

SOME STATISTICAL ASPECTS OF THE LONG-TERM GILL NET MONITORING PROGRAMME FOR PIKE *ESOX LUCIUS* IN WINDERMERE (ENGLISH LAKE DISTRICT)

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Introduction

For more than 55 years, data have been collected on the population of pike *Esox lucius* in Windermere, first by the Freshwater Biological Association (FBA) and, since 1989, by the Institute of Freshwater Ecology (IFE) of the NERC Centre for Ecology and Hydrology. During this time the fishing methodology has been constant although the actual fishing effort has lessened considerably as the rationale behind the programme has changed. The original aim of the fishery was to reduce pike numbers (Worthington 1950), in order to protect stocks of brown trout *Salmo trutta* - for which there was a sport fishery - and stocks of Arctic charr *Salvelinus alpinus*, which had been exploited for several centuries by seine netting and a small plumb-line fishery (Kipling 1972, 1984). However, through time this original policy has evolved into a population monitoring programme.

Long-term data such as those available for Windermere are essential for the determination of factors that affect the dynamics of fish populations. However, it is important first to evaluate any possible sources of bias and error in the collection and interpretation of such data. For example, Bagenal (1972) investigated some sources of variability in the catch of gill nets and concluded that a large sampling effort was required to obtain precise estimates of the numbers of pike. Frost & Kipling (1967) addressed sampling biases associated with growth and sex of pike, and found that as males are thinner and grow more slowly than females, gill netting was biased towards females; e.g. with a female cohort mean length of 65 cm (normally small 3-year-old fish) about 80% of females would be retained. In contrast, only about 70% of males would be caught at this length and normally they would be 4-year-old fish.

The aim of this article is to explore some methodological and statistical issues associated with the precision of pike gill net catches and catch-per-unit-effort (CPUE) data, further to those examined by Bagenal (1972) and especially in the light of the current deployment within the Windermere long-term sampling programme. Specifically, consideration is given to the precision of catch estimates from gill netting, including the effects of sampling different locations, the effectiveness of sampling for distinguishing

between years, and the effects of changing fishing effort. Although rather technical in places, we think that our account will be of historical and general interest to members of the FBA, bearing in mind that the Association originally began the programme and has supported its continuation over many years.

All ages of pike given in this article refer to completed years from hatching. This contrasts, for example, with Kipling & Frost (1970) (see also Frost & Kipling 1967), where the ages given are in fact completed growing seasons; for samples taken in autumn/winter, this equals completed years +1.

Background and methods used for catching pike

Details of collection methodology for the pike are given by Bagenal (1972) and Frost & Kipling (1959, 1961, 1967). Pike netting with bottom gill nets started in the autumn of 1943 and usually was carried out within the period 1 October to 1 March the following year. However, since 1990, the nets generally have been set from mid-October to mid-December only. Data from the 1946-47 season were not included in the present analysis because nets were temporarily frozen in position, leading to uncertainty in fishing effort.

Although the same bar-mesh size of 64 mm has always been used, the net size and material have varied over the period of the study, as summarised in Table 1. Due to the above changes and alterations in the duration and area of

Table 1. Characteristics and changes in gill nets used for catching pike in Windermere during the period 1943 to 1998. Note: Worthington (1950) refers to nets with a depth of 3 yards and this is what they are in 1999 (*c.* 2.74 m). Frost & Kipling (1967) stated that the nets were 3 m deep, but this is likely to be the result of rounding up the actual measurement, and they were probably always the same 3 yards deep.

| Seasons | Material | Mesh | Length | References |
|-----------|---------------------|-------|------------------------------|--|
| 1943-1966 | Flax | 64 mm | 27.4-109.7 m 30-120 yards | Worthington (1950), Frost & Kipling (1967), Bagenal (1972) and log books |
| 1967-1968 | Terylene | 64 mm | 54.8-109.7 m 60-120 yards | Bagenal (1972), inferred from Kipling & Frost (1970), Frost & Kipling 1967) and log books |
| 1969-1974 | Multifilament nylon | 64 mm | 54.8 m 60 yards | Bagenal (1972) and log books |
| 1975-1998 | Multifilament nylon | 64 mm | 41.1 m 45 yards | log books and personal observations |

the net set, fishing effort has varied from year to year and is measured as a standard net-day of a 30-yard (27.4 m) net set for 24 hours.

In contrast to some past practice, gill nets are currently set in four general areas of the lake (16.9 km in length), with a variety of sites fished within each area. The position of the areas can be described as near North Basin, far North Basin, near South Basin and far South Basin, all relative to the middle of the lake. The positions of the nets are not at random because originally they were set where earlier exploratory sampling indicated that pike would be found. In the early years of sampling, when removal of pike was the main aim (Worthington 1950), nets were relocated when no more pike were caught at that locality (Frost & Kipling 1967; Bagenal 1972). In later years, nets usually were repeatedly placed in the same localities, regardless of the numbers of fish caught. Since the season 1992-93, fishing effort has been constant.

Bagenal (1972) looked at Windermere pike gill net data from the period 1961 to 1971 and concluded that high levels of sampling effort (i.e. repeated sampling) were required to obtain a reliable mean catch. He also suggested that a longer, 120-yard (109.73 m) net produced slightly more variable results than a shorter, 60-yard (54.86 m) setting. However, in recent years, 45-yard (41.15 m) gill nets have been used.

The constancy of fishing effort for the period 1992-1997 provides an opportunity to examine the precision of the current sampling regime. Not only has effort been the same, but so has the setting pattern; at each site a 45 yard (41.15 m) net has been set for 48 hours, on four occasions during the sampling season. In addition, the majority of sites within each area are sampled each year. Thus replication can be analysed at the individual setting per site level, minimising extraneous variation.

Catch-effort data were also analysed for aged fish from 1944 to 1996 (year-classes 1941 to 1993 for females and year-classes 1940 to 1992 for males) as well as individual catch data for the period 1992-1997.

Precision (repeatability) of sampling in 1992-1997

An analysis of the distribution of catches per 48 hour setting across all sites for the period 1992-1997 demonstrated that more females are caught than males, and that the distribution of the number of fish caught per site setting (i.e. one catch of pike in a 45-yard net set for 48 hours) was not normally distributed (Fig. 1). Nor do the data reflect a random pattern (i.e. a Poisson distribution) of catches (females: $X^2 = 193.6$, $df = 4$, $p < 0.001$; males: $X^2 = 66.0$, $df = 4$, $p < 0.001$). In fact the pattern of catches does not significantly deviate from that expected under a negative binomial distribution (females: $X^2 = 5.51$, $df = 9$, NS; males: $X^2 = 11.37$, $df = 9$, NS). This would suggest that the fish were clumped in some manner (Elliott 1977).

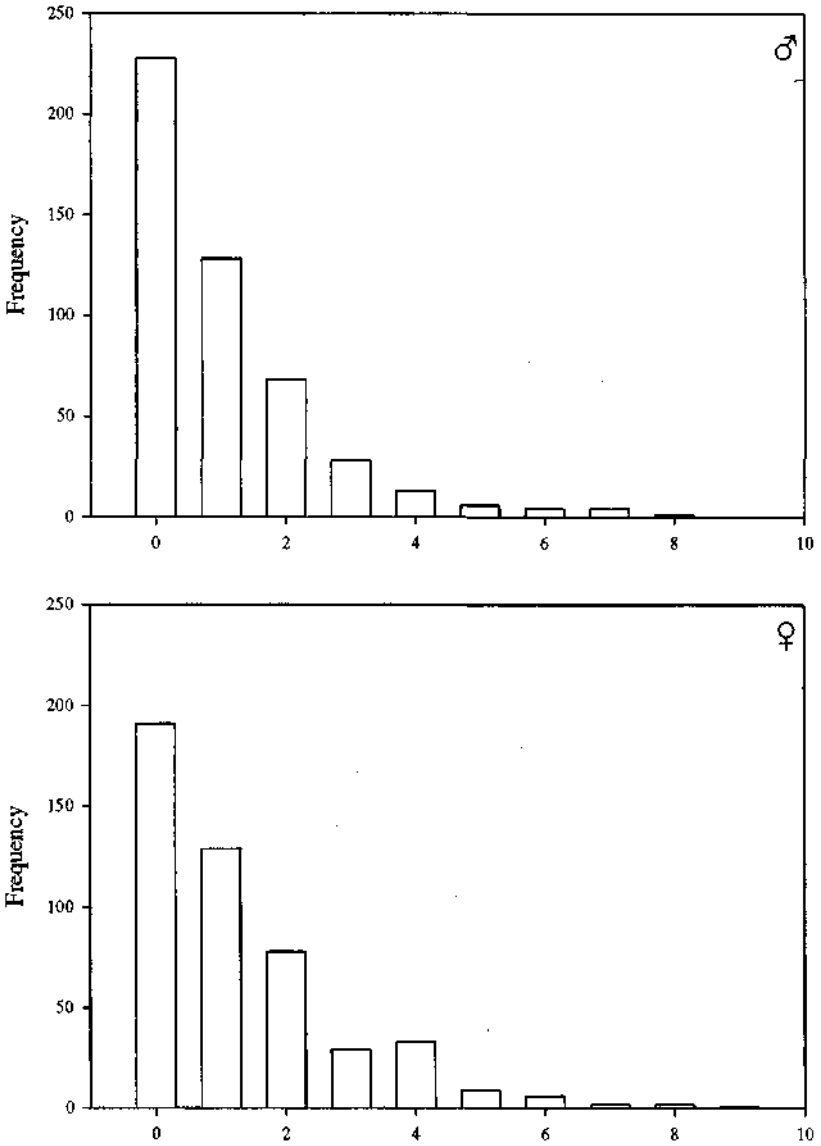


FIG. 1. Frequency distribution of the number of male (*above*) and female (*below*) pike caught per net setting per site in Windermere, 1992 to 1997.

The data cannot be transformed to approach the normal distribution so they must be analysed non-parametrically. Repeatability of the catch per site upon successive fishings can be calculated by using Kendall's Rank Concordance test (Siegel & Castellan 1988). The concordance (i.e. the consistency of the catch) statistic can vary between zero and one. A zero value indicates there is no consistency of catch between fishings and a value of one indicates perfect consistency of catch between fishings. The test examines the null hypothesis that concordance is zero. Table 2 shows the concordance of catch for each sex of pike across all sites for the period 1992-1997. Clearly the concordance of catch per setting across sites is generally high (especially for females), although not necessarily significant every year. If concordance is significant then it also follows (Zar 1996) that there is a significant consistent difference in catch *between* sites for that year because the calculated probability is the same as that for a Friedman's Test, testing the null hypothesis of no difference in catch between sites.

Table 2. Concordance of pike catches across sites in Windermere, 1992-1997. W is the concordance statistic; df = degrees of freedom and *df = 18, as one site was not sampled repeatedly; NS = not significant.

| Year | Male concordance, df = 19 | | Female concordance, df = 19 | |
|------|----------------------------|--------|-----------------------------|---------|
| 1992 | W = 0.36, $\chi^2 = 27.64$ | NS | W = 0.49, $\chi^2 = 37.10$ | p<0.01 |
| 1993 | W = 0.23, $\chi^2 = 17.14$ | NS | W = 0.42, $\chi^2 = 32.29$ | p<0.05 |
| 1994 | W = 0.37, $\chi^2 = 28.31$ | NS | W = 0.43, $\chi^2 = 33.00$ | p<0.05 |
| 1995 | W = 0.44, $\chi^2 = 33.68$ | p<0.05 | W = 0.36, $\chi^2 = 27.55$ | NS |
| 1996 | W = 0.35, $\chi^2 = 26.83$ | NS* | W = 0.50, $\chi^2 = 37.94$ | p<0.01* |
| 1997 | W = 0.32, $\chi^2 = 24.22$ | NS | W = 0.43, $\chi^2 = 33.46$ | p<0.05 |

Comparing concordance statistics across all years does not reveal male concordance to be significantly different from that of females (Wilcoxon Sign Rank Test: N for test = 6, W = 2, but $0.05 < p < 0.1$). This result suggests that whilst more females are generally caught than males (see above and Frost & Kipling 1967; Paxton et al. 1999), at present there is no reason to believe that within a given season the catch of males per site varies more than that of females.

Comparison between years (1992-1997)

The repeated setting of nets at thirteen of the sites each year for the period 1992-1997 also allows us to investigate whether catches significantly differ from year to year, by utilising catches taken only from these same sites

consistently. For this, the total summed catch per site per year was analysed parametrically by a square-root transformation and two-way ANOVA to examine the effects of sites and years simultaneously, thus controlling for the effect of differences between sites. The analysis showed that there are significant differences between the total catches in different sites (males: $F_{12,60} = 2.63$, $p < 0.01$; females: $F_{12,60} = 5.42$, $p < 0.001$), but the mean catch of males at each site did not differ significantly from year to year (males: $F_{5,60} = 1.10$, NS; Fig. 2) although those of female fish did (females: $F_{5,60} = 2.44$, $p < 0.05$; Fig. 2). Therefore, the assumption that variation in catch from year to year is significant is upheld only for females when the same sites are considered for the period 1992-1997.

Comparisons between areas (1992-1997)

Given that catches at sites are significantly different, it is possible that there is also a difference in catch between the four sampled areas of the lake. Analysis of a balanced sample of the transformed summed catches, for two sites from each area, reveals a significant difference between areas ($F_{3,48} = 3.56$, $p < 0.05$). The largest catches came from the most northern (Far North Basin) part of the lake. The reasons for this are unclear, but Kipling & Frost (1970) argued that the smaller habitat available to pike in the North Basin meant that, effectively, a net set at right angles to the shore would cover the width of the available littoral region. Thus any pike moving north or south along the shallows would eventually encounter the gill net. In contrast, in the South Basin there is a wider expanse of shallow areas, so pike movements may take them around nets set close to the shoreline. This general principle also applies even if nets are not always set at right angles to the shore, with the result that in the North Basin the ratio of net to available pike habitat is higher, leading to a greater encounter and capture rate (see below for a related discussion). Alternatively, there could be a greater density of fish per unit area in the North Basin.

The effects of changes in fishing effort between 1943 and 1997

The constant fishing effort of the period 1992-1997 is not representative of the sampling programme as a whole. Prior to the 1992 season, effort has varied considerably from a high of 5842 net-days in 1945-46 to a low of 226.5 net-days in 1991-92, reflecting a general decrease in fishing effort during the programme. The effects of this can be seen clearly from the relationship between catch-per-unit-effort (CPUE) and fishing effort (f) for female pike, caught at 3 years old across the entire lake during 1944 to 1996. CPUE was clearly related to effort (Fig. 3). This effect was further exacerbated because years of high fishing effort were generally consecutive.

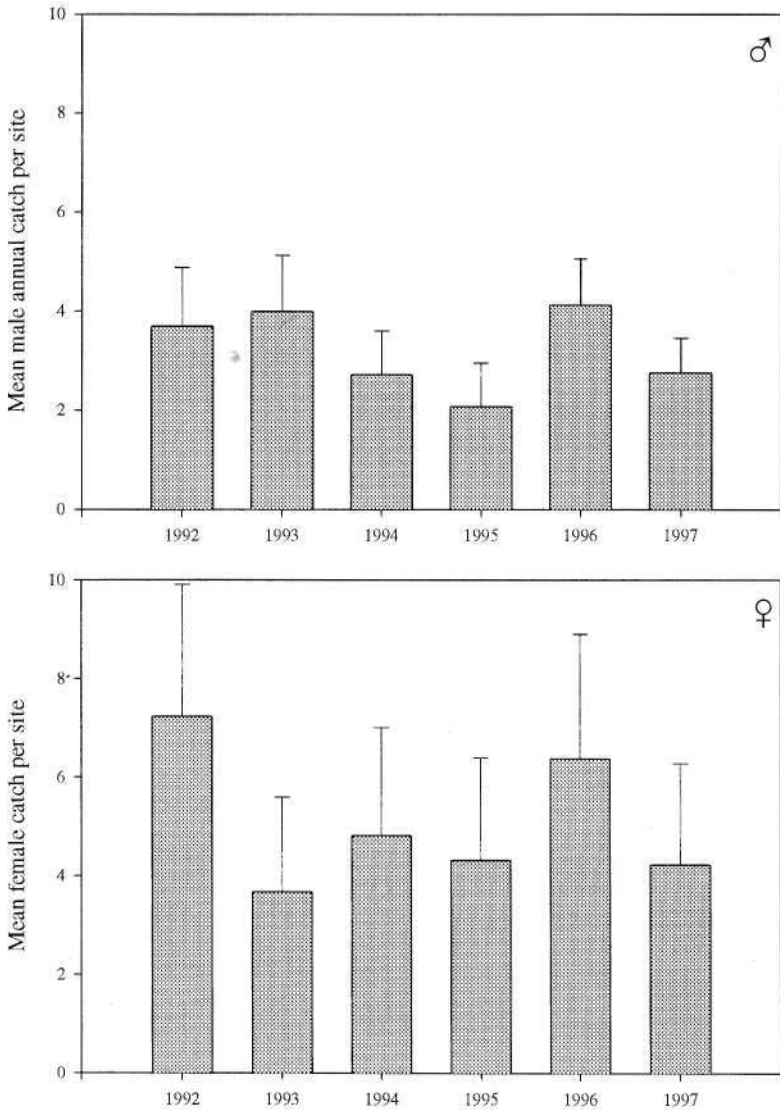


FIG. 2. Mean numbers of pike (back-transformed values, with standard error bars) caught per year over the 13 consistently used netting sites in Windermere, 1992 to 1997. *Above*: males. *Below*: females.

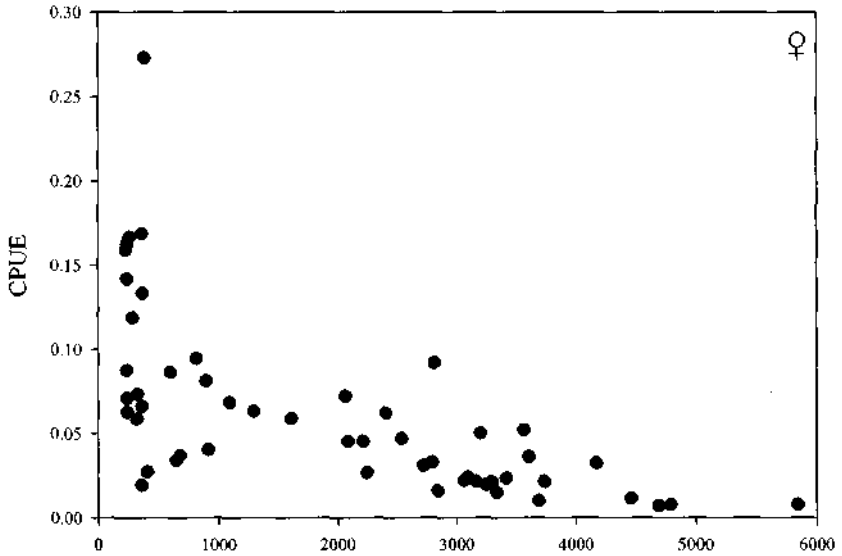


FIG. 3. Relationship between catch-per-unit-effort and fishing effort for 3-year-old females recruited to the gill net fishery in Windermere, 1944 to 1996.

The non-linear relationship between CPUE and f for female pike at age 3 can be modelled linearly (by least squares regression) as:

$$\ln(\text{CPUE}) = 1.05 - 0.587 \ln(f) \quad (1)$$

$$r^2 = 54.0\%, F_{1,50} = 58.64, p < 0.001.$$

However, the relationship shown in equation (1) is unsatisfactory from a mathematical standpoint, as CPUE is actual catch divided by fishing effort, and therefore the latter appears on both sides of equation (1). If, from eqn (1):

$$\begin{aligned} \ln(\text{CPUE}) &= \ln(\text{catch}/f) \\ &= \ln(\text{catch}) - \ln(f) = 1.05 - 0.587 \ln(f) \end{aligned} \quad (2)$$

then:

$$\begin{aligned} \ln(\text{catch}) &= 1.05 + 0.413 \ln(f) \\ r^2 &= 36.7\%, F_{1,50} = 29.03, p < 0.01. \end{aligned} \quad (3)$$

Residuals can then be taken and subtracted from the fitted value for any given amount of f . A similar procedure utilising the linear relationship between \ln (catch) and \ln (f) (as in eqn 3) allows standardisation of fishing effort for any sex-class or age-class within the fishery. Comparison of the two largest age-classes of each sex (3-year-old females and 4-year-old males) standardised for a fishing effort of 240 net-days, demonstrates that they fluctuate similarly from year to year ($r = 0.887$, $df = 48$, $p < 0.001$). This suggests that the patterns of adult recruitment are similar across the sexes despite their different physical sizes. It also means that mortality from 3 to 4 years of age is consistent from year to year across sexes, and this does not substantially alter the rankings of year-class strengths.

The low CPUE in years of high f is unlikely to be due just to high levels of fishing effort within the sample year: f is strongly autocorrelated with itself from the previous year (for 1948 to 1997, \ln (f) versus \ln (f in the previous year): $r = 0.971$, $df = 50$, $p < 0.001$). So in years of high values for/the stock had been fished at similar levels the year before. This high level of fishing effort substantially lowered the population (Kipling & Frost 1970).

However, the relationship between catch and fishing effort in a fixed fishery (e.g. gill nets) can be complicated further by the fact that not all total fishing efforts are the same. The capture rate of a given length of gill net has two components: the encounter rate of fish with the net (a function of the number of fish and how much they move) and the individual per capita capture probability of the net, given an encounter (Rudstam et al. 1984). The encounter rate of fish with the net is increased if more than one net is set simultaneously. Thus the overall probability of capture is greater when nets are set simultaneously, rather than when they are set sequentially, even if there is the same overall level of fishing effort. Examination of the records for the early years of the sampling programme indicates that there was considerable simultaneous netting. For example on 6 October 1949, nine nets were examined which had been set for at least 24 hours. The combined net length was 780 yards. Similar deployments occurred throughout the 1949-50 season, compared with a typical late 1990s deployment of five nets simultaneously with a combined length of 225 yards. Consequently the chance of capture may have been even greater than is indicated by the fishing effort statistics alone, although it is difficult to correct the fishing effort or CPUE figures for this effect.

Local depletion of pike at particular sites in Windermere

The recent consistent fishing regime also allows tests to be made for local depletion of stocks in the lake when the same sites are sampled repeatedly. Again this was examined by non-parametric analysis of site data employing Page's Test of Ordered Alternatives (Siegel & Castellan 1988) to test for

Table 3. Evidence for local depletion of pike by year and sex. We have used the standard normal distribution statistic Z for large samples, with a one-tailed test. Twenty sites were sampled each year from 1992 to 1997, except in 1996 when only 19 sites were used, as not all sites were sampled four times.

| Year | Male depletion | Female depletion |
|------|-------------------|---------------------------|
| 1992 | $Z = 1.084$, NS | $Z = 0.930$, NS |
| 1993 | $Z = -1.084$, NS | $Z = 0.116$, NS |
| 1994 | $Z = -0.154$, NS | $Z = 3.718$, $p < 0.001$ |
| 1995 | $Z = 0.349$, NS | $Z = 0.465$, NS |
| 1996 | $Z = 0.715$, NS | $Z = 0.437$, NS |
| 1997 | $Z = -0.620$, NS | $Z = 1.781$, $p < 0.05$ |

serial depletion of sites upon repeated visits. This test determines if there are trends across sets of sequentially collected data. A significant result indicates that the null hypothesis of no systematic change of catch over successive fishings can be rejected. In 1992-1997, with a 45-yard net set at each setting for two days, there is no significant evidence for sustained local depletion at individual sites in most years (Table 3), apart from females in 1994 and 1997. However, these latter results might represent Type 1 errors (rejecting the null hypothesis of no depletion when it ought to be accepted) as twelve comparisons have been made.

Changes in capture vulnerability and mortality from year to year

Paxton et al. (1999) analysed successive raw (i.e. unstandardised) values of CPUE for male and female pike for year-classes 1943 to 1985 and 1944 to 1985 respectively. Males showed a steady year-on-year decline in CPUE at ages 5 and 6, from the mean largest value for \ln (CPUE) at age 4. As the analysis used natural logarithms, this indicated a steady exponential decline from the fourth to the sixth years of age. Females, in contrast, showed a significant interaction between year-class and age of capture, so whilst there was a decline from the modal CPUE at age 3 through to age 5, this fluctuated significantly from year-class to year-class. Such fluctuations implied changes in vulnerability to capture from year to year, or changes in mortality rate from year to year

One possible source of variation in vulnerability might be the fluctuations in fishing effort mentioned above. In order to test this hypothesis, successive standardised annual catches (as above) of pike year-classes for the modal year of catch, and two years thereafter, were tested (ANOVA) for an interaction of year-class and order of sampling, to see if there was a linear decline (on a natural logarithmic scale) in catches. Therefore the model was:

$$\ln(\text{standardised catch}) = \text{year-class} + \text{age} + [\text{year-class} \times \text{age}] \quad (4)$$

where age (3, 4 and 5 for females; 4, 5, and 6 for males) was a covariate and year-class was a discrete variable. Male year-classes 1943 to 1990 and female year-classes 1944 to 1991 were standardised for effort and placed into the above model. In both models the interaction term [year-class X age] (i.e. testing the hypothesis that the pattern of decline varies between year-classes), was significant (males: $F_{47,48} = 2.0$, $p < 0.001$; females: $F_{47,48} = 2.8$, $p < 0.001$) indicating that correcting for changes in fishing effort has not totally explained the changes in vulnerability/mortality. Certain year-classes (open circles in Fig. 4) appeared to have catch decline curves with significantly different gradients compared to the mean decline curve.

The observed changes in vulnerability/mortality potentially could be due to changes in size of the fish because Frost & Kipling (1967) demonstrated that below 67 cm (males) and 65 cm (females), only a proportion of the pike was caught. However, regression of the standardised (*only*) catch against girth (approximated as mean individual mass/mean individual length), for age 4 males and age 3 females, revealed that girth was not a significant predictor of standardised catch (males: $F_{150} = 0.05$, NS; females: $F_{150} = 0.14$, NS).

Thus it appears that the fluctuations in vulnerability/mortality do not come from any obvious systematic source and, therefore, non-systematic sources must be considered.

Non-systematic causes of change in variability/mortality

The distribution of year-classes that show significant deviations in vulnerability from the simple two-factor (i.e. year-class and age) decline function, suggest several possible explanations. Firstly, some of the "odd" year-classes are clustered in time, suggesting that perhaps there was a *sampling* year of odd physical characteristics (such as water transparency) which affected the vulnerability to capture of the cohorts alive at the time. Secondly, perhaps the few very weak year-classes (e.g. 1985, see Fig. 5) do not have normal sampling variation because the sampling distribution has a lower boundary (zero), and thus the gradient of the catch decline curve is very slight or even positive (all positive gradients were corrected to zero). However, the residuals from the model are acceptably normal, so this does not appear to be a widespread characteristic across slightly weak year-classes. Thirdly, there may be trends in mortality rates (i.e. they were lower for the 1981+ year-classes). Male and female mortality rates during 47 years are significantly correlated ($r = 0.480$, $df = 45$, $p < 0.01$).

Corrections for changes in vulnerability/mortality

One simple method to correct for the apparent fluctuations in vulnerability/mortality is to use the fits of regression lines for each year-class

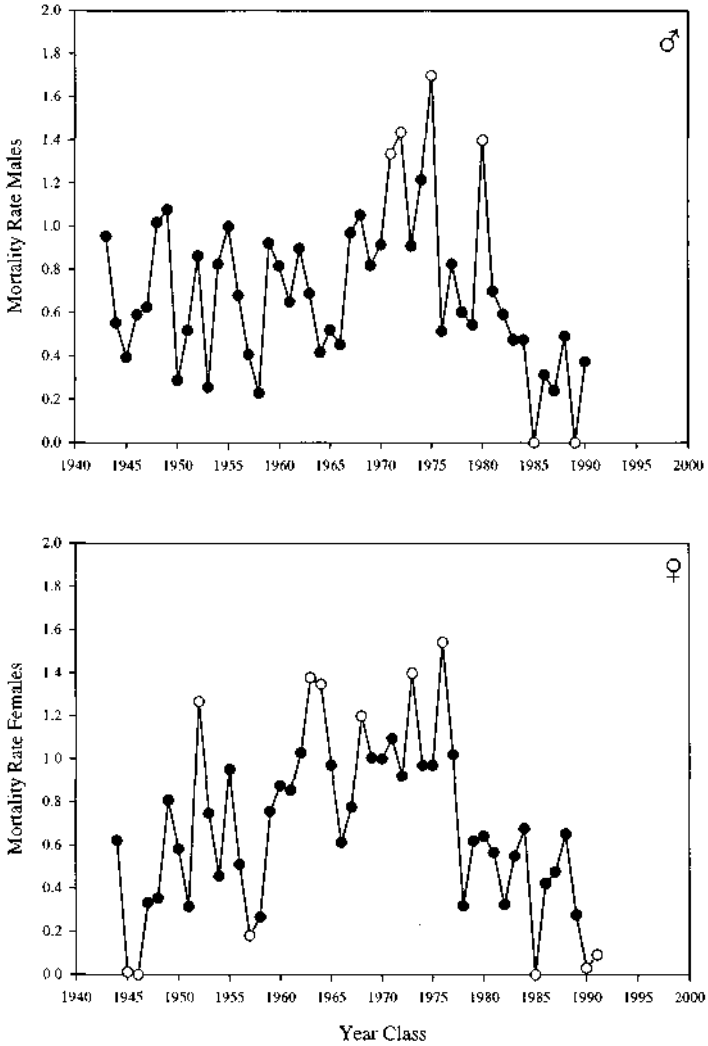


FIG. 4. Mortality rates of pike in Windermere from 1943-94 to 1990-91, based on the regression of catches versus year-classes, standardised for fishing effort (equation 4; see the text). Regressions were applied to females at 3-5 completed years of age (*above*), and males at 4-6 completed years of age (*below*). Open circles indicate an estimated mortality rate that is significantly different from the mean mortality rate (females: 0.678; males: 0.691).

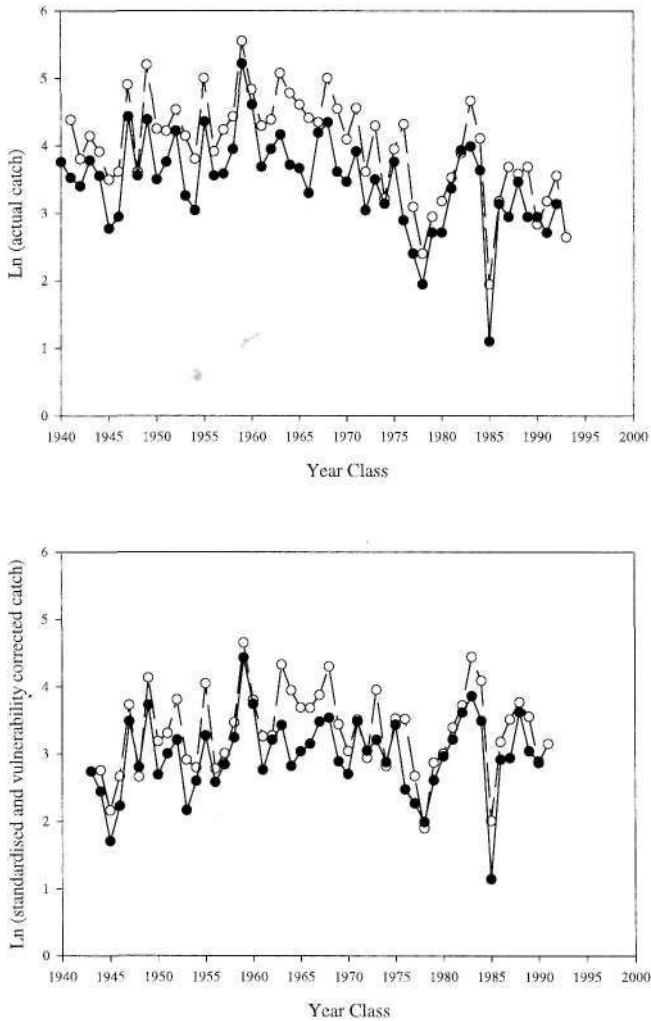


FIG. 5. *Above*: Actual total catch of 3-year-old females (open circles, dashed line) and 4-year-old males (closed circles, solid line) under varying fishing effort (correlation between males and females: $r = 0.900$, $df = 49$, $p < 0.001$) for pike in Windermere, 1940 to 1993. *Below*: Standardised and vulnerability-corrected catches for 3-year-old females (open circles, dashed line) and 4-year-old males (closed circles, solid line) for pike, under a constant fishing effort of 240 net-days (correlation between males and females: $r = 0.868$, $df = 45$, $p < 0.001$).

that were generated by equation (4). For most years this will not substantially alter the year-class strengths. This method gives equal weight to each of the three years in which the cohort is sampled. It is assumed that mortality rates vary *between* but are constant *within* a given year-class, at least over the three years analysed, although this may not be very realistic. Figure 5 gives the standardised, vulnerability-corrected catches of 3-year-old females and four-year-old males (as estimates of relative year-class strength) compared with the actual unadjusted catches of 3-year-old females and 4-year-old males. The overall effect of our corrections has been to make the total catches much more constant from year to year, and it has lowered the estimated catch for the early years.

Conclusions

The catch of pike per 48 hour setting (Fig. 1) in Windermere is non-symmetrically distributed and this prevents parametric analysis of the data. Nonetheless, non-parametric statistical methods indicate that the current sampling effort (i.e. the fishing effort as well as the frequency of net settings) is sensitive enough to detect differences between catches of each sex at each site in about half of all occasions. There are strong differences between sites *within* years. Further, current gill netting practice allows a distinction to be made between years, for the total catch of females per site. Catches of pike are not randomly distributed and there is clustering of fish. Such temporal or spatial clustering would appear to suggest that either pike move around in groups, or specific conditions allow the capture of more pike, or the presence of one or more pike in the net increases the likelihood of capturing others - perhaps by attracting them to the net. It is generally assumed that pike are solitary (Raaf 1988); nonetheless they may aggregate in local favourable microhabitats.

Study of the aged pike data clearly shows that simple interpretation of the catch-per-unit-effort values may be misleading, because the large amount of fishing effort in the early days of the fishery leads to a decreased CPUE. Fortunately, this effect can be partially corrected. In contrast to the high fishing pressure of the past, there is little evidence that the current fishing effort and deployment causes persistent local depletion of pike stocks within Windermere from year to year.

There are significant deviations in catches from the values expected by assuming consistent mortality from year to year. As sometimes the catch of older fish is greater than that of younger fishes, this implies that there are significant fluctuations in vulnerability from year to year. In addition, mortality rates both within and between year-classes may vary at different ages. Fluctuations in vulnerability may be due to environmental fluctuations

(e.g. temperature and water clarity) in the years of sampling, and there may be non-normal sampling biases in those years when weak year-classes were sampled. The fluctuations do not appear to be related to size at capture, if fish above a certain age are considered.

Significant differences between sites, and the lack of consistent evidence for local depletion under current fishing effort, suggest that the same sites should be sampled from year to year.

Even in a long-term sampling programme such as this one on Windermere, sampling biases occur that can be recognised only after a period of years has passed. It is important to make regular tests for sources of extraneous variation and biases in the results, in order to draw robust conclusions about changes in the population that is under study.

Acknowledgements

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