

Abstract—A learning curve analysis is applied to model the change in effort units with time by the commercial fishery for Atlantic cod (*Gadus morhua*) in the Barents Sea. The results indicate that fishing efficiency has increased and that the adjusted commercial catch per unit of effort (CPUE) is more strongly related with stock abundance.

Adjustment of commercial trawling effort for Atlantic cod, *Gadus morhua*, due to increasing catching efficiency

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Fishing fleets and individual fishing vessels are expected to increase their efficiency with time owing to technological improvements. This is a serious problem when a time series of commercial catch per unit effort (CPUE) is used to measure trends in fish stock abundance (Gulland, 1983). A standard effort unit will gradually remove a greater proportion of the stock, and the CPUE corresponding to a given fish stock abundance will increase. Commercial effort units should, therefore, be adjusted to account for gradual changes in catchability (Gulland, 1983).

A learning curve describes how unit costs decline as organizations gain experience in production (Argot and Epple, 1990). The general form of the learning curve is given by

$$y = ax^{-b}, \quad (1)$$

where y = the number of direct labor hours required to produce the x th unit;

a = the number of labor hours required to produce the first unit;

x = the cumulative number of units produced; and

b = the parameter measuring the rate at which labor hours are reduced as cumulative output increases (Argot and Epple, 1990).

If a learning curve is used to describe a fishery, the labor hours required to produce the x th unit can be translated into the effort required to catch a certain fraction of the fish stock, termed effort per stock fraction (*epsf*). Time, instead

of cumulative catch, is assumed to be a better measure of x because fishermen learn even if stock abundance and catches are low. In this study, appropriate learning curves are fitted to the decrease in *epsf* with time for vessels in the Norwegian bottom trawler fleet in the fishery for Atlantic cod (*Gadus morhua*). Effort is then adjusted by using the fitted learning curve, to generate CPUE-indices that better reflect fish stock abundance.

Materials and methods

To calculate the effort per stock fraction (*epsf*) for a given vessel, effort is divided by the ratio of catch and fishable stock biomass (stock fraction caught) in a given time period:

$$epsf = \frac{e}{\left(\frac{c}{B_f}\right)} = \frac{B_f \cdot e}{c}, \quad (2)$$

where B_f = the estimated weight of fishable biomass; and

e = the total effort and c is the total catch (weight) during the time period.

The catch and effort data should be independent from the estimate of B_f . Some catch composition criteria should also be introduced to increase the probability that the vessels were part of the targeted fishery during the period. Note that *epsf* is the inverse of catchability.

By inserting *epsf* for y and time (t) for x in Equation 1, then

$$\ln(\text{epsf}) = \ln(a) - b \cdot \ln(t). \quad (3)$$

By fitting a regression line to $\ln(\text{epsf})$ versus $\ln(t)$, estimates of the parameters $\ln(a)$ and b in the learning curve are obtained. An unbiased estimator for a is $\exp(\ln(\hat{a}) + \text{MSE}/2)$ (Casella and Berger, 1990), where $\ln(\hat{a})$ is the intercept of the regression line and MSE is the mean squared error from the regression. A learning curve can be estimated at the fleet level by using average *epsf* of the vessels, and at the vessel level by using an individual vessel's *epsf*. These two approaches are somewhat different because the efficiency of a fleet is increased both by improvement of existing vessels and by addition of new and better vessels.

The effort units in a time series of CPUE can be adjusted to the level of one of the elements (index time) in the time series as follows:

$$e_i^* = e_i \left(\frac{\text{epsf}_{\text{index}}}{\text{epsf}_i} \right), \quad (4)$$

where e_i^* = the adjusted effort at time i ;
and

$\text{epsf}_{\text{index}}$ = the effort per stock fraction modelled
and epsf_i with the estimated learning curve at the index
time and time i , respectively.

Note that the learning curve model is a continuous function and CPUE is normally given as a discrete time series. Time i should, therefore, correspond to the midpoint of the time interval over which the corresponding CPUE observation is calculated.

The catch and effort data were taken from a logbook database collected by the Norwegian Directorate of Fisheries. Logbooks from the Norwegian bottom trawler fleet have been recorded since 1971 and each individual record includes vessel, species, date, and summarized duration (in hours) and summarized catch (in kilograms) of the trawl hauls each day. Estimates of trawlable biomass (B_p) of Atlantic cod in the Barents Sea were taken from VPA (virtual population analysis) estimates of stock biomass at the beginning of each year (ICES¹). Only 20% of the 3-year-old cod and 50% of the 4-year-old cod were considered to belong in the trawlable part of the biomass because of mesh selection in the trawls. This selection of young cod corresponded broadly to the retention probabilities in the beginning of the year based on a trawl selection curve. The effort (e) is hours of trawling. Because the VPA estimates of stock size are given for the start of the year, the summation of catch and effort for a given year (t) are over the period from July in year $t - 1$ to June in year t . In this way the stock estimates from VPA are given for the middle of the time period. Only records with more than 20%

(in weight) cod for a recorded day were used to increase the probability that cod was the target species. Varying the minimum accepted proportion of a species in catches has been shown to significantly affect estimates of CPUE (Ketchen, 1964). To avoid vessels that did not take active part in the cod fishery, only vessels with at least 10 observations where more than 50% cod were present in a given year were used in the calculation of the fleet's average *epsf*. Only cod records from north of 67°N were used because this latitude is the limit of the distributional area for Atlantic cod along the Norwegian coast.

Changes in yearly *epsf* were analyzed and estimates of the parameters in the learning curve were made at the vessel level and at the fleet level (average *epsf*) in the period 1971–99. Only one vessel was active during the whole period without being rebuilt, and this vessel was chosen for analysis at the vessel level.

The trawl fishery for Atlantic cod in the Barents Sea has existed since about 1920, but the Norwegian trawler fleet did not significantly participate in this fishery until after the end of the Second World War. Year one in the learning process for the Norwegian trawler fleet is therefore set at 1946. In the present study, sufficient data for estimating learning curves exist only from 1971, which is a limited part of the time period in which the Norwegian fishery has existed. This causes the year 1972, the first year where it is possible to estimate *epsf*, to become year 27 in the learning process.

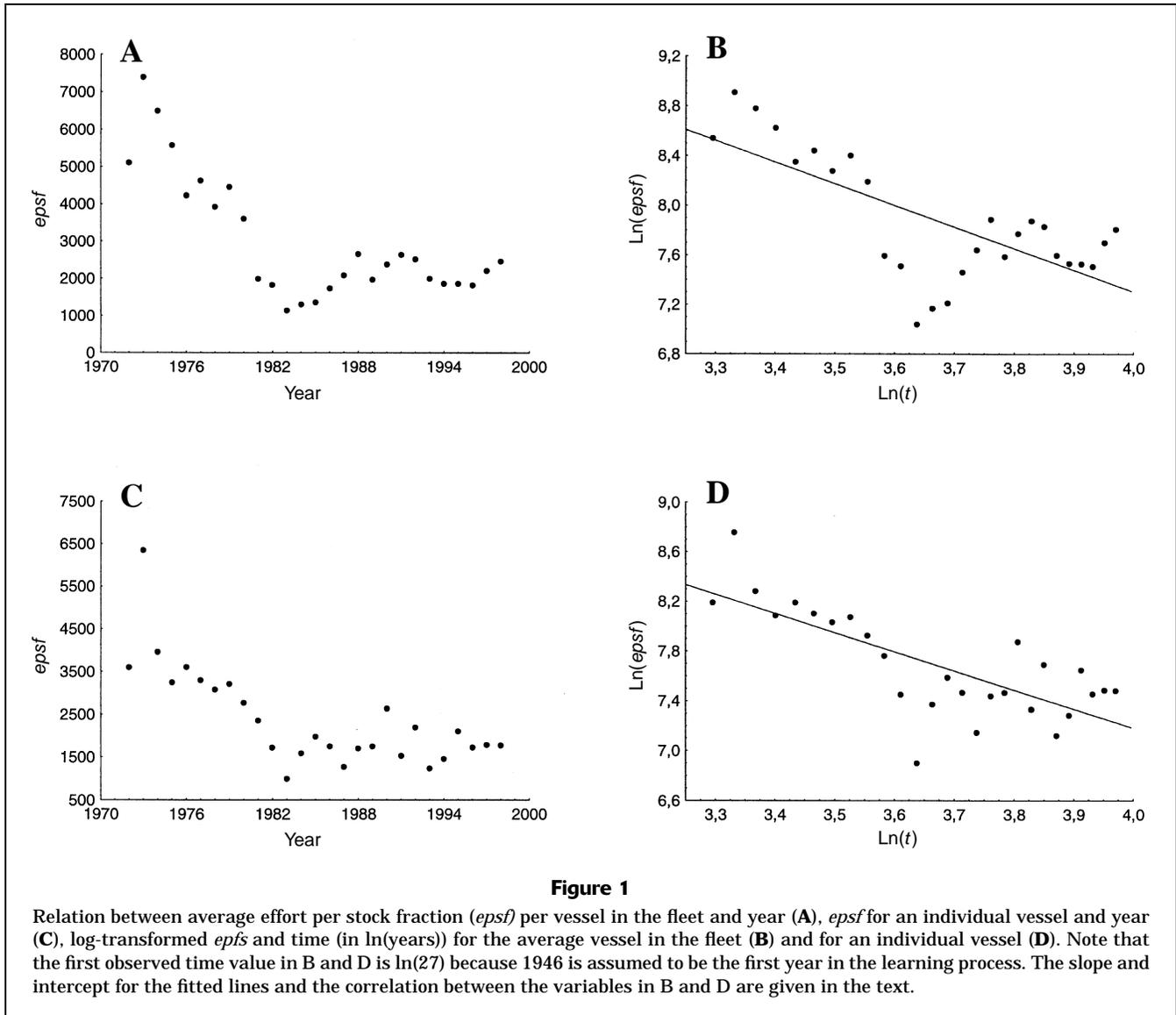
A time series of CPUE for Atlantic cod of the Barents Sea was calculated by using the same catch and effort data as above, and yearly effort was adjusted (Eq. 4) to the level of 1972 by using the estimated learning curve on the fleet level. Only records containing more than 20% cod (in weight) were used. CPUE was set as total catch divided by total effort in the period from July in year $t - 1$ to June in year t .

Results

The estimates of annual *epsf* showed a decreasing trend with time both at the fleet level and at the vessel level (Fig. 1, A and C). The slope and intercept of the fitted regression line at the fleet level (Fig. 1B) were 1.742 and 14.272, respectively, and the correlation given as the r^2 -value was 0.50. At the vessel level the values of the slope and intercept (Fig. 1D) were 1.538 and 13.334, respectively and r^2 was 0.55. The estimated a was 1895039.044 at the fleet level and 714722.761 at the vessel level. The slopes of the two regression lines were significantly different from zero ($P < 0.0001$), but the two regression lines were not significantly different from each other ($P > 0.05$).

The time series of annual CPUE became much more similar to the biomass estimate from VPA when effort was adjusted (Fig. 2), especially in the first and last part of the time period. In the middle of the period (after 1980) the trend in adjusted CPUE suddenly became different from that of biomass estimates from VPA, and CPUE values were much higher than biomass in relation to the ratio in the first and last part of the period for some years.

¹ ICES (International Council for the Exploration of the Sea). 2000. Report of the Arctic Fisheries Working Group, Copenhagen, 23. August–1. September 1999. ICES CM 2000/Assess:3, 311 p. ICES, Palægade 2-4 DK-1261 Copenhagen K, Denmark.



Discussion

A learning curve ideally requires data points from the initial phase of the process. For many fish stocks, catch and effort data, together with an independent estimate of total biomass, exist only for recent years. Given the approximate year the fleet entered the fishery, it is necessary to assume that *epsf* follows the learning curve pattern from that year onwards. Under this assumption, it is possible to adjust effort backwards in time to the level of one year in the time series by using the estimated learning curve. Technical revolutions, such as the introduction of hydraulic wires, may cause a very dramatic change in the fishery, and if this happens the learning curve should be estimated from the time when the new technology appeared. Good knowledge about the history of the fishery is thus necessary. There are also alternative methods for dealing with increases in efficiency with time in a fishery. Gulland

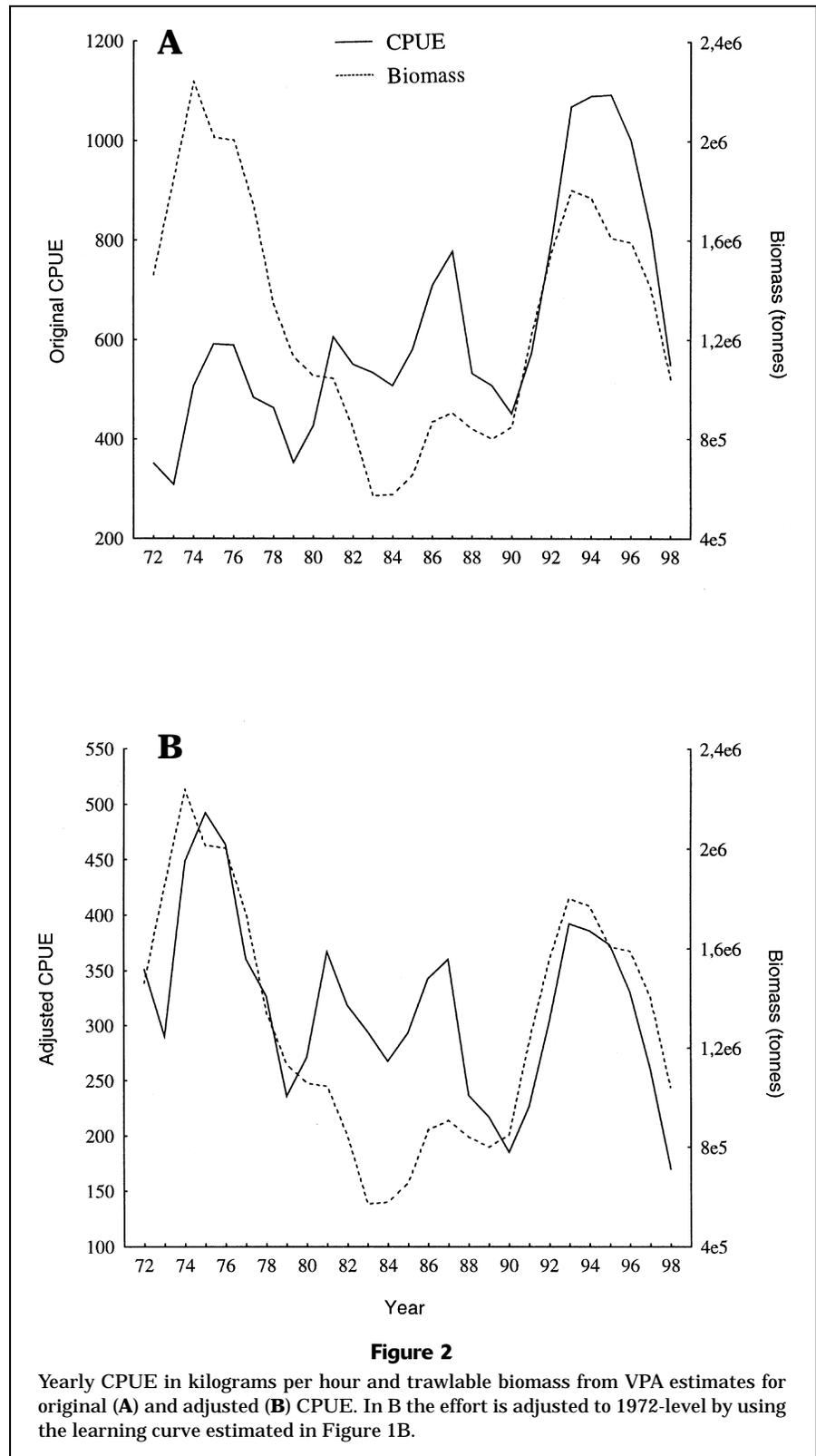
(1983) suggested constant monitoring of the changes in the fishing gears by conducting experiments. This solution may, however, be very expensive.

The question whether the effort should be adjusted with a learning curve from the fleet level or from the vessel level depends on the resolution of the catch and effort data and on other standardization of effort. If effort is first adjusted within the fleet because of the individual differences in fishing power, adjustment of the effort due to learning should be based on a learning curve from the standard vessel or the group of standard vessels to avoid double standardization. It is important to be aware that individual vessels also may show different learning rates and these may differ from the average learning rate of the fleet. An individual vessel may improve its efficiency by increasing the cooperation with other vessels, by buying better searching equipment and more efficient fishing gear, and by hiring more skilled crew.

An important assumption in this work is that a constant fraction of the stock is caught when the fleet has a constant efficiency. Many fish stocks, including the Atlantic cod stock in the Barents Sea, have a seasonal cycle in availability to the fishing fleet because of regular spawning and feeding migrations that cause large peaks in the density of fish. The assumption above is therefore violated if the spatial and temporal distribution of effort in the fleet during the year changes between years. Correction for changes in the seasonal distribution of effort between years are, however, described by e.g. Gulland (1983) and Gavaris (1980). Around 1979 quotas and fishery regulations were introduced in the Norwegian fisheries. As seen from the outliers in Figure 1, it is obvious that something affected the *epsf* after 1980. Dramatic responses are expected when a fishery is regulated (Hilborn and Walters, 1992). Responses to regulations may include changes in the effort distribution during the year, changes in the patterns of competition and cooperation with other vessels, increased misreporting, and increased amounts of discards.

In addition to uncertainties in the reported catch and effort from the vessels, there are also uncertainties in the VPA estimates of stock size (see Ulltang, 1977). The trawlable fraction of the youngest year classes also changes within and among years due to individual growth and yearly differences in growth. The constant retention probabilities used in this work to select the youngest age classes from the VPA estimates, and the use of only one single stock estimate per year is thus, perhaps, an over simplification. To get a better estimate of the learning curve, *epsf* can be estimated based on averaging effort and catch over shorter time periods than in this work. This requires, however, advanced modelling of the selection process, and possibilities for obtaining estimates of total abundance more than once a year.

The VPA estimates and the catch and effort data used in this work are not totally independent from each other.



A time series of commercial CPUE from the Norwegian trawler fleet was used, together with other CPUE time series, to calibrate the most recent VPA estimates of the old-

est fish (owing to lack of survey data for old fish). Total catch data from the fleet were also used in the VPA procedure. Converged VPA were, however, fairly independent of CPUE, and the limited dependence was not considered to have a large effect on the learning curve estimation.

It seems reasonable, as seen from the plots in Figure 1, to assume that *epsf* followed a learning curve pattern with time. The outliers around 1980 affected the regression lines in Figure 1 (B and D) considerably. If these outliers were caused by the fishermen's response to the new regulations, they should perhaps be removed. Another solution is to develop learning curve models that account for such strong interventions.

The sudden change in the relation between CPUE and VPA estimates in Figure 2 may have been caused by the introduction of fishery regulations, but there are other important factors affecting the use of CPUE as an index of abundance. Some of these factors are similar to those mentioned above, under the discussion of the assumptions concerning the estimation of *epsf*. Another explanation for the sudden change of the ratio between CPUE and biomass estimates from VPA in Figure 2B and for the outliers in Figure 1 around 1980 is that CPUE and *epsf* (or equivalently the catchability) are functions of stock abundance. An increase in catchability at low stock size is suggested in Figure 2 by the relatively high catch rates (given the low biomass) in the early to mid 1980s. This increase may, however, be contradicted by the similar trend in biomass and adjusted CPUE in Figure 2B at the end of the time period, when stock abundance became relatively low again. If catchability is shown to be density dependent for Atlantic cod in the Barents Sea, it should be incorporated into the model when the learning curve is fitted. Both long-term changes (e.g. Gordo and Hightower, 1991; Swain et al., 1994) and density-dependent changes (Crecco and Overholtz, 1990; Rose and Kulka, 1999) in catchability of gadoids have been indicated when commercial CPUE is being used as an index of abundance.

Conclusion

Modeling of *epsf* using the learning curve seems to be a promising method for solving the old and well-known problem of learning when time series of commercial CPUEs are used as indices of abundance. Care needs to be taken when selecting data and observations for estimation of learning curves, especially in multispecies fisheries.

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