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EFFECTS OF DEPLOYMENT TIME AND ACCLIMATION ON SURVIVAL AND GROWTH OF HATCHERY-REARED SCALLOP (*PECTEN MAXIMUS*) SPAT TRANSFERRED TO THE SEA

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ABSTRACT Hatchery-produced great scallop (*Pecten maximus*) spat of 1 to 5 mm shell height were transferred to a sea-based nursery from March to August 1995. Because the growth season in Norwegian waters is limited by low sea temperature in the spring (5°C–10°C), acclimation to a colder temperature (10°C) than the 15°C in the hatchery was considered in order to enhance survival after deployment. Survival and growth of spat deployed directly to the sea were compared with spat acclimated for 1 and 3 wk. Results indicated that specific growth rates were 1% to 3% per day. Mean survival of acclimated groups was 0% to 9% for small spat (0.7–2.3 mm) and 25% to 36% for bigger spat (4 mm). Acclimation improved mean survival by up to 7% of the small spat and 11% of the bigger spat. An extension from 1 to 3 wk acclimation did not further improve survival or growth. Duration of exposure to low temperatures (<10°C) and temperature at deployment time were main factors affecting survival and growth considering all spat groups, while size at deployment mainly determined the success for acclimated scallops. Less than 5% of the smallest spat survived when directly transferred to sea temperatures of 5°C to 7°C. Larger spat obtained 25% mean survival, which is comparable with 24% to 60% survival of spat transferred to sea temperatures ≥10°C. Shell growth rate likewise was elevated when the temperature exceeded 10°C. Acclimation to a lower temperature gave only limited increase in survival, and it was determined that small spat (<2.6 mm) should not be transferred to temperatures <7°C. By deploying bigger spat (>4 mm) to low sea temperatures, high survival can be expected, and thereby the production period is extended.

KEY WORDS: acclimation, nursery culture, *Pecten maximus*, scallop spat, survival, growth

INTRODUCTION

Stable spat supply to growers is the main constraint in the development of a scallop cultivation industry. Due to overfishing of scallop populations around the world, and to the fact that scallops are high-value products, the establishment of hatcheries for ensuring a reliable production of spat has become important to the industry. Intensive larval growth in a hatchery is usually followed by growth to commercial-sized spat in semi-intensive growth systems termed "nurseries." A nursery can be sea- or land-based, depending on natural seawater supply or cultured algae as a food source. In cold water areas like the North Atlantic, the growth season in the sea is limited by environmental factors such as the low temperature in the spring. The longer the period of the year in which scallops can take advantage of the natural food production, the more beneficial it is to producers. Making spat available earlier in the year and providing growers with larger spat at the optimum time in the growth season would ease the constraint.

Scallops are shown to be susceptible to small changes in temperature (Dickie & Medcof 1963, Strand et al. 1993, Chauvaud et al. 1998), but their tolerance limits varies with species and natural habitat (Brand 1991). Scallops are more sensitive to environmental changes compared with intertidal bivalves like mussels, oysters, and clams because they are not able to completely close their valves when encountering unfavorable conditions. Changes in temperature may have a direct or indirect impact on survival. Temperature drops of 4°C to 7°C have been shown to cause immobility of sea scallops, which in their natural environment could increase vulnerability to predators and thereby increase mortality (Dickie 1958). Abrupt and considerable changes in environmental conditions are likely to occur in an aquaculture situation during handling and transfer operations. The transfer from hatchery conditions to colder temperature conditions in the sea for nursery growth may therefore be hazardous.

In culture, both the thermal and the nutritional conditions will affect scallop growth performance (Ventilla 1982, Wallace & Reinsnes 1985, Andersen & Naas 1993, Couturier et al. 1995, Pilditch & Grant 1999, Grecian et al. 2000). Exposure to cold water temperatures of <10°C have been shown critical for the great scallop, *Pecten maximus,* at different stages. High mortality of veliger larvae occurs at 7°C to 8°C, and at 5°C, total mortality may be expected (Davenport et al. 1975, Beaumont & Budd 1982). For *P. maximum* juveniles of 20 to 30 mm shell height (SH), a reduction in filtration rate of 50% to 80% was recorded at 5°C compared with 9°C (Strand et al. 1993), and Laing (2000) found no growth or measurable uptake of food at 4.7°C by 5 to 14 mm spat. A 100% mortality at <4°C is reported from growth trials in suspended intermediate culture in Norway (Brynjelsen & Strand 1996), while a temperature of 9°C is suggested as a "biological zero" for shell growth in Irish waters (Wilson 1987).

Acclimation may be a successful way to adjust an animal to different conditions. A three-phase process consisting of an immediate response, a stabilization of this response, and a new steady state can explain the adaptation to new surroundings (Kinne 1963). Studies of the sea scallop have indicated that a rise or fall in acclimation temperature of about 5°C may result in a corresponding change in lethal temperature of 1°C (Dickie 1958). The rate of acclimation tends to follow the rate of metabolism, resulting in longer time needed for acclimation to a decrease in temperature than an increase. The animals' environmental history, genetic background, physiological condition, metabolism, age, and size are all factors affecting the capacity, rate, and effect of thermal acclimation (Kinne 1963, Schmidt-Nielsen 1990).

One method for producing *P. maximus* spat in Norway is intensive hatchery rearing to approximately 2 mm SH at a temperature of 15°C, before further growth to 15 mm in a sea-based nursery. Transfer to the sea is restricted to the period from June to August for the spat to reach a commercial size within one season. A prolonging of the production period would be possible if a method was found to successfully transfer the spat to the sea earlier in the spring when the temperature is low. The prevailing method of transferring spat from the hatchery is by directly deploying the spat to the sea. Acclimation of spat to an environment of 10°C with subsequent transfer to temperatures between 5°C and

10°C was considered a possible solution to ensure that scallop spat would tolerate transfer to the sea during the spring.

The aim of this study was to determine whether exposing the spat to a temperature between the hatchery and the sea temperature, before transfer to the sea in the spring, could enhance survival. Spat groups that had been subjected to the prevailing production method of directly deployment to the sea were monitored throughout the season, and survival and growth rates were compared with spat groups acclimated for 1 and 3 wk.

MATERIALS AND METHODS

The study was carried out during spring and summer 1995 in Øygarden, Hordaland County, western Norway, with spat originating from broodstock collected from the wild. During the period from October 1994 to June 1995, groups of 40 to 60 scallops were conditioned, induced to spawn, and cross-fertilized. Spat of 1 to 5 mm SH were obtained by standard production methods at Øygarden Scallop Hatchery. Survival and growth of spat from 10 different spawning groups (1–10) were determined after deployment to the sea throughout the production season. Spat from spawning groups 3 through 6 were subjected to acclimation treatments for 1 and 3 wk before transfer to the sea (Table 1). For some of the spawning groups, more spat groups of different age and size (A, B, and C) were deployed (Table 1).

Prior to deployment, the spat were removed from 140-μm mesh screens, which served as bottom of cylindrical growth containers or sieves (1,225 cm^2), by gentle brushing in a flow of water, and they were relayed onto plastic trays (60 × 60 × 8 cm) covered with 500 μm mesh. The trays were kept overnight in running seawater, allowing resettlement of the spat. Stacks of four trays, consisting of three experimental trays plus one as lid, were suspended from long lines in the sea at a depth of 8 to 10 m. Grow-out in the sea was within the period from March 1 to September 29 (Table 1). The growth time varied according to deployment date, as the spat grew to a size of 5 to 10 mm, big enough for grading and restocking.

Acclimation took place under conditions of lower temperature and food concentration than were used prior to the treatment. The spat were kept at 10°C and were fed 10 cells per μl of a mix of the monocultured algae *Pavlova lutheri*, *Isochrysis galbana*, and *Skeletonema costatum* in a 1:1:2 ratio, compared with 15°C and 15 to 20 cells per μl, respectively. The spat groups (3, 4A, 4B, 5, and 6A) subjected to acclimation were divided into three subgroups, each consisting of three sieves. One subgroup was deployed directly to the sea without acclimation. The second subgroup was deployed after 1 wk of exposure to acclimation conditions, and the third was transferred after 3 wk of acclimation. Because of limitations in the hatchery, the spat were transferred directly from hatchery conditions to acclimation conditions without a gradual habituation to the lower temperature.

Survival was estimated as the difference in numbers of animals at deployment time and the numbers retained on a 3-mm screen after 52 to 134 days grow-out in the sea. The initial number in each sieve was estimated by counting the spat of a 50 × 1 cm^2 (4%) area of the mesh bottom and multiplying to the total area. The final numbers were estimated by wet weight measurements based on counting subsamples of 100 spat from the trays.

TABLE 1.

Age, size, density, temperature, and grow-out time in the sea of cultivated scallop spat deployed directly to the sea from the hatchery (0), or transferred after 1 or 3 wk acclimation to a temperature of 10°C.

Spat Group	Acclimation (wk)	Trays Deployed (no.)	Deployment Date in 1995	Age at Deployment (days)	Size at Deployment (mm)	Density at Deployment (no. cm^{-2})	Sea Temperature at Deployment (°C)	Grow-Out Time (days)
1	0	3	Mar 01	131	2.6	2.8	5.9	133
2	0	3	Mar 01	106	2.6	3.1	5.9	134
3	0	3	Mar 01	86	2.3	3.0	5.9	133
	1	3	Mar 06	91	2.2	2.8	5.7	128
	3	3	Mar 21	106	2.0	3.6	5.1	113
4A	0	3	Mar 21	56	1.1	2.6	5.1	113
	1	3	Mar 29	64	1.3	2.7	5.3	107
	3	3	Apr 11	77	1.7	2.9	5.6	93
5	0	3	Apr 11	56	0.7	2.7	5.6	93
	1	3	Apr 20	65	0.9	2.4	5.5	85
	3	3	May 04	79	1.2	2.1	7.0	71
6A	0	3	Apr 11	56	0.8	2.8	5.6	92
	1	3	Apr 20	65	1.3	2.9	5.5	85
	3	3	May 04	79	1.6	2.9	7.0	71
4B	0	3	Apr 28	94	4.0	3.3	6.2	77
	1	3	May 04	100	4.0	4.0	7.0	71
	3	3	May 18	114	4.3	3.4	7.1	68
6B	0	2	May 31	106	3.6	2.5	10.0	55
4C	0	2	May 31	127	5.6	1.7	10.0	55
6C	0	2	May 31	106	5.0	1.7	10.0	55
7	0	3	Jun 20	63	1.7	1.9	11.5	57
8	0	3	Jun 22	51	1.6	3.2	11.5	55
9	0	3	Aug 01	63	1.9	2.4	12.8	59
10	0	3	Aug 08	56	1.5	2.7	13.0	52

Growth in the sea was based on mean SH measurements of 50 animals from each sieve at deployment time and from each tray at uptake date. Spat growth during the acclimation period was also measured. Final size of the bigger (4B, 4C, 6B, and 6C) deployed spat was determined by using the weighted average of means from two size groups (3–10 mm and >10 mm). SH growth was calculated as specific growth rate (% day^{-1}): $G = (e^g - 1) \times 100$, where the instantaneous daily growth coefficient $g = (\ln SH_{final} - \ln SH_{initial})$ per days (Ricker 1979, Claus 1981).

Sea temperature and salinity were measured weekly with a WTW Microprocessor Conductivity Meter (LF196) (Wissenschaftlich-Technische Werkstätten G.M.B.H. D-8120, Weilheim, Germany) connected with a WTW conductivity-measuring cell (TetraCon 96 A-4). Food concentration in the sea was measured occasionally using an electronic particle counter (Model ZM Coulter Counter, Coulter Electronics Limited, Luton, England).

The statistical analyses were carried out using STATISTICA®, version 5, and a significance level of 0.05 was applied to the tests. Analysis of variance (ANOVA) was performed on the growth and survival data of the spat that were acclimated, and treatments showing significant differences were further characterized by the Tukey HSD test. The survival data (percentage) of the spat were arcsine transformed before statistical analysis to obtain variance homogeneity for all groups (Sokal & Rohlf 1995). Pearson product-moment correlation coefficients were calculated for shell parameters and grow-out conditions in the sea. Multiple forward stepwise regression analysis was performed for all the spat groups transferred to the sea and for acclimated groups separately. Survival (percentage) and specific growth (percentage per day) were related to the variables; acclimation time, size, density, and sea temperature at deployment time, and the period of exposure to temperatures <10°C during grow-out in the sea.

RESULTS

Seawater Conditions

Sea temperature at the grow-out depth of 8 m increased from 5°C to 15°C during the experimental growth period (Fig. 1). The temperature reached 7°C in the beginning of May and exceeded 10°C in June. Salinity varied between 30 and 33 with occasional drops below 30%. A salinity of 27.6 was the lowest recorded during the period from June to October (Fig. 1). The number of 2- to 10-μm particles at 8 m was below 10 cells per μl in March and April. In the beginning of July, the natural food production had increased, and 50 cells per μl was measured.

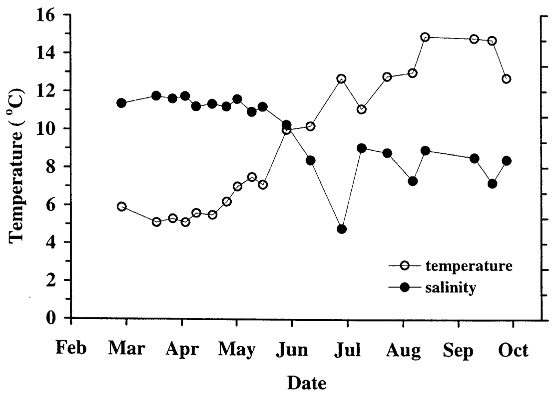

Figure 1. Temperature and salinity at 8 m grow-out depth during the 1995 season, Ulvesundet, Øygarden, Norway.

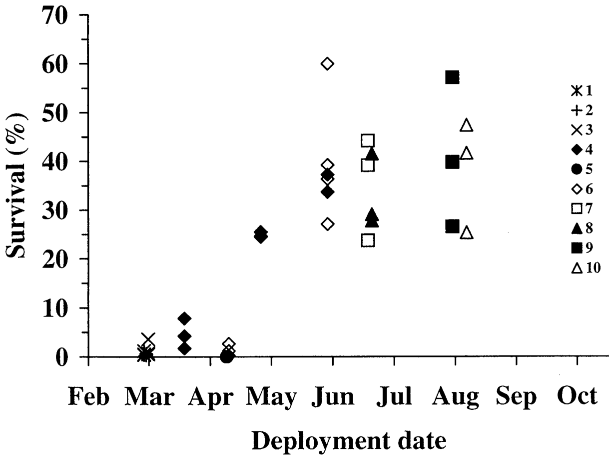

Figure 2. Survival of scallop spat directly deployed to the sea during the 1995 season. Different symbols represent the spat groups number 1 through 10, and each point represents the survival in one tray.

Survival

Survival ranging from 0% to 60% was observed for scallop spat transferred directly from the hatchery to the sea during the 1995 production season (Fig. 2). Dead scallops found upon retrieval passed through the 3-mm screen, indicating that no growth had taken place before mortality occurred. Spat in the size range 0.7 to 2.6 mm directly deployed to a sea temperature below 7°C showed mean survival of less than 5%, while the 4B group, which held a 4 mm SH at deployment, showed 25% survival (Fig. 2; Table 1). A large variation in survival between trays was shown for the spat groups deployed at a sea temperature of 10°C and above. The average survival was 38% (SD = 10.37) for these groups, ranging from 24% to 60% (Fig. 2).

The spat groups (3, 4A, 4B, 5, and 6A) subjected to the acclimation treatment were deployed from March 1 to May 18 when the sea temperature ranged from 5°C to 7°C (Table 1). Mean survival rates from 0% to 9% were obtained for the spat groups of initial average size 0.7 to 2.3 mm. For the 4-mm spat group (4B), mean survival rates of 25% to 36% were found (Fig. 3). Compared to

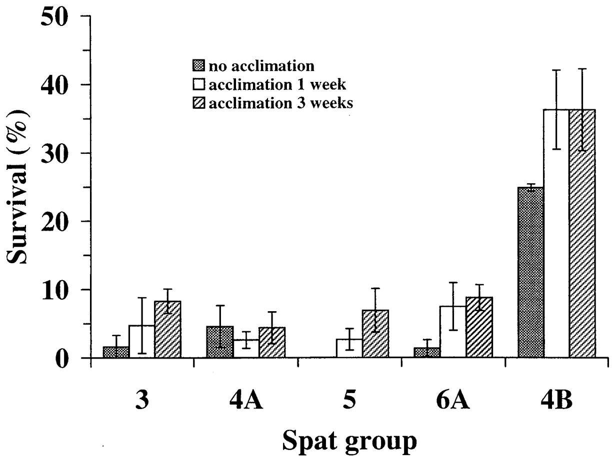

Figure 3. Mean survival of scallop spat subjected to acclimation treatments. Subgroups of spat were deployed directly to the sea (no acclimation) and after 1 and 3 wk of acclimation. Vertical bars show standard deviation.

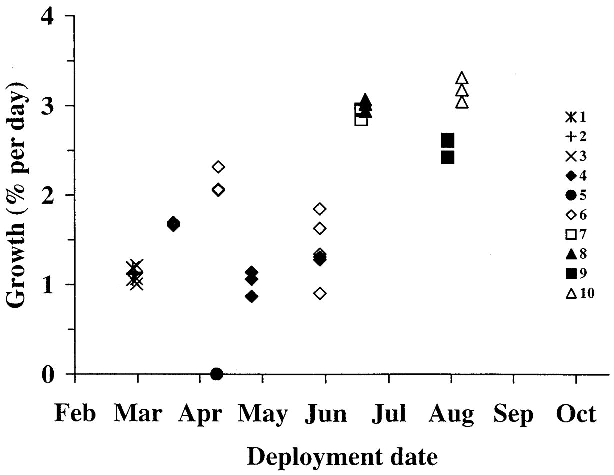

Figure 4. Specific growth rate (percentage of SH per day) of scallop spat directly deployed to the sea during the 1995 season. Different symbols represent the spat groups number 1 through 10, and each point represents the mean growth in one tray.

direct transfer from the hatchery to the sea, acclimation improved the mean survival by up to 7% for the smaller sized spat groups, while the bigger sized group gained a mean increase of 11% (Fig. 3). A one-way ANOVA was carried out for each spat group. The survival of the acclimated spat from the groups number 3 and 4A was not significantly different from the spat deployed directly to sea. For the other spat groups examined, there was a significant difference between the treatments. Survival of the spat transferred directly to the sea was significantly lower than the survival of acclimated spat. Extension of the acclimation time from 1 to 3 wk did not improve survival significantly for any of the spat groups.

Growth

Specific growth rates of the spat deployed to the sea without foregoing acclimation were found to be in the order of 0.9% to 3.3% or 46 to 128 μm increase in SH per day (Fig. 4). No surviving scallops were observed for spat group 5 (Fig. 2), which consisted of the smallest spat deployed during the experiment (Table 1). Hence, no growth could be calculated for this group.

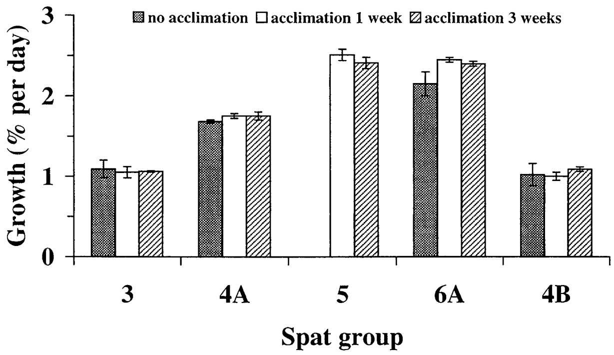

Figure 5. Mean specific growth rate (percentage of SH per day) of scallop spat during the total experimental period (acclimation time included). The spat were deployed directly to the sea (no acclimation) and after 1 and 3 wk of acclimation. Vertical bars show standard deviation.

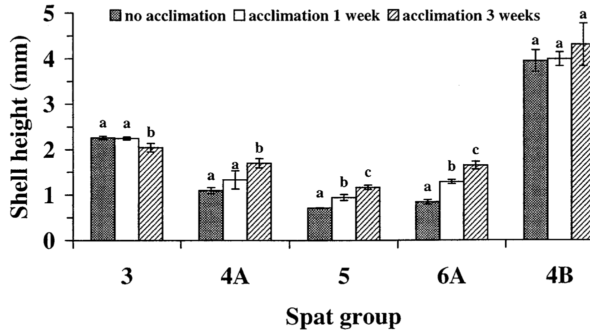

Figure 6. Mean SH at deployment time of scallop spat subjected to acclimation treatments. Subgroups of spat were deployed directly to the sea (no acclimation) and after 1 and 3 wk of acclimation. Values indicated by different letters within each spat group are significantly different. Vertical bars show standard deviation.

The mean final size of the spat groups surviving direct transfer to the sea was 9.1 mm (SD = 1.74). The SHs ranged from 3 to 21 mm.

The mean specific growth rates obtained for the spat groups subjected to acclimation were between 1.0% and 2.5% per day during the grow-out period in the sea, as for the total experimental period, acclimation time included (Fig. 5). The statistical tests showed that acclimation of the spat group 6A significantly improved the growth rate during the total experimental period, and of the spat from group 3 acclimated for 3 wk, considering the grow-out phase in the sea. An extension of the acclimation time from 1 to 3 wk did not result in faster growth for any other spat groups. The SH at time of deployment to the sea differed between the subgroups, and except for group 3 and 4B, the spat groups subjected to acclimation treatment showed growth during the acclimation period (Fig. 6). Upon retrieval, the differences in average SH were evened out, with the exception of the 6A subgroup not acclimated, which obtained a significantly smaller size compared with the acclimated ones (Fig. 7).

Correlation and Regression Analyses

Growth rate and survival are related to short grow-out time at higher temperatures (Table 2). Growth rate correlated with small spat, and survival correlated with large spat. Some of the shell and

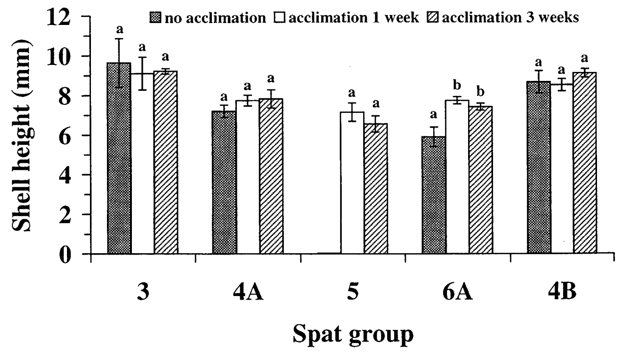

Figure 7. Mean shell height upon retrieval of scallop spat subjected to acclimation treatments. Subgroups of spat were deployed directly to the sea (no acclimation) and after 1 and 3 wk of acclimation. Values indicated by different letters within each spat group are significantly different. Vertical bars show standard deviation.

TABLE 2.

Pearson product-moment correlation matrix for specific growth (% day^{-1}), % survival (transformed), acclimation time, age (days from spawning), size (shell height), density (no. cm^{-2}), and sea temperature at deployment, average temperature during grow-out, total grow-out time in the sea, and time exposed to sea temperatures <10°C. Significant correlation coefficients are indicated with asterisks (*, $P < 0.05$; **, $P < 0.005$; ***, $P < 0.0005$).

Variable	Growth	Survival	Acclimation	Age	Size	Density	Deployment Temperature	Average Temperature	Grow-Out Time
Survival	0.34**								
Acclimation	0.00	−0.09							
Age	−0.54***	0.10	0.17						
Size	−0.40**	0.55***	−0.05	0.77***					
Density	−0.26*	−0.11	0.22	0.15	0.05				
Deployment temperature	0.59***	0.77***	−0.33*	−0.18	0.19	−0.32*			
Average temperature	0.63***	0.80***	−0.20	−0.27*	0.13	−0.26*	0.96***		
Grow-out time	−0.51***	−0.79***	−0.02	0.23	−0.23	0.24*	−0.74***	−0.85***	
Grow-out <10°C	−0.52***	−0.82***	0.02	0.20	−0.26*	0.27*	−0.79***	−0.88***	0.99***

environmental parameters correlated strongly between themselves, like size and age at deployment, temperature at deployment and during the grow-out period, and grow-out time and temperatures (Table 2). According to the stepwise regression analysis, exposure time to temperatures <10°C and size at deployment explained 80% and 90% of the variation in survival of all groups and acclimated groups, respectively (Table 3). Temperature at deployment ranked above the other variables in explaining the growth rate variation regarding all spat groups during grow-out in the sea. Size was the most important factor for the spat acclimated 1 and 3 wk before

TABLE 3.

Multiple forward stepwise regression analysis between % survival (transformed) and specific growth rate (% day^{-1}) in the sea, and the variables acclimation time, size, density, sea temperature at deployment, and the duration of exposure to temperatures <10°C in the sea. The analysis was applied to all the spat groups deployed and for groups acclimated 1 and 3 wk before transfer.

	Stepwise Results							Multiple Results			
									Analysis of Variance		
Dependent Variable/ Independent Variable	Step	Multiple R^2	Partial Correction	*F* Enter	B	*t* Value	*P* Level	Intercept	df	F	*P* Level
Survival											
all groups											
Time <10°C	1	0.674	−0.51	138.393	−0.186	−4.679	0.0000	−5.864	5, 63	74.344	0.0000
Size	2	0.796	0.67	39.749	0.004	7.174	0.0000				
Temperature	3	0.842	0.51	18.792	2.374	4.666	0.0000				
Density	4	0.852	0.24	4.481	0.001	1.922	0.0592				
Acclimation	5	0.855	0.13	1.163	0.732	1.078	0.2850				
acclimated groups											
Size	1	0.811	0.82	119.892	0.007	6.988	0.0000	6.735	5, 24	44.497	0.0000
Time <10°C	2	0.899	−0.54	23.464	−0.155	−3.125	0.0046				
Density	3	0.901	0.17	0.731	0.000	0.831	0.4141				
Acclimation	4	0.903	−0.11	0.279	−0.377	−0.534	0.5983				
Temperature	5	0.903	0.03	0.018	0.212	−0.132	0.8957				
Growth											
all groups											
Temperature	1	0.349	0.48	35.921	0.182	4.368	0.0000	1.308	5, 63	26.301	0.0000
Size	2	0.620	−0.68	47.055	−0.000	−7.292	0.0000				
Acclimation	3	0.665	0.26	8.747	0.117	2.103	0.0395				
Time <10°C	4	0.675	−0.17	2.025	−0.004	−1.361	0.1783				
Density	5	0.676	−0.05	0.154	−0.000	−0.392	0.6961				
acclimated groups											
Size	1	0.630	−0.96	47.739	−0.000	−16.704	0.0000	3.233	5, 24	153.271	0.0000
Time <10°C	2	0.964	−0.90	249.489	−0.014	−9.848	0.0000				
Density	3	0.967	−0.24	2.378	−0.000	−1.237	0.2281				
Acclimation	4	0.969	−0.26	1.350	−0.027	−1.321	0.1990				
Temperature	5	0.970	0.18	0.803	0.041	0.896	0.3790				

deployment. Density neither had significant effect on survival nor on growth, and acclimation time had no significant influence within the acclimated groups (Table 3).

DISCUSSION

The present study shows that the success of scallop spat is highly dependent on temperature at deployment time. The results indicate that transfer of small *P. maximus* from hatchery to natural sea conditions of temperatures <7°C for long durations is likely to be critical. Survival of the spat deployed directly to the sea increased substantially when the sea temperatures reached 7°C (Figs. 1 and 2). There was a strong positive correlation between survival and temperature, despite the wide variation between trays (Fig. 2; Table 2). Lethal temperatures for *P. maximus* larvae and juveniles, according to other studies, are 8°C and <4°C, respectively (Beaumont & Budd 1982, Brynjelsen & Strand 1996). The spat investigated in our study were sized between larvae and juveniles. On the basis of this, it was assumed that transfer of spat to sea temperatures >5°C would not be fatal. Our observations show that some *P. maximus* spat of <2.5 mm are able to survive transfer to 5°C to 7°C, while others suffer high mortality. The low lethal tolerance temperature for another cold water scallop species, *Patinopecten yessoensis*, is also found to be about 5°C (Ventilla 1982), while the sea scallop, *Placopecten magellanicus*, tolerate temperatures down to below 0°C (Couturier et al. 1995). The lower lethal temperature of scallop spat might not be an absolute temperature but rather a range. Each scallop species is distributed within a certain geographical and bathymetric range where the environmental conditions support survival (Brand 1991). Tolerance limits, therefore, will vary between populations of the same species due to the exposure of different local temperature ranges and seasonal variations. Within a population, a high temperature shown to be lethal to the animal during winter may be tolerated by the animal when exposed to summer conditions and vice versa (Schmidt-Nielsen 1990).

A marked increase in shell growth rates was shown at temperatures above 10°C (Fig. 4; Table 1). Several studies have concluded that temperature rather than food availability is the most important environmental factor affecting scallop growth in the sea (Andersen & Naas 1993, Kleinman et al. 1996, Chauvaud et al. 1998, Laing 2000). Others (MacDonald & Thompson 1985, Wallace & Reinsnes 1985, Thorarinsdóttir 1994, Laing & Psimopoulous 1998) stress the importance of food supply for scallop growth. Which of the two factors are most important could not be determined in our study due to lack of regular food concentration measurements in the sea. The food rations in terms of particle counts were lower from March to May compared with later in the season, but the level was not believed to be growth limiting. Spring bloom events of algae probably ensured enough food since similar growth rates of surviving spat were found both early and late in the season.

The low survival in spring found in our study may also be influenced by environmental factors other than temperature and food availability. More site-specific conditions like salinity, flow velocity, presence of predators, and fouling organisms are shown to affect growth and survival of scallop juveniles (Wilson 1987, Cahalan et al. 1989, Wildish & Saulnier 1992, Andersen & Naas 1993, Lodeiros & Himmelman 1996, Freites et al. 2000, Grecian et al. 2000). Likewise will the different environmental factors synergistically affect the growth performance (Kirby-Smith & Barber 1974, Paul 1980, Strand et al. 1993, Grant 1996, O'Connor & Heasman 1998, Pilditch & Grant 1999). In suspended culture, the scallops are exposed to more fluctuations in food supply, salinity, and temperature compared with their natural habitat on the sea bottom (Tebble 1966). By keeping the animals higher up in the water column, as in our study, the temperature and food amount are elevated during spring and summer. The higher survival and growth observed for spat exposed to summer temperatures was probably a result of increased metabolism together with food available in excess. Oxygen consumption and filtration rate of scallops are known to be temperature dependent (McLusky 1973, Bricelj & Shumway 1991), as are energy metabolism, feeding ability, and growth of bivalves in general (Walne 1972, Bayne et al. 1976, de Villiers et al. 1989, Rice & Pechenik 1992, Grant 1996).

Relatively high growth rates were obtained for the spat deployed in the spring (Fig. 4). The growth was based on measurements of spat that had survived the total 7 to 19 wk grow-out in the sea. Seen together with the complementary low survival of the spat transferred early in the year, the good results are due to a few, but very vital, scallops. The growth rate calculations were based on the total grow-out period in the sea. A longer time span combined with a lower average temperature was expected to give a lower daily growth compared with animals allowed to grow at optimal time in the sea. This was confirmed by the significant negative correlation coefficients found between grow-out time and growth (Table 2).

Acclimation from 15°C to 10°C reduced the negative impact of cold water temperature at deployment. According to the regression analysis, size was the most important factor explaining the variation in survival and growth of acclimated *P. maximus* spat (Table 3). The acclimated spat were transferred to the similar temperature range (5.1°C–7.1°C), which might account for the reduced effect of temperature at deployment. Larger spat (4 mm) showed better survival than smaller spat (<2.6 mm) when transferred to low temperatures. Along with the size at deployment, a shorter time of exposure to temperatures below 10°C might have influenced the results, as this was also shown as an important factor explaining growth and survival variation. Grecian et al. (2000) likewise found initial size to have significant influence on growth and survival of *P. magellanicus* spat transferred to sea-based nursery, showing better results for spat of >3 mm SH compared with spat of 1.2 to 2 mm. For *Pinctada margaritifera* spat, on the other hand, it was found that transfer from the hatchery to the sea should occur as soon as possible after settlement in order to maximize growth (Pit & Southgate 2000).

The scallops found dead upon retrieval in the present work were of a small size (<3 mm SH) compared with the majority of the surviving ones. Mortality is therefore likely to have occurred shortly after deployment time. According to the descriptions of the gill organogenesis by Beninger et al. (1994), the spat in our study were anatomically undeveloped. Beninger et al. (1994) found the gill function of *P. maximus* spat up to 4 mm to be different from the adult gill, and suggested that the development from one size stage to the next is critical in terms of survival. This may explain that the spat of 0.7 to 2.6 mm SH used in our study were incapable of rapid adjustment after transfer to the cold water environment. Poorer feeding ability of the spat deployed to the lowest temperatures in addition to the temperature stress may have caused the mass mortalities observed in spring.

The acclimation to an intermediate temperature between the hatchery (15°C) and the sea (5°C–7°C) prior to deployment in spring enhanced the survival of scallop spat. The present study shows increased mean survival of up to 7% for small spat (0.7–2.3

mm) and 11% for larger spat (4 mm). The overall survival rates of the larger spat were higher and comparable to those obtained for spat deployed later in the season (Figs. 2 and 3). Regarding growth rates of the larger spat, they were relatively low, and no improvement was gained from acclimation (Figs. 4 and 5). These results could be due to the fact that smaller individuals of scallops grow faster than larger ones (Bricelj & Shumway 1991, Parsons et al. 1993) (Table 2), or that growth in sea conditions, in spite of suboptimal temperature, is more favorable than hatchery conditions. With respect to the SH of the spat subjected to acclimation, some growth compensation seems to have occurred in the sea since similar final sizes were achieved for the subgroups (Figs. 6 and 7). The spat of group 5 and 6A not acclimated and directly deployed to a temperature of 5.6°C appeared, on the other hand, not to reveal such growth compensation. One group suffered total mortality and the other showed a significantly lower final SH compared with the acclimated spat subgroups. These spat, which were 0.7 and 0.8 mm SH at deployment, belonged to the gill development stage 2 described by Beninger et al. (1994). The other spat in the study were stage 3 at transfer, further implying that the spat were transferred to the cold seawater conditions at a critical stage in life.

Since no significant difference in survival and final SH was found between the groups acclimated for 1 and 3 wk, we believe that 1 wk is sufficient for small scallop spat to adapt to 10°C. Adaptation of mussels to a change in temperature is shown by an immediate response in oxygen consumption and filtration rate, followed by a 2-wk acclimation period for physiological compensation to initial level (Bayne et al. 1976). The observed growth during the acclimation period for most groups (Fig. 6) confirms that 1 to 4 mm *P. maximus* spat can tolerate an abrupt change from 15°C to 10°C. Exposure to a decrease in temperature from 15°C to 5°C to 7°C, on the other hand, seemed to be too stressful for the small spat (0.7–2.6 mm). Compared with the survival (24%–60%) obtained for spat transferred to sea temperatures more equal to the hatchery temperature, the mean survival was low (<9%). A gradual exposure to cold water before deployment early in the season might be a better solution for adjusting the temperature tolerance limit for scallop spat. Laing (2000) successfully acclimated spat of 5 to 14 mm from a rearing temperature of 17°C to 5°C by temperature reduction rates of no more than 1°C per day. The constant and fluctuation temperature regime studied by Pilditch and Grant (1999) did not affect the shell growth rate of *P. magellanicus* differently, but limited ability to alter metabolic energy demands following temperature changes was shown. It is possible that *P. maximus* also has limited capability to regulate its metabolism to sudden changes of low temperatures. Thus, the success of spat production is highly dependent on deployment time, which was also shown for *P. magellanicus* (Grecian et al. 2000), and growth performance will depend on initial scallop vitality before abrupt transfer to colder water.

Temperature at deployment and the period of exposure to low temperatures are found to be the main factors affecting survival and growth for small *P. maximum* spat (1–5 mm) transferred from hatchery to sea conditions. Improvement of tolerance to cold water environment is shown by acclimation to lower temperature, leaving size at transfer a critical factor. From an economical point of view, the result was of limited interest, while the maximum mean survival did not exceed 9% for the smallest acclimated spat. To ensure high survival rates, spat of <2.6 mm SH should not be transferred to sea temperatures below 7°C. Alternatively, enhanced survival of spat transferred to temperatures from 5°C to 7°C may be achieved by deploying bigger spat (>4 mm). If the spat could be kept in the hatchery to approximately 4 mm and acclimated to a colder temperature, we believe that an earlier start of the growth season in early spring is possible.

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