Significant differences in the length-weight relationships of neighbouring stocks can result in biased biomass estimates: examples of haddock (*Melanogrammus aeglefinus*, L.) and whiting (*Merlangius merlangus*, L.)

H. D. Gerritsen[a,*], D. McGrath[b]

[a] Fisheries Science Services, Marine Institute, Rinville, Oranmore, Galway, Ireland.
[b] Commercial Fisheries Research Group, Galway-Mayo Institute of Technology, Dublin road, Galway, Ireland.

Abstract
Length-weight relationships of fish are often used to estimate the biomass of length distributions or to obtain indices of condition. Although large-scale spatial trends are known to exist, it is often assumed that length-weight relationships do not to vary significantly within stocks or between neighbouring stocks. The present study examined length-weight relationships of 1334 haddock (*Melanogrammus aeglefinus*) and 1186 whiting (*Merlangius merlangus*) collected on a groundfish survey in the waters around Ireland in 2004. Additionally, condition indices were estimated for individual fish and for length frequency samples. The length-weight regression showed a significant area effect and no differences between the sexes. The condition indices showed a moderate spatial structure for both species: around 25% of the variability could be explained by the location of the samples, the rest of the variability was due to other sources. Length-weight relationships did not appear to vary significantly within stocks, however differences between stocks were significant. In the present case, a bias of up to 10% could occur in biomass estimates as a result of applying length-weight relationships of one stock to length data of a neighbouring stock.

Key words: length-weight; condition; haddock; whiting; biomass estimate.

1. Introduction

Length measurements can be obtained quicker and under a larger range of circumstances than weight measurements, therefore a limited number of weight observations is often used to construct a length-weight relationship. This relationship can then be used to convert length distributions into weights for biomass estimates. A widely used relationship between length (L; in cm) and weight (W; in grams) is the power function:

$$W = aL^b \quad (1)$$

This relationship can also be used to estimate a condition index. By keeping parameter b constant for a species or stock, parameter a can be estimated for individual fish and used as a condition index (Anderson and Neumann, 1996).

The parameters a and b can either be estimated by linear regression on the log-transformed variables (Ricker, 1975) or by non-linear regression of non-transformed variables (Hayes et al., 1995). The two methods differ in their assumptions on the

* Corresponding author. Tel: +353 91 387297; fax: +353 91 387201; email: hans.gerritsen@marine.ie (H.D. Gerritsen)

error structure. Linear regression on the log-transformed variables assumes that the errors in the observed weights are log-normally distributed and multiplicative, while non-linear regression assumes a normally distributed, additive error structure (Hayes et al., 1995). Linear regression results in a bias due to the logarithmic transformation: the model passes through the geometric mean, rather than the arithmetic mean, but this can be adjusted using a simple correction factor (Sprugel, 1983).

Many biological parameters are known to vary over small geographical ranges (e.g. Armstrong et al., 2004; Gerritsen et al., 2006). However, for stock assessment purposes, length-weight relationships are often assumed to be uniform for an entire stock. Moreover, when data are sparse for a certain stock, length-weight relationships from neighbouring stocks are sometimes applied (e.g. ICES, 2004b). However, regional differences in the length-weight relationships and condition indices of fish are known to exist (Brodziak and Mikus, 2000; Rätz and Lloret, 2003). These differences could potentially bias biomass estimates. It is presently unclear to which extent differences exist within stocks or between neighbouring stocks. The aim of the present study is to investigate the spatial variability in length-weight relationships and condition indices of two example species: haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) in the waters around Ireland. The potential effects this regional variation has on biomass estimates will be quantified.

2. Methods

Length and weight data were collected on the 2004 Irish Groundfish Survey. This survey is carried out annually on the RV "Celtic Explorer" in the months of October and November. The 2004 survey covered 161 stations around the Irish and Northern Irish coasts in a depth range from 10-250m. Trawling took place during daylight hours for 30 minutes at 3kn of speed over the ground using a GOV trawl (ICES, 1999). The survey area was divided into 14 strata, based on ICES Divisions and bottom depth. Each ICES Division was divided into shallow (<75m), medium (75m-125m) and deep (>125m; where present) depth bands (Figure 1). The catch was speciated, weighed and samples were taken for length measurements. Additionally, biological samples were taken on a length-stratified basis to obtain the age, round weight, sex and maturity stage of individual fish. A target of five biological samples per cm length class was set for each stratum. The length of the fish was measured to the nearest cm below the total length and round weights were recorded in grams. Haddock and whiting were the most abundant commercially exploited demersal species caught on the survey. Individual weights were recorded for 1334 haddock and 1186 whiting.

Values in the length-weight relationships that were obviously spurious, were removed from the dataset after examination of plots of the raw and log-transformed variables. These spurious values amounted to less than 0.2% of the observations. In addition, all fish under 15cm were omitted, as the precision of the weighing scales was considered too low for fish at those sizes. The residuals from linear models of the log-transformed lengths and weights were approximately normally distributed and their variance appeared constant over the range of the predictor variable. Therefore linear, rather than non-linear modelling techniques were applied. No bias correction was applied, as the length-weight relationships were only evaluated relative to each other and not in absolute terms.

A stepwise linear regression procedure was employed to identify influential variables in the linear model (Draper and Smith, 1998). The Akaike Information Criterion (AIC) was used to evaluate the improvement of the model when adding or dropping a term (Sakamoto et al., 1986). The predictor variables for *ln(weight)* that were evaluated, were the main effects *ln(length)*; *stratum*; *stock*; *bottom depth*; *age* and *sex* and all possible interactions between them. Age classes of three years and older were collapsed into one group due to the low catch numbers at these ages. The terms *ln(length)* and *depth* were fitted as continuous variables, the terms *stratum*, *stock, age* and *sex* were fitted as factors. Most gonads were inactive and small at the time of sampling; therefore information on the maturity stage was not included as an explanatory variable. The term *stratum* is likely to be correlated with the terms *bottom depth* and *stock*. Therefore, the terms made available to the models included either *stratum* or *bottom depth* and *stock* but never all three terms.

Due to the relatively low numbers of biological samples at each station, it was not possible to accurately estimate both parameters from Equation (1) for each individual haul. Therefore, in order to obtain information on the length-weight relationship on a fine spatial scale, parameter b was estimated for the combined data of the entire survey and the condition index (parameter a) was then estimated for individual fish by solving Equation (1). The condition index for individual fish was used to estimate variability in the condition of individuals within hauls.

The condition index was also estimated for entire length samples for which only a bulk weight was available by solving a in the following equation:

$$W_{bulk} = a\sum_{i=n}^{n} L_i^b \qquad (2)$$

Where W_{bulk} is the bulk weight of a sample of n length measurements L_i (i = 1,2,...,n). This sample condition index was used to investigate the variability between hauls and the spatial structure in the condition. Spurious values and samples of less than 10 fish were removed, leaving in 108 hauls for haddock and 112 hauls for whiting. At some stations the fish were graded into size classes, resulting in two or more length samples per haul. For the current analysis, these samples were combined, resulting in one sample condition index per location. It was considered that this bulk condition index was a more representative measure of the condition of fish in a particular haul than the average condition index of individual fish taken as part of the length-stratified sampling scheme for biological samples. The reason for this is that the latter is a non-random sample of the catch, while the former consists of a large number of individuals, thus incorporating more of the individual variation in condition.

The spatial structure of the sample condition index was investigated using geostatistical methods (Rivoirard et al., 2000). Station positions were taken as the midpoint of the trawl and projected onto a plane using a transformation of longitude based on the cosine of latitude. Distances between stations were calculated as the shortest distance between two points, regardless of the presence of landmasses. Experimental variograms were computed using code written in the R environment (R-Development-Core-Team, 2005). A lag spacing of 10nm ±5nm was used; this distance is close to the mean distance of each station to its nearest neighbour. The maximum distance for which the variograms were calculated was 200nm, which was just over half the maximum distance between stations. No weighting was used because each sample condition estimate is derived from a single sample weight and a number of length measurements. The precision of the estimate does therefore not necessarily improve with larger sample numbers. Isotropy was assumed in the geostatistical models, this assumption was tested by investigating the presence of trends in the data by plotting the condition indices against bottom depth, latitude and longitude. Linear and spherical variogram models were fitted and evaluated using the goodness-of-fit statistic, which was weighted by the number of pairs in each distance bin (Rivoirard et al., 2000).

In order to quantify the influence that the regional differences in the length-weight relationships might have on biomass estimates, separate length-weight regressions were obtained for each stratum. These relationships were then used to estimate the weight of a "standard" length distribution of mature fish. This length distribution was the average catch length distribution of mature fish, assuming knife-edge maturation at 25cm for both species. This corresponds roughly to the knife-edge maturation ogive at age two that is applied for stocks of both whiting and haddock around Ireland (ICES, 2004a; ICES, 2004b). Confidence limits were estimated from the quantiles of 1000 bootstrap replications, using the sampling stations as bootstrapping units (Efron and Tibshirani, 1993).

3. Results

A simple linear model with *ln(length)* as only predictor variable for *ln(weight)* resulted in a high R^2 of around 0.98 for both species (Figure 2). The residuals did not show any obvious patterns, nor did the locally weighted running line smoothers that were fitted through the residuals (loess with a span of 25%; Figure 2; Hastie and Tibshirani, 1990). This suggests that the linear model provides a good fit.

The stepwise regression procedure identified *ln(length)* as the main explanatory variable for *ln(weight)* for both species, resulting in a very large reduction in the residual sum of squares (Table 1). For both species, the factor *stratum* was the second term in the stepwise procedure to be included into the models; it resulted in a highly significant reduction in the AIC. Inclusion of the term *stratum* resulted in a larger reduction in the AIC than the inclusion of the terms *stock* and/or *bottom depth*, either with or without an interaction term. The terms *stock* and *bottom depth* were therefore omitted from further analysis as they were likely to correlate with the term *stratum*.
The next terms that were added to the model in the stepwise selection procedure were *age* and the interactions *ln(length).age* and *ln(length).stratum* (Table 1). Adding these terms reduced the AIC for both species, but the associated reduction in the residual sum of squares was very low. This suggests that these terms have a limited additional explanatory power, even though they are statistically significant. No terms were dropped during the stepwise procedure and the term *sex* could not be included at any stage without increasing the AIC, suggesting that this factor has no influence on the length-weight relationship.

The sample condition index varied significantly between strata (ANOVA, $p<0.02$ for haddock and $p<0.001$ for whiting), confirming the highly significant stratum-effect found for the length-weight relationship. The mean length of the samples did not influence the condition index (ANOVA, $p=0.94$ and $p=0.28$ respectively), suggesting that the sample condition index is not influenced by the size composition in the samples.

The variograms for the sample condition index show a large nugget effect for both species of around 75-80% of the sample variance (Figure 3). This indicates that 75-80% of the variation is either due to factors other than location or takes place on a smaller scale than the sampling resolution. Nevertheless, the condition indices are not entirely independent of their spatial location; samples taken close together were more similar than samples further apart. The variogram model for haddock increases slowly over the entire range, suggesting a moderate large-scale trend in the data. The whiting variogram stabilises around 150nm after which it does not increase further, indicating a large-scale structure. Data were too sparse to conclusively determine if anisotropy existed. However, no patterns could be discerned when plotting the condition indices against depth, latitude or longitude (data not shown).

The condition indices of the individual fish were used to test if the nugget effect observed in Figure 3 was due to variation on a smaller scale than the sampling resolution or due to variation within hauls. For haddock, the mean variance, weighted by sample numbers, within the hauls was 78% of the mean variance of all individual condition indices, for whiting this figure was 73%. This suggests that the nugget effect is not likely to be due to the scale of the sampling resolution, but due to variability that is independent of sampling location. The remaining 22-27% of variability is due to spatial factors.

The ICES working groups for stock assessment (ICES, 2004a,b) distinguish three haddock stocks and four whiting stocks in the waters around Ireland (Figure 1). The haddock stocks are allocated as follows: West of Scotland; Irish Sea; Celtic Sea plus West of Ireland. For whiting, the Celtic Sea stock is considered separate from the West of Ireland stock, the other stocks are allocated in the same way as the haddock stocks. Figure 4 shows biomass estimates obtained by applying separate length-weight relationships for each survey stratum to the average length distribution of mature fish in the catches. The biomass estimates for haddock were highest using length-weight relationships from the West of Scotland stock. For whiting, the highest biomass estimates were consistently obtained from Celtic Sea length-weight relationships. The lowest biomass estimate was obtained from a length-weight relationship from the West of Ireland. The position of the 95% confidence intervals suggests that differences between some of the stocks are significant, while differences within stocks mostly fall within overlapping confidence intervals.

4. Discussion

The linear model appeared to fit the data well and the residuals did not show any patterns. A linear length-weight relationship implies that life-history events like maturation do not influence this relationship (at least not at the time of sampling). In linear regression, all observations are assumed to be independent. However, sampling took place in a grouped way: each sampling station provided a number of length-weight observations. If the observations within hauls are strongly correlated, this assumption might be violated and the variances might not be estimated correctly. Lai & Helser (2004) suggest using linear mixed-effects models for grouped samples but the sample sizes are often too small to allow separate models to be fitted to data from individual stations. The data on the sample and individual condition indices suggested that there was some correlation within the hauls but that most (around 73-78%) of the variability was due to other factors than location. So for the purpose of variance estimation, the observations could be assumed to be effectively independent. However, for the purpose of sampling design, the spatial structure does appear to be significant.

The analysis showed that, after *ln(length)*, the factor *stratum* appeared the most influential variable. Although the stratification was based on bottom depth, the term *bottom depth* itself did not reduce the residual sum of squares much when added into the model for either species. The factor age might play a small role, suggesting a possible year-class effect. The interaction terms suggest that not only the intercept, but also the slope might differ between strata and age classes. However, these effects are very small compared to the stratum effect. It is also interesting to note that the term sex was not a significant variable at any point in the stepwise selection procedure for either species. This suggests that there are no significant differences between the sexes in their length-weight relationship at the time of sampling.

The variograms of the sample condition index showed that there was a moderate spatial component in the distribution of the condition indices: stations that were close to each other were more similar than stations with large distance between them. However, most of the variability does not depend on location, but is due to other sources of variation. This might explain why no spatial trends could be discerned in the condition of fish of either species: the condition indices did not show a clear trend with depth, longitude or latitude. The observed variability is therefore possibly due to a more complicated set of parameters than spatial factors alone. Temperature has been linked to variation in condition of cod (Lloret and Rätz, 2000; Yaragina and Marshall, 2000; Chouinard and Swain, 2002; Rätz and Lloret, 2003). However, these authors refer to variation in temperature on a much larger spatial scale than covered by the present study. Local differences in other environmental conditions, food availability and parasites could also play a role (Lambert and Dutil, 1997; Yaragina and Marshall, 2000), as well as individual differences in energy allocation (Chouinard and Swain, 2002). Movement of fish between locations complicates the spatial variability further.

The length-weight relationships of some neighbouring stocks varied enough to result in significantly different biomass estimates when applied to the same length-frequency distribution. On the other hand, the length-weight relationships within the stocks generally did not appear to vary significantly. In the current study, the largest difference in biomass estimates was between the length-weight relationships obtained from the West of Ireland and Celtic Sea whiting stocks. The estimated weight of the average length distribution of mature whiting per haul over the entire survey was 28.4kg using the West of Ireland length-weight relationship, while the estimated weight of the same length distribution was 31.3kg using the Celtic Sea relationship. This is a difference of 10% (bootstrapped 95% confidence limits of 6-15%). Although the magnitude of this error is relatively small to other errors involved in stock assessment, (e.g. Gerritsen et al. 2006) it is certainly not insignificant. Considering the relatively low cost of obtaining precise length-weight relationships, it seems worthwhile to ensure that this bias is avoided and length-weight data are only applied for areas from which they were obtained.

Acknowledgements
Free R-software has been used for this work and the authors would like to thank the R development core team and all contributors to the R project (http://www.R-project.org). Also thanks to the crew and scientific staff that participated in the 2004 Irish Groundfish Survey. We are also grateful for the constructive comments from dr Colm Lordan and two anonymous referees.

References

Anderson, R.O., Neumann, R.M., 1996. Length, weight and associated structural indices. In: Murphy, B.R. Willis, D.W. (Eds), Fisheries Techniques, second edition. American Fisheries Society, Bethesda, USA, pp. 447-482.

Armstrong, M.J., Gerritsen, H.D., Allen, M., McCurdy, W.J., Peel, J.A.D., 2004. Variability in maturity and growth in a heavily exploited stock: cod (*Gadus morhua* L.) in the Irish Sea. ICES J. Mar. Sci., 61: 98-112.

Brodziak, J., Mikus, R., 2000. Variation in life history parameters of Dover sole, *Microstomus pacificus*, off the coast of Washington, Oregon and northern California. Fish. Bull., 98: 661-673.

Chouinard, G.A., Swain, D.P., 2002. Depth-dependent variation in condition and length-at-age of Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci., 59: 1451-1459.

Draper, N.R., Smith, H., 1998. Applied regression analysis. Wiley, New York.

Efron, B., Tibshirani, R.J., 1993. An introduction to the bootstrap. Chapman & Hall/CRC, Boca Raton.

Gerritsen, H.D., McGrath, D., Lordan, C., 2006. A simple method for comparing age-length keys reveals significant regional differences within a single stock of haddock (*Melanogrammus aeglefinus*). ICES J. Mar. Sci., 63: 1096-1100.

Hastie, T.J., Tibshirani, R.J., 1990. Generalized additive models. Monographs on statistics and applied probability. Chapman & Hall/CRC, Boca Raton.

Hayes, D.B., Brodziak, J.K.T., O'Gorman, J.B., 1995. Efficiency and bias of estimators and sampling designs for determining length-weight relationships of fish. Can. J. Fish. Aquat. Sci., 52: 84-92.

ICES, 1999. Manual for the International Bottom Trawl Surveys. Revision VI. ICES CM 1999/D:2, ICES, Lisbon.

ICES, 2004a. Report of the Working Group on the Assessment of Northern Shelf Demersal Stocks (WGNSDS), ICES, Copenhagen.

ICES, 2004b. Report of the Working Group on the Assessment of Southern Shelf Demersal Stocks (WGSSDS), ICES, Oostende.

Lai, H.L., Helser, T., 2004. Linear mixed-effects models for weight-length relationships. Fish. Res., 70: 377-387.

Lambert, Y., Dutil, J.D., 1997. Condition and energy reserves if Atlantic cod (*Gadus morhua*) during the collapse of the northern Gulf of St. Lawrence stock. Can. J. Fish. Aquat. Sci., 54: 2388-2400.

Lloret, J., Rätz, H.J., 2000. Condition of cod (*Gadus morhua*) off Greenland during 1982-1998. Fish. Res., 48: 79-86.

Rätz, H.J., Lloret, J., 2003. Variation in fish condition between Atltantic cod (*Gadus morhua*) stocks, the effect on their productivity and management implications. Fish. Res., 60: 369-380.

R-Development-Core-Team, 2005. R: A language and environment for statistical computing. R Foundation for statistical Computing, Vienna, Austria.
Ricker, W.E., 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can., 191: 382 pp.
Rivoirard, J., Simmonds, J., Foote, K.G., Fernandes, P., Bez, N., 2000. Geostatistics for estimating fish abundance. Blackwell Science Ltd., Oxford.
Sakamoto, Y., Ishiguro, M., Kitagawa, G., 1986. Akaike Information Criterion Statistics. D. Reidel Publishing Co, Tokyo.
Sprugel, D.G., 1983. Correcting for bias in log-transformed allometric equations. Ecology, 61: 209-210.
Yaragina, N.A., Marshall, C.T., 2000. Trophic influences on interannual and seasonal variation in the liver condition index of northeast Arctic cod (Gadus morhua). ICES J. Mar. Sci., 57: 42-55

Figures

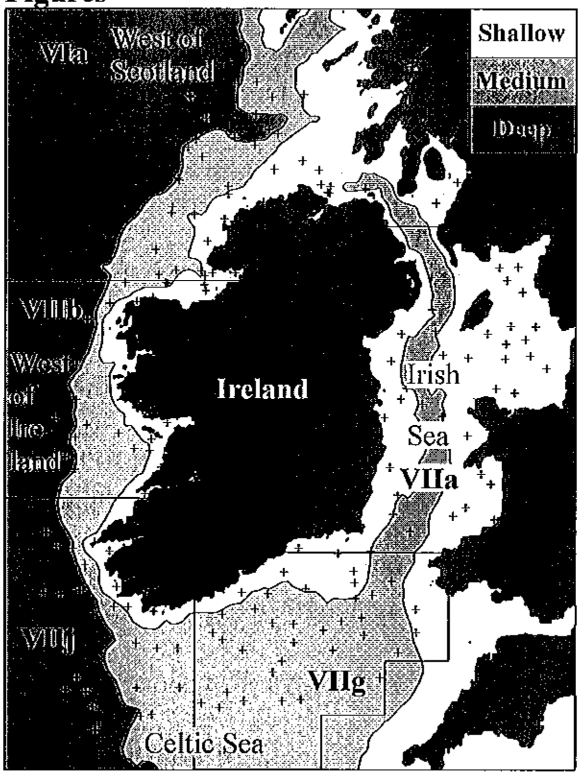

Figure 1.The survey area. The crosses represent the sample locations. The survey covered ICES Divisions VIa, VIIa, VIIb, VIIg and VIIj, each of which was stratified into shallow, medium and deep (where present) depth bands.

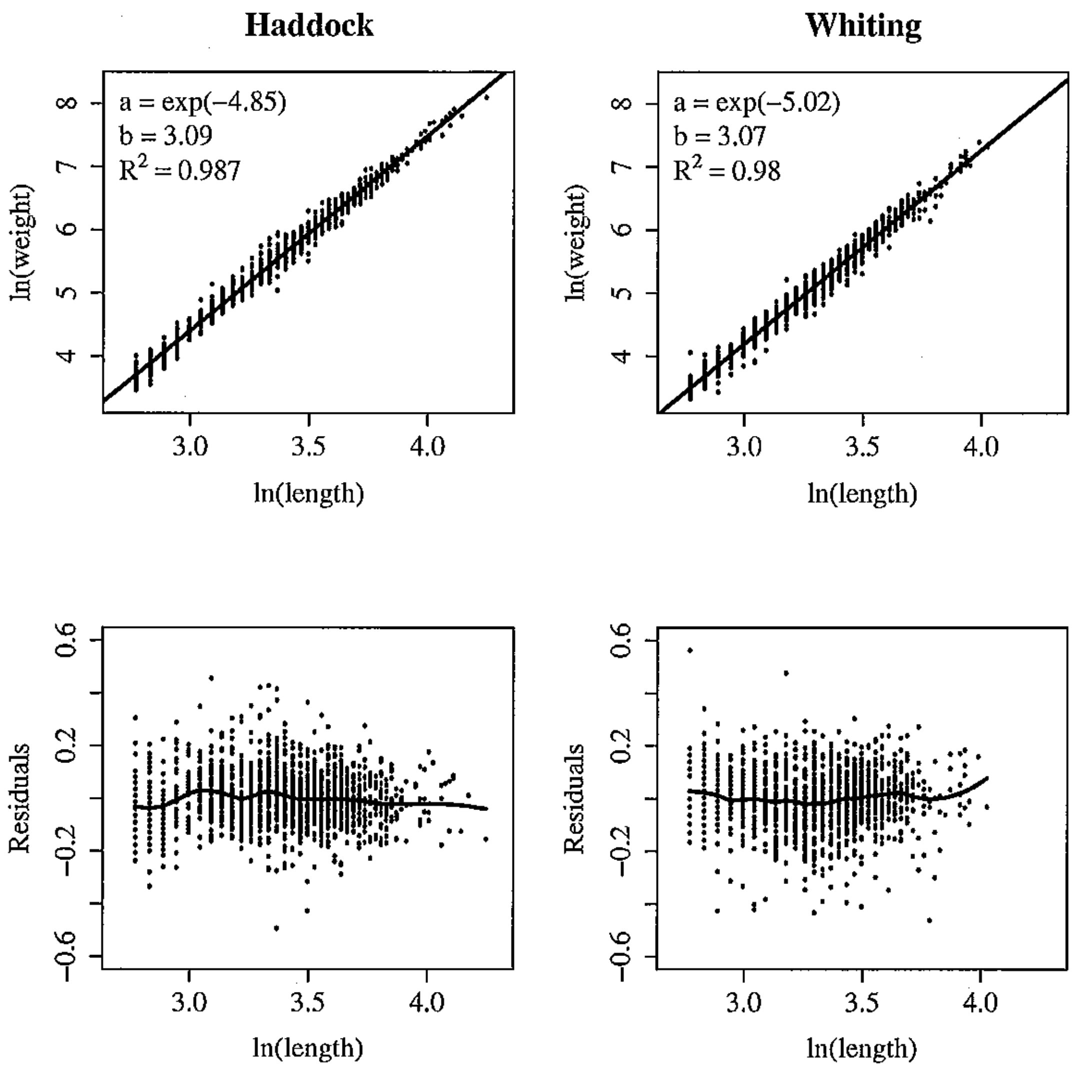

Figure 2. Linear models and residuals of the length-weight relationship for haddock and whiting. All data combined. The parameters a *and* b *refer to equation (1),* R^2 *is the coefficient of determination. A locally weighted running-line smoother (loess) with a span of 25% was fitted through the residuals.*

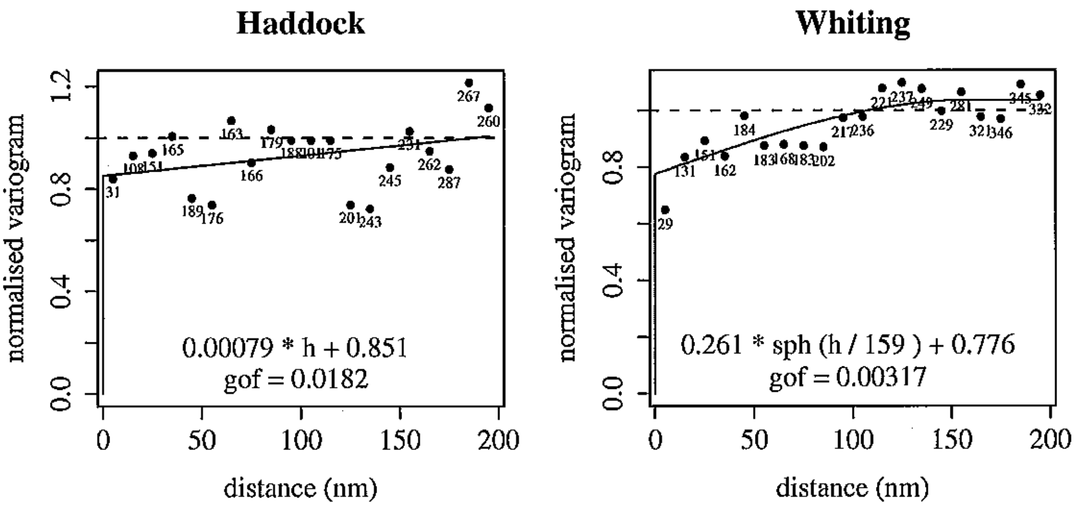

Figure 3. Normalised variograms for the sample condition index of haddock and whiting. The dots indicate the values of the experimental variogram and the numbers indicate the number of paired observations in each distance bin. The solid line is the model with the optimum goodness-of-fit (gof)*. The model parameters and* gov *are given in the bottom of the plots.*

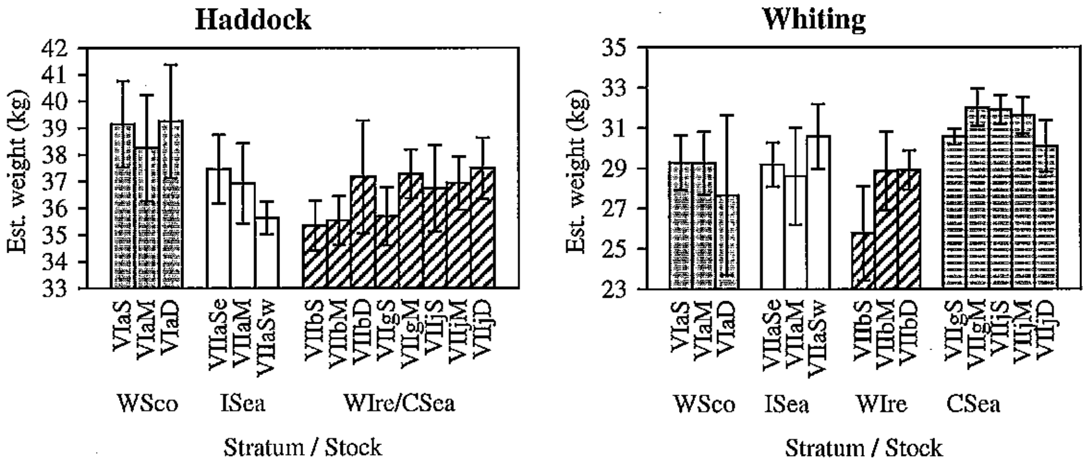

Figure 4. Biomass estimates obtained by applying separate length-weight relationships for each stratum to the same length distribution of mature fish. The error bars indicate the 95% confidence limits, obtained by bootstrapping. The strata are indicated by their ICES Division followed by S, M or D for the shallow, medium and deep strata. The shallow stratum in VIIa was further divided into an eastern (e) and western (w) part. The stocks are identified by WSco for West of Scotland; ISea for Irish Sea; WIre for West of Ireland and CSea for the Celtic Sea. Differences within stocks appeared to be limited, but some consistent differences existed between stocks.