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Relationships between the geometric dimensions and biomass of schools

by

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ABSTRACT

Acoustic measurements of the geometric dimensions and packing density of herring, sprat and saithe schools have been conducted by multi-beam sonars and echo integrator systems. Relationships between the reflected echo energy, the estimated school biomass and the school dimensions were established. The relationships seems quite similar for the three species and rather independent of the size of the fish. Seasonal and regional differences in schooling behaviour of herring were detected. School dimension-to-school biomass conversion may be a useful method for abundance estimation of pelagic species, and also for biomass measurements in capture situations.

INTRODUCTION

If schooling fish are avoiding the vessel during conventional echo-integration surveys, a significant underestimation of the fish abundance may occure (Olsen 1987). Similary, if a fraction of the target population is schooling close to the surface ("the upper dead zone"), it may not be recorded at all (Aglen 1989). Use of sector scanning sonars may reduce such sampling biases, and increase the precision in abundance estimation due to their greater volume coverage (Ehrenberg 1980).

Real biomass estimation from the reflected echo energy of a school by sonar is complicated due to the directivity of the fish back scattering strength, and considerable noise reveberation in horizontal guided beams (Mitson 1983). Absorbtion of the emitted sound beam in high fish densities may in addition cause underestimation of schools (Foote 1978, Røttingen 1976). The most sophisticated fisheries sonars provide a relative, scaled echo quantity of a recorded school (Bodholdt 1982). Ordinary sonars display a school projection proportional to the school size with colour indication of echo strength.

Relationships for converting sonar measured school area to school biomass have been established for herring and mackerel by correlating the area and biomass of purse seine captured schools (Misund 1986, 1988). An average density per unit area of sonar measured and purse seine captured schools has been used as a conversion factor in biomass estimation by sonar of Northern anchovy (Hewitt et. al 1976).

To investigate the generality of such relationships further, acoustic measurements of school dimensions and reflected echo energy were conducted on herring, sprat and saithe schools in different seasons and geographic regions. The basis of the method is that individuals in syncronized and polarized swimming forms compact, high density units (Partridge et al. 1980) which creates proportionality between the biomass and geometric dimensions.

MATERIALS AND METHODS

The schools were recorded on cruises by the vessels R/V "Eldjarn" (1043 GRT, 3600 Hp) and R/V "Fjordfangst" (20 GRT, 180 Hp) in the North Sea and along the Norwegian coast (Table 1). Both vessels were equipped with standard calibrated (Foote et al. 1987) echo integrator systems and multibeam sonars (Furuno CH-12 onboard "Fjordfangst" and Simrad SM600 onboard "Eldjarn").

The sonar picture during a school recording was videotaped as the vessel was turned towards and approached the school. The integrator value (M), depth (D) and vertical extent (h) were noted if the vessel was manovered successfully so that the school was recorded by the echo sounder. Later, the lengthwise (lw) and crosswise (cw) extents (Misund 1990a) of the school projection were measured by a ruler during 10 s interval, still picture playback of the video recordings. The transect length (tl) were measured on the echo sounder recording. By modifying the method of Johanneson & Losse (1977), the real dimensions, fish density and school biomass were calculated by:

Crosswise extent $CW = CW \cdot s - 2R \tan(\varphi_s/2)$ *(m)*

Lengthwise extent $LW_1 = lw \cdot s - ct_s/2$ *(m)*

$LW_1 = lw \cdot \cos\alpha \cdot s - ct_s/2$ *(m)*

School area $A = ((CW \cdot LW)/4) * \pi$ *(m^2)*

Vertical extent $H = h - ct_e/2$ *(m)*

School volume $V = 4/3 \cdot \bar{A} \cdot (H/2)$ *(m^3)*

Transect length $TL_A = tl \cdot (v/pv) - D(2\tan(\varphi_e/2))$ *(m)*

$TL_B = 185{,}2 \cdot (tl/QNM) - D(2\tan(\varphi_e/2))$ *(m)*

Fish density $p = ((C_I \cdot M \cdot K_{NM})/(4\pi \cdot \sigma_{bs} \cdot K^2{}_{NM} \cdot TL \cdot H)$ *(n/m^3)*

School biomass $B = V \cdot p \cdot \bar{W}$ *(kg)*

φ_s, φ_e: beamwidth of sonar (horizontal) and echo sounder (alongship)
t_s, t_e: pulselengths of sonar and echo sounder
R: horizontal distance vessel-to-school
s: sonar scaling factor (sonar distance/screen distance)
C: speed of sound (1500 m/s)

α: tilt angle of sonar
V: vessel speed
pv: paper speed of echo sounder
QNM: 0,1 nautical mile interval
C_I: system calibration constant
K_{NM}: number of meter in one nautical mile
σ_{bs}: back scattering cross section of the fish calculated by $TS_{clupeoid}$ = 20 logL - 71.9 or TS_{gadoid} = 20 log L - 67.4 (Foote 1987)
1: Simrad SM 600
2: Furuno CH 12
A: "Fjordfangst", Sept. 1987
B: all other recordings

The length (L) and weight (W) were measured on subsamples usually of more than 100 speciemens from pelagic trawl samples in the North Sea and purse seine catches along the Norwegian Coast. When using the 70 kHz echo sounder ("Fjordfangst", Sept. 1987), the target strengths were adjusted for the frequency difference according to MaCartney & Stubbs (1971). Only distinct schools recorded during the daylight hours are considered in the analysis.

For the Lofoten 1988 and Gratangen 1989 recordings, a probable absorption loss in reflected echo energy is compensated by applying a correction factor (C = 1/e(-0.00919*M)) established by Toresen (1990) for bottom integrator value as a function of vertical herring school extent (H).

RESULTS

There was significant correlations between the reflected echo energy and the area or volume of the schools in all regions and various seasons (Fig. 1 and 2). The correlations seems somewhat stronger for the school volume connections ($0.58 < r < 0.84$) than for the corresponding school area connections ($0.42 < r < 0.75$). Generally there was a considerable variation in reflected echo energy from about similar sized schools. Averaging the area measurements for each school has no considerable effect on the North Sea 1989 school area-to-reflected echo energy connection as both the correlation and variation are rather similar when using each area measurement or just the average (Fig. 3).

The average biomass per unit area or unit volume of the schools varied from 0.24 kg/m^2 to 16.2 kg/m^2 or from 0.03 kg/m^3 to 1.14 kg/m^3 (Fig. 4a and b). For both these measures, there were no significant differences for schools of the three species (Table 2 and 3), but there were significant differences among the various regions in which the species were recorded. Even if the average biomass per unit area or volume in schools of individuals less than 15 cm (in average) never exceeded 1,45 kg/m^2 or 0,25 kg/m^3 respectively, the differences among the various lengthgroups of a species in a particular region were not significant for both measures (Table 2 and 3).

When relating calculated school biomass to corresponding school area or school volume, quite close and significant regressions appeared for all regions and different seasons (Fig. 5 and 6, Table 4). For both the area-to-biomass and volume-to-biomass regressions there were no significant difference for the various slopes, but the elevations differed significantly (Table 5 and 6). Applying the absorption compensation on the Lofoten (1988) and Gratangen (1989) recordings increases the calculated school biomasses by average factors of 1.23 and 1.35 or maximal factors of 1.55 and 2.37 for these two areas respectively.

DISCUSSION

The school dimension-to-school biomass relationships are in accordance with Pitcher & Partridge (1979) who concluded that school volume are propotional to the number of individuals multiplied by the cube of the average body length. The existence of such connections is also implicit in the behavioural rules that schooling individuals apply (Partridge 1982, Partridge et. al. 1980); as the individuals maintain a miniumum approach distance and prefer a certain distance and direction to their neighbours, there must also be proportion between the total volume occupied and the number of fish in schools. Since our area-to-biomass or volume-to-biomass relationships are obtained by regressions of two connected variables, our school dimension-to-school biomass connections are just tentative. Their excistense are, however, indicated by the close correlations between the independent recordings of reflected echo energy and corresponding school area or school volume. The integrator value is a measure of school size as it is proportional to individual scattering cross section (σ_{VS}) and the number of individuals in the school transect (Mitson 1983).

Contrary to our results, Hewitt et al. (1976) failed to establish any correlation between horizontal dimensions, reflected echo energy, or biomass of purse seine captured schools of Northern anchovy insonified by a single beam sonar. To point out a particular reason for this discrepancy is diffucult, but it is probably caused by method differences. Our relationships are based on measurements in a vessel-to-school distance from 50 to 450 m, while Hewitt et.al (1976) used a range interval from 200 to 800 m. In our case, the swimming behaviour of the schools was usually influenced by the approaching vessel (Aglen & Misund 1990), which probably causes a more strict schooling behaviour and thereby a more homogenous internal density distribution and a definite external shape (Freon, Soria & Gerlotto 1990).In addition to greater accuracy in dimension measurements by sonar at shorter range (Misund 1990), this will clearly contribute to a strengthening of dimension-to-biomass relationships. In addition, the biomass measures of Hewitt et al. (1976) were not excact, as they were based on skippers estimates of the fraction of a target school caught by purse seine.

The school-geometry-to-reflected echo energy correlations are caracterized by great variations among the schools. Therefore, no noticable improvement is gained by averaging the area measurements of the single schools as shown for the North Sea 1989 connection. Similar large variations among the schools are a feature also of the estimated biomass per unit school area or school volume. The reason is obviously a great variation in packing density from one school to another, which Misund (1990) has explained to be a consequence of the internal dynamics of a moving mass of individuals. Even if there are species specific tendencies in schooling behaviour (Partridge et. al. 1980), no species difference in biomass per unit school area or school volume were detected. There was, however, differences among the various seasons and regions in which the species were recorded. Such differences probably reflects variations in packing density as a response to different predator exposures among the various regions and seasons (Misund 1990). That the biomass per unit school area or school volume is rather independent of the fish length is due to the antagonisme of packing density and fish weight. Both are related to the cube of the fish length, but the length-to-density connection is inversely while the length-to-weight relation is directly.

The packing density variations induces substantial scattering in the estimated school dimension-to-school biomass regression. Generally there is variation by a factor of about 10, extremely by a factor of about 100. As the biomass per unit school volume or school area differed between various seasons and regions, similar differences were found for the elevations of the biomass-to-dimension regressions. The slopes did not differ, however, indicating that the way the external school dimensions grew were season or region independent. The strength of the area-to-biomass relationships is about similar to that of the volume-to-biomass relationships, which shows that the horizontal dimensions are more important determinants of school size than the vertical.

There is some uncertainty connected to the frequency adjustment of the Møre 1987 recordings, as Simmonds (1986) found that herring exhibited a falling frequency response in the interval 27 - 54 kHz. Omitting the frequency compensation would reduce the calculated biomass of these schools by about 30%. However, Misund and Øvredal (1988) estimated an in situ target strength of the Møre 1987 herring halfway between the frequency adjusted and the applied 38 kHz target strength.

The level of our relationships is generally somewhat lower than that of other comparable dimension-to-biomass relationships. Only the Møre 1987 average biomass per unit area of 16.2 kg/m^2 is comparable to the estimate of Hewitt et. al. (1976) of 15,6 kg/m^2 for Northern anchovy schools. For other regions and seasons, the average estimates were usually lower than 10 kg/m^2. Similarly, Misund (1988, 1990) has established school area-to-school biomass relationships for herring and mackerel, which for a 1000 m^2 school yields estimates around 30 tons. For a similar school size our relationships give maximum 12 tons (Møre 1987), usually around 5 tons, and only 0,2 tons for the Troms 1989 relationship. Both the Hewitt et.al (1976) and Misund (1988, 1990) relationships are based on measurements of schools singled out for purse seining, while we attempted to measure all schools recorded by the sonar. The lower averages of our relationships are therefore probably caused by our sampling strategy, as estimates of the purse seine established dimension-to-biomass relationships usually are within the interval of variation of our connections.

As shown when using the compensation factor established by Toresen (1990), the relationships suffers from a general underestimation of biomass due to absorbtion of acoustic energy in the schools. Application of the absorption compensation to the Lofoten 1988 and Gratangen 1989-recordings is justified by the fact that Toresen (1990) established the factor by measurements on similar sized herring (about 33 cm long) of the same yearclass (1983) that during daytime was schooling at about the same average packing density (1-2 individuals/m^3, Misund 1990) in the nearby Ofoten fjord. However, the compensation factor is based on an outline by Foote (1983) assuming a uniform density distribution within schools, which does not seem to be the case for herring schools (Misund 1990). Also the compensation factor does not account for large average density variations among the schools, but the average reflected echo energy adjustment are probably valid for the Lofoten 1988 and Gratangen 1989 - recordings.

Our investigations demonstrates that there exists relationships which enables conversion of sonar measured school dimensions to school biomass. Such relationships can also be established favourably by purse seine capture of sonar measured schools (Misund 1990, 1988), and thereby eleminating the uncertainties and sources of errors connected to acoustic packing density measurements. Wide-beamed fisheries sonars projects schools with a considerable distortion (Misund 1990), that induces an uncertainty of about 90 m on the crosswise extent of a school 250 m away when insonified by a 10° wide beam. Therefore, the strength of dimension-to-biomass relationships can be improved by using narrowbeamed, rather high frequency equipment with stochastic distortion compensation (Misund, Dalen & Aglen 1989). Established relations may be a helpfull tool in abundance estimation of schooling species, and if implemented in fisheries sonar, also used for precapture school biomass estimation.

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Table 1. Seasons, areas, and fish size for the recorded schools, and characteristics for the acoustic instruments. (N: no. of schools, KH_Z: frequency, φ: beamwidth: horizontal * vertical for sonar, and alongship * awartship for echo sounder, S: sonar, ES: echo sounder, no. of sizegroups in brackets). FF = R/V "Fjordfangst, E = R/V "Eldjarn".

Species	Season and year	Area	N	Average size (cm)	Vessel	KH_Z		φ		Pulse (ms)	
						S	ES	S	ES	S	ES
Herring	Sept 1987	Møre (fjord)	52	28.1 (1)	FF	150	70	6°*4,5°	11°*11°	2.4-5.6	0.6
	Mar 1988	Møre (fjord,coast)	41	29.3-30.0 (2)	E	34	38	10°*7°	8°*8°	3-9	1
	July 1988	North Sea	113	7.3 - 27.5 (19)	E	34	38	10°*7°	8°*8°	3-9	1
	Sept 1988	Lofoten (fjord)	71	32.3 (1)	FF	150	38	6°*4.5°	8°*8°	2.4-5.6	1
	July 1989	North Sea	87	23.8-29.3 (9)	E	34	38	10°*7°	8°*8°	3-9	1
	Sept 1989	Troms (fjord)	64	9.6-18.7 (3)	FF	150	38	6°*4,5°	8°*8°	2.4-5.6	1
	Oct 1989	Gratangen (fjord)	79	33.0 (1)	FF	150	38	6°*4,5°	8°*8°	2.4-5.6	1
Sprat	July 1988	North Sea	16	12.9-14.0 (2)	E	34	38	10°*7°	8°*8°	3-9	1
	July 1989	North Sea	3	11.0 (1)	E	34	38	10°*7°	8°*8°	3-9	1
Saithe	Sept 1987	Møre (fjord)	5	36.7 (1)	FF	150	70	6°*4,5°	11°*11°	2.4-5.6	0.6
	Sept 1989	Tromsø (fjord)	7	57.8 (1)	FF	150	38	6°*4.5°	8°*8°	2.4-5.6	1

Table 2. Results of nested analysis of variance using biomass/unit area (kg/m^2) as dependent variable.

	d.f.	Mean square	F-value	p	r^2
Model	30	337.9	6.31	<0.001	0.30
Source					
species	2	117.9	2.20	0.112	
region (species)	7	1023.2	19.10	<0.001	
length (species, region)	21	28.1	0.53	0.960	

Table 3. Results of nested analysis of variance using biomass/unit volume (kg/m^3) as dependent variable.

	d.f.	Mean square	F-value	p	r^2
Model	30	1.36	7.37	<0.001	0.34
Source					
species	2	0.24	1.28	0.278	
region (species)	7	4.16	22.56	<0.001	
length (species, region)	21	0.27	1.49	0.077	

Table 4. School area and school volume to school biomass regression equations (SE: standard error, abs.comp.: absorption compensated according to Toresen (1990)).

Species, region	log (Area) to log (Biomass)				log (Volume) to log (Biomass)			
and year	Area	SE	Intercept	r^2	Volume	SE	Intercept	r^2
Herring								
Gratangen 1989	1.44	0.08	-0.54	0.84	1.05	0.04	-0.59	0.89
abs.comp.	1.53	0.09	-0.72	0.82	1.14	0.04	-0.87	0.91
Lofoten 1988	1.15	0.14	0.12	0.56	1.12	0.08	-1.02	0.77
abs.comp.	1.17	0.16	0.16	0.52	1.17	0.08	-1.14	0.78
Møre 1987	1.21	0.15	0.48	0.59	1.00	0.09	-0.04	0.73
Møre 1988	1.58	0.20	-0.97	0.76	1.36	0.10	-2.14	0.91
Troms 1989	1.16	0.17	-1.33	0.44	0.85	0.11	-1.12	0.51
Herring and sprat								
North Sea 1988	1.53	0.11	-1.08	0.67	1.10	0.06	-0.93	0.76
North Sea 1989	1.55	0.09	-1.10	0.82	1.03	0.07	-0.59	0.79
Saithe								
Møre 1987/Troms 1989	1.76	0.21	-0.49	0.88	1.03	0.07	-0.69	0.96

Table 5. Comparison of slopes and elevations of the school area to school biomass regression equations for the different regions according to Zar (1984).

Region	Σx	Σxy	Σy	N	Slope	res SS	res Df
Gratangen 1989	16.9	24.3	41.9	69	1.44	6.96	67
Lofoten 1988	10.5	12.1	25.4	57	1.15	11.46	55
Møre 1987	6.0	7.3	15.0	45	1.21	6.12	43
Møre 1988	3.9	6.2	12.9	22	1.58	3.04	20
North Sea 1988	28.9	44.0	100.1	106	1.52	33.11	104
North Sea 1989	16.7	25.8	49.0	62	1.55	9.14	60
Troms 1989	10.2	11.8	31.2	61	1.16	17.55	61
Pooled						87.38	410
Common	93.1	131.5	275.5		1.41	89.76	416
Total	115.9	184.2	504.4	424	1.59	211.5	422

H_0: equal slopes: $F = 1.86$, $F_{0.05,\,7,\,410} \approx 2.03$ $p > 0.05$

H_0: equal elevations: $F = 93.97$, $F_{0.05,\,7,\,416} \approx 2.03$ $p < 0.05$

Table 6. Comparison of slopes and elevations of the school volume to school biomass regression equations for the different regions according to Zar (1984).

Region	Σx	Σxy	Σy	N	Slope	res SS	res Df
Gratangen 1989	34.0	35.7	41.88	69	1.05	4.42	67
Lofoten 1988	15.5	17.4	25.44	57	1.12	5.93	55
Møre 1987	10.95	10.95	15.01	45	1.00	4.06	43
Møre 1988	6.35	8.64	12.93	22	1.36	1.17	20
North Sea 1988	61.85	68.67	100.07	106	1.11	23.86	104
North Sea 1989	36.68	37.78	49.00	62	1.03	10.09	60
Troms 1989	21.54	18.52	31.27	63	0.86	15.34	61
Pooled						64.87	410
Common	186.87	197.66	275.60		1.06	66.53	416
Total	257.0	305.8	504.60	424	1.19	140.7	422

H_0: equal slopes: $F = 1.75$ $F_{0.05,\,7,\,410} \approx 2.03$ $p > 0.05$

equal elevations: $F = 77.30$ $F_{0.05,\,7,\,416} \approx 2.03$ $p < 0.05$

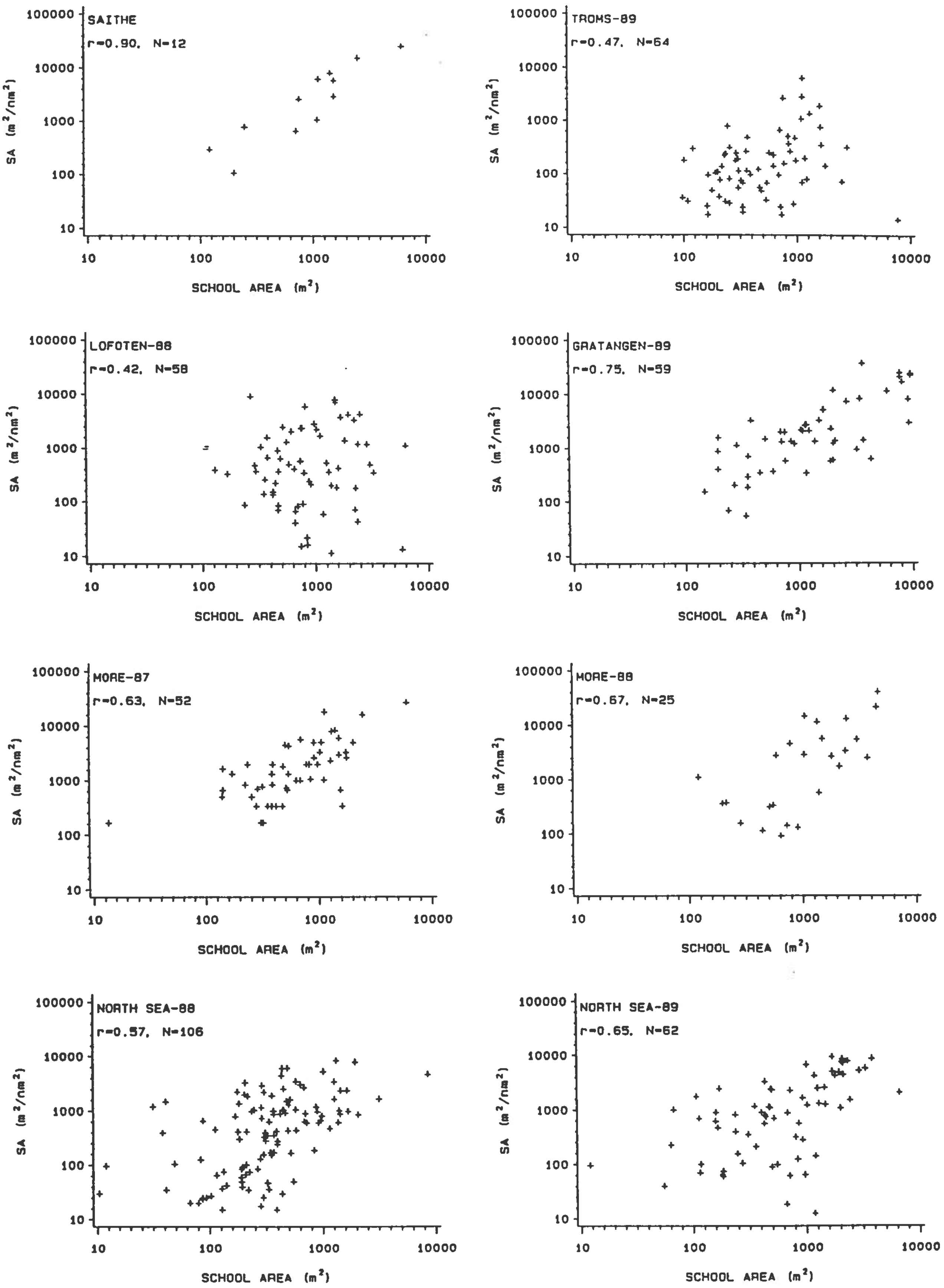

Figure 1. Correlations of reflected echo energy (SA = $C_I \cdot M$) and school area for saithe and herring and sprat schools in different areas and seasons.

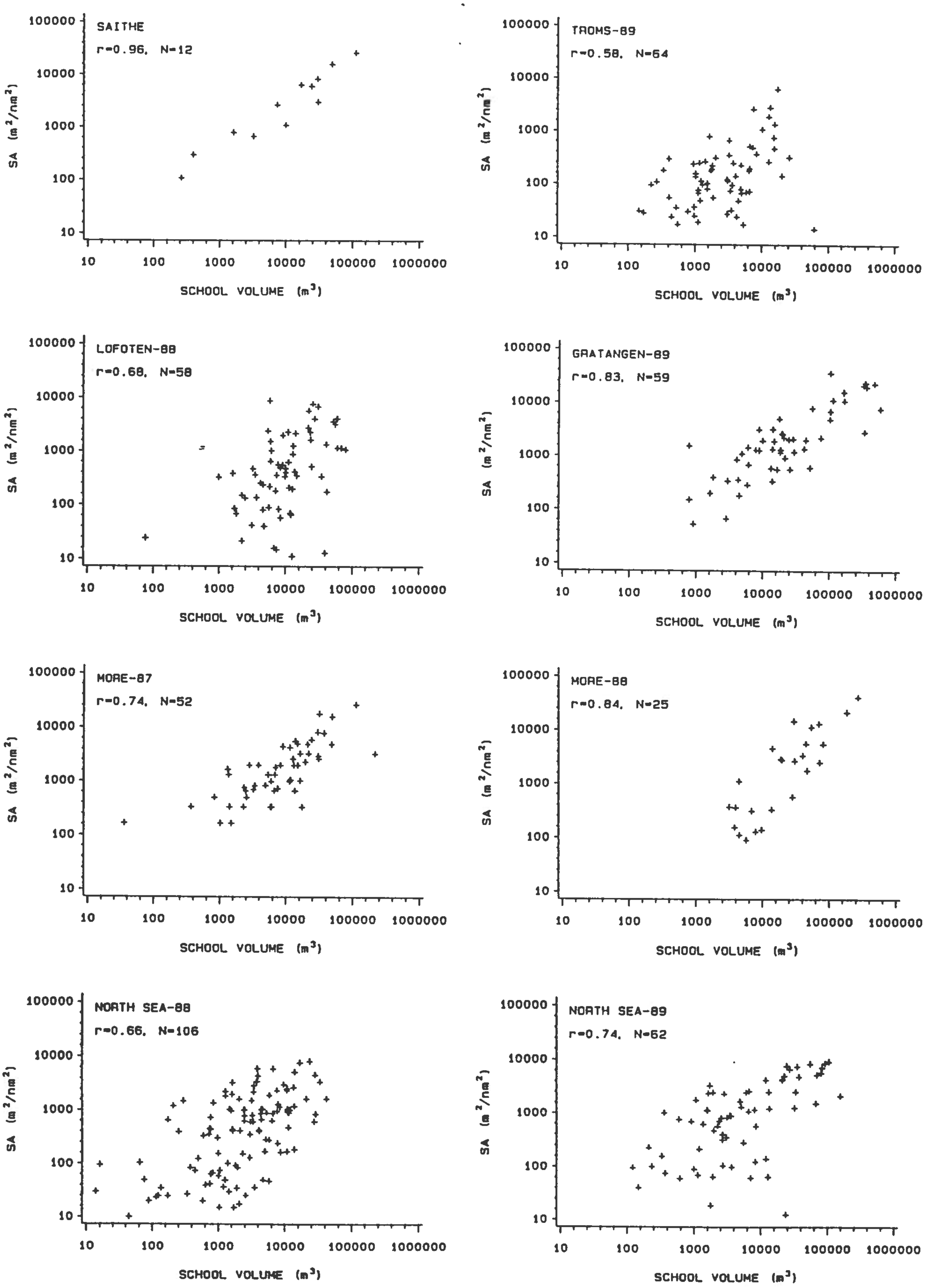

Figure 2. Correlations of reflected echo energy and school volume for saithe and herring and sprat schools in different areas and seasons.

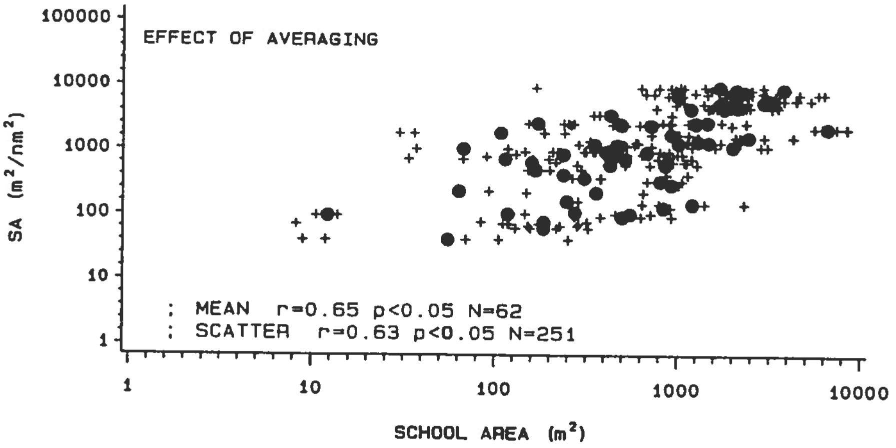

Figure 3. Effect of averaging measurements of school area on correlation between reflected echo energy and school area for herring and sprat schools recorded in the North Sea 1989.

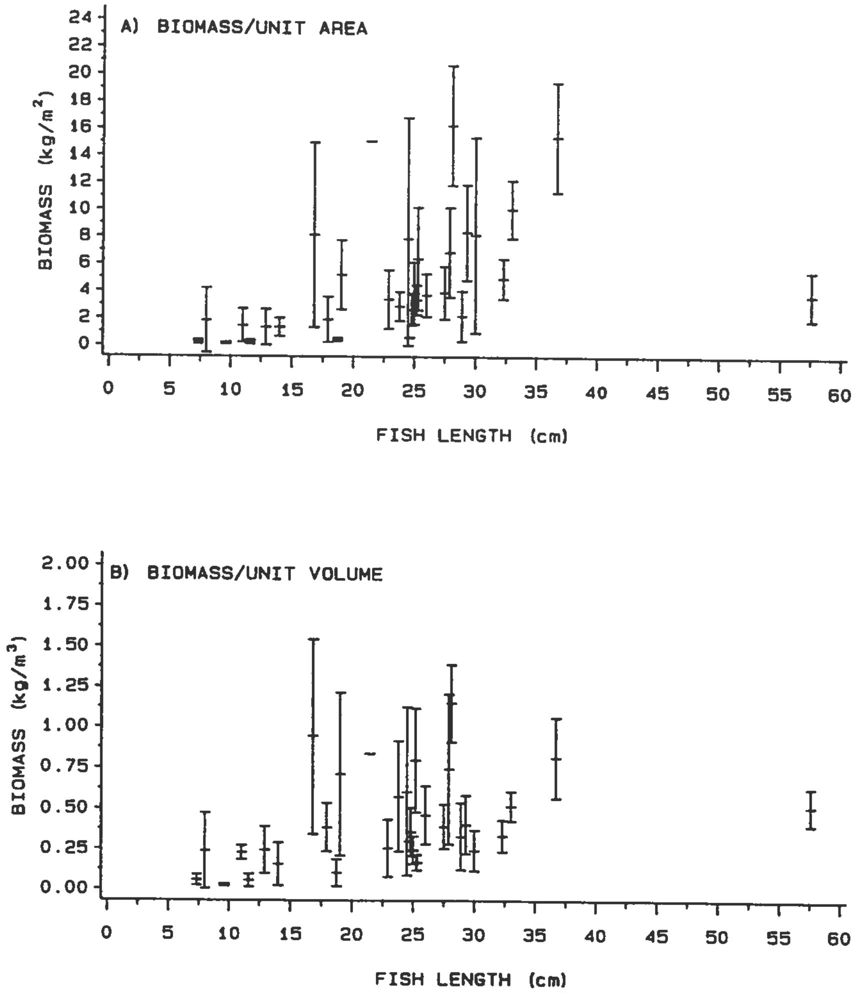

Figure 4. A) Average biomass per unit school area related to fish length .

B) Average biomass per unit school volume related to fish length (vertical bars: ± standard error).

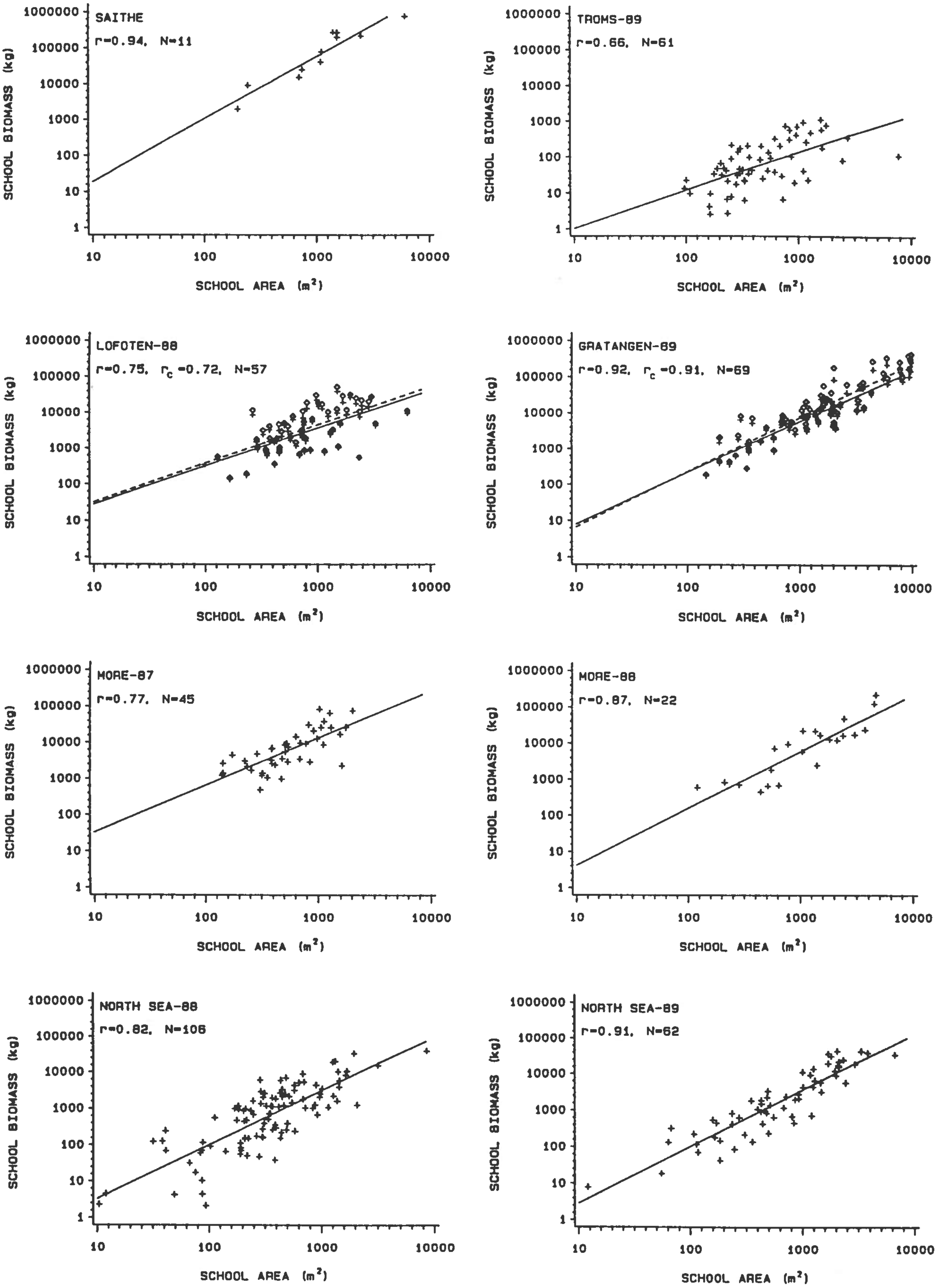

Figure 5. Regressions between biomass and area of saithe schools and herring and sprat schools in different areas and seasons (◊, r_c: absorption corrected).

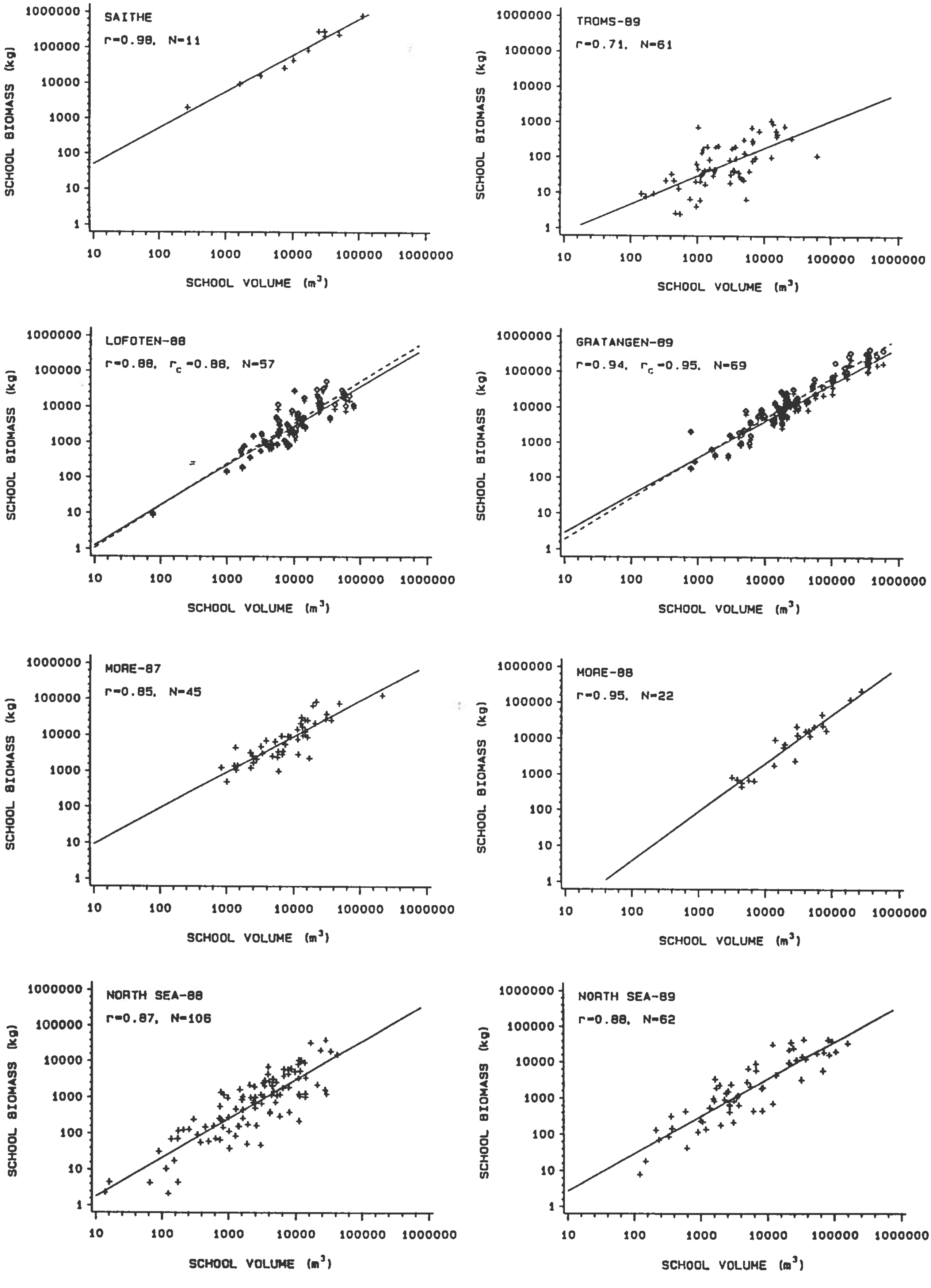

Figure 6. Regressions between biomass and volume of saithe schools and herring and sprat schools in different areas and seasons (◊, r_c: absorption corrected).