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1. Introduction

Stock assessment scientists use time-series fishing effort data either directly for correlation with estimates of fishing mortality or indirectly to calculate catch per unit effort (c.p.u.e.) for correlation with estimates of stock biomass. These uses assume that a given amount of fishing effort will always generate the same level of fishing mortality, and that a given c.p.u.e. will always reflect a particular level of abundance. However, both of these assumptions will be invalid when the efficiency of a fleet is varying significantly with time, either as a result of changes in fleet composition or because of changes in the efficiency of individual trawlers from one period to another. Under these circumstances effective fishing effort, which is defined as fishing effort multiplied by fishing power (P), must be used throughout. It is therefore important to evaluate the property called 'fishing power' and to investigate its relationship with as many known or measurable determinate variables as possible. A predictive equation for P can then be developed, and, if the variables used are monitored within a fleet across time periods, effective fishing effort can be calculated.

The Lowestoft offshore trawl fleet has undergone major changes in both vessel composition and deployment since the 1950s. Prior to 1950 the fleet consisted of small steam trawlers and drifter-trawlers and fishing was restricted to grounds in the southern North Sea (ICES Division IVc). From 1955 onwards the steam trawlers were gradually replaced by more powerful diesel vessels and more fishing effort was expended on grounds in the central North Sea (ICES Division IVb). During the late 1960s both the older diesel trawlers and the remaining drifter-trawlers were replaced by a smaller number of new trawlers of over 30 m in length and up to 1500 brake horsepower (BHP). The size, power and sea-keeping qualities of these vessels facilitated a further expansion of fishing onto grounds in the northern North Sea (ICES Division IVa). Although several very powerful trawlers of up to 2000 BHP were built during the early 1970s, the trend towards larger vessels of increasing engine power was reduced by the oil crisis of 1973/4 and the resultant increase in fuel costs. This coincided with a substantial decline in the size of the fleet caused mainly by the transfer of many older side-trawlers to oilrig standby duties. This decline was further exacerbated in 1979 by the combined effects of a second oil crisis and depressed quayside fish prices, and the fleet at the start of the 1980s was probably smaller than at any time since the second world war.

The Lowestoft offshore trawl fleet has therefore been declining in size since the mid-1960s, but the effect of this decline on effective fishing effort may have been offset by the introduction of more powerful trawlers.

The aim of this study, therefore, is to develop a predictive equation for the fishing power of Lowestoft offshore trawlers. The trawlers chosen for study are those which were fishing between 1972 and 1979, and the method used to calculate P is that adopted by Gulland (1956). The vessel characteristics of each trawler and the size of trawl used are evaluated, and these variables are then used to develop a suitable predictive equation. The attempt is made to identify any unexplained trends in P which may have existed during the period studied. The predictive equation is then compared with similar equations developed in previous investigations, and the attempt is made to determine whether the equation is suitable to predict P for Lowestoft motor trawlers fishing during the 1950s and 1960s. The equation is then used to estimate the average fishing power of Lowestoft trawlers in each year between 1972 and 1979.

2. Methods

The following vessel characteristics were evaluated for all offshore trawlers landing at Lowestoft between 1972 and 1979: brake horsepower (BHP), gross registered tonnage (GRT), registered length (RL) and date of building (DOB). Offshore trawlers were defined as vessels of more than approximately 25 m in length which regularly completed trips in excess of three days duration. Following Gulland (1956) in principle, a group of 'standard' trawlers was selected whose vessel characteristics had remained constant between 1972 and 1979, and which, on as many occasions during as many years as possible, had fished alongside each other but not necessarily all together at the same location. The relative fishing power of the standard trawlers was calculated by comparing the c.p.u.e. of each pair of trawlers when two or more fished the same ground at the same time. In the context of the data available, 'same ground' means the same ICES standard statistical rectangle and 'same time' means vessels fishing within the same calendar month; trips were allocated to the month in which their trip midpoint occurred. The fishing power of the ith standard trawler ($i = 1, n$), relative to the other trawlers in the standard group ($\ell = 1, n-1$), was therefore calculated over the m months ($j = 1, m$) for which comparisons were available:

$$P'_i = \frac{1}{n-1} \Sigma_\ell \frac{1}{m} \Sigma_j (d'_{ij} - d'_{\ell j}) \qquad (1)$$

where P'_i = log fishing power of the ith standard trawler, and $d'_{ij}(d'_{\ell j})$ = log c.p.u.e. of the ith (ℓth) standard trawler in the jth month.

An estimate of the mean density of fish within each rectangle was then determined from the c.p.u.e. and fishing powers of the standard trawlers, for as many months and rectangles as possible:

$$D'_j = \frac{1}{n} \Sigma_i (d'_{ij} - P'_i) \qquad (2)$$

where D'_j = mean log density in the jth month for a specified rectangle, and n = number of standard trawlers which fished in the rectangle in the jth month.

The fishing power of the 'non-standard' trawlers was calculated by comparing their c.p.u.e. with the density estimates derived from the standard trawlers, on each occasion when both categories of trawler fished the same rectangle in the same month:

$$P'_k = \frac{1}{m} \Sigma_j (d'_{kj} - D'_j) \qquad (3)$$

where P'_k = mean log fishing power of the kth non-standard trawler over the m months ($j = 1, m$) for which estimates of fishing power were available.

Trawlers having only a small number of monthly estimates (<6) were excluded from analysis. Gulland advocated that P should be defined relative to one species of fish, and in this study the above calculations have been carried out on plaice (*Pleuronectes platessa* L.) c.p.u.e. data recorded for trips in which plaice accounted for more than 50% of the total catch. Logarithms to base 10 have been used throughout (log P was coded $+0.5$ to avoid negative values).

Only five standard trawlers fulfilled the criterion of fishing 'side by side' in each year between 1972 and 1979 (analysis A), although more trawlers were available if separate analyses were carried out over shorter time periods. Two additional fishing power analyses were therefore carried out for the periods 1972—74 (analysis B) and 1976—79 (analysis C).

The relationship between P and vessel characteristics was then investigated by both simple and multiple regression analysis, and the results for each time period were compared by analysis of covariance. The effect of size of trawl on P was analysed by a combination of multiple regression and analysis of covariance. An attempt was made to identify any unexplained trends in the fishing power of individual trawlers by comparing their average fishing powers in each year of the period studied.

3. Data

The analyses of fishing power were carried out on data derived from the records of catch, effort and location of fishing for individual trips made by each trawler, stored on the Ministry of Agriculture, Fisheries and Food (MAFF) H-form historical fish-landings file. The records for 1975 were unsuitable for analysis due to a technical problem in that year with the recording and allocation of statistical rectangle information. Information on vessel characteristics was obtained from MAFF records, the Sea Fish Industry Authority (Grimsby Office) and the Lowestoft fishing companies. The latter also supplied information on the types and dimensions of net used by each trawler.

4. Results

4.1 Vessel characteristics and size of trawl

Vessel characteristics were available for all but two of the 133 offshore trawlers which landed at Lowestoft between 1972 and 1979. Figure 1 shows that the majority of trawlers had main engines of between 450 and 1200 BHP, lengths of between 28 and 38 m, and tonnages of between 150 and 350 t. The oldest trawler was built in 1927 but 60% of vessels were built between 1955 and 1964. Figure 2 shows that the average BHP and GRT of trawlers increased substantially between 1972 and 1979 (689.0 to 917.5 BHP and 224.3 to 268.7 GRT), whereas the size of the fleet decreased by over 17% (85 to 70 vessels). Average length increased only marginally (33.2 to 34.5 m), although average age increased by 9% (13.1 to 14.3 years). Many older trawlers were either withdrawn or temporarily laid up after the first oil crisis, and this is reflected by a sharp drop in average age between 1974 and 1975.

Several different sizes of otter trawl were used by Lowestoft offshore trawlers during the period studied, although the size used tended to vary between rather than within vessels. The approximate dimensions of the different trawls and the number of trawlers using each size are described in Table 1.

4.2 Fishing power

Estimates of P were available for 79 of the 133 offshore trawlers fishing between 1972 and 1979, 54 of the 95 trawlers fishing between 1972 and 1974 and 56 of the 91 trawlers fishing between 1976 and 1979. These ships had a similar range of BHP, RL etc, to that observed in the fleet in each time period, although estimates of P were not available for the majority of trawlers of less than 30 m in length, 200 GRT and 450 BHP.

Figure 3 shows that the variance of log P in the non-standard trawlers from analysis A (1972—79) is independent of the mean, and the deviations from the means of the monthly estimates of log P for these trawlers are shown in Figure 4 to be approximately normally distributed. Similar results were obtained for analyses B (1972—74) and C (1976—79).

4.3 Predictive models of fishing power

Regression analysis was used to examine the hypothesis that P is unrelated to any single vessel characteristic (simple regression) or combination of characteristics (multiple regression). The simple regression equations fitted were a linear relationship $P = a + bX$ and a log-log relationship $\log P = \log a + b.\log X$ (equivalent to a power relationship $P = aX^b$), where X is BHP, GRT etc. Table 2 shows that P, in both regression models, is positively correlated with BHP, GRT and RL in all three time periods, and that, with the exception of analysis B (1972—74), there is also a significant tendency for younger trawlers to have greater P. BHP

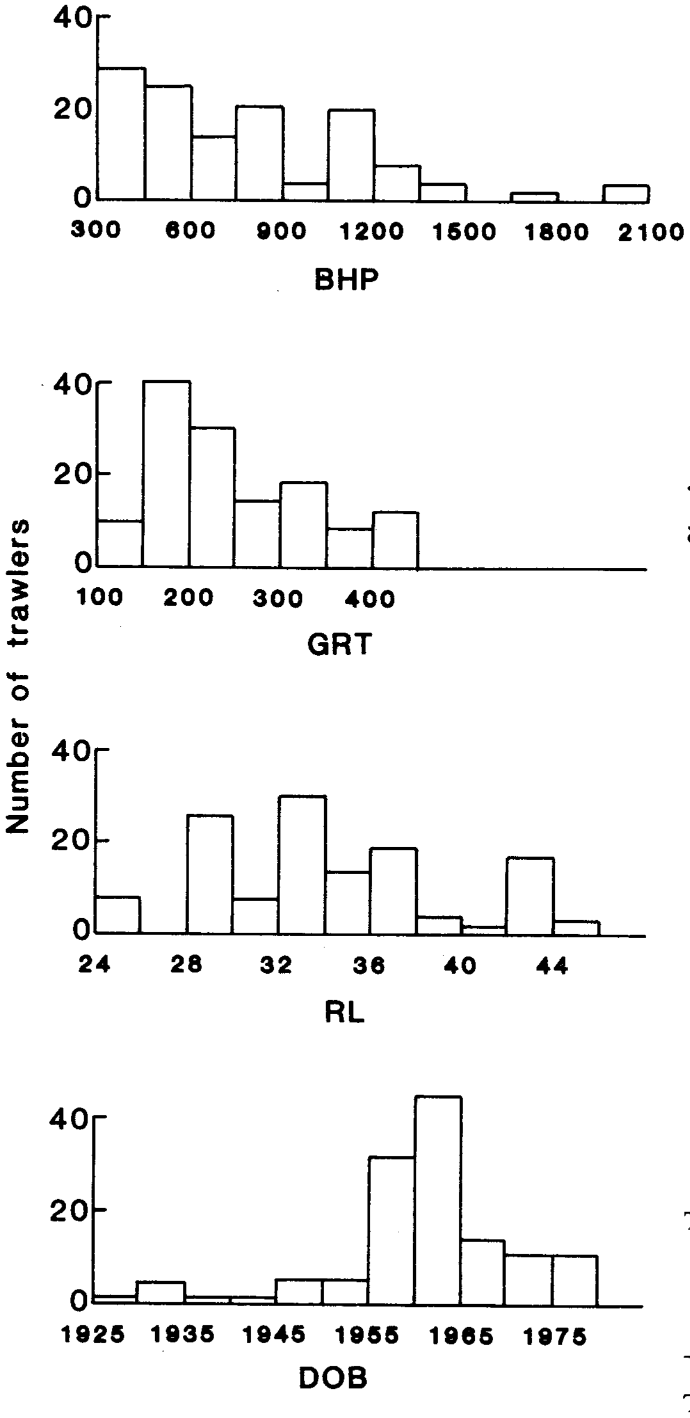


Figure 1 Frequency distributions of the vessel characteristics of offshore trawlers landing at Lowestoft between 1972 and 1979 ($n = 131$).

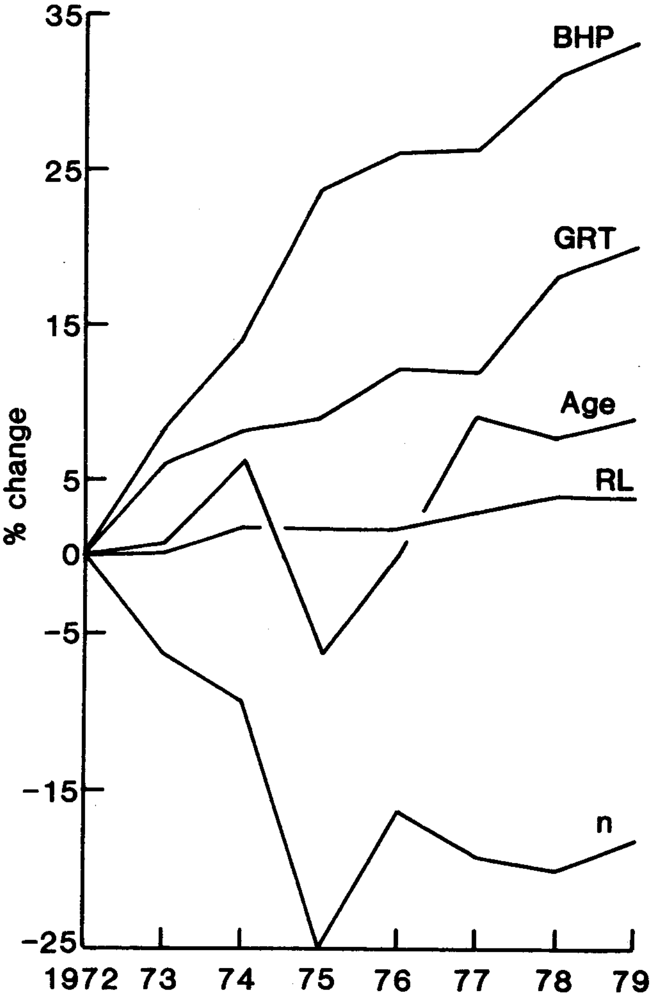
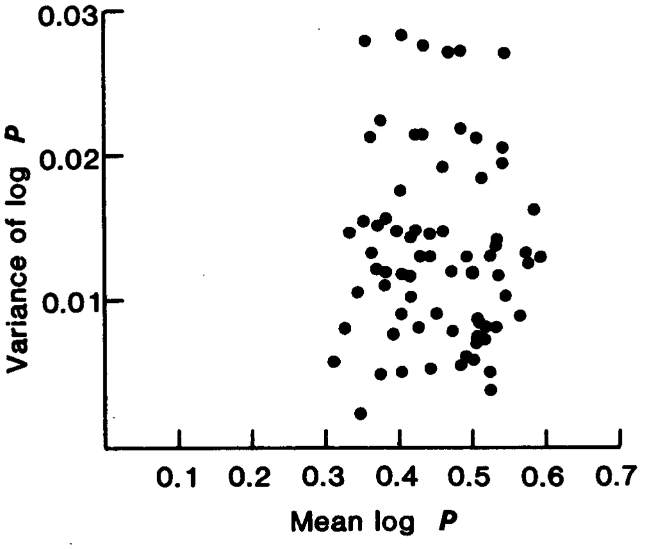


Figure 2 Percentage change in the average vessel characteristics of Lowestoft offshore trawlers between 1972 and 1979. The % change in the size of the fleet is also shown (n).

Table 1 Approximate dimensions of the different trawls used and the number of vessels using each size of trawl between 1972 and 1979

Type of otter trawl	C3	C4	C5 and others
Length of headline (m)	22	25	28
Length of groundrope (m)	29	35	40
Number of vessels	50	78	3

explains the greatest proportion of variation in P in all three time periods, and GRT consistently explains more variation than either RL or DOB. Log transformation gave improved correlations between P and GRT, suggesting that this relationship is best described by a power function. However, the form of the relationship between P and BHP is not clear, since although log transformation gave marginally improved correlations in analyses A (1972—79) and B (1972—74) the relationship in the trawlers studied in analysis C (1976—79) is better described as linear.



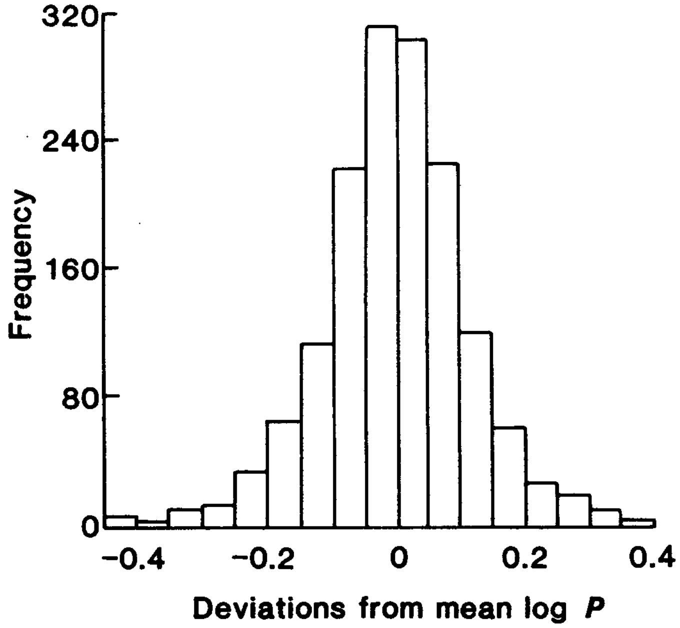


Figure 3 Variance against mean log fishing power (P) for 74 non-standard trawlers in analysis A (1972—79), showing approximately constant variance.

Figure 4 Aggregate frequency distribution of the deviations from the mean log fishing power (P) of individual non-standard trawlers in analysis A (1972—79) (n = 74).

Table 2 Simple correlation coefficients (r) between fishing power (P) and vessel characteristics (X). The proportion of variation in P explained by each characteristic is given in parentheses.

Regression model	Period	No. of vessels	BHP	GRT	RL	DOB
Linear	1972—79	79	0.796** (63%)	0.537** (29%)	0.449** (20%)	0.336** (11%)
	1972—74	54	0.700** (49%)	0.563** (32%)	0.516** (27%)	0.251 (6%)
	1976—79	56	0.822** (68%)	0.439** (19%)	0.350** (12%)	0.406** (16%)
Log-log	1972—79	79	0.804** (65%)	0.584** (34%)	0.457** (21%)	0.275* (8%)
	1972—74	54	0.732** (54%)	0.603** (36%)	0.549** (30%)	0.195 (4%)
	1976—79	56	0.799** (64%)	0.483** (23%)	0.346** (12%)	0.349** (12%)

* Significant at 5% level
** Significant at 1% level

Table 3 Summary of the results from forward stepwise multiple regression analyses on the relationship between fishing power (P) and BHP (1), GRT (2), RL (3) and DOB (4).

Model	Time period	Multiple equation at each step	Proportion of variation explained (R^2)	R^2 change at each step	F ratio
Linear	1972—79	P_1	0.634	0.634	141.74**
		$P_{2.1}$	0.641	0.007	1.57
		$P_{234.1}$	0.669	0.035	2.61
	1972—74	P_1	0.490	0.490	54.94**
		$P_{2.1}$	0.519	0.029	3.25
		$P_{234.1}$	0.563	0.073	2.73
	1976—79	P_1	0.675	0.675	117.49**
		$P_{4.1}$	0.707	0.032	5.57*
		$P_{2.14}$	0.707	<0.001	—
		$P_{23.14}$	0.707	<0.001	—
Log-log	1972—79	P_1	0.646	0.646	141.85**
		$P_{2.1}$	0.653	0.007	1.54
		$P_{234.1}$	0.663	0.017	1.24
	1972—74	P_1	0.535	0.535	62.57**
		$P_{2.1}$	0.562	0.027	3.15
		$P_{234.1}$	0.581	0.046	1.24
	1976—79	P_1	0.638	0.638	97.13**
		$P_{4.1}$	0.663	0.025	3.81
		$P_{2.14}$	0.664	0.001	0.15
		$P_{23.14}$	0.665	0.002	0.15

* Significant at 5% level
** Significant at 1% level

The relationship between P and combinations of vessel characteristics was then investigated by forward stepwise multiple regression analysis. Two models were fitted, a linear additive model $P = a + b_1X_1 + b_2X_2 + \dots b_nX_n$ and a log-log model $\log P = \log a + b_1 \log X_1 + b_2 \log X_2 + \dots b_n \log X_n$ (equivalent to a multiplicative model). The order of inclusion of vessel characteristics was determined by the respective contribution of each characteristic to the explained variation in P. The characteristic explaining the greatest amount of variation (BHP) was entered first, the characteristic explaining the greatest amount of variation in conjunction with BHP was entered second, and so on. If the characteristic introduced at either the second or third step did not explain a significant additional amount of variation, the additional variation explained by the combined effects of this characteristic and those still outstanding was then tested. The results for each model and time period are summarised in Table 3.

With the exception of analysis C (1976—79), the variation explained by BHP in either a linear or log-log regression model is not significantly increased by the inclusion of other vessel characteristics. DOB, in addition to BHP, has a significant positive effect on P between 1976 and 1979 despite the fact that the trawlers studied from this period had a similar age composition to those studied in analyses A (1972—79) and B (1972—74). It would appear, therefore, that the effect of age may have been varying with time, and this suggests that age would have an uncertain effect if included in a predictive model.

Table 4 Analysis of covariance on the linear relationship between fishing power (P) and BHP within each of the three time periods studied (1972—79, 1972—74 and 1976—79).
Equation: $P = a + b\,BHP$

Source of variation	Sums of squares	Degrees of freedom	Mean square	F ratio
Overall slope	2.3310	1	2.3310	280.84**
Between slopes	0.0026	2	0.0013	0.16
Between intercepts	0.0048	2	0.0024	0.29
Residual error	1.5280	183	0.0083	—
TOTAL	3.8664	188		

** Significant at 1% level

Table 5 Analysis of covariance on the log-log relationship between fishing power (P) and BHP within each of the three time periods studied (1972—79, 1972—74 and 1976—79).
Equation: $\log P = \log a + b \log \text{BHP}$

Source of variation	Sums of squares	Degrees of freedom	Mean square	F ratio
Overall slope	0.5530	1	0.5530	291.1**
Between slopes	0.0005	2	0.00025	0.13
Between intercepts	0.0012	2	0.0006	0.31
Residual error	0.3517	183	0.0019	—
TOTAL	0.9064	188		

** Significant at 1% level

Table 6 Analysis of covariance using multiple regression methods on the fitted log-log models of fishing power against BHP and size of trawl for 79 Lowestoft offshore trawlers fishing between 1972 and 1979 (analysis A)

Source of variation	Sums of squares	Degrees of freedom	Mean square	F ratio
BHP.N adjusting for BHP and N (saturated model)	0.0027	1	0.0027	1.69
N, adjusting for BHP (unsaturated model)	0.0095	1	0.0095	5.73*
Residual	0.1233	75	0.0016	—

* Significant at 5% level

The linear and log-log simple regressions of P on BHP for each time period were then examined by covariance analysis, and the results are given in Tables 4 and 5. The regressions were found to have common slopes and intercepts when either linear or log transformed data are used, confirming that the effect of BHP on P is similar in each period.

In a further attempt to improve the predictive power of a regression based on BHP, the additional variation explained by the introduction of a factor for size of trawl was examined. The following models were fitted to both linear and log transformed data for the vessels studied in analysis A (1972—79):

Unsaturated model: $P = a + b_1\,\text{BHP} + b_2 N$ (4)

Saturated model: $P = a + b_1\,\text{BHP} + b_2 N + b_3\,(\text{BHP}.N)$ (5)

where P = plaice fishing power,
N = dummy variable for net size, and
BHP.N = interaction term.

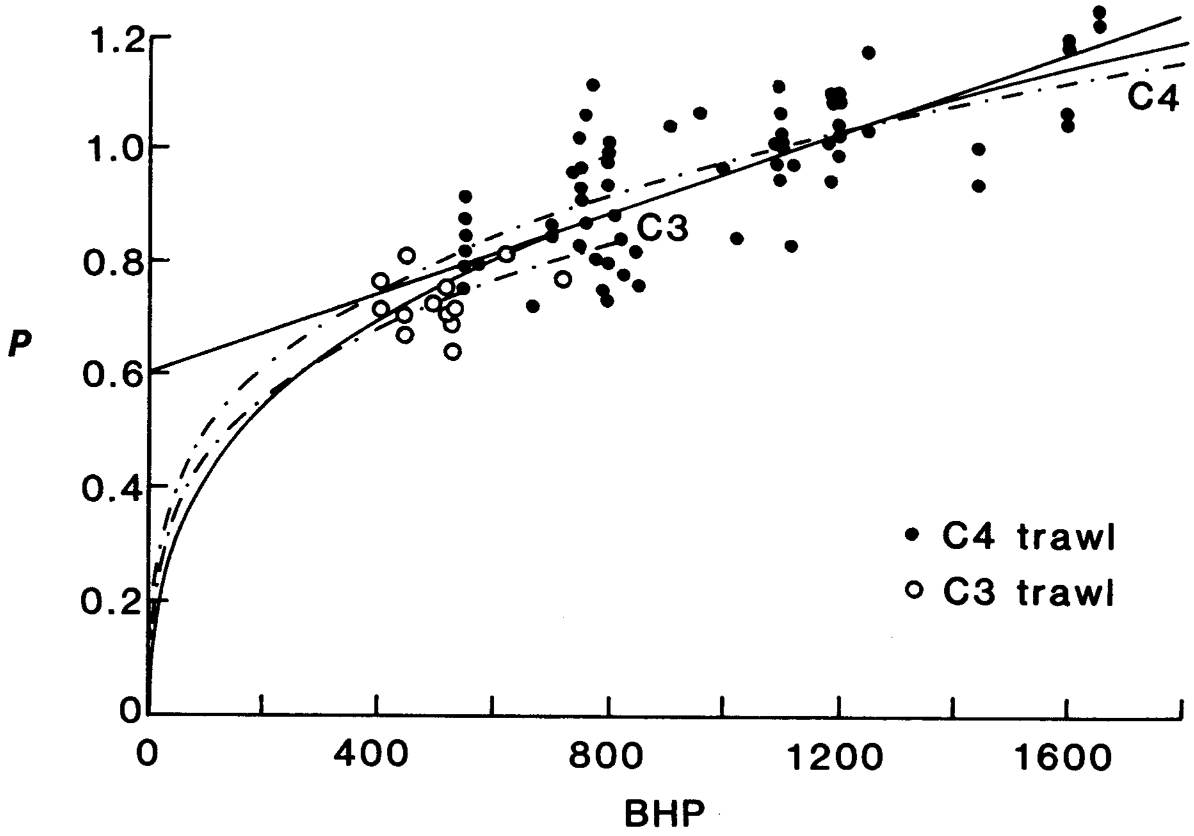


Figure 5 Regressions of fishing power (P) on BHP for Lowestoft trawlers fishing between 1972—79 (analysis A) showing linear and log-log regressions for all 79 trawlers — full lines (equations: $P = 0.6045 + 0.00035$ BHP and $P = 0.0868\ \mathrm{BHP}^{0.3488}$), and also the log-log regressions for trawlers using each size of trawl — broken lines (equations: C3 trawl $P = 0.11768\ \mathrm{BHP}^{0.2930}$ and C4 trawl $P = 0.1284\ \mathrm{BHP}^{0.2930}$).

The dummy variable (N) was given a value of 0 for trawlers using a C3 trawl and a value of 1 for those using the larger C4. Multiple regression methods were then used to perform an analysis of covariance on both models. For simplicity only the results from the analyses on log transformed data are summarised in Table 6.

The variation explained by the interaction term after fitting both BHP and size of trawl is not significant, indicating that there is no difference between the predictive power of either the saturated or the unsaturated model; both explain 67% of the total variation in P. The effects of BHP and size of trawl can therefore be assumed to be additive, implying that if two regressions of P against BHP are constructed, one for trawlers using each particular size of trawl, the regressions have similar slopes. The variation explained by differences in size of trawl after fitting BHP is significant, indicating that the two regressions have significantly different intercepts. Similar results were obtained using linear data, and the combined effect of BHP and size of trawl again explained 67% of the total variation.

The equations for the log-log regression of P on BHP for trawlers using each size of trawl can be derived from the fitted unsaturated model as follows:

Fitted unsaturated model:

$$\mathrm{Log}\,P = -0.4297 + 0.2930 \log \mathrm{BHP} + 0.0381N \quad (6)$$

For the 13 trawlers using a C3 trawl:

$$\mathrm{Log}\,P = -0.4297 + 0.2930 \log \mathrm{BHP} \quad \text{since } N = 0 \quad (7)$$

For the 66 trawlers using a C4 trawl:

$$\mathrm{Log}\,P = (-0.4297 + 0.0381) + 0.2930 \log \mathrm{BHP} \quad \text{since } N = 1 \quad (8)$$

$$= -0.3916 + 0.2930 \log \mathrm{BHP}.$$

Figure 5 shows both regressions and the points to which they were fitted, and also the linear and log-log regressions for all 79 trawlers. (The log-log regressions have been plotted as power curves).

The linear and log-log regressions for all 79 trawlers are shown to be almost identical over much of the observed range of BHP, and therefore within this range there is little difference between the predictive power of either regression; both explain a similar proportion of the total observed variation in *P*. Although the additional variation explained by including a factor for size of trawl in each regression is significant, any improvement in predictive power obtained by using separate regressions for trawlers using each size of trawl will be small since size of trawl explains only a further 2 to 4% of the total variation.

However, BHP and size of trawl are factors which tend to produce differences in *P* between trawlers rather than trends in the *P* of individual trawlers, the only exceptions being when either the BHP of a vessel changes due to re-engining or when a vessel changes from using one size of trawl to another. It is therefore important to determine whether individual trawlers exhibited any significant trends in *P* which cannot be explained adequately by either changes in BHP or the size of trawl used.

Annual estimates of *P* were available for 18 of the 37 vessels in the fleet which fished in each year between 1972 and 1979 (analysis A). None of the trawlers was re-engined during the period, and, so far as is known, each vessel used the same size of trawl throughout. An analysis of variance was carried out to test the hypothesis that the fishing power of these trawlers had remained constant, and the results are given in Table 7. There are significant differences in *P* both between ships and within ships between years. The former was expected since the 18 trawlers had main engines of differing BHP (403—1444 BHP), but the latter suggests that vessels were performing differently from year to year. In Figure 6 the average *P* of the trawlers in each year (excluding 1975) has been plotted against time, showing it to be significantly lower during 1974 and 1976 than in 1978. Changes in the *P* of 6 trawlers accounted for a large proportion of the differences observed between years, although 16 vessels suffered a decrease during 1974 and the *P* of 14 vessels increased between 1976 and 1978. However, the *P* of each trawler has been estimated relative to a group of standard vessels which may have also exhibited trends in *P*. These cannot be determined because for each standard vessel *P* has been estimated in relation to that of the other trawlers in the standard group. An increase in one vessel will by definition result in an apparent decrease in the relative *P* of the other standard trawlers, and the sum of deviations in *P* across the standard vessels is therefore always equal to zero. Consequently, any underlying trends which may exist cannot be quantified (Houghton, 1977). This in turn suggests that the absolute sign and magnitude of the trends observed in the 18 non-standard vessels cannot be determined since they may have been confounded to an unknown extent by trends in the *P* of the standard trawlers. However, the standard trawlers used in analyses B (1972—74) and C (1976—79) differed substantially from those used in analysis A (1972—79), and consequently the non-standard vessels from these analyses can be used to verify the trend observed in the 18 trawlers.

Annual estimates of *P* were available for 35 non-standard vessels in analysis B (1972—74) and 30 vessels in analysis C (1976—79), and 14 of the 18 vessels fishing between 1972

Table 7 Analysis of variance on the annual estimates of fishing power (*P*) for 18 non-standard trawlers fishing between 1972 and 1979 (analysis A). (Estimates of *P* were not available for 1975)

Source of variation	Sums of squares	Degrees of freedom	Mean square	F ratio
Between ships	0.2204	17	0.0130	3.51**
Between years	0.0602	6	0.0100	2.70*
Residual	0.3820	102	.0037	—
TOTAL	0.6626	125		

* Significant at 5% level
** Significant at 1% level

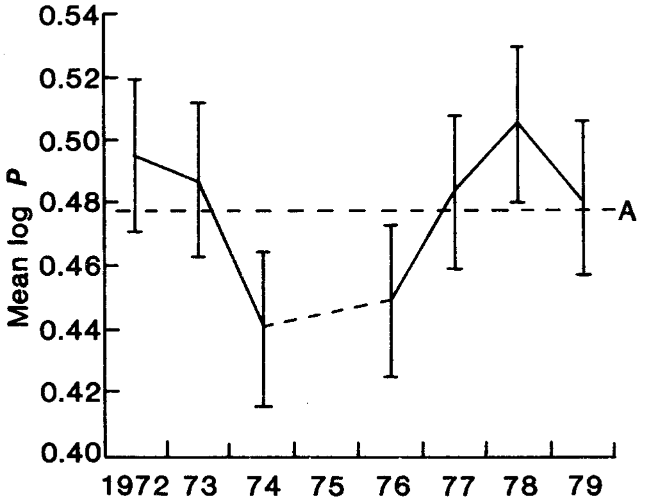


Figure 6 Trend in the annual mean log fishing power (*P*) of 18 non-standard vessels from analysis A between 1972 and 1979 (excl. 1975). The dotted line (A) represents the average *P* of the vessels over the full period.

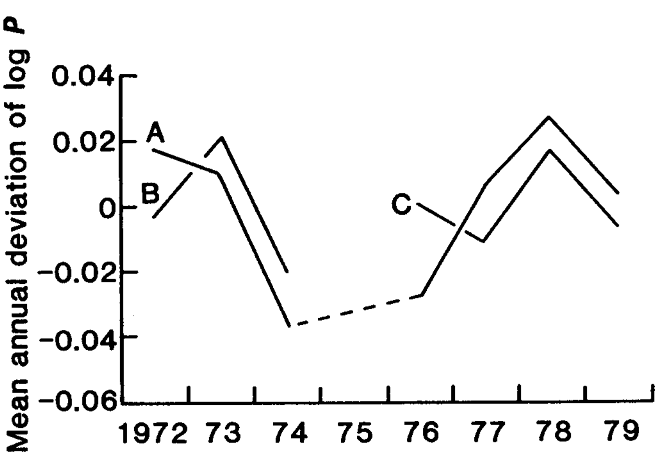


Figure 7 Trend with time of the mean annual deviation of log fishing power (*P*) from the individual vessel average for 18 non-standard vessels from analysis A (1972—79), 35 vessels from analysis B (1972—74) and 30 vessels from analysis C (1976—79).

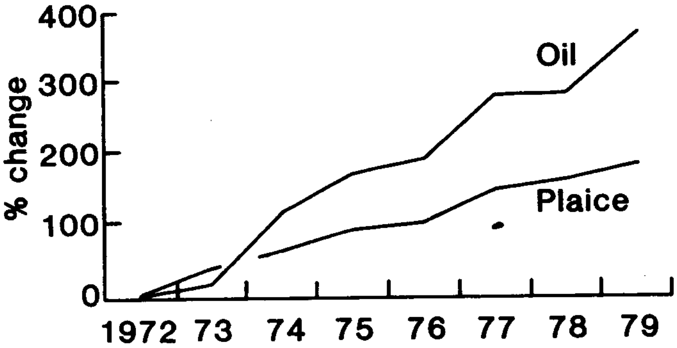


Figure 8 Approximate percentage change in the cost of fuel-oil and the annual average price of plaice at Lowestoft between 1972 and 1979.

and 1979 were present in each group. In Figure 7 the mean annual deviation of *P* from the individual vessel average for the 35 vessels from analysis B is shown to have also decreased during 1974, and that of the 30 vessels from analysis C, whilst not at a low level in 1976, is shown to have also increased during 1978 and decreased in 1979. This suggests that the trend in *P* observed in the 18 non-standard trawlers from analysis A is largely independent of any trends which may have existed in the standard trawlers, and also that similar trends may have occurred in other vessels in the fleet. Both the relevance and possible causes of these trends will be dealt with in the following section.

5. Discussion

The relationship between fishing power and vessel characteristics has been investigated in a wide range of fleets fishing for a variety of different species (Gulland, 1956; Beverton and Holt, 1957; Zijlstra and de Veen, 1963; Hovart and Michielsen, 1975; Guichet, 1975; Houghton, 1977; de Veen, 1979), and differences in BHP between trawlers have frequently been found to explain a greater proportion of the variation in *P* observed in each fleet than differences in either GRT, RL or age. Similarly, in the present study, differences in BHP are shown to explain a greater proportion of the variation in *P* observed across Lowestoft offshore trawlers than differences in any other vessel characteristic. Furthermore, the variation explained by BHP is shown to be increased by the inclusion of a factor for size of trawl. However, the successful application of a predictive regression for *P* is dependent on whether all its main determinants are included as independent variables, and there is some evidence that other untested factors are involved.

The average *P* of 18 trawlers from analysis A was shown to be significantly higher in 1978 than in 1974 and possibly 1976, and therefore a predictive equation based on BHP, which predicts the average *P* of each trawler between 1972 and 1979, will tend to produce biased estimates in each of these years. The average *P* of the 18 trawlers between 1972 and 1979 is shown in Figure 6 by the dotted line A. If this is taken to represent performance in each year, *P* in 1974 and 1978, for example, will be overestimated by 9% and underestimated by 6% respectively. Similar overall trends in *P* are shown by trawlers from analyses B and C, and by examining the causes of these trends it is possible to deduce that they may have also occurred in other trawlers.

Nearly all the trawler skippers at Lowestoft use heavy tickler chains to maximize the plaice catching power of the traditional otter trawl, and these trawls can only be towed at the required speed (between 3 and 5 knots) by trawlers fitted with relatively powerful main engines. The fuel consumption of these trawlers is high and consequently the profitability of the fleet has been adversely affected by large increases in the price of fuel-oil, especially at times when fish prices have been relatively depressed (McDiarmid *et al.*, 1980). Figure 8 shows that the average price of fuel-oil at Lowestoft increased by approximately 175% between 1972 and 1975, whereas the average price of plaice increased by only 98%. The profitability of the fleet, particularly from 1973 onwards, was therefore severely reduced, and two fishing companies attempted to reduce fuel consumption by encouraging skippers to use lighter tickler chains and in some cases smaller trawl-doors. These measures may also have had an adverse effect on *P*, and this is confirmed by the results from analyses A and B in that the majority of trawlers exhibiting a decline in *P* between 1973 and 1974 were owned by one of these companies.

However, changes in the towing speed of trawlers may also have been a contributory factor. Whereas it has been the practise of some trawler skippers to tow at greater speed in an attempt to increase catch-rates by covering more ground per tow, the extra thrust required to tow at higher speeds has an adverse effect on fuel consumption. Therefore, it is possible that the sudden increase in fuel costs between 1973 and 1974 may have caused some skippers to tow at lower speeds in an attempt to reduce fuel costs. Although the price of oil continued to increase at a greater rate than plaice prices between 1975 and 1979 oil prices did stabilise temporarily between 1977 and 1978, and this may have encouraged some skippers to again attempt to increase catch-rates by towing harder. This would explain the increase in *P* observed in trawlers from analyses A and C, particularly as there is no evidence that any of the skippers attempted to increase the weight of tickler chain, etc. Other factors which can affect *P*, changes of fishing-skipper, for example, can be dismissed, since, so far as is known, many of these trawlers had the same skipper throughout.

However, the increase in oil prices between 1973 and 1979 has probably not had the same influence on *P* throughout the entire fleet, since several companies did not take any explicit steps to reduce fuel costs. Although it is likely that a predictive equation based on BHP will produce biased estimates of *P* for a considerable proportion of the fleet during several years, the exact number of trawlers involved cannot be evaluated because annual estimates of *P* were not available for the majority of vessels.

The application of a predictive equation to trawlers fishing outside the period from which it is derived also has to be considered. Although there is likely to be little difference between the predictive power of either a linear or a log-log equation based on BHP over the range of BHP observed in the fleet between 1972 and 1979 (403—2000 BHP), the majority of trawlers during the 1950s and 1960s had main engines of less than 400 BHP, and from Figure 5 it can be seen that the ability of either regression to predict *P* for these trawlers will depend on whether the overall relationship between *P* and BHP is linear or curvilinear.

Gulland (1956) found that the relationship was linear in Lowestoft motor trawlers of between 150 and 400 BHP fishing for demersal species during the early 1950s, and a linear relationship was also found in Brixham trawlers fishing for plaice (Houghton, 1977) and La Rochelle trawlers fishing

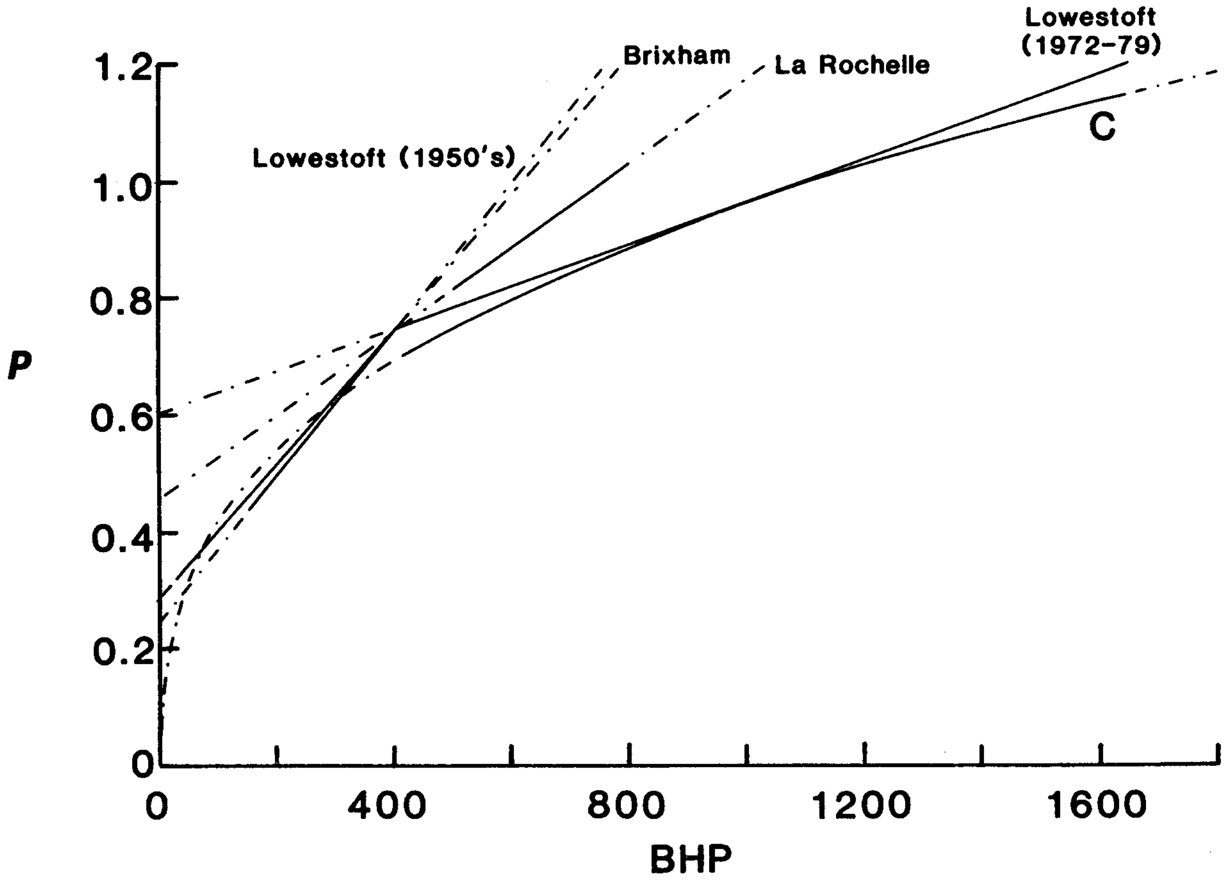


Figure 9 Regressions of fishing power (*P*) on BHP for different groups of trawlers plotted on a combined scale. Whole lines denote the range of BHP actually occurring in each group of trawlers. The curve C represents the power curve derived from the log-log regression of *P* on BHP for Lowestoft trawlers fishing between 1972 and 1979 (analysis A). Equation $P = 0.0868\ \text{BHP}^{0.3488}$.

for hake (*Merluccius merluccius*) (Guichet, 1975). The equations for these regressions and also the linear regression of P on BHP developed in the present study are:

$$P = 0.0055\,\text{BHP} + 1.22 \quad \text{Lowestoft — early 1950s} \quad (150 \text{ to } 400 \text{ BHP}) \tag{9}$$

$$P = 0.0034\,\text{BHP} + 0.829 \quad \text{Brixham} \quad (30 \text{ to } 360 \text{ BHP}) \tag{10}$$

$$P = 0.00067\,\text{BHP} + 0.431 \quad \text{La Rochelle} \quad (500 \text{ to } 800 \text{ BHP}) \tag{11}$$

$$P = 0.00035\,\text{BHP} + 0.6045 \quad \text{Lowestoft — 1972 to 1979} \quad (403 \text{ to } 1650 \text{ BHP}). \tag{12}$$

Although the scale of P is different in each group of trawlers the various scales can be standardised by making the regressions coincide at one point, and this has been taken as a Lowestoft trawler of 400 BHP fishing between 1972 and 1979. The regression equations then become:

$$P = 0.001197\,\text{BHP} + 0.2656 \quad \text{Lowestoft — early 1950s} \tag{13}$$

$$P = 0.001156\,\text{BHP} + 0.2820 \quad \text{Brixham} \tag{14}$$

$$P = 0.000714\,\text{BHP} + 0.4591 \quad \text{La Rochelle} \tag{15}$$

$$P = 0.00035\,\text{BHP} + 0.6045 \quad \text{Lowestoft — 1972 to 1979} \tag{16}$$

and these are plotted in Figure 9. It can be seen that taken together the regression lines give a consistent but curvilinear relationship of a similar form to that derived from the log-log regression of P on BHP in this study (shown in Figure 10 as the curve C).

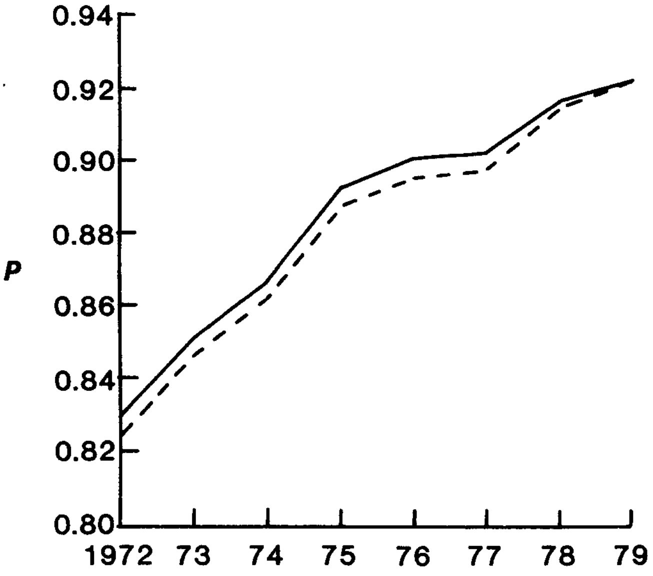


Figure 10 Trend in the average fishing power (P) of Lowestoft offshore trawlers between 1972 and 1979, as estimated by the power relationships derived from the log-log predictive regression of P on BHP (full line) and the log-log fitted unsaturated model of P on BHP and size of trawl (broken line).

Further evidence suggesting that the general relationship between P and BHP is curvilinear can be found in the Dutch beam trawl fleet fishing for sole (*Solea solea*), since for these trawlers de Veen (1979) observed that a power relationship exists over a range of 150 to 900 BHP.

Therefore, although the relationship between P and BHP in Lowestoft trawlers is approximately linear over the range of BHP observed between 1972 and 1979, it seems likely that the overall relationship across the entire range of BHP observed since the 1950s (150 to 2000 BHP) is best described by a power curve.

The power relationship derived from the fitted log-log predictive equation of P on BHP can be used to estimate P for each offshore trawler fishing from Lowestoft between 1972 and 1979, and these values can then be used to calculate the average P of trawlers in each year. This can be repeated using the power relationships derived from the fitted log-log predictive model of P on BHP and size of trawl. Figure 10 shows that the former tends to overestimate average P, but only by less than 1% in each year. This confirms that the increase in predictive ability obtained by developing separate predictive equations for trawlers using each particular size of trawl is minimal. We can therefore conclude that the overall power relationship observed in the 79 trawlers from analysis A

$$P = 0.0868\,\text{BHP}^{0.3488} \tag{17}$$

is a suitable predictive equation for the fishing power of Lowestoft offshore trawlers fishing both within and outside the period 1972—79. However, average P increased by only 12% between 1972 and 1979 even though average BHP increased by 33% over the same period, and this result reflects the fact that as BHP increases the increment in P diminishes. Figure 9 suggests that this will apply to trawlers in general, and therefore trends in the average BHP of fleets will probably have a greater effect on P (and therefore effective fishing effort) when the fleets consist of trawlers of relatively low BHP (50—400 BHP). In other words fishing power corrections to the effort trend for the Lowestoft offshore fleet will be particularly important between 1950 and 1965, but rather less important thereafter.

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