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A pilot-study: Evaluating the possibility that Atlantic Herring (*Clupea harengus L.*) exerts a negative effect on lesser sandeel (*Ammodytes marinus*) in the North Sea, using IBTS-and TBM-data.

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Danish abstract

Er sultne sild en potentiel trussel for tobis bestanden i Nordsøen?
Siden 2002 har størrelsen af Nordsøens tobis-bestand ligget på et historisk lavt niveau. Værst så det ud i 2005, hvor man frygtede et kollaps af bestanden. I dag har det derfor en høj prioritet at undersøge hvad som påvirker tobis bestandens størrelse.

Tobiser forefindes i store dele af Nordsøen, hvor den lever i tilknytning til sandbanker i dybder fra tyve til et hundrede meter. Voksne tobiser bevæger sig kun op i de frie vandmasser mens de søger føde, hvilket foregår om dagen og hovedsagligt i månederne april, maj og juni. Resten af tiden er de nedgravet i sandet, dog med undtagelse af gydningen, som finder sted omkring nytår. De første måneder af tobisens liv tilbringes permanent i de frie vandmasser, hvor de i høj grad føres af sted af havstrømmene. Når de er omkring tre måneder gamle påbegynder de den karakteristiske nedgravningsadfærd, men vil fortsætte med at søge føde i månederne efter de voksne tobis har påbegyndt deres overvintring.

Hvor tobis findes, udgør de ofte enorme antal. I Nordsøen udgjorde de en større biomasse end nogen anden fiskeart, og i kraft af deres ringe størrelse og enorme forekomster spiller de en vigtig rolle som føde for havfugle og havpattedyr såvel som fisk. Men i de seneste år er silden i Nordsøen gået stærkt frem og udgør i dag en lige så stor biomasse som tobis.

Et for nylig afsluttet pilot-arbejde under Danmarks Fiskeri Undersøgelser (DFU), havde til formål at undersøge om Nordsøens sild havde nogen effekt på tobis bestandens størrelse. Undersøgelsen benyttede information om sild fanget under IBTS (International Bottom Trawl Survey) og kommercielle tobis fangster i perioden 1983 til 2003.

Det var ikke muligt at nå en endelig afgørelse på grund af begrænsninger i data, men resultatet af undersøgelsen gav grund til ikke at forkaste muligheden for, at sild kan have indflydelse på tobis-bestandens størrelse. Det blev foreslået, at især store koncentrationer af unge sild kan udgøre en trussel i de år, hvor tobis-ynglen dominerer dyre-planktonet om foråret. Det er ikke ukendt at sild spiser tobis-yngel og endda voksne tobis, hvis muligheden foreligger. Der var dog intet som tydede på at sild alene kan have forårsaget den alvorlige nedgang i tobis-bestanden, som var en realitet i 2002.

Content

1. Introduction

Following the alarmingly reduced sandeel recruitment in 2002 in the North Sea (ICES, 2005b) and the indications of total stock collapse in 2005 (ICES Press Release, 2005 17. October: Overhaul deep-sea fisheries, sharks in trouble, good and bad news for other fish stocks, www.ices.dk), identifying the factor or factors that may influence the sandeel in the North Sea, has become of high priority.

The lesser sandeel (*Ammodytes marinus*) is a fairly small and eel-shaped fish. In the North Sea in general only a few percent reaches length of more than 15-20 cm. The lesser sandeel can easily be confused with several other sandeel species such as *Hyperolpus lanceolatus, Hyperolpus immaculatus, Ammodytes tobianus,* and *Gymnammodytes semisquamatus.* However, in the off-shore North Sea the absolute majority of sandeel consist of *Ammodytes marinus*. Lesser sandeel is found in large parts of the North Sea with a distribution closely related to well-oxygenated bottom substrate consisting of gravel or coarse sand, and water depths between 20 and 100 meters (Reay, 1970). Such habitats are often associated with banks. The sandeel is characterized by an unusual seasonal behavioural rhythm. The lesser sandeel spend most of the year, from about July to April, buried in the substrate (Winslade, 1974a). This winter hibernation behaviour is only interrupted by the spawning which occurs in December/January. In the southern North Sea the age at 50 % maturity occurs around age 1 (Macer, 1966), while 50 % maturity in the northern North Sea occurs around age 2 (Bergstad et al., 2001). The eggs stick to the substrate on the banks, often partly buried. They normally hatch during February and Marts (Wright and Bailey, 1996; Macer, 1965). After hatching the larvae enter the pelagic environment and are found in most of the water column (Conway et al, 1997). Metamorphosis occurs at a length of around 45 mm and around 33 to 90 days from the time of hatching (Wright and Bailey, 1996). However, gear avoidance is evident from the length of only 20 mm (Jensen et al, 2003).

The sandeel appears in the water column again around April, the exact time and emergence pattern may be dependent on location, temperature etc. Before August almost all the 1-group (sandeel with one winter ring in the saggitae otolith) and older fish will again be buried in the substrate and will not appear in the water column again before the spawning event. The 0-group fish often stay in the water column for longer than the adult sandeel and can still be found in the pelagic environment in vast quantities in September (Winslade, 1974a; Reeves, 1994). During the feeding period the adult

fish stay in the vicinity of the banks and continue their burying behaviour from dusk until dawn and possibly also for shorter periods during the day when feeding conditions are suboptimal (Winslade, 1974b). This behaviour is likely to have been evolved as a way to minimize predation risk.
It has not been established whether the lesser sandeel in the North Sea should be considered as one stock, several individual stocks, or a dynamic complex of several temporary stocks. There seems, however, to be demographic differences between bank systems (Pedersen et al., 1999).
The sandeel are most likely to play a very important role in the ecosystem as a link between the lowest trophic levels and the higher trophic levels. Sandeel play an important role in the diet of a long list of piscivorous fish, mammals, and sea birds (Monaghan et al., 1989; Sparholt, 1990;).
And since the sandeel constitutes one of largest biomasses by species in the North Sea (Temming, 2004; ICES, 2005a), a complete stock collapse is likely to have a broad and severe effect on the entire ecosystem of the North Sea.

Among the factors that are known to affect recruitment of lesser sandeel in the North Sea is water temperature, Calanus abundance, and a density dependent regulation on the recruitment.
The density dependent effect is expressed as a negative autocorrelation of recruitment. This negative autocorrelation have proved to be more important than the spawning stock biomass (SSB), which is often assumed to play an important role regulating the recruitment of fishes (Arnott and Ruxton, 2002). It is however, worth noticing that regional differences in the magnitude of influence of these factors may exist (Arnott and Ruxton, 2002; Pedersen et al., 1999).
While there may be indications of a long term decline in copepod concentrations for the North Atlantic in general, the North Sea does not follow this trend. Furthermore, there were no indications that unusual low copepod abundances could have been responsible for the recent recruitment failures in 2002 or 2004 (ICES, 2005c).

It is tempting to suggest that the global climatic changes may be responsible for the recent recruitment failures of the sandeel in the North Sea. The southern part of the North Sea and the Irish Sea constitute the southern boarders of the sandeel distribution range. The global climate changes could have caused the water temperatures of the North Sea to rise, which in turn will shift the southern boarders of the distribution range toward the north. Brander et al. (2003) used sea surface temperature (SST) data from the ICES Ocean Climate Status Summary dating from the beginning of the 20th century and up till the late 1990s. They found support of an average sea surface SST

increase over most of the North-east Atlantic of at least 0,4 degrees celcius since the late 1980s, and that the majority of the species studied displayed a shift in distribution apparently as a result of this (only flatfishes and gadoids). However, the North Sea was not entirely consistent with the general temperature trend. The North Sea showed an increase in SST in the period from the late 1980s to the early 1990s followed by a decrease in SST. Brander et al. also emphasizes that the temperature data available is fragmented and often based on less than sufficient sampling. In contrast to Brander et al. Carl et al. (2004) focused on the North Sea, Kattegat and Skagerrak and found that the invasion rate in the North Sea of arctic and sub-arctic species equals the invasion rate of species with a more southern distribution range.
Furthermore, a look on available temperature data (SST) from the North Sea (e.g. Brander et al., 2003) does not indicate any relationship between SST and sandeel recruitment.

According to ICES fishery mortality does not play any significant role in the regulation of sandeel population dynamics. The Danish sandeel fishery was established in the 1950s. The Danish commercial fishery on sandeel has been monitored since the beginning of the 1980s by the Danish Institute of Fisheries Research. In the 2005 ICES report on sandeel it was stated that the mortality of the sandeel appears to be determined mostly by natural causes (ICES, 2005b).

It has been suggested that herring of the North Sea (*Clupea harengus L.*) is an important predator on early life stages of a number of demersal species. This was based on the observation that the recruitment of a number of demersal stocks increased in the 1970s simultaneous with the collapse of the North Sea Herring stock (Last, 1989). However, there have never been made any attempt to present scientific proof for this relationship. In the West Atlantic, however, Sherman (1981) found that an increase in the sandeel numbers was associated with an overexploitation of the herring stocks of the area.

The North Sea Herring is an important player in the North Sea ecosystem. And has become more and more so since the recovery of the stock in the 1970s (Nichols, 2000). Today the stock constitutes one of the largest biomasses in the North Sea (ICES, 2005a).

Herring are mainly planktivorous fish and the main food source in the North Sea and adjacent waters is likely to be *Calanus finmarchicus* (Bainbridge et al., 1978; Dalpadao et al., 1996; Planque and Fromentin, 1997). They appear, however, to be flexible when it comes to feeding behaviour.

Several different feeding strategies have been reported ranging from selective zooplankton feeding (Dalpadao et al., 1996), filter feeding (Batty et al., 1986; Gibson and Ezzi, 1992), to selective feeding on fish (from personal communication with Palle Brogaard, pb@dfu.min.dk; Dalpadao, et al. 1996). The latter includes observations of herring preying on 1-group sandeel in ICES rectangles 41E8 and 41E9 in the morning 16th of May (from personal communication with Palle Brogaard, pb@dfu.min.dk) and an arctic study in which pearl sides (*Maurolicus muelleri*) was found to be abundant in the herring stomach samples in April (Dalpadao et al., 1996). The literature also describes the presence of sandeel larvae and post-larvae in herring stomachs from the North Sea (Savage, 1937; Pommeranz, 1981; Hopkins (symposium), 1989; Last, 1989). In a study conducted from 1930 to 1934, the sandeel-larvae were found to be the second most important source of food in the southern North Sea in May/June (Savage, 1937). Lastly, Hopkins (1989 (Symposium)) observed large numbers of larvae in the stomach of herring in localized geographically areas of high larvae incidence in the North Sea.

The herring often aggregate in large schools. They tend to stay near the surface at night time were the schools often disaggregate and the feeding stops. At dawn the schools will form again and the herring will seek away from the surface. Feeding tend to peak during dusk and dawn, however this pattern may vary (Freon and Misund, 1999; Darbyson et al., 2003).

The North Sea stock of the Atlantic Herring consist of autumn spawners (and a relatively small proportion of winter-spawners), which spawn along the British east coast, in both inshore and off-shore areas. The first significant spawning events take place in the northern part of this area in August/September and are followed by spawning events further south as the autumn progresses. The last spawning event takes place around December-January in the English Channel. The North Sea stock can be subdivided into three sub-stocks or populations with different associations to the geographic spawning sites (Northwestern -, Central- and English Channel -subcomponent). The long term trends have been that the two most northerly stock components, Northwestern- and Central, tend to migrate north-east after spawning to overwintering areas in the Norwegian trench. In the spring they migrate from the overwintering areas to feeding grounds in the northwestern North Sea. In contrast, the Downs-herring tend to overwinter in the southern North Sea and migrates in the spring to feeding areas mainly in the central North Sea. For all three populations the larvae are transported in the currents to nursery areas in Skagerrak, Kattegat, and the eastern parts of the North Sea (Corten, 2001; Nichols, 2001).

In this report the possibility that the North Sea Herring exert a negative effect on the lesser sandeel stock of the North Sea will be evaluated and an ecological sensible hypothesis, explaining a potential interaction, will be proposed.

2. Materials and Methods

2.1. Data

IBTS-data (International Bottom Trawl Survey) on herring from quarter 1 and quarter 3, IBTS-data on herring larvae from quarter 1, and TBM-data on Danish commercial catches of lesser sandeel were used. The time series in the study was 1983 to 2003.

Data on herring were downloaded, with permission, from the ICES database. Data were given in CPUE (in numbers) per length group, ICES-rectangle, quarter, and year. IBTS data on Herring-larvae given as abundances per m^2 for each sample were provided by Peter Munk, Danish Institute for Fisheries Research. Data from quarter 1 were sampled in January/February and data from quarter 3 were sampled in August/September.

TBM-data on total catches of sandeel in tons per ICES-rectangle, month, and year were provided by the EU BECAUSE-project. Catches were given as catches in tons per day fishing standardised to a 212 GT vessel.

2.2. GIS Maps

A range of maps, visualising overlaps between herring and sandeel on ICES rectangle level, were produced in GIS (Geographical Information System). A layer displaying the distribution of commercial sandeel fishing areas was added to the maps (Jensen, 2005 (to be published)).

2.3. Study areas

Figure 1 presents the study areas.

The North Sea was subdivided into three sub-areas, region 1 through 3, and the areas were assessed individually. Pedersen et al. (1999) found, for corresponding regions, that the regions differed with respect to population dynamics. The area in the vicinity of Firth of Forth and Shetland Islands was not included in this report because of partial lack of TBM-data from these areas.

Hydrology based drift-simulations forced by metrological data (Asbjørn, 2005 (to be published)) supported that region 1 through 3, were relatively closed systems with respect to sandeel population dynamics.

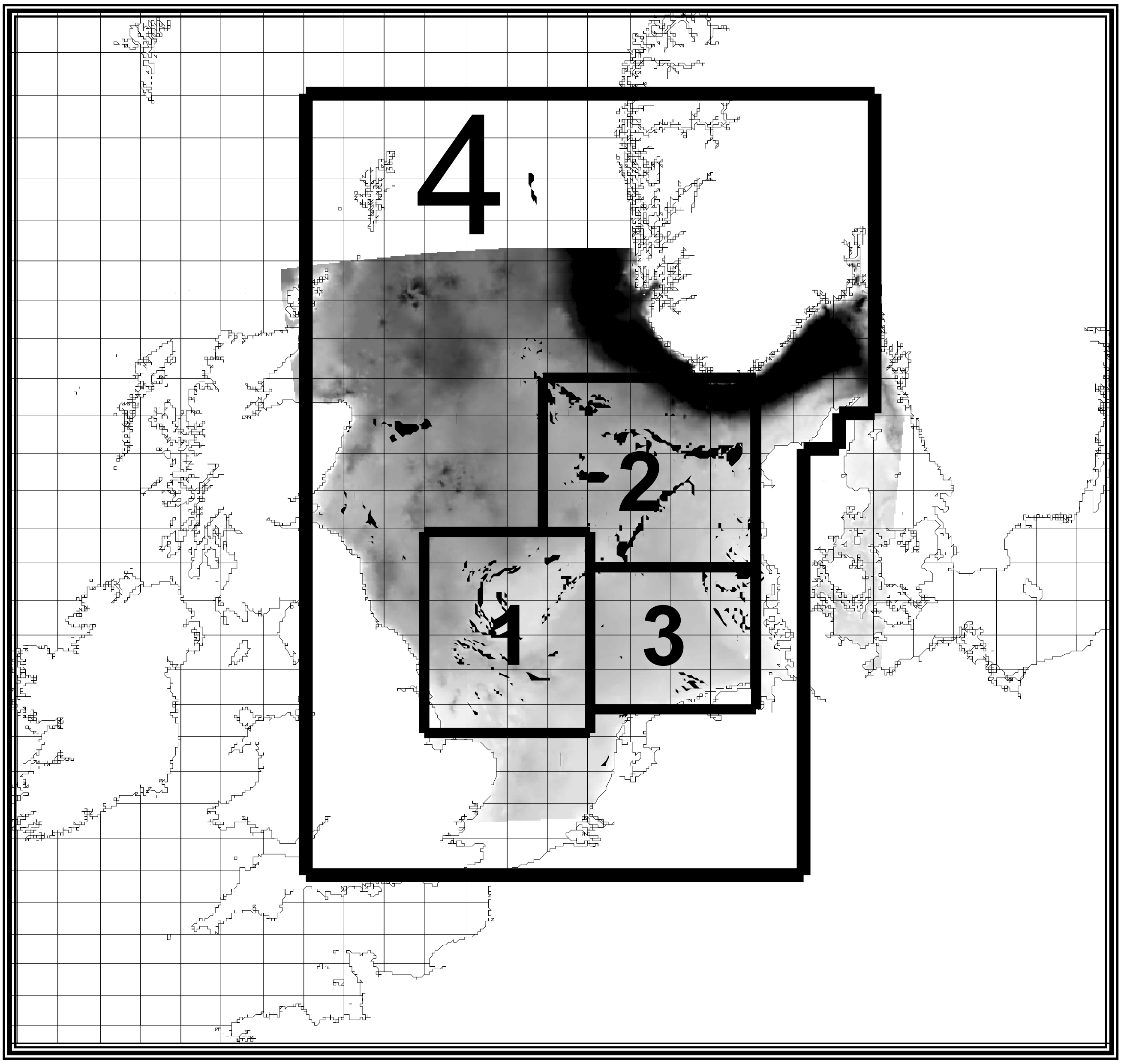


Figure 1: Presentation of the study areas (region 1 through 3) used in this report. Region 4 are only used in cases where it made sense to include sandeel catched or herring samples from outside the study areas. Region 1 through 3 are adopted from Pedersen et al. (1999).

2.4. Statistical approach

The problem is approached by screening for potential relationships between various sandeel- and herring-indexes. Eleven different herring related indexes and five sandeel indexes were applied. All indexes were calculated for 1983 through 2003 (IBTS quarter 3, were only available from 1991) and for region 1 through 3 (defined in section 2.3.). Relationships between herring-indexes and sandeel-indexes were identified by conducting a simple linear regression-analysis (altogether 156 regression-analyses). Slope, R-square, and p-value were derived from the regression-analyses. The P-value refers to a null-hypothesis which states that the slope of the regression line equals 0. Some of the herring-indexes are calculated from the same data and may be highly correlated. The herring-indexes were therefore grouped in 5 independent index-“families”. Study region 1 through 3 were also assumed to be independent. This resulted in 72 independent combinations of variables to conduct 72 independent simple linear regression models. However independent model belonged to a “family” of dependent models or one could say variations of the same model (the highest number of dependent models within a “family” was four). To cancel out the risk of committing a type 2 error due to multiple model-testing, the binomial distribution probability was applied. According to the binomial distribution probability one would expect 6 out of the 72 P-values to be 0.05 or less just by chance. It was therefore found plausible to consider the possibility of a relationship between sandeel and herring if more than six P-values, out of the 156 P-values derived from 72 independent tests, came out smaller than 0.05.

2.6. Calculating indexes

Ten region-specific herring-abundance indexes were calculated as well as five region-specific recruitment index for sandeel. Indexes were calculated for each year over a period of 21 years (1983-2003). The sandeel-indexes were calculated for region 1-3 respectively, while the herring-indexes were calculated also for region 4. Information on the individual indexes and how they were calculated are presented next:

Sandeel_biomass_index:	This index is a sandeel biomass index. CPUE-values from the month containing the maximum CPUE-value in each ICES-rectangle within the given region were applied. The sum of these peak CPUE-values were used as the sandeel

	biomass index **Sandeel_biomass_index**. The CPUE-values were given as catch in tons per day, standardized to a 212 GT fishing vessel: **Sandeel_biomass_index** = $\text{maxCPUE}_{sq(1)} + \text{maxCPUE}_{sq(2)} \ldots + \ldots \text{max-CPUE}_{sq(n)}$, where sq(1) through sq(n) represent each ICES-rectangle within the region in question.
Sandeel_spawning.stock_index:	This index is an index for sandeel spawning stock biomass. The index is the fraction of the **Sandeel_biomass_index** that consists of 2-group and older. The age-distribution was based on quarter 2 age: **Sandeel_spawning.stock_index** = ([2-group and older]/ [all ages]) * **Sandeel_biomass_index**, where [] denote count of ... (e.g. [all ages] ~ total number of sandeel in the age samples).
Sandeel_1wr_index:	This index is an index for the abundance of 1-group sandeel based on the fraction of **Sandeel_biomass_index** consisting of 1-group sandeels: **Sandeel_1wr_index** = ([1-group] / [all ages]) * **Sandeel_biomass_index**
Sandeel_recruitment_index:	This index is an index for the size of the sandeel recruitment. No reliable data on 0-group sandeel were available. Instead **Sandeel_1wr_index** calculated for the following year was used: **Sandeel_recruitment_index**$_y$ = **Sandeel_1wr_index**$_{y+1}$, where y represent a given year. This approach was also applied by Arnott and Ruxton (2002).
R/SS:	This index is an index describing the recruitment relative to the size of the spawning stock. This index is calculated from the formula: (**Sandeel_recruitment_index**) /

(**Sandeel_spawning.stock_index**).
This type of relative recruitment measure, inspired by the Ricker function (Hilborn and Walters, 1992), and were also applied by Arnott and Ruxton (2002).

Survival.of.1wr: This index gives a proportion of 1-group sandeel surviving long enough to enter the 2-group: **Survival.of.1wr** = ([1-group]$_{y+1}$ / [all ages]$_{y+1}$) * **Sandeel_biomass_index**$_{y+1}$ / **Sandeel_1wr_index**$_{y}$, where y is the year in question.

Residuals.of.R&1wr: **Residuals.of.R&1wr** is the residuals of the regression line derived from **Sandeel_1wr_index** (x-axis) plotted against **Sandeel_recruitment_index** (y-axis). The residual are then calculated from: (observed y-value) - (calculated y-value).

Herring_Q1_mean.CPUE: **Herring_Q1_mean.CPUE** aims to reflect the number of herring in quarter 1. IBTS herring-data from quarter 1 given as CPUE in numbers per length group per ICES-rectangle (www.ices.dk). Since CPUE are given for each of several length groups the CPUEs are summed for each square resulting in one fish-length independent CPUE-value per ICES-rectangle:
Herring_Q1_mean.CPUEmass = (CPUE''$_{sq(1)}$ + CPUE''$_{sq(2)}$ …+… CPUE''$_{sq(n)}$) / n, where sq(1) through sq(n) represent each ICES-rectangle within the region in question. CPUE'' represent the fish-length independent CPUEs.

Herring_Q1_median.CPUE: As for the index above, this index aims to reflect the number of herring in quarter 1. The index was calculated in the same way as the index above except that the median was used instead of the mean. This was done to avoid that the mean should be driven by one on a few very large or very small values. As can be seen in Figure 7 the CPUE-values varies enormously from square to square and even from haul to haul within the squares. The index is given in millions.

Herring_Q1_mean.CPUEmass: This index aims to reflect the biomass of herring in quarter 1. The index was calculated from IBTS herring-data from quarter 1 given as CPUE in numbers per length group per ICES- rectangle (www.ices.dk). The following relationship between herring length and weight were used to transform the length-groups into weight-groups: $\text{weight(g)}=e^{(2,5 * \ln(\text{length(mm)}) - 9)}$ (derived from Acoustic Survey data from 2003, Danish Institute of Fisheries Research). The original CPUEs were given as number (in millions) of herring per length group per ICES-rectangle. A new biomass related CPUE-value was calculated for each ICES-rectangle by multiplying the original CPUE by the corresponding weight-group. The sum of these products within each ICES-rectangle were taken as the new square specific biomass related CPUE. The mean of these square specific biomass related CPUEs constituted **Herring_Q1_mean.CPUEmass**:

Herring_Q1_mean.CPUEmass = ($\text{CPUE'}_{sq(1)}$ + $\text{CPUE'}_{sq(2)}$ …+… $\text{CPUE'}_{sq(n)}$) / n, where sq(1) through sq(n) represent each ICES-rectangle within the region in question. CPUE' is the biomass related CPUE.

Herring_Q1_median.CPUEmass: As for the index above, this index aims to reflect the biomass of herring in quarter 1 in tons. The index was calculated in the same way as the index above except that the median was used instead of the mean. This was done to avoid that the mean should be driven by one or a few very large or very small values. As can be seen in Figure 7 the CPUE-values vary enormously from square to square and even from haul to haul within the squares.

Herring_Q1_>150mm: It is possible that only the larger herring prey on sandeel. Especially in cases where herring feed on adult sandeel. It is therefore the purpose of this index to focus on larger herring.

This index was designed to reflect the biomass of herring, in quarter 1, larger than 150 mm. The index was calculated using the same procedure as for **Herring_Q1_median.CPUEmass**, except only length-group 150 mm and up were included.

Herring_Q3_mean.biomass: This index was designed to reflect the biomass of herring in tons in quarter 3. The index is calculated in the same way as **Herring_Q1_mean.weight**, except IBTS-data from quarter 3 was applied.

IBTS-data from quarter 3 was only available from 1991 to 2003.

Herring_Q3_median. biomass: As for the index above, this index aimed to reflect the biomass of herring in quarter 3. The index was calculated in the same way as the index above except that the median was used instead of the mean. This was done to avoid that the mean should be driven by one or a few very large or very small values.

IBTS-data from quarter 3 was only available from 1991 to 2003.

Herring_Q3_>200mm: This index was designed to reflect the biomass of herring in quarter 3 and larger than 200 mm. The index was calculated using the same procedure as for **Herring_Q3_median.biomass**, except only length-group 200 and up were included.

In contrast to **Herring_Q1_>150mm** this index uses a larger size limit of 200 mm. This was done to adjust for the relatively larger size of the 0-group sandeel in quarter 3 compared to quarter 1.

IBTS-data from quarter 3 was only available from 1991 to 2003.

Herring.larvae_mean: This index aimed to reflect the abundance of herring larvae in February. The index was based on larvae sampling from the IBTS-cruises. The larvae data were available as calculated numbers of larvae per m^2 per haul per ICES-rectangle. The mean of these calculated abundances were used as the index: **Herring.larvae_mean** = ($L_{sq(1)} + L_{sq(2)}$ …+… $L_{sq(n)}$) / n, where sq(1) through sq(n) represent each ICES-rectangle within the region in question, and L represents the larvae abundance estimates given in the IBTS-data.

Herring.larvae_median: As for the index above, this index is intended to reflect the abundance of herring larvae in February. It is calculated in the same way as the index above except that the median were used instead of the mean. This was done to avoid that the mean should be driven by one or a few very large or very small values.

Her.larvae_median*mean.size: As for the indexes above, this index is intended to reflect the abundance of herring larvae in February. However, it also takes into account the mean size of the larvae when sampled in February. This was simply done by multiplying **Herring.larvae_ median** by the mean of the mean length (mm) per ICES-rectangle, as given in the IBTS-data: **Her.larvae_median*mean.size** = ML * **Herring.larvae_median**, where ML is the mean of ICES-rectangle specific mean lengths within the region in question.

2.8. Programming

R (www.R-project.org) was used to design a program to assist in the otherwise time consuming process it is to calculate 15 different indexes and cross-relate them via 156 linear regression analyses.

The program is a helpful tool when a large amount of data needs to be screened in ways similar to the approach used in this report. The program can easily be modified and used to evaluate the possibilities of interaction between any species of fish, as long as the data are sorted by ICES-rectangle and are available for a relatively large number of years in continuation.

3. Results

3.1. The big picture

The failed recruitment in 2002 coincided with very high relative abundances of herring in all regions in both quarter 1 and 3, most pronounced in quarter 3. There was however no unusual high herring abundances in 2004 in any region (Figure 2).

The year 2002 was not a year of relatively high abundances of herring larvae in any region including region 4, and 2004 was in fact a year of very low larvae abundances (Figure 2).

Sandeel catches overlapped (on an ICES-rectangle level) sporadically with the herring (Figure 3, Figure 4, and Figure 5). It is however important to keep in mind that the time of sampling of herring did not coincide with the time of the sandeel-catches (sandeel catches shown in Gis-maps are from June and the herring samples from February/Marts). The largest proportion of the herring tended to be located just outside the fishing areas but inside the defined region 1 to 3. The overlap between herring and sandeel catches did not change notably from quarter 1 to quarter 3, the overlap may however have been a bit more pronounced in quarter 3 with respect to region 2 and 3. The size-distribution of the herring within the overlap did not change notable either from quarter 1 to 3. One exception was the area associated with Firth of Forth (east coast of southern Scotland). This area seemed to attract fairly large amounts of herring in quarter 3 in some years. These herring were relatively large compared to that of region 1 to 3 and may have entered the area from feeding grounds in the north-west North Sea to initiate the autumn spawning event. Herring tended to be relatively small in region 1 and 2, in all years, compared to the north-west North Sea. Herring larger than 30 cm occurred frequently, and in relatively large numbers, in region 1, whereas they were rare in region 2 and basically not existing in region 3. The majority of the herring were 20-30 cm in region 1 and region 2, and 10-20 cm in region 3. (Figure 6)

The abundance of herring larvae in February/Marts change dramatically between years the overlap with fishing areas by the time of larvae sampling were however minute with the greatest proportion of the overlap restricted to region 1 (Figure 5).

Figure 7 reveals that, even though the general majority of the herring was found just outside the fishing areas, large quantities of herring were occasionally found on the banks and fishing areas.

Figure 8 shows a shift in the distribution of herring larvae in February over the last twenty years (this data and the shift in distribution was previously reported in (ICES, 2004a).

The general trends for sandeel and herring abundance in region 1 to region 3 between 1983 and 2004 will be summarized next: From 1983 to around 1990, region 1 possessed the greatest quantities of sandeel, however since the beginning of the 1990s the quantity of sandeel in region 2 increased to levels similar to region 1. Figure 2 reveals large variation in the herring abundance with as much as a factor seven from one year to the next. There was a more pronounced year-to-year variation after 1994 with peak years reaching high levels of herring abundance not seen between 1983 and 1994. The fewest herring were found in region 2 while the concentration of herring larvae was about the same in February for all three regions. However, region 3 in 2001 stood out with a larvae concentration about five to ten times larger that in other years.
There was also variation between regions. The sandeel recruitment and spawning stock biomass followed only roughly the same trend whereas the biomass tended to vary a lot between regions. There was only little conformity between regions with respect to herring abundances (Figure 9).

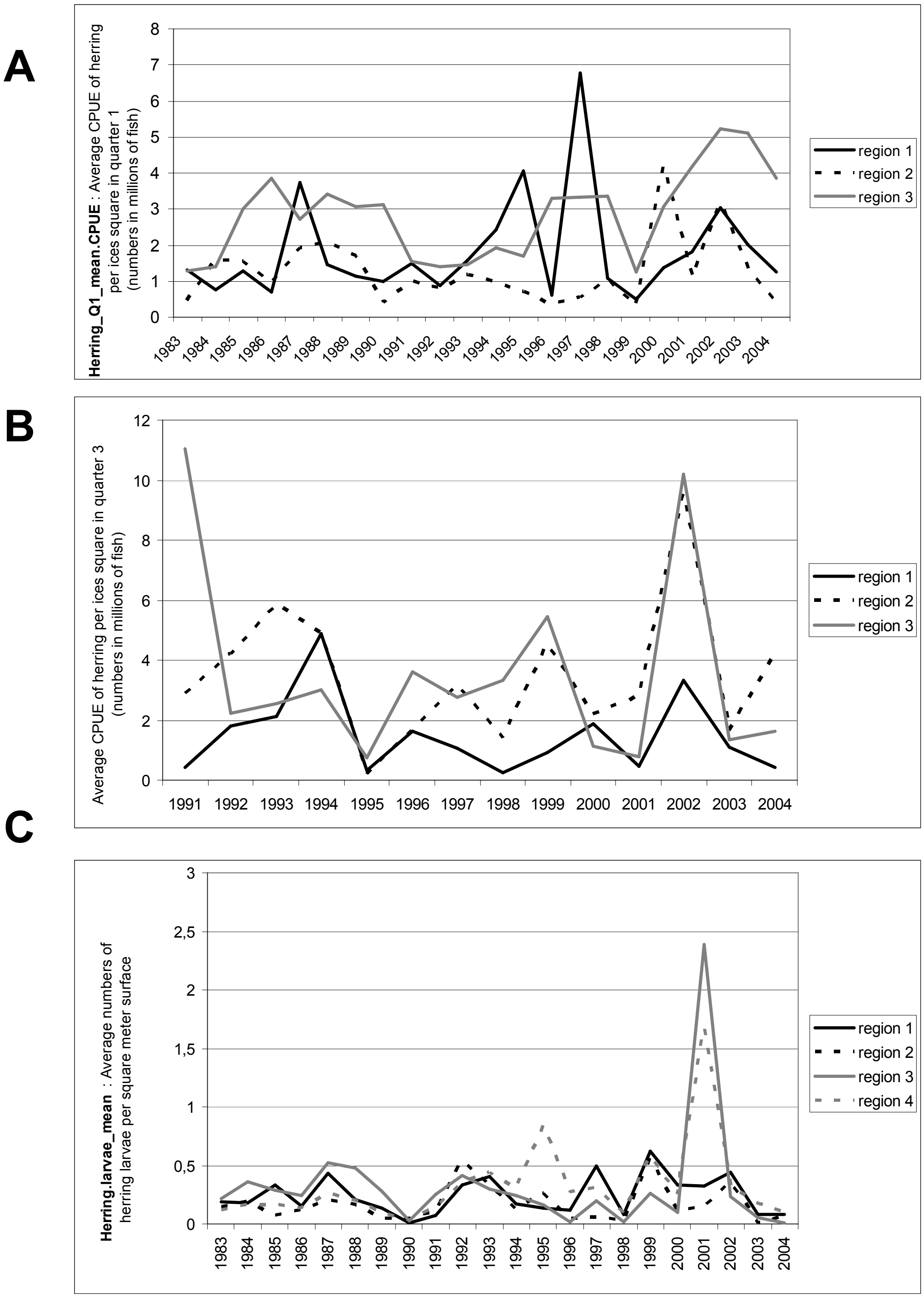


Figure 2: A: Average CPUE of herring in quarter 1 for the respective regions. B: Average CPUE of herring in quarter 3 for the respective regions. C: Average abundance of herring-larvae in February/Marts for the respective regions (region 4 was included to get an estimate of the average number of larvae in first quarter in the North Sea (region 4 does only partly correspond to the North sea) with out respect to the location of the larvae).

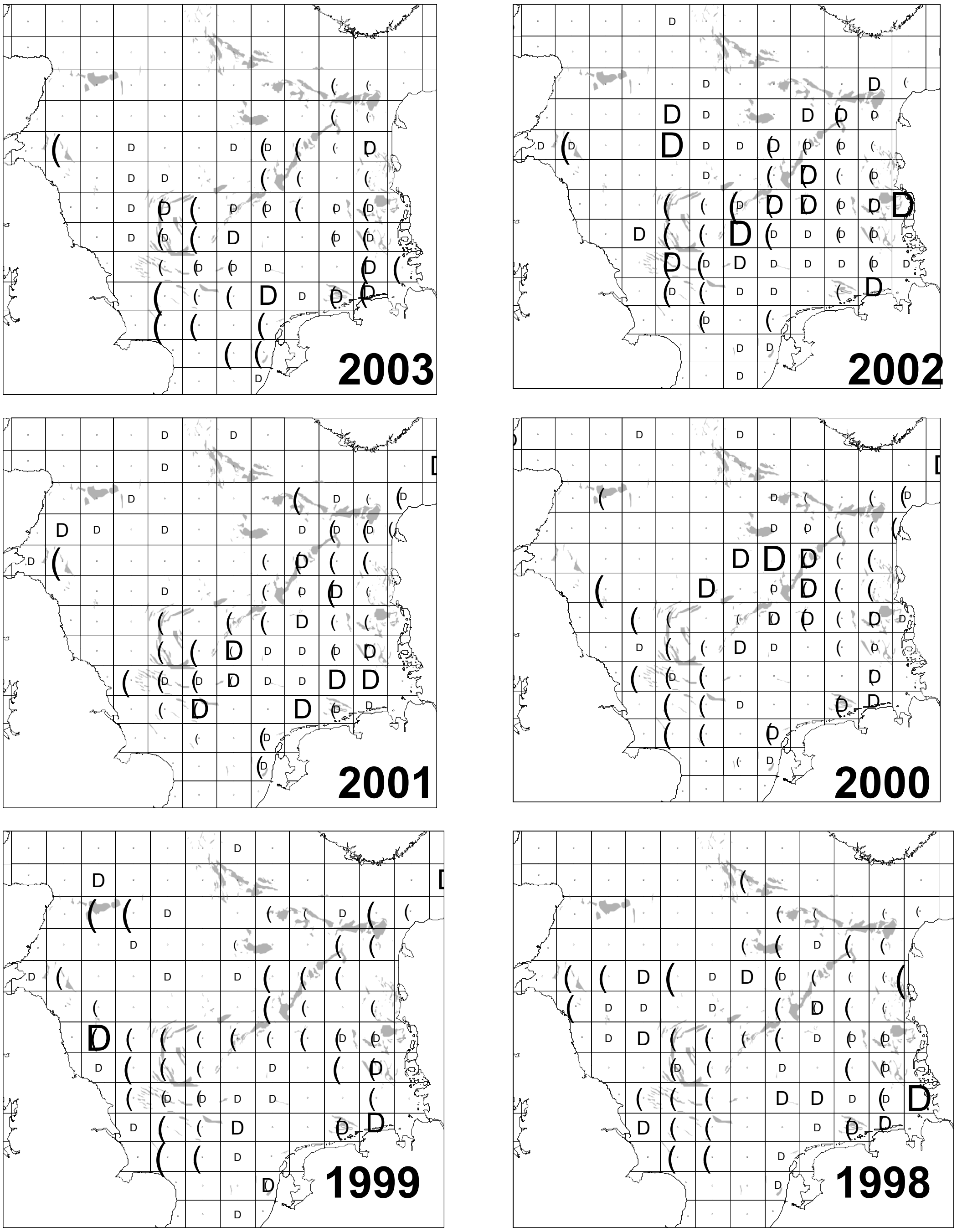


Figure 3: Distribution of herring in January/February (quarter 1) and Danish sandeel catches in June in the North Sea from 1998 to 2003. Empty circles (O) represent sandeel catches and crosses (X) represent herring. The size of the symbols is a measure of the abundance in the individual ICES-rectangles relative to the other squares on the map. Values for herring are average IBTS CPUE-values and given in numbers. Values for sandeel catches are CPUE-values given as tons caught per day standardised to a 212 GT vessel. Symbol sizes should not be compared between years. Squares without the presence of a symbol (X, O) or if a dot (·) is present instead of a symbol, it means no data were available. Sandeel bank-systems are given as grey fields (Jensen, 2005 (to be published)).

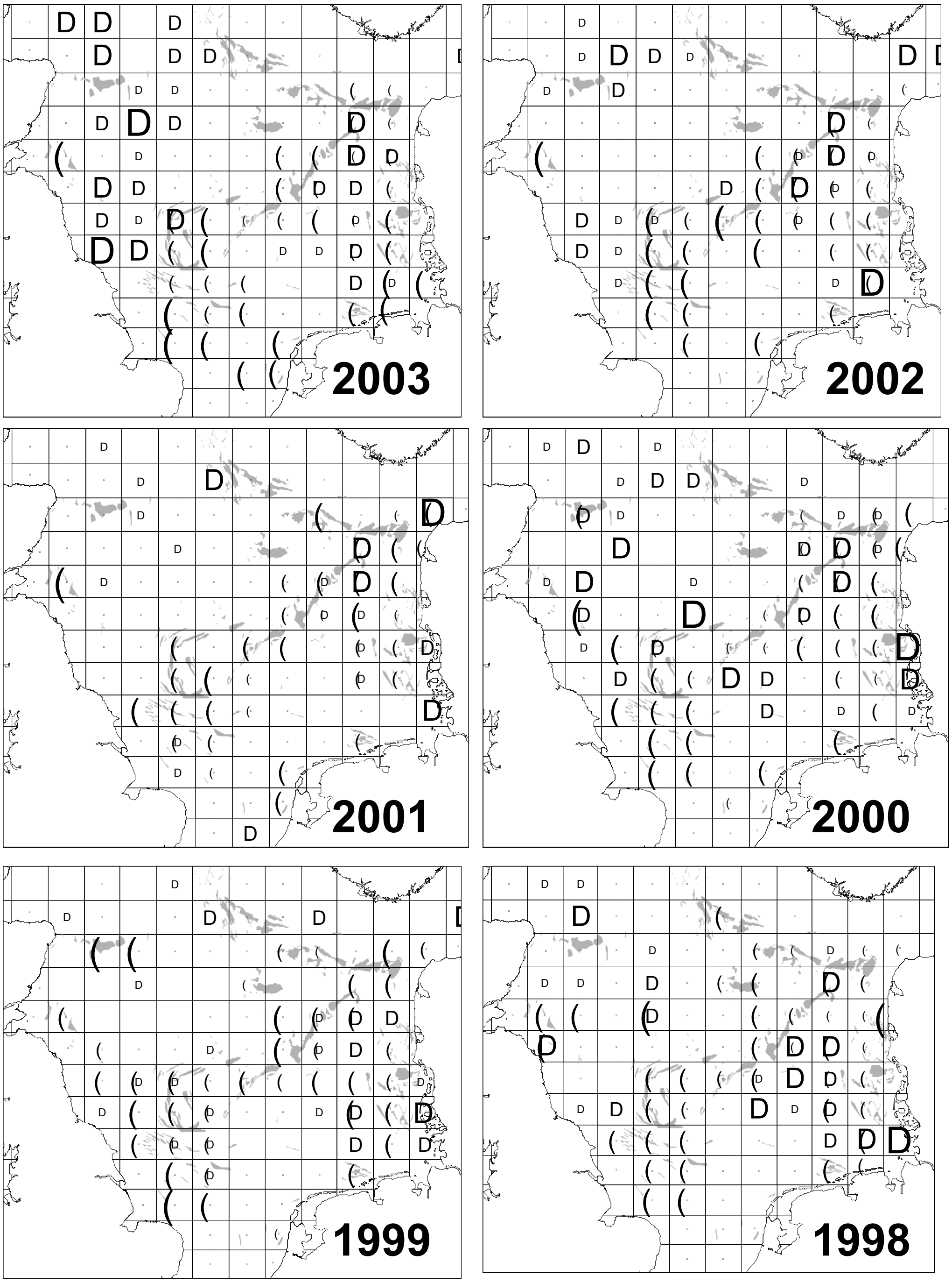


Figure 4: Distribution of herring in August/September (quarter 3) and Danish sandeel catches in June in the North Sea from 1998 to 2003. Empty circles (O) represent sandeel catches and crosses (X) represent herring. The size of the symbols is a measure of the abundance in the individual ICES-rectangles relative to the other squares on the map. Values for herring are average IBTS CPUE-values and given in numbers. Values for sandeel catches are CPUE-values given as tons caught per day standardised to a 212 GT vessel Symbol sizes should not be compared between years. Squares without the presence of a symbol (X, O) or if a dot (·) is present instead of a symbol, it means no data were available. Sandeel bank-systems are given as grey fields (Jensen, 2005 (to be published)).

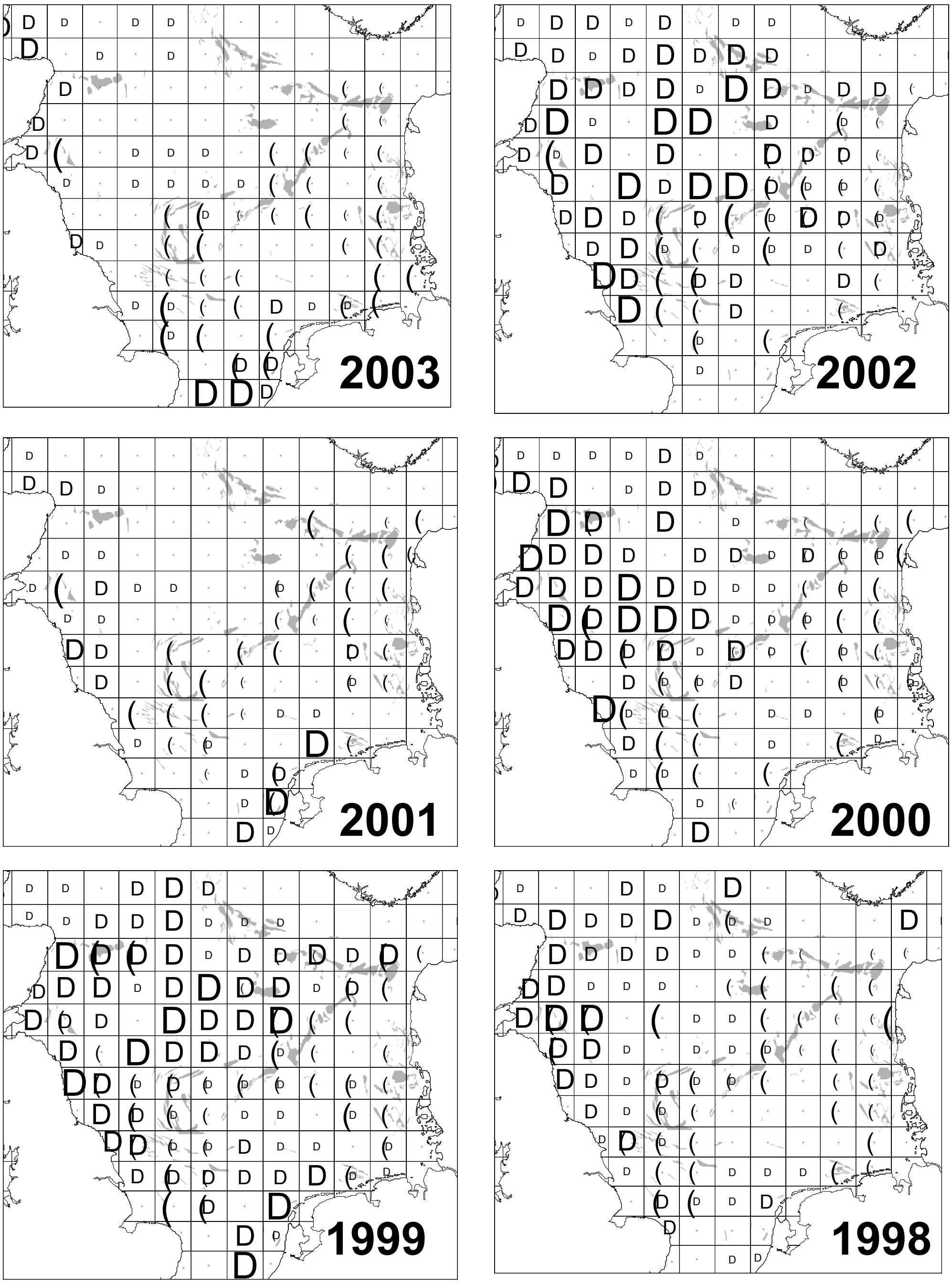


Figure 5: Distribution of herring larvae in January/February (quarter 1) and Danish sandeel catches in June in the North Sea from 1998 to 2003. Empty circles (O) represent sandeel catches and crosses (X) represent herring larvae. Values for herring larvae are given as average numbers per square meter of surface. Values for sandeel catches are CPUE-values given as tons caught per day standardised to a 212 GT vessel. The size of the symbols is a measure of the abundance in the individual ICES-rectangles relative to the other squares on the map. Symbol sizes should not be compared between years. Squares without the presence of a symbol (X, O) or if a dot (˙) is present instead of a symbol, it means no data were available. Sandeel bank-systems are given as grey fields (Jensen, 2005 (to be published)).

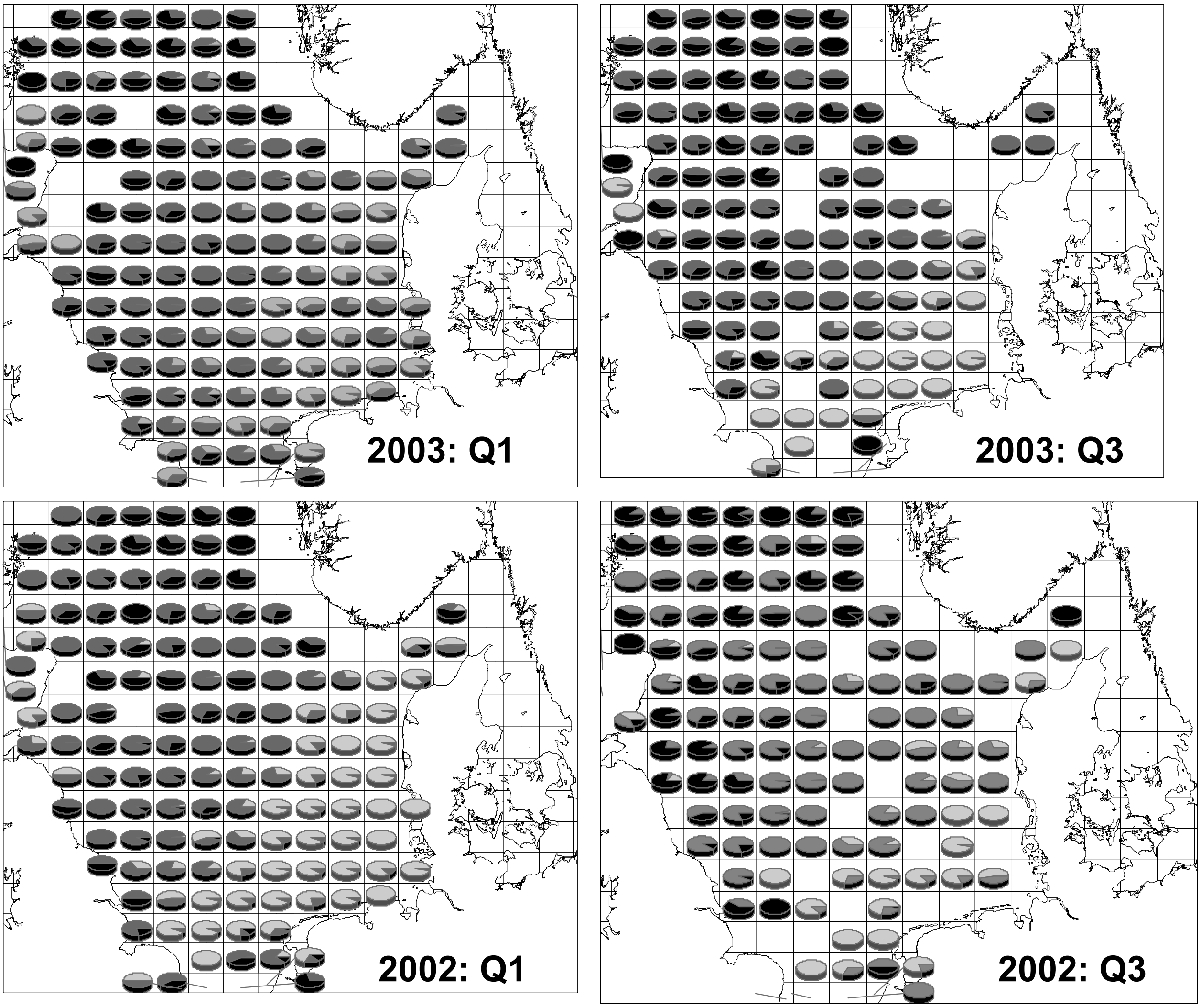


Figure 6: Length distribution of herring per ICES-rectangle in the North Sea in quarter 1 (January/February) and quarter 3 (August/September) for 2002 and 2003. White = 0-10 cm, light grey = 10-20 cm, dark grey = 20-30 cm, and black = >30 cm. Sizes of the individual pies are not related to abundances. Squares with missing pies are the same as lag of data.

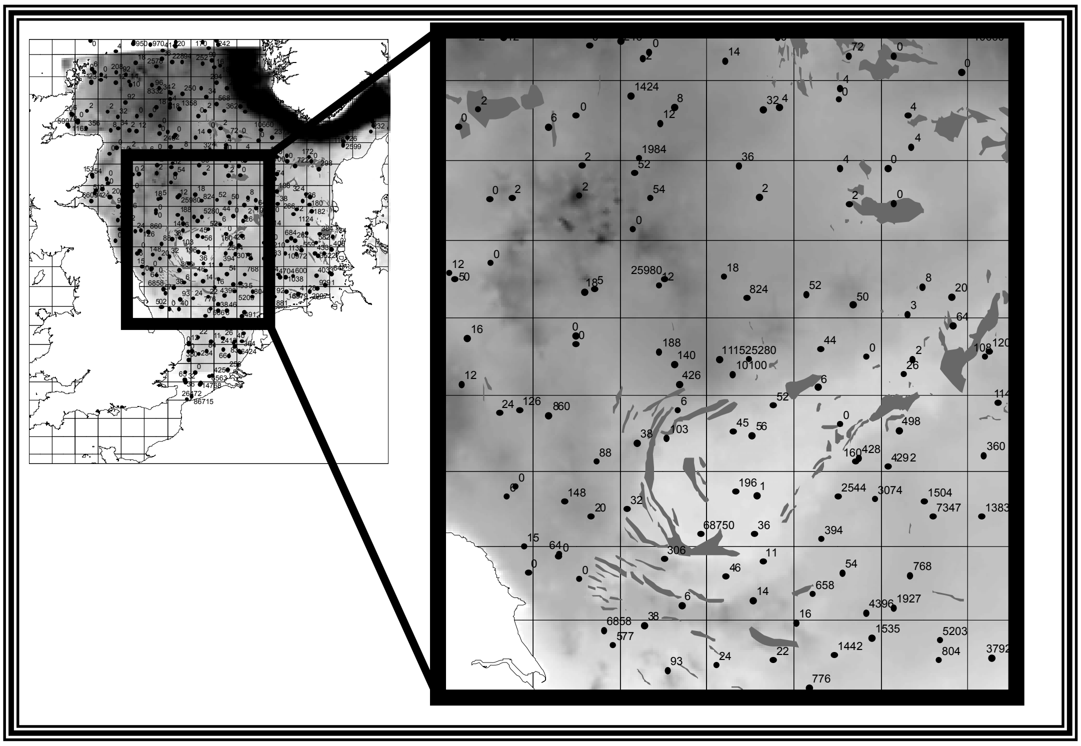


Figure 7: Haul details. The map to the right is a sub section of the smaller map to the left. Dots indicates start position of IBTS trawls and number refers to the number of herring caught in the trawls. Sandeel bank-systems are given as grey fields (Jensen, 2005 (to be published)). Shades in the background illustrates the water depth with light shades being relatively shallow water.

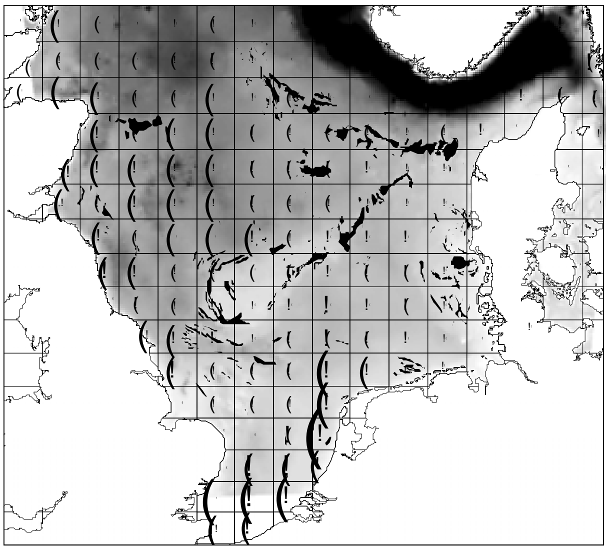


Figure 8: An illustration of a shift in larvae distribution over the period from 1983 to 2004. Empty circles = 1996 – 2004, filled circles = 1983 – 1995. The symbols are averages over the time period. Sandeel bank-systems are given as grey fields (Jensen, 2005 (to be published)).

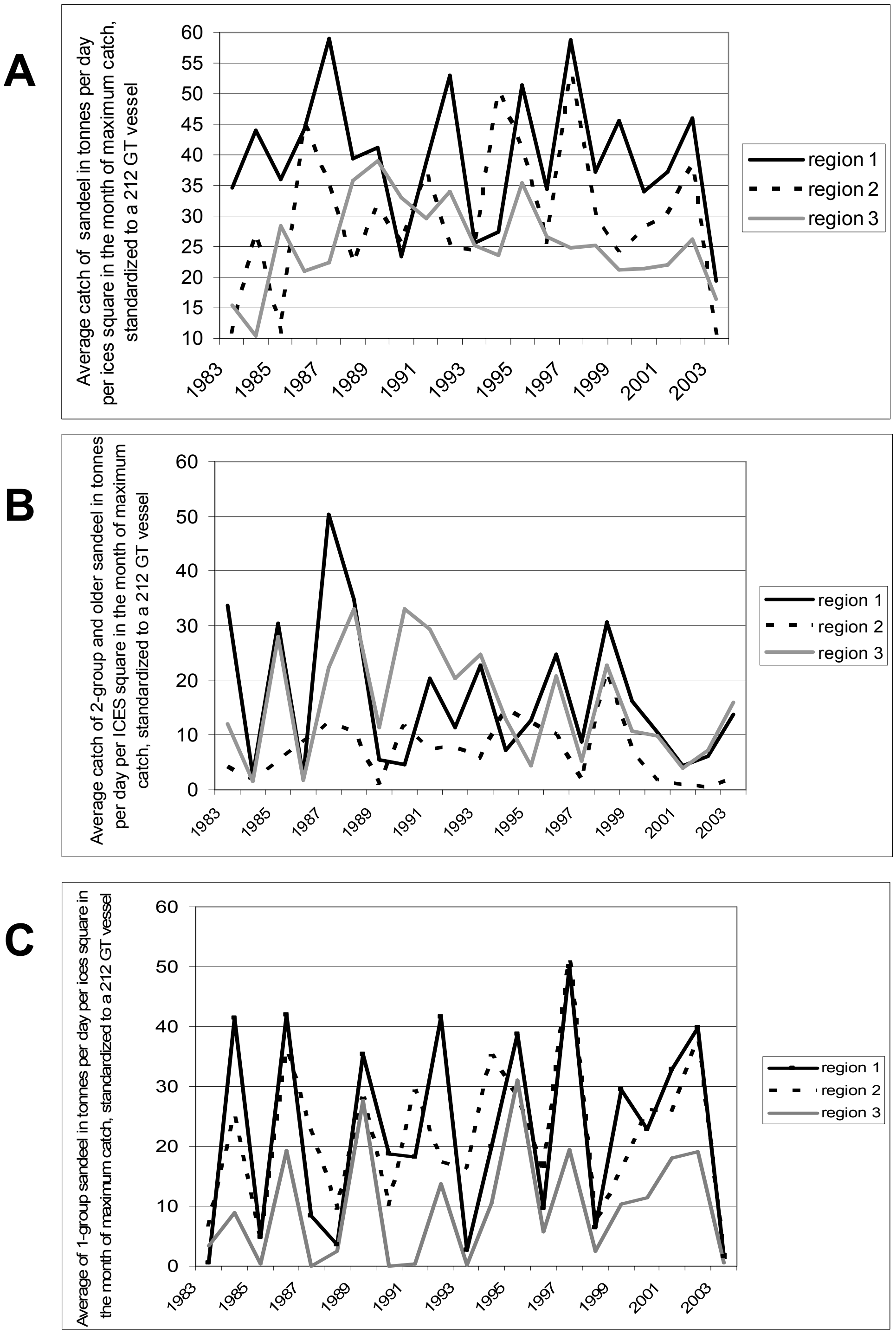


Figure 9: A: Average of total catches of sandeel in tons in June per ICES-rectangle for the respective regions. B: Average catch of the sandeel spawning stock (group-2 and older) in tons in June per ICES-rectangle for the respective regions. C: Average catch of 1-group sandeel in tons in June per ICES-rectangle for the respective regions.

3.2. Comparing calculated sandeel indexes with the literature

To evaluate the reliability of the calculated sandeel indexes, the indexes were compared to available numbers in the literature. Figure 10 presents plots of relationships between sandeel recruitment estimates from this study and recruitment estimates from the literature. Pedersen et al., (1999) estimated the recruitment in region 1 and 2, between 1984 and 1997. ICES working group sandeel assessment estimated the recruitment for ICES division IV between 1983 and 2004 (ICES, 2005b). R-squares of 0.865, 0.568, and 0.743 were found for region 1, 2 and 4 (~ ices division IV) respectively. There were no estimates for region 3 in the literature. It should be noted that the numbers from the literature were log transformed to achieve a linear relationship.

A negative autocorrelation in the sandeel recruitment has been reported (Arnott and Ruxton, 2002). In this study the negative autocorrelation was significant in region 1 (linear regression $P = 0.005$), but not in region 2 and 3 (Figure 11).

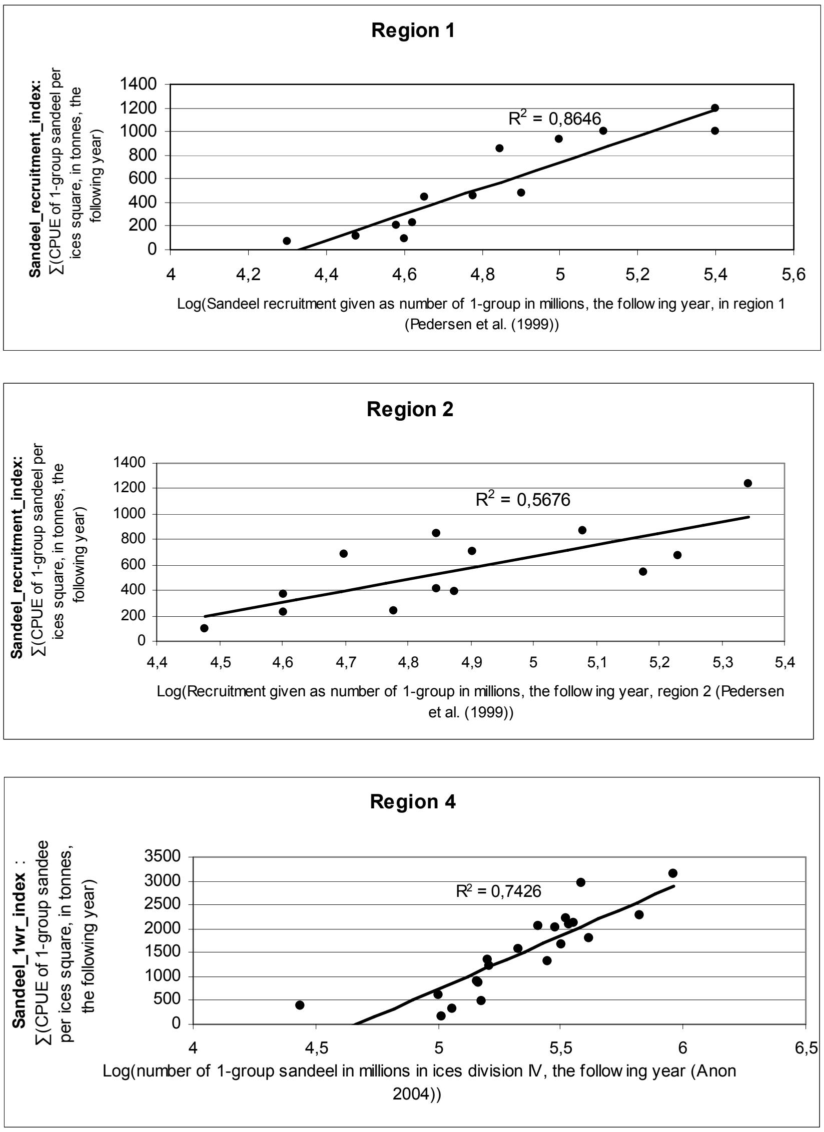


Figure 10: Sandeel-indexet estimated in this report compared to corresponding estimates in the literature for region 1, 2, and 4. Region 4 was compared to estimates in the literature for ICES division IV, which roughly corresponds to region 4. There was no estimates in the literature for region 3.

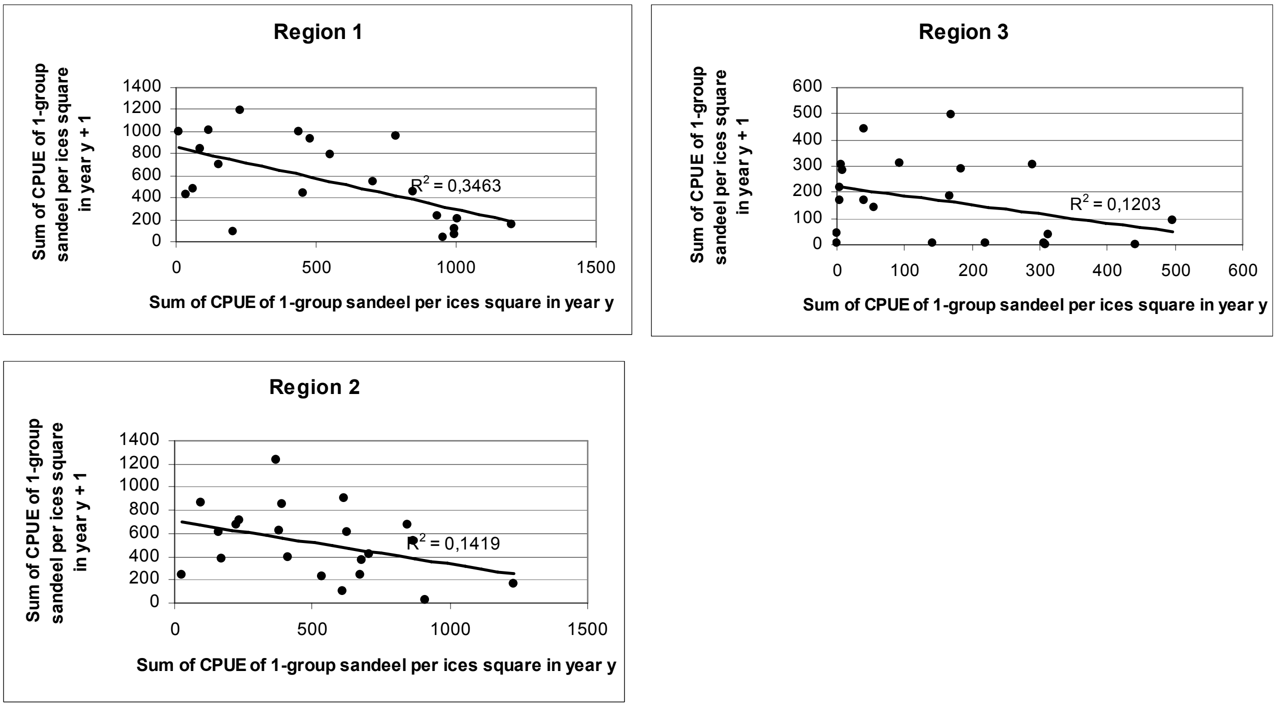


Figure 11: Plots of how the number of 1-group sandeel in the catches one year relates to the number of 1-group sandeel the previous year, for region 1-3. The purpose of this was to illustrate the negative auto-correlation of the sandeel recruitment as reported in Arnott and Ruxton (2002).

3.3. Relationships between herring and sandeel

Table 1, Table 2, and Table 3 shows intercept, slope, P-value, and R-square derived from a simple linear regression analysis for all relevant combinations between herring-indexes and sandeel-indexes.

Eight out of the 72 model-“families” came out with p-values below 0.05 (see section 2.4 for details), which is two more than the six expected to occur by chance.

	Region 1	Residuals.of.R&1wr	R/SS	Survival.of.1wr	Sandeel_recruitment_index
INTERCEPT	Herring_Q1_mean.CPUEmass	-55,83	2,22	1,08	634,78
	Herring_Q1_median.CPUEmass	-122,16	2,54	0,56	545,37
	Herring_Q1_mean.CPUE	-93,98	2,69	0,86	732,66
	Herring_Q1_median.CPUE	-200,21	2,81	0,99	643,83
	Herring_Q1_>150mm	-86,08	2,13	1,35	715,81
	Herring_Q3_>200mm	-80,70	2,38	0,38	611,41
	Herring_Q3_median. biomass	-131,54	2,98	0,34	738,41
	Herring_Q3_mean. biomass	-35,77	1,73	0,42	544,62
	Herring.larvae_ median	-105,59	3,19	0,94	744,83
	Herring.larvae_mean	-82,46	10,33	0,92	722,12
	Her.larvae_median.x.mean.size	-83,78	7,59	0,79	695,25
	Herring.larvae_mean (region 4)	86,38	9,65	1,23	528,53
	Herring_Q1_mean. biomass (region 4)	-59,95	17,18	1,40	534,57
	Herring_Q3_mean. biomass (region 4)	-181,26	3,03	0,51	734,72
SLOPE	Herring_Q1_mean. biomass	0,75	0,00	0,00	-1,07
	Herring_Q1_median. biomass	15,71	-0,05	0,05	1,32
	Herring_Q1_mean.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_median.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_>150mm	0,03	0,00	0,00	-0,05
	Herring_Q3_>200mm	51,83	-0,36	0,11	-51,13
	Herring_Q3_median. biomass	18,65	-0,18	0,02	-35,44
	Herring_Q3_mean. biomass	-0,10	0,00	0,00	0,29
	Herring.larvae_ median	579,24	-5,82	0,12	-1038,06
	Herring.larvae_mean	329,18	-14,10	0,16	-664,75
	Her.larvae_median.x.mean.size	17,14	-0,16	0,04	-28,57
	Herring.larvae_mean (region 4)	-269,65	-8,90	-0,84	84,54
	Herring_Q1_mean. biomass (region 4)	0,78	-0,14	-0,01	0,27
	Herring_Q3_mean. biomass (region 4)	1,16	0,00	0,00	-1,36
P-VALUE	Herring_Q1_mean. biomass	0,48	0,87	0,73	0,41
	Herring_Q1_median. biomass	0,20	0,54	0,33	0,93
	Herring_Q1_mean.CPUE	0,28	0,35	0,79	0,09
	Herring_Q1_median.CPUE	0,04 *	0,33	0,94	0,49
	Herring_Q1_>150mm	0,46	0,99	0,43	0,26
	Herring_Q3_>200mm	0,67	0,70	0,34	0,73
	Herring_Q3_median. biomass	0,40	0,28	0,26	0,17
	Herring_Q3_mean. biomass	0,89	0,52	0,67	0,74
	Herring.larvae_ median	0,27	0,10	0,96	0,10
	Herring.larvae_mean	0,44	0,59	0,93	0,20

	Her.larvae_median.x.mean.size	0,36	0,89	0,66	0,22
	Herring.larvae_mean (region 4)	0,20	0,02 *	0,36	0,75
	Herring_Q1_mean. biomass (region 4)	0,70	0,79	0,51	0,91
	Herring_Q3_mean. biomass (region 4)	0,28	0,59	0,64	0,29
R-SQUARE	Herring_Q1_mean. biomass	0,03	0,00	0,01	0,04
	Herring_Q1_median. biomass	0,08	0,02	0,05	0,00
	Herring_Q1_mean.CPUE	0,06	0,05	0,00	0,14
	Herring_Q1_median.CPUE	0,20	0,05	0,00	0,03
	Herring_Q1_>150mm	0,03	0,00	0,03	0,07
	Herring_Q3_>200mm	0,02	0,01	0,08	0,01
	Herring_Q3_median.biomass	0,06	0,11	0,11	0,16
	Herring_Q3_mean. biomass	0,00	0,04	0,02	0,01
	Herring.larvae_ median	0,06	0,13	0,00	0,13
	Herring.larvae_mean	0,03	0,02	0,00	0,08
	Her.larvae_median.x.mean.size	0,04	0,00	0,01	0,08
	Herring.larvae_mean (region 4)	0,08	0,03	0,04	0,01
	Herring_Q1_mean. biomass (region 4)	0,01	0,07	0,02	0,00
	Herring_Q3_mean. biomass (region 4)	0,10	0,00	0,02	0,10

Table 1: Intercept, Slope, P-value, and R-square derived from simple linear regression analyses of each relevant combination of herring- and sandeel-indexes, in region 1.

	Region 2	Residuals.of.R&1wr	R/SS	Survival.of.1wr	Sandeel_recruitment_index
INTERCEPT	Herring_Q1_mean. biomass	-24,48	3,41	0,43	556,04
	Herring_Q1_median. biomass	-7,77	1,67	0,44	510,22
	Herring_Q1_mean.CPUE	-92,42	4,43	0,43	631,23
	Herring_Q1_median.CPUE	-209,49	8,21	0,46	748,87
	Herring_Q1_>150mm	-48,44	1,91	0,43	530,50
	Herring_Q3_>200mm	-24,31	9,96	0,25	514,53
	Herring_Q3_median.biomass	-100,61	8,60	0,23	655,22
	Herring_Q3_mean.biomass	-94,26	10,45	0,26	655,44
	Herring.larvae_ median	-64,91	7,62	0,49	596,43
	Herring.larvae_mean	-28,98	2,95	0,50	553,54
	Her.larvae_median.x.mean.size	-54,56	7,32	0,47	579,26
	Herring.larvae_mean (region 4)	94,19	-0,91	0,48	442,25
	Herring_Q1_mean.CPUEmass (region 4)	-25,97	4,61	0,49	535,30
	Herring_Q3_mean.biomass (region 4)	-196,59	10,15	0,29	720,33
	Herring_Q1_mean.CPUEmass	0,88	0,10	0,00	-1,40

SLOPE	Herring_Q1_median.CPUEmass	1,13	0,66	-0,01	0,99
	Herring_Q1_mean.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_median.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_>150mm	7,68	0,68	-0,01	-2,14
	Herring_Q3_>200mm	-27,63	-7,91	-0,04	48,40
	Herring_Q3_median.biomass	9,32	-0,18	0,00	-17,30
	Herring_Q3_mean.biomass	0,45	-0,02	0,00	-0,92
	Herring.larvae_ median	517,10	-11,31	-0,94	-632,74
	Herring.larvae_mean	165,72	-5,04	-0,77	-208,97
	Her.larvae_median.x.mean.size	16,48	-0,34	-0,03	-18,80
	Herring.larvae_mean (region 4)	-294,06	22,21	-0,36	233,41
	Herring_Q1_mean.CPUEmass (region 4)	0,34	0,02	0,00	-0,24
	Herring_Q3_mean.biomass (region 4)	1,42	-0,02	0,00	-1,65
P-VALUE	Herring_Q1_mean.CPUEmass	0,81	0,40	0,73	0,72
	Herring_Q1_median.CPUEmass	0,93	0,11	0,61	0,94
	Herring_Q1_mean.CPUE	0,30	0,55	0,70	0,23
	Herring_Q1_median.CPUE	0,03 *	0,56	0,60	0,03 *
	Herring_Q1_>150mm	0,58	0,13	0,69	0,89
	Herring_Q3_>200mm	0,90	0,32	0,73	0,83
	Herring_Q3_median.biomass	0,31	0,60	0,97	0,05 *
	Herring_Q3_mean.biomass	0,61	0,46	0,73	0,30
	Herring.larvae_ median	0,37	0,56	0,32	0,31
	Herring.larvae_mean	0,69	0,16	0,26	0,64
	Her.larvae_median.x.mean.size	0,45	0,65	0,40	0,43
	Herring.larvae_mean (region 4)	0,13	0,00 *	0,27	0,28
	Herring_Q1_mean.CPUEmass (region 4)	0,86	0,74	0,61	0,91
	Herring_Q3_mean.biomass (region 4)	0,18	0,54	0,41	0,13
R-SQUARE	Herring_Q1_mean.CPUEmass	0,00	0,04	0,01	0,01
	Herring_Q1_median.CPUEmass	0,00	0,13	0,01	0,00
	Herring_Q1_mean.CPUE	0,06	0,02	0,01	0,07
	Herring_Q1_median.CPUE	0,22	0,02	0,01	0,23
	Herring_Q1_>150mm	0,02	0,12	0,01	0,00
	Herring_Q3_>200mm	0,00	0,09	0,01	0,00
	Herring_Q3_median.biomass	0,10	0,03	0,00	0,31
	Herring_Q3_mean.biomass	0,03	0,05	0,01	0,10
	Herring.larvae_ median	0,04	0,02	0,05	0,05
	Herring.larvae_mean	0,01	0,10	0,07	0,01
	Her.larvae_median.x.mean.size	0,03	0,01	0,04	0,03
	Herring.larvae_mean (region 4)	0,12	0,59	0,06	0,06
	Herring_Q1_mean.CPUEmass (region 4)	0,00	0,01	0,01	0,00
	Herring_Q3_mean.biomass (region 4)	0,16	0,04	0,06	0,20

Table 2: Intercept, Slope, P-value, and R-square derived from simple linear regression analyses of each relevant combination of herring- and sandeel-indexes, in region 2.

	Region 3	Residuals.of.R&1wr	R/SS	Survival.of.1wr	Sandeel_recruitment_index
INTERCEPT	Herring_Q1_mean.CPUEmass	13,91	0,56	7,91	136,97
	Herring_Q1_median.CPUEmass	71,08	0,45	7,39	72,92
	Herring_Q1_mean.CPUE	33,63	0,52	16,21	145,87
	Herring_Q1_median.CPUE	52,28	0,24	7,87	105,68
	Herring_Q1_>150mm	34,08	0,23	14,17	122,62
	Herring_Q3_>200mm	-52,11	1,29	3,64	213,73
	Herring_Q3_median.biomass	-60,84	1,47	5,00	197,01
	Herring_Q3_mean.biomass	-58,28	1,57	-3,53	202,19
	Herring.larvae_ median	-51,91	1,18	-1,58	220,25
	Herring.larvae_mean	24,99	11,29	13,86	149,17
	Her.larvae_median.x.mean.size	-53,01	3,10	-2,48	217,17
	Herring.larvae_mean (region 4)	46,22	-0,01	19,30	141,64
	Herring_Q1_mean.CPUEmass (region 4)	139,27	0,41	8,86	23,72
	Herring_Q3_mean.biomass (region 4)	-64,81	1,57	3,50	227,02
SLOPE	Herring_Q1_mean.CPUEmass	-0,19	0,00	0,08	0,42
	Herring_Q1_median.CPUEmass	-2,18	0,01	0,19	2,89
	Herring_Q1_mean.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_median.CPUE	0,00	0,00	0,00	0,00
	Herring_Q1_>150mm	-7,59	0,14	-0,15	9,94
	Herring_Q3_>200mm	5052,15	-33,29	-73,43	-5475,00
	Herring_Q3_median.biomass	1,50	-0,02	-0,10	0,04
	Herring_Q3_mean.biomass	0,20	0,00	0,06	-0,04
	Herring.larvae_ median	271,53	-1,61	78,83	-277,16
	Herring.larvae_mean	-74,19	1,70	-1,11	53,73
	Her.larvae_median.x.mean.size	8,89	-0,05	2,68	-8,36
	Herring.larvae_mean (region 4)	-144,30	2,73	-18,14	79,99
	Herring_Q1_mean.CPUEmass (region 4)	-1,82	0,01	0,06	1,88
	Herring_Q3_mean.biomass (region 4)	0,24	0,00	0,00	-0,26
P-VALUE	Herring_Q1_mean.CPUEmass	0,83	0,54	0,72	0,66
	Herring_Q1_median.CPUEmass	0,17	0,30	0,63	0,08
	Herring_Q1_mean.CPUE	0,66	0,55	0,88	0,79
	Herring_Q1_median.CPUE	0,33	0,12	0,67	0,29
	Herring_Q1_>150mm	0,32	0,01 *	0,94	0,22
	Herring_Q3_>200mm	0,17	0,37	0,78	0,17
	Herring_Q3_median.biomass	0,54	0,47	0,55	0,99
	Herring_Q3_mean.biomass	0,56	0,28	0,00 *	0,91
	Herring.larvae_ median	0,31	0,44	0,22	0,33
	Herring.larvae_mean	0,27	0,79	0,95	0,46
	Her.larvae_median.x.mean.size	0,24	0,13	0,14	0,31

	Herring.larvae_mean (region 4)	0,15	0,00 *	0,46	0,46
	Herring_Q1_mean.CPUEmass (region 4)	0,05 *	0,42	0,80	0,06
	Herring_Q3_mean.biomass (region 4)	0,59	0,45	0,98	0,60
R-SQUARE	Herring_Q1_mean.CPUEmass	0,00	0,02	0,01	0,01
	Herring_Q1_median.CPUEmass	0,10	0,06	0,01	0,15
	Herring_Q1_mean.CPUE	0,01	0,02	0,00	0,00
	Herring_Q1_median.CPUE	0,05	0,12	0,01	0,06
	Herring_Q1_>150mm	0,05	0,31	0,00	0,08
	Herring_Q3_>200mm	0,17	0,07	0,01	0,17
	Herring_Q3_median.biomass	0,03	0,05	0,03	0,00
	Herring_Q3_mean.biomass	0,03	0,10	0,75	0,00
	Herring.larvae_ median	0,05	0,03	0,08	0,05
	Herring.larvae_mean	0,06	0,00	0,00	0,03
	Her.larvae_median.x.mean.size	0,07	0,12	0,11	0,06
	Herring.larvae_mean (region 4)	0,11	0,64	0,03	0,03
	Herring_Q1_mean.CPUEmass (region 4)	0,19	0,03	0,00	0,18
	Herring_Q3_mean.biomass (region 4)	0,03	0,05	0,00	0,03

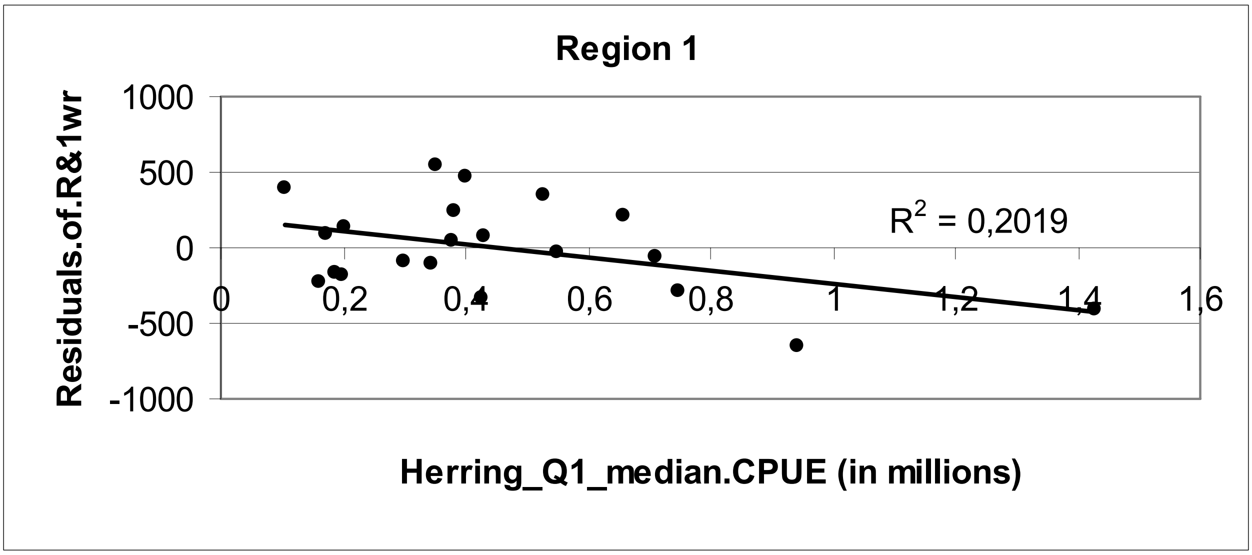
Table 3: Intercept, Slope, P-value, and R-square derived from simple linear regression analyses of each relevant combination of herring- and sandeel-indexes, in region 3.

A regression model for **Residuals.of.R&1wr** as a function of **Herring_Q1_median.CPUE** was not found to be driven by outliers in either region 1 or 2, however the R-squares were low 0.2 and 0.22 for region 1 and 2 respectively (Figure 12). The relationship was positive, which corresponds to a situation where herring exerts a negative effect on sandeel, in view of the fact that residuals were calculated by extracting the observed values from the calculated values.

It was accepted, based on 95% confidence zones attached to the individual regression models, that a general model could be applied in both region 1 and region 2, but not in region 3 (Figure 13).

The covariances calculated for region 1 and region 2 were 0.68, 0.75, and 0.19 for **Residuals.of.R&1wr**, **Sandeel_recruitment_index**, and **Herring_Q1_median.CPUE** respectively.

Data passed the test for normal distribution but failed the test for equal variance, Fisher´s Combining Probabilities (Sokal & Rohlf, BOX 18.1) was used to calculate combined probabilities for region 1 and region 2 (Normality Test: combined P = 0.264; Constant Variance Test: combined P = 0.015).



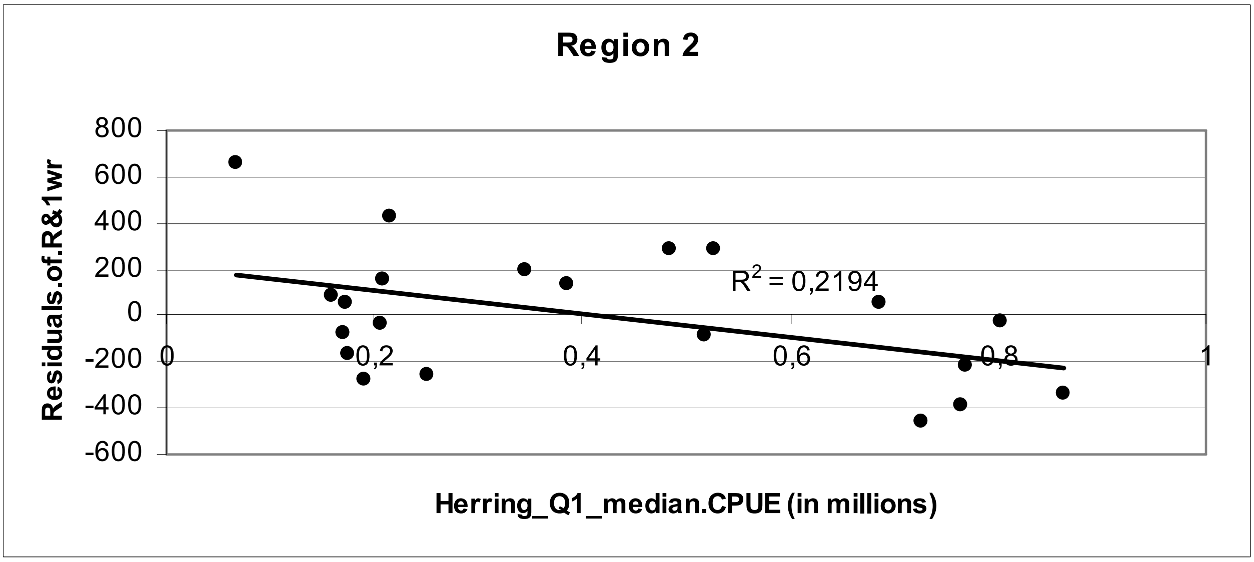


Figure 12: X,y-scatter plot of the regression models based on the sandeel-index “Residuals.of.R&1wr” versus the herring index “Herring_Q1_median.CPUE” for region 1 and 2 respectively.

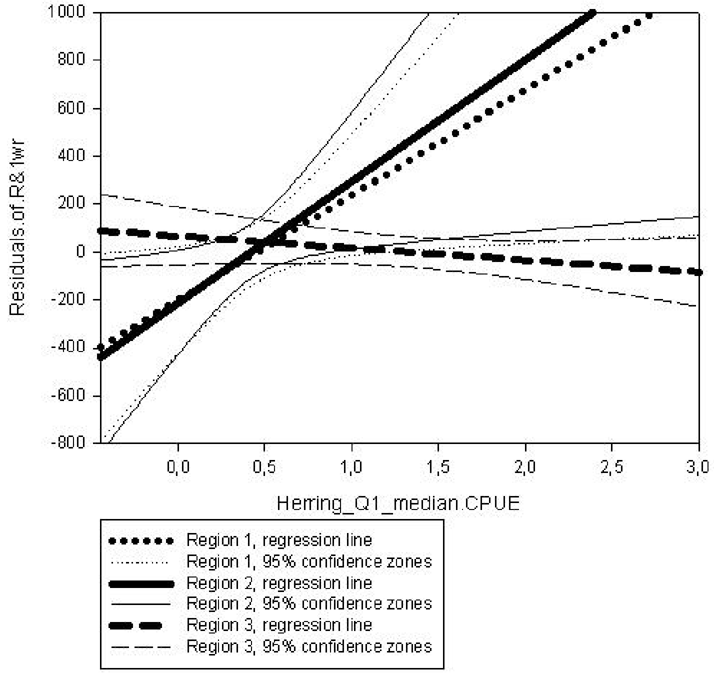


Figure 13: Regression lines derived from the sandeel-index "Residuals.of.R&1wr" plottet against the herring-index "Herring_Q1_median.CPUE", for region 1, 2, and 3 respectively. 95% confidence zones are added.

The regression model was now tested for consistency. The data from region 1 and region 2 was pooled and the relationship between **Residuals.of.R&1wr** and **Herring_Q1_median.CPUE** was tested. The test for equal variance failed again (P = 0.013). Spearman`s test of correlation was applied instead. The result was a significant correlation (P = 0.033; Correlations coefficient = 0.33).

The pooled data were split in two, with data from 1983 to 1993 in one and data from 1994 to 2003 in the other. Fisher´s Combining Probabilities was used to calculate combined probabilities. Data passed the test for normal distribution and equal variance, (Normality Test: combined P = 0.484; Constant Variance Test: combined P = 0.186). The two models were significant when P-values were combined (combined P = 0.005).

The simple linear regression model was extended to a multiple linear regression model on the form:

Sandeel_recruitment_index = α (**Sandeel_1wr_index)** + β (**Herring_Q1_median.CPUE)** + γ

The multiple model was investigated for region 1, region 2, and for pooled data from region 1 and 2. The probability-estimates given (Pr) are the probability for being wrong in claiming that the model would change if the variable were left out. The data passed the test for normal distribution and equal variance (Normality Test: combined region 1 and 2 P = 0.726, pooled data P = 0.577; Constant Variance Test: combined region 1 and 2 P = 0.639, pooled data P = 0.24).

Region 1:

```
Coefficients:
                          Estimate   Std. Error   t value    Pr
(Intercept)               1.157e+03  1.671e+02    6.923    1.8e-06 ***
Sandeel_1wr_index        -6.981e-01  1.703e-01   -4.100    0.000672 ***
Herring_Q1_median.CPUE   -4.970e-04  2.147e-04   -2.314    0.032674 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 281.3 on 18 degrees of freedom
Multiple R-Squared: 0.4962,     Adjusted R-squared: 0.4402
F-statistic: 8.863 on 2 and 18 DF,  p-value: 0.002092
```

Region 2:

```
Coefficients:
                          Estimate     Std. Error    t value    Pr
(Intercept)               8.932e+02    1.395e+02     6.404     4.98e-06 ***
Sandeel_1wr_index        -3.184e-01    1.915e-01    -1.663     0.1136
Herring_Q1_median.CPUE   -5.139e-04     2.262e-04   -2.272     0.0356 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 262.7 on 18 degrees of freedom
Multiple R-Squared: 0.3331,     Adjusted R-squared: 0.259
```

```
F-statistic: 4.495 on 2 and 18 DF,  p-value: 0.02609
```

Region 1 & 2 pooled:

```
Coefficients:
                                    Estimate    Std. Error   t value      Pr
(Intercept)                         1013.5491   107.4219     9.435    1.29e-11 ***
Sandeel_1wr_index                    -0.5434      0.1229      -4.423    7.59e-05 ***
Herring_Q1_median.CPUE             -441.2507    150.6216    -2.930     0.00565 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 271.8 on 39 degrees of freedom
Multiple R-Squared: 0.3877,     Adjusted R-squared: 0.3563
F-statistic: 12.35 on 2 and 39 DF,  p-value: 7.008e-05
```

For comparison R-square values were also derived from a simple linear regression on the form:

Sandeel_recruitment_index = α(**Sandeel_1wr_index)** + β.

A comparison of R-squares are presented in the table below.

	Adjusted R-squares	
	Simple regression: Sandeel_recruitment_index = α(Sandeel_1wr_index) +β	Multiple regression: Sandeel_recruitment_index = α(Sandeel_1wr_index) + β(Herring_Q1_median.CPUE) + γ
Region 1	0.312	0.44
Region 2	0.097	0.259
Region 1 & 2 pooled	0.234	0.356

4. Discussion

4.1. Potential relationship between herring and sandeel

The sandeel recruitment failure in 2002 and 2004 did not coincide convincingly with years of large herring abundances. It is therefore unlikely that the herring alone is responsible. The possibility that herring does exert some effect on the sandeel stock can, however, not be entirely excluded, and based on results in this pilot study it is recommended not to reject the hypothesis that herring play a role, possibly in association with other ecological factors, in regulating the sandeel recruitment. The important observations leading to this statement will be summarized here: The majority of herring captured in the IBTS in the North Sea in quarter 1 stems from hauls in the vicinity of the sandeel fishing areas. A weak but significant linear relationship between **Herring_Q1_median.CPUE** and the residuals of the negative recruitment autocorrelation (**Residuals.of.R&1wr**) was found for two out of three study-areas. The relationship inferred that herring exerts a negative effect on sandeel, which are the most biological likely relationship (as opposed to a positive). The relationship was approximately similar in both areas and it existed both between 1983 and 1993 and between 1994 and 2003. In both region 1 and region 2, **Herring_Q1_median.CPUE** was found to improve the prediction of the sandeel recruitment, compared to a model in which a recruitment-index for the previous year was the only independent variable (As mentioned in the Introduction Arnott and Ruxton (2002) found that sandeel recruitment in the North was related to recruitment in the previous year). In region 1 the effect of the herring index seemed to of minor importance compared to the effect of the negative recruitment autocorrelation whereas in region 2 the herring-index was the only index that contributed to the recruitment model. A biologically explanation for the lack of significant recruitment autocorrelation in region 2 could be that habitat resources are more plentiful in region 2 relatively to the number of sandeel inhabiting the region. This is, however, only speculations. Arnott and Ruxton (2002) found that the abundance of 1-group sandeel in January (back calculated from VPA abundance estimates based on catch data from the entire fishing season) contributed about the same, in region 1 and region 2 respectively, to the prediction of the recruitment, which contradicts the findings in this study.

4.2. Sources of bias

The statistical approach was based on the assumption that the regions were independent, which hold true only for the herring-indexes. The sandeel recruitment in region 1 was clearly correlated to recruitment in region 2. This, however, does not necessary means that the population dynamics are dependent between region, it could just be that the factors regulating the dynamics are the same and follow the same trends in both region 1 and 2.

It was assumed that commercial sandeel catches are closely related to the biomass of sandeel and that this relationship remains unchanged over years. It is not known whether this assumption holds, however, this assumption also plays a critical role in the sandeel assessment.
By using values from the month of maximum CPUE it was avoided that the length of the fishing season would influence the index. E.g. the entire sandeel sub-stock within a given region is expected to be available for the fisheries only within a limited time span. Therefore in years when this time span covers more than one month the index may be overestimated due to “double counting” compared to years where the time span only covers one month. Due to the fishing mortality and natural mortality, there may, however, be a chance that years, in which the month of maximum CPUE appears late in the season, generate underestimations of the index compared to years, in which the month appear earlier.

The spawning stock was assumed to consist only of 2-group and older fish, which is not entirely true. Macer (1966) found for the southern North Sea that the age at 50 % maturity occurred around age 1.

The sandeel recruitment index built on the assumption that the quantity of 1-group sandeel in a given year is highly correlated to the quantity of 0-group sandeel by the end of the previous year. This approximation of a recruitment measure was also applied by Arnott and Ruxton (2002). For this assumption to hold true natural mortality during the hibernation of 0-group sandeel and fishing mortality and natural mortality of the 1-group sandeel must be relatively constant between years.

The age composition derived from the TBM-data is questionable. It was observed in several occasions that the number of sandeel in the cohort increased from age 1 to age 2. This could after all mean that the regions are not closed systems, it could, however, also mean that the TBM age-data are not representative for the regions.
It has been shown that the age composition varies a lot between samples. Reasons for this variation may be found in a difference in burial behavior between 1-group and older fish, and in the

laboratory age reading process (Kvist et al. 2001). Kvist et al. also did not find any differences in the age-composition between the sub-areas used in this study (the same sub-areas as was presented by Pedersen et al., (1999)), it may therefore have been preferable to use a common age-composition based on all the data instead of a region-specific composition).

The herring-data available draws a picture of the distribution patterns and abundances only in the weeks of the cruise that is in January/February for IBTS quarter 1 and August/September for IBTS quarter 3. There is no data available to fill out the gap between these dates for time series of more than a few years, since quarter 2 IBTS-data were only collected between 1991 and 1996. It was in this study attempted to fill out the gaps by applying data from commercial catches of herring, however almost no commercial fishing for herring during spring occurs within the regions defined for this study. The lack of commercial fishing within these regions is probably due to a concentration of fishing effort further north where the bulk of large adult herring feed during spring and summer. Due to the length of the time-gap of approximately 6 month between these dates an interpolation is likely to miss important temporary distribution patterns within the time-gap. Interpolation was therefore rejected as a solution to the time-gap problem.

A very large variation existed in the number of herring between adjacent samples. This variation is clearly not a stochastic variation in the sampling but is more likely due to a large heterogeneity in the herring distribution, which raises a question of how many samples are necessary to achieve a reliable estimate of the herring abundance.

Two sources of potential bias associated with the sandeel data were identified. First, the sandeel-indexes were not corrected for a potential non-linear relationship between catch and biomass, since the actual relationship between catch and biomass are unknown. This source of bias get even more complex if the relationship change over time as fisheries get more efficient and adapt to decreases in biomass.

4.3. The herring source

What herring could potentially prey on sandeel? The herring present in early spring in region 1 through 3 are likely to be a mix of juvenile and mature herring with an overweight of juveniles. The bulk of the mature herring are likely to be from the relatively small fraction of the North Sea stock that spawns and overwinter in the most southern regions of the North Sea and the English Channel (This sub-stock is also referred to as the Downs Herring). The rest of the mature part of the stock, tend to overwinter in the Norwegian trench and feed in the north/west North Sea. The juvenile herring are probably a mix of herring from all three sub-spawning-stocks of the North Sea Herring, which tend to remain in the eastern part of the North Sea until they reach maturity (Wallace, 1924; Nichols, 2000). This is also in correspondence with the relatively small sizes of herring found in the eastern part of the North Sea in this study. Assuming that the immature herring does not migrate out of the southern North Sea between early spring and July, acoustic survey results from IVb (IVb covers the part of the North Sea within the 53^{o}N and 57^{o}N) provides an estimate of the biomass of immature herring that potentially could feed on sandeel in early spring. Biomass of immature herring in July 2003 in ICES subdivision IVb was estimated to approximately 800 thousand tons with the majority being 2-group herring (ICES, 2004a).

4.4. Proposing a hypothesis

The result of this report does not infer anything about causality. The possibility that the relationship is not a general one or indirect can not be excluded. The next step must therefore be a study with focus on the causality of this potential relationship. A hypothesis about the causality will be discussed and proposed next.

There was only found a relationship between sandeel recruitment and quarter 1 herring samples. Furthermore, the herring were mainly found in the vicinity of sandeel fishing areas (and not directly on the sandeel banks) which indicates that they did not prey on adult sandeel but if anything on the sandeel larvae. It is therefore reasonable to suggest that the herring feed on the newly hatched sandeel larvae that are abundant in February/March.

As already mentioned in the introduction, it has been suggested that herring of the North Sea (*Clupea harengus*) is an important predator on early life stages of a number of demersal species. The literature also contains findings of both sandeel larvae and post-larvae in herring stomachs from the North Sea (Savage, 1937; Pommeranz 1981; Last 1989; Hopkins 1989 (symposium)).

Herring are mainly a planktivory fish and the main food source in the North Sea is likely to be *Calanus finmarchicus* (Dalpadao et al., 1996; Planque and Fromentin, 1997), except for the most south/eastern part of the North Sea where *Calanus helogolandicus* tend to be more abundant. The

Calanus biomass in the North Sea is very low between November and March. The first spring peak of Calanus is found in April/May (Planque and Fromentin, 1996).
A general accepted theory is that the first generation of *Calanus finmarchicus* each year arrives in the North Sea with the currents from the north/east Atlantic, where they existed in an overwintering state of hibernation in the deep water beyond the continental shelf (Backhaus et al., 1994). Before the concentrations of Calanus begins to increase around April and in years with low Calanus concentrations in general, sandeel larvae may play a much more dominant role in the plankton in that they constitute a larger proportion in the plankton, relative to the total plankton biomass. Depending on the feeding activity of herring in February/March, herring could therefore hypothetically consume large numbers of sandeel larvae. In some areas of particular high concentrations of sandeel larvae (hotspots) the herring may even select for sandeel larvae. Hopkins (1989, symposium) suggested, based on a field study, that the herring occasionally make opportunistic switches from copepods to fish larvae when the larvae are concentrated. Furthermore, the literature does contain evidence for some feeding activity as early as January/February in the central North Sea (Daan, 1976; Pommeranz, 1981; Last, 1989).
Arnott and Ruxton (2002) found, for region 1, a positive correlation between Calanus stage V and VI and the sandeel recruitment. The strongest correlation existed in February and grew weaker as the year progressed. The earliest larvae are not likely to feed on Calanus stage V and IV because of the relative large sizes of these stages, however, they may prey on their nauplii larvae (Ryland, 1964). The eggs of *A. marinus* are known to often hatch much earlier than the occurrence of the peak in plankton production, which is a characteristic of the species (Sherman et al., 1984). This indicates that nauplii larvae are not abundant during the first period of the life of the sandeel, and that the effect found by Arnott and Ruxton (2002) is not related to Calanus as a food-source.

Based on the above discussion the hypothesis put forward in this report can be summerized as follows: Juvenile (mainly 1- and 2-group) herring exerts a negative effect on the sandeel recruitment by feeding on newly hatched sandeel larvae before the first Calanus peak.
Ways to evaluate this hypothesis will be discussed next.

4.5. Suggestions for future research

With respect to the hypothesis put forward in section 4.4 a number of research initiatives will be discussed in this section.

Efort should be made to reproduce the relationships found in this study, between herring and sandeel recruitment, on other geographical locations independent of the locations studied here. Such areas could be Firth of Forth, the Shetland Islands and the coast of Norway. It is also of great importance, for the strength of the hypothesis proposed in section 4.4, to collect herring stomachs in early spring in region 1 and region 2. This could be done during the quarter 1 North Sea IBTS cruise.

If the effect of herring abundances depend on Calanus concentrations, as hypothesised here, then it should be emphasized, that multivariable modelling are essential in solving the problem. Furthermore, the negative recruitment autocorrelation may also interact with the predation effect of herring, functioning as a buffer.

Continuous data on Calanus concentrations in the North Sea during early spring may be of great value. This kind of data may be available from the CPR (Continuous Plankton Recorder) (Corten and Lindley, 2003).

Heath et al. (1999) found that the most important entrance for *Calanus finmarchicus* to the North Sea was through the Faroe-Shetland Channel at depth greater than 600 meters. The highest concentrations were found in association with the overflow of Norwegian Sea Deep Water (NSDW) across the Iceland-Scotland Ridge. The input of this water mass was found to correlate to the Calanus abundance in the North Sea. When the Calanus arrives in the surface water the north-westerly wind seems to be another factor responsible for the transport of Calanus into the North Sea. Therefore data on the timing and magnitude of the input of water across Iceland-Scotland Ridge, the incidence of the north-westerly wind in spring, and the exact time of the hatching of sandeel larvae could contribute to a multiple variable sandeel recruitment model, if the hypothesis presented above holds true. This challenge invites for a multidisciplinary and ecosystem based study.

If the presence of hotspots causes the feeding rate of herring on sandeel larvae to increase, then identification of yearly locations and temporal durations of those hotspots may help tuning the herring related variable in the recruitment model.

Both in the case of hotspots and that of the Calanus supply, it is important to consider internal circulation patterns and interannual variation in the North Sea. Does the current in some years drive Calanus further south? Is it possible to predict the location of hotspots, using drift-models?
Lastly temperature seems to play a role in the determining "good" Calanus years (Corten, 2001).

The growth of fish larvae is often closely tied to the survivorship (Pepin, 1991). If the assumption that the predation rate of the herring increase in hotspots areas is true and the growth-rate:survivorship relationship apply in the case of herring preying on sandeel, then one would expect that the size distribution of the larvae from hotspots is different from size distributions in areas outside hotspots. Sandeel otolith archives in combination with a drift-model could provide the base of such a study.

Lastly, the spatial and temporal resolution of this study was coarse. The coarse resolution was chosen, opposed to a finer, to avoid a mismatch between the detail level of the model and the detail level of the information in the data used in this study. A next step could therefore be to investigate the possibilities of using a finer spatial and temporal resolution. Such resolution could be on ICES-rectangle level or on bank level, with the latter probably being the biological most sensible approach but also the most complicated. There are several problems to assess in the case of a fine resolution model approach, which can be summarized in the following questions. How much does herring move around on a temporal scale of days, weeks, and month? An answer to this question is important to ask for reasons discussed in section 4.3. How precise information on hatch date and the quantitative egg distribution are needed for a drift model to predict the location and quantity of sandeel larvae in different time steps and the exact location of settling? Time steps could be days, weeks or month. As it is now, the best way to estimate the recruitment is by estimating the number of 1-group the year after. One must therefore ask what factors influence the exact location of the settling of sandeel larvae? And how much does active transport influence the drift pattern and location of the settling of sandeel larvae?

5. Conclusion

The possibility that herring interact with sandeel in the North Sea was investigated, using IBTS herring-data and commercial CPUEs for sandeel. The result provides a reason to believe that herring may exert some negative effect on the recruitment of lesser sandeel in the North Sea. It is, however, clear that the herring alone are not responsible for the severe recruitment failure to the fishery in 2002.

The result does not infer anything about the causality. Ways to test the hypothesis, that juvenile herring prey on newly hatched sandeel larvae during the time before the first spring Calanus peak, are therefore suggested.

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