 56 days post-spawn. The mean shell height was 1.7 mm (S.D.=0.2, range 1.4–2.3 mm) and the mean ash free dry weight was 31.5 μg (S.D.=1.9). The broodstock originated from a local *P. maximus* population in western Norway (60°N). Prior to being placed into experimental conditions in the hatchery, the spat were cultivated in a standard hatchery production environment. The spat were held in cylindrical sieves (height 15 cm, diameter 39.5 cm, 140 μm mesh as bottom) partly submerged in tanks (6×1×1 m) supplied with seawater from 70-m depth, and filtered through 1-μm bag filters. The rearing temperature was 15 °C and the food consisted of a mixture of monocultured algae, *Pavlova lutheri*, *Isochrysis galbana*, *Chaetoceros mülleri* and *Skeletonema costatum* in a 1:1:1:2 ratio. The algae were added continuously to the tanks maintaining a concentration of 10 cells μl^{-1}. Airlifts provided a downwelling flow of 1 l min^{-1} $sieve^{-1}$ and 83% of the water flowing through the tank was recirculated.

During the experimental period of 25 days, starting July 15 1997, the spat were exposed to combinations of three salinities—20, 25 and 30, and two temperatures—15 and 18 °C. The salinity of 30 was used as the control condition. A salinity of about 30 is normally encountered during spring in landlocked basins or "polls" (Gaarder and Spärck, 1932; Gaarder and Bjerkan, 1934; Strand, 1993). The spat were kept in experimental sieves made of PVC pipe (height 15 cm, diameter 25 cm, 300 μm mesh as bottom) in individual tanks (height 45 cm, diameter 40 cm), which in turn were placed in two water bath tanks (130×130×60 cm), one for each temperature. The sieves were submerged into 38 l of water down to 25 cm off the outer tank bottom. A downwelling flow of 1 l min^{-1} was maintained by an airlift system. Each of three replicate sieves of the six salinity–temperature combinations contained a number of 500 spat.

Seawater was obtained from 70-m depth and filtered through a 1-μm bag filter. The seawater was mixed with fresh tap water to make the experimental salinities. Salinity and temperature were measured daily with a WTW Microprocessor Conductivity Meter LF196 with WTW conductivity measuring cell TetraCon 96 A-4. Weekly measurements of pH were undertaken with an Aqualytic digimeter pH 21. The water in the experimental tanks was renewed every third day. Subsequent to water change, the spat were fed a mixture (1:1 cell/cell) of monocultured *S. costatum* and *I. galbana* at a concentration of 50 cells μl^{-1}. Equal amount of algae cells were supplied daily to every experimental tank providing concentrations of 25–75 cells μl^{-1}. The quantitative determination of algae was based on counting a sub-sample of cells using a Bürker counting chamber.

Mortality and attachment rate was registered at intervals of 2–5 days. Attachment rate (%) was calculated from a direct count of the number of spat attached to the mesh screen by byssus. Mortality was determined from observing detached animals under a dissection microscope. The dead scallops were counted, shell height measured and removed. Shell height was measured to the nearest 1 μm under a dissection microscope with a calibrated ocular micrometer. A spat was considered dead if the shell was empty or the body mass was disorganised together with lack of response when touched. The foot movements, mantel withdrawal from the shell margin, gaping and heartbeat frequency (beats per minute) of live scallops were examined for estimation of behavioural activity level. At the termination of the experiment the number of dead, live attached and detached individuals were counted.

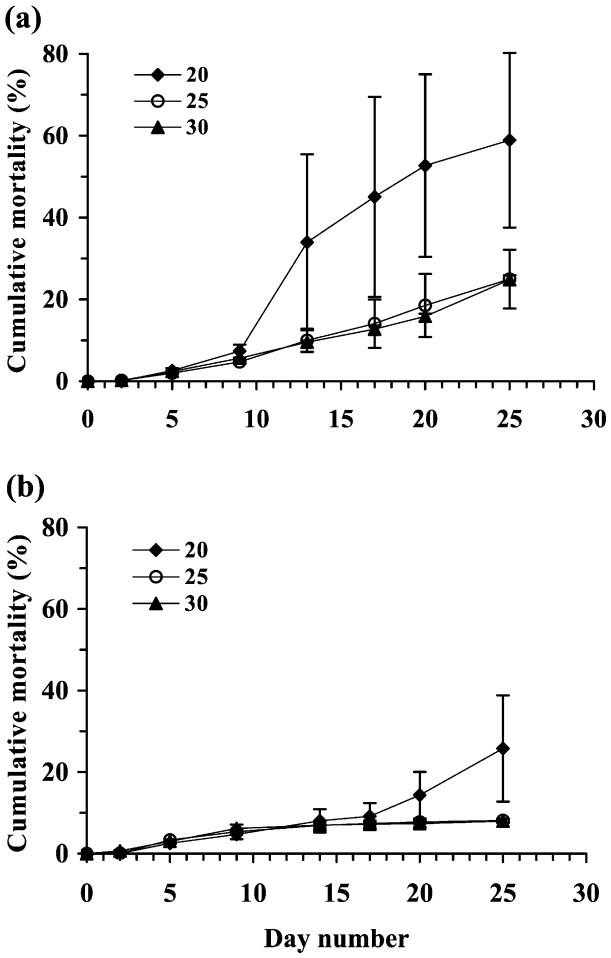

Fig. 1. Mean cumulative mortality of scallop spat reared at salinities of 20, 25 and 30 and temperatures of (a) 15 °C and (b) 18 °C. Vertical bars show standard error (n=3).

Sub-samples of 25 individuals were used for clearance and growth measurements. Spat from each experimental sieve were detached and removed by using a 2×5 cm piece of transparency film. The filtration studies were conducted on days 5 and 11 in 1-l glass bowls containing 600 ml of water. Air diffusers prevented the food algae from sedimentation. Clearance rate was estimated from the reduction of algae particles from the water during 24 h and using the indirect method for filtering rate determination (Coughlan, 1969). The initial concentrations of algae were 25–35 cells μl^{-1} of the same mixture as added to the experimental sieves. Particles ranging from 3.1 to 11.4 μm were counted initially and again after 24 h. A volume of 10 ml water was collected with a pipette and algae were counted in triplicate samples of 50 μl with an electronic particle counter (Coulter Counter Model ZM). The weight specific clearance rate (WCR) was calculated by using the equation $(\ln C_i/C_f \times V/nt)/\mathrm{AFDW}$, where C_i and C_f are the initial and final cell concentrations, V is the water volume, n the number of scallops, t the time and AFDW the ash free dry weight. Growth was estimated from measurements of shell height on individual spat and AFDW on the whole group of 25 spat, on days 0, 5, 11 and 23. Subsequent to shell height measurements, the spat were rinsed in fresh water and immediately frozen to −20 °C for later weight determinations using a Sartorius micro M3P balance. Total AFDW was determined by subtracting the total ash weight from the total dry weight after drying at 60 °C for 72 h followed by combustion at 490 °C for 6 h.

The mortality, growth and filtering data were analysed by using Statistica, version 5. Two-way analyses of variance (ANOVA) were performed and significant effects of temperature and salinity was further tested by the Tukey HSD test. The number of dead spat (N_d) were log (N_d+1) transformed prior to statistical analysis for obtaining variance homogeneity (Sokal and Rohlf, 1995). All the statistical tests were carried out at a 0.05 significance level.

3. Results

The mean salinities were 20.1 (S.D.=0.1), 25.0 (S.D.=0.1) and 30.0 (S.D.=0.2) throughout the experimental period. Temperatures were 15.4 (S.D. 0.4) °C and 18.0 (S.D. 0.8) °C, and pH was 7.9 (S.D. 0.14).

Mortality of the scallop spat was significantly influenced by salinity (p=0.007) and temperature (p=0.000). After 25 days' exposure to experimental conditions, the mortality

Table 1
Matrix of significant p values from Tukey HSD test for the mean mortality at day 25 of scallop spat reared at 15 and 18 °C and salinities of 20, 25 and 30

Temp/Salinity	15/20	15/25	15/30	18/20	18/25
15/25	ns				
15/30	ns	ns			
18/20	ns	ns	ns		
18/25	0.0038	0.0080	0.0031	0.0047	
18/30	0.0086	0.0185	0.0069	0.0107	ns

ns=not significant (p>0.05).

Table 2
Daily mean mortality (number±S.D., n=3) of scallop spat reared at 15 and 18 °C and salinities of 20, 25 and 30

Temperature [°C]	Salinity	Day interval						
		0–2	2–5	5–9	9–13/14	13/14–17	17–20	20–25
15	20	0.2±0.3	4.2±1.9	5.7±2.2	29.9±38.7	7.2±4.5	15.7±13.4	8.1±4.9
	25	0.5±0.5	3.0±0.3	3.3±0.5	5.9±5.1	4.6±6.0	6.7±4.7	5.5±1.5
	30	0.5±0.9	3.7±0.9	3.8±0.8	4.4±0.8	3.6±1.0	4.7±0.7	7.6±1.4
18	20	0.2±0.3	4.1±0.5	2.6±2.5	3.0±2.6	1.7±1.2	7.8±6.3	9.7±10.8
	25	0.2±0.3	5.4±0.2	2.4±0.6	1.4±0.3	0.7±0.6	0.6±0.5	0.3±0.3
	30	1.7±0.8	3.9±2.0	3.8±1.0	0.7±0.4	0.3±0.3	0.2±0.2	0.5±0.6

of scallops held in salinities of 30 and 25 at 18 °C was significantly lower than for the spat kept at the other salinity–temperature combinations (Fig. 1, Table 1). No significant difference in final mortality was found between the 18/25 and 18/30 spat groups, nor within the spat groups kept at 15 °C (Table 1). The ANOVA revealed a significant interaction between salinity and temperature (p=0.013).

Until day 9, the mean mortality was found to be less than 6 individuals per day for all treatments (Table 2). For scallops held at salinity of 20, a higher mean mortality rate commenced 1–2 weeks earlier at 15 °C (day 9) than at 18 °C (days 17–20) (Fig. 1, Table 2). The abrupt increases in mean mortality were, however, caused by mass mortality in only one of the three replicate experimental sieves. The mortality in the other sieves at salinity of 20 was within the same range as for spat kept at salinities of 25 and 30 (Table 2). Mean final cumulative mortality for the different temperature and salinity combinations was 59% for 15/20, 25% for 15/25 and 15/30, 26% for 18/20 and 8% for 18/25 and 18/30

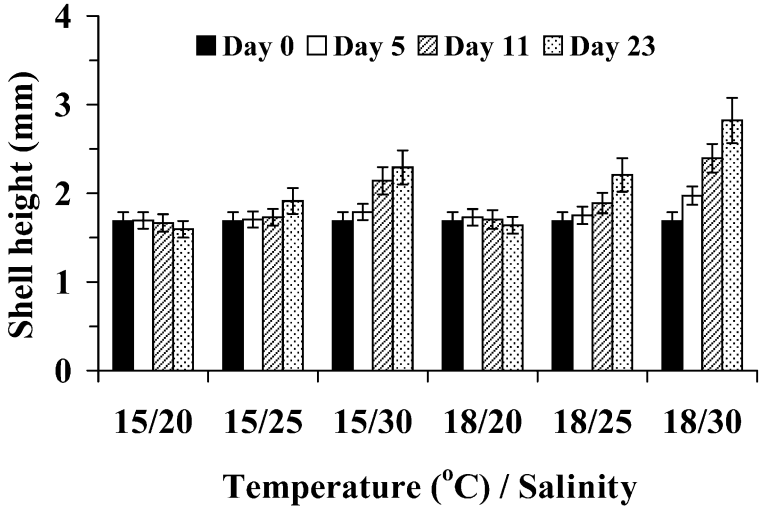

Fig. 2. Mean shell height of scallop spat reared at salinities of 20, 25 and 30 and temperatures of 15 and 18 °C. Vertical bars show standard error (n=3).

Table 3
Matrix of significant p values from Tukey HSD test for the mean shell height at day 23 of scallop spat reared at 15 and 18 °C and salinities of 20, 25 and 30

Temp/Salinity	15/20	15/25	15/30	18/20	18/25
15/25	0.0342				
15/30	0.0002	0.0051			
18/20	ns	0.0432	0.0002		
18/25	0.0004	0.0279	ns	0.0003	
18/30	0.0002	0.0002	0.0005	0.0002	0.0002

ns=not significant (p>0.05).

(Fig. 1). The shell height of dead scallops ranged from 1.2 to 2.7 mm and averaged 1.6, 1.8 and 1.9 mm in salinities 20, 25 and 30, respectively.

The shell growth of the spat was significantly affected by salinity and temperature (p=0.000), and a significant interaction was found between the two factors (p=0.006). The size successively increased with increased salinity at both temperatures (Fig. 2). The differences in mean shell height obtained on day 23 were significant between the salinities of 20, 25 and 30 within each temperature (Table 3). At salinities of 25 and 30, shell growth was higher at 18 °C than at 15 °C. The spat in the18/30 group showed significantly bigger size than all other groups from day 5 and onwards (Fig. 2). Maximum average size obtained was 2.3 and 2.8 mm for the 15/30 and 18/30 groups, respectively. Throughout the experiment there was no significant difference in shell height for spat held in salinity of 20 at either temperature, and the growth was retarded with time (Fig. 2). However, the shell of these spat was observed to become very thin and fragile, and therefore easily damaged.

Likewise for the shell growth, salinity (p=0.000) and temperature (p=0.007) had significant effect on the mean ash free dry weight (AFDW) growth of the spat. A positive

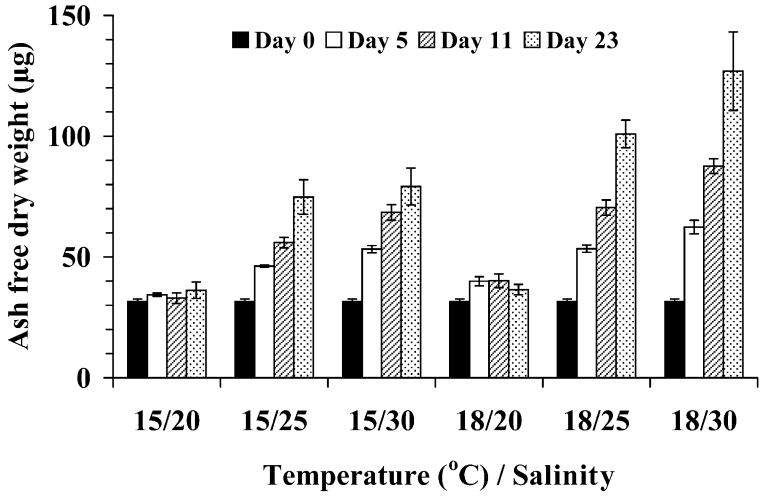

Fig. 3. Mean ash free dry weight of scallop spat reared at salinities of 20, 25 and 30 and temperatures of 15 and 18 °C. Vertical bars show standard error (n=3).

Table 4
Matrix of significant p values from Tukey HSD test for the mean ash free dry weight at day 23 of scallop spat reared at 15 and 18 °C and salinities of 20, 25 and 30

Temp/Salinity	15/20	15/25	15/30	18/20	18/25
15/25	ns				
15/30	ns	ns			
18/20	ns	ns	0.0461		
18/25	0.0066	ns	ns	0.0030	
18/30	0.0006	0.0136	0.0238	0.0003	ns

ns=not significant (p>0.05).

growth in AFDW took place for spat at every temperature and salinity combination in the period from days 0 to 23 (Fig. 3). The increase was approximately 5 μg for spat in salinity of 20 at both temperatures, while in salinity of 25 and 30 the increments were 43 and 48 μg in 15 °C and 69 and 95 μg in 18 °C. At 18 °C, the AFDW obtained was significantly lower for spat kept in salinity of 20 than for the spat held in salinity of 25 and 30 (Table 4). The 18/30 spat group differed significantly from any other group on days 5 and 11, but on day 23 the AFDW could not be distinguished from the 18/25 group (Table 4).

Mean weight specific clearance rate (WCR) decreased from day 5 to day 11 for the spat kept at salinity of 25 and 30 (Fig. 4). On day 11, the WCR increased with reduced salinity within each temperature treatment. No significant effect of temperature on WCR was found either on day 5 or 11, but a significant effect of salinity (p=0.022) was found on day 11.

Byssal attachment behaviour was clearly affected by salinity exposure rather than temperature conditions (Fig. 5). The difference in response between the experimental salinities was very distinct from day 2 and onwards. No attachments were observed in

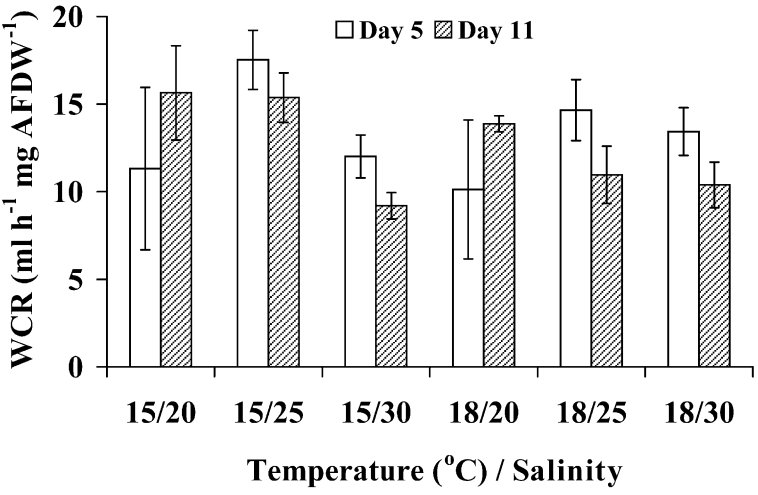

Fig. 4. Mean weight specific clearance rate of scallop spat reared at salinities of 20, 25 and 30 and temperatures of 15 and 18 °C. Vertical bars show standard error (n=3).

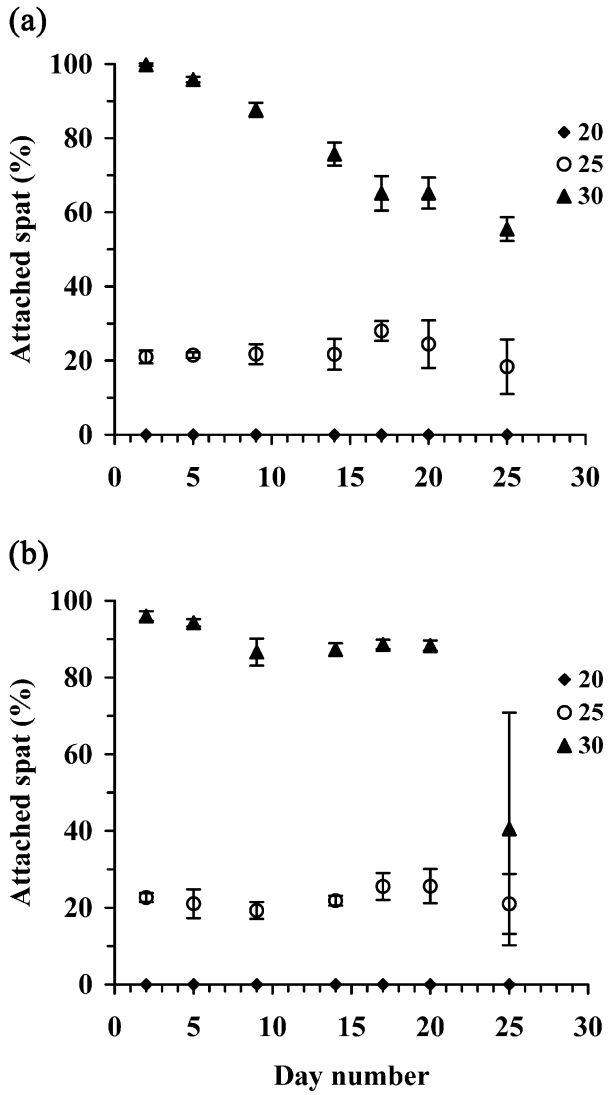

Fig. 5. Mean byssus attachment rate of scallop spat reared at salinities of 20, 25 and 30 and temperatures of (a) 15 °C and (b) 18 °C. Vertical bars show standard deviation (n=3).

salinity of 20 for any of the two temperatures. In water of salinity 25 the mean attachment rate ranged from 18% to 28% throughout the experimental period. The attachment rate decreased with time in water of salinity 30 and 15 °C (Fig. 5a). During the first 20 days, the attachment rates in 18 °C were within the range of 83–97%. On day 25, the number of attached spat varied greatly among the replicates in the 18/30 sieves, resulting in a dramatic reduction in mean attachment rate (Fig. 5b). At the end of the experiment, there was no difference in shell height between live detached and attached spat.

Activity behaviour was in general affected by reduced salinity. Relatively few or no movements of the foot were observed in scallops exposed to salinity of 20, compared to observed activity for scallops reared in salinity of 25 and 30. The scallops kept at salinity of 20 showed retraction of the mantle during the whole period. In salinities 25 and 30, withdrawal of the mantel edge was found on days 2 and 5, but was extended, to or beyond the shell margin, from day 9 on. No gaping was observed in salinity of 30, but in 25 0–10% of the scallops performed gaping. In salinity of 20, the number of gaping animals increased with time. On day 2, there were no gaping scallops, day 5 approximately 10% and from day 9 to the end, 10–35% showed this behaviour. The registered heartbeat frequency showed a response to salinity at day 2 that was kept throughout the growth period. The trend was towards an increase in heartbeats per minute with salinity, and the counts were in the order of 24–72, 54–78 and 60–84 in salinity of 20, 25 and 30, respectively.

4. Discussion

A reduction in salinity was in the present study shown to affect mortality, growth and behaviour of small *P. maximus* spat. The mortality of scallops held in salinities of 30 and 25 at 18 °C was 8% after 25 days, which was significantly lower than for the spat kept at the other salinity–temperature combinations. Growth in terms of shell and AFDW increase was severely affected by the reduction in salinity. The salinity of 20 was shown detrimental to shell production, which indicates that the lower extreme of the salinity tolerance range for 2-mm *P. maximus* spat was encountered. The effect of reduced salinity on byssal attachment and activity behaviour was evident, while in regards to clearance rate the influence of low salinity was less pronounced.

Salinity and temperature clearly interfere with each other inasmuch as significant interaction was found for both the differences in final cumulative mortality and shell height. Increased salinity resulted in enhanced growth at both temperatures studied. Growth at salinities of 25 and 30 was faster at 18 °C than at 15 °C. A synergetic effect of the two environmental parameters therefore was apparent.

The scallops in our study were less affected by reduction in salinity at 18 °C than at 15 °C. In contrast, the scallop *Chlamys opercularis* showed decreased tolerance to low salinity with increased temperature in the range from 5 to 20 °C (Paul, 1980a). Likewise, the scallop *Argopecten irradians* is shown to suffer the greatest mortality in combinations of low salinity and high temperatures of 19 and 24 °C (Mercaldo and Rhodes, 1982). The improved growth shown for spat kept at the highest temperature in our study indicates that the upper limit where temperature affects physiological processes important for salinity tolerance, is not reached at 18 °C. Laing (2000) showed decreased condition (ratio of dry meat weight to dry shell weight) of *P. maximus* spat (5–14 mm) grown outside a temperature range of 10.3–17.2 °C. The experimental temperatures of 15 °C and 18 °C used in our study, therefore should have been within the range that ensures good growth. Low temperatures also affect tolerance to low salinity. Significant lower tolerance to reduction in salinity is shown for juvenile *P. maximus* (30 mm) held at 5 °C compared to scallops held at 9 °C (Strand et al., 1993).

A salinity of 20 had serious impact on the scallop spat with degeneration of the shell, absence of byssus formation and suppressed growth and behavioural activity. Poor development of the shell is in accordance with other findings that structural properties like shell growth of molluscs are affected by low salinities (reviewed in Kinne, 1964). The responses to low salinity, as shown for the scallop spat in our study, are consistent with reactions shown for bivalves subjected to other sub-optimal environmental conditions. For instance, similar symptoms are described for oysters and mussels exposed to low pH (Bamber, 1990), and reduced behaviour activity following air emersion stress is shown for larger *P. maximus* scallops (Minchin et al., 2000).

One evident effect of reduced salinity was found on the attachment rate. No attachments were observed in salinity of 20 while in salinity of 30, rates up to 100% was monitored. At salinity of 30, the attachment rate during the second half of the experimental period was higher at 18 °C than at 15 °C. Decrease in attachment rate between day 9 and day 17 in the 15/30 spat group also coincided with increased mortality. The reduction in number of feeding scallops may have caused overloading of algae and accumulation of organic matter, which, in turn, could have changed the environmental conditions affecting attachment. In the same way, this could explain the dramatic fall in numbers of settled spat at 18 °C the final experimental day.

According to the assumption that attachment rates mirror favourable growth conditions (Paul, 1980a,b), our results shows that salinities of 20 and 25 are sub-optimal for *P. maximus* spat growth. The low attachment rates at salinity of 25, while maintaining a relatively high survival and growth, indicates that energy is being expended on other processes than byssus formation. Marine bivalves from inshore and estuarine environments have been found to require a higher salinity for byssus production than is necessary for other activities (Castagna and Chanley, 1973). Rapid initial attachment, together with high and stable attachment rates, are found for scallops in temperature and salinity conditions where high growth and survival occur (Paul, 1980b; Heasman et al., 1996; O'Connor and Heasman, 1998). The number of reattached *P. fumatus* spat declined from a high level to 50% and less after 4 weeks at sub-optimal growth temperatures (Heasman et al., 1996). Likewise, Paul (1980b) found the maximum byssus attachment for *C. opercularis* to be temperature-dependent, with attachment rate to decline and becoming more variable at higher and lower temperatures than the optimal temperature of 18 °C.

At salinity of 20, there was a clear difference in growth response as the tissue weight increased while the shell height was reduced during the experimental period. Navarro and Gonzalez (1998) demonstrated that reduction in salinity affected physiological processes like clearance rate, absorption, oxygen uptake and excretion of the scallop *A. purpuratus*. They observed negative scope for growth values at salinities below 27, which implies that growth is highly affected by salinity stress (Navarro and Gonzalez, 1998). The positive AFDW growth found in salinity of 20, in contrast to the negative shell growth, may indicate that heavily stressed scallops use the energy to maintain soft parts instead of producing shell.

In our study, the scallop spat were directly transferred from high to low salinity. The abrupt change in salinity itself could possibly have affected the spat in a more adverse way, than if a more gradual adaptation to reduced salinity had been allowed. Juvenile scallops are shown to survive short-term, low-salinity exposure (Mercaldo and Rhodes, 1982;

Bergman et al., 1996), while rapid and dramatic falls in salinity which might happen in nature, for instance, during heavy rainstorms, have resulted in mass mortality of bay scallops (Tettelbach et al., 1985). Nevertheless, successful survival is recorded for several bivalves after direct transfer to salinity 10–15 lower than at the collection sites (Castagna and Chanley, 1973), which is comparable to the salinity steps in our study. For other species studied by Castagna and Chanley (1973), a rapid change in salinity of 15 was, however, observed to be lethal. In general, oceanic species show limited capacity for tolerance, regulation and adaptation to salinity stress in comparison to brackish or hypersaline forms (Kinne, 1964). The severe impact the salinity of 20 had on the scallops in the present study, therefore, could well have been caused by the abrupt salinity change.

Changes of salinity might have caused osmotic shock reactions, especially to the spat transferred to salinity of 20. Gill cilia activity is reported to reflect the osmotic resistance, as ciliary activity stops in too low salinity (Vernberg et al., 1963; Ventilla, 1982). Despite severely retarded growth and behavioural activity, the spat kept at low salinity in our study did not suffer 100% mortality within the experimental period. This indicates that the *P. maximus* spat are able to acclimate to reduced salinity. Scallops, like other marine bivalves, are demonstrated to be osmoconformers although the ability to adjust to ambient salinity may be restricted within a salinity tolerance range (Shumway, 1977; Singnoret-Brailovsky et al., 1996). For other bivalve species, it has been found that acclimation is a useful method to increase the tolerance to extreme salinities (Chanley, 1958; Castagna and Chanley, 1973). Scallop cultivation is, however, broadly recommended to take place at sites of high salinity and with a low rate of salinity fluctuations (Mercaldo and Rhodes, 1982; Strand et al., 1993; Bergman et al., 1996; Singnoret-Brailovsky et al., 1996; Navarro and Gonzalez, 1998; O'Connor and Heasman, 1998).

No difference in weight specific clearance rate (WCR) was found after 5 days at salinities and temperatures studied. The effect of salinity found after 11 days might be related to differences in the size of the spat. A decrease in WCR with size has been demonstrated for 2–9 mm *A. irradians concentricus* spat (Lu and Blake, 1997) and *P. maximus* from 6 to 63 mm (H. Skjæggestad, personal communication). Accordingly, the larger spat kept at salinity of 30 in our study performed lower mean WCR than the spat kept at salinities of 25 and 20. The clearance rates varied from 9 to 18 ml h^{-1} mg $AFDW^{-1}$, which are considerably lower than clearance rates of 35–153 ml h^{-1} mg $AFDW^{-1}$ achieved by 2-mm bay scallop spat in the study of Lu and Blake (1997). This might be due to species differences and metabolism at different temperatures. The spat were allowed to filter for 24 h in our experiment, which could have contributed to a deterioration of the water quality. A change in the water environment may have affected the feeding activity. A peak in the filtering rate could well have been camouflaged by a time lag during the first hours after transfer and a lowering in food uptake in the last. Optimal food concentrations for early scallop stages are suggested 10–20 cells μl^{-1} (Lu and Blake, 1996; H. Skjæggestad, personal communication). Our food supply was in abundance and may have depressed the WCR.

This study clearly shows that growth, mortality and behaviour of early stage *P. maximus* spat are affected by rearing conditions of low salinity and high temperature likely to be met in shallow coastal systems. Nursery locations exposed to salinities below 25 for an extended period are not to be recommended. Retarded growth may occur at

salinity below 30. Consequently, scallop spat should be kept in water of high salinity not less than 30 to provide optimal conditions for cultivation.

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References

Bamber, R.N., 1990. The effects of acidic seawater on three species of lamellibranch mollusc. J. Exp. Mar. Biol. Ecol. 143, 181–191.

Brand, A.R., 1991. Scallop ecology: distribution and behaviour. In: Shumway, S.E. (Ed.), Scallops: Biology, Ecology and Aquaculture. Dev. Aquacult. Fish. Sci., vol. 21. Elsevier, Amsterdam, Netherlands, pp. 517–584.

Bergman, C., Parsons, J., Couturier, C., 1996. Tolerance of the giant sea scallop, *Placopecten magellanicus*, to low salinity. Bull. Aquacult. Assoc. Can. 96-3, 62–64.

Castagna, M., Chanley, P., 1973. Salinity tolerance of some marine bivalves from inshore and estuarine environments in Virginia waters on the western mid-Atlantic coast. Malacologia 12, 47–96.

Chanley, P.E., 1958. Survival of some juvenile bivalves in water of low salinity. Proc. Natl. Shellfish Assoc. 48, 52–65.

Christophersen, G., Magnesen, T., 2001. Effects of deployment time and acclimation on survival and growth of hatchery-reared scallop (*Pecten maximus*) spat transferred to the sea. J. Shellfish Res. 20(3), 1043–1050.

Claus, C., De Pauw, N., Jaspers, E. (Eds.), 1981. Nursery Culturing of Bivalve Molluscs. Eur. Maricult. Soc. Spec. Publ., No. 7. Bredene, Belgium, 394 pp.

Coughlan, J., 1969. The estimation of filtering rate from the clearance of suspensions. Mar. Biol. 2, 356–358.

Gaarder, T., Bjerkan, P., 1934. Østers og østerskultur i Norge. John Griegs Boktrykkeri, Bergen (in Norwegian), 96 pp.

Gaarder, T., Spärck, R., 1932. Hydrographisch–biochemische Untersuchungen in norwegischen Austern-Pollen. Bergens Mus. Årbok, Naturvidensk. Rekke 1, 144 pp.

Heasman, M.P., O'Connor, W.A., Frazer, A.W.J., 1996. Ontogenetic changes in optimal rearing temperatures for the commercial scallop, *Pecten fumatus* Reeve. J. Shellfish Res. 15, 627–634.

Kinne, O., 1964. The effects of temperature and salinity on marine and brackish water animals. II. Salinity and temperature salinity combinations. Oceanogr. Mar. Biol. Annu. Rev. 2, 281–339.

Laing, I., 2000. Effect of temperature and ration on growth and condition of king scallop (*Pecten maximus*) spat. Aquaculture 183, 325–334.

Lu, Y.T., Blake, N.J., 1996. Optimum concentrations of *Isochrysis galbana* for growth of larval and juvenile bay scallops, *Argopecten irradians concentricus* (Say). J. Shellfish Res. 15, 635–643.

Lu, Y.T., Blake, N.J., 1997. Clearance and ingestion rates of *Isochrysis galbana* by larval and juvenile bay scallops, *Argopecten irradians concentricus* (Say). J. Shellfish Res. 16, 47–54.

Mercaldo, R.S., Rhodes, E.W., 1982. Influence of reduced salinity on the Atlantic bay scallop *Argopecten irradians* (Lamarck) at various temperatures. J. Shellfish Res. 2, 177–181.

Minchin, D., Haugum, G., Skjæggestad, H., Strand, Ø., 2000. Effect of air exposure on scallop behaviour, and the implications for subsequent survival in culture. Aquacult. Int. 8, 169–182.

Navarro, J.M., Gonzalez, C.M., 1998. Physiological responses of the Chilean scallop *Argopecten purpuratus* to decreasing salinities. Aquaculture 167, 315–327.

O'Connor, W.A., Heasman, M.P., 1998. Ontogenetic changes in salinity and temperature tolerance in the doughboy scallop, *Mimachlamys asperrima*. J. Shellfish Res. 17, 89–95.

Paul, J.D., 1980a. Salinity–temperature relationships in the Queen scallop *Chlamys opercularis*. Mar. Biol. 56, 295–300.

Paul, J.D., 1980b. Upper temperature tolerance and the effects of temperature on byssus attachment in the Queen scallop, *Chlamys opercularis* (L.). J. Exp. Mar. Biol. Ecol. 46, 41–50.

Shumway, S.E., 1977. Effect of salinity fluctuation on the osmotic pressure and Na^{+}, Ca^{2+} and Mg^{2+} ion concentrations in the hemolymph of bivalve molluscs. Mar. Biol. 41, 153–177.

Singnoret-Brailovsky, G., Maeda-Martinez, A.N., Reynoso-Granados, T., Soto-Galera, E., Monsalvo-Spencer, P., Valle-Meza, G., 1996. Salinity tolerance of the catarina scallop, *Argopecten ventricosus-circularis* (Sowerby II, 1842). J. Shellfish Res. 15, 623–626.

Sokal, R.R., Rohlf, F.J., 1995. Biometry: the Principles and Practice of Statistics in Biological Research, 3rd edn. Freeman, New York, 887 pp.

Strand, Ø., 1993. Enhancement of bivalve production capacity in Norwegian heliothermic polls. Dr. Scient. Thesis, University of Bergen, Norway, 144 pp.

Strand, Ø., 1996. Enhancement of bivalve production capacity in a landlocked heliothermic marine basin. Aquacult. Res. 27, 355–373.

Strand, Ø., Solberg, P.T., Andersen, K.K., Magnesen, T., 1993. Salinity tolerance of juvenile scallops (*Pecten maximus* L.) at low temperature. Aquaculture 115, 169–179.

Tettelbach, S.T., Auster, P.J., Rhodes, E.W., Widman, J.C., 1985. A mass mortality of northern bay scallops, *Argopecten irradians irradians*, following a severe spring rainstorm. Veliger 27, 381–385.

Ventilla, R.F., 1982. The scallop industry in Japan. Adv. Mar. Biol. 20, 309–382.

Vernberg, F.J., Schlieper, C., Schneider, D.E., 1963. The influence of temperature and salinity on ciliary activity of excised gill tissue of molluscs from North Carolina. Comp. Biochem. Physiol. 8, 271–285.