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The effects of environment and fishing on the abundance and condition of Iceland scallop (*Chlamys islandica*) in Breidifjordur

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Sea temperature is one of the primary factor limiting the overall geographical range of most marine species, including the Icelandic scallop. In Iceland, the sub-arctic Icelandic scallop resides at its southern limits. As a result, it is likely to be especially vulnerable to changes in the immediate environment. During the last 5 years, the stock size of Iceland scallop in Breidifjordur on the West coast of Iceland has undergone a dramatic decline. This period has been characterized by steady increase in summer sea temperature and in 2003 the temperature had reached a historical maximum of the last century. As well, since 1998, there have been fluctuations in chl-a level, with the lowest values observed in 1999 and 2000. At the same time, muscle weight has declined and a minimum weight was attained in 2001-2002. In the following years, natural mortality of scallops in Breidifjordur increased significantly. The mortality was however quite localized within the main fishing area in the southern part of Breidifjordur. At the same time two Coccidia parasites have been described in Iceland scallop from Breidifjordur. These parasite may have influenced the survival of the scallops. Recruitment into the fishable stock in Breidifjordur was highly variable during the 1993-2003, with low recruitment towards the end of the 1990's. Due to high total fishing mortality during the 1990-2000, the fishery depended on relatively few year classes. Therefore the fragile status of the stock did not endure the medium-high exploitation rates in conjunction with several years of poor recruitment.
Keywords: Iceland scallop, *Chlamys islandica*, recruitment, mortality, environment, temperature.
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Introduction

Population fluctuations are recognized as common phenomena of both marine and terrestrial animals (Elton, 1924). In scallop stocks, population size can be influenced by numerous factors. In a review by Orensanz *et al.* (1991) these factors were classified into three groups of phenomena: 1) Variability in recruitment. 2) Catastrophic mortality from various sources. 3) In short lived scallops where recruitment is not buffered by the survival of the adult stock. Caddy & Gulland (1983) classified fish (including shellfish) stocks into steady stocks, cyclical stocks, irregular stocks and spasmodic stocks according to their pattern of fluctuation. Long-lived arctic and boreal scallops may fall into the steady stock group (Orensanz *et al.*, 1991).

The Iceland scallop (*Chlamys islandica*) is distributed within the sub-arctic transitional zone at maximum sea temperatures of 12-15°C (Sundet, 1988; Hovgaard *et al.*, 2001) and at depths above 100 m (Wiborg, 1963). Iceland scallop is a longevity species with maximum observed age of at least 23 years (Vahl, 1981). Fluctuations in populations of Iceland scallop have been observed at several locations in the North

Atlantic, for example, due to changes in temperature and / or salinity (Wiborg, 1963), predation (Brun, 1968) and heavy fishing (Hovgaard *et al.*, 2001).

All major populations of Iceland scallops in Icelandic waters have undergone a decline since 1999. Stock biomass indices for small scallop stocks northwest of Iceland have decreased by 45-80% and the greatest decline was detected in an area where fishing was insignificant (Marine Research Institute, Reykjavík, unpublished data.). The stock size index of the largest scallop population in Iceland, which is located in Breidifjordur at 22-70 m depth, declined by 70% in the period 2000-2003. The fishery in this area dates back to the year 1970. Landings reached a peak of 12.700 t in 1986, decreased slightly in the following years and remained rather stable around 8.000-9.000 t during most of the 1990s. In 2000-2003 the stock collapsed and annual landings decreased from 8.600 to 800 tonnes (Anonymous, 2003). The collapse of the stock coincided with an increase in sea surface temperature (SST) on scallop grounds in Breidifjordur with the highest mean observed in 2003 (Jónasson *et al.*, 2004).

The objective of this study is to look for possible causes for the dramatic decline in stock size of Iceland scallop in Breidifjordur, by exploring data from stock surveys and available environmental data, such as sea temperature and food supply (chlorophyl a).

Material and methods

Survey data

Data used in this paper was obtained from scallop surveys conducted by the Marine Research Institute (MRI) in Breidifjordur, west of Iceland (Fig. 1). From 1993, annual surveys have been carried out in March-April. In each survey approximately 120 standardized tows were taken. From 1973 until 1996 a 410 kg and 1.5 m wide sledge dredge was used. Since 1997, a 710 kg and 1.2 m wide roller dredge of an Icelandic design was used. Both dredges were equipped with 60 mm steel rings. Each tow covered about 0.4 nautical mile and tow speed varied from 3-4 knots/hour. Variable tow lengths were standardized to 0.4 nautical mile. For each tow the total catch was weighted and a random sub-sample of about 25 kg taken. In each sub-sample, all scallops were weighted and about one hundred scallops measured for height. The remaining scallops were counted.

The survey area was divided into subareas, according to pre-grouped squares. Squares containing the main scallop grounds were cut diagonally into two subareas (Fig. 1). The total region fished was divided into a northern area (subareas 31-42), north of Bjarneyjaall (which is a trench transecting the fjord from west to east) and a southern area (subareas 2-14), south of the trench. The size of the scallops beds in each subarea were estimated during the early annual surveys.

Stock biomass indices was estimated as:

$$B_y = \sum_{i=1}^{n} \frac{\overline{x}_s * a_s}{dw * tl * 1.852} \, / \, e \qquad (1)$$

where B_y is total biomass in tonnes, n is the number of subareas, $\overline{x}_s$ the average biomass per subarea in kg, a_s the size of the scallops beds per subarea in km^2, dw the width of the dredge in meters, tl the tow length in nautical miles and e the dredge efficiency.

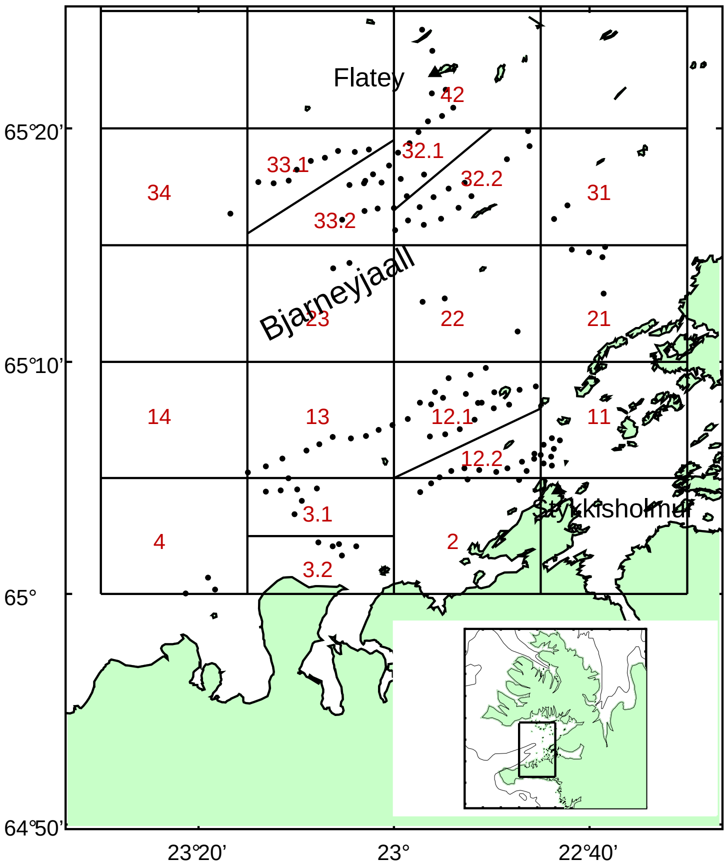

Figure 1: The survey area in Breidifjordur. Each square containing a subarea is labelled. Squares on the main scallop grounds often contain two subareas. Survey stations are marked with dots. Stations used for temperature recordings (Flatey and Stykkisholmur) are marked with triangles.

CPUE data

Catch per unit effort (landings per hour fishing) within each subarea is based on logbook catch reports. The effort data reach back to late 1972, although some data before 1993 are lacking.

Fishing mortality

Fishing mortality was calculated by two non-model methods for four major subareas (11, 12.1, 12.2 and 32.2);

Beverton-Holt length-based estimates:

$$^{BH}F_s = K\frac{L_\infty - \overline{L}_s}{\overline{L}_s - l_c} - M_s \tag{2}$$

Where in each subarea s, $^{BH}F_s$ is Beverton-Holt length based fishing mortality (Quinn & Deriso, 1999), K is a growth constant from the von Bertalanffy growth function (VBGF)(Ricker, 1975) (eq.7), L_∞ is the asymptotic shell height (SH) from VBGF, $\overline{L}_s$ is the mean SH beyond l_c, that is here 60mm and Ms is the calculated natural mortality (eq.5).

Equilibrium fishing mortality estimates:

$$^{Y}F_s = \frac{Y\tau_s}{B_s} \tag{3}$$

Where in each subarea s, ${}^{Y}F_s$ is equilibrium fishing mortality (Quinn & Deriso, 1999), Y is landings of scallops in tonnes for a one year period ($\tau = 1$) and B is estimated biomass (eq.1) in tonnes. This method does not consider indirect fishing mortality (non-yield) from fishing gear.

Environmental and biological data

Due to lack of complete sea surface temperature (SST) data series from Breidifjordur, an estimate of SST was calculated. The estimate is based on the relationship of SST in Flatey and the air temperature in Stykkisholmur (Fig. 1) All available monthly mean SST data from Flatey (May-August, 1990-2001, n=35) were used ($r^2 = 0.942, P < 0.001$ (Jónasson *et al.*, 2004)).

Estimates of chlorophyl a in Breidifjordur were derived from the NASA SeaWiFS project. The data was processed at NASA and consisted of a level-3 data which are statistical data products derived by mapping level-2 GAC data to a fixed global grid whose resolution elements are approximately $9*9\,\mathrm{km}^2$ (Campbell *et al.*, 1995). Fifty monthly mean values were obtained from the regions determined by 23°38'-22°41' West and 65°02'- 65°29' East. Mean values from March - September were calculated for each year in 1998-2003.

For measurement of the wet weight, scallops were sampled from Thorisholmi in subarea 11 (Fig. 1). The sampling took place during September-Desember each year in 2000-2003. Adductor muscle wet weight of scallop was fitted to shell height (SH) by the following equation:

$$W = a * SH^{\beta} \tag{4}$$

where W is the muscle wet weight and a, β are constants from a linear regression model of wet weight on SH after log-transformations of the variables.

Natural mortality data

Natural mortality was based on the occurrence of cluckers (dead scallops attached on their hinges) in survey tows, according to Dickie (1955):

$$\alpha = 1 - e^{-(\frac{C}{t})(\frac{1}{L})365} \tag{5}$$

where α is the yearly ratio of natural death, C is the number of cluckers in the sample, t is the average time in days required for the shells of the cluckers to separate (i.e. 211 days according to Jónasson (2004)) and L is the number of live scallops in the sample. The exponent is equal to the instantaneous mortality rate. The number of cluckers (C) in the sample was adjusted for the numbers of scallop that disarticulated during the tow, by multiplying the number of cluckers with 1.211 (Naidu, 1988).

A weight based index of natural mortality was calculated by replacing $\overline{x}_s$ in eq.1, by:

$$\overline{m}_s = \frac{\sum_{i=1}^{n} \frac{x}{(1-\alpha)} - x}{n_s} \tag{6}$$

where $\overline{m}_s$ is the mean biomass of dead scallops in each subarea (s), x is the biomass of scallop per station within subarea, α (natural mortality) is taken from eq.5 and n_s is number of stations in each subarea,.

The geographic distribution from the spring surveys of scallop abundance and the natural mortality of scallops were plotted. In the latter plots, stations with fewer than 5 kg of scallops or less than 5 scallops measured were excluded. The data were spatially interpolated using a kriging method (a linear variogram model (Anonymous, 1996)).

Age determination and recruitment

Age was determined from shell height using Bhattacharya's method (Sparre & Venema, 1998). Graphs were used for visual identification of frequencies perceived to belong to one age group. GAM smoothed data from 1993-2003 in subarea 12.1 were used in this procedure, although in some years younger year-classes were poorly represented.

The VBGF (Ricker, 1975) was fitted to the mean shell height at age by linear regression (Crawley, 2002), with data from subarea 12.1, using Bhattacharya's method. The VBGF was formulated as:

$$SH_t = SH\infty[1 - exp\,(-K(t - t_0))] \tag{7}$$

Where SH_t is the SH (mm) at age t (years), $SH\infty$ is the asymptotic SH, K is the growth constant and t_0 is the intercept of the growth curve on the age axis. The VBGF fitted well to the estimated mean age of the scallops, calculated with Bhattacharya's method (Fig. 2).

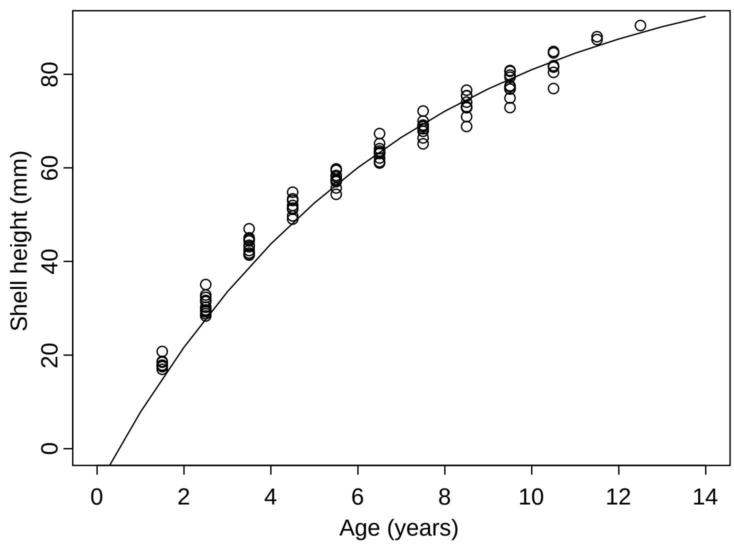

Figure 2: Shell height at age from surveys (1993-2003), calculated from Bhattacharya's method in subarea 12.1, fitted with VBGF.

For analysis of year class strength the divergences from the mean shell height frequency indices of 1993-2003 were calculated for subareas with the highest cumulative catch (32.2, 12.1, 11 and 12.2), during the same period, based upon common method e.g. described by Sund (1930). The height frequency of each subarea was weighted with the numbers of scallops for each subarea that were estimated with following equation:

$$N = \frac{\overline{x} * a}{dw * tl * 1.852} \,/\, e \tag{8}$$

where N is total number of scallops (1000) per subarea, $\overline{x}$ the average number per station, a the size of the subarea in km^2, dw the width of the dredge in meters, tl tow length in nautical miles and e the dredge efficiency. The data were then smoothed with a GAM model using cubic B-line smoother with 20 degrees of freedom (Venables & Ripley, 1997).

All statistical analysis were performed using Version 6.0 S-PLUS software (MathSoft 2001) except the Bhattacharya's method that was performed with the Version 1.0 FISAT II statistical program (FAO, 2002).

Result

Temporal changes in catch and stock size

The stock index of Iceland scallop in Breidifjordur was relatively stable during the 1990s, but declined sharply in 2000-2003 (Fig. 3). As such, the stock index fell to 24 thousand tonnes in 2003 attaining a historically low level which was only 35% of the average stock size in the 1990s.

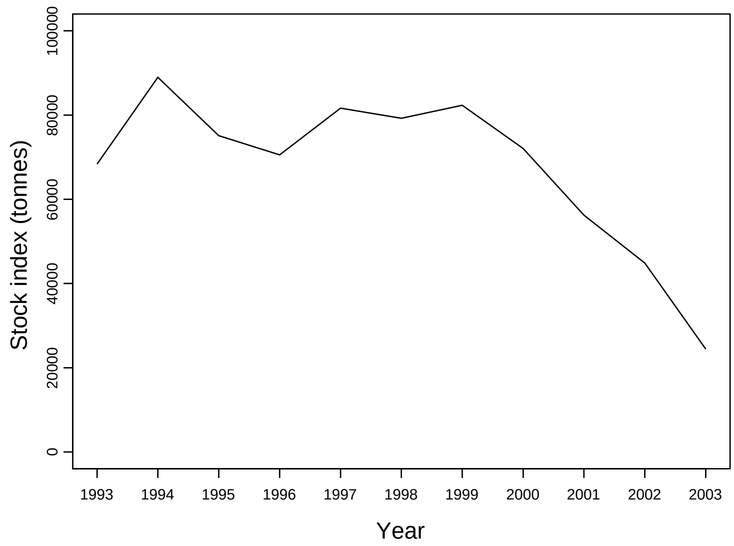

Figure 3: Stock index from annual surveys of Iceland scallop in Breidifjordur, during 1993-2003.

The main trends in stock size differed between subareas (Fig. 4). In subarea 12.1, which is the major fishing area in southern Breidifjordur, the stock index declined gradually from 1994. In subarea 32.2, which is the major fishing area in northern part of Breidifjordur, the stock index fluctuated during 1993-2000, reached a climax in 1997, after which it showed a steady decline until reaching a historical low level in 2003. In other subareas a decline in stock size was detected after 2000, although a steady decline was observed in subareas 13 and 3.1 from 1993 and 1994 respectively (Fig. 11).

Catch per unit effort (CPUE) pooled for all areas in Breidifjordur, was relatively stable during 1986-1990, but increased considerably during 1991-1996 (Fig. 5). During 1996-1998 the CPUE stayed at relatively high levels, 220-228 kg/hour/feet. However, in 1999-2003 the CPUE declined sharply to 75 kg/hour/feet . The changes in the CPUE coincided with changes in the scallop fishery in the early 1990's, when the fleet changed from sledge to roller dredges.

Throughout 1993-2000, the quotas (total allowable catch) were relatively stable, about 8000-10000 tonnes. Quotas have been based on 10% of estimated biomass. The effort varied from one time period to another, being significantly higher during 1986-1993 compared to 1994-2003, i.e. opposite to the trends in CPUE (Fig. 5).

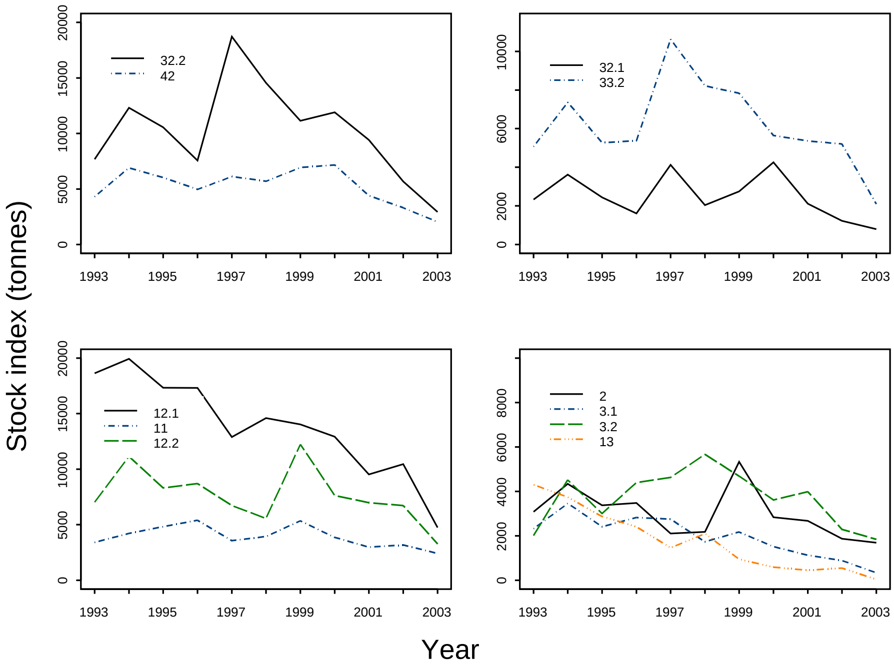

Figure 4: Stock index in all major subareas from annual survey in Breidifjordur, during 1993-2003. Northern areas are shown above and southern below. Note different scale on y-axis.

Between 1993 and 2003, the variability in fishing mortality was low. However, in subarea 12.1 there was a slow decline in Beverton - Holt length based fishing mortality (${}^{BH}F$) from 0.55 to 0.10 (Fig. 6). The equilibrium fishing mortality (${}^{Y}F$) was substantially lower than the ${}^{BH}F$ in subareas 32.2, 12.1 and 12.2 (0.1-0.2)(Fig. 6). The difference is likely partly due to indirect fishing mortality which the ${}^{Y}F$ mortality does not explain. Higher ${}^{Y}F$ was observed in subarea 11, where the mortality fluctuated from 0.3 in 1993 to 0.1 in 1997 and then increased up to 0.5

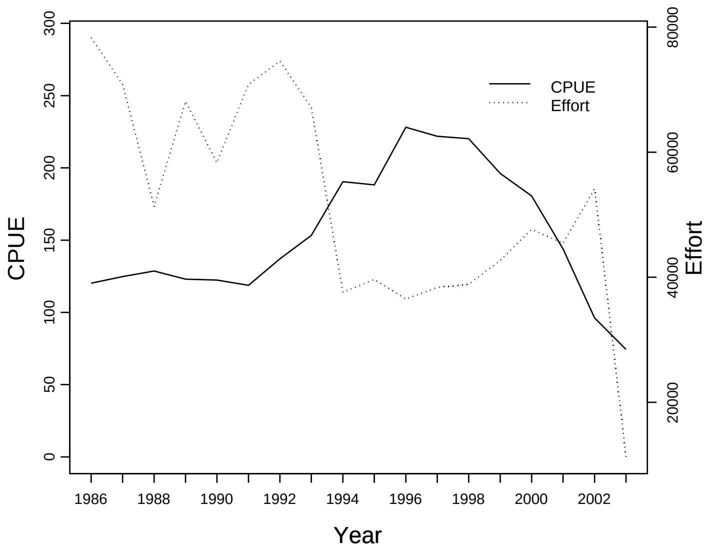

Figure 5: Catch per unit effort (kg of scallops/hours fishing/feet) and effort(hours of fishing pr. dredge feet) in Breidifjordur, during 1986-2003.

in 2000. However, the actual area fished in subarea 11 is larger than the estimated area where the calculated biomass is drawn from.

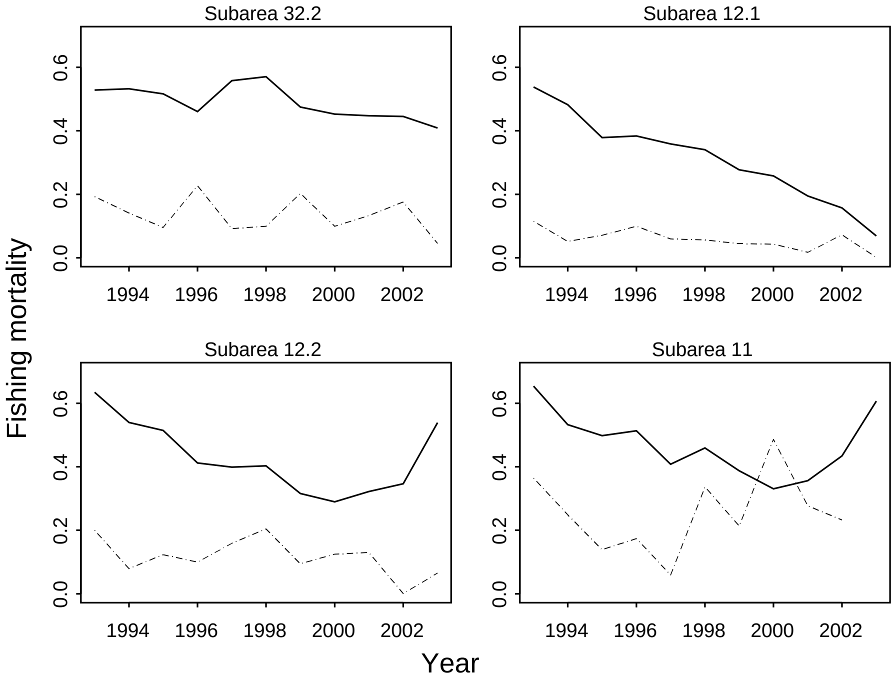

Figure 6: Fishing mortality estimates by subareas in Breidifjordur, during 1993-2003. Beverton Holt length based fishing mortality (solid line) and equilibrium fishing mortality (broken line).

Condition of Iceland scallop in relation to environmental parameters

The estimated mean summer sea surface temperature (SST) in Flatey showed periodic fluctuations during the last century, with values above average in 1930-1950 and values mainly below average during 1960-1990 (Fig. 7). After an extended low in the 1980s, the SST increased in 1990-91, declined again in 1992-1993. Since then, temperature has been gradually increasing towards a similar level as was experienced in the 1930s.

Estimate of mean chlorphyl a(chl-a) data in summer months in Breidifjordur was available from 1998 until 2003 (Fig. 8). The mean chl-a values fluctuated during this period with minimum values in 1999 and 2000. The highest value measured was in the summer of 2003.

Measurements of muscle wet weight initiated in the fall of 2000 when fishermen noticed that the scallops were in poor condition. The relationship between scallop height and muscle wet weight was examined among scallops from Thorisholmi during fall of 2000-2003. The fit of the relationship was low, especially in 2001-2002 , as the muscle weight was not isometric with the shell height in all years (Table 1). The number of scallops in abnormally poor condition increased from 2000-2002. The muscle weight of calculated 70 mm SH was 7.28, 7.03 and 6.61 g in the years 2000-2002 respectively, compared to 8.46 g in 2003. The muscle weight during these years fluctuated in a similar way as the chl-a (Fig. 8). The scallops in 2003 differed in condition (intercepts) from scallops in 2000-2002 (Tukey t-test, $p < 0.005$), when all the years were regressed with the same slope.

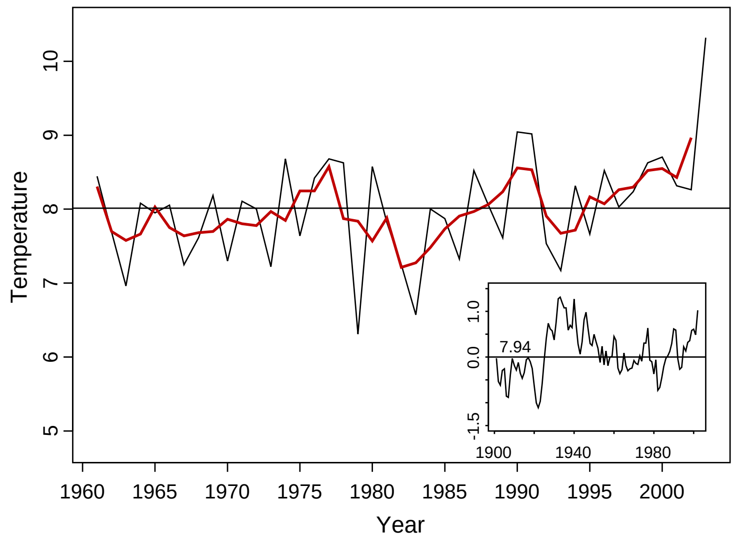

Figure 7: Estimated mean sea surface temperature (black line) and annual 3-year running mean of sea surface temperature (red line) in Flatey, Breidifjordur, during 1960-2003 (May-August), the horizontal line indicates the mean. The subplot shows annual 3-year running deviance from the mean (7.94°C) at the same location from 1900-2003 (May-August).

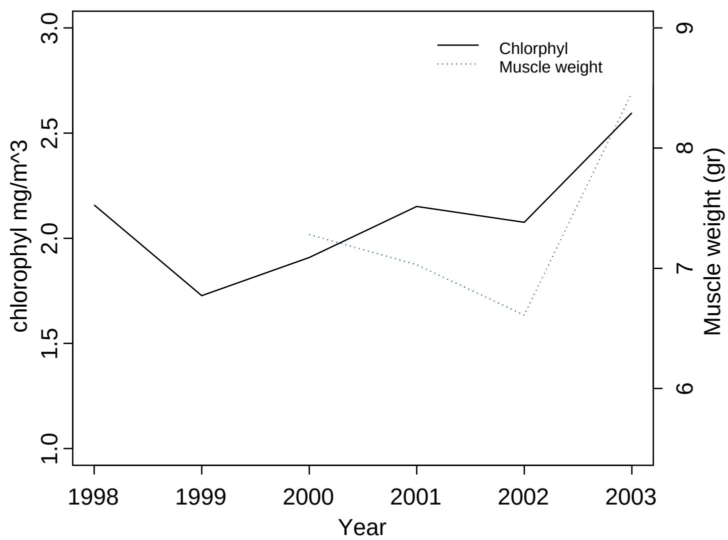

Figure 8: Average chl-a from March to September in Breidifjordur, during 1998-2003 (The data are provided by NASA SeaWIFS project.). Calculated mean scallop muscle weight at 70 mm shell height from Thorishólmi, in fall 2000-2003.

Natural mortality

The natural mortality of scallops has increased during the recent years in Breidifjordur. As such, following 2001, there was a sudden increase in natural mortality in most areas (a, yearly ratio of natural mortality) (Fig.9). The mean natural mortality increased substantially in subarea 12.1 from 0.1 in 2001 to 0.4 in 2003 (Fig. 11). The rise in natural mortality was not as well represented in other subareas in the southern area. However, there were years with higher natural mortality than 0.15 in subareas 2 and 13. In the northern area natural mortality was low or about

Table 1: Regression parameters for muscle weight versus shell height for Iceland scallop, during the fall of 2000-2003 from Thorisholmi Breidifjordur.

Year	n	Slope(β)	S.E. (β)	Intercept	r^2	P($\beta = 3$)	**Calcuated SH** 70mm	90mm
2000	200	1.87	0.15	-5.97	0.44	$P < 0.001$	7.28	11.67
2001	588	1.44	0.10	-4.18	0.27	$P < 0.001$	7.03	10.10
2002	600	1.23	0.12	-3.35	0.16	$P < 0.001$	6.61	9.00
2003	100	2.13	0.21	-6.93	0.53	$P < 0.001$	8.46	14.46

0.05 from 1993 - 2000, followed by an increase to 0.1 during 2001 - 2003.

Weight based natural mortality indices varied between areas and years (Fig. 10). Largest values in the natural mortality indices were observed in subarea 12.1 located within the southern area, as shown by exceptionally high natural mortality index in 1995 and again in 2002 and 2003. High natural mortality index was also observed in subarea 13 in 1993, as well as during 1999-2001 in subarea 2. The weight based natural mortality indices did, however, not vary as extensively in the northern areas, and were low throughout the study period. The natural mortality indices are dependant on the size of the stock index. As such the natural mortality indices are relatively higher after 2000 due to considerable drop in the stock size.

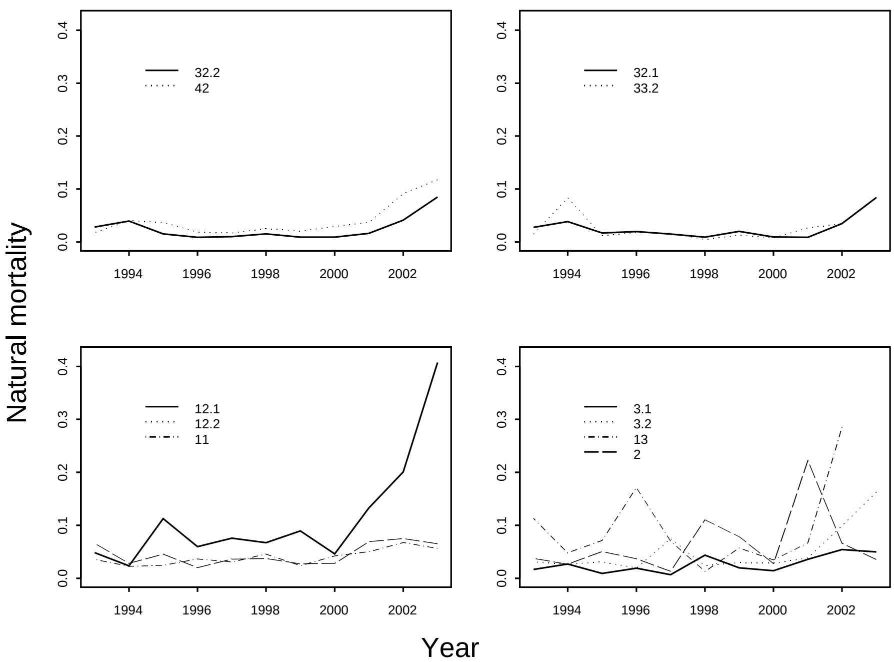

Figure 9: Yearly ratio of mean natural mortality (a) by subareas in Breidifjordur, during 1993-2003. Northern areas are shown on graphs above and southern below.

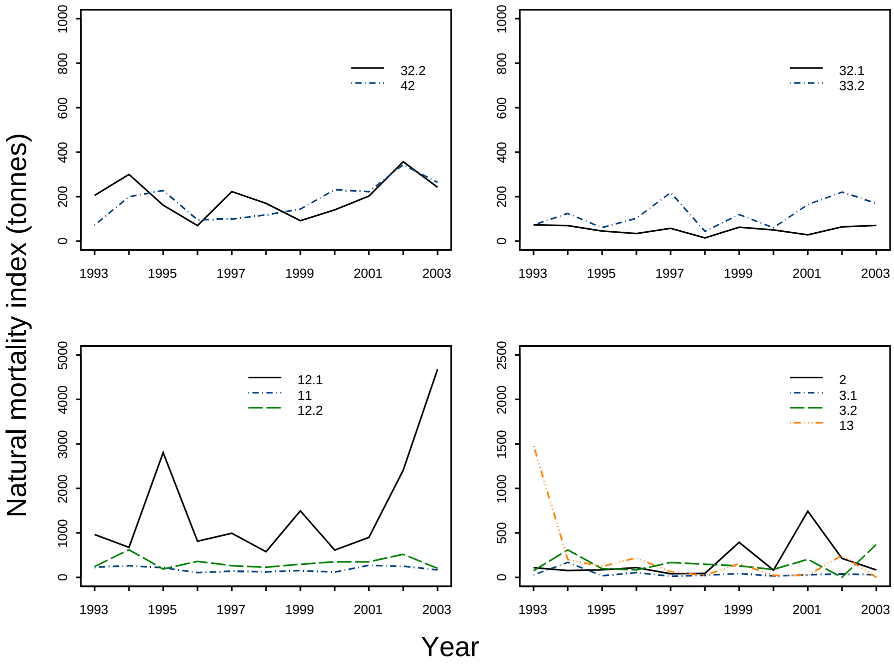

Figure 10: Index of natural mortality by subareas in Breidifjordur, during 1993-2003. Northern areas are shown above and the southern below. Note different scale on y-axis.

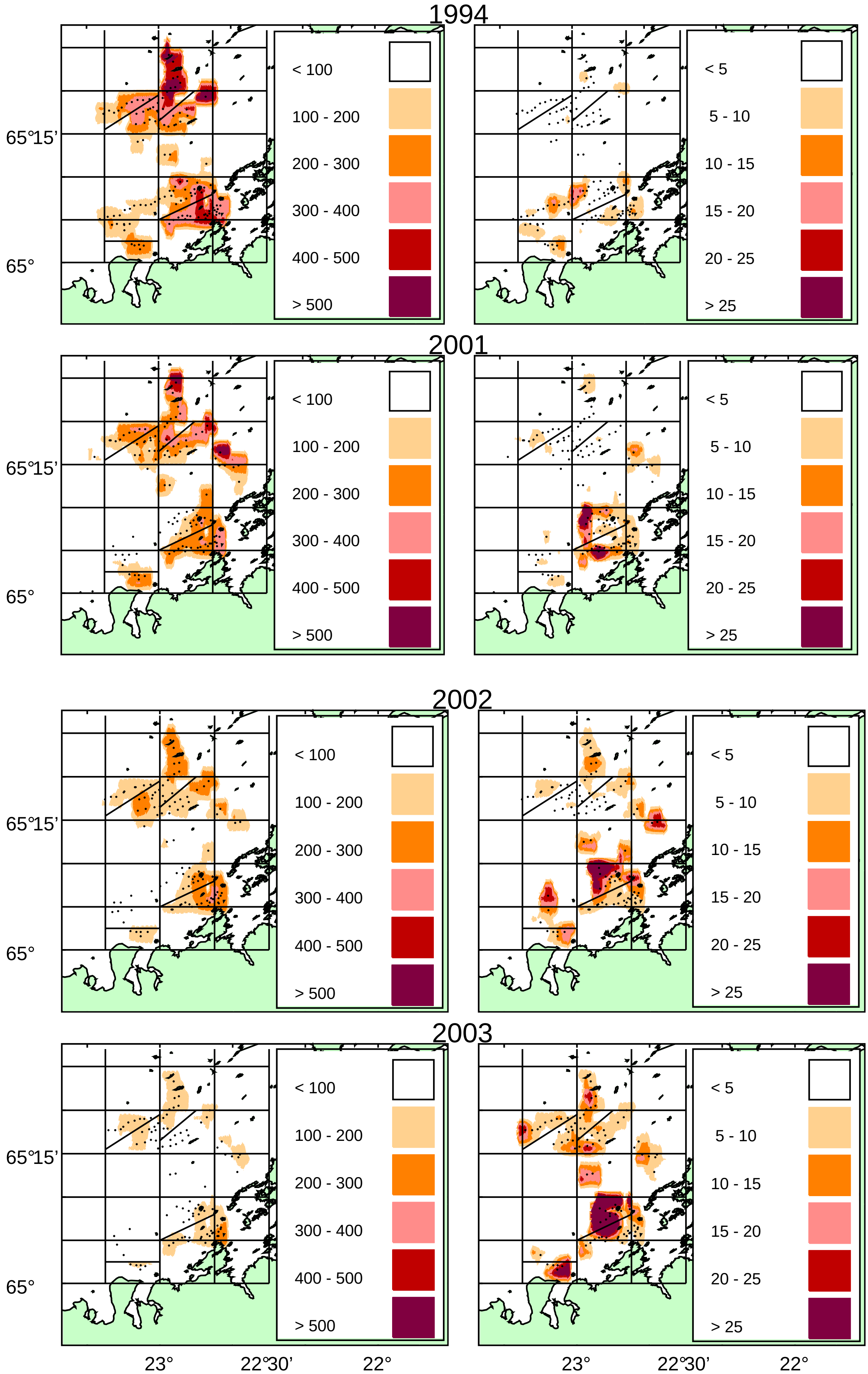

Figure 11: Geographic distribution in Breidifjordur of the weight of scallops (kg per survey tow), (left column) and natural mortality of scallops (right column), during 1993-2003 spring surveys (Stations are marked with dots.)

Growth and recruitment

The size of scallops in Breidifjordur, measured as shell height, changed considerably towards the end of last century. In general, the average shell-height increased from 1993 to the end of the decade (Fig. 12). However, the maximum values were followed by a great decline in average height. In subarea 11 the average shell-height reached a maximum in 1998 and in subarea 12.1 and 12.2 a year later. In subarea 32.2 the maximum shell height was attained in 2000, followed by a less pronounced decline than in other subareas.

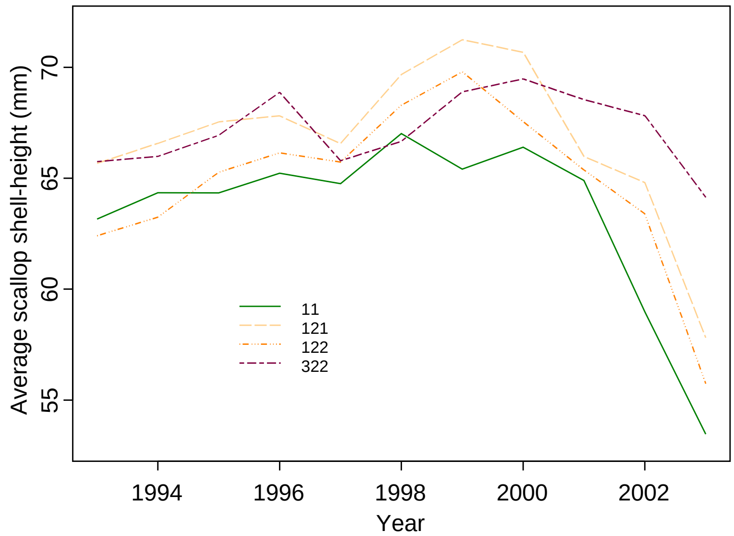

Figure 12: Average shell height (mm) of scallops from four different subareas in Breidifjordur, during 1993-2003.

The deviations of indices from the mean of 1993-2003, illustrates well how the stock size had evolved (Fig. 13). However, the survey data have the disadvantage that younger age groups are poorly represented due to dredge selection.

In subarea 12.1, relatively strong year classes entered the fishable stock (60 mm+) in 1993-1997. In the following years, medium and weak year classes dominated until 2003. In 1993, the survey catch was dominated by shells that were approximately 70 mm, or 8 years old, according to length based conversion (Fig. 2). However, 80 mm (10 years+) scallops were rare (Fig. 13). During 1994-1996 the strong year classes grew up and filled the 80 mm gap observed in 1993. Medium or weak year classes from 1990-1992, appeared to have entered the fishable stock in 1997-1998. In 1998 the relatively strong 1993 year class was observed by high abundance of ∼55 mm shells. In 1999 and 2000, small year classes from 1994-1995 entered the fishable stock. As a result, a gap in shell-height from 60-70 mm was formed. During 2001-2003 small year classes continued to enter the fishable stock, resulting in greater gap in the older year classes. In 2003 a year class from 1997 and reasonably large year class from 1998, appeared to be recruiting into the fishable stock. Younger year classes from 2000 and 2001 were detected (Fig. 13).

The temporal changes in subarea 12.2 were quite similar to those seen in subarea 12.1. In 1993 individuals about 65 mm were numerous and old age groups (10 years+) were poorly represented (Fig. 13). In 1994-1996 strong year classes grew up and filled the gap apparent among the older age groups during 1993. In 1997 and 1998 a low stock index was measured, with rather low recruitment into the fishable stock being evident. However, the individuals from the 1993 year class could be detected as ∼55 mm in 1998, although slightly under average in numbers. The highest stock index was measured in 1999, with substantial amount of large scallops (∼ 80 mm), but the recruitment to the fishable stock was poor. The decline of the stock in 2001 was not as severe compared to subarea 12.1, due to the strong 1996 year class (then ∼55 mm). In 2003 in subarea 12.2, there was little left of the fishable stock, but year classes from 1998 - 2001 seemed to be entering the fishable stock.

Subarea 11 was characterized by less fluctuations in the stock index than subareas 12.1 and 12.2. In 1993 the fishable stock was built up of small scallops (∼65 mm)(Fig.13). From 1994 to 1996 the strong year classes seen in 1993 grew and the proportion of larger scallops increased. In 1999 a lack of recruitment occurred in the fishable stock, followed by a strong 1996 year class seen as ∼55 mm in 2001. Also, there seemed to be better recruitment in subarea 11 as the 1997 year class recruited to the fishable stock in 2003. Year classes from 1998 and younger were also promising.

Subarea 32.2 in the northern area differs from subareas in the south as recruitment is not as well represented, but similar trends were however evident (Fig. 13). In 1993 the number of large scallops (∼70mm) were below average. In the following years there were fluctuations in the stock index, as large scallops gradually became better represented. The 1993 year class was well pronounced as 40 mm in 1997 and can been seen all the way to the year 2002 as 75 mm shells. In 1999-2003, a lack of recruitment to the fishable stock was evident, as a consequences of poor year classes from 1994-1999. In 2003 there was little left of the fishable stock and only the prerecruited 2000 year class was above average.

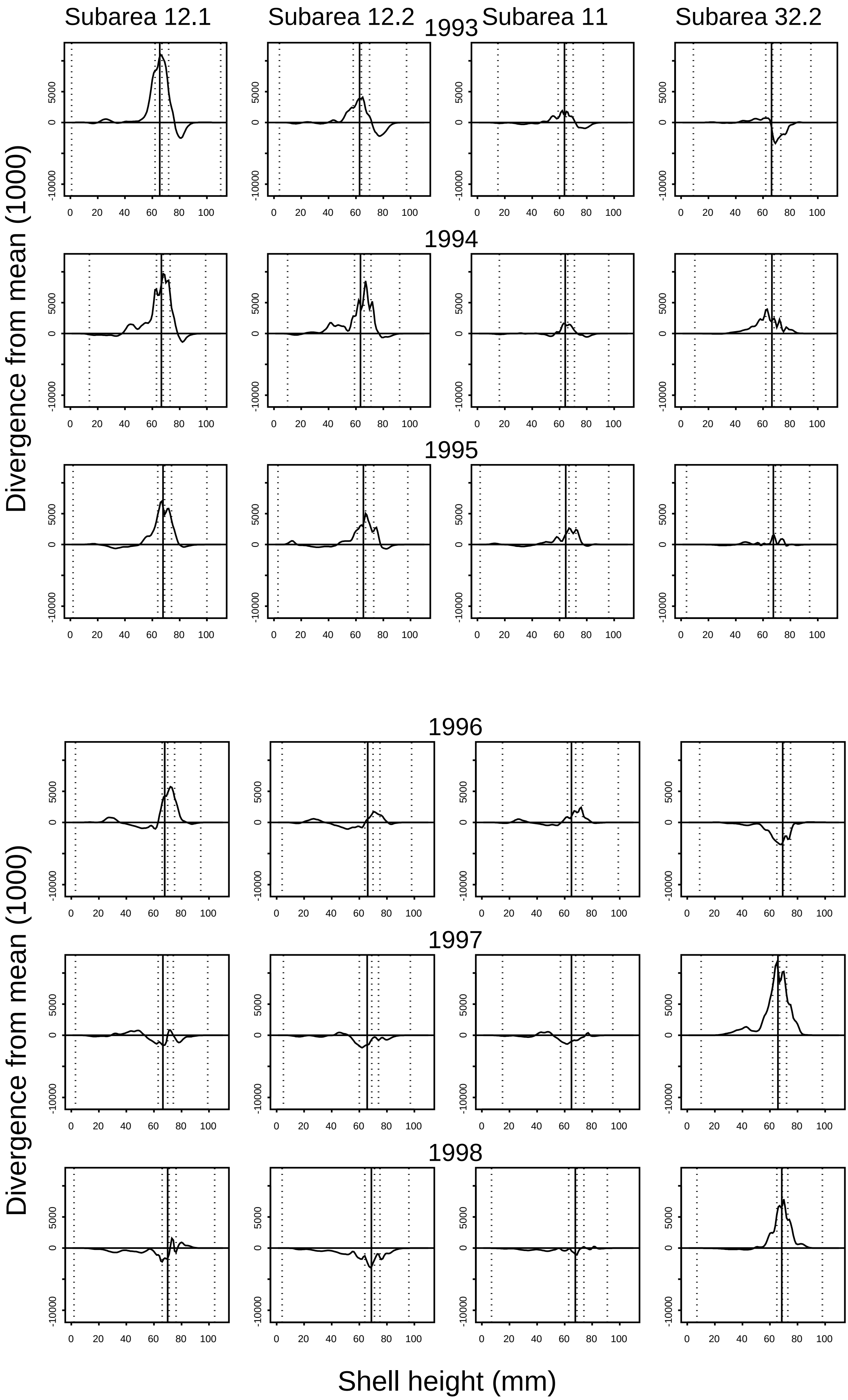

Figure 13: Divergence from mean shell-height index from 1993-2003 in subareas 11, 12.1, 12.2 and 322. The data was transformed with GAM smoother. The vertical dotted lines are the quantiles and the vertical line is the mean. (Fig. 13 concluded on next page.)

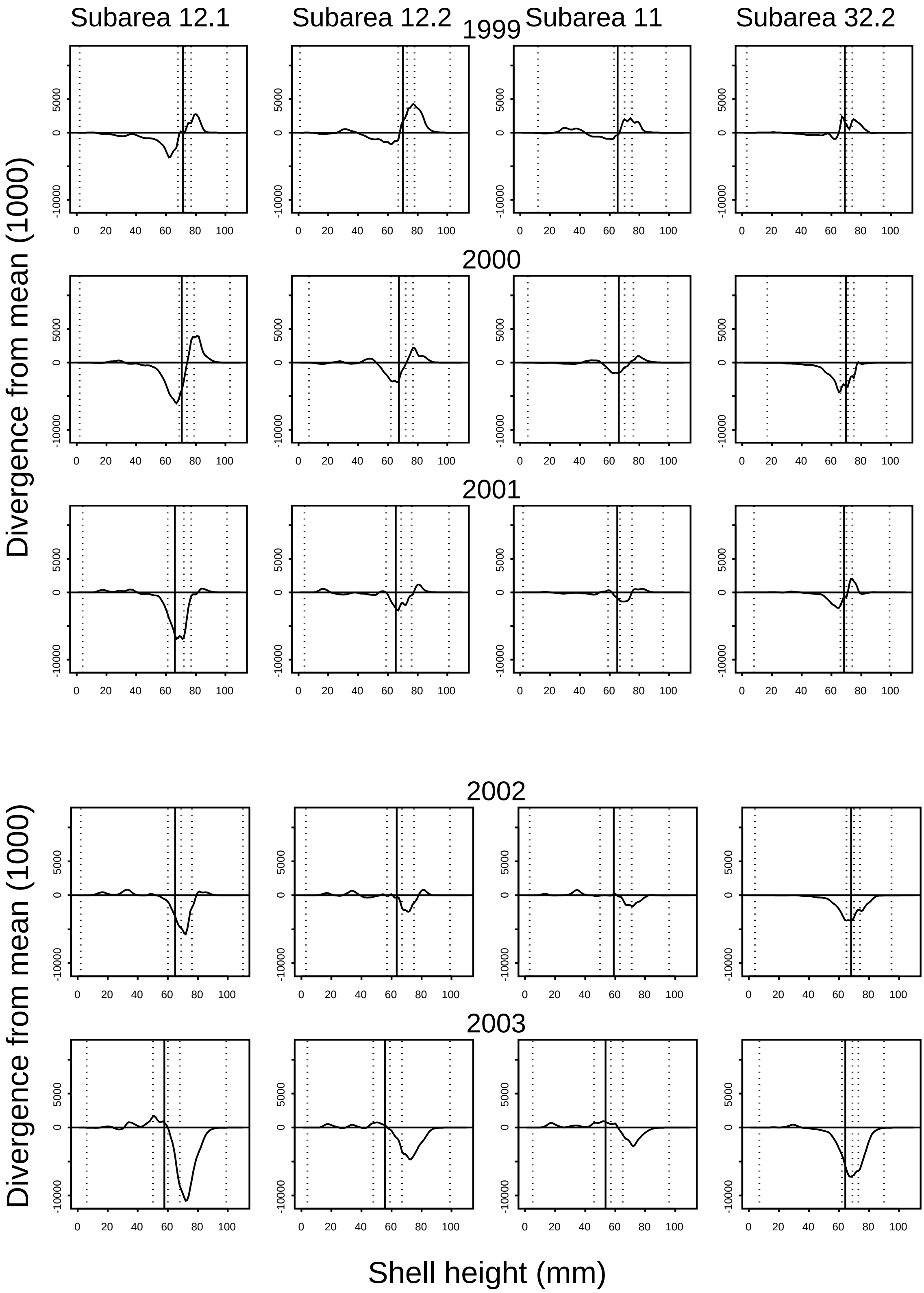

Fig. 13 (concluded).

Discussion

The Iceland scallop stock in Breidifjördur declined considerably towards the end of the 1990's, due to poor recruitment that was followed by an unusually high natural mortality in the fishable stock. This period was characterized by a steady increase in sea temperature and poor condition of the scallops.

Temporal changes in catch and stock size

The decline in the stock index in the Iceland scallop varied between subareas and was greatest in the two main fishing grounds, subarea 12.1 and 32.2. The stock index started to decline as early as 1994 in subarea 12.1 and after 2000 in subarea 32.2.

A new dredge introduced to the fishery around 1990 increased the fishing efficiency greatly. The new dredge was heavier, could be towed on both upper and lower side and at a greater speed than the old one. Due to this fact, the CPUE increased in all subareas during the next years but the total catch was stable, due to limited catch-quotas.

A high fishing mortality was observed throughout the study period. The equilibrium fishing mortality was low compared to the Beverton-Holt fishing mortality. The equilibrium fishing mortality only represents landings and will be negatively biased if there is non-yield fishing mortality. The difference between the two estimates may indicate a substantial indirect fishing mortality. Even though little fluctuations were detected, the Beverton-Holt fishing mortality decreased in subarea 12.1, coinciding with decreasing stock index and fishing effort. Under high fishing mortality, a stable recruitment is necessary to ensure sustainable fisheries. The gradual decrease in stock index in subarea 12.1 is most likely due to consistently insufficient recruitment to the fishable stock. Other beds of Iceland scallops in the North Atlantic have historically been depleted in a short time. For instance, intense fishing in 1986-1987 on scallop beds around Svalbard, Jan Mayen and Bear Island, resulted in fishing ban on most of the beds in 1989 (Hovgaard *et al.*, 2001; Anonymous, 1990).

Indirect fishing mortality is accompanied with scallop dredge fisheries. Heavy gear inevitably imposes a high probability of incidental damage to scallops, whether they were retained, passed out through the ring, inter-ring spaces, or run over by the dredge (Caddy, 1989). In the present investigation, when estimating the difference between the Beverton - Holt F and equilibrium F, the mean indirect fishing mortality over a 11 year period, was estimated as high as 0.255 - 0.354 (Fig. 6). Naidu (1988) estimated, based on cluckers and crushed scallops, that in an exploited scallop area in Canada, indirect fishing mortality could have been as high as 0.364, when using a heavy dredge that was similar to the one used in Breidifjördur in the years past 1990.

Myers *et al.* (2000) showed that in the presence of indirect fishing mortality, rotational harvest strategy in the fishery management would provide equal or greater yield, maintaining a higher spawning biomass. However, such strategy would require a precise and accurate estimates of scallop density and distribution by size classes, which can be monitored by a developing technique like an underwater photography as the dredge is only a "semiquantitative tool" (Caddy, 1989; Stokesbury, 2002).

Condition of Iceland scallop in relation to environmental parameters

Incident to the decline in the scallop population, the sea temperature in Breidifjördur increased and the mean temperature reached the highest estimated values of the last century (the years between 1930-1940). The highest sea temperature was observed in 2003 during the end of the study period. Possible scallop mortality during that warm summer was not analyzed in the present study and little is known about the status of the scallop stock during the warm years between 1930-1940. Fisheries of Iceland scallop in Breidifjördur started in 1970 (Eiríksson, 1987), and have therefore only been conducted during a relatively cold period. The temperature increase during the last years has brought summer maximum temperature close to the stock tolerance limits, which is about 14°C (Jónasson *et al.*, 2004). Wiborg (1963) assumed that Iceland scallop located outside fjord sills in Northern Norway may be depleted at intervals due to variations in temperature and/or salinity. The southernmost population of Iceland scallop in Iceland is located in Hvalfjördur, a fjord on the southwest coast. The scallop stock in Hvalfjördur declined drastically in 1983. This decline was thought to have resulted from an increase in the sea temperature in the previous year (Eiríksson, 1987). High sea temperature has also been associated with mass mortality on several occasions for *P. magellanicus* in Canada (Dickie & Medcof, 1963).

Chlorophyl (chl-*a*) provides an estimate on food availability for Iceland scallop. Since 1998, there have been fluctuations in chl-*a* estimates, with low values in 1999 and 2000. The highest mean value observed in 2003 was 50% higher than the lowest observed value in 1999 illustrating considerable annual difference in food availability in Breidifjördur. It's difficult to compare the SeaWifs chl-*a* with an in-situ data from other areas, although it has been shown that chl-*a* data derived from SeaWifs fits well to in-situ chl-*a* data in shallow water (Tang *et al.*, 2003). Few series of chl-*a* measurements are available from Breidifjördur, but in the study of Thorarinsdottir (1991) monthly samples were taken in 1990-1991. The mean chl-*a* from March until September at 8 m depth was 1.82 and 1.51 mg/m^3 in 1990 and 1991, respectively. Those values fall in the lower ranges of the data presented here (1.73 - 2.60 mg/m^3). The mean chl-*a* at 2 m depth near scallops ground in the mouth of Hvalfjördur in 1997 from March until September was 2.63 mg/m^3 (Eydal, 2003), corresponding to the higher ranges of the data observed in this study.

Muscle weight increased in 2003, coinciding with high values of chl-*a*. Large variations in muscle weight were observed with lowest weight in 2001-2002. At the same time two Coccidia parasites were identified in Iceland scallop from Breidifjördur. One of them causes infections in the muscle tissue (Kristmundsson *et al.*, 2004). The prevalence of the infections was about 90% with severe infections in larger scallops. The poor condition of scallop muscles in 2001-2002 is likely to be connected with the infection, although a more complex interaction of infection, chl-*a* and temperature is proposed here. Further, it has been shown in other shellfish species that parasites prevalence are connected to rise in sea temperature (Cook *et al.*, 1998). Yungkul & Powell (2004) proposed that malnourishment leading to death of surf clams (*Spisula solidissima*), was caused by environmental shift, mismatching food supply and feeding rate.

Natural mortality

High natural mortality was observed in scallop grounds in Breidifjördur during 2002 and 2003. The mortality was mainly localized in subarea 12.1, were it was estimated to be 0.41 or approximately 5000 tonnes in 2003 or 50% of the estimated biomass in 2002. In other heavily fished areas, the natural mortality has been reported to be as high as 0.21 (Naidu & Cahill, 1984). To our knowledge the mortality in subarea 12.1 in 2003 is higher than reported previously. The mortality in subarea 13 and in subarea 2 in 2002 is also exceptionally high.

The same adjustment factor was used here for tow-induced disarticulation as described by Naidu (1988) for 0.25 nm tows. He noted that on longer tows greater numbers may be expected to disarticulate, but the average here was 0.4 nm tows. The natural mortality values presented in the present study, could therefore be underestimated.

Growth and recruitment

Recruitment into the fishable stock was highly variable during 1993-2003, with low recruitment towards the end of the 1990s. This was evident as the mean shell height increased from 1997 while the stock index decreased and few young shells recruited to the population. Furthermore, the poor recruitment was seen as a gap in the mean shell height index between 50 and 70 mm in 1999 and 2000. Recruitment varied considerably between subareas. For example, recruitment in subarea 11 was more or less stable. It was quite apparent that in year classes from 1990-1997 only the 1993 year class was well represented in every subarea as well as the 1995 year class in subareas 11 and 12.2. New recruits were again estimated to enter the fishable stock in 2004, in concordance with good representation of the 1998-2003 year classes. However, in subarea 32.2 only the year class from 2000 was detected. The lack of visible recruitment in subarea 32.2 could be due to different ontogenic habitat shifts between subarea 32.2 in northern grounds compared to the subareas in southern ground. Arsenault *et al.* (2000) observed recruitment into adult populations that involved swimming of juveniles from the nursery areas. However, it is not known if nursery areas exist near subarea 32.2.

When other Iceland scallop beds in the Atlantic are compared, a variability in recruitment and growth rate between areas is evident. In the Iceland scallop fishery off Jan Mayen and Svalbard, that collapsed due to overfishing, the proportion of +65 mm scallops declined (Anonymous, 1988). Decline of older age groups is what could be expected in selective overfishing scenario, but the opposite trend was observed in the present study. Good recruitment was rare in the Svalbard region after the depletion of the grounds during 1986-1987, as marked recruitment was first seen in 1996 as small juveniles (Anonymous, 2002). In West Greenland, the Iceland scallop population is mainly composed of old scallops. The area is characterized by low level of recruitment and scallop beds can be quickly depleted by fishing (Pedersen, 1994). Naidu & Anderson (1984) suggested that the presence of several consecutive year classes of Iceland scallops in St. Pierre Bank in Canada, indicated relatively stable recruitment, in comparison to irregular recruitment of Sea scallop on the same grounds. Furthermore, growth rate was considerably lower among scallop stocks off Svalbard and Greenland, compared to Norway, Iceland and Canada (Pedersen, 1994), therefore making them less tolerant to fishing.

It is difficult to estimate the effects of size and age composition of the spawning stock biomass on the variable year class strength observed in the present study. Density-dependant responses of fish populations (particulary involving recruitment) are often obscured by variability, presumably due to the density-independent effect of fluctuating environmental factors (Sissenwine, 1984). As such, Dickie (1955) demonstrated that fluctuations in catch and landings of *P. magellanicus* in the Bay of Fundy where largely due to input of strong year classes into the catchable population. Recruitment in this stock was also shown to be correlated with temperature that prevailed during pelagic larval stages which further affected wind driven transport (Dickie, 1955). Furthermore, spatial and temporal patterns in settlement of benthic invertebrate can be strongly linked to transport by wind-driven currents (Bertness *et al.*, 1996). The differences in recruitment between years and within subareas in the present study, could possibly be explained by wind driven factors.

To enhance the recruitment and survival of spat, several possibilities are available. Guay & Himmelman (2004) found that addition of dead scallop shells to Iceland scallop grounds would have a positive impact, increasing the number of scallops as well as numerous invertebrates in the area. In areas with strong currents, as in Breidifjördur, it has been shown that juvenile scallops grow faster when located underneath shells, likely due to to reduced exposure to high velocity currents (Arsenault *et al.*, 1997). Shells of dead scallops function also as a refuge from predators for juveniles, therefore increasing their survival (Arsenault & Himmelman, 1996). Further, filamentous organisms that often colonize the adult scallop shells may function as settlement substratum (Stokesbury & Himmelman, 1995). Marine protected areas (MPAs) have been shown to increase scallop biomass manyfold and increase recruitment outside of the protected areas. This was evident with *P. magellanicus* in Georges Bank where scallop biomass increased 14 fold in protected areas during 4 years of closure, although with moderate or below average recruitment during the same period (Murawski *et al.*, 2000). With increasing biomass in MPAs there was also a higher proportion of older individuals (Bradshaw *et al.*, 2001). Langton *et al.* (1987) showed increased importance of gamete production with age in *P. magellanicus* and Vahl (1984) in Iceland scallop. High density of scallops also increases the fertilization rate, as shown by Claereboudt (1999) in a fine scale three-dimensional simulation model of fertilization process of *P. magellanicus.*

Conclusions

The fishable scallop stock in Breidifjördur consisted of rather few year classes. As the total (indirect and direct) fishing mortality was high, the stock was vulnerable to several years of poor recruitment. Furthermore, there was a high natural mortality in one of the major subarea, possibly due to diseases and unfavorable environmental conditions. The great decline, was caused by a mixture of poor recruitment, high natural mortality and high fishing mortality. In the future, new methods should be considered to estimate the biomass of spatfall and juvenile scallops which could be used to predict future catch levels and fishing effort. Further, initiation of MPAs in Breidifjördur or rotational harvest strategy should be strongly considered, as it could provide equal or greater yield and maintain a higher spawning biomass.

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