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Factors affecting the recruitment of riverine coarse fish: phase 3

Science Report: SC030214/SR1

SCHO0406BKST-E-P

ea/br/e/sci/v1

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This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84432-695-2

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Author(s):
R.Musk & R.Britton.

Dissemination Status:
Publicly available

Keywords:
Recruitment, roach, chub, dace, ageing, population dynamics, Statistical model, habitat, parasites.

Research Contractor:
Environment Agency
National Fisheries Technical Team
Mance House,
Arthur Drive,
Hoo Farm Industrial Estate,
Worcester Road,
Kidderminster, Worcs DY11 7RA.
Tel: 01562 534 100 Fax: 01562 534122

Environment Agency's Project Manager:
Stephen Axford, York Office

Science Project Number:
SC030214/SR1

Product Code:
SCHO0406BKST-E-P

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Steve Killeen Head of Science

Executive Summary

The aim of Phase III of the 'Factors affecting the recruitment of riverine coarse fish' (FARRCoF) project was to identify:

- the extent to which ageing drift adversely influenced the year class strength (YCS) outputs of the FARRCoF Phase II project data;
- how such issues may be remedied in future studies;
- a new method for dealing with ageing errors and assessing YCSs
- why and how the FARRCoF project should proceed to the next phase.

In Phase II of FARRCoF, ageing drift was identified as an issue that affected the calculation of YCSs as indices of recruitment, by causing apparent changes in relative YCSs between survey samples. Examples were found of characteristically strong year classes moving to both earlier and later years, as well as oscillating between surveys. It was suggested that this might have been caused by errors in the ageing of these fish, which then produced an erroneous YCS output. The re-ageing of approximately 1200 scales from roach, dace and chub from the River Stour in Essex suggested that errors had indeed occurred in the original age determinations. These errors arose from the subjective interpretation of certain scale features, such as indistinct checks, and the growth season to which growth at the edge of the scale was ascribed. It was concluded that, without independent validation, such issues can never be eliminated from scale ageing and that their influence on existing YCS calculations was undesirable. As a result, it was recommended that new methods of assessing recruitment strength should be devised that can incorporate the subjectivity of scale ageing.

A continuing need was identified to understand and assess the factors affecting coarse fish recruitment in rivers. This relates particularly to the requirement in the EU Water Framework Directive to determine ecological status and distinguish direct anthropogenic effects from natural variation and the effects of climate change. The requirement for the Environment Agency to base its management decisions on sound science was also highlighted as a major reason why the FARRCoF project should progress to a further phase.

Gap analysis was used to identify those aspects of the Environment Agency's understanding of recruitment that remain incomplete. This highlighted the following gaps in knowledge.

- Aspects of 0-group fish biology that determine the subsequent recruitment strength of cohorts.
- The key abiotic and biotic factors in the early life history of cohorts that impact upon subsequent recruitment success.
- The reproductive and life history traits that determine egg and larvae production, survival and subsequent recruitment.

- The roles of habitat, discharge and flood plain management in regulating the carrying capacity of the fish stock, both in juvenile and adult life phases.

It is recommended that these gaps in knowledge should be filled in future phases of the FARRCoF project. A number of discrete projects are proposed to assist in this process.

Contents

1. Introduction

1.1 Overview of the project

More than one million anglers in England and Wales buy rod licences each year and up to a further two million fish on an occasional basis (Environment Agency 2004). Many of these anglers fish in riverine coarse fisheries, so making the coarse fish populations in these fisheries an important social and economic resource. Understanding the interactions between fish and their environment is fundamental to the development of science-based fishery management strategies for rivers. In particular, an understanding of the factors influencing the abundance of the major coarse fish species, especially those factors affecting the numbers of fish that recruit into the adult populations each year, is of utmost importance (Cowx *et al.* 1995).

This led the Environment Agency to instigate the 'Factors affecting the recruitment of riverine coarse fish' (FARRCoF) project. The first two phases of this project have now been completed and were partially successful in demonstrating links between coarse fish recruitment and environmental variables. However, many of the associations were weak and many questions were left unanswered.

The specific aims of Phase III of the FARRCoF project were to:

- further investigate some of the Phase II recommendations;
- devise means of overcoming some of the problems of data analysis and inadequacies in the existing year class strength (YCS) calculation methods;
- provide a baseline for the current status of the Environment Agency's knowledge of riverine coarse fish recruitment;
- identify how the FARRCoF project should progress into the next phase.

1.2 What is recruitment?

Recruitment can be defined in a number of ways. All fish ecologists agree that the term describes the number of fish at some age or stage, but the precise age or stage can vary: it may be when fish enter the fishery or when they first spawn. For the purposes of this project, an early decision was made to define recruitment as the number of fish at maturation.

The process of recruitment involves the development of fish from eggs, through a series of density-dependent and density-independent processes, to the specific stage of interest. Many simple questions concerning recruitment require estimates of quantities that are very difficult to determine. For example, the question 'When is the magnitude of recruitment determined?' requires quantitative estimates of the amount of fertile eggs produced and the density-dependent and density-independent components of mortality. These questions are usually addressed by correlating estimates of abundance at early stages with later ages, as reviewed by Cushing (1996). Although such studies are useful, they are very seldom carried out with estimates of measurement error variability that are crucial for estimates of the truly important parameters.

In this project, direct measurement of recruitment at maturation proved impracticable, and so, as a baseline, recruitment was described in terms of the numbers of fish surviving at some specific point during the first year of life. This had to be carried out largely by back-calculation from numbers of older – often mature – fish that were caught by the standard fish population survey techniques of seine netting and electric fishing. Many coarse fish are very difficult to catch in winter and as they begin their second year of life, but the highest mortality rates for coarse fish usually occur early within their first year of life. Therefore, fish numbers estimated towards the end of the first year are likely to provide a good baseline index of the numbers likely to survive to maturation, whether measured directly or indirectly.

1.3 Recruitment and life history traits

The abundance of coarse fish varies greatly both spatially and temporally. Individual species also show a wide range of life history traits (Hutchings 2002). Small species often display rapid growth, early maturity and a short lifespan (r-selected), while large species have slower growth, later maturity and a long lifespan (K-selected). However, within a single species, populations at different locations can exhibit r or K traits. For instance, bullheads were found to show K traits in northern England (Mills and Mann 1983) and r traits in a southern chalk stream (Mann 1971), and roach displayed r traits in Slapton Ley and Alderfen Broad (Townsend *et al.* 1990) but K traits in the River Avon (Mann 1971). Temporal variations in recruitment, growth and mortality rates can be shown by one species at a single location. Until 1976, perch in Windermere were relatively long-lived and stocks consisted of several year-classes. However, following an outbreak of perch ulcer disease in 1976, a shift in life history traits occurred. The perch subsequently grew faster, but died earlier, so that the population consisted of a low number of year classes of relatively young fish (Paxton and Winfield 2000).

The potential fish productivity and life history traits of fish species at a specific location are the factors that determine suitable management strategies for a fishery. A common goal is to increase both the abundance and size of the fish. However, relatively low productivity in freshwater systems means that a high abundance of large fish can only be achieved by ensuring a high biomass to production ratio – in other words, long survival. In contrast, migratory salmonids can produce an abundance of large fish by migrating to more productive areas at sea (Myers 2002).

The age at maturity in a particular population of fish can be predicted from the means and variances in juvenile and adult survival rates, on the basis of age-specific expectations of producing future offspring. It has been found that reductions in the age at maturity are stimulated by decreases in the ratio of adult to juvenile survival rates and by increases in the variance in adult survival relative to the variance in juvenile survival. This means that relatively risky environments for adult fish encourage early maturity and its associated effects on growth after maturity. If the environment is riskier for juveniles than adults, then later maturity and longer survival are generally favoured. Thus, roach in environments that provide low risks to juveniles of displacement or starvation, but high risks to adults of mortality from parasites and predation, such as Alderfen Broad, have early maturation and few old fish. But in northerly spate rivers, which provide a riskier environment for juveniles than adults, maturation is probably later and there may be a high proportion of large, old fish.

The effects of these differences in relative risks should also be reflected in stock-recruitment relationships and the influence of environmental factors on these relationships. Thus, the influences of environmental factors on recruitment are likely to vary between rivers according to the relative risks to juvenile and adult life stages. Future research needs to take this into account, as very different life histories would be expected in, for example, a fenland drain, a southern chalk stream and a northerly spate river. Varying life histories can even occur in the same river if there are major changes in risk, such as water quality improvements or marked increases in predation.

Temperature, and its effects on a species' metabolic rate, seems to be a major factor in fish life history. Temperatures close to the optimum for growth produce rapid rates of growth and good early survival with early maturity, but after maturity much energy is channelled into reproduction, causing lower growth rates and high mortality rates (r-selected). Temperatures below the optimum for growth cause slow rates of growth and poor early survival, late maturity and low mortality rates after maturity. Hence, roach in warm, southern rivers, such as the Thames, can form abundant populations, but with relatively few large fish. Roach in the nearby, cooler River Itchen are not very abundant, but there is a greater proportion of large individuals.

1.4 Stock-recruitment relationships

The stock-recruitment relationship is the basis for the key parameters needed to understand and manage many aspects of fisheries. For many very fecund fish, the spawning stock seems to have little relationship to the number of subsequent adult recruits until the stock falls to a very low level. Presumably, this is because density-independent factors affecting survival from eggs to spawners mask density-dependent factors until the number of spawners, and thus the number of eggs laid, reaches a very low level.

Unlike the case for salmonids, there have been too few studies of the population control mechanisms affecting coarse fish to allow the development of models of management measures. For salmon, population studies have allowed stock-recruitment models, along with estimates of natural and fishing mortality and vulnerability, to be used to produce optimum sustainable yield or conservation limit targets that are related to rod catch. Management actions are then triggered if these targets are not met (Salmon Action Plans). In comparison with many coarse fish species, salmon show little variation in life history. Density-dependent factors that affect the mortality of juvenile stages have the largest influence on reducing variation in the numbers of smolts (juvenile salmon) and thus the number of adults.

Most coarse fish, particularly the cyprinids, are highly fecund compared with the salmonid species, and thus are capable of producing very large numbers of juveniles. In favourable conditions, these juveniles may survive to produce an abundance of mature fish, because density-dependent factors do not appear to be so important in regulating numbers. Equally, in less favourable conditions, the smaller sizes of the eggs, larvae and fry mean that they are vulnerable to a wider range of predators.

They also, particularly in rivers, have limited availability of food of suitable size and quantity, limited amounts of suitable habitat and are vulnerable to displacement by river flows. Therefore, in periods without suitable conditions, few survive to maturity.

1.5 Summary of factors affecting recruitment

Comparing different fish populations in terms of the factors affecting recruitment to age of first maturity requires knowledge of differences in age of first maturity, juvenile and adult mortality rates and temperature regimes, as well as stock-recruitment relationships. Without such knowledge, life history traits cannot be predicted, observations cannot be compared with these predictions and suitable management strategies cannot be formulated. It is therefore essential that these issues are investigated in further phases of this research project.

2. Revisiting Phase II: investigating the role of 'ageing drift' on YCS analyses

2.1 Introduction

Integral to YCS calculations is the ability to describe accurately the age structure of a fish population. For the Environment Agency, determining fish age (ageing) is based upon scale reading, whereby marks (checks) laid down on fish scales in accordance with seasonal growth are used as a guide to age. As the technique relies heavily on a subjective interpretation of the features on the scale and the ability to distinguish these clearly, the practice is known to be prone to errors (Mann and Steinmetz 1985; Britton *et al*. 2004).

The FARRCoF Phase II project raised the problem of 'ageing drift' in YCS analyses (Frear and Cowx 2003). This was the term given to the perceived end result of accumulated errors in ageing fish that arose from the inherent difficulties of accurately ageing individual fish from scales.

These errors arise from the problems of accurately identifying the marks on scales as annual growth features, commonly termed 'annuli'. Particular problems arise in relation to:

- identifying the first annulus;
- supposed growth checks actually caused by incidents, such as pollution or capture ('false' checks are perceived as true checks (annuli));
- distinguishing annuli that are very close together;
- scale erosion removing outer checks.

The outputs from Phase II demonstrated the problems likely to have arisen from such ageing errors in YCS analyses. In the 1980 survey of the upper Suffolk Stour, for example, the 1975 year class of chub appeared to be very strong, the 1976 year class weak and the 1977 year class very weak. In the 1985 survey, the 1976 year class appeared to have become strong, in addition to the 1975 year class, and the 1977 year class also appeared to have increased in strength. In the 1988 survey, both the 1976 and 1977 year classes appeared to have increased in strength again, while the strength of the 1975 year class had decreased. These apparent changes in later years were, almost certainly, largely caused by the difficulty in determining the age of older fish from scale marks.

In Phase II, these kinds of ageing errors were believed to have resulted in a number of the YCS outputs being unreliable. This was because the composition of the age structure data in the cohort analysis aspect of the YCS calculation was probably incorrect, although this could not be quantified (Frear and Cowx 2003). Further support for this possibility was provided by the lack of validation or quality control procedures applied at the time of the original ageings. The Phase II report recommended that a sample of the ages originally assigned should be cross-checked, in an attempt to eliminate the shifting YCSs in the YCS analyses that were assumed to result from ageing drift (Frear and Cowx 2003). A drawback of the method used in Phase II to calculate YCSs is that it combines YCSs derived from separate surveys. This means that ageing drift usually reduces the variance between apparent YCSs in individual surveys and reduces the ability to determine the strengths of the relationships between YCSs and environmental variables. If the influence of ageing drift could be reduced, it would reveal the true strength and persistence of year classes initially noted as strong and allow a better examination of environmental relationships.

If YCSs are largely determined by environmental conditions in the first year of life, and if older fish are to be used to investigate the relationships between YCS and environmental conditions, then it is fundamental that their ages are accurately determined. In the absence of validation of the ages by other ageing methods independent of interpretation of scale features, the effects of the subjective process of age determination on these investigations cannot be removed. However, greater consistency and precision in scale reading should help to reduce the effects of ageing drift and this study explores the benefits likely to arise from this reduction.

2.2 Materials and methods

A key feature of the data used to calculate YCSs in Phase II was the high recruitment strength of the 1975 year class of many species in initial surveys and how this strength appeared to diminish as the cohort became older (Frear and Cowx 2003). Therefore, it was decided that an examination of the ageing of a sample that included this year class should provide a good indication of the extent to which YCS outputs from different surveys, including this cohort, were likely to be affected by inaccurate scale ageing. As oscillations between YCSs for species in the River Stour were shown to be notable features of the Stour data sets (Frear and Cowx 2003), the sample chosen for detailed study was the 1985 survey of that river, for which the scales were still readily available. The issue of ageing drift was examined by re-reading the scales from roach, chub and dace in an ageing quality control exercise.

The scales that were re-aged comprised 627 roach, 457 dace and 179 chub. Scales were initially re-read without reference to the age that was originally determined. Any disagreements between the original and re-read ages were then investigated to identify possible causal factors. The data were used to produce a revised age-length key and YCS analysis, using the method of Cowx and Frear (2004), which allowed the outputs from the original ageing and the revised ageing to be compared.

2.3 Results

2.3.1 Roach

Following examination of the scales from 627 roach, the ages of 194 fish (31 per cent) were revised (Figure 1). The ageing agreement declined with increasing length and age, corroborating the assumption that as fish become older they become more difficult to age because the scale features are more difficult to interpret (for example, compression of annuli at the scale edge; Figure 2). It was apparent that the older fish were the most likely to have been wrongly aged, with most of them under-aged. It is likely that this under-aging accounted for much of the variation in the strengths of the 1975 and 1976 roach year classes between surveys in the River Stour data set used in Phase II (Frear and Cowx 2003).

A revised YCS analysis for roach suggested a recruitment pattern that differed markedly from that found in Phase II. The 1970, 1971 and 1972 cohorts were suggested as being present in the population and the recruitment strength of the 1975 year class was indicated to be higher than previously thought (Figure 3). This revised YCS profile also had a greater correlation with water temperature (Figure 4).

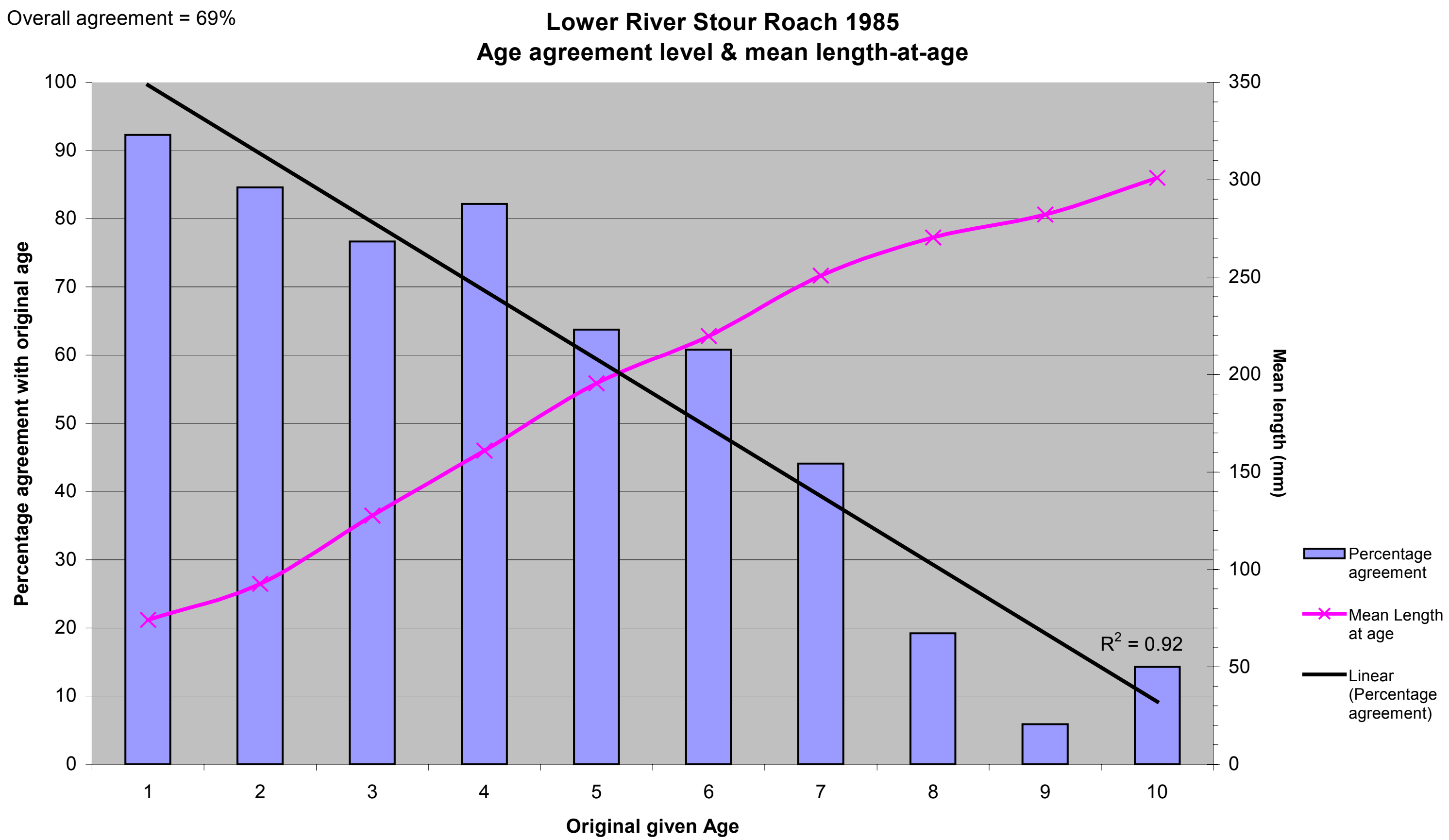

Figure 1 **Percentage agreement with original ages on re-examination of original scales for roach from the River Stour (Essex) sampled in 1985 (blue bars), and mean length at age (x).**

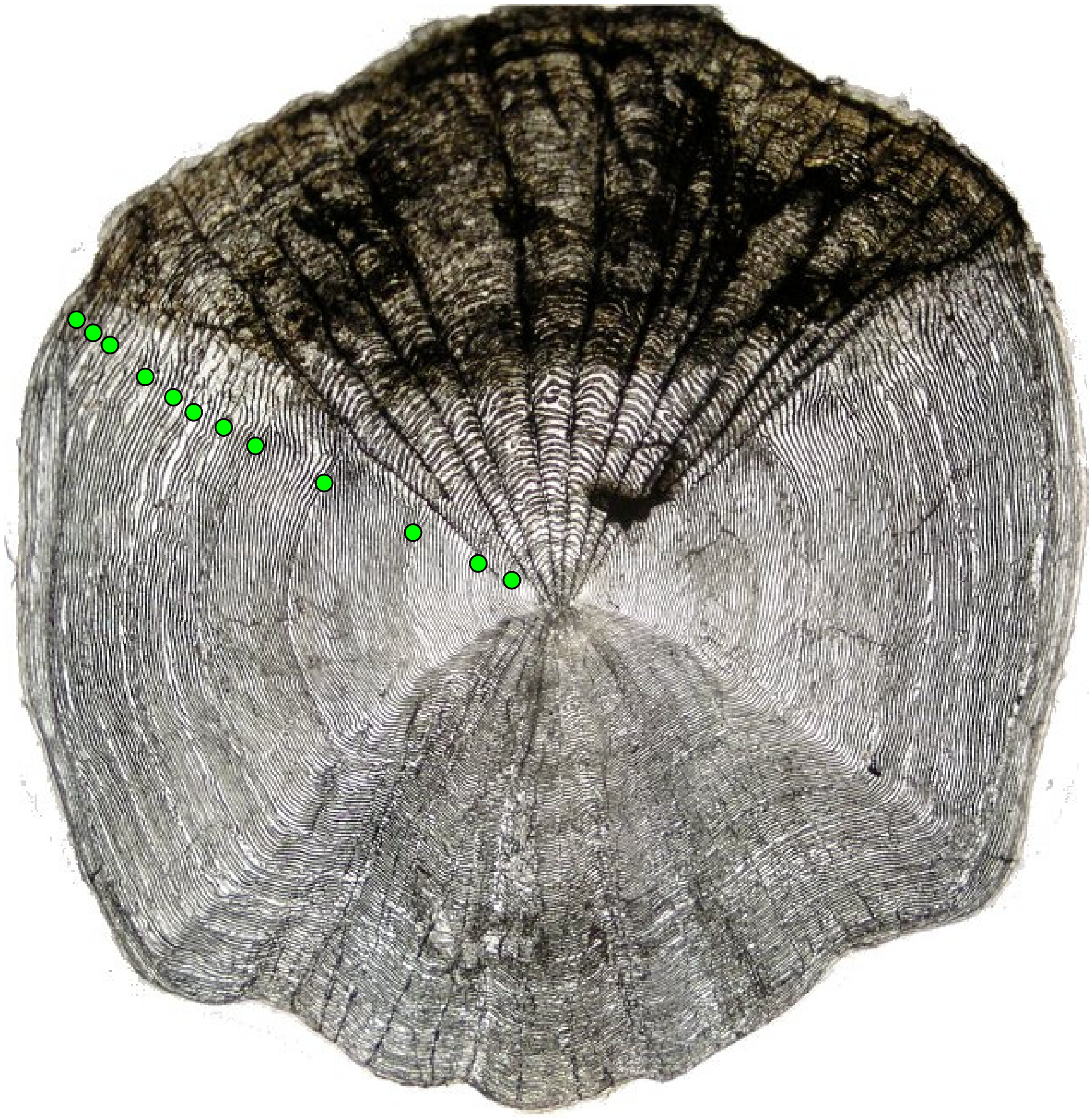

Figure 2 Chub of 365mm showing compression of annuli close to scale edge

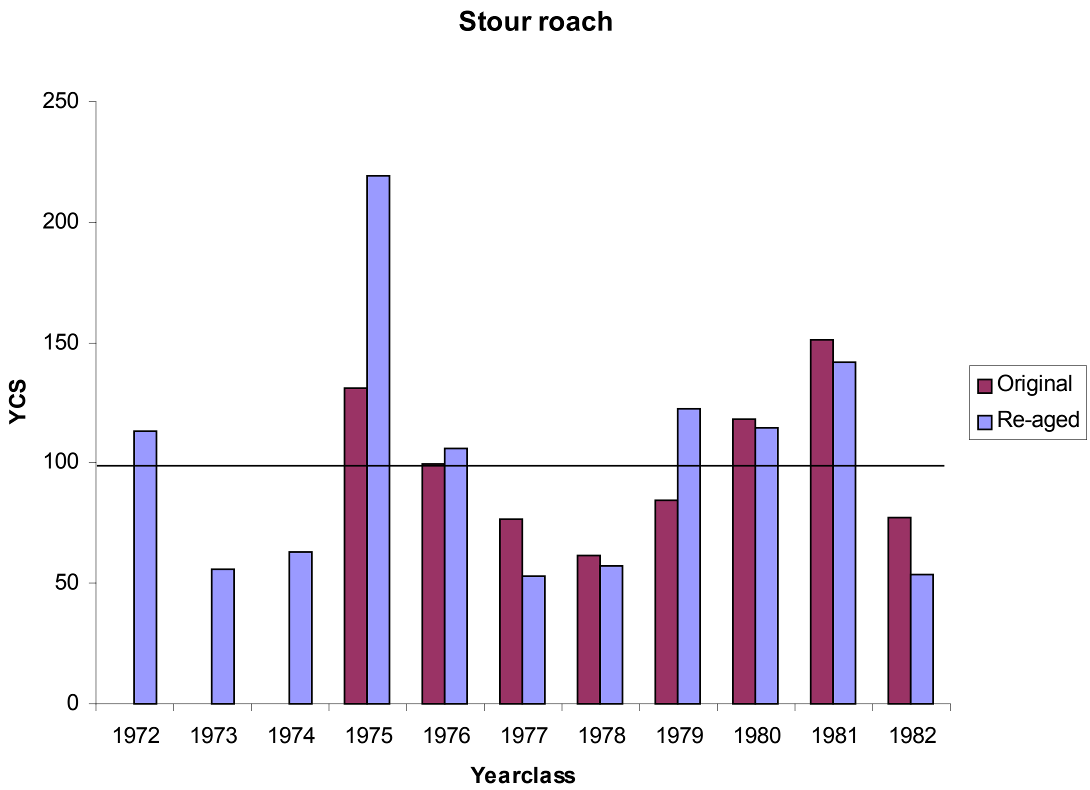

Figure 3 **Year class strength profile of roach sampled from the River Stour (Essex) in 1985.** Notes: Initial profile based on the original given ages (maroon bars) and the profile based on the re-checked ages (blue bars); the black line delineates a strong year class from a weak year class (Cowx and Frear 2004).

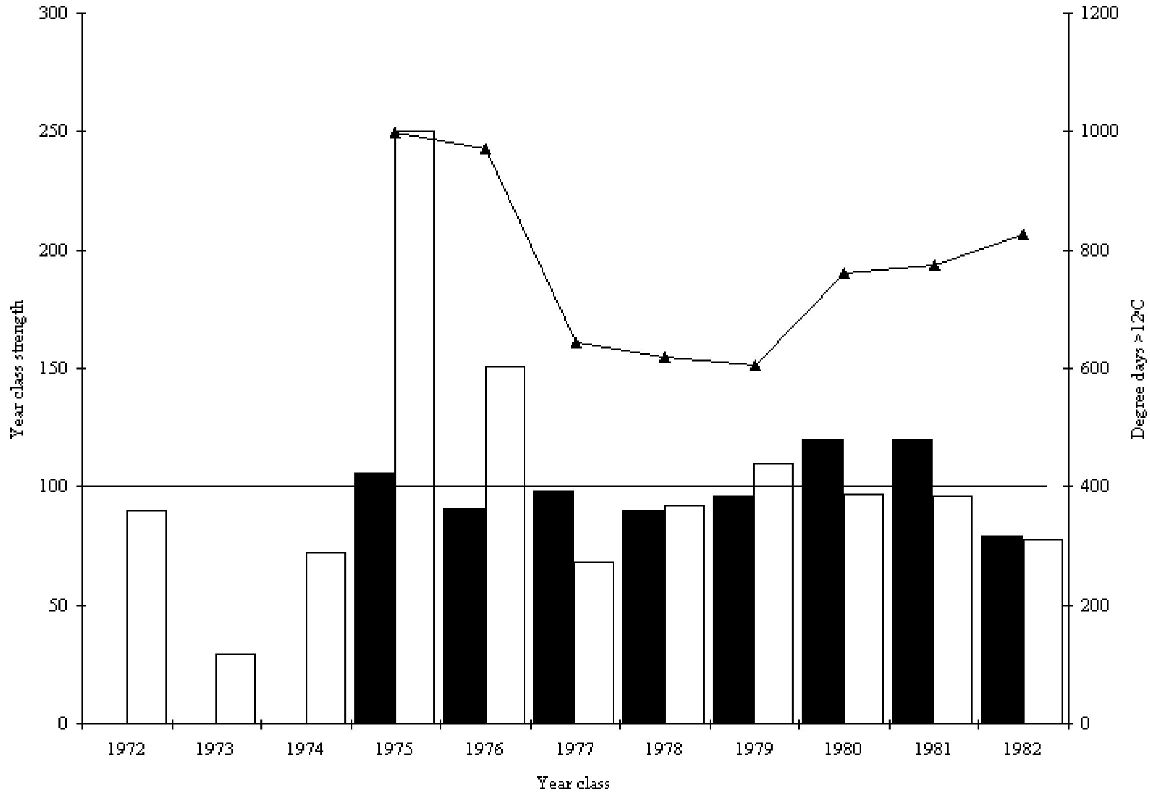

Figure 4 **Difference in the YCS output for roach in the River Stour (Essex) from the original ageing in 1985 (■) and the re-ageing completed in 2004 (□), with comparison to the number of degree-days >12°C (▲).** Note: The black line delineates a strong year class from a weak year class (Cowx and Frear 2004).

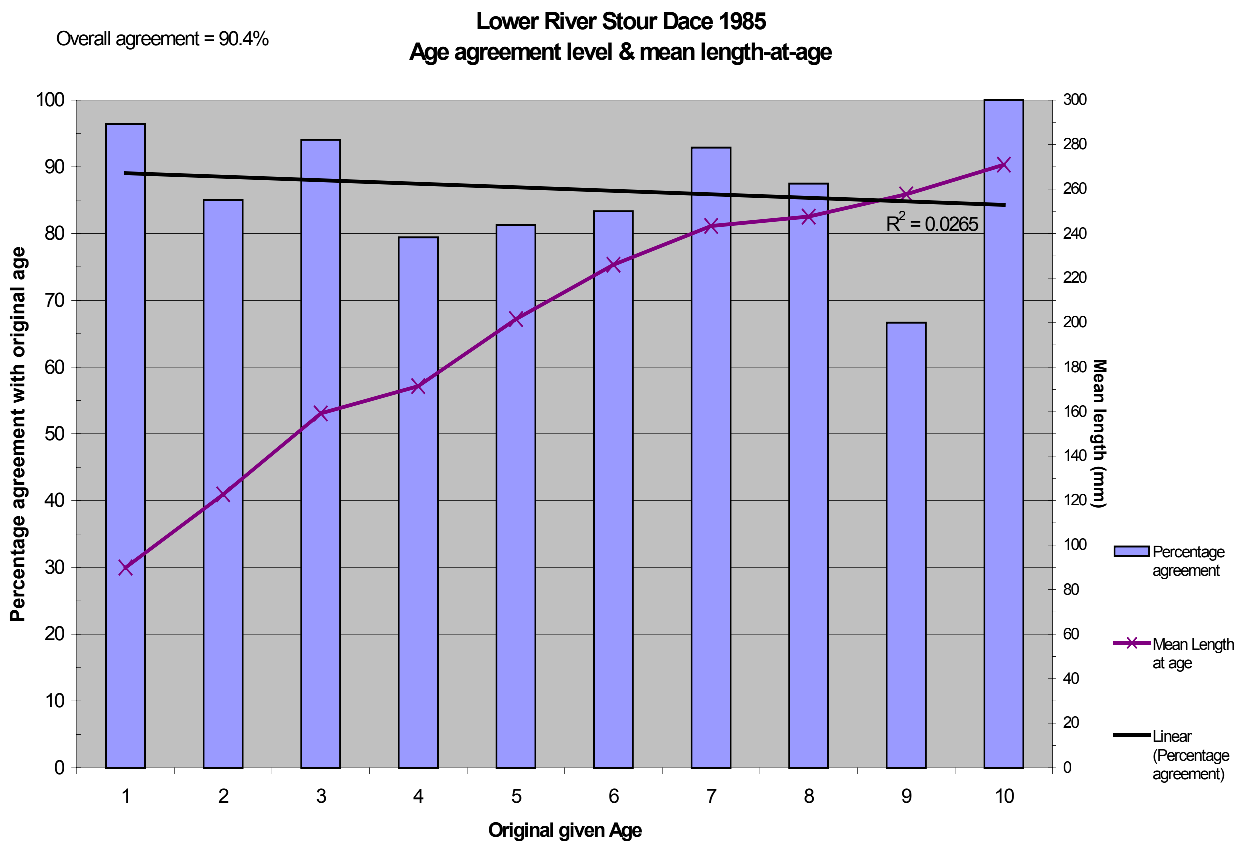

Figure 5 **Percentage agreement with original ages on re-examination of original scales for dace from the River Stour (Essex) sampled in 1985 (blue bars), and mean length at age (x).**

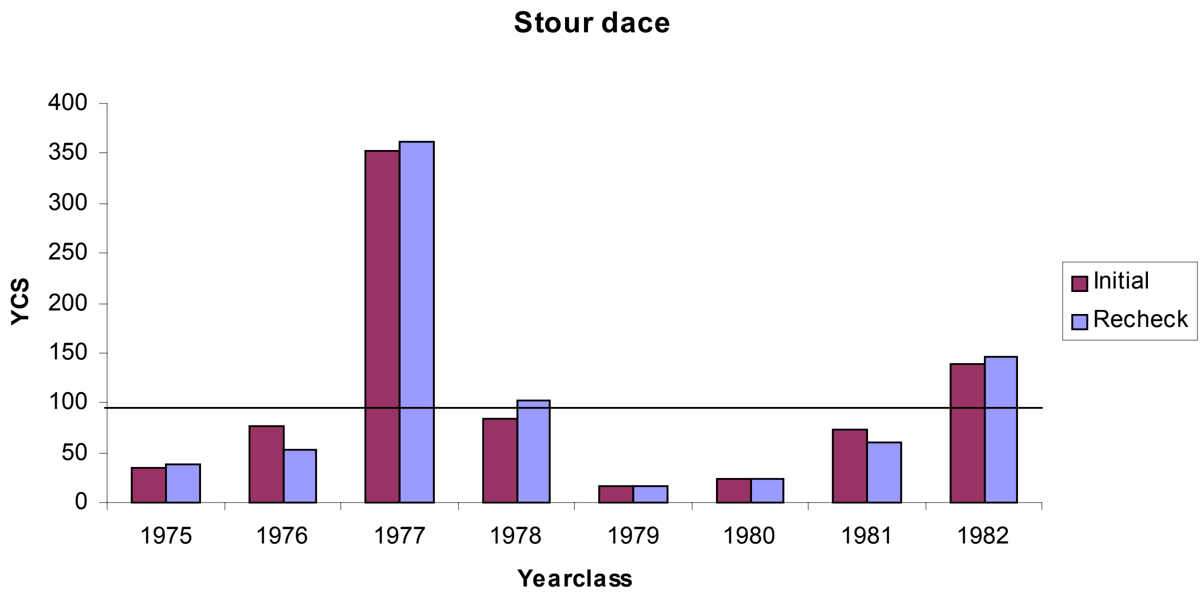

Figure 6 **Year class strength profile of dace sampled from the River Stour (Essex) in 1985.** Notes: Initial profile based on the original given ages (maroon bars) and the profile based on the re-checked ages (blue bars); the black line delineates a strong year class from a weak year class (Cowx and Frear 2004).

2.3.2 Dace

Following examination of the scales from 457 dace, the ages of only 44 fish were revised (Figure 5). By comparison with the roach data, the age determinations showed closer agreement. However, it should be noted that the majority of dace were less than five years old, with only 57 fish from older age groups. As it was the older age groups that proved more difficult to age in the roach, this may explain the closer agreement between the two readings for dace.

The revised YCS analysis revealed a similar recruitment pattern to the original ageing (Figure 6).

2.3.3 Chub

Following examination of the scales from 179 chub, the ages of only 18 fish (10 per cent) were revised (Figure 7). As with dace, the high level of agreement may have been due to the majority of the fish in the sample being from younger age groups. There were no chub in the original or revised ageing that were more than 12+ years. A key feature of many chub populations is the presence of individuals over 15 years old. These older chub have several closely compressed annuli on the scale edge, making them very difficult to age precisely. However, this was not a feature of the Stour chub population.

The revised YCSs revealed a similar pattern to the original ageing (Figure 8). However, the recruitments of the 1981 and 1982 year classes, which were identified as strong in the original data set, were weak in the revised output. This was an unexpected result, as the ages of only three fish from these year classes were changed. This demonstrates that even an adjustment of only 10% of the ages used in the YCS calculations can have a marked impact upon recruitment strength estimates and interpretation when using the Cowx and Frear (2004) method. This was probably a result of the unsatisfactory method for determining survival rates of young fish, and confounding survival and recruitment rates when using this method (see following section).

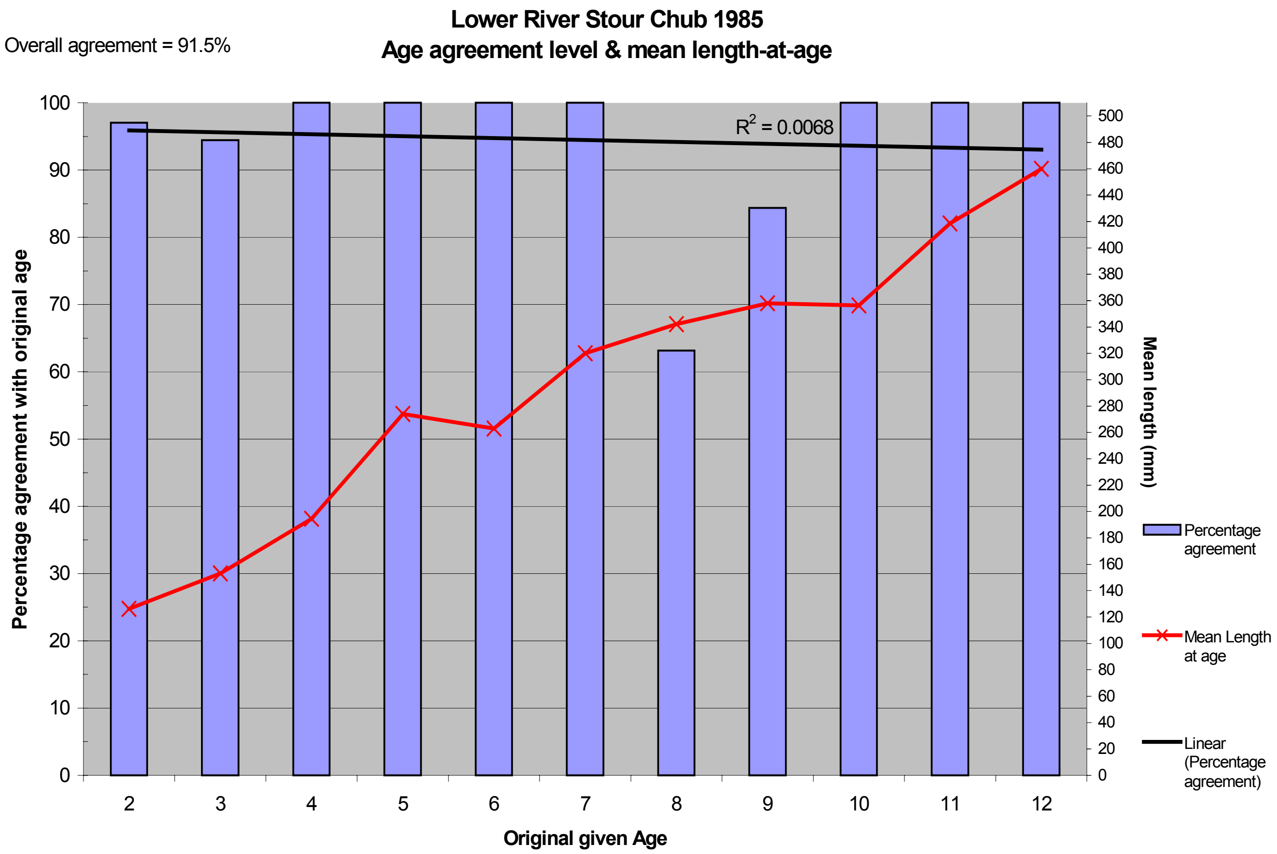

Figure 7 **Percentage agreement with original ages on re-examination of original scales for chub from the River Stour (Essex) sampled in 1985 (blue bars), and mean length at age (x).**

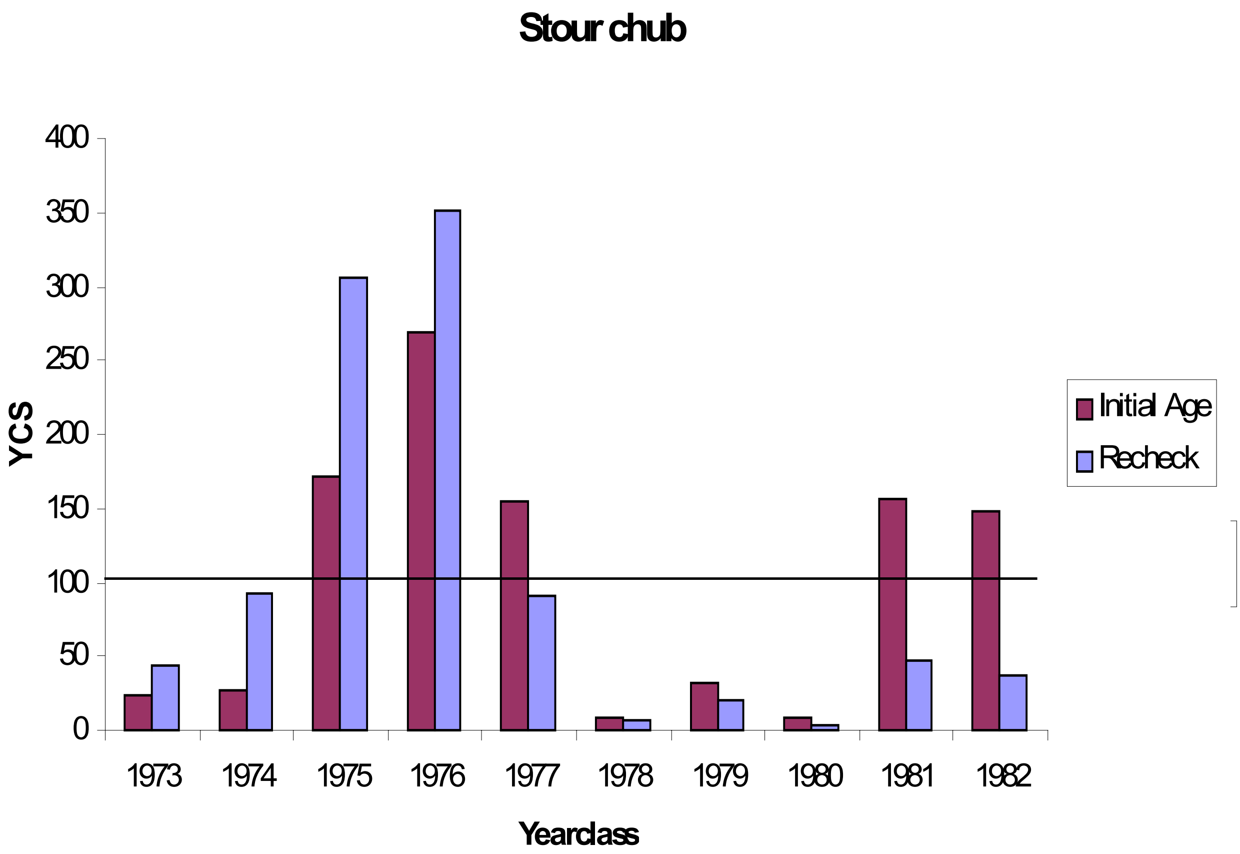

Figure 8 **Year class strength profile of chub sampled from the River Stour (Essex) in 1985.** Notes: Initial profile based on the original given ages (maroon bars) and the profile based on the re-checked ages (blue bars); the black line delineates a strong year class from a weak year class (Cowx and Frear 2004).

2.4 Discussion

2.4.1 Causes of ageing disagreement

The main reasons for disagreement appeared to be associated with the designation of checks close to the scale edge as true annual checks and the interpretation of other checks as either true or false. There was also some disagreement between agers over the presence or otherwise of true checks very close to the centre of some of the scales (see Figures 17.1 and 18.1).

Scale edge interpretation

The sampling records indicated that the scales were collected during surveys undertaken in June 1985. At that time, the fish would have been either in the process of laying down the check marking the transition between the 1984 and 1985 growth seasons, or this process would have finished and any growth observed outside of the last annulus would be ‘plus’ growth produced in that year. Subjective interpretation of this feature was a major factor in the ageing disagreements affecting young fish. In general, fish of below 10cm in size at ages 1+ and 2+ appeared to have growth outside of the last annulus that was interpreted as growth produced in 1985 (Fig. 9). Fish of above 10cm appeared to have minimal growth outside of this annulus and, in many cases, still appeared to be producing the 1985 annulus (Fig. 10). This may have led to the original reader to interpret all of the previous year’s growth as the new ‘plus growth’, producing an age discrepancy of one year.

Figure 9 Scale photo from a 78mm roach aged 2+, showing ‘plus growth’ after the previous annulus, sampled in June 1985 from lower River Stour (Essex).

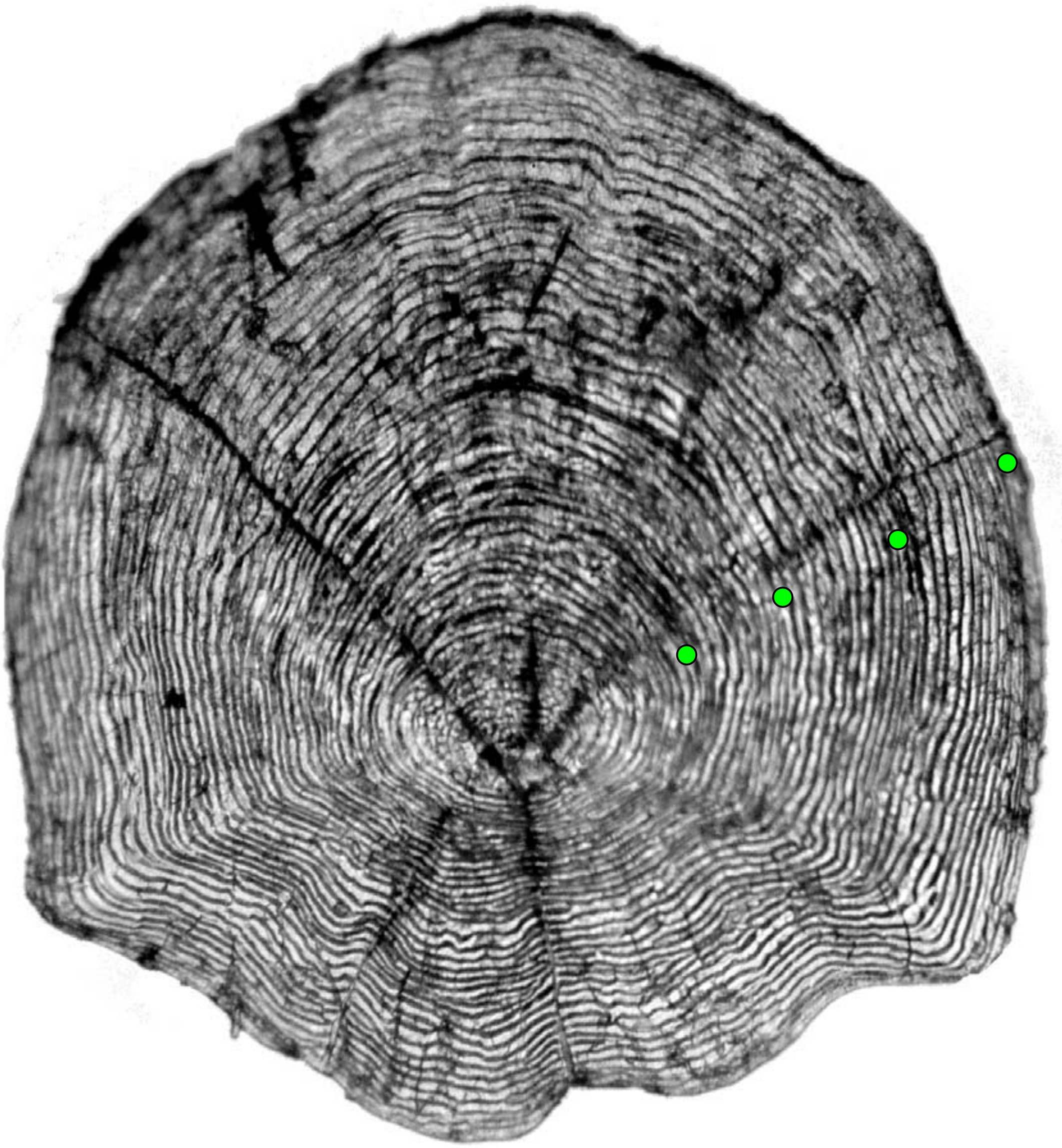

Figure 10 Scale photo from roach no. 416, length 143mm, aged 4+ showing minimal 'plus growth', sampled in June 1985 from lower River Stour (Essex).

Subjective interpretation of checks on the scale

Where indistinct checks were observed on scales, a decision had to be made as to whether these constituted true annuli or were merely 'false' checks that should be ignored for the purposes of ageing that scale (Figure 11). In old fish, the annual checks are laid down closer to each other at the scale edge, as the annual growth increments reduce. This makes precise ageing of the older fish difficult (especially in slow-growing fish, such as old roach) and, in some cases, introduces a high degree of uncertainty (Figure 12). This uncertainty was the primary cause of the disagreements affecting the ageing of older roach in the River Stour 1985 sample.

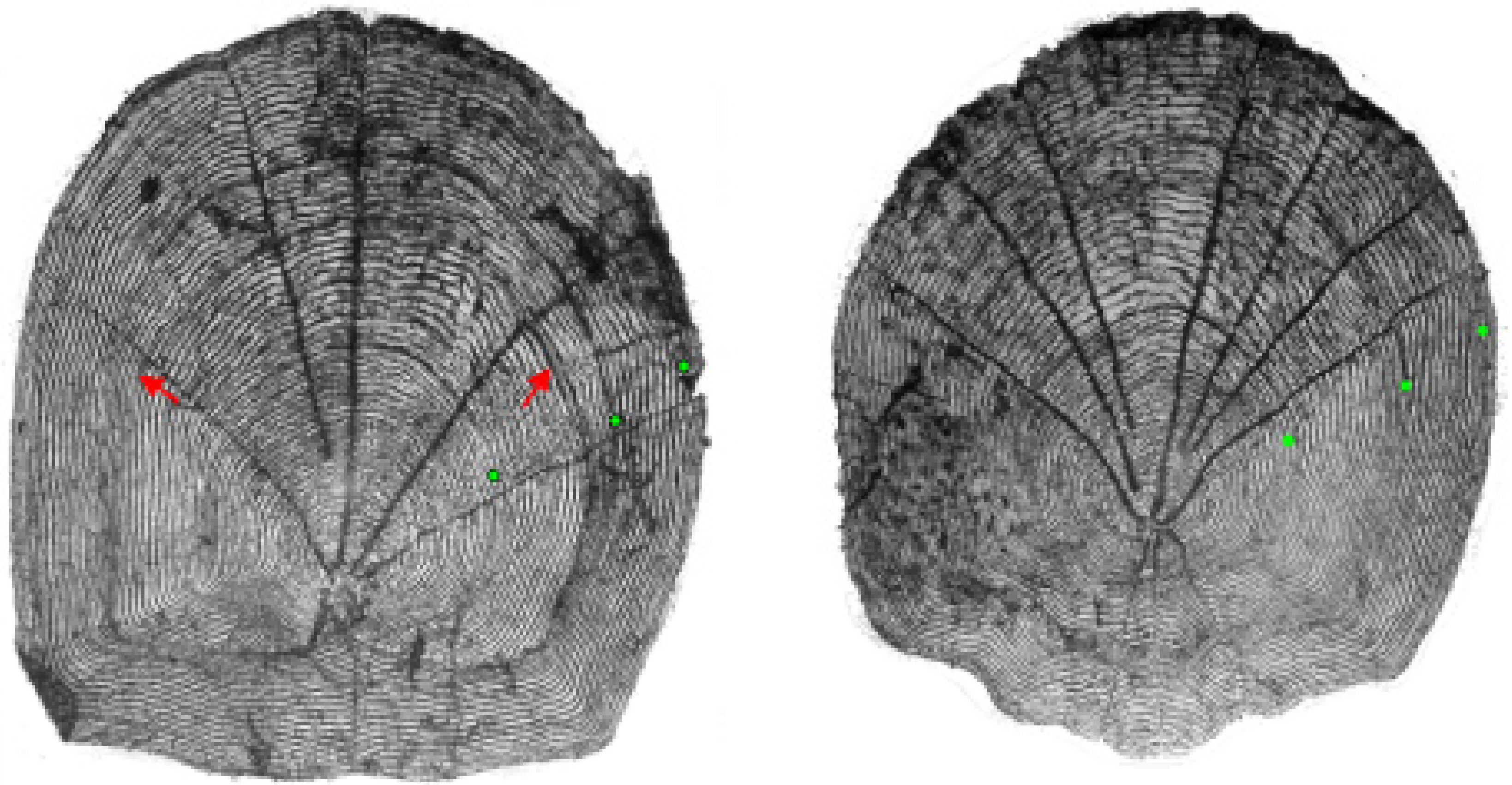

Figure 11 Scale images from the same 130mm roach captured from the River Stour in June 1985.
Notes: The ages derived for the scale were 3+ and 4+, with the arrow indicating the feature that produced the subjectivity in interpretation.

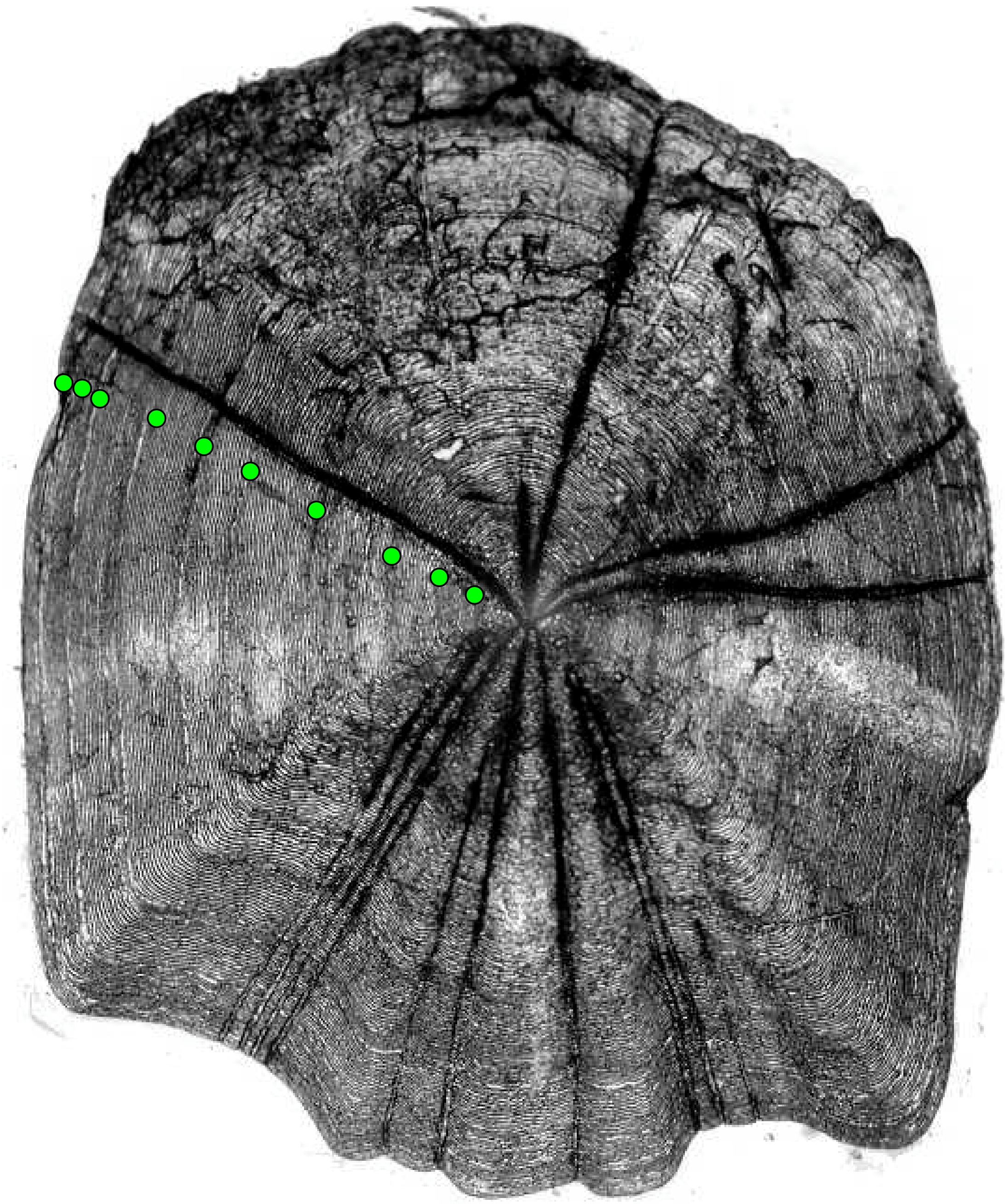

Figure 12 Scale photo from a 240mm roach aged 10+, sampled in June 1985 from lower River Stour (Essex) showing compression of annuli toward the scale edge.

2.4.2 Recommendations

The re-ageing exercise highlighted the need for accurate age determinations in order to ensure that subsequent calculations of YCSs by the Cowx and Frear method are correct. It demonstrated that a prerequisite for ensuring accuracy in age determinations using scales is a rigorous quality control procedure. Ideally, quality assurance checks should be combined with an ageing validation exercise. There are various age validation techniques available, including the mark-recapture of fish of known age. This method combines marking body structures with chemical markers such as tetracycline (Frost *et al*. 1961) and radiochemical dating (Campana 2001). However, within the operational constraints imposed by the Environment Agency's National Fisheries Monitoring Programme, few methods for reducing ageing errors are feasible.

Avoiding sampling around the period of annulus formation – between May and early July – would remove many of the difficulties of deciphering scale features that either constitute annulus formation or plus growth on the scale edge. Annual sampling of populations allows the identification of scale growth patterns that can be followed in subsequent years, thereby confirming true annuli. Furthermore, patterns associated with strong and weak year classes can be identified early in the life of the fish, and their subsequent progress tracked. Thus, it should be possible to reduce the effects of ageing errors in the analyses of YCSs.

2.4.3 Impacts on Phase II data-sets

There were marked discrepancies between the ages originally determined from the River Stour scales and used in the YCS calculations, and from the re-ageing exercise, particularly in the roach sample. If it were assumed that such discrepancies had been replicated throughout all the Phase II data-sets, then there is the potential for the recruitment trends within a river and the inter-river variations in YCS to be at best slightly inaccurate and at worst wholly misleading. If YCSs cannot be ascertained with accuracy, then there is little point in trying to deduce which factors are the key determinants of the differences in recruitment success. Ageing drift has produced uncertainties in the data that blur the trends in recruitment success and mask the relationship with the abiotic and biotic variables that regulate the recruitment processes.

2.4.4 Resolution of ageing drift in Phase II data-sets

Much time and effort went into calculating YCSs from the data sets used in Phase II. It was suspected that many of these calculations had been affected by ageing drift, and this study confirmed the influence of ageing drift in the case of the Stour. This means that the preliminary conclusions made about the effects of environmental factors were severely compromised by ageing drift. It therefore needs to be decided how to treat Phase II data in future analyses.

There are three potential ways that the issue of 'ageing drift' can be tackled:

- do nothing;
- re-age all Phase II data sets to ensure scale ageing is more 'accurate';
- devise a new method of YCS analysis that can incorporate a known factor of ageing variance and then re-analyse existing Phase II ageing data.

The do nothing option is clearly unsatisfactory, because it paints an uncertain picture of the factors affecting recruitment.

Re-ageing all Phase II data sets would be a large task and, in the absence of validation data, the subjective nature of scale ageing would mean that the inaccuracies in the ageing data, and thus in the calculated YCSs, would remain unknown and unquantified. Therefore, such an exercise would provide little benefit and would be unlikely to provide adequate resolution of the issue.

The fact that even experienced scale agers can never say with full confidence that a derived age for a fish correctly reflects its true age suggests that a method is required to incorporate ageing subjectivity errors into YCS calculations.

2.5 Revising year class strength calculations to account for subjectivity in scale ageing

Without adequate age validation procedures, even highly experienced agers of fish scales will make subjective judgements that are likely to result in unsatisfactory amounts of unquantified errors in estimates of the YCS. These will then render futile any further analyses of the factors affecting recruitment. Therefore, developing a model that can incorporate the subjectivity of scale ageing into recruitment calculations would be a major advance.

The YCS calculation method used in Phase II and in this section (Cowx and Frear 2004) does not account for any possibility of ageing error and so cannot provide any level of confidence about the calculated YCS. Therefore, the reliability and credibility of the output cannot be quantified. Furthermore, it is a simplistic method that has been overtaken by developments in computing that allow complex statistical analyses to be made. Some shortcomings of the method are detailed below.

- It involves a number of steps without including error terms, which means that no confidence intervals can be applied to the results.
- It involves unnecessary or unjustified data manipulations, including spatial and temporal averaging of data, data transformation and loss of reference to actual numbers of fish involved (e.g. l /log (per cent (number))), data editing to remove age groups that may bias the result unduly (e.g. removal of data from young fish that are not regarded as having been sampled efficiently) and calculating survival rates from age structure data that include variations in recruitment.
- It depends on assumptions that do not allow for sampling bias on a particular occasion, such as using a survival rate estimated from the age-frequency distribution from a single survey.
- It cannot be readily refined or extended to give a better fit to the data (e.g. changes in survival rate with time).
- It requires the influence of environmental variables to be assessed in a second stage, again with no idea of confidence intervals.

Many of these problems could be resolved by using a model based upon contemporary statistical methods, which would offer the following advantages.

- The raw data could be analysed with a statistical software package that requires no editing of data and can run without intervention.
- This single analysis could provide simultaneous estimates of the survival rate (z), relative YCSs and year-to-year variation.
- Assumptions are explicit and can be readily investigated or modified and then modelled and tested against observed data (for example, a comparison of age

structures expected in subsequent surveys with the age structures actually observed).
- The assumptions (model) can be readily refined to give a better fit to the data and to analyse and test hypotheses about the influences of various factors (for example, does survival rate show systematic trends between cohorts, or vary with age?).
- Measures of uncertainty are available for all outputs (such as YCSs).

The Statistics and GIS Group of the Environment Agency's National Fisheries Technical Team have developed a statistical Population Dynamics Model (PDM) for coarse fish. Details are given in a separate report (Wyatt *et al* 2006).

3. The ‘FARRCoF’ project: the current position

3.1 Introduction

The complexity of recruitment in riverine coarse fisheries involves many independent and interacting factors, most of which are not yet fully understood. This complexity is demonstrated in Figure 13 and indicates that the early life history of a year class appears crucial in determining the number of fish that subsequently recruit into the adult stock. However, the links between early life history and subsequent recruitment as adults have not been adequately determined for coarse fish in British rivers.

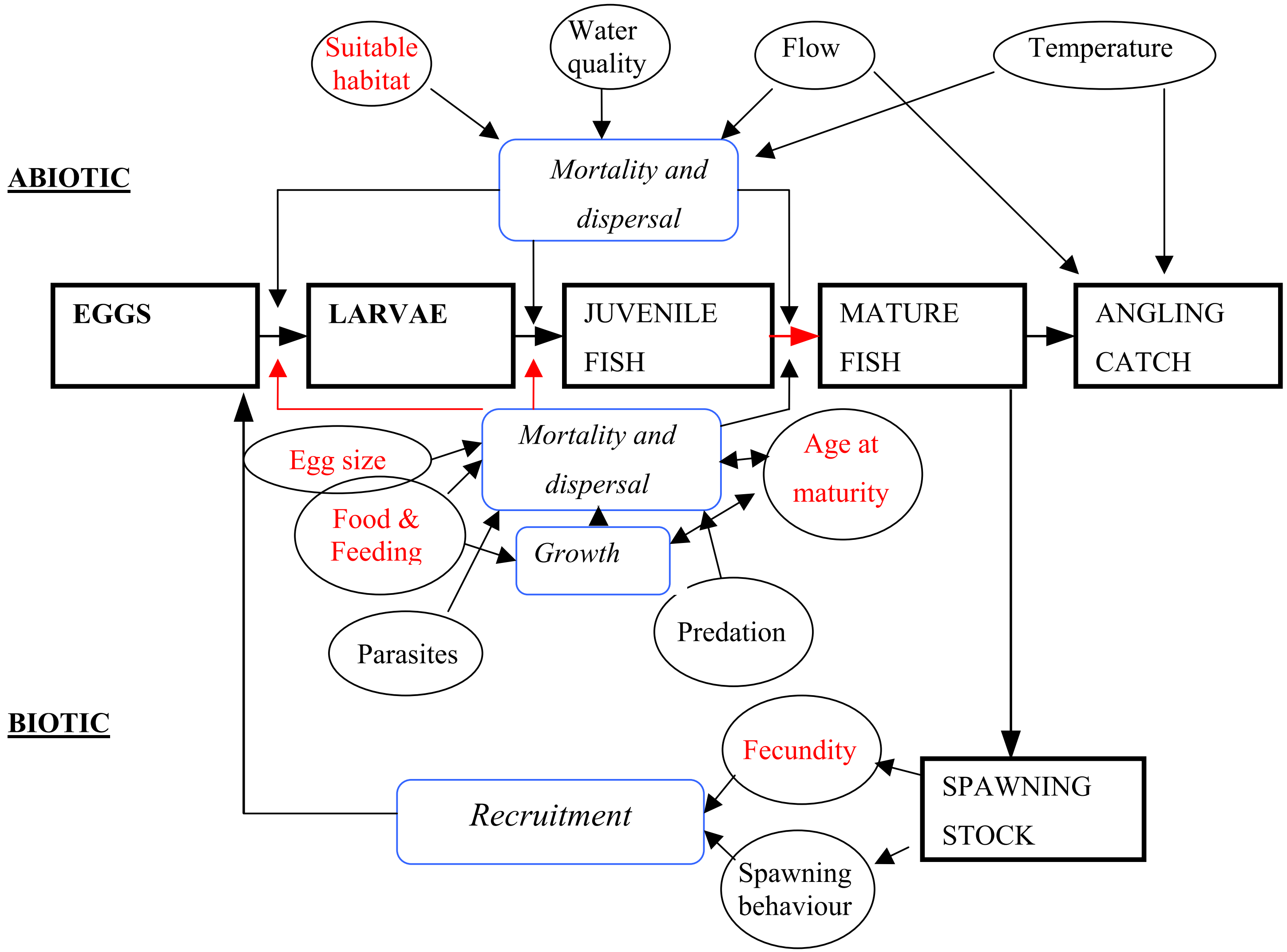

Figure 13 Model illustrating the complexity of factors that govern fish abundance in a cyprinid fishery.
Note: Gaps in the Environment Agency's knowledge are in red.

3.2 Extent of Environment Agency knowledge on riverine coarse fish recruitment processes

The Phase II project revealed that the recruitment of strong year classes in riverine cyprinids can be sporadic (Frear and Cowx 2003). The production of a strong year class appeared to be reliant upon a combination of biotic and abiotic factors that allowed sufficient numbers of fry to successfully over-winter and subsequently recruit into the mature stock. It has been postulated that water temperature in the first growth year determines the potential YCS of a cohort, with discharge determining the actual YCS (Nunn *et al*. 2003). However, factors associated with the position of the North Wall of the Gulf Stream in the first growth year, intra- and inter-specific competition associated with density-dependent and density-independent mechanisms, suitable habitat and food availability for fry, and parasitic loading have all been suggested as potentially playing key parts in the recruitment process (Cowx and Frear 2004, Mann 1997, Feist *et al.* 1997). Therefore, the use of tools such as key factor analyses to tease out which of these factors are the most important in determining recruitment strength would appear to be a priority. The PDM could be very valuable in elucidating these relationships.

3.3 Gaps in Environment Agency knowledge on riverine coarse fish recruitment processes

Despite the work completed in FARRCoF Phase I and II, large gaps remain in the Environment Agency's knowledge of recruitment processes in riverine coarse fish. Figure 13 indicates that an understanding of the early life history of a cohort is a prerequisite in understanding its subsequent recruitment strength. Nevertheless, data sets collected by the Environment Agency, as identified in Phases I and II, deal principally with samples of the adult stock. In Phase II, this meant that when recruitment patterns were analysed, the underlying factors that produced them had to be elucidated using historical data on abiotic factors, such as temperature and discharge. From these data, crude indices were derived – based on temperature requirements for growth (degree-days >12^{o}C) and flows above normal (number of days with mean daily flow above monthly basal flow) – that might be expected to affect the survival of juvenile fish. The influence of these indices on the recruitment pattern was then investigated (Frear and Cowx 2003). In addition to the inherent problems with this method discussed earlier, another concern is that the abiotic data were only available from sampling stations at fixed locations on the study rivers, with no regard to the conditions in fry habitats. Therefore, YCSs had to be related to a general overview of the conditions in the river during the first year of life of each cohort. They may not have reflected the actual conditions to which the underyearling fish were exposed.

The main focus of the Environment Agency's National Fisheries Monitoring Programme remains sampling of adult stocks. There is no element of the programme that covers sampling of juvenile fish. Therefore, there are very few data available that allow the tracking of a cohort from within its first year of life through to its recruitment into the mature stock. There is also a paucity of biological and environmental data, and very few data sets that might reveal how various factors interact to produce what are subsequently identified as weak or strong year classes. This is a fundamental gap in the Environment Agency's knowledge that requires filling urgently and certainly before key factor analysis of factors affecting recruitment can be considered.

Despite the extent of adult monitoring completed since the 1970s, there are still certain gaps in the Environment Agency's knowledge regarding reproductive biology. Although there were studies in the 1970s of reproductive traits of coarse fish in rivers that involved the sacrifice of individuals for maturity and fecundity analyses (Hellawell 1971, Mann 1973, 1974, 1976, Mills 1991), few studies since then have investigated the maturity and fecundity of coarse fish in England and Wales. The importance of gaining an additional understanding of the links between fecundity and recruitment has been emphasised by concerns about the influence on fish recruitment of the intersex condition, which is now commonly found in male fish below sewage works (Jobling *et al.* 2002).

Life history traits reflect the trade-off between somatic growth, maintenance, reproduction and survival. Sections 1.3 and 1.4 emphasised that life history traits may vary between populations of the same species, according to the biological and environmental conditions to which they are exposed (Vila-Gispert and Moreno-Amich 2002). However, there is very little knowledge of the extent of differences in life history traits in species such as roach, dace and chub among the rivers of England and Wales. No analyses of the variations shown between populations have yet been made, despite the opportunity provided by the Environment Agency's National Fisheries Monitoring Programme and National Fish Population Database. Thus the extent and causes of spatial and temporal variations in life history traits, some of which may be amenable to fishery management, remain unknown. One important factor that is likely to influence variations is the recruitment process, as demonstrated by the work on YCSs. There are particularly large gaps in knowledge regarding the early life of fish.

The gaps in the Environment Agency's knowledge can be summarised by the following questions that cannot at present be answered.

- What is the role of underyearling fish ecology in determining the subsequent recruitment strength of cohorts?
- What roles do key abiotic and biotic factors play in the early life history of cohorts and how do they impact upon the subsequent recruitment success?
- What are the roles of different reproductive and life history traits in larval production, survival and subsequent recruitment?
- How are the above factors affected by differences in habitat, discharge and flood plain management between rivers and between years?

3.4 Do the gaps in Environment Agency knowledge require filling?

The gap analysis has revealed a series of questions on factors affecting coarse fish recruitment that cannot be answered at present. However, do these questions require answering in order for the Environment Agency to carry out its business according to the principles of sound science? To examine this, the following three considerations will be explored:

- the EU Water Framework Directive (WFD);
- climate change;
- efficient and effective fishery management.

There is an urgent need to demonstrate what constitutes good ecological status for fish populations, as this is a key feature of the Environment Agency's fisheries responsibilities under the WFD. The Fish-based Assessment Method for the Ecological status of European Rivers (FAME) project within WFD has produced a framework for determining the ecological status of a river in terms of the fish species present and their abundance in its fish population. But the project has not covered the requirement to determine how the age structures of the fish communities might reflect failures of reproduction or development of particular species. Indeed, a methodology for determining how age structure (and therefore mortality/survival, recruitment) can be related to ecological status is still outstanding. Work within any future FARRCoF phases should help to elucidate the relationships between recruitment (as shown by age structure) and the ecological status of river systems.

Climate change could have profound impacts on the recruitment processes of riverine coarse fish. Within Phase II, the climatic variables of temperature and rainfall (via discharge) were identified as important drivers of the recruitment processes of riverine cyprinids (Frear and Cowx 2003, Nunn *et al*. 2003, Britton *et al*. 2004). Climate change scenarios suggest that England and Wales will experience warmer, drier summers and milder, wetter winters (Hulme *et al*. 2002). It is unclear how these scenarios will affect the recruitment process. Whilst higher temperatures in summer periods may appear beneficial *prima facie*, possible consequences such as low flows and associated water quality issues require consideration. Furthermore, an increased frequency of rainstorms in these periods is likely to produce more episodes of elevated discharge that result in increased downstream displacement of 0-group fish, perhaps to unsuitable habitats (Nunn *et al*. 2003). Such events are believed to eliminate the possibility of a strong year class, irrespective of the water temperatures prior to the episode of elevated discharge (Nunn *et al*. 2003).

The effects of climate change may also impact on a further suite of factors that are already believed to play a major part in determining recruitment success. Climate change could potentially affect winter discharge, the length of the fish growth season and the timing of spawning. Any increases in winter discharge may result in increased downstream displacement of over-wintering fry, which would have a deleterious impact on the number of fish able to recruit. However, extension of the growing season could allow fish to grow to a larger size by their first winter, thereby providing some mitigation. Increased body length enables fry to hold position in higher discharges, avoiding downstream displacement (Environment Agency 2001).

The spawning of many riverine coarse fish species is triggered by temperature as well as photoperiod (Cowx 2001). This means that, if spring temperatures do increase, spawning times may shift to an earlier date. This could extend the growing season, but there would need to be a similar change in the timing of a suitable food supply for fish larvae to ensure that larvae are able to switch successfully from an internal food supply (yolk) to an abundant and nutritious external food supply, which is an essential step affecting recruitment (see Section 3.5.3). In addition, the Environment Agency's response to the environmental effects of climate change, such as further flood defence schemes with raised flood defences and channelling of water courses to improve discharge rates, may adversely impact upon the riverine coarse fish recruitment processes by promoting increased downstream displacement and the loss of marginal habitats and lateral connectivity with the flood plain (Nunn *et al*. 2003), where spawning and sheltered habitats for juveniles can occur.

The aim of the research by the Environment Agency is to provide a scientific basis for management decision-making. However, with only a perfunctory understanding of the riverine coarse fish recruitment process, the suitability of management decisions will be uncertain at best. For example, constructing off-river refuges for fry to shelter in during spates would appear to be beneficial. However, little is known about fry population movements during these periods or about the use of refuges during low flow periods. Limited studies have shown that predators may be abundant in such areas, thereby reducing survival. Furthermore, research on parasites and fry suggests that the conditions provided in refuges are ideal for some parasites to infest fry, with the result that refuges may actually be counter-productive (see Section 3.5.4; Feist *et al.* 1997).

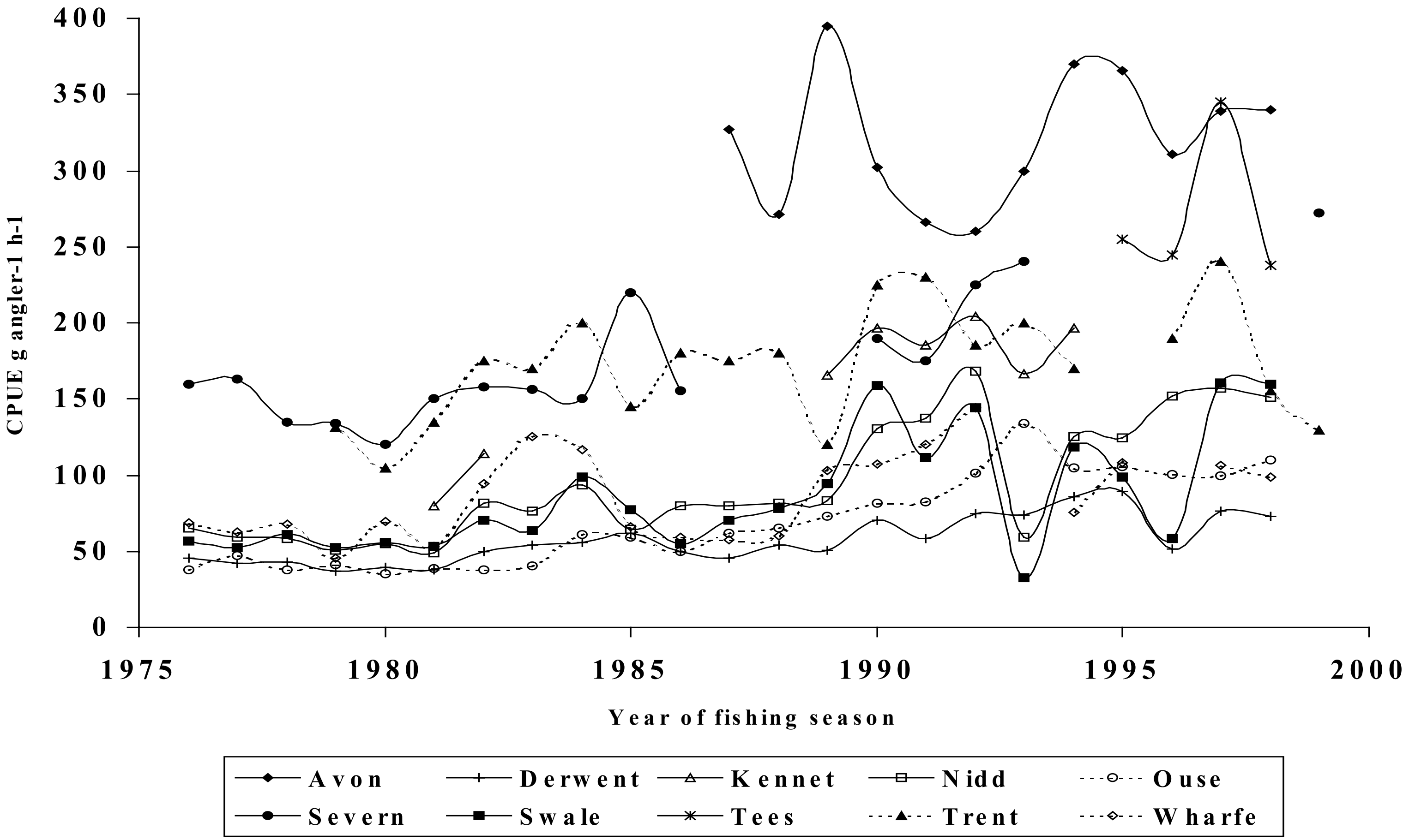

Figure 14 **Catch per unit effort (CPUE) for ten rivers expressed as g.angler^{-1} h^{-1} for various years over the period 1976–99 (Robinson *et al.* 2001)**

Angler catch data reveal annual fluctuations in catch rates across many rivers (Figure 14). It has been postulated that these fluctuations are related to variations in recruitment, yet this link remains speculative. If recruitment analyses and angler catch data are able to demonstrate that catch rates increase in years following the strong recruitment of key species, this provides the Environment Agency with a powerful tool to incorporate into its strategic decision making and fishery management activities. For example, it may demonstrate that recruitment processes are affected by a flood alleviation scheme and that the impact assessment should include cost-benefit analyses of the effects on angling. Similarly, endocrine-disrupting chemicals released from sewage works may affect fish recruitment and so the cost-benefit analyses of any scheme to reduce discharges of these chemicals should also include effects on angling.

There is, therefore, a strong case for the continuation of the FARRCoF work.

4. Moving the FARRCoF project into the next phase

4.1 Road map

The gaps in the Environment Agency's knowledge about coarse fish recruitment that were outlined in Section 3.3 suggest that further work is necessary to ensure that it is in a position to understand more clearly the recruitment processes of riverine coarse fish (Section 3.4). However, the extent of the knowledge gaps means that the overall problem is too complex to be treated as a single unit and that any research project should be broken down into suites of sequential, manageable components (Figure 15).

There are two routes by which this work can be completed. The research projects could be funded and completed separately on an ad-hoc and priority-based system, depending upon the finances available. Alternatively, they could run concurrently under a subsequent FARRCoF phase entitled 'Elucidating the critical factors affecting riverine coarse fish recruitment'. Irrespective of the route taken, it is recommended that collaborative parties be identified. This will promote the sharing of data, ideas and workload, and allow alternative funding streams to be explored, in conjunction with the sponsorship of post-doctoral and post-graduate positions.

4.2 Scoping the projects on the road map

In order to plug the identified knowledge gaps, the following research projects are proposed under the overall title of 'Elucidating the critical factors affecting riverine coarse fish recruitment'.

- Critical stages affecting survival of 0-group fish.
- Effects of parasites on 0-group fish growth and mortality.
- Relating recruitment success to life history traits.
- Roles of juvenile habitat and floodplain and flow management in the recruitment of coarse fish.

Each of these research projects is discussed in more detail below.

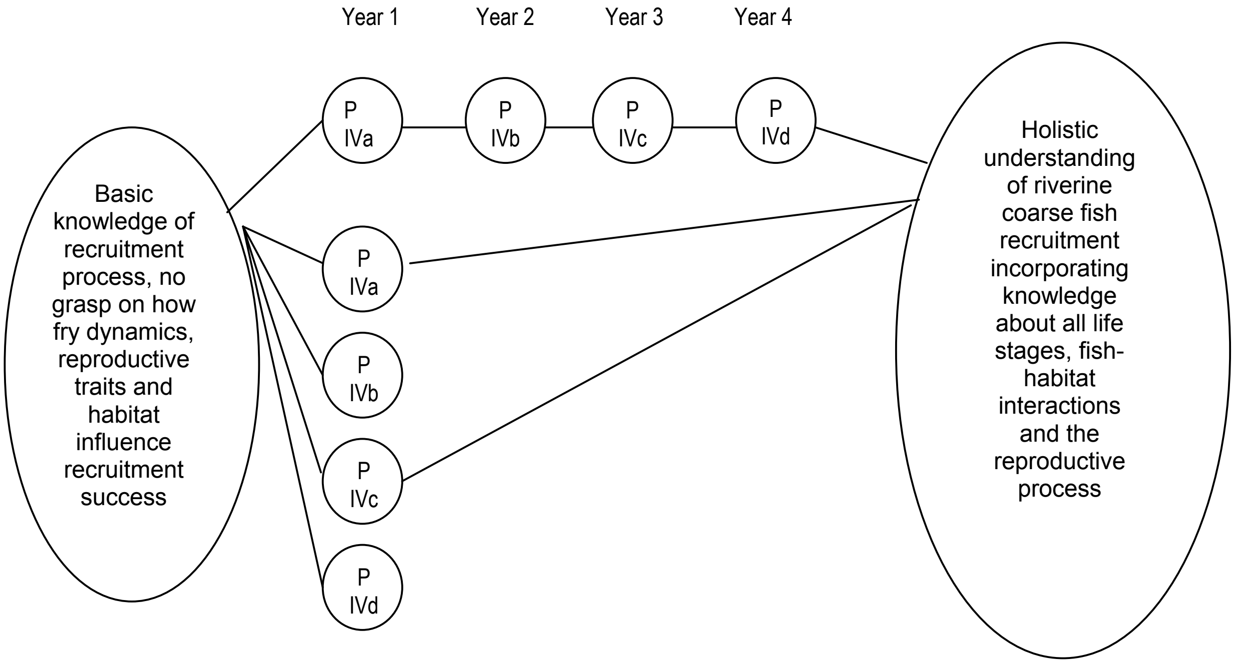

Figure 15 Road map to elucidate the critical factors affecting riverine coarse fish recruitment.

Key: P IVa: Critical periods affecting survival of 0-group fish and their recruitment.
P IVb: Effects of parasites on 0-group fish growth, mortality and subsequent recruitment.
P IVc: Relationship of recruitment success to life history traits.
P IVd: Roles of habitat and floodplain and flow management in the recruitment of coarse fish.

4.3 Critical stages affecting the survival of 0-group fish and their recruitment

Juvenile fish mortality is a major factor in determining the number of fish able to recruit into the mature stock. There are believed to be three principal factors associated with juvenile fish mortality:

- adequate food resources;
- achieving a sufficient size to reduce predation;
- achieving a sufficient size to over-winter successfully.

The growth of larvae involves the successful transition from the food resource of the yolk sac to external food. Therefore, it has been postulated that it is vital that periods of sufficient external food resources occur before exhaustion of the yolk sac(Cushing 1990, Garner 1996). Otherwise, food will be limiting, the growth of larvae will be poor and high mortality may result. This sequence of events is known as the food mismatch theory. Its importance has been recognised in the development of management practices at Calverton fish farm, where production of an abundance of suitable food is carefully timed to coincide with stocking of larvae into ponds.

The likely importance of this mismatch theory can be quantified by comparing the dietary intake of fry against available food resources. In the period of spawning/hatching/early development, the composition of the diet of 0-group fish needs to be assessed and compared with natural availability. The major areas for measurement are:

- abundance and size of available foods;
- optimal size of food in diet;
- food preferences;
- ontogenetic shifts in diet.

These data will enable the relationships between food availability, food intake, growth rates and health of fry to be ascertained, and allow the critical periods in fry development – when natural mortality rates are at their highest – to be determined.

Recent work has indicated that good recruitment of 0-group fish is not necessarily a consequence of achieving a critical size at the end of the growth season to avoid predation and successfully over-winter Correlations have been found between temperature, length achieved in the first year and YCS, which suggest that a critical size may exist (Mills and Mann 1985). However, it has become apparent that although temperature appears to regulate the growth of fry and their subsequent recruitment, it only provides a potential measure of recruitment. Discharge has been found to be a major factor affecting realisation of potential recruitment success (Nunn *et al*. 2003). In the River Tees, survival of 0+ dace and chub was far greater than expected on the basis of water temperatures after the installation of a barrage. This was perhaps related to reduced levels of displacement after barrage installation, caused by lower water velocities during cold, wet summers (Welton *et al*. 1999).

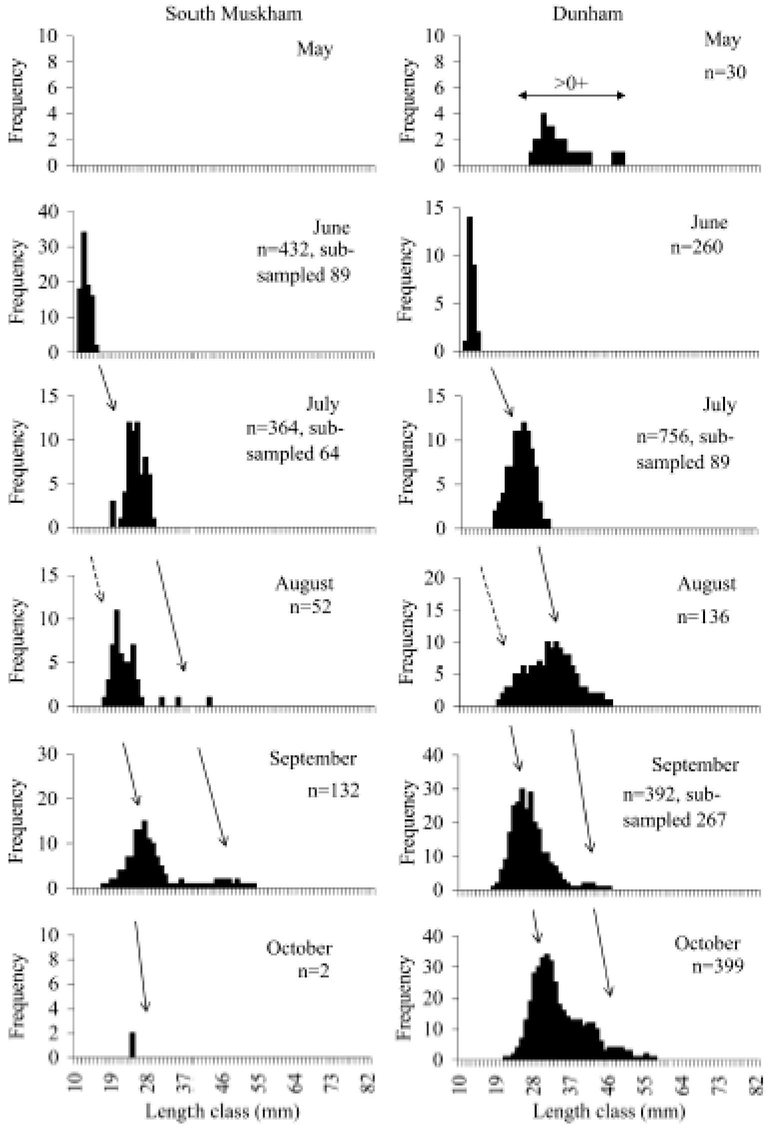

Figure 16 **Length frequency histograms by month for 0-group chub from the River Trent, showing the appearance of newly hatched fish between June and August (the result of batch or fractional spawning (Nunn *et al*. 2003)).**

A further indication of this complexity is the revelation of possible multiple spawnings by chub (Nunn *et al*. 2003). Fry samples taken monthly from the River Trent, Nottingham, showed a marked modality in lengths of chub at the end of their first growth year (Figure 16). This suggests that juvenile chub hatched at various times between June and August, although the modality might also be explained by other causes of differential growth, such as parasite infestations or migration from other areas. Back-calculation of adult scale samples has also indicated that individuals of less than 20mm in length are able to survive the winter period successfully (Figure 17), alongside larger individuals (Figure 18). However, the uncertainty of ageing means that some of these larger fish could actually be fish that were one year older but had not laid down a clear check at the end of their first year. Therefore, the concept of a critical size being necessary in order to survive the winter period may not be general amongst coarse fish in all rivers. Certainly, the mechanisms at present are not fully understood and require further study.

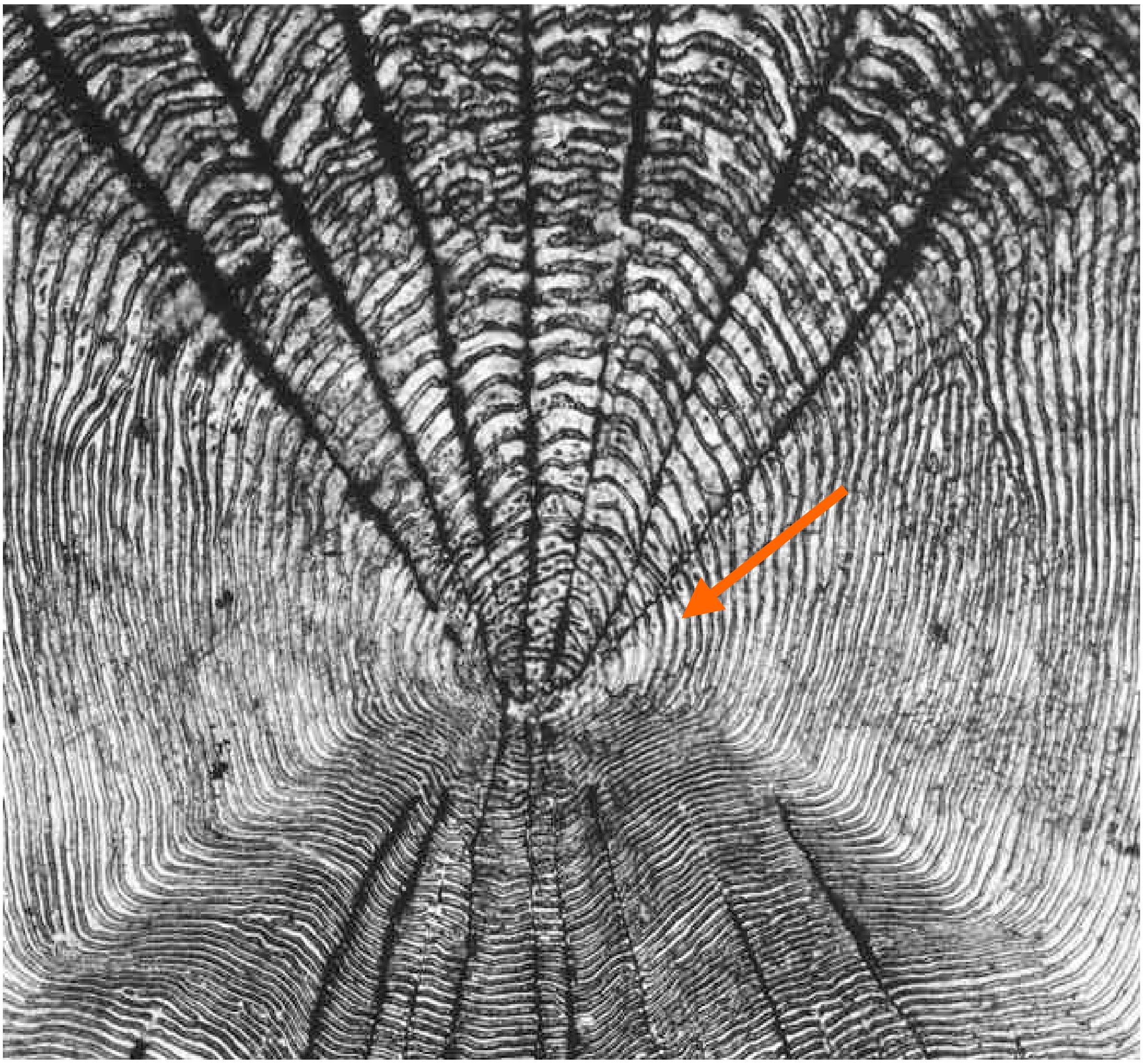

Figure 17.1 Close-up image of 1st annulus in chub from the River Trent showing small 1st year. Note: Arrow indicates the position of the 1st annulus.

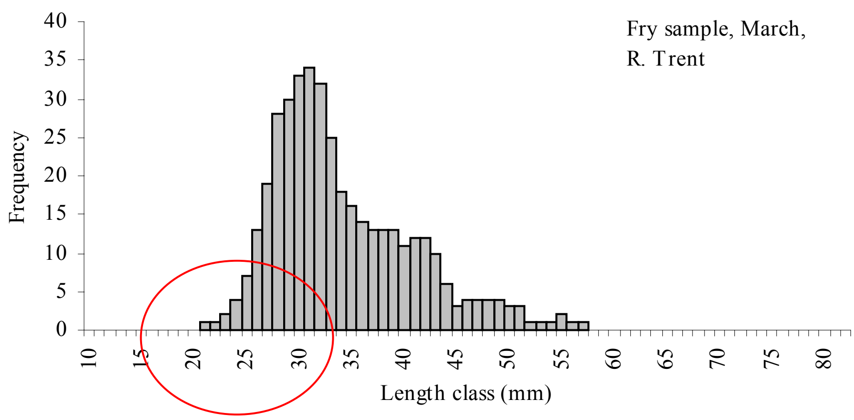

Figure 17.2 Length-frequency plot of chub fry from the River Trent.
Note: The circle indicates the likely length range this fish was in at the end of its first year.

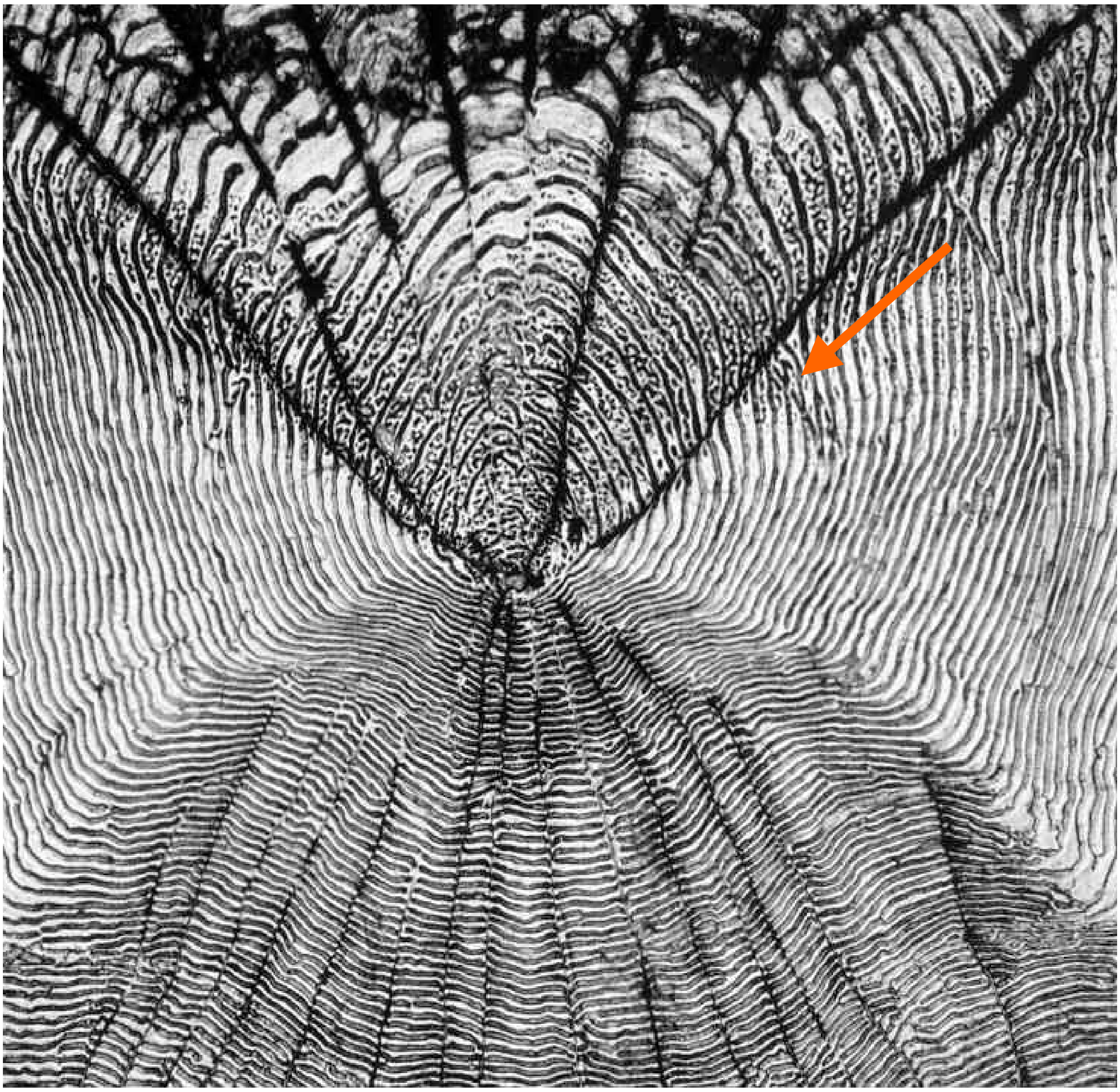

Figure 18.1 Close-up image of 1st annulus in chub from the River Trent showing large 1st year. Note: Arrow indicates the position of the 1st annulus.

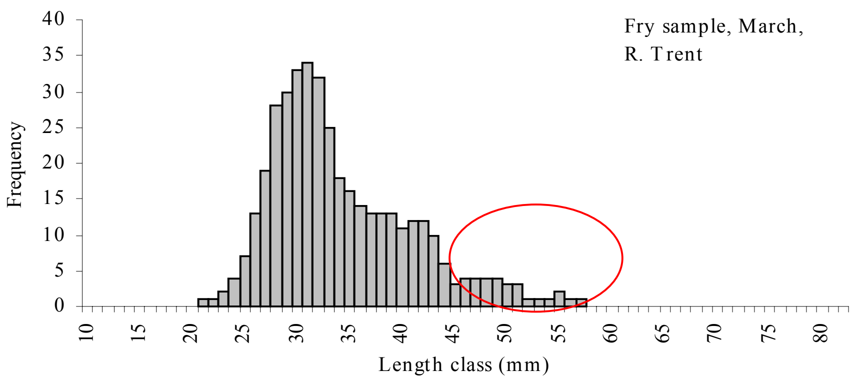

Figure 18.2 Length-frequency plot of chub fry from the River Trent.
Note: The circle indicates the likely length range this fish was in at the end of its first year.

A series of studies is required to improve understanding of all of these relationships. Data collection should be conducted using the same sites and cohorts as for the food mismatch theory, in order to elucidate further the critical periods of fry mortality.

Any study to identify the critical periods of coarse fish fry mortality should involve a range of rivers across England and Wales. It is suggested that the sampling regime should have the following characteristics:

- intensive – probably daily – sampling in all immediate post-hatching periods (20 days) for the major species of interest;
- fortnightly samples after this period until October;
- monthly samples in the winter period.

Juvenile habitat data should be collected at the same time in order to address questions relating to the role of habitat in the population dynamics of juvenile coarse fish. Complications are likely to arise in the sampling regime from the need for quantitative samples of fry numbers and changes in preferred habitats with size and season.

It will then be important to continue to monitor the population as the year class is recruited into the mature stock. This will allow YCSs as adults to be related to the factors studied over their first year of life.

Economic considerations, together with the ability to build on existing knowledge of coarse fish ecology, suggest that the sites used should be based upon the availability of existing baseline data. For example, fry samples have been collected monthly from a series of sites on the Yorkshire Ouse, River Trent and Warwickshire Avon since 1999. Other intensively monitored sites include the River Tees and the Suffolk Stour. These rivers should provide suitable sites for this project, although the rivers are mostly rather large for quantitative sampling of adults to determine YCS.

4.4 Effects of parasites on 0-group fish growth, mortality and subsequent recruitment

The FARRCoF Phase II report (Frear and Cowx 2003) details a number of studies completed in the 1990s on parasitic infections of 0-group fish. The following text has been lifted from the report:

'*Aspects of fish diseases affecting wild adult stocks are well documented and yet little work has focussed on the role of parasites and diseases at the critical fry stage. The CEFAS work described here indicates that coarse fish fry are infected at a very early stage in their development, with a range of potentially pathogenic parasites. One of the most significant of all these is* Myxobolus cyprini*, which is relatively widespread and abundant across species and rivers in Yorkshire. The incidence of infection has been 100 per cent in some populations, with chub appearing the most susceptible. The intensity of infection by several parasite groups is likely to lead to increased mortality (Feist* et al. *1997) suggesting this is another avenue of research to determine the significance of fish diseases in population dynamics. It should be noted that some of the highest infection rates of* M. cyprini *were observed in 1993, a cool, wet year which produced one of the weakest of all year classes, whilst infections* *were low or absent in 1995 in several rivers, when strong year classes were produced.*' (Frear and Cowx 2003).

This work on parasites has continued: 5000 fish having been collected between 1993 and 2002, incorporating 28 sites on 17 rivers (S. Feist personal communication). Clear spatial and temporal trends have been identified, although the reasons behind these trends have not been elucidated as yet. The presence of 40 parasite species has been identified across 0-group fish populations, with several believed to be of significance and concern. Chub was the worst affected species, followed by roach, minnow and dace. Most of the parasite infestations were transmitted via water rather than food. The annual mortality rates caused by the parasitic infestations were calculated as 0.4–0.9 for roach and 0.2–0.6 for chub (S. Feist personal communication), which could mean that parasites were the dominant factor determining recruitment success. Previous studies of the factors affecting recruitment on the same rivers suggested that temperature, discharge and the position of the North Wall of the Gulf Stream were the key factors in determining recruitment success. However, years with increased parasitic loading coincided with years of poor recruitment. This demonstrates that, although parasite loading might be a major cause of fry mortality, the mechanisms involved are likely to be complex and interrelated with environmental and biological conditions that leave the primary causes difficult to determine.

In addition to direct lethal effects, the parasite loadings are believed to have the following sub-lethal effects on the affected fish:

- organ dysfunction, including reduced fecundity in later life;
- reduced swimming speeds;
- poor escape behaviour;
- increased shoaling;
- increased susceptibility to depredation;
- increased possibility of being out-competed for resources by unaffected individuals;
- poor assimilation rates;
- reduced somatic growth.

For myxosporidian parasites, it is unlikely that there is a density-dependent link with host numbers, either in the fish or the oligochaete (worm) host. This is because the number of actinosporeans released from even a low number of oligochaetes is considerable and they will infect any fish present. The timing of the release of the actinosporeans in relation to the emergence and development of fish larvae may well be a key factor. As fry are vulnerable to myxozoan infection prior to ossification of their vertebrae, early spawning and development in relation to emergence of infective stages may result in low rates of infection. Equally, low rates of infection may result from late spawning, well after emergence of the actinosporeans.

It has been demonstrated that parasitic infections in the first year of life of a cohort can impact at a lethal and sub-lethal level. However, few rivers where fry abundance data are also available have been studied in detail, and the mechanisms of transmission and subsequent infection rates are not yet fully understood. It is recommended that further studies into parasitic infection, with the following enhancements, are conducted.

- An increased number of river catchments to increase geographical range.
- An increased number of fish species to gain an understanding of the host-specific and non-specific interactions.
- Key factor analysis to elucidate the role of parasites in determining recruitment success, as against environmental factors such as temperature and discharge.
- Development of models incorporating direct and indirect mortality rates, in order to examine how parasitic loading can influence recruitment under a range of environmental and biological conditions for different fish species. The PDM would be a useful way to integrate these aspects.

It is recommended that future work should tie in with the project 'Critical periods affecting the survival of 0-group fish and their recruitment'. This would help to ensure that samples are collected from the same sites and allow in-depth studies to be completed. These samples would be complemented by samples collected later in the growth season from a larger number of sites in the catchments, which would help determine the spatial component of infection.

It should also be remembered that fish diseases can have enormous effects on adult stock numbers at later stages. Outbreaks of roach ulcer disease in the late 1960s severely impacted roach stocks throughout England and Wales. In the River Nidd, Yorkshire, angler catch rates of roach in 1968 fell to an eighth of those in 1967 and took nearly a decade before starting to recover (Axford 1991).

Similarly, perch ulcer disease severely affected stocks in most of England and Wales during the 1970s. In Windermere, it is estimated that 98 per cent of the adult perch stock died during the 1976 outbreak, with the effects on recruitment persisting into the 1990s. Both biotic and abiotic factors were found to influence perch YCS in Windermere, but disease was the biggest single influence at age 2+ years (Paxton *et al.* 2004). Reductions in adult spawning stock could be great enough to affect recruitment via effects on population fecundity.

4.5 Relationships between recruitment success and life history traits

The projects outlined in Sections 3.5.3 and 3.5.4 deal with the dynamics of those larvae and fry already produced from a successful spawning event. In addition to understanding these aspects, it is important to understand what happens in the lead up to that spawning event, through the study of the reproductive traits of the adult fish. Reproductive traits are influenced by the trade-off between somatic growth, maintenance and gonad development in the life history strategy of both the individual and the population (Vila-Gispert and Moreno-Amich 2002). Despite the importance of this trade-off, there have been few studies that have evaluated variations in the reproductive bionomics, especially fecundity, of coarse fish species.

Cowx (1988) found considerable inter-annual variation in the fecundity and egg size of roach and dace of a similar size and age. It was suggested that this was linked to food availability and competition, but empirical evidence was not available to confirm this suggestion. In the River Frome, dace were found to show consistent relationships between ovary weight and fish length, and an inverse relationship between mean egg size and egg number, in most years. Fecundity and egg size both increased with fish length. However, egg sizes for fish of any particular length varied from year to year. Years of large egg sizes were related to good feeding and high somatic growth rates in the previous summer, apart from the exceptionally warm summer of 1976, when both egg size and number were low the following year (Mann and Mills 1985). Both Mann and Mills (1985) and Bagenal and Braum (1968) showed that larger eggs resulted in larger larvae, which were believed to result in higher survival rates compared with years when smaller larvae were produced. Mann and Mills (1985) showed that larger larvae survived starvation longer, which might be significant in the case of any mismatch with food availability, and would also be less vulnerable to invertebrate predators.

These issues need further work to enable better understanding of their role in riverine coarse fish recruitment. The reproductive bionomics of fish populations appears to vary between years, and this will probably influence the number and quality of eggs that are deposited.

Little is also known about geographical variations in fecundity. This can have direct implications for the development of each cohort because the starting population size (number of eggs deposited) and survival of the larvae (size of eggs) contribute to the recruitment dynamics of the population. Spawning stock numbers have been found to be an important explanatory variable for variations in the YCSs of perch in Windermere (Paxton *et al*. 2004).

The main issues that need addressing are the following.

- How important are stock sizes in determining recruitment?
- What are the factors that influence the reproductive bionomics of coarse fish?
- How do food and density-dependent interactions regulate the reproductive success of the population?
- How are these intertwined with life history traits?

Further complexity is added by the role of batch or serial spawning in the reproductive success of the population. It has long been thought that serial spawning is a strategy to ensure that at least a proportion of the eggs and larvae are laid and hatch under optimal conditions, in order to guarantee a contribution to the cohort development. How this influences YCS and sustainability of the population has yet to be identified, but it is a fundamental issue in the recruitment process that needs to be teased out.

Therefore, it is recommended that a study of reproductive success in coarse fish is carried out. This should begin with a literature review to provide a baseline of existing knowledge. Should this show that further work is needed to obtain a greater understanding of the role of the reproductive process in recruitment, then field and laboratory work should be incorporated into the study. As this may raise concerns about the effects of the loss of mature fish from a population in order to study their reproductive biology, it is recommended that only abundant species, such as roach, are used to provide baseline data in the first instance.

4.6. Roles of juvenile habitat, discharges and flood plain management in the recruitment of riverine coarse fish

Micro-habitat requirements

For the purposes of integrated river and fisheries management, it is vital to understand the critical factors that affect the distribution and abundance of juvenile coarse fish. Multivariate models have been developed that show different groupings of fish species, coinciding with classical upstream-downstream fish communities, and identify key environmental factors relating to these different groupings. Habitat Suitability Index (HSI) models have also been developed to determine the key habitat factors that limit the abundance of different species (Pinder *et al.* 1997). Although these models are crude, they can be used as a tool to provide an overview of the factors influencing the distribution and abundance of the main coarse fish species in lowland rivers.

Ultimately, the information will be useful for understanding the habitat and environmental factors that influence recruitment success. However, at present, these models do not account for seasonal variation in distribution and abundance or the habitat requirements for all life stages, and models generated for juveniles are generally poor or absent. The models are also not sufficiently robust to be used for management purposes. There is therefore an urgent need to upgrade these HSI models to support investigations into the critical habitat features that constrain coarse fish population recruitment.

Macro habitat evaluation

In addition to microhabitat preferences of juvenile coarse fish, a broader-scale approach is needed to identify macrohabitat needs, such as the importance of bays, tributaries, marinas and backwaters. These are key features that probably aid the overwinter survival of juveniles and also afford refuge during periods of inclement flow. Habitat enhancement schemes have been implemented to improve conditions for underyearling coarse fish, but there is little information about their effectiveness. In one of the few studies, Langler and Smith (2001) showed that there was a significant positive benefit of habitat manipulation in the Huntspill River for 0-group fishes.

Studies in this area should be intrinsically related to investigations on fish distribution and dispersal (National Rivers Authority 1995), although these would be difficult to assess. The basic aim should be to assess habitat usage under various environmental and climatic conditions. It will be necessary to undertake this work on a macro-scale, because long reaches of river need to be surveyed to show distribution patterns of juveniles in relation to key habitat features. To this end, boom-mounted electric fishing surveys over several kilometres of river are necessary if the study is to show distribution patterns. The sections of river selected must have a wide range of features, in order to discriminate between heavily utilised regions and those not occupied by juveniles. Change in habitat usage with season, particularly to avoid adverse flow conditions, is another factor that needs to be investigated.

These macrohabitat studies would complement the microhabitat studies and help to identify where sampling effort for the former should concentrate.

This type of study has intrinsic value for river management because rehabilitation measures usually target macroscopic changes in habitat (such as provision of backwaters and alteration of flow dynamics). It should also reveal the importance of lateral connectivity to side channels and off-river lakes in supporting recruitment to the catchable cohorts. This is a much-neglected area of research but fundamental to rehabilitation activities.

5. Conclusions and recommendations

Although comprehensive data sets on riverine coarse fish abundance have been compiled and developed by the Environment Agency and its predecessors since the 1970s, issues remain over the reliability of these data sets and their YCS outputs. The sources of error in the data that were suggested in FARRCoF Phase II (Frear and Cowx 2003) were partially corroborated by the outputs of Section 2 of this report. The original scale reading of one of the data sets used in Phase II was shown to be unreliable due to subjective interpretations of scale features, particularly for roach scales. Although the re-ageing of these scales completed in Phase III demonstrated marked variance with the original data and produced a different YCS output, the subjective element of scale interpretation in fish ageing could not be removed.

As a consequence of these problems, the conclusions drawn in FARRCoF Phase II, which were based upon the original ageing data, may not be completely valid. A re-ageing exercise carried out to ‘correct’ these data sets would be an expensive and time-consuming exercise. In addition, much subjectivity would remain due to the gaps between sampling episodes and the lack of information that might provide validation of scale annuli. Therefore, it is recommended that, at most, only a small number of those Phase II data sets providing time-series of sampling occasions in combination with good environmental data should be re-examined. These data sets have already been identified in Phase II (Frear and Cowx 1993). Furthermore, data collated in population surveys since 1998 can be added to these data, especially as the new data incorporate annual sampling. However, it is not suggested that another detailed scale re-ageing exercise should be conducted. Rather, these data should be run through the PDM (Wyatt *et al*, 2006), with assumptions made about ageing errors.

The development of the PDM has provided an alternative approach to the YCS models. It has allowed subjective scale ageing, as well as many other aspects of fish ecology, to be incorporated into the recruitment analysis and provided confidence intervals for these estimates.

The model should also be used with non-Environment Agency data sets. The Centre for Ecology and Hydrology holds data from long-term studies for the rivers Frome and Tees. These data could be used in the new model to provide an improved picture of recruitment trends, for use as an historical baseline. In the case of the River Frome, data are available on the fecundity and reproductive bionomics of the dace population, and this is an extra dimension that can be incorporated into the modelling process.

Completion of the recommended work should provide the Environment Agency with an improved understanding of some of the factors affecting coarse fish recruitment. However, the fact remains that most of this work is based solely on adult sampling. The data generated from this work are used to identify the strong/weak year classes within that adult population and then, by comparison with crude indices of water temperature and flow, to identify factors affecting those year classes as juveniles. This ignores a whole suite of factors that may have profound influences on coarse fish recruitment, but which have not been examined by the Environment Agency and its predecessors because of cost and sampling difficulties. However, unless opportunities are taken to study these factors, large gaps will remain in the Environment Agency's knowledge of coarse fish recruitment processes. This, in turn, may result in a failure to manage riverine coarse fisheries on the basis of sound science. It is therefore recommended that the following projects be initiated:

- critical stages affecting survival of 0-group fish;
- effects of parasites on 0-group fish growth and mortality;
- relationships between recruitment success and life history traits;
- roles of habitat and floodplain and flow management in the recruitment of coarse fish.

Fulfilment of these projects, as outlined in Section 4, would enable the Environment Agency to progress to a stage where the whole life history of coarse fish is taken into account when considering the recruitment process. This would ensure that a holistic overview of the recruitment process is developed and allow sound science to provide the basis for management decisions about coarse fisheries. It is recommended that collaborative institutions are identified and partnerships initiated, because the scope of the work is such that the Environment Agency would be unable to complete the programme without collaboration.

At present, the National Fisheries Monitoring Programme only encompasses the sampling of adult stocks, with minimal data collection on the biotic and abiotic factors that impinge on these populations. In order to ensure that future studies of the recruitment of coarse fish populations have access to comprehensive data on juvenile and adult fish and the factors that influence their development, it is recommended that the National Fisheries Monitoring Programme starts to incorporate the sampling of both juvenile and adult stocks.

Additional data collection should also be conducted for aspects such as habitat characteristics and site-specific flow and temperature regimes. Due to time and cost constraints, it is recommended that this be completed for only a small number of 'Index' rivers across England and Wales. This will generate data that can be developed into models that provide improved understanding of the temporal and spatial influences on fish abundance. This understanding can then be transferred to other catchments in England and Wales, where such intensive sampling is not deemed appropriate. This would greatly complement the project work already outlined.

In conclusion, the work completed to date by the Environment Agency on the factors affecting the recruitment of riverine coarse fish has been partially successful in identifying a range of factors that influence recruitment success. However, large gaps remain in the Environment Agency's knowledge and these must be filled if the FARRCoF project is to be considered successful in delivering its objectives. If the opportunity is not taken to complete this work, then the Environment Agency may not be able to deliver on its aim of managing river coarse fisheries on the basis of sound science.

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Published by:

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Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
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