

THE DYNAMICS OF EXPLOITED POPULATIONS OF SCALLOPS  
(*PECTEN MAXIMUS* L.) AND QUEENS (*CHLAMYS OPERCULARIS* L.)  
IN THE NORTH IRISH SEA.

Thesis submitted in accordance with the requirements of the  
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by

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## Note added in proof: change in nomenclature

In a recent revision of the family Pectinidae (Mollusca: Bivalvia), the queen scallop, *Chlamys opercularis* L. was reassigned to the genus *Aequipecten* (Waller, 1991). The new nomenclature appears to have been accepted, and the queen scallop has been referred to as *Chlamys (Aequipecten) opercularis* or *Aequipecten (Chlamys) opercularis* in recent publications (Ansell *et al.*, 1991; Beaumont & Barnes, 1992).

Much of this thesis, including the majority of the figures and tables, were prepared before Waller's (1991) publication became available, so the old name has been retained throughout.

## References.

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## ABSTRACT

Fisheries for *Pecten maximus* and *Chlamys opercularis* have existed in the North Irish Sea for 55 and 24 years respectively. Together, they form the most valuable fisheries on the Isle of Man. Since 1981 the stocks have been monitored using catch-effort statistics collected by the issue of logbooks to commercial fishermen, and by a programme of sampling the major fishing grounds to obtain age-structures and growth rates. Mark-recapture experiments have been used to obtain estimates of mortality rates. The catch-statistics, population age-structures, growth rates and mortality rates calculated in this work have been used for stock assessments, in order to provide advice on the management of the fishery. The spatial variability in dynamic processes is taken into account in the assessments.

Age-based assessment methods have been used throughout. Pectinids are aged by means of the growth rings on the shell, which are laid down annually and are clearly distinguishable in North Irish Sea pectinids.

Age-structures of *P. maximus* and *C. opercularis* differ spatially within the stock due to patchy recruitment, which generates non-random fishing activity. Inshore *P. maximus* fishing grounds are dominated by the recruiting year-class. Stock-recruitment relationships are difficult to elucidate, but low temperatures during the larval dispersal phase may favour recruitment.

The growth rates of both pectinid species vary spatially within the stocks. The von Bertalanffy growth equation provides a good fit to population length-at-age and weight-at-age data. Growth models which account for the seasonal oscillation in the weight of the edible portions of scallops have also been fitted.

Fishing mortality rates of *P. maximus*, estimated from mark-recapture experiments, are highest on inshore grounds to the west of the Isle of Man. Grounds further offshore and to the east of the Isle of Man were only lightly exploited in the period 1982-89. There was an increase in fishing mortality rate on all grounds between 1982 and 1983, but between 1983 and 1990, mortality rates were fairly constant. Estimates of natural mortality rate from tagging experiments are high, but will include incidental fishing mortality. A natural mortality rate of 0.12 is calculated from the relationship between exploitation rate and total mortality. Incidental fishing mortality exceeds natural mortality on some fishing grounds.

Mark-recapture experiments were tested as a means of estimating mortality rates in *C. opercularis*. The first of two releases resulted in very few returns due to the low visibility of the tag. When the experiment was repeated with a more visible tag, an exploitation rate of 25% was obtained from a single fishing season. Tagging appears to be an appropriate method of studying the dynamics of this species.

Catch-rates of *P. maximus* have been declining since 1983. A Yield per recruit assessment of the stocks indicates that fishing mortality on inshore grounds exceeds that which is likely to be sustainable. Fishing effort on inshore grounds should be cut by up to 60% to maintain a stable, viable fishery on those grounds. Offshore grounds were under-exploited in 1987-89, but are likely to be fully exploited now. In order to allow stocks to recover, additional conservation measures are required. A restricted licensing scheme is proposed.

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## INTRODUCTION

In October 1981, the Isle of Man Board of Agriculture and Fisheries commissioned a study by the Port Erin Marine Laboratory into the population dynamics and fisheries for scallops (*Pecten maximus* L.) and queen scallops (or 'queens': *Chlamys opercularis* L.) in the North Irish Sea. This study was financed in response to concern within the fishing industry that the stocks were in danger of collapse, and in need of additional management control. The collection of detailed catch-effort statistics from the fishing fleet was initiated in order to monitor changes in both the fleet and the exploited stocks. Much research effort was also channelled into obtaining the biological information necessary for management of the stocks (growth and mortality rates, population age structures and recruitment variability).

The research programme was designed to investigate spatial variations in stock abundance and population dynamics. The spatial variability in recruitment, growth and mortality has been shown to be important in determining the pattern of exploitation of sedentary or semi-sedentary shellfish stocks (Caddy, 1975; Allen, 1979; Sluczanowski, 1984; Murawski & Fogarty, 1986; Orensanz *et al.*, 1991) and must therefore be taken into account in assessments to provide better advice for management.

Initially, the research programme focused on *Pecten maximus*, and a detailed report on the findings of the first three years of research into the fishery and population biology of this species was prepared by Murphy (1986). The importance of continued monitoring of the stocks has been recognised by the Manx Government, and the research programme has been maintained and expanded in recent years to include studies on the biology and fisheries for the queen scallop, *Chlamys opercularis*, and the possibility of enhancing scallop stocks through a re-seeding programme (Brand *et al.*, 1991a).

The work described in this thesis includes the collation and analysis of fishery statistics for the period 1980 to 1990, the results of the biological sampling programmes undertaken between January, 1987 and November, 1989 and analysis of mark-recapture experiments carried out in 1982-83 and 1987-89. The work on *Pecten maximus* biology is necessarily an extension of Murphy's (1986) studies, and the work on *Chlamys opercularis* initiates a data collection programme on this species. This study is part of an on-going research programme, so the data from previous studies have been included where appropriate. Reviews of previous



research on these stocks, a history of the fishery, descriptions of fishing and processing methods and an outline of the current fishery legislation are given below, to put the present study in context.

### **Research on North Irish Sea Pectinids**

This thesis is the latest contribution of the Port Erin Marine Laboratory to studies on the Pectinidae of the North Irish sea; the abundance of these molluscs and the subsequent development of important fisheries for *Pecten maximus* and *Chlamys opercularis* have focused the attention of biologists in this area on this group of animals since early last century, when the presence of *Pecten maximus* and *Chlamys opercularis* around the Isle of Man was first reported by E. Forbes, the Manx naturalist (Forbes, 1838; 1839; Forbes & Hanley, 1853). A monograph on *P. maximus* and *C. opercularis*, the largest and most widely distributed pectinid species in the locality, was produced by Dakin (1909), and as part of a study of the evolution of the genus *Pecten*, Davenport (1903) examined variability in the shell morphology of *Pecten (Chlamys) opercularis* from different localities in the British Isles, including the Isle of Man. Jones (1941; 1950) described the importance of these species in the subtidal soft-bottom benthic community around the south of the Isle of Man.

With the start of the commercial fishery in 1937, the requirement for studies on the biology of *P. maximus* prompted Tang (1941) to study the reproductive cycle (concluding that the main breeding season was April-May) and growth rate and age structure of the fished population, while Smith (1938; 1940; 1943a; 1943b; 1944; 1946) collected landings statistics from the developing fishery. A mark-recapture experiment (Mason & Colman, 1955) and an assessment of the state of the fishery (Mason, 1959a), showed that exploitation rates were high on the grounds off Port Erin, while studies on the age structure and growth rate (Mason, 1957) and histological investigation of gonad structure and the reproductive cycle (Mason, 1958a; 1958b) made valuable contributions to knowledge of local stocks and remain important contributions to the study of the biology of this species. Mason's thesis (1953), from which the above publications are derived, also included a useful review of contemporary local fishing and marketing practices, and a study of meat yield and food value of the scallop and its seasonal variation (Mason 1959b).

Mason's observation that young scallops were scarce on the commercial fishing grounds led Eggleston (1962) to search intensively for spat, finding them bysally attached to erect hydroids and polyzoans, suggesting the importance of these substrates for attachment prior to settlement on the seabed sediments.

Research on the biology of the other pectinid species found in the North Irish Sea was also being carried out (Aravindakshan, 1955; Reddiah & Williamson, 1958; Reddiah, 1959; 1962) with an emphasis on the study of reproduction.

Fishery investigations on scallops continued with A. B. Bowers' mark-recapture experiments to determine exploitation rates (reported in Colman, 1956; 1957; 1958; 1959) and an analysis of the activities of the commercial fleet (Bowers, 1967). Concern for the state of the stocks (Gruffydd, 1967) prompted the I.o.M. government to fund a search for new scallop grounds (Gruffydd, 1966), with the data from this survey proving useful in estimating natural mortality rates (Gruffydd, 1974a) and the effects of depth and substrate type on growth patterns (Gruffydd, 1974b). A further mark-recapture experiment yielded contemporary estimates of exploitation rate and fishing mortality (Gruffydd, 1972).

In 1969 a fishery for queen scallops developed (Colman, 1969) and a requirement for information on commercially relevant population statistics was met by the work of Soemodihardjo (1974) on distribution, biometry and reproductive biology. A survey to locate stocks of queens was also undertaken off the Northern Ireland coast, without success, by Watson (1973). Queens have since been found to be fairly abundant in Strangford Lough. Large stocks of queens are also present off the north coast of Anglesey, and to the north of the Isle of Man and in the Solway Firth (Mason, 1983).

With the Island depending increasingly on its pectinid fisheries, the importance of maintaining continuity of supply and the possibility of enhancing the stocks justified investigations into the aspects of the biology of scallops and queens relevant to their cultivation, such as spat collection, post-settlement mortality, early growth, and temperature and salinity tolerance of *Chlamys opercularis* spat (Paul, 1978; 1980a; 1980b; 1981; Brand *et al.*, 1980; Paul *et al.*, 1981) and predation on *Pecten maximus* by the common starfish, *Asterias* spp. (Briggs, 1983).

Since 1981, studies have focused on the investigation of spatial variations in growth, population structure, mortality and recruitment (Murphy, 1986; Murphy and Brand, 1992; Duggan, 1987) with a view to incorporating the spatial variability in stock assessment models (Murphy & Brand, 1987). Temporal and spatial variations in settlement and recruitment of pectinids have recently been investigated by using artificial spat collectors to establish settlement times and settlement variability (Duggan, 1987; Brand *et al.*, 1991a), and biochemical genetics have been employed to elucidate larval origins (Macleod *et al.*, 1985; Duggan, 1987; Lewis, 1992). Much of the research on population genetics of these stocks has been undertaken by scientists at Menai Bridge (reviewed in Beaumont 1991, and Beaumont & Zouros, 1991). From this work emerges the general conclusion that genetic differentiation within the North Irish Sea stocks is low in both *Pecten maximus* and *Chlamys opercularis*. These findings have recently been called into question by Lewis (1992), whose intensive study of *C. opercularis* suggested that genetic differences exist between populations to the east and west of the Isle of Man.

The North Irish Sea scallop and queen stocks are also exploited by fleets from the surrounding nations (N. Ireland, Eire, Scotland, Wales and England) and population and fisheries studies have been carried out on the Northern Ireland stocks (Stanley, 1967; Briggs, 1980; 1987; 1991) the North Irish Sea queens landed by the Scottish fishing fleets (Mason *et al.*, 1979; Mason, 1983) and the queen fishery based in England and Wales (Rolfe, 1973).

On-going research programmes at Port Erin include studies on the commercial feasibility of rotational closed area management, together with artificial restocking, as a management option for the scallop fishery (Brand *et al.*, 1991a) while a related study considers the effect on scallop population dynamics and benthic community ecology of closure of a previously heavily fished ground. Biochemical genetic studies on larval origins and the genetic variability of *Chlamys opercularis* and *Pecten maximus* stocks continue, as does basic research into the physiology of scallop feeding and respiration, and reproductive patterns. All these studies are providing information complementary to the findings in this thesis, and will be useful in determining assessment methods and management strategies for these fisheries.

## The history of the fishery

There has been an important fishery for the great scallop, *Pecten maximus*, based on the Isle of Man, for more than 50 years. For the last 20 years the queen scallop, *Chlamys opercularis*, has also been heavily exploited. These two species are prominent members of the benthic fauna and their wide distribution and abundance in the North Irish Sea is recorded in many early faunal surveys of the area (Forbes, 1838; Darbishire, 1886; Herdman, 1886; 1895).

Directed fishing for *Pecten maximus* began in the Isle of Man in October 1937, when a visiting Irish fisherman alerted local fishermen to the commercial possibilities of the dense beds of scallops off Bradda Head (Smith, 1938). At this time scallops were already being exploited in the English Channel (Baird, 1952; Franklin *et al.*, 1980a), France (Priol, 1930) and Ireland (Baird, 1952; Gibson, 1956). Exploitation in Scotland also began in the late 1930's (Mason & MacIntyre, 1963; Mason, 1983).

Queen scallops were fished in Scotland and England, and probably also in the Isle of Man, much earlier than scallops, for between the 1880s and the 1920s they were used mainly as bait in long-line fisheries for cod or for local consumption (Fullarton, 1888; Mason, 1983). The early history of scallop fisheries in the British Isles is reviewed by Mason (1983).

During the pre-war years, scallops were commercially valuable to the Manx fleet but were only fished by a small number of vessels. The Isle of Man fishing industry at that time was largely dependent on landings of herring by visiting fleets (Smith, 1940). For example, in 1939, only 8 boats fished for scallops, out of a total of 56 Manx registered vessels but they earned 43% of the value of landings by Manx vessels. However, the Manx fleet accounted for only 32% of the total value of fish landed in the Isle of Man during that year. In contrast, during 1987, scallops and queen scallops together made up over 95% of the value of fish landed in the Isle of Man, 55 out of 68 Manx registered boats fished for them and landings of fish by non-Manx vessels were negligible.

The various interrelated factors that influenced the development of the scallop and queen fisheries have recently been reviewed by Brand *et al.* (1991b), and other historical accounts of these fisheries can be found in Mason (1953; 1983), Soemodihardjo (1974) and Murphy (1986).

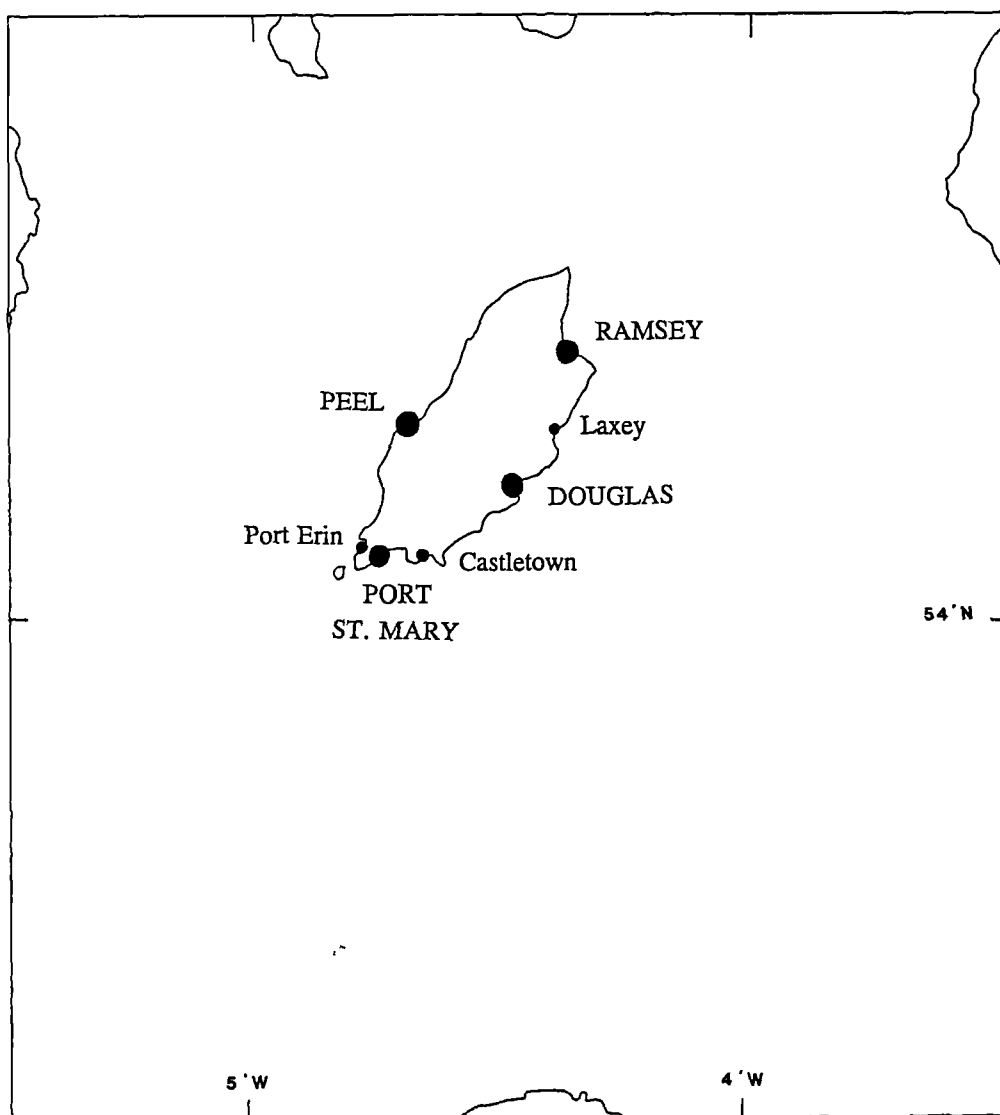
Between 1937 and 1955, the scallop fishery remained a localised small-scale fishery, involving between 9 and 14 boats, fishing during the winter months off Port Erin, Peel, Ramsey and Douglas (Fig. 1). The fleet size doubled between 1962 and 1969, as new grounds were discovered to the south and east of the Isle of Man, and shore-based processing facilities developed to supply new European markets for fresh and frozen scallop adductor muscles ('meats') and gonads ('roes').

In 1969 the fishery for queen scallops started, with the queens at first fished during the summer closed season for scallops. Various types of gear were used to catch queens (Mason, 1983; Brand *et al.*, 1991b); the current fishery uses two types of gear, spring tooth-bar scallop dredges and otter trawls. These trawls are similar to groundfish nets, with heavier bobbin wheels or rock-hoppers on the groundline, and are usually between 8 and 13 fathom headline length (described in Chapman *et al.*, 1979). The doors are generally attached to the mouth of the net but bridles are sometimes used to increase the fish by-catch.

The success of the queen fishery in the early 1970s prompted fishermen to invest in larger vessels, usually second-hand Dutch beam-trawlers, which could tow a wider spread of gear and handle the large, heavy dredges used for queens. Fleet size and overall fishing capacity continued to increase through the 1970s and has since fluctuated at between 50 and 70 boats, all between 10 and 30 metres long.

Spring tooth-bar dredges, described by Chapman *et al.*, (1977) and Mason (1983) were introduced in 1972 and used in both the scallop and queen fisheries. These were thought to increase efficiency by reducing the tendency of the dredges to fill with rocks and preventing the gear coming fast on boulders but tests by Chapman *et al.* (1977) suggest that this gear is no more efficient than the standard fixed tooth bar dredge.

Since 1980/81, the Manx fleet has switched to fishing for scallops with small 2'6" (0.83 m) or 2'0" (0.75m) spring tooth-bar dredges, fished in 'gangs' from a heavy steel pipe on large solid rubber rollers. These smaller dredges are thought to follow the bottom contours more closely than larger dredges, hence spending more time on the seabed (Howell, 1983). They are considered by fishermen to be more efficient on the rough ground which predominates around the Isle of Man but this can not be substantiated as most gear comparison studies to date have been carried out on clean hard sand (Mason, 1970; Chapman *et al.*, 1977; Mason *et al.*, 1979a). The small dredges are also rigged to fish for queens



**Fig. 1.** Map of the Isle of Man showing the position of the fishing ports. The four major ports are labelled in capital letters.

by shortening the teeth and fitting smaller ring-diameter bellies (Mason, 1983; Brand & Allison, 1987).

Recent poor catches and unfavourable market conditions, especially for queens, have led to some fleet reduction from a maximum of some 70 boats in 1983/4, to about 48 fishing actively in 1990. *At the time these studies were completed, the fleet consisted mainly of boats less than 15 m in length as stocks could no longer support the catches required by larger vessels. More than half the boats in the fleet were over 20 years old and there had been no investment in new boats since 1981. During the last two years, however, some of the more successful fishermen have purchased newer, larger vessels, with a view to competing with recently commissioned purpose-built scallopers fishing from Kirkudbright. These vessels also give skippers the flexibility to fish scallop and queen grounds off Scotland, the north-east coast of England and the Channel, as well as the ability to switch to other fisheries, primarily for groundfish. This investment in updating the Manx fleet has been supported by grants for vessel purchase by the Isle of Man Industry Board.*

### **Processing and marketing**

Scallops are hand-shucked in shore-based processing factories, located in the ports of Peel, Port St. Mary and Douglas. There is no auction for scallops or queens in the Isle of Man, each boat supplying one or two processing factories by private agreement. The fishermen are paid according to the weight of shucked meat and roe obtained from their catch. Shuckers are also paid piece-work rates; the rate of pay per unit weight depending on the meat count (number of meats per pound). Eight processing factories currently operate, and fresh scallop meat (including the roe) is air-freighted to Belgium and France.

The fleet expansion which occurred in the 1960s, partially as a result of improved processing and new markets and was maintained in the 1970s by the start of the north Irish Sea queen fishery, which itself followed the discovery of a U.S. market for frozen queen adductor muscle meat by the Scottish industry in 1968 (Mason, 1983). The presence of processing facilities on the Island allowed an important fishery for queens to develop within one year. Previously queens had been discarded when caught in scallop dredges. In this early period, several of the factories purchased shucking machines to cope with gluts in queen landings.

The strength of the U.S. market in the early 1970s has not been maintained in recent years, although some queens are still sent there at minimal profit to alleviate over-supply and to maintain marketing links. After a period of poor catches and prices the market for queens recently showed some signs of recovery with the establishment of a new outlet for fresh roe-on queens in Europe ( Mason, 1983; Brand & Allison, 1987). This change in market caused a return to hand-shucking of queens, since machines cannot supply a roe-on product. However, prices and catches have not been adequate to support the fleet. Attempts to diversify to other fisheries during the last few years were largely unsuccessful and several boats have recently been sold. Some small-scale processing of white-fish, *Nephrops norvegicus* and crabs takes place, mainly for local markets. Kipper-smoking is also declining as a local industry, with only one kipper curer remaining in business.

## **Legislation**

The Isle of Man is independent of the U.K. Government and this has allowed it to implement its own fisheries policy. Since the 1927 Fisheries Act, the Isle of Man Government has had sole jurisdiction over a three-mile territorial sea. The 1927 Act gave the Isle of Man Government the right to grant permits to fish within the 3-mile limit and restricted permits to vessels under 50 ft in length. The Isle of Man has recently (July 1991) negotiated successfully for an extension of territorial limits to 12 miles, but does not have jurisdiction to make legislative changes unilaterally in the zone between 3 and 12 miles. The right to make unilateral decisions within three miles remains, however. This has recently been exercised by the closure to dredging and trawling of an experimental area of 1 km<sup>2</sup> within the Bradda Head scallop fishing ground - nominally from March 1989, but in practice the regulations was not enforced until early 1991.

An annual closed season for scallop fishing within the 3-mile limit has been imposed almost since the inception of the fishery and has remained in operation ever since, with several slight modifications in the dates: it currently extends from 1st June to 31st October inclusive. A minimum landing size of 4<sup>1</sup>/<sub>2</sub> inches "across the broadest part of the shell" was also stipulated in the same fisheries act. Again, the size limit still operates, although since metrification in 1976 it has been reduced slightly to 110 mm shell length. In 1976 the closed season legislation was reinforced to prohibit not only the catching and landing of scallops but also their



possession or importation into the island or its territorial waters. A further clause, introduced in 1963, makes it illegal to land scallops which have more than 20% spawned individuals in the catch. This occasionally restricts fishing in some areas during the spring spawning period (April/May).

In 1984 and 1986, reciprocal legislation was adopted by the U. K. Government, so that the same closed season and minimum legal landing size of 110 mm now operates throughout the whole of ICES area VIIa (apart from Republic of Ireland territorial waters).

No regulations exist to restrict queen fishing, other than the law prohibiting boats more than 50 ft (15m) long fishing within the three-mile limit. However, processors do not usually accept catches that contain a high proportion of queens below 55 mm shell height, a size reached at age 14-18 months in most fishing areas. Most of the boats have a mechanical sorter on board so that small queens are returned to the seabed. Processors may also impose weekly quotas on their contracted boats, depending on catches and market demand.

In January, 1992, an industry-led conservation measure was introduced to reduce fishing effort within the 3-mile limit; the spread of scallop dredges was limited to 12' 6" (3.81 m) fished off each beam. In practice this means 4 or 5 dredges each side. This small spread of gear is generally only towed by boats less than 40' (12.2 m) long. The gear restriction also applies to dredging for queens within the 3-mile limit. Technical difficulties with interpretation of this law have been encountered, and it is currently being redefined to fulfil its original objectives.

Fishery regulations were enforced by the British Navy Fisheries Protection fleet until 1987 when the Isle of Man acquired its own small inshore protection boat. Policing the 3-12 mile zone is the joint responsibility of the British Navy and the Isle of Man. Recent reduction of patrol duties by the British Navy fleet and the unsuitability of the Manx vessel for offshore patrol work have led to complaints that the current level of enforcement activity in the area is inadequate. The closed season and minimum size regulations are also enforced through spot-checks of processing factories on the Isle of Man. As the scallop fisheries are less important to the other nations surrounding the Irish Sea, less effort is directed towards enforcing scallop fishing legislation in Scotland and the U.K. than on the Isle of Man.

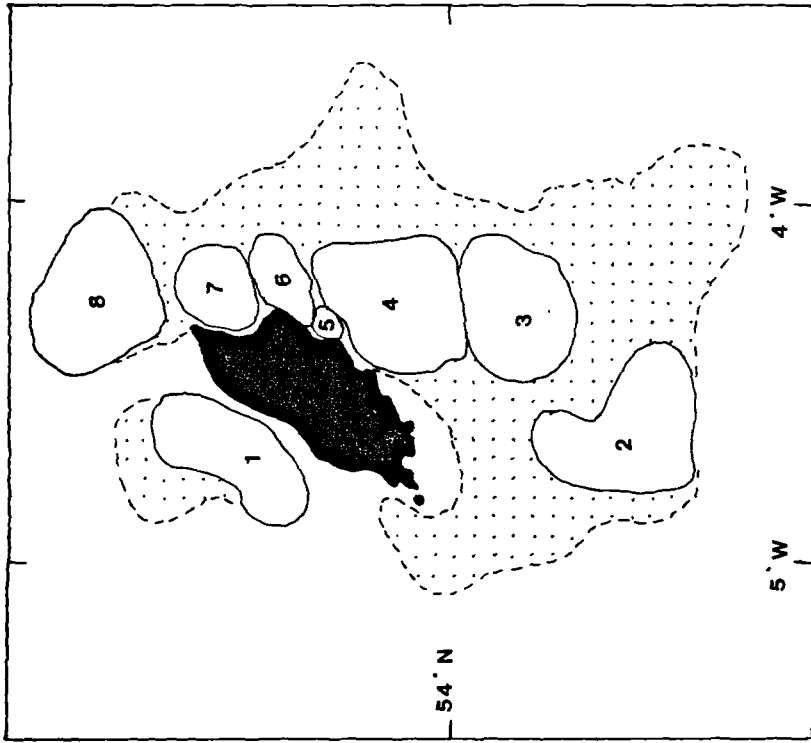
## Catch statistics

The review of Brand *et al.* (1991b) details the changes in the exploited stocks of scallops over the last 54 years. The history is a familiar one of initial high catch rates by a few vessels attracting an increasing number of boats, with the grounds quickly showing signs of growth overfishing and decline in catch rates due to the 'fishing down' of the virgin stock. As the fishery developed and the number, size and power of the boats increased, new scallop beds were discovered and the area exploited extended farther offshore, now covering much of the North Irish Sea (Fig. 2a). The start of the queen fishery in 1969 was also a major influence on the exploitation of new scallop grounds. The two species coexist in many areas, so scallops have subsequently been fished on grounds where they occur in densities which would not be viable, if it were not for the lucrative queen by-catch (or queen main catch and scallop by-catch, depending on their relative abundance). Queens are fished mainly off the Point of Ayre, east of Douglas, south of Port St. Mary and on the Targets (Fig. 2b). These are all areas which were already being fished in 1972-74 (Soemodihardjo, 1974).

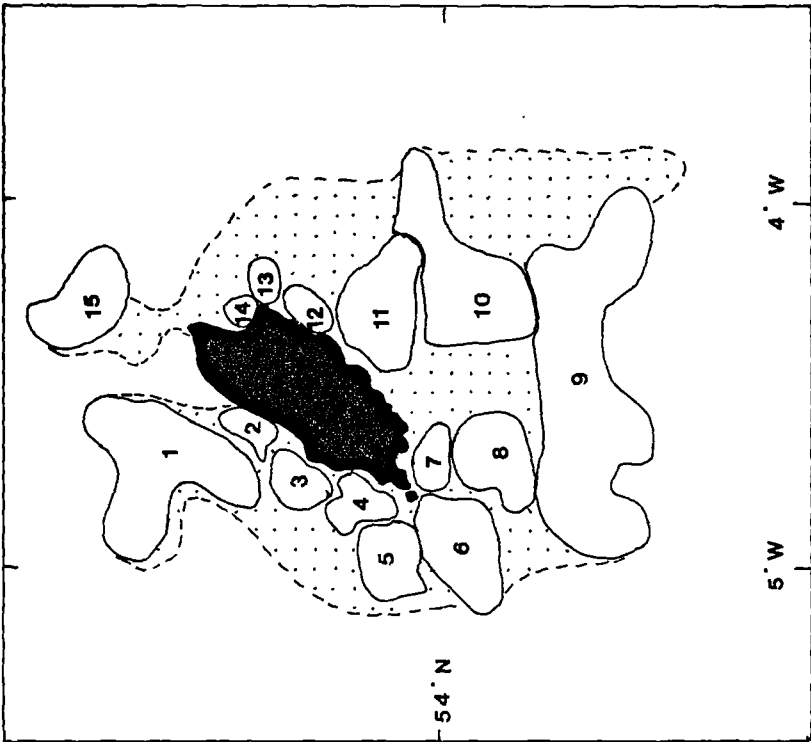
Between 1937 and 1948, annual catches of scallops were between 20 and 228 tonnes liveweight. Unfortunately, no records of catches are available for the major phase of fishery development in the late 1950s and early 1960s although total catches in 1958-9 and 1965 can be estimated from a sample fleet analysis (Bowers, 1967) to have been about 1 100 t and 1 700 t respectively.

Since the start of the queen fishery in 1969, the Isle of Man government has collated total catch and first-sale value statistics (Figs 3a & 3b). The queen fishery initially took place in the closed season for scallops (May - October), but proved so profitable that the majority of boats continued to fish for queens throughout the winter the following year. With high catch rates from previously unfished stocks, the fishery developed very rapidly and annual catches reached a maximum of 7 627 t in 1972. This diversion of effort to queen fishing resulted in a decline in scallop catches from 1 369 t in 1969 to 472 t in 1972. Queen catch rates then declined from the initial very high levels and a shift in market demand caused a return to scallop fishing in the winter months, while the sudden revival of the Manx herring fishery in 1977-79 diverted fishing effort away from queens in the summer months. Annual catches of queens thus fell rapidly to 2 192 t in 1977 and scallop catches increased again. Over the last 12 years scallop catches have

**Fig. 2b** *Chlamys opercularis*



**Fig. 2a** *Pecten maximus*



**Fig. 2a.** North Irish Sea *Pecten maximus* fishing grounds. Numbered areas bounded by solid lines are the major fishing grounds, hatching and shading indicates areas where scallops occur and are occasionally fished. All boundaries are approximate - many grounds are contiguous.

Fishing ground names are:

- 1 The Targets
- 2 Kirkmichael Bank
- 3 Peel Head
- 4 Bradda Head
- 5 Offshore Bradda/West Calf
- 6 The Chickens
- 7 Port St. Mary Inshore
- 8 Port St. Mary Main
- 9 H/I Sector & Offshore South
- 10 Southeast Douglas
- 11 East Douglas
- 12 Laxey Bay
- 13 Maughold Head
- 14 Ramsey Bay
- 15 Point of Ayre

**Fig. 2b.** North Irish Sea *Chlamys opercularis* fishing grounds. Numbered areas bounded by solid lines are the major fishing grounds, hatching and shading indicates areas where scallops occur and are occasionally fished. All boundaries are approximate - many grounds are contiguous.

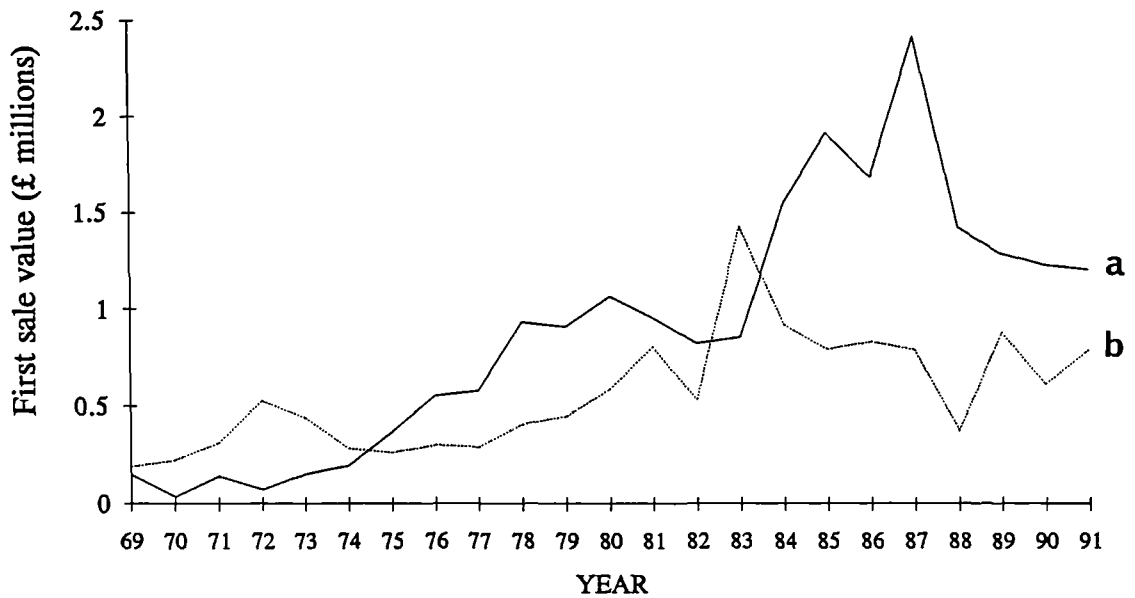
Fishing ground names are:

- 1 The Targets
- 2 H/I Sector
- 3 Southeast Douglas
- 4 East Douglas
- 5 Laxey Bay
- 6 Maughold Head
- 7 Ramsey Bay
- 8 Point of Ayre

**Fig. 3a.** Landings of a) *Pecten maximus* and b) *Chlamys opercularis* to the Isle of Man, 1969-91. Data from the Isle of Man Department of Agriculture, Fisheries and Forestry.



**Fig. 3b.** First sale value of a) *Pecten maximus* and b) *Chlamys opercularis* landed to the Isle of Man, 1969-91. Data from the Isle of Man Department of Agriculture, Fisheries and Forestry.



remained fairly constant at between 1 300 - 2 000 t. Queen catches have been more variable at 2 000 - 6 000 t, with the recent decline due largely to a reduction in effort resulting from poor market demand. Queens are still fished by the majority of boats during the scallop closed season as alternative fisheries have not proved viable.

The total value of the catch of queens peaked in 1983, and that of scallops in 1988. Since then, there has been a steady decline in the value of landings of both species (Fig. 3b). Apart from the large earnings from herring in the late-1970s (which was landed mostly by visiting boats), the Isle of Man fishing industry is mainly dependent on scallops and queens. These fisheries now account for some 95% of the first sale value of all fish landed in the Island and, after processing, constitute a very valuable export industry.

The stocks of scallops and queens within the North Irish Sea are also subject to exploitation by other fleets - mainly from the ports of Kirkcubright, Fleetwood, Holyhead and Portavogie. Little data is available on the activities of these fleets; only total catches are known with any certainty, and are analysed in Chapter 6.

The catch data by themselves give little information on the effect of fishing on the stocks, but fragmentary data on stock abundance, age composition and mortality rate are available over the whole history of the scallop fishery. Increasing exploitation over the last 54 years has resulted in reduced scallop abundance, low catch per unit effort, high fishing mortality and the depletion of the older age groups. For many of the main inshore fishing grounds there is evidence of growth overfishing, with the success of the fishery each year highly dependent on the strength of recruitment (Brand *et al.*, 1991b).

Few data are available on abundance of queen stocks prior to 1981, although a survey by Soemodihardjo (1974) in 1972-4 investigated the distribution and regional variation in population parameters of queens around the Isle of Man and gained some insight into their relative abundance. The areas which Soemodihardjo (1974) found supported the highest catch rates per 15 minute dredge haul are still the main commercial queen grounds today.

## Research programme design

The objectives of the research programme were to provide estimates of catches, fishing effort, growth rates, mortality rates and population structures for input into stock assessment models of the scallop and queen fisheries. As population parameters have been shown to vary spatially within scallop stocks (Orensanz *et al.*, 1991, for review) it is necessary to estimate these parameters on a spatial scale relevant to the fishery. Assessments can then be made which allow the spatial structure of the stock and the distribution of fishing effort to be taken into account.

Most sedentary invertebrate populations show a degree of population contagion, the scale of aggregations varying between species (Andrews & Mapstone, 1987; Caddy, 1989a). The degree to which this scale of aggregation can be perceived is dependent on the size of the sampling unit.

The scales of aggregations in scallops have been classified by a number of workers, (e.g. Orensanz, 1986; Orensanz *et al.*, 1991; Caddy, 1989b; Brand, 1991). The largest spatial scale is the stock or reproductively isolated population (termed 'megapopulation' by Orensanz, 1986). In decreasing order of dimension, there is the 'fishing ground', the 'bed', and the 'patch'. For scallops and queens in the North Irish Sea, the scale of these classifications can be regarded as similar for the two species. The North Irish Sea stocks of scallops and queens, previously considered to be single, panmictic populations (Beaumont & Beveridge, 1984; McLeod *et al.*, 1985; Beaumont, 1991) may consist of more than one such population (Lewis, 1992), and therefore more than one 'megapopulation' (*sensu* Orensanz, 1986) may be present.

Within the area covered by the one or more stocks or megapopulations are a number of fishing grounds, such as The Chickens, The Targets etc., (Fig. 2a & Fig. 2b), where substratum is suitable for scallops and queens (and for the fishing gear). Dense aggregations exist within these grounds (known as 'beds' to the fishermen); these are generally 1-10 km<sup>2</sup> in area, and are the minimum scale perceived by commercial fishing gear and local fishery practice. Both within and outside beds are 'patches', which may be a few metres in area (Baird & Gibson, 1956; C. Darby, MAFF, Lowestoft, personal communication, 1990). The size of this smallest scale of aggregation cannot be perceived by dredge sampling following commercial practice (where dredges are towed for approximately one hour,

covering 1.5-2.5 km). Many population processes (growth, recruitment, natural mortality) may be subject to control at the patch level, so some knowledge of this scale of aggregation is ultimately desirable (Orensanz *et al.*, 1991).

Mason *et al.* (1982) have reviewed the methods available for sampling scallop populations; dredges can only be regarded as semi-quantitative, as their efficiency is variable. Diver surveys are impractical in the North Irish Sea populations, due to the depth of the fishing grounds. Underwater television is a useful means of assessing distribution, but cannot provide samples, and is expensive to use. Submersibles have been used in studies on *Placopecten magellanicus*, (Caddy, 1970; Langton & Robinson, 1990), but are not a realistic tool for routine sampling. Previous work with underwater TV has successfully mapped distributions of scallops and queens in the Channel (Franklin *et al.* , 1980*b*) and determined their density.

In an assessment programme, the patchy, or negative binomial distribution of scallops is of importance in deciding on the spatial pattern of sampling. The most commonly used method for surveying scallops with a view to calculating abundance is stratified random sampling. The method of stratification varies. In surveys to estimate stock size of *Placopecten magellanicus* on Georges Bank, US fishery workers stratify by depth (Serchuk & Wigley, 1987) whereas Canadian scientists studying the same fishery use the previous season's commercial catches by area as the stratification parameter (Robert & Jameison, 1986). Surveys stratified by depth probably give better estimates of total biomass, whereas those stratified by commercial catch give better estimates of fishable biomass (Caddy, 1989*b*). New sampling programme designs include systematic sampling methods (Smith & Naidu, 1981; Naidu & Smith, 1982) and geostatistical techniques (Conan, 1985). These survey methods have the advantages of simplicity of design, and do not require prior knowledge of scallop distribution patterns.

In this study, the research budget did not allow large-scale abundance and distribution surveys to be carried out. Abundances were calculated from commercial fishery data, with an estimate obtained for each of the 5 Nautical mile squares on a grid constructed from the lines of latitude and longitude (see Fig. 4). The only previous extensive stock surveys in the North Irish Sea were the exploratory surveys of Gruffydd (1966) in search of new scallop grounds, and Soemodihardjo (1974) who sought to map the distribution of queens around the Isle of Man. The U.K. Ministry of Agriculture and Fisheries have also undertaken



surveys of small-scale distribution patterns of scallops off Port St. Mary, in 1987 and 1989, using dredges on short (15 min) tows and underwater TV (P.J. Dare, MAFF, Lowestoft, personal communication, 1989).

The sampling programme undertaken during 1987 to 1989 was designed not to map distributions of scallops and queens, but to quantify differences in population parameters between areas on a scale relevant to the fishery, and subject to logistic constraints. A programme of sampling the major fishing grounds for *Pecten maximus* was already in existence (Mason, 1957; 1959; Gruffydd, 1966; 1972; 1974a; 1974b; Murphy, 1986; Duggan, 1987 and Brand *et al.*, 1991b), making it desirable to continue sampling the same grounds, adding samples for *Chlamys opercularis*, which has not been the subject of a population study since the work of Soemodihardjo (1974). This sampling programme meets the immediate need for providing estimates of population age structures and growth rates for the major fishing grounds (Chapters 2 & 3). Mortality rate estimates for *Pecten maximus* from the major fishing grounds have been obtained from a large scale tagging experiment, from catch statistics and from empirical relationships between mortality and other life-history parameters (Chapter 4). The use of mark-recapture techniques in the study of *Chlamys opercularis* population dynamics has also been investigated (Chapter 5).

This considerable sampling effort was undertaken to obtain realistic parameter estimates for input into assessment models for individual fishing grounds (Chapter 6) with the aim of developing a yield model of the fishery in which spatial, seasonal and interannual variability of all of the input parameters into fishery models (growth, fishing and natural mortality, recruitment) are quantified.

## DATA COLLECTION METHODS

The data required for stock assessments were collected by the issue of logbooks to commercial fishing vessels, a programme of sampling conducted mainly from the R.V. 'Cuma' and a series of mark-recapture experiments.

### 1. Fishery statistics

Total landings (in tonnes liveweight) of scallops and queens to the Isle of Man were obtained from the annual reports of the Isle of Man Department of Agriculture and Fisheries. These data, collected since 1969, are based on returns submitted by processing factories on the I.o.M. The factories record monthly production of scallop and queen meats, which are then converted to tonnes liveweight assuming a ratio of 1:7 (meat and roe weight : liveweight) for scallops and 1:10 (meat weight : liveweight) for queens. These approximate conversion factors were established in the early 1970's, when queens were processed roe-off (adductor muscles only). An unknown proportion of queens are now sold roe-on and the conversion factor may need some readjustment.

Landings of scallops and queens to other ports around the North Irish Sea are recorded by the U.K. Ministry of Agriculture, Fisheries and Food (MAFF) and the Scottish Office Agriculture and Fisheries Department (SOAFD), formerly the Department of Agriculture and Fisheries for Scotland (DAFS) and are summarised, together with the I.o.M data, in the statistical summaries produced by the International Council for the Exploration of the Sea (ICES) in the ICES Bulletin Statistique (e.g. Anderson, 1989) from which they were obtained for this study.

Since 1981, catch-effort statistics have been collected from the Isle of Man fishing fleet by the distribution of log-books, which are completed on a voluntary basis by the vessel skippers. A £75 incentive is offered for the satisfactory completion of a logbook each year. The books are distributed annually to the skippers or owners of each registered fishing vessel. Completed logbooks are generally returned soon after the end of the scallop season (June-July) although some skippers return their books at the end of each calendar year. Late submission of logbooks means that records have to be continually updated, and finalised statistical summaries are seldom calculable until 10 months after the season has ended.

The vessel skippers are asked to record each day's fishing activity; the number of hours spent fishing, catches obtained, fishing gear used (number, size and type of dredge, or queen trawl) and areas fished. The areas fished can be recorded as Decca co-ordinates or as the reference number of the grid-square fished. A map of the grid-squares is included in the front of each log-book. The grid is based on 5 Nautical mile squares, constructed from the lines of latitude and longitude, starting at 54°N and 5°W. This scale gives sufficient spatial resolution, with most fishing grounds covering at least one grid square, without making the logbook difficult to complete. Since 1988 the map included in the front of each logbook has also shown the main Decca lines (Fig. 4). The Decca lines were added because some completed logbooks which contained both Decca and grid references indicated inconsistencies between the Decca positions given and the grid-square which the fishermen thought corresponded to those readings. To produce tractable summaries of spatial distribution of fishing activity, all catches were assigned to individual grid squares. Where Decca readings indicated that the fishing gear was towed through more than one square, the catch and effort was divided evenly among the number of squares covered by the day's fishing. No attempt was made to divide catches by the proportion of the total distance towed in each square, as in Murphy's (1986) analysis of scallop fishing, 1980-83. Decca readings given were not normally precise enough to justify such refinement.

Catches were recorded in bags (all scallops and queens caught by Manx boats are landed whole in standard nylon bags). For scallops, the number per bag is normally recorded (in dozens) as the scallops are counted individually into the bags. Where estimates of numbers per bag were not available, the average for the fleet was used. Catches of queens were converted from number of bags to weight, based on the mean weight of bags (obtained from processing factories). Numbers per bag were estimated from average weights of queens of commercial size (calculated by pooling all weighed queens from samples of commercial catches) and the mean weight of a bag of queens.

The unit of effort used in this analysis of the scallop fishery (and that of Murphy, 1986) was taken as one hour towing one metre width of dredge. Towing time is generally one hour in this fishery, and the width of gear towed varies from between 4 and 15m. Two types of gear are used in the queen fishery; dredges and trawls. Initially similar effort units were used; one hour towing one metre of dredge, and one hour towing one metre of trawl, with the width of the trawl assumed to be headline length  $\times$  0.67 (Brand & Allison, 1987). However very high

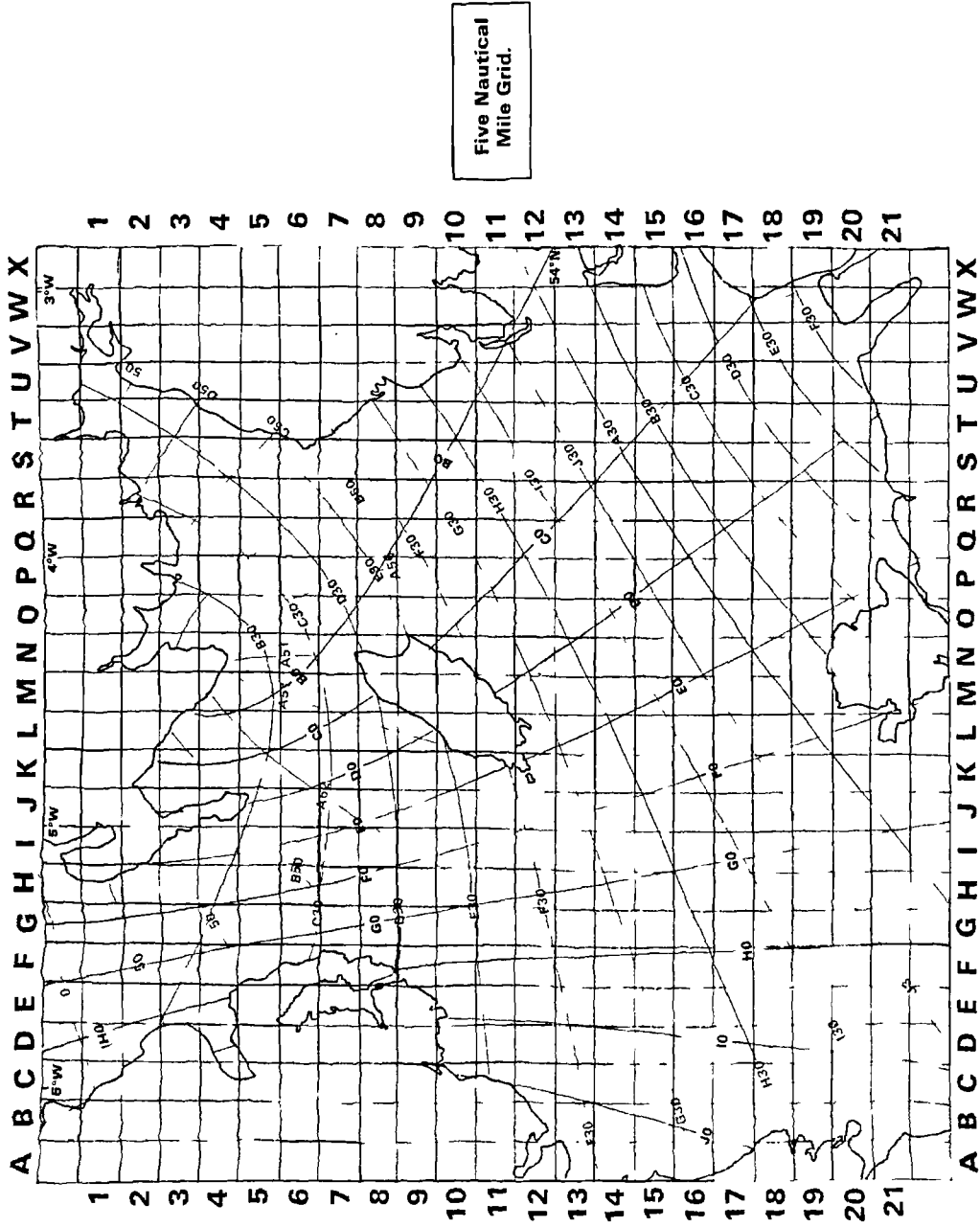


Fig. 4. Map of the North Irish Sea showing main Decca lanes and 5 Nautical mile grid. This map is pasted in the front of logbooks distributed to fishermen. Fishing positions in completed logbooks are given as Decca readings or as a grid-square reference.

variances in calculated catch rates indicate that a less precise unit of effort may be more suitable for analytical purposes. Chapter 6 discusses the suitability of different effort units in this fishery.

Data on the fishing fleet (number of boats, year built, tonnage, registered length, engine horsepower) were obtained from the Isle of Man Fishing Vessel Register.

The catch and effort data for the sample fleet (that part of the fleet which returns logbooks) and basic fishery statistics are utilised in the calculation of fishing mortality rates (Chapters 4 & 5) and in assessments of the stocks and the options for their management (Chapter 6).

## 2. Biometric data

To complement the collection of fishery data, samples of *Pecten maximus* and *Chlamys opercularis* were collected from October 1986 to November 1989 by the University of Liverpool 20 m stern-trawler, the R.V. "Cuma". The sampling programme was designed to provide samples for analysis of growth rates and population age structures of the major fishing grounds.

Between October, 1986 and December, 1988 the R.V. "Cuma" towed two dredges, 1.1 m wide, one each side on a single wire warp. The dredges were standard Manx scallop dredges with a spring-loaded toothbar, steel ring bellies and rope top-mesh (see Chapman *et al.*, 1977 and Mason, 1983, for descriptions). The teeth on each bar were spaced 8.6 cm apart but the length of the teeth varied: typically they were 11 cm long when new but wore out rapidly and, during the first few months of this work, were not replaced until the dredges were beginning to clog with dredged material - a consequence of the shorter teeth causing the toothbar to 'bulldoze' a mound of sediment into the mouth of the dredge. This clearly had implications for the selectivity and efficiency of the dredges so tooth-length was subsequently regulated more carefully.

Despite precautions, it is likely that the condition and therefore the performance of the R.V. Cuma's fishing gear has also varied in past studies. Care must therefore be exercised in interpreting changes in CPUE of research vessel data and age-frequency histograms to quantify recruitment variability. Dredge

performance is also likely to vary with substratum type. These dredges cannot be considered as a fully quantitative sampling tool in studies of population density and recruitment fluctuation. However Duggan (1987) and Brand *et al.* (1991b) have shown that survey data from the R.V. Cuma, pooled within each season's sampling, is sufficiently consistent to show the presence of strong year-classes in the *Pecten maximus* population over successive years.

Samples were also taken from commercial vessels whenever time permitted, to supplement information from research-vessel samples. During 1988 funding was obtained to purchase new dredges and the opportunity was taken to standardise the R.V. Cuma's gear with that towed by commercial vessels. Accordingly, four 2'6" (0.83 m) spring-loaded dredges were purchased and were rigged to be fished off 2 metal pipes which run along the seabed on hard rubber wheels. It is likely that dredges fished off a pipe will behave differently to those fished off a single warp and will be closer in behaviour to commercial gear in this fishery, where 'gangs' of 3-12 dredges are towed from pipes each side of the vessel. Two dredges were fitted with 7.0 cm rings and two were fitted with 5.7 cm rings (internal diameter). These correspond to the ring sizes commonly used in the Manx scallop and queen fisheries respectively. A selection of tooth-bars was available for each dredge, so that different combinations of teeth and dredge bellies could be tested. The new dredges have since been used for two surveys where the effects of changing teeth/belly combinations on gear performance has been tested. The length of the teeth, rather than the size of the bellies, has the greatest effect on the selectivity of the dredges (unpublished data). Catches from the different dredge types were pooled for analysis of growth rates and qualitative assessments of population structures.

A summary of the different dredge-types used by the R. V. Cuma from October, 1986 to November, 1989 is given in Table 1. A summary of all sample dates, areas, and sampling gear used is given in Appendix 1.

*Chlamys opercularis* samples were taken with dredges and with trawls. The trawl used on the R.V. "Cuma" was a 6 fathom (10.98m) fish and prawn trawl with 5 cm diamond mesh codend and was not adapted to fish specifically for queens: the ground line was not as heavy as that of a queen trawl and the doors were not attached directly to the wings of the net. Chapman *et al.* (1979) provide a description of rock-hopper queen trawls similar to those used in this fishery. *C. opercularis* samples were also taken from commercial vessels during the summers of 1988 and 1989 from the main East Douglas ground (see Fig. 2b), using both

		PORT				STARBOARD				
Dates	No.Dredges	D. width	Tooth-length	Tooth-spacing	Bellies	No.Dredges	D. width	Tooth-length	Tooth-spacing	Bellies
28-10-86 to 24-02-87	1	0.84m	variable	8.6cm	6.35cm	1	0.84m	variable	8.6cm	6.99cm
13-03-87 to 01-12-88	1	0.84m	variable	8.6cm	6.35cm	1	0.84m	variable	8.6cm	6.35cm
31-01-89 to 30-11-89	2	0.76m	11 or 6.4 cm	8.6 or 7.6cm	5.72cm	2	0.76m	11 or 7.6cm	8.6 or 7.6cm	6.99cm

Table 1. Specification of spring-toothbar dredges fished from the port and starboard beams of the R.V. 'Cuma', October, 1986 to December, 1989.

dredges and trawls.

The majority of samples were taken during the winter (November to March) when the shell of both species is not growing, so that comparative studies of samples taken on different dates could be made without introducing additional variability due to seasonality. Surveys also took place over wide areas during July, 1987 and June, 1988, while tagging scallops (Chapter 4). Comparisons between areas could also be made for these samples as the surveys were both completed within a short time (approximately 1 week).

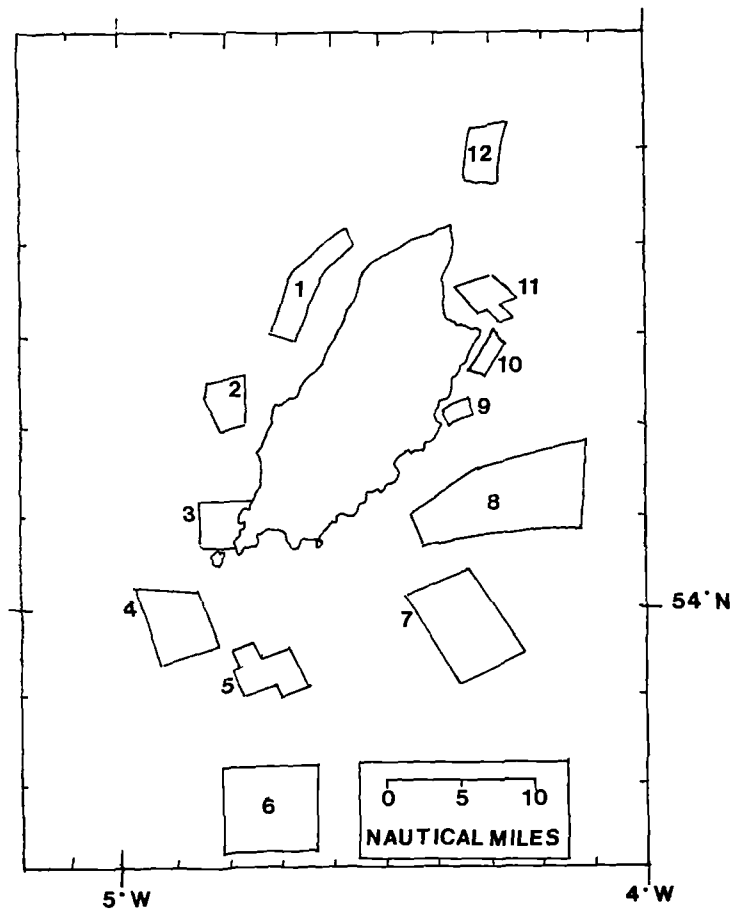
The design for the research vessel sampling programme used throughout this study was linear transect sampling. Two or three dredge hauls of approximately 1 hours duration, covering 9 500-25 000 m<sup>2</sup>, constituted a sampling event. The population age structure and growth rates of scallops and queens from linear transect samples were assumed to be representative of these parameters on the whole fishing ground. This assumption was tested, both in this study (Chapter 2) and by Murphy (1986) by taking commercial vessel samples from different areas within a fishing ground and comparing them with linear transect samples from the same ground. No obvious differences in age structure were observed within fishing grounds.

Locations of linear transect samples, commercial-vessel samples and surveys of *Pecten maximus* undertaken in the summers of 1987 and 1988 as part of a mark-recapture experiment are shown in Fig. 5. Decca co-ordinates and other sampling details are given in Appendix 1.

### **3. Mark-recapture experiments**

Regional differences in mortality rates of *Pecten maximus* were investigated by a mark-recapture study, where tagged scallops were released over a number of areas fished by commercial vessels (Chapter 4). The utility of mark-recapture techniques for the study of the dynamics of *Chlamys opercularis* was investigated by experimental tagging programmes off Douglas in May, 1987 and May, 1989 (Chapter 5).





**Fig. 5.** Fishing grounds sampled for *Pecten maximus* and *Chlamys opercularis*, November, 1986 to November, 1989. (S = sampled for scallops, Q = sampled for queens)

1	The Targets	S,Q
2	Peel Head	S
3	Bradda Head	S
4	The Chickens	S
5	Port St. Mary	S,Q
6	H/I Sector	S,Q
7	SE Douglas	S,Q
8	E Douglas	Q
9	Laxey Bay	Q
10	Maughold Hd.	S,Q
11	Ramsey Bay	S,Q
12	Point of Ayre	S,Q

# CHAPTER 1 - AGE DETERMINATION IN *PECTEN MAXIMUS* AND *CHLAMYS OPERCULARIS*.

## 1.1. INTRODUCTION

The correct determination of the ages of *Pecten maximus* and *Chlamys opercularis* is fundamental to the studies of growth, mortality, population structure and recruitment that form the first part of this thesis. Incorrect estimates of these parameters will in turn lead to errors in population assessments.

The possibility of using the marks or rings on the shells of scallops, *Pecten maximus*, to determine their age were mentioned by Dakin (1909), Priol (1930), Tang (1941) and Elmhirst (1945). Gibson (1956) and Mason (1957) confirmed that the rings were annual, and the latter established they were laid down between March and May in the North Irish Sea. Annual rings are commonly found in many of the Pectinidae and other bivalves in temperate seas (Fairbridge, 1953; Stevenson & Dickie, 1954; Merrill *et al.*, 1966; Jones *et al.*, 1990; Sephton & Bryan, 1990) and are generally correlated with the resumption of growth in the spring after a period of slow or non-growth during the winter.

The use of annual rings to age large samples of scallops on a routine basis is now universal in temperate scallop fishery assessment studies (e.g. Mason, 1983; Caddy, 1989c; Young & Martin, 1990) although the rings are not always clearly visible. There are particular problems in determining the position of the first growth ring in many scallop species (see Mason, 1969; 1983; Posgay, 1979; Paul, 1981; Roddick & Mohn, 1985; Murphy, 1986 and Dare & Deith, 1991) and later rings in old scallops are not always clearly visible due to erosion of the shell and the close proximity of the rings (Merrill *et al.*, 1966; Murphy, 1986). The rings on queens, *Chlamys opercularis*, have also been used for ageing (Aravindakshan, 1955; Ursin, 1956; Soemodihardjo, 1974; Pickett & Franklin, 1975; Paul, 1978; Taylor & Venn, 1978; Broom & Mason, 1980 and Duggan, 1987) but the rings are seldom clear in this species and some authors consider that no ring is laid down during the first winter in late-spawned animals (Pickett & Franklin, 1975; Broom & Mason, 1980; Paul, 1981) or that the first two rings represent spawning rings, not winter annual rings (Aravindakshan, 1955). However Soemodihardjo (1974) and Paul (1978, 1981) subsequently demonstrated that both first and second rings were true winter rings, laid down in late spring (May or June).

A further complication in the interpretation of age from annual rings is that populations may have more than one spawning a year. The offspring may therefore show a bimodal distribution in the position of the first and subsequent growth rings. Mason (1957) considers that *P. maximus* from Port Erin has two peaks in spawning, in spring and late summer or early autumn, and that size-frequency distributions of the first and second rings show bimodality, reflecting a minor spatfall resulting from the spring-spawning and a major spatfall following the autumn spawning.

Bimodality in the size-frequency distribution of the first growth ring has also been proposed for North Irish Sea *C. opercularis* populations (Aravindakshan, 1955; Soemodihardjo, 1974; Paul, 1981) again due to two or three peaks in spawning activity each year.

Spat collection studies on both species have indicated, however, that only one peak in settlement of *P. maximus* occurs each year - following partial spawning in the early summer - and that *C. opercularis* has a protracted settlement period, but with a single peak in June or July (Paul, 1978; Brand *et al.*, 1981; 1991a; Duggan, 1987). A re-examination of the size-frequency distributions of first and second rings would help to clarify these apparent discrepancies.

Correct age determination of *Pecten maximus* from annual rings will depend largely on consistent interpretation of the first growth ring as subsequent rings are clearly visible in these stocks (Mason, 1957; Murphy, 1986; Dare & Deith, 1991). This work presents the results of a study of the size distribution of the first and second growth rings and compares my interpretation of their position with those of previous studies on these stocks.

## 1.2. METHODS

Annual rings were counted on the flat (upper or left) shell-valve of *Pecten maximus* and on the left (upper) valve of *Chlamys opercularis*. All shells were 'read' while the scallop or queen was alive; the rings are more clearly visible when the shell is wet. Removal of epibionts prior to age determination was generally not necessary for scallops, but was often required to detect the rings on queen shells. Information on the size distribution of over-wintering spat (Paul, 1978; U.A.W. Wilson, Port Erin Marine Laboratory, unpublished data) and on the sizes of scallop spat caught by monthly sampling with fine-mesh dredges off Port Erin in 1950-53

(scallop shells provided by the late A.B. Bowers, Port Erin Marine Laboratory) were used to develop a consistent method of interpreting the appearance of the first growth ring. Samples collected between October and December, 1986, at the start of this study, were excluded from analysis in this thesis due to possible inconsistencies in age determinations.

The first and second growth ring radii (umbo to growth ring distance on the flat or ventral valve) of scallops and the left shell-valve of queens in sub-sampled catches of the R.V. "Cuma" were measured to the nearest 0.5 mm using callipers. Size-frequency distributions of first and second growth ring positions were constructed for *Pecten maximus* from two areas, the Bradda Head and South East Douglas fishing grounds, and for *Chlamys opercularis* from the South East Douglas ground. The size-frequency distributions obtained were compared visually with distributions obtained in similar studies by Mason (1957) on *P. maximus* and Soemodihardjo (1974) on *C. opercularis*, and with first and second ring positions determined from stable oxygen isotope analysis in *P. maximus* (Dare & Deith, 1991).

### 1.3. RESULTS

The size-frequency distribution of the first growth ring in *Pecten maximus* appears to be unimodal on both the Bradda Head and South East Douglas grounds (Fig. 1.1). The tails of the distributions of first and second rings overlap, with the size-distribution of the first ring being positively skewed. Mean first ring size of Bradda scallops (all ages, 2-14, mixed) is 16.4 mm, with a standard error of 0.16. The mean first ring size of S.E. Douglas scallops is similar (16.1 mm  $\pm$  0.18) but the mean size of the second rings differ, as the difference in growth rates between the two areas becomes evident (see Chapter 3). The mean second ring size is 40.9 mm ( $\pm$  0.23) for Bradda scallops, and the mean for S.E. Douglas scallops is 36.2 mm ( $\pm$  0.22).

The observed distribution of the first growth ring in Mason's (1957) samples appears to correspond to the distribution of first and second growth ring sizes in my samples. It seems likely that Mason's 'spring-spawned' scallops were in fact autumn or late summer spawners in which the first growth ring was too close to the umbo to be clearly visible. Dare and Deith (1991) offer the same interpretation of Mason's data, based on isotopic analysis of ring formation in scallops. The first

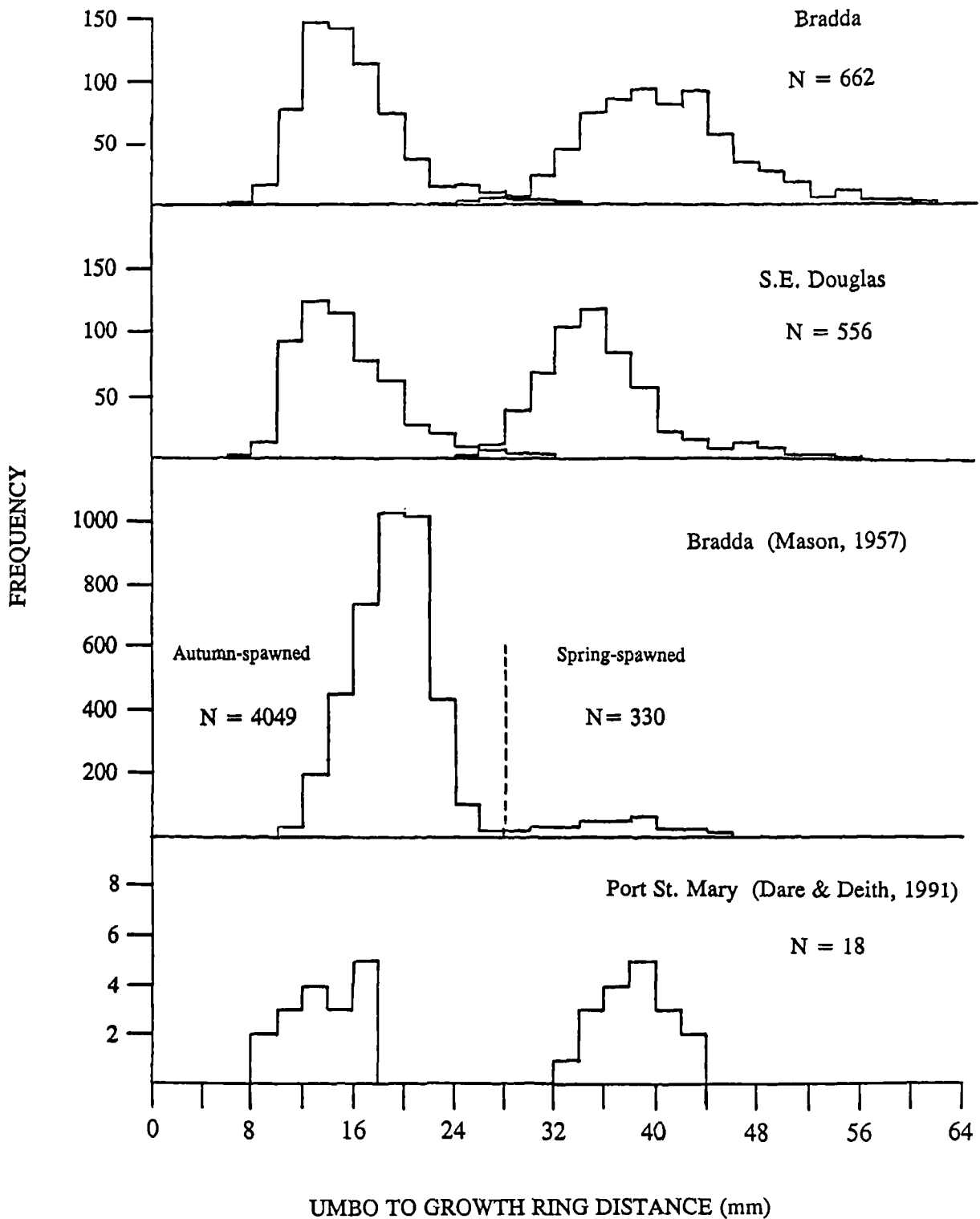
and second growth ring positions observed in this study correspond well with those identified using analysis of the ratio of stable oxygen isotopes in scallop-shell calcium carbonate (Dare & Deith, 1991) These authors recorded mean first and second growth ring sizes of 13.4 and 38.0 mm for North Irish Sea scallops from the Port St. Mary and Bradda Head grounds.

The first and second growth rings therefore appear to have been correctly recorded and identified visually in this study. Subsequent rings are easily visible in most North Irish Sea scallops although exact age determination becomes difficult in scallops more than 10 years old.

Mean first and second growth ring positions ( $\pm$  standard errors) for *Chlamys opercularis* from S.E. Douglas are 24.5 mm  $\pm$  0.282 and 48.3 mm  $\pm$  0.256. The first growth ring shows a wide size-distribution (Fig. 1.2) - the probable result of a protracted settlement period (possibly incorporating two or more 'recruitment pulses') and high variability in early growth rates. The clear bimodal distribution in the position of the first ring observed in the samples taken off Bradda Head by Soemodihardjo (1974) is not evident in my data. However, while the determination of the number of growth rings on the shell of *C. opercularis* may be relatively straightforward, their exact position is open to subjective interpretation. The annual rings often appear as fairly wide bands, particularly for the first two rings. More than one apparent ring may be present within a growth band. The mean and mode of the first ring distribution observed in my samples fall between the two modes in the first ring size-distribution obtained by Soemodihardjo (1974), (Fig. 1.2). The difference in distribution patterns between my study and that of Soemodihardjo (1974) is more likely to be due to differences of interpretation than a difference in settlement patterns between the Bradda and S.E. Douglas fishing grounds.

#### 1.4. DISCUSSION

The sizes of the first growth ring of *Pecten maximus* measured in this study do not show a bimodal frequency distribution, as has previously been proposed by Mason (1957) and Stanley (1967). The positions of first and second growth rings show good agreement with those obtained by Dare and Deith (1991) for North Irish Sea scallops. The study of Dare and Deith (1991) used stable oxygen isotope ratios ( $^{16}\text{O}:^{18}\text{O}$ ) to provide a profile of sea water temperature changes throughout each yearly cycle of shell carbonate deposition, as the ratio of  $^{16}\text{O}:^{18}\text{O}$  incorporated in



**Fig. 1.1.** Frequency distributions of first and second annual ring sizes of *Pecten maximus* in samples from Bradda Head and S.E. Douglas, January, 1987 to November, 1988. The distributions are compared with first ring size distributions from the Bradda ground, collected by Mason in 1950 to 1953 (Mason, 1957) and isotopically located first and second rings on scallops collected from the Port St. Mary ground in November, 1987 (Dare and Deith, 1991).

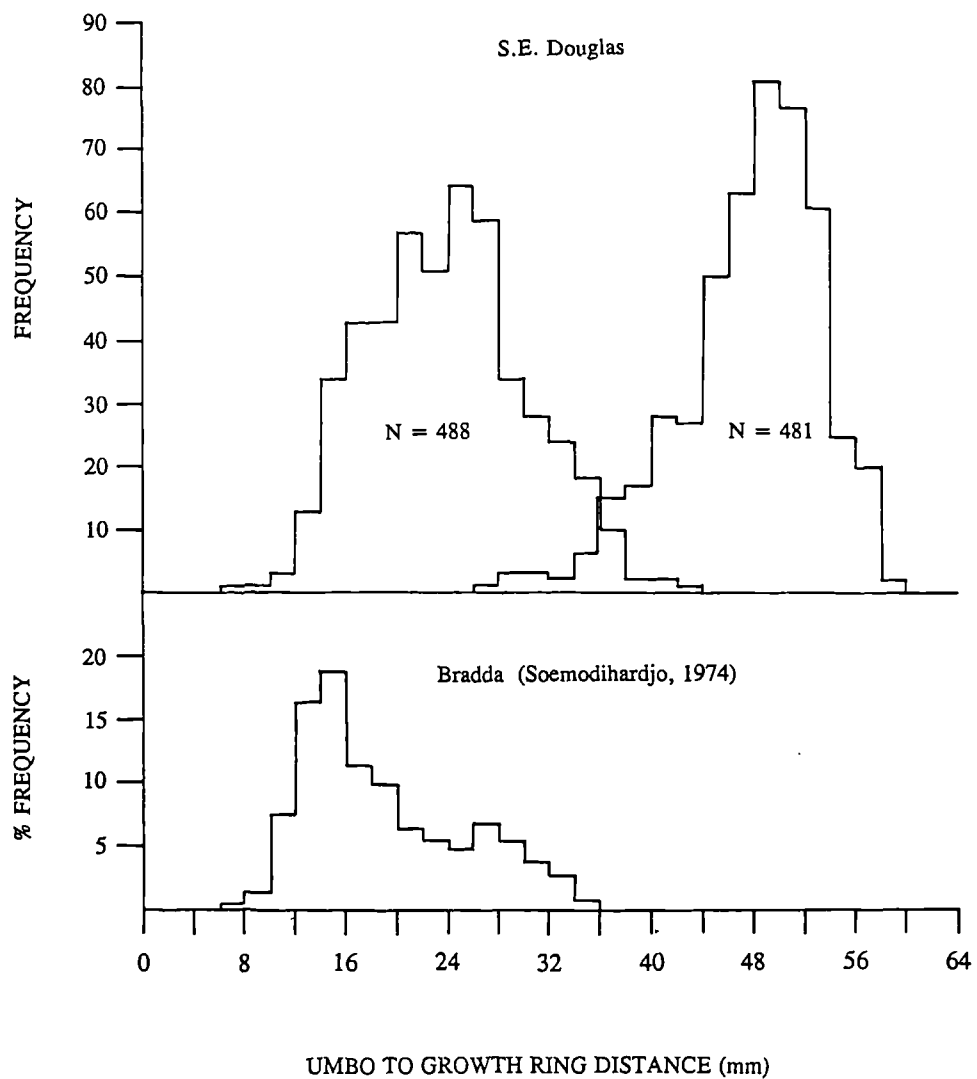


Fig. 1.2. Frequency distribution of sizes of the first and second annual rings on *Chlamys opercularis* from the S.E. Douglas ground, January, 1987 to November, 1988. The distributions are compared with first ring distributions observed by Soemodihardjo (1974) on Bradda Head queens sampled between 1971 and 1973.

the shell carbonate is temperature dependent (Epstein *et al.*, 1953). Taking carbonate samples along the dorso-ventral axis of the flat shell of the scallop reconstructs the temperature profile experienced by the scallop during growth, allowing the age to be determined from the number of annual temperature cycles, and the size during the first winter to be correctly established. Dare & Deith (1991) show that Mason's (1957) spring-spawned scallops were probably individuals with small, not clearly visible first growth rings. The findings of this study agree with their interpretation but I disagree that the first ring is never clearly visible. Both Mason (1957) and I have been able to locate a reasonably clear first ring in over 90% of inshore scallops - the ring is often less clear in offshore scallops, where it may be closer to the umbo.

Dare and Deith's study can be regarded as giving the correct positions of the first and second growth rings, the oxygen isotope technique having also been successfully used for checking the validity of age determination based on reading the visible annual rings on the giant scallop, *Placopecten magellanicus* (Kranz *et al.*, 1984; Tan *et al.*, 1988). On the basis of the concordance between the findings of this study and that of Dare and Deith (1991) the ages given for scallops in this thesis, determined by visual inspection of annual growth rings, can be regarded as unbiased estimates subject only to random error. Previous studies may have incorrectly aged scallops with small or not clearly visible first rings. Such scallops probably only account for some 10% of inshore populations around the Isle of Man, but a higher and more variable fraction of offshore populations.

Further evidence supporting the observed unimodal distribution of the first growth ring in scallops comes from studies of spat-collection and reproductive cycles. While spent gonads are present in April to May, and nearly all gonads are spent in late August or September, spat collection studies in these populations (Paul, 1978; Paul *et al.*, 1981; Brand *et al.*, 1980; 1991a; Duggan, 1987) and in Scotland (Fraser, 1983; 1987; 1991; Mason & Fraser, 1987) and France (Beustel *et al.*, 1979) have shown that neither spawning results in appreciable settlement. Peak settlement of *Pecten maximus* occurs during the summer (July) following partial or trickle spawning during June. Several authors have recently suggested that the so-called autumn spawning is actually a resorption of gonadal material to build up muscle reserves in the winter (Lubet *et al.*, 1991, for review). It is also possible that spring-spawning is a stress-response to capture. The gonads are certainly full at this time of year, but scallops may not otherwise have spawned until later if unstressed by capture. Many scallops caught at this time of the year are



spawning when brought to the boat or kept in the laboratory. The collection of diver-caught scallops and examination of their gonads during the spring would provide a useful validation of the causes of this apparent premature spawning, which does not appear to result in major settlement of spat.

The apparent bimodality in the position of the first growth-ring in *Chlamys opercularis* has been proposed by Aravindakshan (1955) and Soemodihardjo (1974) to support the existence of two peaks in settlement, the higher peak with smaller mean size corresponding to queens settling from the autumn spawning, with a smaller peak as a result of a minor summer spawning. Paul (1978, 1981) has argued convincingly that while there may be up to three spawning periods and two peaks in settlement of *C. opercularis*, the major peak in settlement arises from the partial summer spawning and the small-ringed individuals which constitute the higher modal peak are the result of this settlement. The minor modal peak of larger first-ring animals are the result of the autumn spawning, and settle late in autumn, over-wintering at a very small size. Growth in spring is then a gradual acceleration so no visible ring is laid down, consequently the first visible ring in these animals is not a large first ring, but a ring laid down after their second winter when they are 18 months old.

It is not clear from my samples whether the frequency distribution of first ring sizes is multimodal or just shows a wide peak (platykurtic). Both Soemodihardjo (1974) and Paul (1978, 1981) note that queen spat can be found bysally attached at all times of year. Settlement probably takes place over a fairly extended period during the summer and early differential growth dependant upon settlement time may cause high variability in the position of the first growth ring. Subjective errors in locating the first ring (and indeed subsequent rings) must not be discounted.

The approach to age-determination used in these studies has proved consistent enough to allow good agreement to be reached with other workers at the Port Erin Laboratory. Errors will of course arise, but this traditional approach to age-determination is likely to remain standard practice in scallop fishery studies. Age determination by oxygen isotope analysis is too costly and time-consuming to be used on a routine basis. Length-frequency analysis provides a possible alternative to age-determination from growth rings on the shell. The techniques for analysing length-frequency distributions have developed considerably over the last decade, and a wide range of methods are available to derive growth and mortality

rates from size-composition data (see MacDonald & Pitcher, 1979; Pauly & Morgan, 1987; Rosenberg & Beddington, 1988; Fournier *et al.*, 1990). The high growth variability, slow growth rate and large number of age-classes in the population will make size-frequency analysis difficult for scallop stocks but may prove useful for queens, where age-determination is more difficult, growth rate is faster and fewer cohorts are present.

Size-frequency analysis provides a means of estimating the parameters used for traditional age-based assessment methods by converting length to age. Some authors have advocated a length-based assessment approach; e.g. Length-cohort analysis (Jones, 1981). This by-passes the requirement for age determination, and may be preferable on theoretical grounds as most dynamic processes are size rather than age-related. In a fishery managed by size limits such an approach to assessment may prove useful and relevant.

## CHAPTER 2 - AGE STRUCTURE AND RECRUITMENT.

### 2.1. INTRODUCTION

The collection of data on the age-structures of the populations of *Pecten maximus* on the fishing grounds around the Isle of Man has been a major part of scallop population studies at Port Erin since the start of the fishery (see Brand *et al.*, 1991*b* for review). The major fishing grounds have been sampled regularly, either from commercial vessels or from research vessels. These data have traditionally been used to identify variations in year-class strength and changes in population structure due to increasing exploitation (Murphy, 1986; Duggan, 1987; Brand *et al.*, 1991*b*). This work initiates a similar dataset on the queen scallop (*Chlamys opercularis*).

The aims of this chapter are to continue with the qualitative assessment of recruitment variability, based on population age-structure data collected between January, 1987 and November, 1989, and to assess if these studies can be placed on a more quantitative footing. Particular consideration is given to the possibility of using population age-structure data from research vessel catches in combination with commercial catch-effort statistics to calculate catch-at-age or abundance-at-age matrices. Age-structured modelling approaches, such as Virtual Population Analysis, (Jones, 1964; Murphy, 1965, and references in Gulland, 1983) could then be used for stock assessments.

The major assumption required in combining research vessel data on age-composition with commercial catch statistics is that the age-composition of the recruited fraction of the research vessel catch is representative of commercial catches. The recruited fraction is here defined as the part of the population vulnerable to commercial fishing. In *Pecten maximus* this corresponds to all scallops  $\geq 110$  mm, the minimum legal landing size. In *Chlamys opercularis*, queens  $\geq 55$  mm shell length are those of acceptable commercial size. This assumption requires that the selectivity pattern of the different gear types used is similar for scallops and queens of these sizes. The population structure derived from linear transect samples over a limited area of the fishing ground must also be applicable over the fishing ground as a whole, implying complete age-class mixing at the scale perceived by commercial fishing gear. In pooling samples taken at different times within each winter fishing season, one further assumption is

required: that there is no size or age selection within the exploited part of the population.

As well as testing the above assumptions and computing abundance-at-age matrices, an important part of this study is to understand the effects of exploitation on population structure, and to use population age-frequency data to examine spatial and temporal recruitment patterns.

While the effect of sustained heavy fishing on population structure of long-lived species, including scallops, is well known (e.g. Gulland, 1983; Ricker, 1975a; Caddy, 1979; Brand *et al.*, 1991b), the factors causing recruitment variability in scallops and many other invertebrates are difficult to determine (Hancock, 1973; Caddy, 1989a). Several studies have investigated recruitment mechanisms in scallops, and have observed density-dependence of recruitment in high-density populations of *Chlamys islandica* (Vahl, 1982) and *Chlamys tehuelpcha* (Orensanz, 1986), possible recruitment overfishing in low density populations (Hancock, 1973; Dredge, 1988; Young & Martin, 1989) and lack of a stock-recruitment relationship in most other scallop populations (Dickie, 1955; Caddy, 1979; Mason, 1983 and Sinclair *et al.*, 1985). In many studies, the problem of deducing which parent stock is responsible for the production of recruits has precluded the determination of the nature or existence of a stock-recruitment relationship; a problem now being addressed in many fish and invertebrate stocks by the application of models of water movement and larval behaviour which can predict the dispersal of pelagic offspring (Rothlisberg *et al.*, 1983; McShane *et al.*, 1988; Bartch *et al.*, 1989; Hill, 1990).

This study investigates recruitment variability using the available data, which is not fully quantitative, to suggest the factors which control recruitment levels in these populations. A more detailed discussion of the processes which may control the size and distribution of these populations is given as part of the General Discussion. This discussion is based on reviews of the available knowledge of the residual circulation pattern in the Irish Sea, scallop and queen population genetics, the duration of the pelagic veliger stage and the studies on population dynamics in this thesis.

## 2.2. METHODS

### 2.2.1. Population structure and recruitment anomalies

From October 1986 to November 1989, samples of *Pecten maximus* and *Chlamys opercularis* were collected from all major fishing grounds around the Isle of Man (see Fig. 4 and Appendix 1), either using the R. V. "Cuma's" dredges and queen-trawl, or from commercial vessels. It was not possible to control all variables affecting fishing gear performance (weather, tidal currents, substrate type and gear specification) so samples taken with all gear types were pooled for analysis of age composition. Samples taken in winter (November to March) were combined and age-frequency distributions were plotted for each ground in each of the winters of 1986/7, 1987/8, 1988/9 and 1989/90. For the 1986/7 winter only samples collected between January and March, 1987 were used; earlier data being discarded due to the possibility of inconsistency in ageing technique during early samples. Age-frequency data for the 1989/90 winter are based on a single survey carried out in November, 1989. Exceptionally poor weather prevented sampling between January and March, 1990.

Age-frequency of catches used for tagging experiments on *Pecten maximus* in the summers of 1987 and 1988, and on *Chlamys opercularis* in late spring 1987 and 1989 have also been included in the data series for comparison. These catches were taken over wide areas of fishing grounds also sampled by single linear transects by the R. V. "Cuma", and provide a useful assessment of the applicability of age-structures derived from linear transects to the age structure of the fishing ground as a whole.

Age-frequency distributions of catches of *P. maximus* and *C. opercularis* from winter samples and tagging surveys, standardised as percentage frequency histograms, were examined to identify modes and troughs representing the presence of strong and weak year classes in the population.

### 2.2.2. Seasonal changes in population age and size structures

Approximately monthly samples (weather and boat time permitting) of *P. maximus* population structure were taken from the S.E. Douglas and Bradda Head grounds from January, 1987 to December, 1988. These samples provide

information on seasonal changes in population age structure and the timing of annual ring formation.

Size-structures of *P. maximus*  $\geq 110$  mm shell length (in samples taken from Bradda Head and S.E. Douglas over the 1987-1988 scallop fishing season) were also compared. Bartlett's test for homogeneity of variances (Zar, 1984, p181-182) was applied to assess if strong size-selection reduces variance over the fishing season. The significance of within-season changes in mean length were assessed by fitting a regression line through the mean sizes of scallops in catches over the season and testing if the slope differs significantly from zero (i.e. if there is any change in the mean size of scallops in the catch over the fishing season).

### 2.2.3. Statistical comparison of age-structures

To establish whether differences in population structure occurred between fishing grounds, a  $9 \times k$  contingency table was constructed for the comparison of age-frequency distributions of *P. maximus* between areas for each winter. Following standard statistical practice, the age-frequency matrix from each area was reduced to 9 elements by summing the values at the tails of the frequency distributions to reduce the number of cells with low frequency values ( $f_{\text{obs}} < 1$ ,  $f_{\text{exp}} < 5$ ) which would introduce bias into the Chi-square procedure (Zar, 1984). The first element in the table contained scallops of 0-2 yrs old, and the 9th element was the frequency of scallops  $\geq 10$  years old. The value of  $k$ , the number of areas compared, varied each year.

The same rationale was used to construct  $5 \times k$  contingency tables for the comparison of age-frequency distributions of *C. opercularis* between areas, with the first element being the frequency of 0-1 yr olds, and the fifth element being the frequency of queens  $\geq 6$  years.

The null hypothesis being tested in each case was that for each year, the population structures of scallops and queens were the same on all fishing grounds, i.e.- the stock is homogenous in any given year. No comparisons between years are made here, as recruitment variation through time is assessed in more detail elsewhere. The purpose of this comparison was to show whether, in any given year, population structure (which is determined by recruitment, mortality and sampling/fishing gear selectivity) varies between fishing grounds. If the null

hypothesis was rejected (i.e.- the population is not homogenous, and the unit stock concept is therefore violated) it is then desirable to identify homogenous substocks, if they are present. Although not strictly valid statistically, the only way of subdividing Chi-square tables is to re-run the Chi-square test, removing areas contributing the largest Chi-square values (those differing most from expected frequencies).

Statistical comparisons of the median ages of scallops and queens from different fishing grounds have also been made using the multi-sample comparison of medians procedure (Mood, 1950; Zar, 1984, p179-80). The median is chosen for comparison, rather than the mean, as the median provides a useful statistic of central tendency in all types of frequency distribution, and has some relevance to fisheries studies, where it is common to talk about 50% selection lengths, *etc.*, (Gulland, 1983).

The grand median age of all observations in all  $k$  samples was first calculated, and a  $2 \times k$  contingency table of the frequency of occurrence of scallops or queens above and not above the median age were compared by Chi-squared tests for each year, the null hypothesis being that all  $k$  populations have the same median age.

#### **2.2.4. Calculation of stock abundance-at-age and recruitment index**

The analysis of population age frequencies and their spatial and temporal variability was extended to quantify stock abundance-at-age. Abundances-at-age were calculated by combining population age structures with catch per unit effort (CPUE) data derived from logbooks completed by commercial fishermen.

CPUE values (number of scallops caught per hour's fishing per metre width of dredge) have been calculated from sample-fleet catch-effort statistics for each of the 5 Nautical mile grid squares for which age-structure data are available. The calculated CPUE values are means, weighted by fishing effort, of a whole winter season's fishing (November to May inclusive) by up to 14 vessels (Table 2.1). On the major fishing grounds CPUE values are based on hundreds to thousands of hours fishing. A weighted mean is chosen, as otherwise the CPUE of a vessel fishing a ground for 2 hours would have the same weight as one fishing for 2000 hours, and clearly the longer a boat has fished a particular area, the better its

catches will reflect the mean yearly abundance of scallops in that area. The standard errors of the CPUE values are also given, and are the result of differing boat efficiency, dredge towing speed (and therefore distance covered) and different areas fished within each grid square. Although variability is high and CPUE will be declining through the fishing season, it is assumed that the mean CPUE is proportional to the mean abundance of scallops in the fished area over the whole winter.

CPUE data were combined with age structure data from the same grounds to give an index of abundance at age for commercial-size scallops ( $\geq 110$  mm). CPUE-at-age values were then used to obtain crude density and abundance-at-age estimates.

Density is given by:

$$\text{Density} = \frac{\text{CPUE/Gear efficiency}}{\text{Distance covered in 1 hour fishing}} \quad (2.1)$$

Distance covered in 1 hour fishing was calculated assuming a mean towing speed of 1.5 Knots ( $2.78 \text{ km h}^{-1}$ ) for the fishing fleet (Murphy, 1986). A value of 20% was chosen for gear efficiency, based on estimates available in the published literature (Rolfe, 1969*b*; Gruffydd, 1974*a*; Chapman *et al.*, 1977; Mason *et al.*, 1982). It is assumed that gear efficiency is independent of scallop density, and is the same on all grounds.

To produce estimates of stock abundance for each fishing ground, the density estimates were multiplied by the area of the grid squares from which the CPUE data were obtained ( $5 \text{ Nautical miles}^2$  or  $85.857 \times 10^6 \text{ m}^2$  per square). The abundance estimates for the Bradda, Peel, Ramsey Bay, Port St. Mary and Chickens grounds relate to single squares; those for The Targets, Point Of Ayre, Maughold and S.E. Douglas relate to two squares, and the abundance estimate for the H/I Sector ground relates to the three grid-squares from which the CPUE data were obtained. Table 2.1 indicates the grid-squares representing each fishing area. In calculating abundance it is assumed that the CPUE values are representative of abundance over the square as a whole and that the stock covered the whole of one or more squares. These assumptions may be reasonable for the major grounds, where fishing takes place over the whole area covered by the grid squares. No attempt is made to calculate an overall stock abundance, as some grid squares are



Area	CPUE (scallops m-hr <sup>-1</sup> )	S.E. (CPUE)	N. Boats	Fishing effort (m-hrs)
<b>1986/7</b>				
Bradda - K11	20.23	0.075	14	6973
Peel - K10	18.89	0.062	7	5273
SED - N13/O13	29.31	0.172	13	5463
PSM - L14	33.11	0.292	3	674
Chickens - K13	34.14	0.093	4	4237
<b>1987/8</b>				
Bradda - K11	17.42	0.043	8	7414
Targets - L8/9	19.38	0.053	4	1643
SED - N13/O13	20.80	0.135	4	2443
H/I - L15/M15/L16	28.33	0.056	2	429
Chickens - K13	31.49	0.086	6	7354
<b>1988/9</b>				
Bradda - K11	18.47	0.021	8	7843
Peel - K10	16.24	0.024	5	4541
Targets - L8/9	15.48	0.070	4	1461
P. of Ayre - L6/O6	17.05	0.135	2	106
Ramsey Bay - N8	13.40	-	1	76
Maughold - N9/O9	19.33	0.191	1	534
SED - N13/O13	25.35	0.073	4	968
H/I - L15/M15/M16	23.85	0.058	4	2762
Chickens - K13	25.17	0.021	6	10608
<b>1989/90</b>				
Bradda - K11	21.61		8	7141
Peel - K10	18.03		6	2437
Targets - L8/9	21.70		3	887
Maughold - N9/O9	20.21		2	1012
H/I - L15/M15/M16	6.64		2	1215
PSM - L14	18.02		4	4469
Chickens - K13	20.93		5	3480

**Table 2.1.** Catch per unit effort (CPUE) values for *Pecten maximus* (with standard errors) calculated from sample fleet catch-effort statistics. CPUE is shown only for areas where corresponding age-structure data is available. Standard errors have not been calculated for 1989/90 as only summary data were available at the time of writing.

Age	2	3	4	5	6	7	8+	N
<b>1986/7</b>								
Bradda	0	4	64	93	99	100	100	748
Peel	0	0	26	76	92	94	100	219
Targets	0	25	92	100	100	100	100	49
SED	0	0	30	70	91	100	100	400
PSM	0	0	17	92	100	100	100	116
Chickens	0	5	86	98	100	100	100	524
<b>1987/8</b>								
Bradda	0	9	75	98	99	100	100	1280
Targets	0	86	100	100	100	100	100	194
SED	0	1	24	82	94	98	100	703
H/I	0	0	56	96	100	100	100	313
Chickens	0	1	78	96	100	100	100	784
<b>1988/9</b>								
Bradda	0	11	81	94	100	100	100	691
Peel	0	0	73	95	100	100	100	198
Targets	0	87	100	100	100	100	100	212
P. of Ayre	0	0	80	100	100	100	100	166
Ramsey	0	42	100	100	100	100	100	95
Maughold	0	100	100	100	100	100	100	107
SED	0	0	13	72	97	99	100	1033
H/I	0	0	58	100	100	100	100	128
Chickens	0	6	89	100	100	100	100	258
<b>1989/90</b>								
Bradda	0	50	95	97	100	100	100	204
Peel	0	0	54	85	88	100	100	132
Targets	0	32	93	100	100	100	100	128
P. of Ayre	0	0	88	100	100	100	100	59
Ramsey	0	68	93	100	100	100	100	123
Maughold	0	44	100	100	100	100	100	66
PSM	0	0	80	96	100	100	100	172
H/I	0	8	95	100	100	100	100	132
Chickens	0	18	86	98	100	100	100	147

**Table 2.2.** Recruitment ogives, *Pecten maximus*. Values are percentages of recruited scallops ( $\geq 110$  mm shell length) by age in research vessel catches during the winters (November - March) of 1986/7, 1987/8, 1988/9 and 1989/90. N = sample size.

not fished over their whole area, and data is not available for all fished squares.

Similar calculations using *Chlamys opercularis* age-structures and CPUE await longer and more reliable data series, the development of a suitable unit of effort (see Chapter 6) and estimates of gear selectivity and efficiency.

A recruitment index is also calculated from CPUE at age data. Apparent differences in the number of recruits (defined here as the youngest year class in which > 50% of scallops are  $\geq 110$  mm shell length) from year to year could be the result of differences in growth rate as well as variations in year-class strength. In order to eliminate variations due to differences in growth rate from year to year, as well as differences in growth rate between areas, recruitment ogives were calculated for each fishing ground in each year. The recruitment ogives are presented as percentages of each age class which have attained commercial size (Table 2.2). CPUE-at-age values for the recruiting year class are adjusted by the appropriate % selectivity coefficient to give the theoretical CPUE if all that age class were legally retainable. The theoretical CPUE is used as an index of recruiting year-class strength. Recruitment indices are comparable for the same ground in different years, but not between grounds, as the age at first recruitment varies between 3 and 5 years. Recruitment indices are compared with subjectively determined recruitment anomalies (from Section 2.2.1).

#### **2.2.5. Long-term changes in recruitment levels**

A recent study (Brand *et al.*, 1991b) has presented data on long-term changes in the population structure and CPUE of *P. maximus* on the Bradda Head and Chickens fishing grounds. By combining the age structure and CPUE series presented in that paper, using the methods described in section 2.2.4, it is possible to produce estimates of stock and recruit abundance in each year for which data are available, and a stock-recruitment relationship can be fitted to data from years where an estimate of both are available. The parent stock abundance of the recruiting age 4 class is represented by the CPUE during the year of birth.

A Ricker-type stock-recruit relationship (Ricker, 1954; 1975a), modified to include the effect of temperature variability on recruitment, was fitted to data on CPUE (assumed proportional to spawning stock biomass), CPUE of age 4+ scallops (assumed to represent recruit abundance) and water temperature.

The model has the form:

$$R_t = aS_{t-4} e^{-bS_{t-4}} f(T) \quad (2.2)$$

where:

$R_t$  = recruit numbers (CPUE of 4 yr. olds).

$a$  = a constant

$S_{t-4}$  = Parent stock abundance (CPUE of exploited stock).

$b$  = reciprocal of stock size above which density-dependent processes tend to dominate over density-independent processes (defines position of dome in stock-recruit curve).

$f(T)$  = a function of the temperature series hypothesised to affect recruitment.

It was hypothesised that temperature differences during the pelagic dispersal phase (assumed to occur in July) would affect the development time, and therefore the mortality and dispersal of larvae. Temperature differences during this period can therefore be expected to influence recruitment success, if mortality variations in this period of the life-cycle have a strong influence on subsequent recruitment to the commercial fishery, 3-4 years later. The annual temperature minimum occurring during the first winter after settlement was also hypothesised to influence recruitment levels by affecting survival of over-wintering spat. The temperature series used were July mean surface temperatures, and the lowest monthly mean temperature in the winter, both calculated from readings taken daily off Port Erin Breakwater since 1902. The data were obtained from the Annual Reports of the Port Erin Marine Biological Association (Slinn, D.J. & co-authors, 1954-72: *Ann. Rep. P.E. Mar. Biol. Assoc.* 67- 85) and from D. J. Slinn, Port Erin Marine Laboratory (unpublished data).

The functional nature of the temperature-recruitment relationships were first tested by plotting both un-transformed and log-transformed recruitment data (dependent variable) against temperature, and determining the type of model which best fit the data (if any). A larger number of data-pairs were available for fitting temperature-recruitment relationships than for the stock-recruitment relationships. If a significant temperature-recruitment relationship was established from the larger

temperature-recruitment dataset, a temperature function was incorporated into the Stock-Recruitment relationship (Equation 2.2). The parameters of the modified Ricker-equation were calculated by linearizing the equation and using the computed estimates as starting values for fitting the un-transformed equations using the Quasi-Newtonian and Simplex direct-search algorithms in the 'NONLIN' module of SYSTAT (SYSTAT Inc. Evanston, Ill., USA).

## 2.3. RESULTS

### 2.3.1. Comparison of age structures and recruitment anomalies

Examination of *Pecten maximus* age-% frequency histograms (Fig. 2.1) allows subjective assessment of recruitment variability through time for each area sampled, and comparison of population structure between areas.

Samples taken on the inshore grounds (< 5 miles offshore) of Bradda Head, The Targets, The Chickens and Ramsey Bay are dominated by young scallops (2-5 yrs old) over all the four winters covered by the sampling programme. The dominance by pre-recruit and recruiting year class scallops on these grounds suggests both heavy exploitation, reducing the longevity of the population by increasing mortality rate, and regularity of recruitment. Without regular recruitment, continued dominance of young age classes would not occur. Some inshore grounds (Peel and Maughold Head) and the offshore grounds (S. E. Douglas, Port St. Mary, H/I sector) have a wider range of age-classes significantly represented, implying lower exploitation rates.

Age frequency histograms of *Chlamys opercularis* populations are more difficult to interpret comparatively, as fewer age classes are represented (Fig. 2.2). Some of the offshore grounds (S. E. Douglas, Port St. Mary, H/I sector) have a higher percentage of 4, 5 and 6 year old queens, with other areas being dominated by 1, 2 and 3 year olds, including the offshore ground off the Point of Ayre which is, however, heavily exploited by Scottish vessels, being the most accessible queen fishing ground for these boats.

The age-frequency histograms can also be used to look for recruitment anomalies, which will show up as peaks or gaps in the age-frequency histograms. If recruitment were regular, the shapes of the frequency distributions would approximate to a normal or log-normal distribution, with the left tail of the distribution representing selectivity, and the right tail representing mortality rate. Deviations from a smooth distribution indicates recruitment anomalies, and several such anomalies can be seen in the histograms in Figs 2.1 and 2.2.

For *Pecten maximus*, the modal peak on the Bradda ground in 1986/7, at age 4, becomes the modal peak in the summer, 1987 samples at age 5 (Fig. 2.1a). By winter, 1987/8, the modal peak has shifted to the age 3 class which remains the

## **Figs 2.1a - 2.1j.**

Age-frequency histograms of *Pecten maximus* populations sampled on ten fishing grounds in the North Irish Sea, January, 1987 to November, 1989. Samples were pooled within each winter (November to March inclusive). Population structure of samples taken as part of a mark-recapture experiment in June/July 1987 and June 1988 are also included.

Ages are given as number of annual rings; ring formation is assumed to occur in April/May. Subjectively determined strong year-classes are marked with arrows and dates (e.g. 82 indicates a strong 1982-spawned year-class).

Fig. 2.1a. Bradda Head

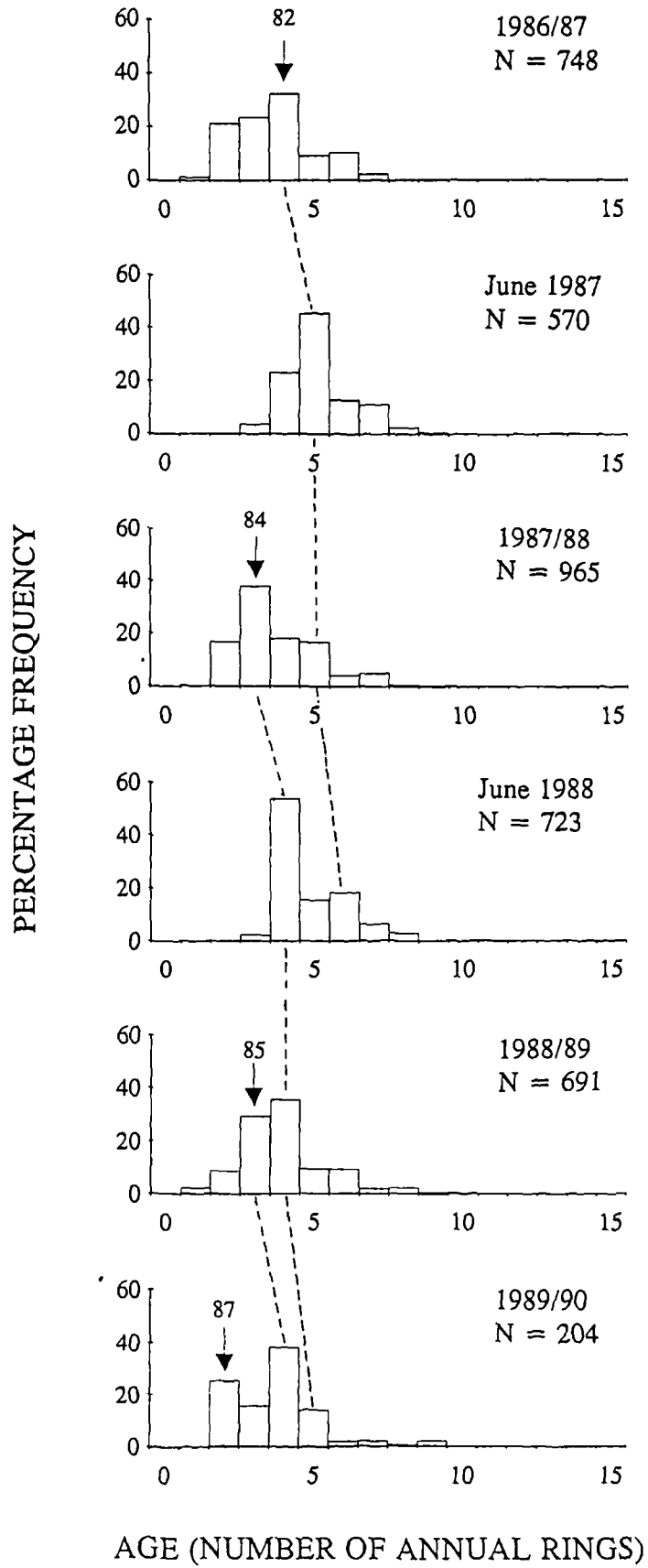




Fig. 2.1b. Peel Head

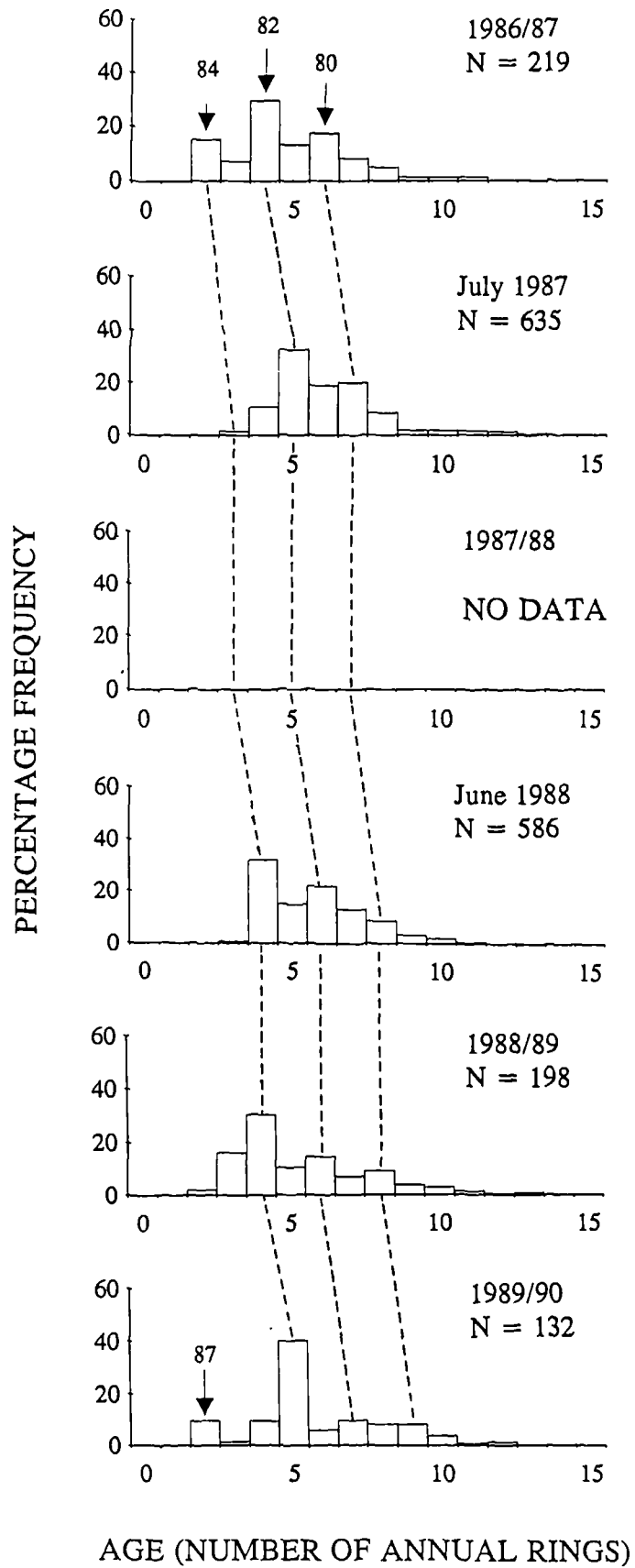


Fig. 2.1c. The Targets

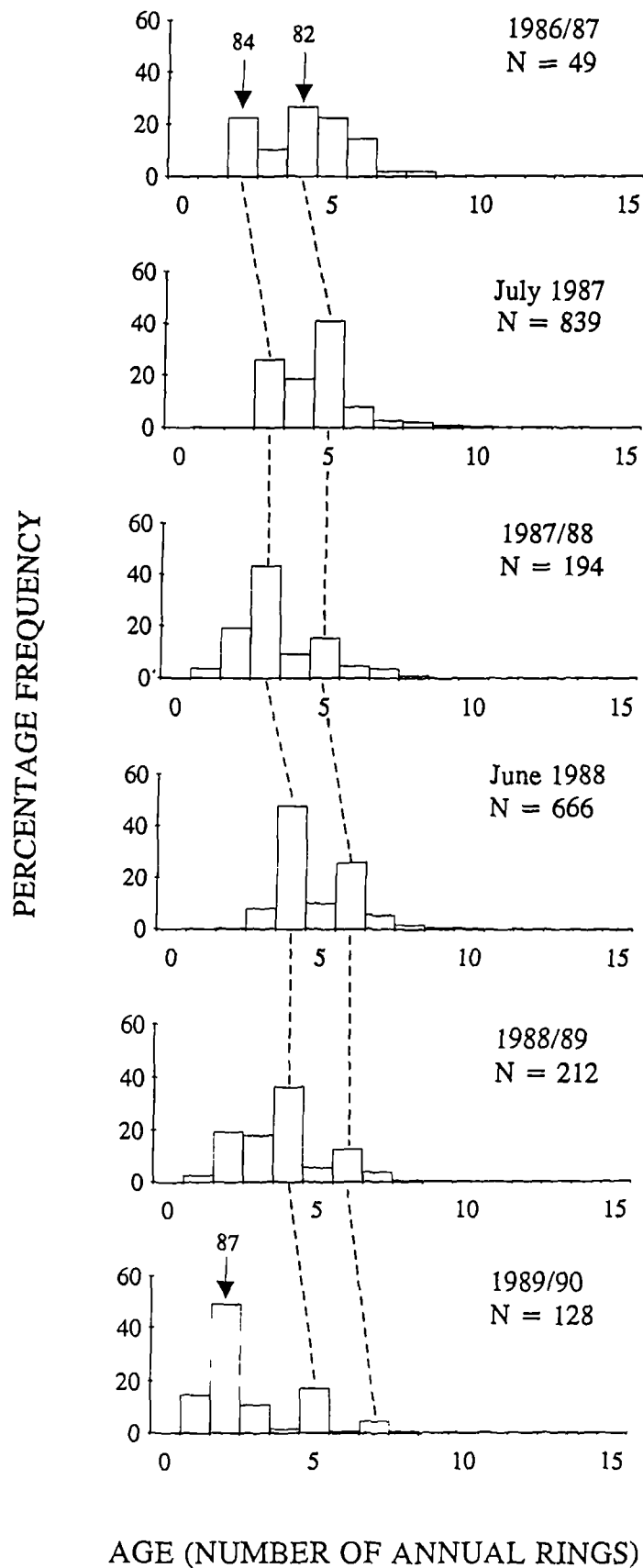


Fig. 2.1d. Port St. Mary

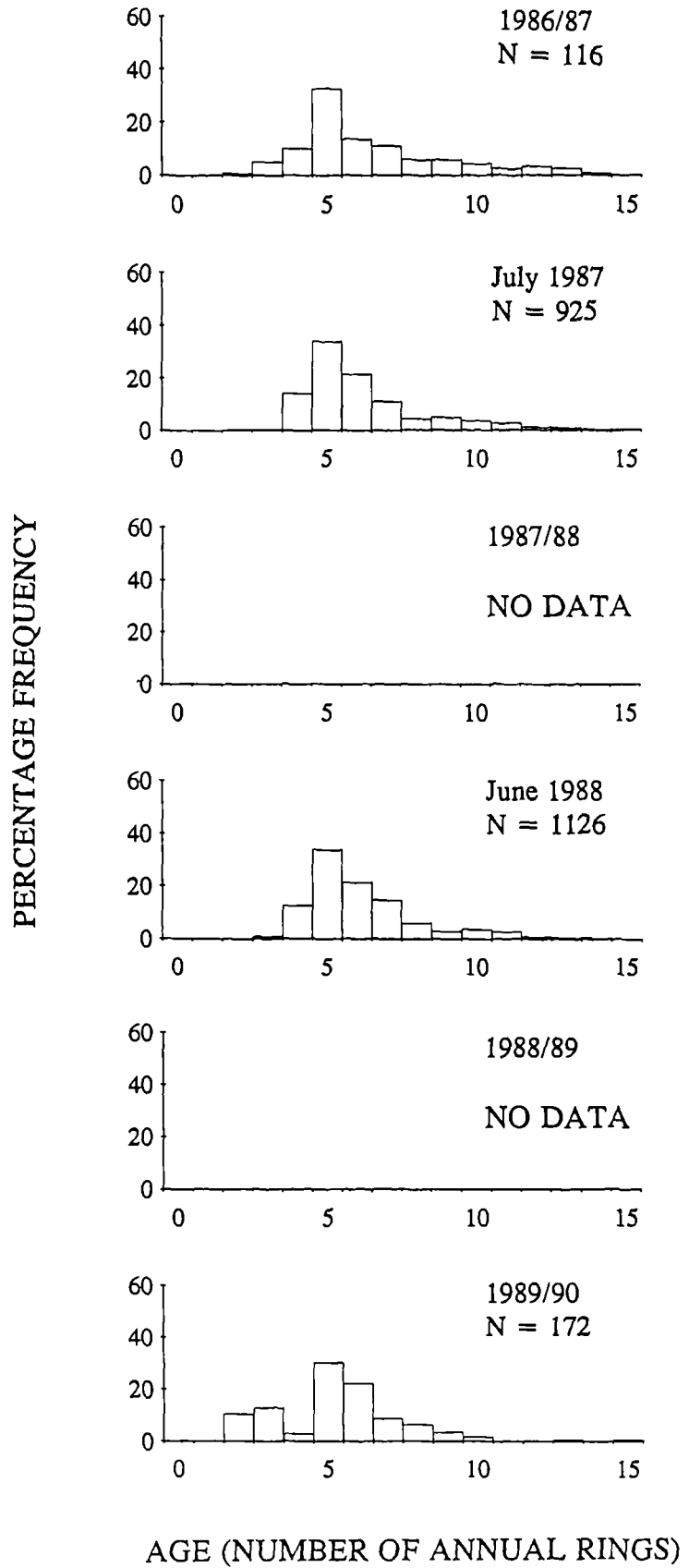


Fig. 2.1e. H/I Sector

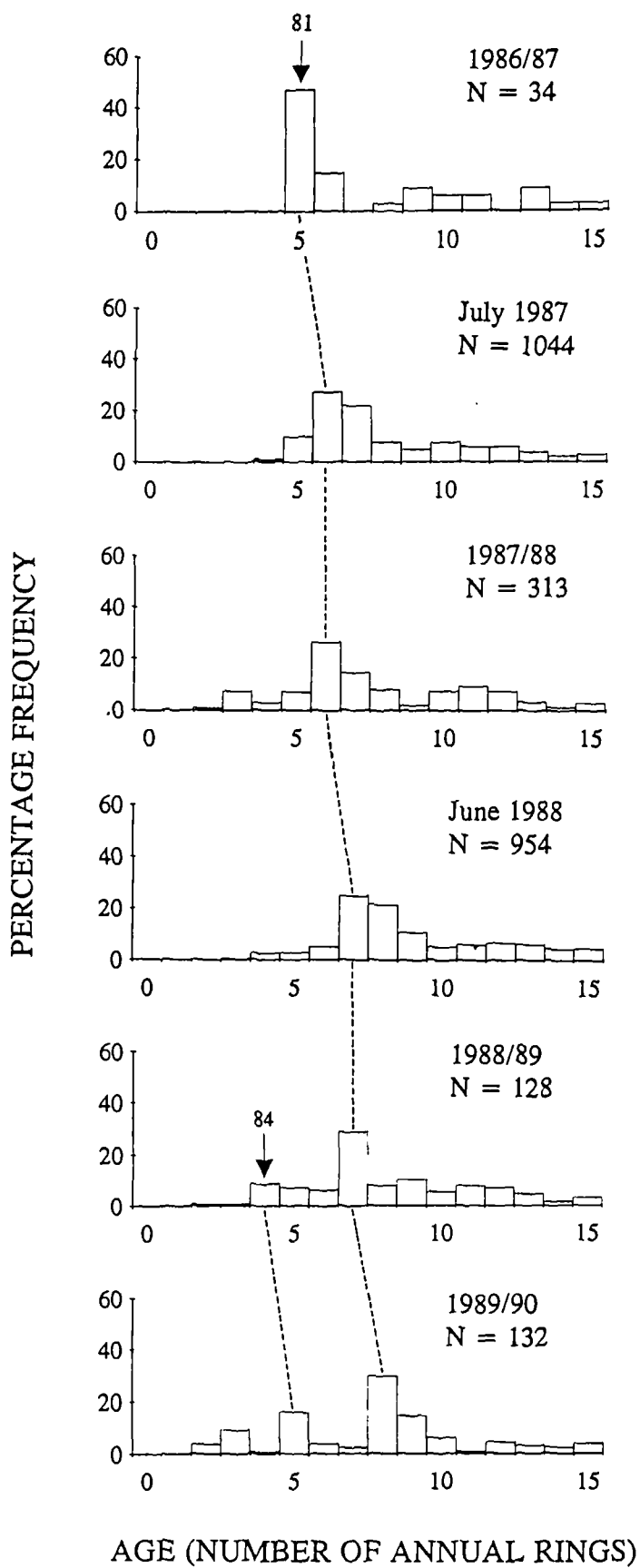


Fig. 2.1f. The Chickens

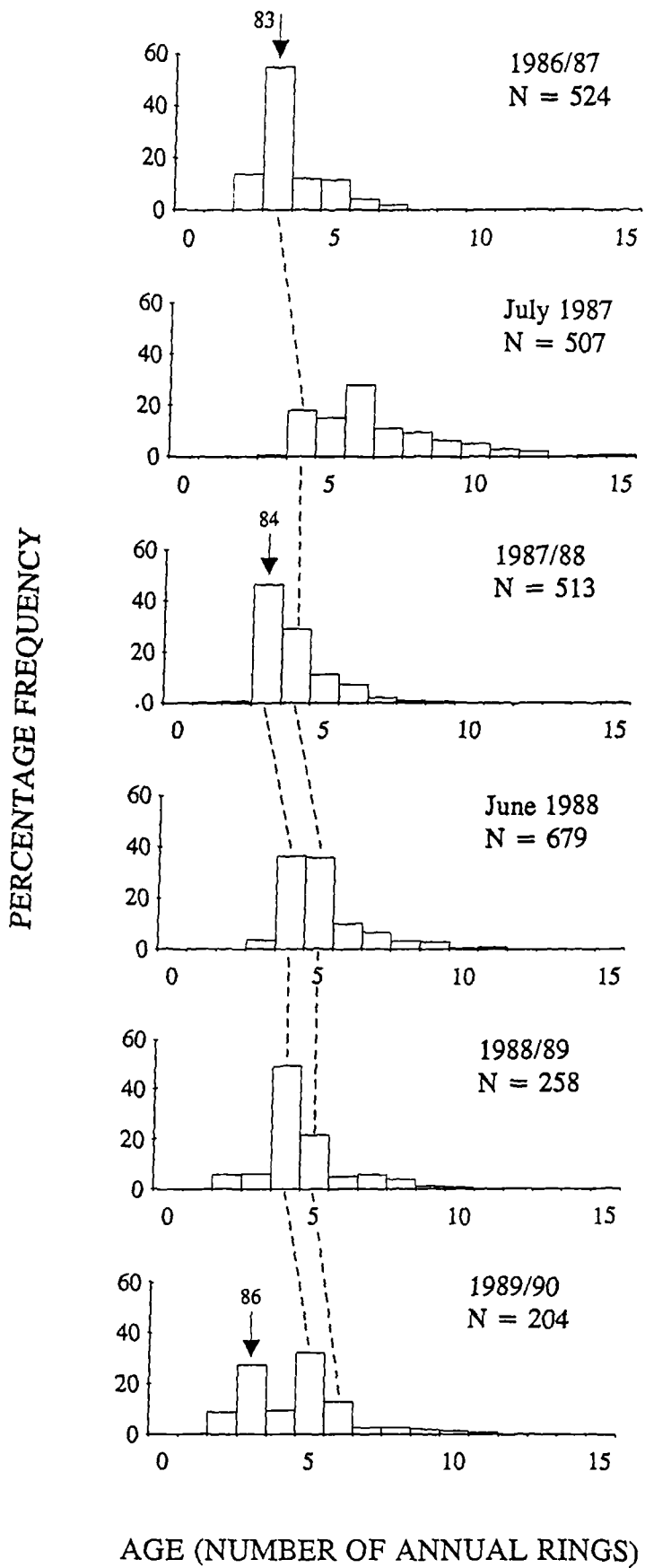


Fig. 2.1g. Ramsey Bay

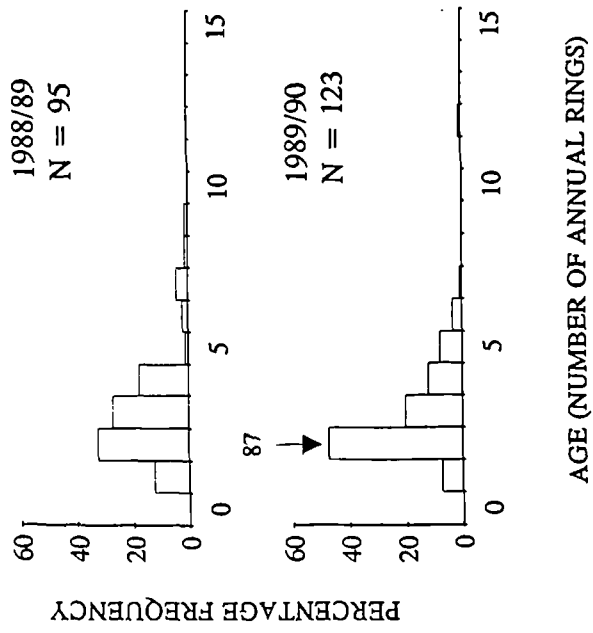


Fig. 2.1h. Maughold Head

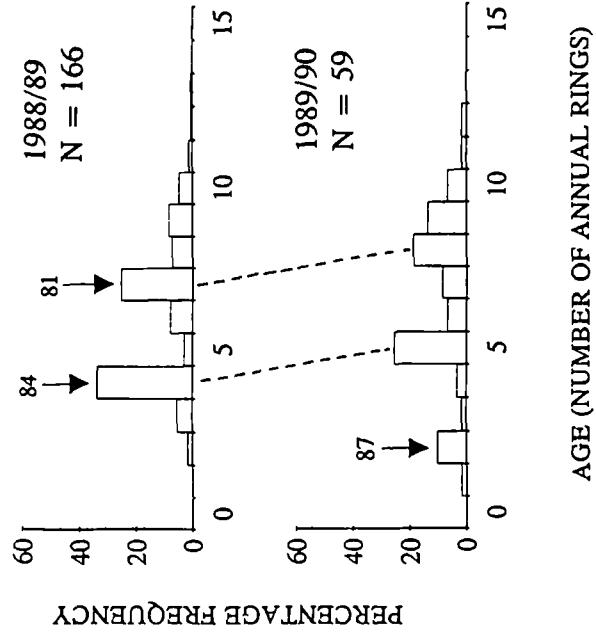


Fig. 2.1i. Southeast Douglas

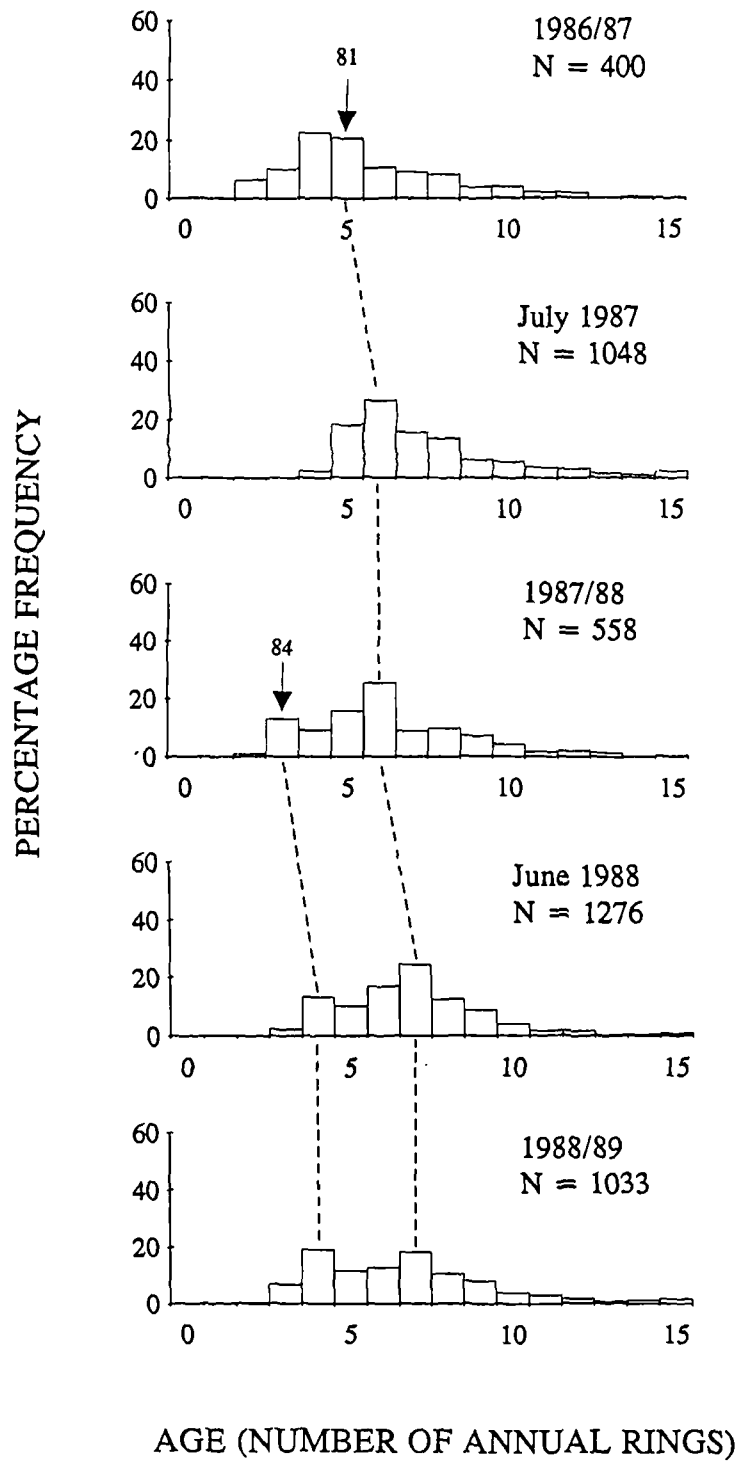
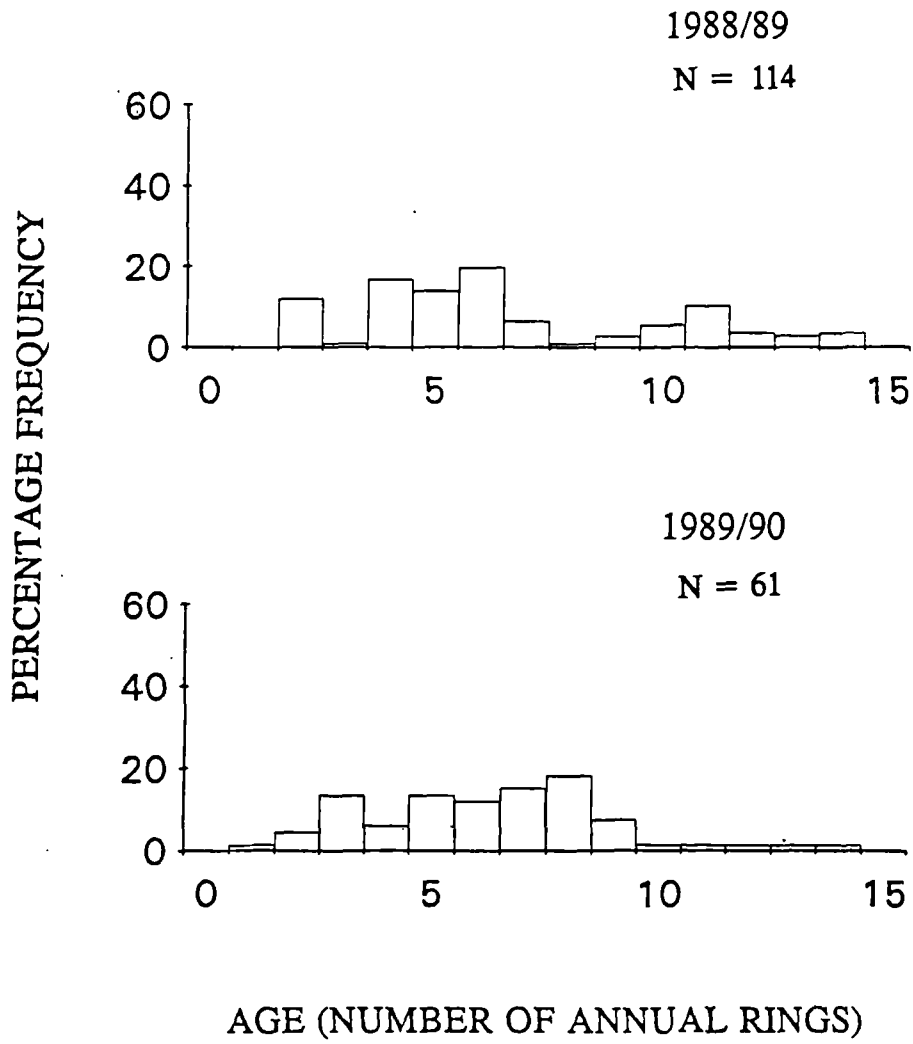


Fig. 2.1j. Point of Ayre.





### **Figs 2.2a - 2.2g.**

Age-frequency histograms of *Chlamys opercularis* populations sampled on seven fishing grounds in the North Irish Sea. January, 1987 to November, 1989. Samples were pooled within each winter (November to March inclusive). Also included are population structures on the East Douglas fishing ground, calculated from samples taken as part of a mark - recapture experiment in May 1987 and June 1989, and commercial vessel catches sampled in July and August 1988.

All samples were taken with queen dredges, with the exception of the Summer 1988 East Douglas sample, which is the un-sorted catch (i.e. before discard of undersize queens) from a commercial trawl.

Ages are given as number of growth (annual) rings; ring formation is assumed to occur in April/May. Subjectively determined strong year-classes are marked with arrows and dates (e.g. 87 indicates a strong 1987-spawned year class).

Fig. 2.2a. The Targets.

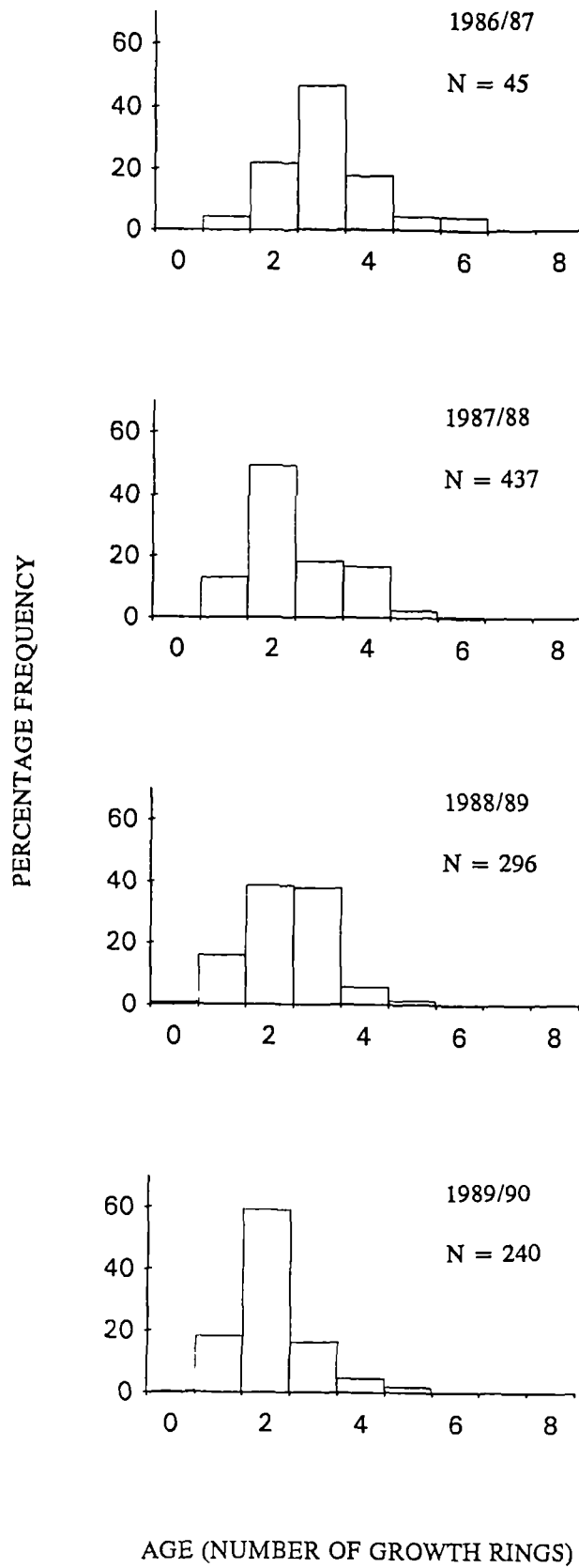


Fig. 2.2b. Point of Ayre

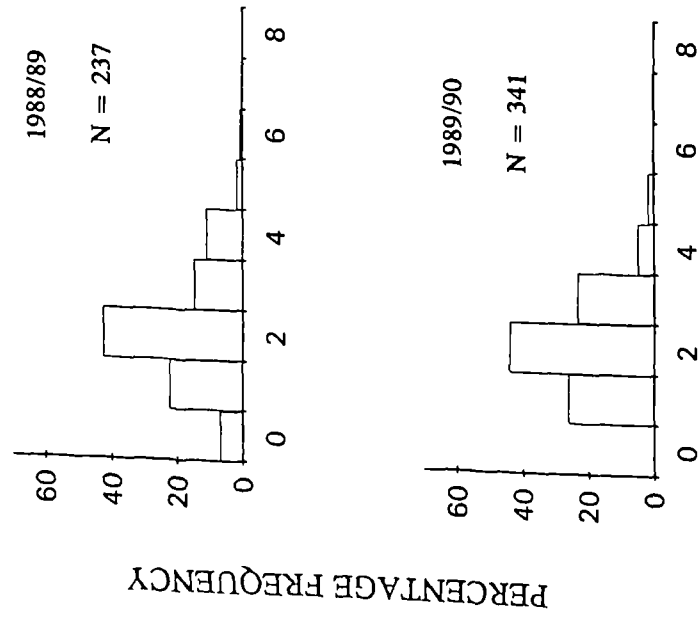


Fig. 2.2c. Ramsey Bay

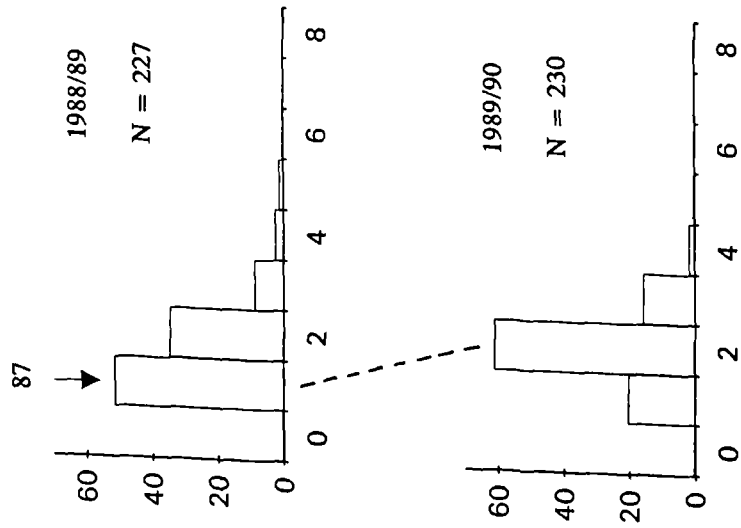
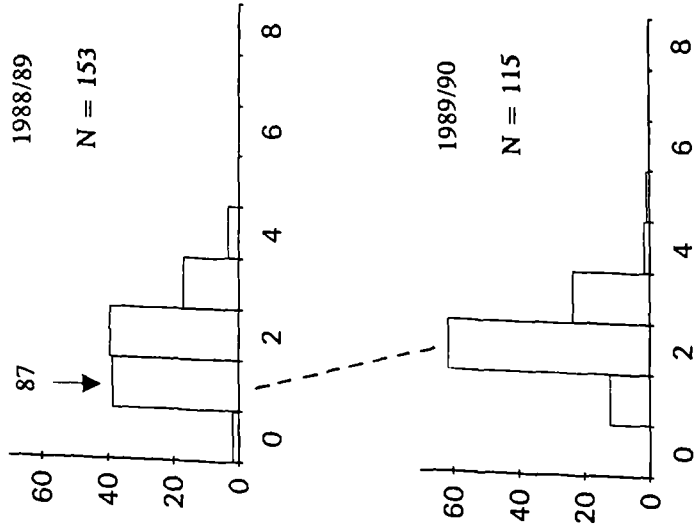


Fig. 2.2d. Maughold Head



AGE (NUMBER OF GROWTH RINGS)

Fig. 2.2e. East Douglas.

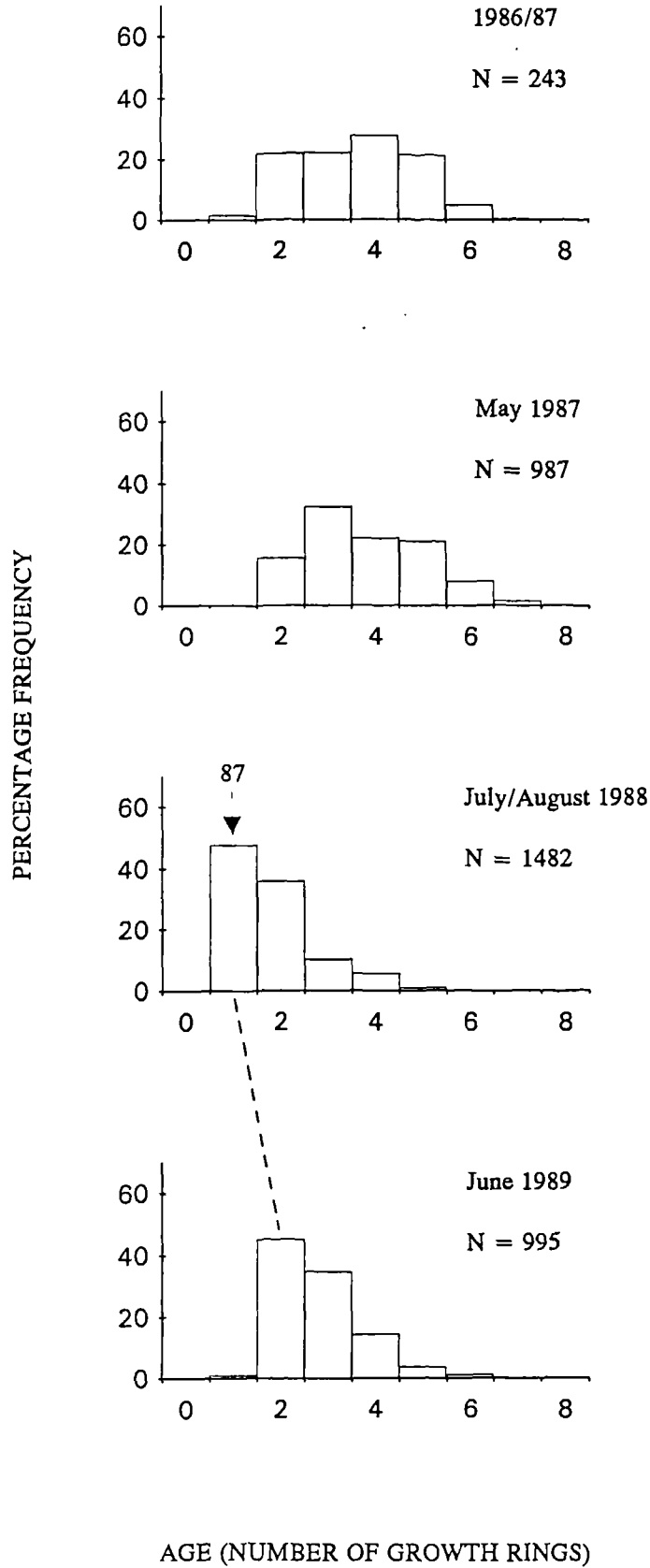


Fig. 2.2f. Southeast Douglas.

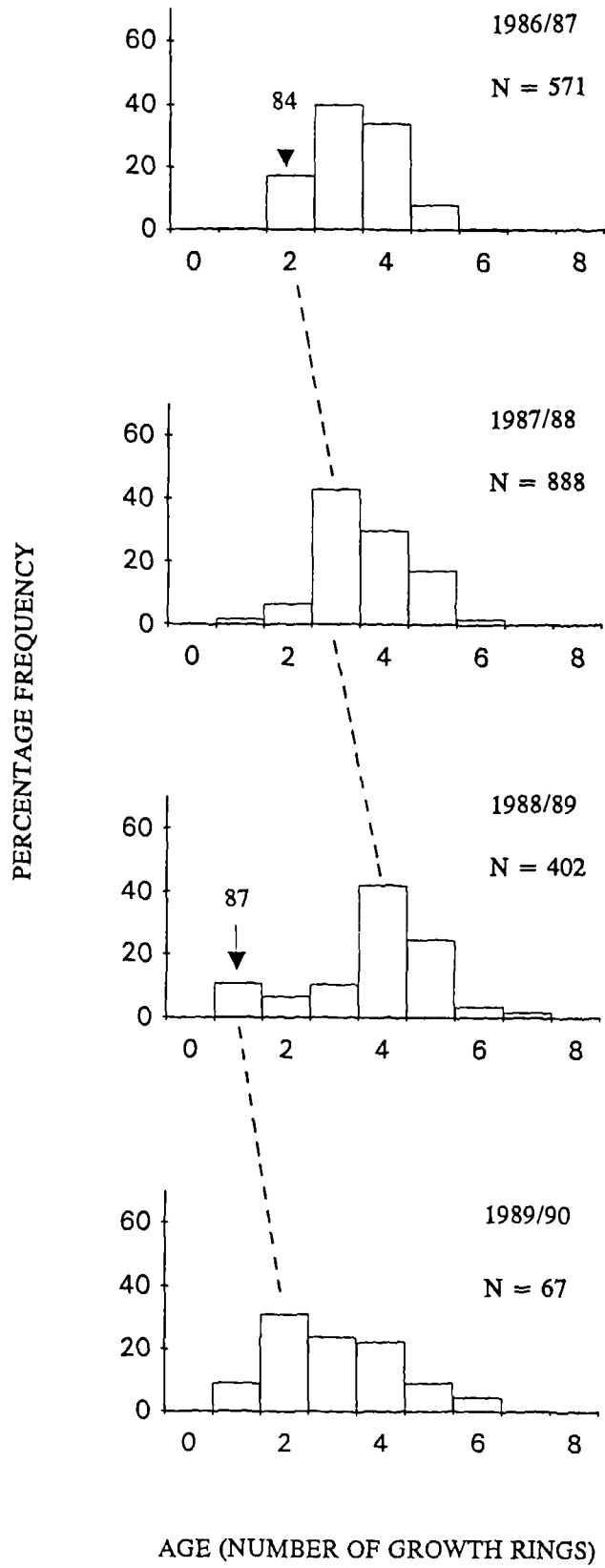
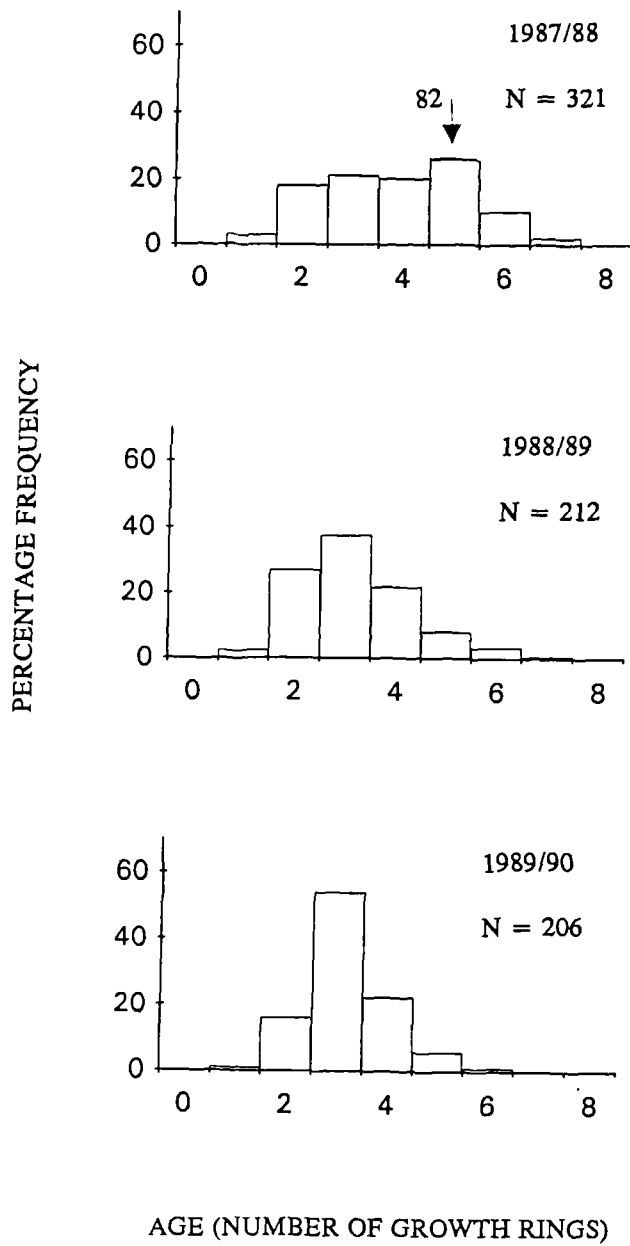


Fig. 2.2g. H/I Sector.



dominant age class in the 1988/9 fishery at age 4. The 1989/90 samples show modal peaks at ages 2 and 4. These distributions imply that of the year classes settling on the Bradda ground recently, those spawned in 1982, 1984 and 1987 were the strongest. The 1986 spawned year class was noticeably weaker. This year class was the main group recruiting to the fishery in the 1990/91 season.

Modal peaks are even more apparent on the adjacent Peel Head ground, where the age-structure is less dominated by young scallops (Fig. 2.1b). Strong year classes in the age distributions are those spawned in 1980, 1982, and 1984, with a suggestion of a strong 1987-spawned year class in the winter 1989/90 sample. The latter three strong year classes are also evident on the Targets ground, just to the north of the Peel ground (Fig. 2.1c).

The fishing grounds to the south of the Isle of Man show a slightly different pattern of recruitment variability. The extensive Port St. Mary ground appears to have received regular recruitment over the last decade, with the age-frequency distribution approximating to a smooth log-normal curve. The only anomaly is a weak 1985 spawned year class evident in the 1989/90 samples (Fig. 2.1d). The farthest offshore ground sampled, (H/I sector), has more irregular recruitment (Fig. 2.1e). The mid- 1970s (1975-77) appear to have been good years for the settlement of scallops on these grounds. More recently, the 1981 and 1984 year classes have been strong, and the 1985 spawned year class poor.

The Chickens ground has a pattern of recruitment anomalies which differs from both the inshore west and offshore south grounds (Fig. 2.1f). The 1986/7 sample is heavily dominated by 3 year old pre-recruits (the 1983 spawned year class). The summer 1987 sample has a modal peak at age 6 (the 1981 spawned year class), but this peak is not visible in later samples. The summer 1987 sample was caught by a commercial vessel, the MFV "Mathilde" of Port St. Mary, during the tagging experiment. The "Mathilde" may have located an aggregation of scallops within the fishing ground which was dominated by this age class.

The inshore grounds on the east coast, Maughold Head and Ramsey Bay, are both small, localised areas, and have markedly different age structures. Ramsey Bay is dominated by pre-recruits (Fig. 2.1g) and Maughold has a wide spread of age classes present in samples (Fig. 2.1h). Sample sizes are small for both grounds, but there is a suggestion of strong 1981, 1984 and 1987 spawned year classes on the Maughold Head ground.

The age frequency histograms of the *Pecten maximus* population on the S. E. Douglas ground show clear peaks for the 1981 and 1984 spawned year classes (Fig. 2.1i).

The Point of Ayre samples are also small, and no single strong year class is apparent from the wide and variable age distributions (Fig. 2.1j). The 1985 spawned year class appears to be weaker than the preceding 1984 spawned year class.

It is difficult to use age-frequency histograms of *Chlamys opercularis* populations to examine recruitment anomalies, as fewer year classes are represented, and the year fully vulnerable to capture by the sampling gear appears to dominate on most grounds (Fig. 2.2). There is some suggestion of a strong 1982 spawned year class on the H/I Sector ground, a strong 1984 spawned year class on the S.E. Douglas ground, and a strong 1987 year class in the S.E. Douglas, Maughold and Ramsey Bay samples. In order to make meaningful analyses of recruitment variability of *C. opercularis*, actual abundance estimates will be required.

Table 2.3 provides a summary of subjectively determined recruitment anomalies in North Irish Sea *Pecten maximus* and *Chlamys opercularis* populations. The fishing grounds to the south of the Isle of Man show good recruitment of *Pecten maximus* of the 1981 and 1984 spawned year classes, and weak recruitment of the 1985 spawned year class, with recruitment to the extensive Chickens and Port St. Mary grounds being very regular. The east coast grounds show a very similar pattern, with the 1981, 1984 and 1987 year classes being the strongest. The 1987 year class is not yet evident in samples from the S.E. Douglas ground, as slow growth rate on this ground results in later recruitment to the sampling gear. The 1985 spawned year class appears to be weak on most southern and eastern grounds, with a suggestion of weak 1983 and 1986 spawned year classes on all but the Chickens ground also. The grounds to the west also show patterns of recruitment anomalies very similar to each other, suggesting that recruitment - determining factors act at a regional level, over adjacent fishing grounds with different local conditions (substrate type, depth, exploitation rate). There appear to be two recruitment regions, the west and the south/east. The western grounds received strong recruitment from the year classes spawned in 1980, 82, 84 and 1987. Weak year classes are the 1986 spawned cohort, and possibly the 1983 spawned cohort.



	<i>Pecten maximus</i>		<i>Chlamys opercularis</i>	
	Strong	Weak	Strong	Weak
SOUTH				
H/I	1981, 84	1985	1982	
PSM		1985		
Chickens	1983, 84, 86			
EAST				
E Douglas			1987	
SE Douglas	1981, 84	1983	1984, 87	
Maughold	1981, 84, 87	1985	1987	
Ramsey Bay	1987		1987	
NORTH				
Point of Ayre		1985		
WEST				
Bradda	1982, 84, 85, 87	1986		
Peel	1980, 82, 84, 87	1986		
Targets	1982, 84, 87	1983		

**Table 2.3.** Summary of recruitment anomalies (variations in year-class strengths) in *Pecten maximus* and *Chlamys opercularis*, determined subjectively from age-frequency histograms of samples taken from North Irish Sea fishing grounds, January 1987 - November 1989. The year refers to the time the age-class was spawned.

The 1984 spawned cohort appears to have been strong on all fishing grounds. The 1987 spawned year class has appeared as a strong age 2 cohort in samples on most grounds to the east and west in the 1989/90 survey, but is not evident on the grounds to the south.

Strong year classes of *Chlamys opercularis* are those spawned in 1987 in most areas, with individual grounds showing peaks in the 1982 spawned age class (H/I sector), and 1984 (S.E. Douglas).

### 2.3.2. Seasonal variability of population structure

In order to determine whether changes in population structure occur during the fishing season, monthly age structures of *Pecten maximus* on a heavily fished inshore ground (Bradda Head) and a less heavily fished offshore ground (S.E. Douglas) are examined. The monthly age-structures show reasonable consistency of histogram shape in successive months (Figs 2.3 & 2.4). On the S.E. Douglas ground (Fig. 2.3) the age 5 class is the modal class in March and April, 1987; the peak having shifted to age 6 by June, 1987 due to the formation of a new annual ring in May/June. The 6 age class remains dominant throughout the 1987/8 fishing season, becoming the 7 year class in June, 1988 and remaining dominant through until December, 1988 when monthly sampling ceased. The relative proportion of the younger age classes in the sample changes during the summer, as younger scallops grow to become large enough to be retained by the sampling gear. There is no obvious increase in the proportion of younger year classes during the winter fishing season. This is consistent with the low exploitation rate estimates for this ground.

Monthly age structures for the Bradda Head ground (Fig. 2.4) show a modal peak corresponding to the age 4 class in the January-March 1987 samples. Growth ring formation took place either in late April or May. By the start of the 1987/8 winter fishing season, the 3 age-class had grown large enough to be selected by the sampling gear, and formed the modal class. The height of the modal peak increased through the season due to the fishing out of the older year classes. The age 3 class became the age 4 class between 7th March and 14th April 1988 due to annual ring formation, and remained the modal class in all subsequent samples.

Changes in population structure of *Chlamys opercularis* during the winter

would not be expected, as most fishing takes place during the summer.

The mean lengths of scallops in samples taken from the Bradda Head and S.E. Douglas grounds just before and during the 1987/88 fishing season are shown in Figs 2.5 and 2.6. Bartlett's tests for homogeneity of variances accept the null hypotheses that there are no significant differences ( $p < 0.05$ ) in sample variances on either fishing ground - an indication that size-class selection is not sufficiently strong to cause a reduction in population variance about the mean. Neither is there a significant change in mean size over the season as a whole on either ground: regressing size against days after the start of the fishing season gives a slope of 0.004 on the Bradda ground (not significantly different to zero,  $0.30 > p > 0.35$ ) and -0.008 on the S.E. Douglas ground (not significantly different to zero,  $0.05 > p > 0.10$ ). Therefore it appears that no strong size (and therefore age) selection takes place within the recruited part of the population within a fishing season.

### **2.3.3. Statistical comparison of spatial differences in population structure**

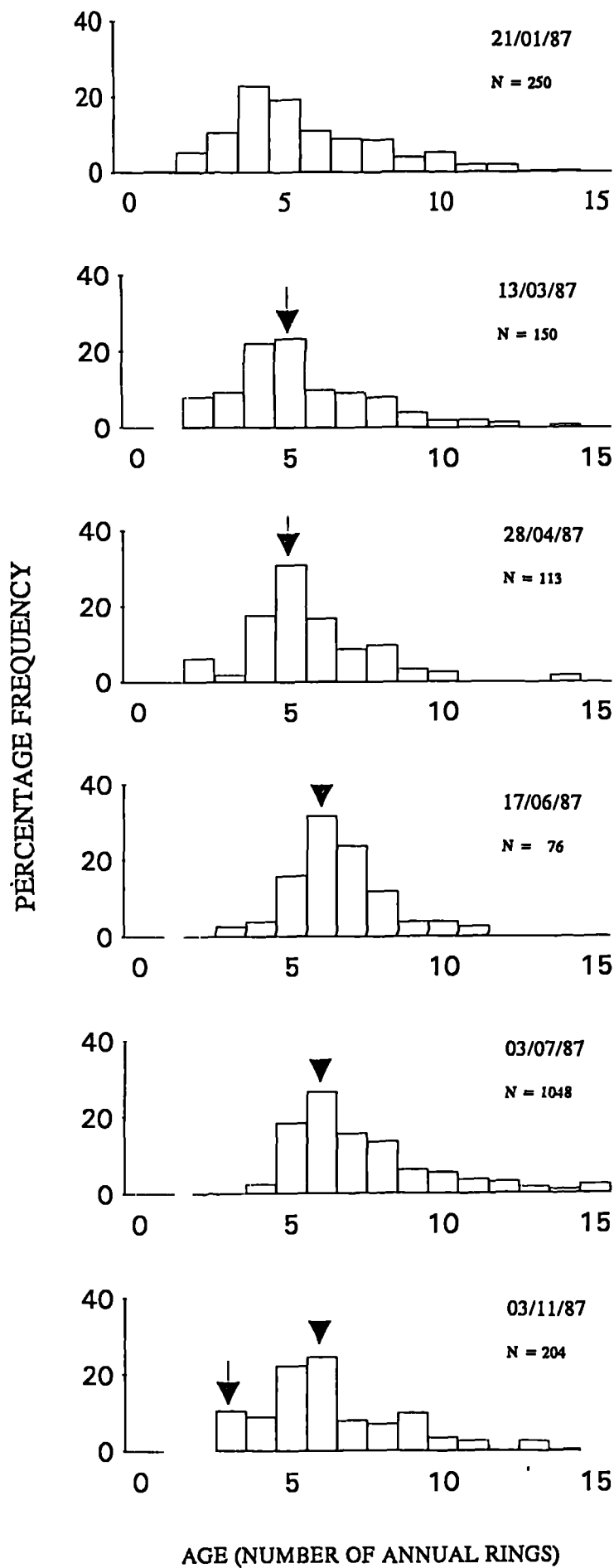
More objective comparison of age-frequency distributions between areas can be made by comparing age-frequency distributions in a contingency table. Chi-square contingency tests indicate that highly significant differences ( $p < 0.0001$ ) in population age-frequency occur between grounds sampled in all years for both *Pecten maximus* and *Chlamys opercularis* (Tables 2.4 & 2.5). Subdivision of the contingency tables to test for differences between adjacent grounds all indicated significant differences ( $p < 0.01$ ), although such testing is not strictly valid as there is a high probability of type 1 errors due to multiple runs of the Chi-square test.

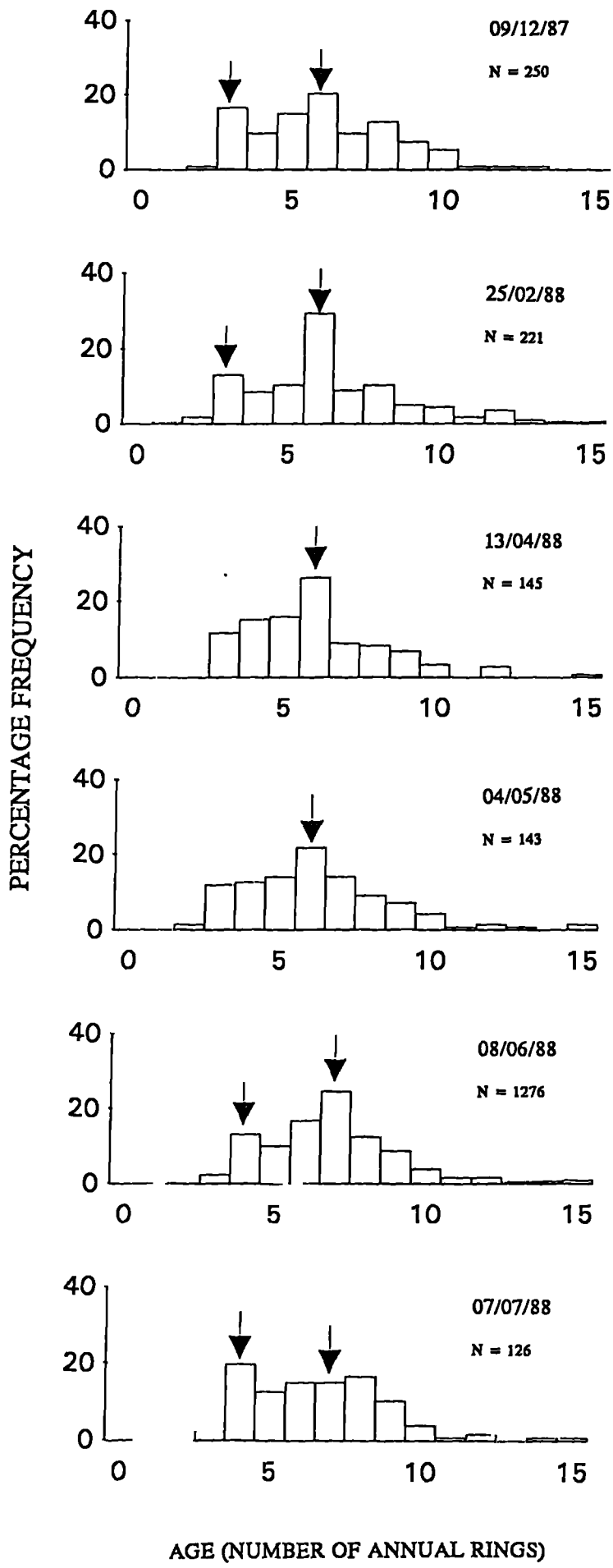
Comparison of median ages for all grounds in each year also indicate that there are spatial differences in median age at the fishing ground level ( $p < 0.0001$  for all comparisons) in both scallops and queens (Tables 2.6 & 2.7). Tukey-type multiple comparisons to test where the differences lie were not possible as sample sizes were not equal or nearly equal (Levy, 1979).

### **2.3.4. Stock abundance-at-age and recruitment index**

Density-at-age values, computed from population age structures and commercial vessel CPUE are presented in Tables 2.8a, 2.8b and 2.8c. The figures given are for commercial-size scallops only. The actual density of younger year-

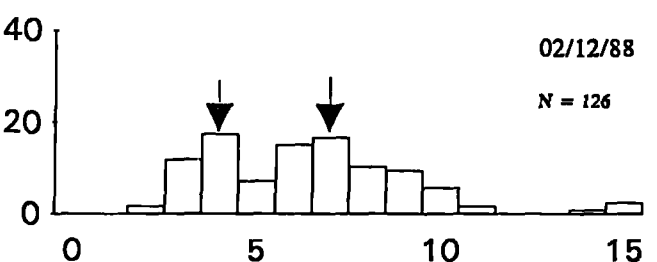
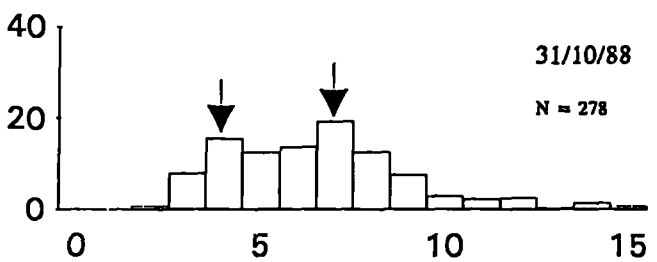
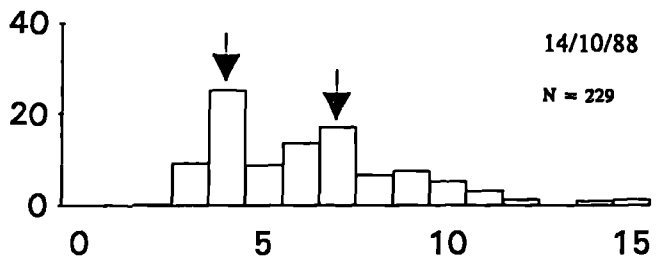
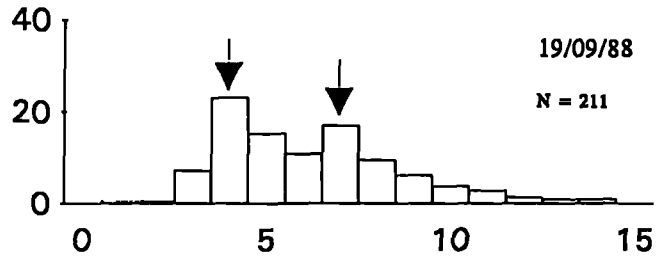
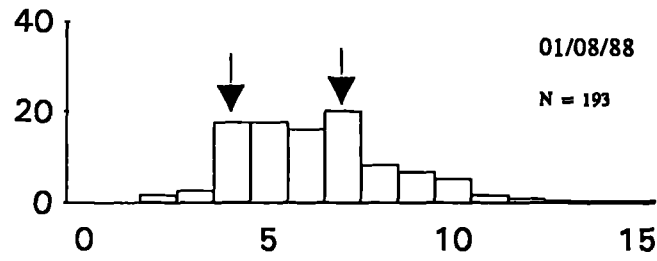
**Fig. 2.3.** Population age-structure of *Pecten maximus* from samples taken approximately monthly on the Southeast Douglas fishing ground, January, 1987 to December 1988. Modal peaks are indicated with arrows and can be traced through successive samples.





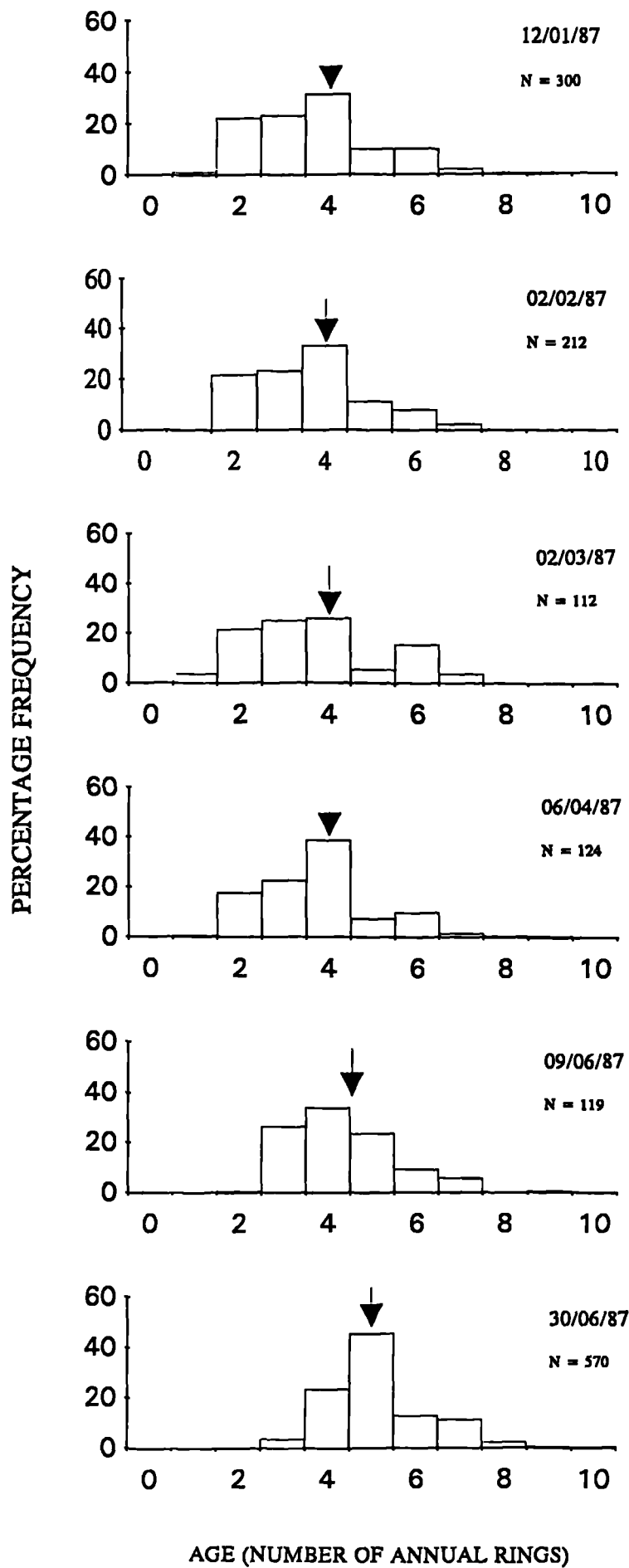
AGE (NUMBER OF ANNUAL RINGS)

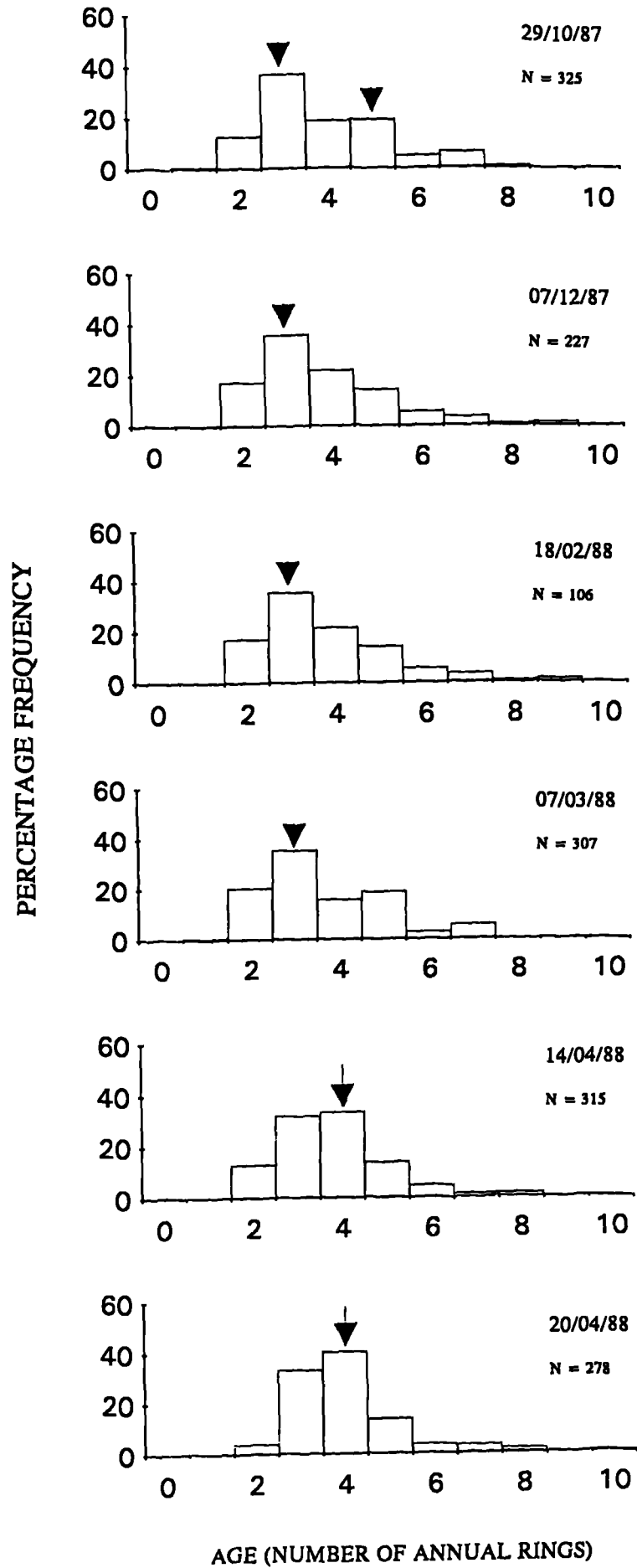
PERCENTAGE FREQUENCY



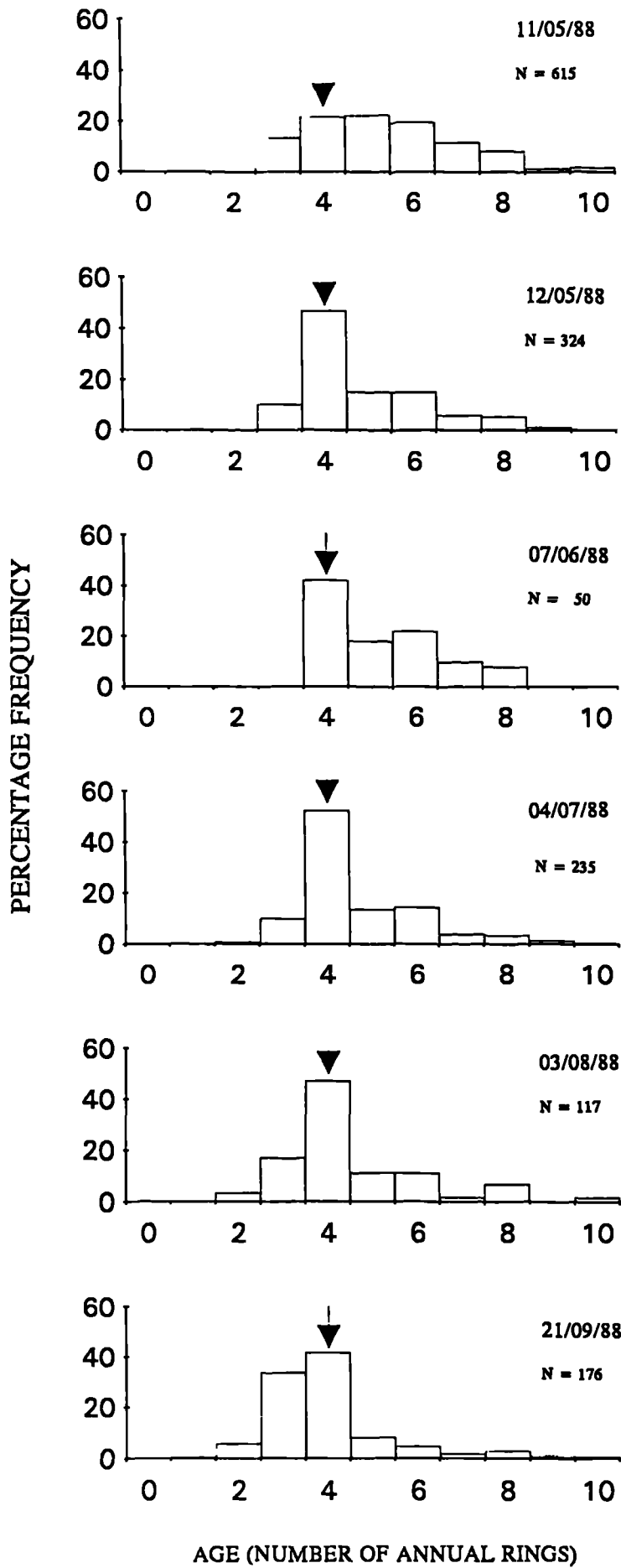
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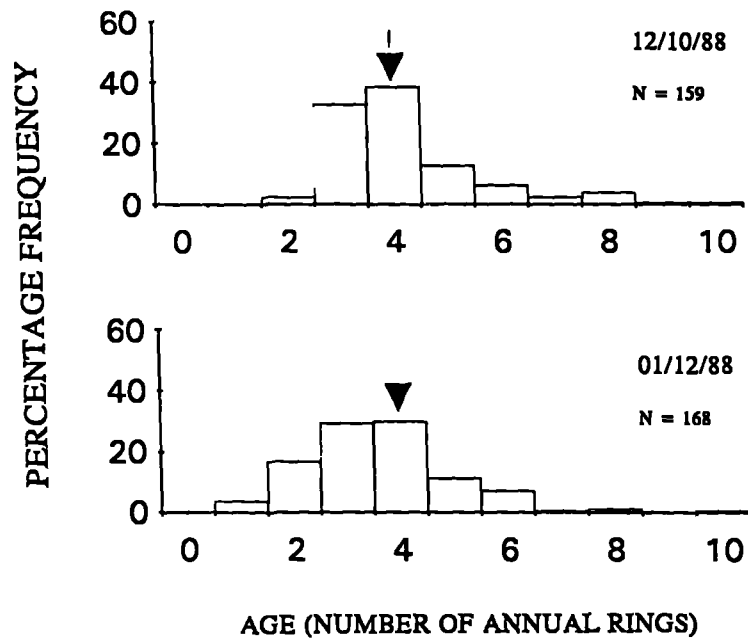
**Fig. 2.4.** Population age-structure of *Pecten maximus* from samples taken approximately monthly on the Bradda Head fishing ground, January, 1987 to December 1988. Modal peaks are indicated with arrows and can be traced through successive samples.











**Table 2.4. *Pecten maximus***

Year	N (areas)	D.F.	Total $X^2$	Reject/Accept $H_0$	P
1986/87	5	32	786.6	R	0.0001
1987/88	5	32	1417.4	R	0.0001
1988/89	9	64	1388.3	R	0.0001
1989/90	9	64	892.0	R	0.0001

**Table 2.5. *Chlamys opercularis***

Year	N (areas)	D.F.	Total $X^2$	Reject/Accept $H_0$	P
1986/87	5	20	196.5	R	0.0001
1987/88	4	15	971.6	R	0.0001
1988/89	7	30	1135.0	R	0.0001
1989/90	6	25	360.4	R	0.0001

**Tables 2.4 & 2.5. Results of  $X^2$  contingency analyses comparing age-frequency distributions of *Pecten maximus* and *Chlamys opercularis* from different fishing grounds within the study area. The null hypothesis, that no significant difference in population age structures occur within the North Irish Sea stocks, is rejected.**

**Table 2.6. *Pecten maximus***

Year	N	D.F.	Median age	Total $X^2$	Reject/Accept $H_0$	P
1986/87	7	6	4	639.6	R	0.0001
1987/88	5	4	5	909.8	R	0.0001
1988/89	9	8	5	662.0	R	0.0001
1989/90	10	9	4	326.8	R	0.0001

**Table 2.7. *Chlamys opercularis***

Year	N	D.F.	Median age	Total $X^2$	Reject/Accept $H_0$	P
1986/87	5	4	3	381.2	R	0.0001
1987/88	4	3	3	265.6	R	0.0001
1988/89	7	6	2	631.6	R	0.0001
1989/90	7	6	2	282.4	R	0.0001

**Tables 2.6 & 2.7.** Results of multiple comparison of medians tests (Mood, 1950). The null hypotheses, that the median ages of scallops or queens is the same on all fishing grounds sampled, is rejected for both species; i.e. there are highly significant differences in the median ages between different fishing grounds within the population.

Fig. 2.5. Bradda Head

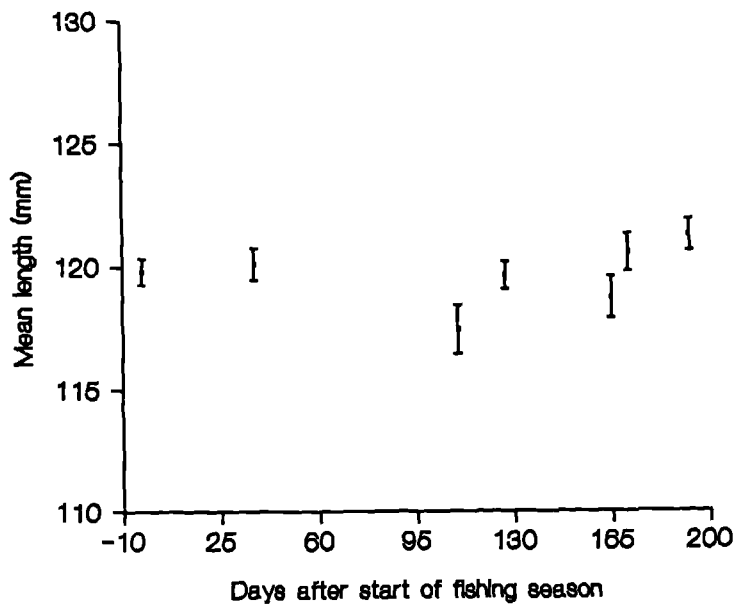
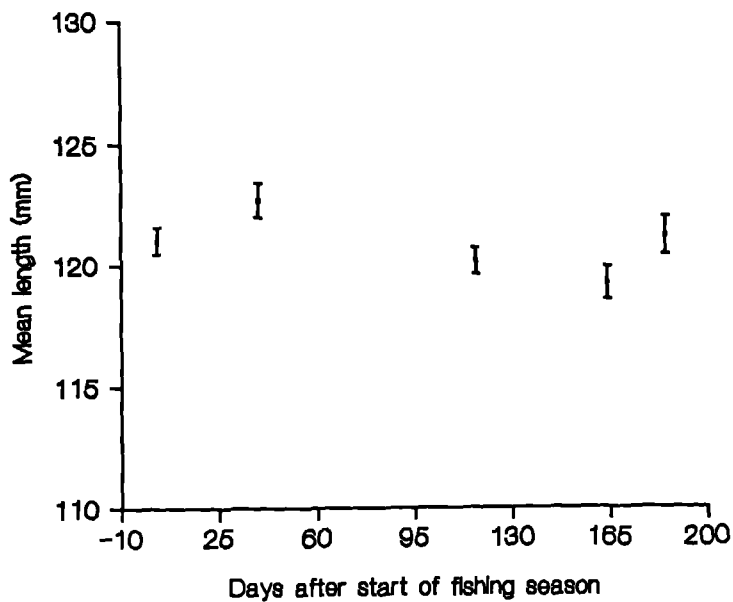


Fig. 2.6. S.E. Douglas



Figs 2.5 & 2.6. Mean lengths, with standard errors, of the recruited fraction ( $\geq 110\text{mm}$ ) of *Pecten maximus* samples taken from the Bradda Head and S.E. Douglas fishing grounds during the 1987/88 scallop fishing season. The season runs from November 1st to May 31st.

Density (No. scallops per 100m<sup>2</sup>)

Age	BRADDA HEAD				PEEL HEAD				THE TARGETS					
	1986/87	1987/88	1988/89	1989/90	1986/87	1987/88	1988/89	1989/90	1987/88	1988/89	1989/90	1987/88	1988/89	1989/90
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.079	0.245	0.194	0.474	0.000	0.000	0.000	0.000	1.822	0.574	0.478	1.822	0.574	0.478
4	1.740	0.972	1.723	2.190	0.518	0.885	0.885	0.222	0.455	1.339	0.204	0.455	1.339	0.204
5	0.722	1.178	0.539	0.831	0.673	0.403	0.403	1.433	0.758	0.210	2.357	0.758	0.210	2.357
6	0.853	0.292	0.562	0.121	1.073	0.584	0.584	0.225	0.225	0.468	0.110	0.225	0.468	0.110
7	0.194	0.360	0.114	0.121	0.517	0.284	0.284	0.411	0.176	0.140	0.644	0.176	0.140	0.644
8	0.025	0.043	0.131	0.030	0.335	0.364	0.364	0.348	0.049	0.033	0.110	0.049	0.033	0.110
9	0.025	0.029	0.036	0.121	0.094	0.160	0.160	0.348	0.000	0.018	0.000	0.000	0.018	0.000
10+	0.000	0.014	0.024	0.000	0.188	0.240	0.240	0.256	0.000	0.000	0.000	0.000	0.000	0.000
Total	3.638	3.133	3.323	3.887	3.397	2.921	2.921	3.243	3.486	2.784	3.903	3.486	2.784	3.903

Table 2.8a. Density of commercial-size scallops on Inshore-west fishing grounds, calculated from commercial CPUE and age-structure data from research vessel samples.

Density (No. scallops per 100m<sup>2</sup>)

Age	POINT OF AYRE		RAMSEY BAY		MAUGHOLD HEAD	
	1988/89	1988/89	1988/89	1988/89	1988/89	1989/90
2	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.609	0.609	0.192	0.192	0.031
4	0.501	0.872	0.872	1.196	1.196	0.142
5	0.521	0.579	0.579	0.106	0.106	1.058
6	0.730	0.236	0.236	0.277	0.277	0.283
7	0.242	0.057	0.057	0.898	0.898	0.354
8	0.034	0.000	0.000	0.255	0.255	0.775
9	0.104	0.000	0.000	0.298	0.298	0.567
10+	0.935	0.057	0.057	0.255	0.255	0.425
Total	3.067	2.410	2.410	3.477	3.477	3.635

Table 2.8b. Density of commercial-size scallops on northern fishing grounds, calculated from commercial CPUE and research vessel age-structure data.

Density (No. scallops per 100m<sup>2</sup>)

THE CHICKENS

PORT ST. MARY

H/I SECTOR

SE DOUGLAS

Age	SE DOUGLAS		H/I SECTOR		PORT ST. MARY		THE CHICKENS				
	1986/87	1987/88	1988/89	1989/90	1986/87	1989/90	1986/87	1987/88	1988/89	1989/90	
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
3	0.000	0.006	0.004	0.010	0.000	0.000	0.000	0.534	0.058	0.020	0.276
4	0.589	0.108	0.155	0.010	0.126	0.100	0.203	2.818	2.401	0.460	0.460
5	1.265	0.648	0.529	0.216	2.172	1.254	2.239	1.366	1.190	1.767	1.767
6	0.834	1.193	0.780	0.052	0.993	0.956	0.852	0.915	0.274	0.727	0.727
7	0.786	0.431	1.138	0.031	0.806	0.376	0.407	0.260	0.318	0.152	0.152
8	0.716	0.485	0.659	0.401	0.432	0.277	0.039	0.124	0.214	0.152	0.152
9	0.349	0.365	0.509	0.196	0.432	0.151	0.039	0.074	0.066	0.113	0.113
10+	0.733	0.505	0.785	0.279	0.993	0.125	0.000	0.049	0.044	0.118	0.118
Total	5.272	3.741	4.559	1.194	5.995	3.241	6.140	5.664	4.527	3.764	3.764

Table 2.8c. Density of commercial-size scallops on Offshore-south fishing grounds, calculated from commercial CPUE and age-structure data from research vessel samples.



THE TARGETS

PEEL HEAD

BRADDA HEAD

Age	BRADDA HEAD				PEEL HEAD				THE TARGETS					
	1986/87	1987/88	1988/89	1989/90	1986/87	1987/88	1988/89	1989/90	1987/88	1988/89	1989/90	1987/88	1988/89	1989/90
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	67 561	210 244	166 444	406 672	0	0	0	0	3 128 663	986 466	820 895	781 368	2 299 410	350 198
4	1 493 879	834 303	1 479 069	1 880 018	444 540	759 967	190 532	190 532	1 302 279	361 064	4 047 992	1 302 279	361 064	4 047 992
5	620 226	1 011 422	462 863	713 567	577 523	345 986	1 230 249	1 230 249	386 483	804 477	188 279	386 483	804 477	188 279
6	732 006	250 847	482 149	103 611	921 549	501 628	193 268	193 268	302 465	240 710	1 106 137	302 465	240 710	1 106 137
7	166 728	309 001	97 456	103 611	443 734	243 942	352 837	352 837	84 018	57 010	188 279	84 018	57 010	188 279
8	21 747	37 080	112 843	25 903	287 840	312 659	298 831	298 831	0	31 672	0	0	31 672	0
9	21 747	24 730	30 775	103 611	80 595	137 432	298 831	298 831	0	0	0	0	0	0
10+	0	12 360	20 517	0	161 191	206 149	219 623	219 623	0	0	0	0	0	0
Total	3 123 894	2 689 987	2 852 117	3 336 992	2 916 973	2 507 763	2 784 173	2 784 173	5 985 276	4 780 809	6 701 780	5 985 276	4 780 809	6 701 780

Table. 2.9a. Abundance of scallops on Inshore-west fishing grounds, calculated from commercial CPUE and age-structure data. The Bradda and Peel grounds are assumed to cover areas of approx. 86E+06 m<sup>2</sup> each, and the Targets ground an area of approx. 170E+06 m<sup>2</sup>.

	POINT OF AYRE	RAMSEY BAY	MAUGHOLD HEAD	
Age	1988/89	1988/89	1988/89	1989/90
2	0	0	0	0
3	0	523 101	328 950	53 511
4	859 495	748 515	2 052 892	243 232
5	895 307	496 965	182 750	1 817 084
6	1 253 430	202 467	475 150	486 463
7	415 678	49 083	1 541 192	608 079
8	57 555	0	438 600	1 330 620
9	179 061	0	511 700	972 927
10+	1 605 158	49 083	438 600	729 695
<b>Total</b>	<b>5 265 684</b>	<b>2 069 213</b>	<b>5 969 834</b>	<b>6 241 612</b>

**Table 2.9b. Abundance of scallops on northern fishing grounds, calculated from commercial CPUE and age-structure data. The Point of Ayre and Maughold Head grounds are assumed to cover an area of approx. 170E+06 m<sup>2</sup> and the Ramsey Bay ground, an area of 86E+06 m<sup>2</sup>.**

Age	SE DOUGLAS				H/I SECTOR				PORT ST. MARY				THE CHICKENS				
	1986/87	1987/88	1988/89	1988/89	1987/88	1988/89	1989/90	1989/90	1986/87	1989/90	1986/87	1987/88	1988/89	1988/89	1987/88	1988/89	1989/90
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	11 072	7 333	0	0	0	53 511	0	0	0	458 770	49 495	17 513	49 495	17 513	236 791	
4	1 011 694	185 389	266 378	580 187	239 359	243 232	243 232	108 218	86 177	0	1 743 989	2 419 111	2 061 432	2 419 111	2 061 432	395 136	
5	2 171 769	1 111 993	908 490	814 215	990 451	1 817 084	1 817 084	1 864 979	1 076 916	1	1 922 178	1 172 593	1 021 583	1 172 593	1 021 583	1 516 702	
6	1 432 109	2 049 239	1 339 009	732 794	3 861 579	486 463	486 463	852 887	820 911	731 372	785 977	235 388	235 388	785 977	235 388	623 898	
7	1 348 925	740 184	1 953 835	3 361 547	2 122 394	608 079	608 079	692 198	323 164	349 064	223 048	273 050	273 050	223 048	273 050	130 583	
8	1 229 020	832 535	1 132 377	907 269	1 179 108	1 330 620	1 330 620	370 820	237 730	33 244	106 213	183 602	183 602	106 213	183 602	130 583	
9	599 522	626 547	873 548	1 186 428	280 038	972 927	972 927	370 820	130 009	33 244	63 728	56 493	56 493	63 728	56 493	96 728	
10+	1 258 997	866 867	1 348 068	3 466 232	4 451 133	729 695	729 695	852 887	107 721	0	42 485	37 662	37 662	42 485	37 662	101 565	
Total	9 052 036	6 423 826	7 829 038	11 048 672	13 124 061	6 241 612	6 241 612	5 112 809	2 782 628	5 271 861	4 862 651	3 886 723	3 886 723	4 862 651	3 886 723	3 231 987	

Table 2.9c. Abundance of scallops on Offshore-south fishing grounds, calculated from commercial CPUE and age-structure data. The SE Douglas ground is assumed to cover an area of approx 170E+06 m<sup>2</sup>, the H/I Sector ground, an area of 258E+06 m<sup>2</sup>, and the Port St. Mary and Chickens grounds, an area of 86E+06 m<sup>2</sup> each.

classes will be higher, as not all the scallops in a year-class are recruited to the fishery. The density of individual year-classes is very low: less than 1 scallop per 100 m<sup>2</sup> of seabed in most cases. Overall densities of commercially exploitable scallops are of the order 3 to 6 scallops per 100 m<sup>2</sup>. Mean density of scallops is higher on the offshore-south grounds (Table 2.8c). The calculated densities are highly sensitive to the values for gear efficiency and towing speed chosen for their calculation. If gear efficiency of 30 % and towing speed of 2 knots (3.71 km h<sup>-1</sup>) are used in the calculation (both within the range of possible values) the density is half that calculated with a 20% efficiency and 1.5 knot (2.78 km h<sup>-1</sup>) towing speed.

The abundance-at-age estimates (Tables 2.9a, 2.9b & 2.9c) are likewise sensitive to chosen values for gear efficiency and towing speed, but are additionally subject to errors in the assumptions made about the area that the fishing grounds cover. The figures indicate that about 0.5 to 1.5 million scallops recruit to a grid-square each year, and the grid-squares which are most regularly fished support populations of the order of 2 to 5 million commercial sized scallops. Stock size is highest in 1986/7 and 1989/90 for most grounds. Poor recruitment to the more heavily fished grounds in 1987/8 and 1988/9 is the main cause of the lower total abundances in these years.

Recruitment index (RI) values calculated from CPUE, age-structure data and recruitment ogives, are given in Table 2.10. The calculated recruitment indices show generally good agreement with the subjectively designated 'strong' and 'weak' year classes in Table 2.3. The 1982-spawned year class gave rise to high RI values on the Peel, Bradda Head and Targets grounds. These high RI values correspond to visually detectable anomalies in the age-frequency histograms on all these grounds. A high RI value for 5 year olds recruiting to the S.E. Douglas ground also corresponds with a 'strong' 1981-spawned year class, but a similarly high RI value for 5 year olds recruiting to the Port St. Mary ground does not appear as an anomaly in the age-frequency distribution from this ground. A peak corresponding to the 1983-spawned year class on the Chickens ground is also reflected in a high RI value in the 1987/8 fishery. The 1984-spawned year class, while appearing to be anomalously strong on most grounds, did not, however, give rise to particularly high RI values for most grounds. Relatively good recruitment was observed on The Targets, where the visually detected 1984 anomaly was reflected in a high RI value for 3-year olds in the 1987/8 fishery, and on the Bradda and Chickens grounds, where high RI values for 4-year olds were observed in the 1988/9 fishery.

Changes in overall stock abundance are reflected in the CPUE-based estimates, whereas in the subjective methods in Section 2.2.1 no account is taken of actual, rather than relative, abundances. Recruitment levels differ between inshore and offshore grounds, with the former generally receiving more recruits each year. Of the offshore grounds, Port St. Mary appears to have the highest recruitment levels and the H/I sector ground, the lowest.

### 2.3.5. Long-term variation in recruitment

Combination of datasets on long-term changes in population structure and CPUE from Brand *et al.*, (1991b) using 4 year olds (i.e. scallops with 4 rings) as the recruiting year class, give an incomplete series of estimates of recruitment index from the Bradda and Chickens grounds, resulting from spawnings since 1946 (Fig. 2.7). Early CPUE estimates are based on various research vessel surveys (see Brand *et al.*, 1991b for details) and CPUE estimates since 1981 are calculated from logbook catch and effort statistics. The estimates cannot be adjusted by the recruitment ogive, as the frequency distributions of length classes within each age class are not available in all years. However, since a large proportion of 4 year olds are recruited each year on these grounds, despite annual variations in growth rate, the estimates of CPUE will provide a reasonable estimate of recruit abundance.

Recruitment to the Bradda ground appears to have been at a similar level since the early 1960s (Fig. 2.7). The decline in stock size on the Bradda ground from 1950-51 (Fig. 2.8) was largely due to a low recruitment from the 1947 spawned year class. It is not known if the high recruitment level of 1946 was typical of preceding years or not, and the parent stock size (in 1942) is not known. Since 1962, when the next surveys were undertaken, stock sizes have been of a similar order of magnitude (Fig. 2.8) and recruitment has been correspondingly fairly regular but low. During the period of study, there has been no overall trend in sea-surface temperatures (Fig. 2.9), but annual fluctuations are evident. Particularly cold winters were those of 1946/7, 1962/3 and 1985/6. Warmest July temperatures were in 1949, 1959 and 1975.

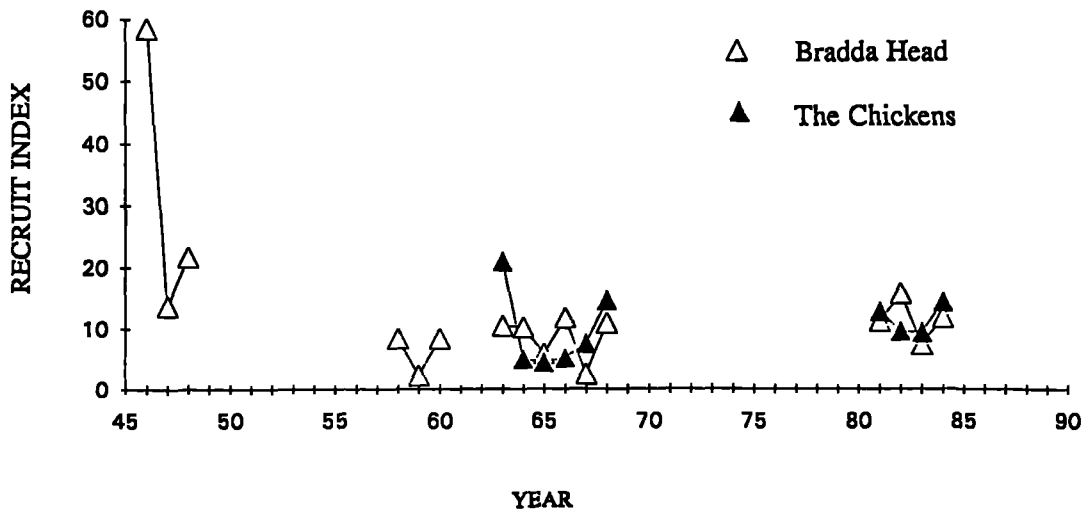
Plotting mean temperature during the pelagic phase ( $T_j$ ) against recruitment ( $R_j$ ) for the Bradda Head ground indicates a possible linear relationship (Fig. 2.10a). If  $R_j$  is regressed against  $T_j$ , the fitted regression line ( $R_j = 80.53 - 5.36T_j$ ) indicates a significant negative relationship between the two variables ( $r^2 = 0.304$ ,

### Recruitment Index

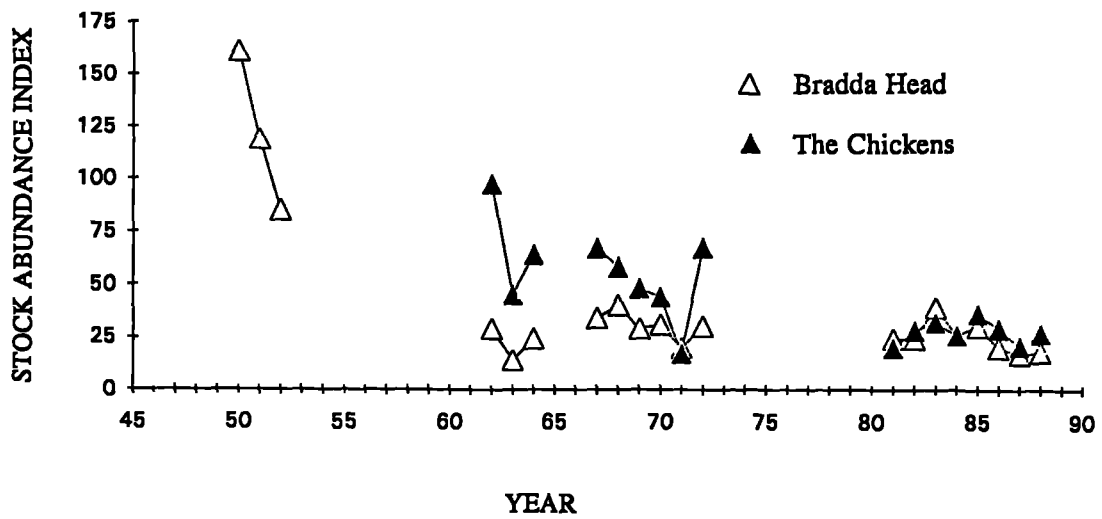
Area	Recruit. Age	1986/87	1987/88	1988/89	1989/90
Bradda Head	4	15.12	7.21	11.83	12.82
Peel Head	4	11.08		6.74	2.28
The Targets	3		11.78	3.67	8.31
Point of Ayre	4			3.48	
Ramsey Bay	4			3.06	
Maughold Head	4			6.65	1.80
S.E. Douglas	5	8.68	4.01	4.12	
H/I Sector	4		0.96	2.16	0.06
Port St. Mary	5	13.13			7.26
The Chickens	4	1.31	20.09	15.00	2.98

Table 2.10. Recruitment indices, calculated from CPUE at age data, with the CPUE of the recruiting year-class (>50% recruited) adjusted by the percentage >110mm shell-length (from the recruitment ogives in Table 2.2).

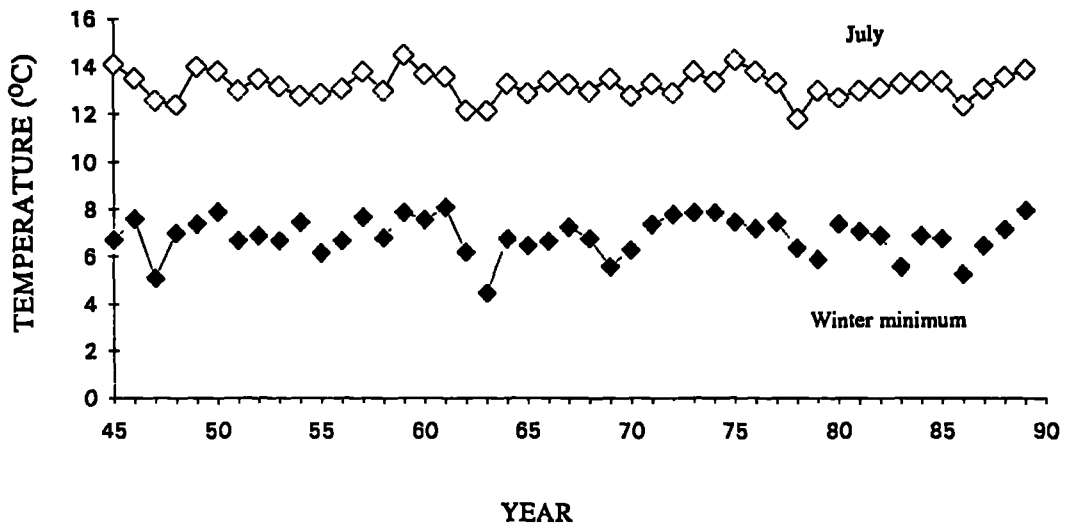
**Fig. 2.7.** Recruitment Index (CPUE of 4 yr. olds), Bradda and Chickens scallop fishing grounds.



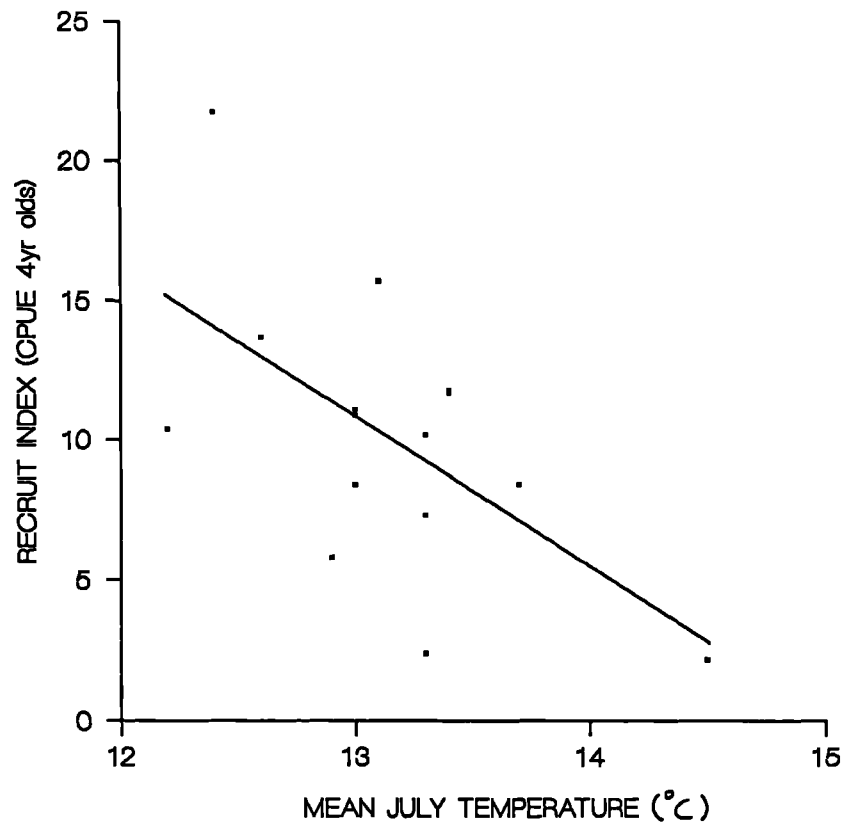
**Fig. 2.8.** Stock abundance index (commercial-size scallop CPUE) Bradda and Chickens fishing grounds.



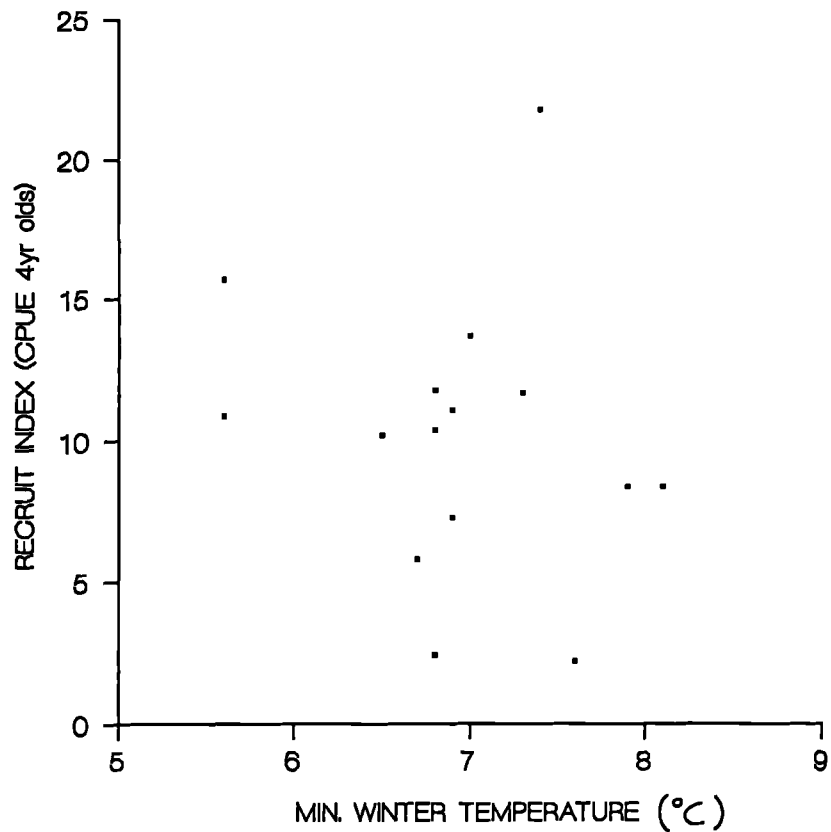
**Fig. 2.9.** July mean surface temperatures and minimum Monthly mean temperatures, Port Erin Breakwater, 1945- 1989.



**Fig. 2.10a.** Relationship between scallop recruitment index and mean July sea-surface temperatures.



**Fig. 2.10b.** Plot of scallop recruitment index against minimum Winter sea-surface temperature. No significant relationship exists between the two variables.





$F = 7.117$ ,  $0.02 < p < 0.05$ , 1 numerator degree of freedom (NDF), 14 denominator degrees of freedom (DDF)) within the range of observed temperatures. There is no significant relationship between  $R_t$  and the lowest monthly mean temperature in the winter after spat-settlement (Fig. 2.10b;  $r^2 = 0.04$ ,  $F = 0.497$ ,  $0.4 < p < 0.5$ , 1 NDF, 14 DDF). There are only 8 data-pairs for the Stock size index ( $S_t$ )-  $R_t$  relationship. The two-parameter Ricker stock-recruit model gives a significant fit ( $r^2 = 0.771$ ,  $F = 10.100$ ,  $0.01 < p < 0.02$ , 2 NDF, 7 DDF) to this limited data.

There is no relationship between  $R_t$  and either temperature series or  $S_t$  for the Chickens data.

If the linear relationship between July temperature and recruitment index is incorporated in the Ricker Stock-Recruitment equation (Equation 2.1 in Section 2.2.5), the equation becomes:

$$R_t = aS_{t-4} e^{-bS_{t-4}} + (cT_{J,t-4}) \quad (2.3)$$

where  $R_t$  = recruit numbers (CPUE of 4 yr. olds).

$a$  = constant

$S_{t-4}$  = Parent stock abundance (CPUE of exploited stock).

$b$  = reciprocal of stock size above which density-dependent processes tend to dominate over density-independent processes (defines position of dome in stock-recruit curve).

$c$  = constant defining the relationship between recruitment and temperature.

$T_{J,t-4}$  = July surface temperature ( $^{\circ}\text{C}$ ) during the year recruits were spawned.

This multiple regression equation provides a slightly better fit than the unmodified Ricker equation ( $r^2 = 0.774$ ,  $F = 10.274$ ,  $0.01 < p < 0.02$ , 3 NDF, 7DDF). Calculated parameter values are:

$$a = 2.65$$

$$b = 0.048$$

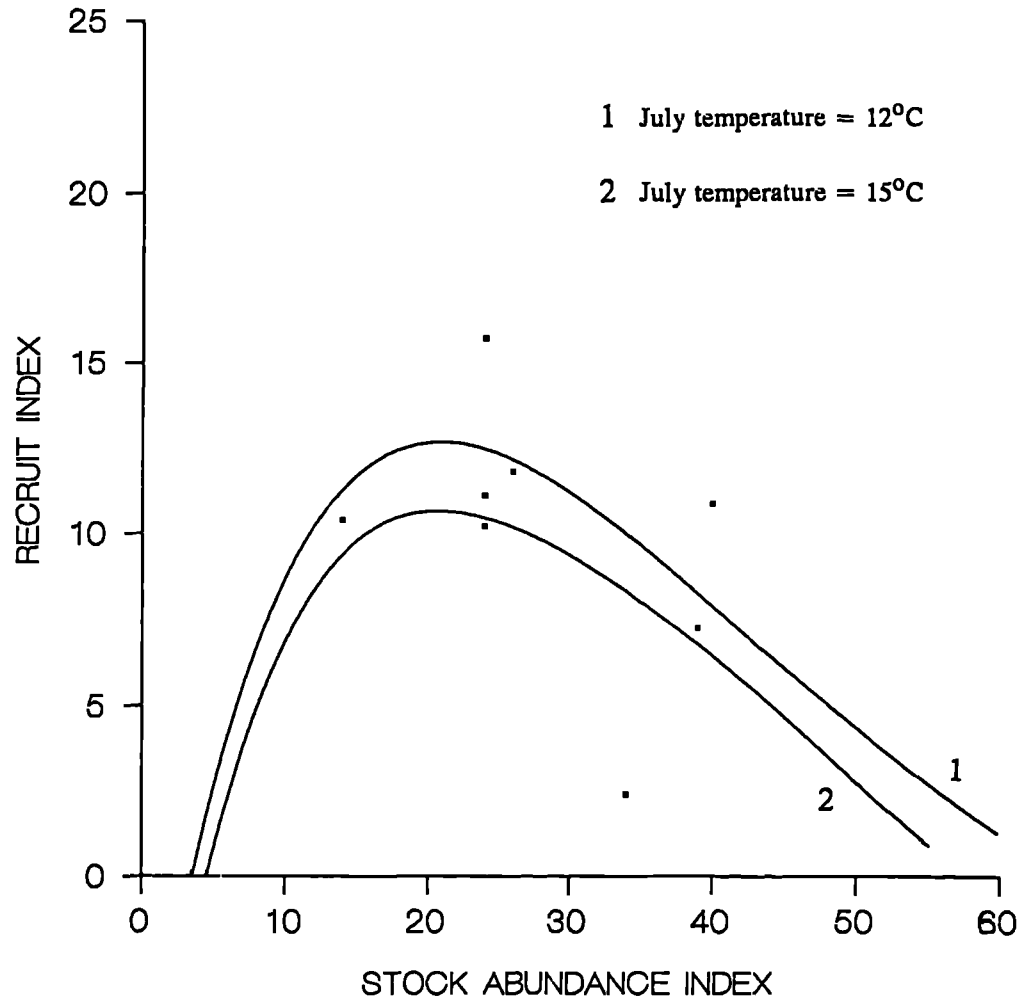
$$c = -0.64$$

These parameter values allow a family of stock-recruit curves to be developed - one curve for each July temperature value. Fig. 2.11 shows the stock-recruit curves for July temperatures of 12 and 15° C. As the temperature-recruitment term is linear and additive, it simply shifts the stock-recruit curve up and down. The two curves shown in Fig. 2.11 include the range of all observed July temperatures. Note that the negative temperature-recruitment relationship in the multiple regression equation (slope = -0.639), obtained from only eight data points, is not as pronounced as that obtained from the larger series of temperature-recruitment data (15 data pairs, slope = -5.359). The larger dataset includes two points which have a strong influence on the relationship. As no stock-size estimates are available for these years, they are not included in the multiple regression equation.

The stock-recruitment relationship suggests that maximum recruitment occurs at a stock-density corresponding to a CPUE of approximately 21 scallops per metre-hour. Recruitment levels in the 1940s (Fig. 7) were higher than present ones (RI in 1946 was 58), with stock-sizes of over 100 scallops per metre-hour in the 1950's (Fig. 8). Unfortunately no stock-recruit data pairs are available for this period. If the stock-recruit relationship is valid, some inshore grounds, which support stock sizes leading to CPUE figures of 15 to 19 scallops per metre-hour, are currently recruit-overfished. By this criteria, recruitment to offshore grounds would benefit from fishing them down to densities corresponding to 21 scallops per metre-hour fishing. For offshore grounds, catch rates of this level are uneconomical for many vessels.

These speculations on stock and recruitment assume that the derived relationship has some validity. These relationships are included in order to indicate which factors may influence recruitment - they are far from definitive. Spurious fits are always a possibility with so few data points. More data will be required to confirm the effect of both stock-size and environmental factors on recruitment.

**Fig. 2.11.** Stock-recruitment relationships, Bradda Head scallops.



## 2.4. DISCUSSION

### 2.4.1. Spatial variations in age structures

Samples of *Pecten maximus* and *Chlamys opercularis* taken from different fishing grounds within the north Irish Sea show marked differences in population structure both with respect to the number of age-classes present, and their relative abundance.

Catches taken by commercial vessels in July, 1987 and June, 1988, included in the age-frequency series in Fig 2.1, have demonstrated that *Pecten maximus* age-frequency distributions obtained from research vessel samples are representative of age distributions of commercial catches, for larger scallops. Research vessel samples contain more undersized scallops, making them useful for qualitative forecasting of recruitment levels to the fishery one or two years in advance. It has also been shown that line transect samples are reasonably representative of the age-class distributions of scallops over the whole fishing ground (Fig. 2.1) and that the major differences occur between, rather than within, fishing grounds. This implies that age-class separation within a fishing ground does not occur at a scale perceptible by either one-hour linear transect samples or commercial catches. As age-class separation is not perceptible by normal fishing activity, the targeting of high-density patches of a single year class by fishing boats, evident in some other scallop fisheries (Jameison & Chandler, 1981; Robert & Jameison, 1986) is not usual in this fishery. The only evidence of large-scale age-class separation in this study comes from samples from the Chickens ground, taken by the MFV 'Mathilde' in July, 1987. A strong age 6 class was evident in the catch (Fig 2.1f), but the peak was not visible in previous or later samples. The 'Mathilde' may have located an aggregation of scallops of age 6, which were then fished out the following season.

Baird & Gibson's (1956) diving observations on the Bradda Head ground have also shown that all age classes were present within a bed, with some evidence of small scale age-class grouping. Age-class separation probably occurs at the patch level in this population and is not usually perceptible from dredge-sampling or from commercial fishing activities, and therefore cannot be a determinant of fishing practice. All recruited age classes on a fishing ground can therefore be considered equally vulnerable to encounter with fishing gear, and as catchability does not appear to vary with age either (see Chapter 4) it appears that all scallops > 110 mm

shell-length are therefore equally vulnerable to exploitation.

From the data available for *Chlamys opercularis* it appears that all age-classes co-exist within a fishing ground, with no large-scale age-class separation.

The fact that commercial size scallop population age-structures and the mean length of catches do not vary within a fishing season (apart from the shift by one year in April/May associated with ring formation), implies that no strong age-directed fishing or large differences in size-selectivity occur within a fishing season, despite high annual exploitation rates (see Chapter 4). Age and length structures derived from different times within a season can therefore be taken as representative of the whole fishing season, i.e.- the relative abundances of each recruited age class do not change within the fishing season. The relative abundance of partially recruited age-classes may change through the season, if a substantial fraction are less than 110 mm shell length.

Changes in size-structure of a fished population of *Chlamys opercularis* will certainly take place within a summer fishing season, due to growth of the individuals in the population. This in turn leads to changes in the age-structure of catches, as a new cohort becomes vulnerable to fishing in the latter part of the season. No changes in population structure are expected within the winter, as the queens are not growing and are not subject to heavy fishing on most grounds. This allows comparison of population structures from different grounds based on samples taken over the winter.

The semi-quantitative studies on population structure consistency between samples taken at different times and by different methods show that research vessel line-transect samples taken during the winter fishing seasons provide reasonable estimates of the age structure of commercial catches of *Pecten maximus* from a fishing ground, and can therefore be combined with commercial catch statistics from logbooks to give realistic catch at-age matrices (given good catch statistics) for input into cohort models. These are important considerations in sampling programme design, as obtaining samples from the desired areas at the desired time from commercial vessels or from dockside samples would be difficult to achieve, and surveying entire grounds may prove too costly.

In the case of *Chlamys opercularis*, it may be better to sample commercial catches over the summer fishing season to compute catch-at-age matrices, and use

winter research vessel samples only for comparison of age-structures and biometry. There are so many variables affecting *C. opercularis* catch composition (gear-type, substrate, tide, time of year) that research vessel catches are unlikely to reflect commercial catches.

It may be possible to assume complete age-class mixing within a fishing ground and no size-selection within a fishing season (for *Pecten maximus*) but differences in population age-structure between grounds are significant, and must be considered in assessments. The spatial differences in age-structure are due to a combination of factors which may include: variation of fishing gear selectivity between areas due to differences in substrate, fishing mortality rate differing between areas due to spatially non-random fishing, or spatial variation of natural mortality rate (dependent on the abundance of predators, competitors, and levels of siltation). Finally, the number of recruits may vary both temporally and spatially.

Considering each of the above factors in turn, substrate-specific differences in selectivity do occur and appear to influence the quantity of pre-recruit scallops caught (ages 1-3) but there is no evidence to suggest significant differences between areas in the relative selectivity among the older, commercial size scallops,  $\geq 110$  mm, (unpublished data). Differences in selectivity cannot therefore account wholly for differences in *Pecten maximus* age-structure.

Fishing mortality rates certainly vary spatially in *Pecten maximus* (see Chapter 4) and are an important cause of the observed differences in population structure on different fishing grounds. A clear inshore-offshore difference in population structure is evident (Fig 2.1) in the *P. maximus* samples, with offshore grounds having significantly higher percentages of older scallops (5+). This observation is consistent with an inshore/offshore difference in fishing mortality rates, as determined by mark-recapture experiments (Murphy, 1986; Murphy & Brand, 1990; Allison *et al.*, 1989 and Chapter 4). The inshore grounds are dominated by pre-recruits and the recruiting year class. This depletion of older, larger scallops and a shift in the catch composition to smaller, younger animals is characteristic of heavily exploited populations, and can lead to "growth overfishing" if the fishery is dependant on animals still in the exponential phase of the logistic growth curve (see Ricker, 1975a and Gulland, 1983).

Natural mortality rate may also vary between areas, affecting the mean longevity. This may be the case for *Chlamys opercularis* where inshore grounds are

dominated by young (1-3 yr old) animals and offshore grounds by older (3-6 yr old) animals, for there is no evidence that higher fishing mortality rates on inshore areas are responsible for this difference, as the major *C. opercularis* fishing grounds are further offshore (Chapter 6, Fig. 6.8). Differences in natural mortality rate of adult scallops and quecns may vary between areas due to differences in the size and composition of the predator populations, and possible substrate-specific differences in mortality due to clogging by silt (Stevens, 1987) or burying by shifting sediments during storm events, likely to be more significant in shallow waters (Tettelbach *et al.*, 1990).

The mark-recapture experiments in Chapter 4 have shown spatial differences in natural mortality rates, but as these values may include different losses due to tagging and fishing-induced indirect mortality, they cannot at present be used to infer differences in natural mortality rate between areas. With no reliable data available, it must be assumed that *M*-at-age is constant spatially.

Finally, it has been demonstrated by the comparison of catch per unit effort values of the same year class on different grounds (Table 2.10) that recruitment varies spatially in any given year, and differences in population structure between areas are partly due to spatial and temporal recruitment variability (see 2.4.3).

#### **2.4.2. Density and abundance at age**

In calculating density and abundance of scallops, I have made the basic assumption that CPUE is proportional to abundance. This is equivalent to assuming that fishing mortality is proportional to fishing effort (Gulland, 1963). In order for these relationships to apply, each scallop in the space and time unit under consideration must be equally vulnerable to capture. In this case the spatial unit is the 5 Nautical mile grid and the temporal unit is one fishing season.

Several authors have contended that CPUE does not reflect abundance in scallop fisheries (reviewed in Caddy, 1989*b* and Orensanz *et al.*, 1991). These authors argue that fishermen do not fish at random, but exploit patches within a fishing ground, fishing each patch until density drops to some threshold level, when the fishermen move to another patch. Given the sequential pattern of patch-depletion, stock-size is not reflected by CPUE.

If, however, patches within a fishing ground are not detectable by fishermen in the course of normal fishing activity, then they cannot be a determinant of fishing strategy. I contend that if high-density patches are present within fishing grounds, they are not perceived by fishermen prosecuting this fishery, especially as overall densities are very low. Murphy (1986) shows that scallop CPUE declines significantly through a fishing season on the major grounds with the declining CPUE reflecting declining abundance. For the major fishing grounds, it appears reasonable to assume a relationship between CPUE and abundance. This relationship can be assumed to be density-independent, as gear performance is not affected by scallop density (which is too low to cause dredge-filling), but the relationship may vary between fishing grounds due to substrate-specific differences in gear efficiency.

Orensanz *et al.*, (1991) concede that changes in CPUE may reflect changes in abundance where "... individual areas of relatively homogenous density can be analysed independently. " These conditions may arise " .. in dredge fisheries where (1) dense patches are small compared to length of fishing tows (i.e. when they are 'invisible' to fishermen) and (2) the boundaries of the fishing ground are well defined."

These conditions apply to the major, traditionally fished grounds of the North Irish Sea *Pecten maximus* fishery.

The estimates of scallop density obtained from CPUE appear reasonable, falling within the range of densities of other commercially fished *Pecten maximus* populations (see Table 1 in Orensanz *et al.*, 1991). Recent surveys of inshore fishing grounds around the Isle of Man by divers have also produced estimates of density similar to those derived here from commercial CPUE, dredge efficiency and towing speed (U.A.W. Wilson & D. MacDonald, Port Erin Marine Laboratory, unpublished data, 1989-91).

Abundance estimates are dependent on the assumed value for the area covered by each bed. These areas are well known to fishermen, but not to scientists, as many of the grounds have never been surveyed. Without survey data, it is not possible to assess the reliability of the estimates, or the total stock size. Comparison of these estimates with those calculated from the combination of a tagging experiment with sample-fleet catch-effort statistics (Chapter 6) suggest that they are overestimates. It appears that the fished area within each grid-square may



be substantially less than the area of the whole square.

### 2.4.3. Recruitment variability and processes

Recruitment to the north Irish Sea *Pecten maximus* and *Chlamys opercularis* grounds fluctuates annually, as evidenced by peaks and troughs in the year-class frequency distributions in Figs 2.1 and 2.2. From a visual analysis of the years in which these peaks and troughs occur, it appears that there are two separate recruitment regions within the North Irish Sea - the grounds to the east and offshore to the south of the Isle of Man form one region and the grounds to the west of the Isle of Man form the other. Differences in the pattern of recruitment to these regions may occur as a result of environmental differences between the two regions, or some degree of stock separation. This latter explanation seems feasible in the light of recent work by Lewis (1992), who found genetic differences between *C. opercularis* populations from grounds to the east and west of the Isle of Man, implying some degree of stock separation, if not total reproductive isolation. It seems likely that the tidal front which becomes established south of the Isle of Man during the summer months (Ramster & Hill, 1969) acts as a barrier to dispersal of larvae between areas to the east and west of the front. Larvae which are advected into the frontal region may become entrained and settle in that area. This tendency for accumulation of biomass of planktonic organisms at fronts and associated increase in benthic productivity (see Franks, 1992, for review) may explain the high productivity of the scallop grounds to the south and south-west of the Chicken Rock.

Age-frequency histograms can only provide an order of magnitude estimate of the extent of recruitment variability, but it is clear from these studies and the longer term study of Brand *et al.*, (1991b) that recruitment of *P. maximus* to some fishing grounds has been fairly regular (within one order of magnitude) for the last 30-40 years.

The fishery on inshore grounds around the Isle of Man is now dominated by the recruiting year classes, and on the Bradda Head ground, this has been the case since the early 1960s (Brand *et al.*, 1991b). The fact that pre-recruits and recent recruits to the commercial fishery have dominated in these areas for such a long period and have been sufficient to support commercial fisheries every year since 1937 suggest the existence of a stable population with fairly regular annual

recruitment - an atypical situation in most scallop fisheries around the world (e.g. Yamamoto, 1950; Fairbridge, 1953; Olsen, 1955; Dickie, 1955; Baird, 1966; Buestel *et al.*, 1979; Caddy, 1979; Franklin & Conner, 1980; Boucher *et al.*, 1985; Orensanz, 1986; Moyer & Blake, 1987; Wolff, 1988; Aoyama, 1989; Young & Martin, 1990).

Hancock (1979) considers that the degree of irregularity in some populations is such that scallop fisheries based on them should, in management terms, be regarded as non-renewable resources. Mason (1983) endorses this view with regard to *Chlamys opercularis* fisheries by suggesting that when fishable concentrations are located, they should be 'hit hard' as they may not be there next year, or even next week. While this may be true on a small scale, due to the motility and short life-span of the queen, the relative stability and persistence of the major queen fishing grounds in the North Irish Sea would suggest a longer-term management view to be more appropriate. The major queen fishing grounds of the early-1970s are still the major grounds today (Brand *et al.*, 1991b) although populations at 'Queenie Corner' (on the Chickens ground) and the Port St. Mary grounds have disappeared in recent years.

Much has been made of the inherent variability of recruitment to scallop and other invertebrate stocks, even those which are spatially persistent (e.g. Hancock, 1973; 1979; Caddy, 1989a; Young & Martin, 1990) with a general theory emerging that invertebrate recruitment is strongly influenced by environmental variability (Drinkwater & Myers, 1987; Fogarty, 1988). In contrast, recruitment to most demersal fish stocks has traditionally been thought to be largely determined by parent stock numbers or total egg production (Ricker, 1954; Beverton & Holt, 1957), with environmental factors (temperature, salinity, wind stress *etc.*.) causing variability in the relationship (Shepherd *et al.*, 1984).

It is of obvious importance to be able to forecast the size of year classes entering the fishery, and to understand the effect of different management actions on future recruitment, especially in fisheries such as these, which rely heavily on the exploitation of the incoming year class to maintain economically viable catch rates.

Ideally, an understanding of the causes of recruitment variability would lead to the establishment of predictive models, such as stock-recruitment models (Ricker, 1954; Beverton & Holt, 1957; Shepherd, 1982), empirical models relating

recruitment to physical or biological factors (see reviews by Dow, 1978; Cushing, 1982; Shepherd *et al.*, 1984 and Harris *et al.*, 1988), or a combination of the two types of model (Tang, 1985; Penn & Caputi, 1986; Fifas *et al.*, 1990).

The data available for investigation of the stock-recruit relationship in North Irish Sea *Pecten maximus* is rather limited and it has been assumed in fitting the Ricker-type relationship that the Bradda ground is self-recruiting, which may not be the case. If the ground is not self-recruiting, then the relationship between adult stock size (commercial CPUE) and recruitment (CPUE of 4 yr olds) will be represented only by the descending part of the curve (the density-dependent survival of settling spat). A different stock will be responsible for the ascending part of the curve (the production of recruits). The relationship between recruitment and i) size of stock which produced larvae; and ii) size or density of stock where larvae settled can only be established if the movements of larvae can be traced.

Neither can it be stated unequivocally that there is a strong relationship between recruitment and temperature: the evidence is again based on too few points to rule out the possibility of a spurious relationship. It is also difficult to theorise why lower temperature should favour recruitment. It is conventionally assumed that higher temperatures (within the normal range of temperatures) favour survival as larval-stage duration is reduced due to faster development times, reducing losses due to predation (Cushing, 1975; 1982). Lower temperatures may, however, act to reduce the activity and food consumption of predators on larvae or settling spat. For example, reduced predation by shrimps on post-larval plaice in cold years has been invoked as the mechanism explaining enhancement of plaice recruitment in cold years (van der Veer *et al.*, 1990). Alternatively, the longer development time of scallop veliger larvae in colder temperatures may favour the advection of larvae from offshore grounds onto the inshore grounds, which may be out of advective distance in warmer years when the length of larval life is shorter.

Two different types of stock-recruitment relationships for scallops have recently been proposed. Mason *et al.* (1991) obtained a linear relationship between log-transformed recruitment to the fished stock of scallops west of Kintyre, Scotland, in year  $t$  and log-transformed recruitment the previous year ( $t-1$ ). The authors conceded that the relationship may be an artefact - a high degree of autocorrelation can be expected in this type of relationship. A more detailed study on scallop recruitment in the baie de Saint-Brieuc, the Channel, (Fifas *et al.*, 1990) incorporated the effects of fishing activity on pre-recruits and variables derived

from temperature series in a Beverton-Holt type stock-recruitment function (Beverton & Holt, 1957). Increased fishing effort on recruited scallops increased the mortality of 0-group scallops. The analysis also detected two periods when temperature differences were critical to recruitment success. These periods (the first fortnight of March and the second fortnight of July) corresponded to the start of sexual maturation and the first spawning and larval development periods in this population. Cooler than average temperatures during early March were thought to favour egg production, but no mechanism was invoked to explain the less significant positive association between higher temperature in late July and subsequent recruitment.

Further progress in establishing relationships between stock and recruitment in these fisheries is unlikely to be made for at least another decade using the population monitoring techniques currently in use. Detailed knowledge of larval dispersal patterns will be required, together with more quantitative information on stock size, particularly of the fraction of the spawning stock which is below the legal landing size. With such data available, the effects of environmental variability on recruitment success could also be assessed in more detail, as Fifas *et al.* (1990) have done for the Saint-Brieuc stock.

As an interim measure, forecasts of recruitment can be made by quantifying the number of juveniles or pre-recruits. Several studies have linked settlement of pectinid spat on artificial collectors with subsequent recruitment to the fishery (Boucher, 1985; Sause *et al.*, 1987; Coleman, 1988) and similar work on *P. maximus* is underway in Scotland (Fraser, 1983; 1987; 1989; 1991 and Mason & Fraser, 1987). All these studies have taken place in semi-enclosed bays, where it is reasonable to assume that the larvae in the water column which settle out onto artificial off-bottom collectors would have settled on the sea bed within the bay.

Spat collection studies of *P. maximus* at Port Erin (Brand *et al.*, 1991a) indicate that good spat settlements in 1984 and 1987 have since yielded strong year classes in population samples (see Fig. 2.1) indicating some promise in this approach to recruitment prediction, despite the fact that it cannot be assumed that the spat settling on these collectors would have settled on the sea bed in the vicinity.

On Georges Bank, Canada, scallop surveys are conducted annually to assess the stock abundance of pre-recruits, but due to the selectivity of the dredges, recruitment can only be forecast one year in advance (Mohn *et al.*, 1989). In order

to apply survey techniques to estimating pre-recruit abundance of North Irish Sea scallops and queens, dredge capture efficiency for undersize scallops and queens, either absolute or relative to commercial size scallops, must be known. Better predictive studies in the North Irish Sea scallop fisheries would greatly enhance the perceived usefulness of this research programme in the eyes of fishermen, even though prediction is not yet a necessary prerequisite of management in these fisheries, which are not subject to quota management.

Only one study has linked spatfall with egg production of the parent stock (Buestel *et al.*, 1979). The difficulty is often in establishing which parent stock is responsible for spatfall in a given area.

Linking spatfall or pre-recruit abundances with subsequent recruitment to the commercial fishery does not advance our understanding of the stock-recruitment relationship beyond establishing that the 'critical period' (Hjort, 1914; Elliot, 1989) in determining recruitment success in most pectinids occurs somewhere between egg production by the parent stock and survival of the larvae to be collected from spat-bags a few weeks after metamorphosis and settlement stages. This 'critical period' (the planktonic and post-larval stage) is the least well understood stage of bivalve life-history, although new techniques for studies of this type are being applied (Levin, 1990, for review). There is a requirement for a study of the early stages of scallops if recruitment to these populations is to be predicted effectively.

## 2.5. CONCLUSION

The significant and persistent spatial differences in population age structure necessitate the application of area-specific age-structured stock assessment models. The population cannot realistically be described by a single dynamic pool model (Shaefer, 1957) and the 'megapopulation' is not a unit stock (*sensu* Beverton & Holt, 1957). The two most important causes of spatial variability in population structure appear to be non-random fishing, and non-random recruitment within the population. As the pattern of fishing depends largely on the pattern of past recruitment, an understanding of the recruitment processes is vital to understanding the dynamics of the fishery.

## **CHAPTER 3: GROWTH STUDIES ON *PECTEN MAXIMUS* AND *CHLAMYS OPERCULARIS*: SPATIAL, SEASONAL AND LONG-TERM VARIABILITY.**

### **3.1. INTRODUCTION**

A knowledge of the growth characteristics of exploited stocks is essential for the assessment of their potential yield to a fishery and the determination of optimal age at harvesting. In simple Yield per Recruit (Y/R) models (Thompson & Bell, 1934; Beverton & Holt, 1957), a single set of growth rate parameters is normally assumed to represent the growth of individuals in an homogeneous stock living under steady state conditions. There is no provision for the inclusion of differences in growth rate within stocks, seasonal growth patterns and long term changes in growth rates. In many cases these simplifying assumptions may be justified: the growth rate of mobile teleost fish may not show great differences in growth rate within a population or stock (but see Francis & Winstanley, 1989; Bromley, 1989); seasonal growth fluctuations may be insignificant compared to interannual growth in slow-growing, long-lived species (such as North Sea plaice) or irrelevant in species with a short, well-defined annual fishing season. And while growth rates may fluctuate with climactic variation, there may not be any trend in the pattern of growth of individuals in an exploited population over decadal timescales.

One objective of these growth studies is to assess the importance of violations in the assumptions implicit in Y/R and other 'dynamic pool' models (see Pitcher & Hart, 1982, for review) by determining the extent of spatial, seasonal and long-term variation in growth rates of the north Irish Sea stocks of scallops and queens. The growth of the shell (increase in length) and of the marketable parts of the scallop and queen (the gonad and adductor muscle) are both modelled, and the length/weight relationship is calculated.

The Pectinidae and many other sedentary and semi-sedentary bivalves are known to show considerable variability in growth rate over both a geographical and local (intra-population) scale (Broom, 1976; Taylor & Venn, 1978; Hancock, 1979; Antoine *et al.*, 1979; Mason, 1983; Bricelj *et al.*, 1987a; Shumway & Schick, 1987; Caddy, 1989a; Ansell *et al.*, 1991; Orensanz *et al.*, 1991; Thouzeau *et al.*, 1991a). The high degree of spatial variability in growth rate of pectinids is due to the strong dependence of growth on environmental factors which affect either their feeding efficiency and metabolic rate (e.g. food particle

concentration, silt concentration, and temperature) or the availability of food (e.g. population density, depth, current speed and substrate type - reviewed by MacDonald & Thompson, 1985a; 1985b; Schick *et al.*, 1987; Brand, 1991 and Bricelj & Shumway, 1991).

Mason (1957), Gruffydd (1974b) and Murphy (1986) have previously described spatial variability in growth of the shell in *Pecten maximus* on the fishing grounds in the north Irish Sea. No assessment of intra-population growth rate differences in *Chlamys opercularis* has been published for this area, although Soemodihardjo (1974) noted some variability in population parameters of queens from around the Isle of Man. This study aims to assess quantitatively the assessment and management implications of spatial variations in the growth of the shell and marketable yield (the gonad and adductor muscle) of both the scallop and queen.

The importance of the seasonal cycle in determining the yield to the fishery must also be considered in order to assess the optimum seasons for fishing both species from the point of view of maximising Y/R, and to compare them with the current legislated fishing season. The growth of most bivalves, including *Pecten maximus* and *Chlamys opercularis*, shows strong seasonality, correlated to the annual temperature cycle (Ansell, 1974; Comely, 1974; Soemodihardjo, 1974; Taylor & Venn, 1979). Seasonality is particularly evident in the gonad and adductor muscle, both of which exhibit considerable variability in weight, condition or appearance, and biochemical composition (Mason, 1959b; Connor, 1978; Ansell *et al.*, 1991, and references above). This study focuses explicitly on the effect of seasonal reproductive and growth cycles on yield and exploitation strategy in these fisheries.

A preliminary assessment has also been made of the extent to which the growth rate varies annually, and in the long term (over the last 53 years). Growth rate parameters of exploited organisms are normally calculated from several years' data for population length-at-age, back-calculated lengths-at-age from samples of individuals, or from the increase in size of particular cohorts over several years, all of which will include variability due to environmental or climatic variation (see Cushing, 1975 and 1982, for reviews), but assume no underlying trend. The assumption of steady state growth parameters is implicit in the use of Y/R models, but recent studies on long series of growth data from several heavily exploited stocks subject to size-selective fishing have shown that mean population growth

rates may change over time as a result of exploitation (Gwyther & McShane, 1988, for Australian scallops; Law & Grey, 1989, for Arcto-Norwegian Cod). The extent to which growth patterns of *Pecten maximus* on a heavily fished ground have changed over the last 53 years is investigated here. These populations provide an ideal opportunity for assessing the effects of size-selective fishing on growth patterns as data are available on age and size structure of the virgin stock (Tang, 1941) and a minimum legal landing size of between 110 and 114 mm shell length has operated since the inception of the fishery in November, 1937.



## 3.2. METHODS.

### 3.2.1. Data Collection.

The dredge sampling and trawling programmes undertaken from the R.V. Cuma and commercial fishing vessels between January, 1987 and November, 1989 have been described in the Data Collection Methods (pp 15-17). Each research vessel sampling event yielded 30-300 scallops and from 0-1000+ queens, depending on the ground fished. Commercial vessel catches were subsampled during trips on board the vessels.

The shell length (anterio-posterior axis, see Fig. 3.1) of all *Pecten maximus* in each sample were measured to the nearest millimetre with a scallop measuring board. (see Mason, 1983). *Chlamys opercularis* catches were generally subsampled if > 400 animals were caught. Both species were aged by means of the growth rings on the shell, following the method outlined in Chapter 1. The rings were most clearly visible on the left (upper valve) in both species, although epifauna had to be removed from some shells before ageing was possible.

Weight-at-age was measured by randomly subsampling approximately 50 to 100 scallops and/or queens from each sample. In addition to measuring shell length and age, the total live weight (to the nearest gram), adductor muscle and gonad weights (to the nearest 0.1 g) were all determined using a Mettler 3000 PC electronic balance, after removing surface moisture from the tissues by blotting with absorbent paper and leaving the scallops to air dry at room temperature for 1-2 hours. Macroscopic gonad stages, assigned following the subjective methods of Mason (1958a) for scallops and Soemodihardjo (1974) for queens (see Fig 3.2) were also recorded.

The majority of samples were taken between November and March as neither scallop species is growing during the winter months (Mason, 1957; Soemodihardjo, 1974), allowing comparison between areas using samples taken at different times in the winter without the addition of variability due to seasonality. Data from week-long summer surveys undertaken in 1987 and 1988 as part of a scallop mark-recapture programme were also analysed for separate comparisons of shell growth rates on different fishing grounds. The analysis of the 1987 data has not been presented here as no younger scallops (< age 4) were retained for measuring and tagging (all scallops < 100 mm were used elsewhere for scallop

farming studies) leading to a poor fit of growth models for many grounds and unreliable parameter estimates.

In all, the shell growth data from ten scallop fishing grounds within the north Irish Sea are analysed. Eight of these grounds also supported queen populations, whose growth rates have been similarly analysed, together with the growth of queens on three other grounds where scallops were not sampled. Their co-existence on many of the same grounds allows comparison of the growth performances of the two species on these grounds. The locations of the sampling areas are shown in Fig 3.3. Decca co-ordinates for all sampling areas are given in Appendix 1.

In addition, seasonal growth in length and weight for scallops was studied on an inshore (Bradda Head) and an off-shore fishing ground (S.E. Douglas) by taking approximately monthly samples from January, 1987 to October, 1988. Monthly queen samples from S.E. Douglas were also used to evaluate seasonal variability in this species. A more limited set of queen length and weight data sampled from commercial vessels fishing the extensive East Douglas ground during the summer of 1988 has also been analysed.

### 3.2.2. Fitting growth models.

#### 3.2.2a. Annual Shell growth.

Annual growth in shell length of both species was described by fitting the von Bertalanffy growth equation (von Bertalanffy, 1938; 1964) to population length-at-age data:

$$L_t = L_{\infty}(1 - e^{-k(t-t_0)}) \quad (3.1)$$

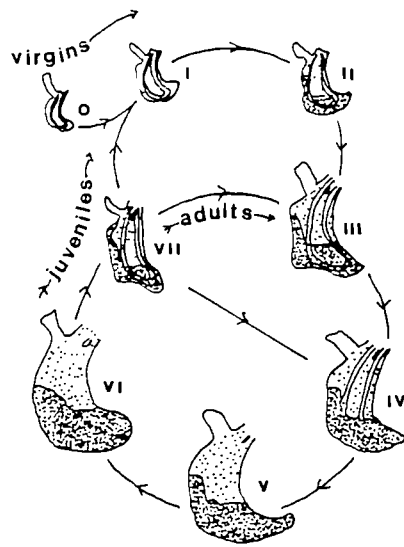
where:

$L_t$  = length at age  $t$

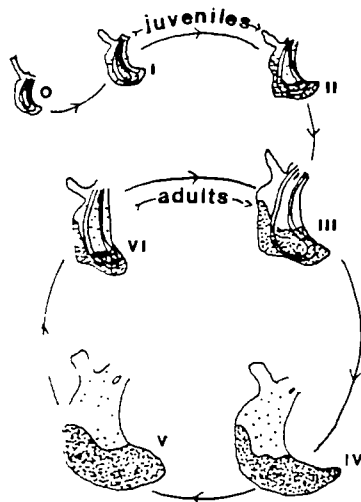
$L_{\infty}$  = asymptotic length

$k$  = Brody/Bertalanffy growth coefficient

$t_0$  = age at length = 0

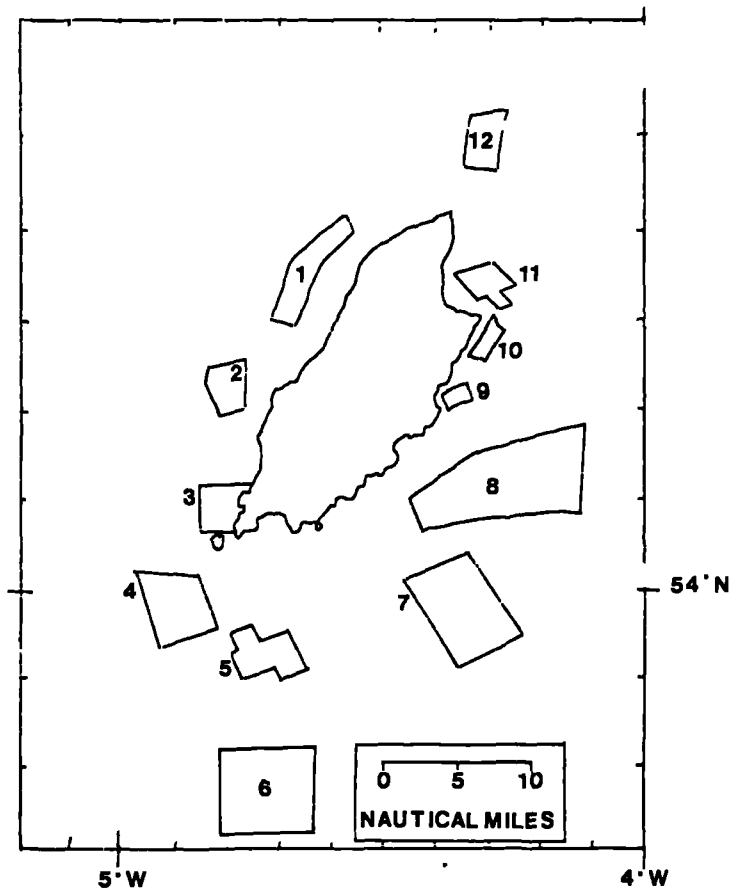


a) *Pecten maximus*



b) *Chlamys opercularis*

**Fig. 3.2.** Macroscopic gonad stages in a) *Pecten maximus* (following Mason, 1958b) and b) *Chlamys opercularis* (following Soemodihardjo, 1974). Line drawings adapted from Mason (1983).



**Fig. 3.3.** Fishing grounds sampled for *Pecten maximus* and *Chlamys opercularis*, November, 1986 to November, 1989. (S = sampled for scallops, Q = sampled for queens)

1	The Targets	S,Q
2	Peel Head	S
3	Bradda Head	S
4	The Chickens	S
5	Port St. Mary	S,Q
6	H/I Sector	S,Q
7	SE Douglas	S,Q
8	E Douglas	Q
9	Laxey Bay	Q
10	Maughold Hd.	S,Q
11	Ramsey Bay	S,Q
12	Point of Ayre	S,Q

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In all, the shell growth data from ten scallop fishing grounds within the north Irish Sea are analysed. Eight of these grounds also supported queen populations, whose growth rates have been similarly analysed, together with the growth of queens on three other grounds where scallops were not sampled. Their co-existence on many of the same grounds allows comparison of the growth performances of the two species on these grounds. The locations of the sampling areas are shown in Fig 3.3. Decca co-ordinates for all sampling areas are given in Appendix 1.

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$$L_t = L_{\infty}(1 - e^{-k(t-t_0)}) \quad (3.1)$$

where:

$L_t$  = length at age  $t$

$L_{\infty}$  = asymptotic length

$k$  = Brody/Bertalanffy growth coefficient

$t_0$  = age at length = 0

The von Bertalanffy growth function (VBGF) was fitted to the shell length-at-age data from each area using the NLR procedure in SPSSX, which fits data to user-defined models iteratively using the Levenberg-Marquadt algorithm (SPSSX Inc., 1988, Chapter 36). The procedure requires initial estimates of the parameters  $L_{\infty}$ ,  $k$  and  $t_0$ , but is robust with respect to them, converging to the same solution from a wide range of starting values.

The output provides estimates of the above three parameters and their asymptotic standard errors and 95% confidence intervals, the coefficient of determination ( $r^2$ ) indicating the fit of the data to the model, the asymptotic correlation matrix of the parameter estimates, the model-predicted length-at-age values and the residuals. The equation was fitted to raw length-at-age data for each area (rather than mean length-at-age) so the confidence intervals reflect both variability in length within each age class and the fit of the model to length-at-age. By using raw data to fit the model, the age-classes with more observations (presumably those where length is most likely to be correctly estimated) have more weight in the regression. The youngest age-class in the *Pecten maximus* samples was not used to fit the equation, as it is likely that only the larger fraction of the length distribution would be retained by the size-selective fishing gear.

### 3.2.2b. Length/weight relationships.

Length-weight relationships were calculated to provide parameter estimates for fitting models of growth in weight. The major difficulty in computing the relationship between length and weight in scallops is that weight varies seasonally, and the variability of the constituent tissues (especially the gonad and adductor muscle) vary out of phase. In order to assess the seasonality of the length/weight relationship, the parameters of the linearised allometric length/weight regression equation (Ricker 1975a) were calculated from monthly samples of scallops (from the Bradda and S.E. Douglas grounds) and queens (from S.E. Douglas and E. Douglas).

$$\ln W = a + b(\ln L) \quad (3.2)$$

Functional or geometric mean regression, rather than ordinary least squares (OLS) regression was chosen for computation of the relationship of these two variables, as they have a functional rather than a dependent relationship (see Ricker,

1973, 1975a, 1975b and Laws & Archie, 1981, for discussion)

The functional regression is expressed as:

$$Y = u + vX \quad (3.3)$$

where Y and X are both random variables.

The slope of the functional regression (v) is:

$$v = \frac{\sigma_Y}{\sigma_X} \quad (3.4)$$

where  $\sigma_Y$  = standard deviation of Y  
 $\sigma_X$  = standard deviation of X.

Ricker (1973) shows that v can be related to the slope of the OLS regression (b) simply by  $v = b/r$ , where r is the correlation coefficient of the linear correlation between X and Y. The standard error of v, ( $s_v$ ), is equal to the standard error of b, as calculated by OLS regression, and confidence intervals (CI) are calculated from the critical value of the t distribution for the desired significance level (95% CI are used throughout this study):

$$CI = v \pm s_v t_{\alpha(2), n-2} \quad (\text{Zar, 1984}) \quad (3.5)$$

The intercept of the functional regression is calculated from:

$$u = \bar{Y} - v\bar{X} \quad (3.6)$$

where in this case  $\bar{Y}$  is mean ln(Weight) and  $\bar{X}$  is mean ln(length). The standard error of u ( $s_u$ ) is given by:

$$s_u = \sigma_Y \sqrt{\frac{1-r^2}{n} + \frac{X^2}{\sigma_X^2}} \quad (\text{Saila et al., 1988}) \quad (3.7)$$

The confidence intervals can be calculated as above.

OLS regression equations were calculated from the pairs of log-transformed length and weight data in each comparison, with length as the predictor (independent) variable. The slope and intercepts of the functional regressions and their associated standard errors and 95% confidence intervals were then calculated from the above formulae. The following functional regressions were computed for each area for which data were available:

- i) Length/total yield (gonad weight + adductor muscle weight), scallop winter samples (November-March).
- ii) Length/total yield and length/adductor muscle weight, queen winter samples. Queens are processed either with or without the gonad, so both relationships are of interest.
- iii) Length/yield and length/adductor muscle weight, queens, June-October (the main fishing season).
- iv) Monthly length/adductor muscle and length/gonad weight regressions, scallops, S.E. Douglas and Bradda Head.
- v) Monthly length/adductor muscle and length/gonad weight regressions, queens, S.E. Douglas and E. Douglas.

### 3.2.2c. Annual growth in weight.

Yield-based assessment models require the inclusion of growth in terms of weight. The Beverton-Holt Yield per Recruit (Y/R) equation (Beverton & Holt, 1957) has traditionally incorporated the parameters of the VBGF although it is easily modified to include the parameters of other growth models (Gulland, 1983).

When the VBGF is used, the parameters of weight-growth equations are calculated either by fitting models directly to weight at age data, or by fitting models to length at age data and using the length/weight regression equation to convert  $L_{\infty}$  to  $W_{\infty}$ . The parameters  $k$  and  $t_0$  should theoretically remain the same, if the relationship between length and weight is applicable to the whole size and age range (Ricker, 1975a). The latter method is often used as it requires no weight sampling once the length/weight relationship has been determined, the length-model



is generally easier to fit, and the data are less variable. Both methods are used in this study, as it is helpful to examine the fit of weight data to the VBGF in order to establish if the assumption of attainment of an asymptotic weight is justified.

VBGF and third-order polynomial regression equations were fitted to scallop and queen weight-at-age data for each area sampled in the winters of 1986/7 and 1987/8. Queen weight-at-age data from four areas sampled in the Summer (June-October) of 1987 and 1988 were also used to obtain growth in weight equations representative of the main queen fishing season. The weights used in these studies are the marketable yield of both scallops and queens and weight of queen adductor muscles. Growth in total weight has not been calculated as it is not of immediate relevance to the commercial fishery.

Both types of growth equation were fitted to raw data using the NLR procedure of SPSSX, as described in section 3.2.1. Examination of the fit of the two model types showed that the fit ( $r^2$ -value) of both model types was virtually identical, and the predicted values of weight-at-age were very similar for the age-classes which were best represented in the samples. The polynomial regression, however, generally provided unrealistic values for younger year-classes and for the older year-classes in some areas. The VBGF has therefore been used throughout this study, as there does not appear to be any strong case for doubting its validity.

The VBGFs for yield at age and adductor muscle at age are given by:

$$Y_t = Y_\infty [1 - e^{-k(t-t_0)}]^\nu \quad (3.8)$$

$$M_t = M_\infty [1 - e^{-k(t-t_0)}]^\nu \quad (3.9)$$

where,

$Y_t$  = yield at age  $t$

$M_t$  = adductor muscle weight at age  $t$

$Y_\infty$  = asymptotic yield

$M_\infty$  = asymptotic adductor muscle weight

$k$  = growth coefficient

$t$  = age in years

$t_0$  = age at  $M$  or  $Y = 0$

$\nu$  = slope of functional regression of  $Y$  or  $M$  on length

The VBGF for weight is normally fitted with the exponent  $v = 3$ , as for most fish  $v$  is approximately equal to 3 and this physiologically derived formula is strictly correct only when this is the case (see Beverton & Holt, 1957, p 280-281, and Pauly, 1979, 1981, for discussion). Many of the functional regression slopes computed, however, are significantly different from 3, and therefore the use of  $v=3$  would lead to erroneous parameter estimates. Calculated values of  $v$  are therefore used for all the VBGFs fitted.

### 3.2.2d. Seasonal growth.

In 3.2.2a and 3.2.2c above, fitting of VBGFs has been restricted to winter length and weight, when seasonal variability is at a minimum, (Stanley, 1967; Murphy, 1986). Pectinids, however, show marked seasonal growth patterns, which can be described by incorporating a sinusoidal function in the VBGF (e.g. Pitcher & MacDonald, 1973; Cloern & Nichols, 1978; Pauly & Gaschultz, 1979; Hanumara & Hoenig, 1987; Somers, 1988; Soriano & Jarre, 1988 and Hoenig & Hanumara, 1990):

$$L_t = L_{\infty}(e^{-k(t-t_0)} + S(t)) \quad (3.10)$$

$S(t)$  is the function describing the seasonal perturbation, derived from the equation for a simple sine-wave (e.g. see Batschelet, 1981, p159):

$$Y = M + A \cos \frac{2\pi}{t} \phi \quad (3.11)$$

where  $Y$  = the variable which is oscillating

$M$  = mesor, or mean value of  $Y$

$A$  = amplitude of oscillation of  $Y$

$2\pi/t$  = period of oscillation =  $2\pi$ , if  $t = 1$

$\phi$  = acrophase ( $t-t_s$ , where  $t_s$  defines the beginning of the sine wave).

The papers cited above all give slightly different formulae for  $S(t)$ . The version used in this study, developed by Pauly & Gaschultz (1979), modified by both Somers (1988) and Hoenig & Hanumara (1990) gives the best description of the seasonal oscillation with respect to the unbiased estimation of  $t_0$ :

$$S(t) = \frac{kC}{2\pi} \sin 2\pi(t - t_s) - \frac{kC}{2\pi} \sin 2\pi(t_0 - t_s) \quad (3.12)$$

where  $C$  = amplitude of seasonal perturbation  
 $t_s$  = time of start of oscillation relative to  $t_0$

In order to describe the growth in length of scallops and queens incorporating the seasonal growth pattern, monthly samples of scallop length-at-age data from the Bradda Head and S.E. Douglas grounds, and monthly queen data from S.E. Douglas and E. Douglas were plotted. An ordinary VBGF was then fitted to all the data to obtain initial estimates of the parameters  $L_\infty$ ,  $k$  and  $t_0$  (as in 3.2.2a, equation 3.1). The fitted VBGF was then subtracted from the data, and the residuals of the fit of the data to the ordinary VBGF were examined to obtain starting values for the parameters  $C$  and  $t_s$ . The seasonal model was then fitted to raw data using the SPSSX-NLR procedure.

The seasonal patterns of growth of the edible portions of the scallop (gonad and adductor muscle) were modelled by converting the seasonally oscillating growth curve for length to weight using the length-weight relationship appropriate to the time of year that the sample was taken. The computational steps were as follows:

- i. Mean gonad weight and mean adductor muscle weights-at-age were calculated. Age was expressed in months (entered as decimal fractions of a year).
- ii. For each sample date, functional regression parameters of the relationship between shell length and adductor muscle, and shell length and gonad weight were calculated using the procedure outlined in 3.2.2b
- iii. In order to smooth out variability in the data, a model was then fitted to the calculated values of the exponent of the length-weight functional regression relationship ( $v$ ) and the intercept ( $u$ ). The equation for a sine-wave (equation 3.11) was chosen to model the seasonality of the regression parameters, and was fitted by least squares regression using the Quasi-Newtonian search algorithm in the nonlinear regression module of SYSTAT. Starting values for mesor, amplitude and  $t_s$  are easily obtained by visual inspection of the data.

No model was fitted to the length/gonad regression parameters from south-east Douglas queens, as the parameters did not show an obvious seasonal cycle.

The analysis for these data therefore terminated at this step.

iv. Model parameters from (iii) provide smoothed length-weight regression parameters. These were used to convert monthly length-at-age values (predicted from the seasonally oscillating VBGF) to predicted weight-at-age values for gonads and adductor muscles.

v. To obtain predicted yields, model-predicted gonad and adductor muscle weights were summed.

vi. Fit of the model to the data was evaluated visually, as the computational procedure does not allow for the inclusion of error terms, precluding statistical testing.

vii. Predicted values generally showed good agreement with observed mean weight-at-age data for adductor muscles. Fitting the model to gonad data was more problematic, as the exponent (power function) of the length-weight equation is generally high (5-9), reflecting rapid increase in gonad weight with little increase in length as the scallop or queen attains maturity. This leads to predicted gonad weights which fit observed data well in younger scallops, but lead to overestimation of both mean weight and the amplitude of annual fluctuations in older scallops. In order to correct these errors and obtain realistic values of predicted total yield, post-hoc modifications to models of gonad weight growth were applied. The model described above fitted gonad weights for ages up to 5 years for scallops from Bradda Head, and up to 8 years for scallops from south-east Douglas. In order to simulate the changes in weight of the gonads of older scallops, a sine-wave equation of constant amplitude (equation 3.11) was fitted directly to data on weight-at-age of these gonads. In the case of Bradda Head scallops, gonad weight continued to increase, approximately linearly, over the age range 5 to 11 years, so the mesor (M) in equation 3.11 was modified to give:

$$Y = (a + bt) + A \cos\left(\frac{2\pi}{t}\right)\phi \quad (3.13)$$

Where a and b are the intercept and slope of the linear regression of mean gonad weights between ages 5 and 11. Note that this equation does not imply that gonads continue to increase slightly in mean weight each year, indefinitely. The relationship is applicable only to the age range to which it has been applied and

should not be extrapolated.

The condition of the gonad, which is only acceptable to the market when relatively full and of good colour and firm texture, has also been examined. Spent, spawning or only partially recovered gonads would not be acceptable. There is also a Manx fishery bylaw prohibiting the landing or sale of a catch of scallops which contain more than 20% spawned individuals. Gonads considered marketable are the scallop gonad stages IV, V and VI ( $\frac{1}{2}$  full to full) of Mason (1958a), and the corresponding stages IV and V of Soemodihardjo (1974) for queens. Monthly samples of scallop and queen gonads, together with scallop gonad samples from Murphy (1986) for the years 1982-3 have been collated, and the percentages of marketable gonads for scallops and queens of commercial size in each month have been recorded.

### 3.2.3. Comparing growth in different areas.

Comparison of growth performances of scallops and queens from different grounds were made using two growth performance indices derived from the parameters of the VBGF: the  $\omega$  parameter of Gallucci & Quinn (1979), where  $\omega = L_{\infty}k$ , and the growth performance index  $\phi'$  of Pauly & Munro (1984), where  $\phi' = 2\log_{10}(L_{\infty}) + \log_{10}(k)$ . These growth performance indices are preferred for growth comparisons rather than comparison of  $k$  and  $L_{\infty}$  individually, as these two parameters are highly correlated (negatively). The two growth performance indices are more robust than either  $k$  or  $L_{\infty}$  individually as they take into account the negative correlation between the two VBGF parameters, and fulfil the requirement for a simple single parameter for comparison of growth among several curves. A difference in  $\phi'$  or  $\omega$  is likely to represent a real difference in growth performance rather than a reciprocal change in  $k$  and  $L_{\infty}$ . Statistical comparison using the  $\omega$  parameter is preferred in this study as the standard errors are more readily calculable.

Confidence intervals for  $\omega$  were computed by reparameterising the VBGF:

$$L_t = \frac{\omega}{k}(e^{-k(t-t_0)}) \quad (3.14)$$

The reparameterised equation is fitted by NLR, which gives 95% confidence

intervals for  $\omega$ . Overlap in the 95% CI of  $\omega$  values from different grounds indicates no significant differences in growth performance between those grounds. The procedure is robust, conservative, simple to interpret, and the parameter  $\omega$  is tractable to further analysis (Appeldoorn, 1983). This rule of thumb method is preferred to formal statistical testing as the assumptions of ANOVA cannot be met (the distribution of the parameter is not known and variances are significantly different, leading to problems with subsequent multiple comparison tests). Visual comparisons of 95% confidence limits are, however, also strictly applicable only when variances are equal (Simpson *et al.*, 1960; Andrews *et al.*, 1980).

The length-weight relationships for scallops and queens from different grounds are also compared. The statistical comparison of the slopes of the functional regressions is performed using Clarke's t-test (Clarke, 1980) where the test statistic ( $T_{12}$ ) is:

$$T_{12} = \frac{|\ln v_1 - \ln v_2|}{(1 - r_{12} / n_1) + (1 - r_{22} / n_2)} \quad (3.15)$$

The degrees of freedom are given by:

$$\nu = \frac{2 + 2}{\sigma^2(T_{12}) - 1} \quad (3.16)$$

The variance of the test statistic,  $\sigma^2(T_{12})$ , is calculated according to the formulae in Clarke (1980). The biological and fisheries literature do not contain any multiple comparison methods for functional regressions, and ANCOVA is not applicable to functional regressions, as the test utilises the minimised SS(Y). In order to test for differences between the slopes of functional length/weight regressions among different areas, I have performed multiple paired comparisons using Clarke's t-test, with the significance level of each comparison adjusted by the number of comparisons made (the Bonferroni approximation- see Neter *et al.*, 1983) to protect against type I errors and maintain an overall significance level of 95%.

$\omega$  and  $\phi'$ - values calculated from winter length-at-age data are used to investigate the factors which may cause the observed differences in growth performance between areas. Only depth (from Admiralty charts) and substratum type (from British Geological Survey Sea Sediment Maps, Series U.T.M. 1: 250 000) of each fishing ground are known. Relative density of *Pecten maximus* and

*Chlamys opercularis* (from commercial catch-effort statistics) are also available but can only be used validly with growth increment data (discussed in 3.4.2).

Preliminary analyses determined that substratum type and depth were correlated ( $0.05 < P < 0.10$ ), with the sand-content of substrata being generally higher on the shallower grounds, and gravel-content being higher on the deeper off-shore grounds. Depth and geographical area are also not independent, with the grounds to the west of the Isle of Man being generally shallower than those to the south. Depth, substratum type and locality are all interrelated invalidating multiple regression analysis as a means of investigating their effect on scallop growth. An attempt was made to use Principal Components Analysis to compute new variables from the combination of available environmental data but the two factors generated from four variables (depth, % gravel, % sand and median grain size of the sand fraction) were not partitioned logically between factors, with the correlation of approximately 0.6 between depth and both the first and second principal components. Comparing  $\omega$  values in different areas by ANOVA cannot be used confidently, due to heteroscedacity and lack of knowledge of the error distribution of the parameter, so there does not appear to be any statistical model which can account for the covariance of the predictor (environmental) variables to determine their combined effect on growth performance. The only way to proceed with the analysis is to consider separately the effects of depth and substratum on growth performance by fitting simple regression models to the relationship between  $\omega$  with depth and  $\omega$  with substratum composition (% sand or % gravel). Data on the composition of the substratum were not available in detail, so % values are taken as the median values of substratum categories on the British Geological Survey maps.

#### **3.2.4. Assessment of long term changes in growth rate**

Growth data for scallops from the major North Irish Sea fishing grounds have been collated or calculated for many of the years between 1937 and 1990. The largest and most continuous data set is for the Bradda Head ground, and only the analysis of these data are presented in this thesis.

Long term changes in growth rates of Bradda scallops have been assessed by fitting the VBGF to length-at-age data from the following sources:

1. Data published by Tang (1941) for the 1937/8 fishing season. This data can be

considered as representative of the growth rate of the unfished or virgin stock, as fishing did not commence until November, 1937 (Smith, 1938).

2. VBGF parameters for 1950-52 have been calculated from the data of Mason (1953, 1957) by Pope and Mason (1980) using Ford-Walford plots.

3. Data collected by Brand (1966-1978, unpublished) have been used to fit VBGFs for the following time periods: 1966-69, 1970-74, 1974-78.

4. VBGF parameters for 1981-1983 were obtained from shell breadth-at-age, back-calculated from annual ring measurements (Murphy, 1986). I have converted  $B_{\infty}$  to  $L_{\infty}$  using the functional length/breadth relationship calculated by the same author.

5. VBGF parameters for 1987-90 were calculated using NLR to fit the model to length-at-age data (see 3.2.2a)

Parameters from the 7 different time periods represented above are examined to assess whether any systematic change in the growth pattern has taken place over the last 53 years.

Variability in growth rate between years is assessed by plotting the mean length of scallops with 4 growth rings from each winter (November - March) fishing season against time. The true ages of these scallops are between 3 years 4 months and 3 years 9 months. The 4-ring age-class was chosen as they are fully vulnerable to the fishing gear and newly recruited to the commercial fishery, forming the major recruiting age class over the last 20 years (Brand *et al.*, 1991b). The data series runs from 1966 to the present, with a gap from the years 1979 to 1985. Length-at-age data were collected during this period by Briggs (1983), Murphy (1986) and Duggan (1987), but are not currently available for analysis.

Temperature data from Port Erin Breakwater are also available (Slinn, 1974; more recent data is unpublished). Three year running means have been calculated from these data, to represent the mean temperature over the three full years prior to sampling (covering the three full growing seasons of scallops with 4 annual rings). An exploratory analysis of the relationship between temperature and length of 4-ring scallops is presented. No model is fitted as the missing years leave too few points for meaningful time-series analysis.



### 3.3. RESULTS

#### 3.3.1. Annual growth in length

The VBGF provides a good fit to scallop length-at-age data on most grounds for both the samples from the winters (November - March) of 1986/7, 1987/8, 1988/9 and 1989/90 (Fig 3.4) and to the data from the June 1988 tag release experiment (Fig 3.5). The  $r^2$  values for the fit of the data to the model range from 0.61 to 0.88 for the winter data and 0.60 - 0.83 for the June 1988 data; the relatively low values being due to the fact that the original raw data has been used, rather than the mean length-at-age values. The  $r^2$  values therefore reflect both variability in the original length-at-age data and the fit of the model to the annual growth pattern. The standard deviation of length for each age class is shown on these graphs; standard errors were not used as they were generally smaller than the plot symbols. Numbers at age for each area are given in Table 3.1.

All curves reach an asymptote at biologically realistic lengths, and at ages which approximate to the maximum observed longevity of the scallops from each ground. Data for older scallops are scarce for some grounds (Targets, Ramsey Bay, Bradda Head), reflecting heavy exploitation and possibly shorter natural life-spans, and therefore higher natural mortality rates (Hoenig, 1983). Scallop growth rate ( $k$ ) is faster on the inshore grounds mentioned above (Table 3.2) and the asymptotic length ( $L_\infty$ ) is approached at an earlier age than on the off-shore grounds (Port St. Mary, S.E. Douglas, H/I sector)

The ages against which length is plotted are relative rather than absolute. Age 2 on the graphs in Figs. 3.4 and 3.5 refers to scallops with two growth rings. Scallops are spawned in the summer (Brand *et al.*, 1980) and the first growth ring is laid down at a true age of 8-10 months, at the end of the first winter. In samples taken during the winter (November- March) the true age of scallops with two rings will therefore be 2 years and 3-8 months, depending on the exact time of spat settlement. If no growth takes place in the winter, this age range can be considered a single age for the purposes of fitting a curve to the annual growth in length. If growth is according to the VBGF throughout the life-span,  $t_0$ , the age at length = 0 can be expected to be at a relative age of -4 months (for a July 'birthday'). This corresponds to  $t_0 = -0.33$ . The calculated values of  $t_0$  are generally realistic, with values ranging from -0.59 to +0.22 (Table 3.2). Departures from the theoretical  $t_0$  are usual in fitting the VBGF, and are commonly due to a different growth

pattern in juveniles, such as continuous slow growth through the first winter, or changes in body shape (shell allometry in the case of scallops). Differences in  $t_0$  between areas reflect possible differences in early growth pattern, settlement time and errors in parameter estimation.

The ages given on the graphs in Fig. 3.5 should be approximately one month less than the absolute ages, as the samples were taken in June, and scallops are 'born' around July, the time of peak spat settlement in these populations (Paul, 1978; Brand *et al.*, 1980; Brand *et al.*, 1991b). The value of  $t_0$  should therefore be approximately equal to + 0.1. In fact all values are positive (0.03 - 0.64), indicating only slight departure from the VBGF at the youngest ages. It is sufficient to say that the range of  $t_0$  values obtained for scallop growth curves are realistic and indicate, together with the realistic  $L_\infty$  values and reasonable statistical fit, that the VBGF is an appropriate model to describe growth in shell length.

The lowest  $k$  values, are 0.33 from the off-shore S.E. Douglas ground and 0.35 for the H/I (Off-shore South) fishing grounds. The highest values are for two of the inshore grounds off the west coast of the Isle of Man, Bradda Head ( $k = 0.55$ ) and The Targets ( $k = 0.52$ ). The smallest  $L_\infty$  values are those obtained for the inshore Maughold Head and Peel Head grounds (126.4 mm and 127.5 mm respectively) and the largest (144.4 mm and 144.5 mm) are for The Targets and Point of Ayre grounds. Parameter values from the June 1988 data indicate slightly higher  $L_\infty$  estimates on all grounds, and lower  $k$  values on all but the H/I Sector fishing ground. Table 3.2 gives a full list of all the parameters of the VBGF and their standard errors for each area, together with the growth performance indices  $\omega$  and  $\phi'$ .

The VBGF also gives a reasonable fit ( $r^2$  values range from 0.64 to 0.85) to data on queen length-at-age for the winter 1986/7 - winter 1989/90 data (Fig 3.6). The majority of the growth of queens ( $> 50\%$ ) occurs during the first 12 months, whereas data is only usually available for queens of age 1+ and older, this means that the early pattern of growth must be extrapolated from the data, which is a disadvantage in gaining reliable parameter estimates. The majority of queens sampled on all grounds were from age 2 - 5 only (Table 3.3). With sparse data on younger and older age classes, the fitting of any type of growth curve is problematic. Good fits and reasonable parameter estimates are obtained for queens from S.E. Douglas, H/I sector and The Targets, where the 0+ age class data are excluded for curve fitting, as size selectivity of fishing gear has led to a biased

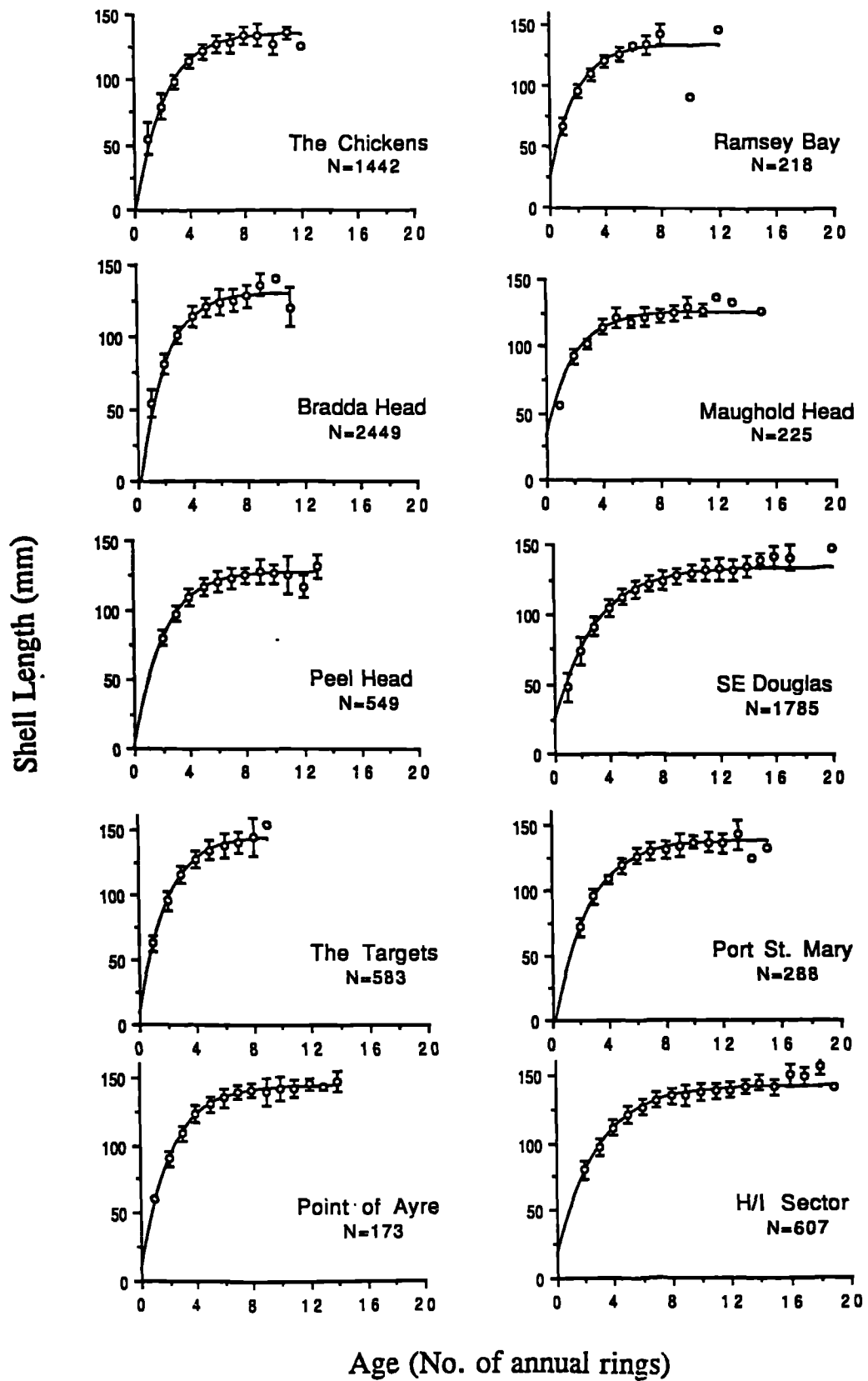
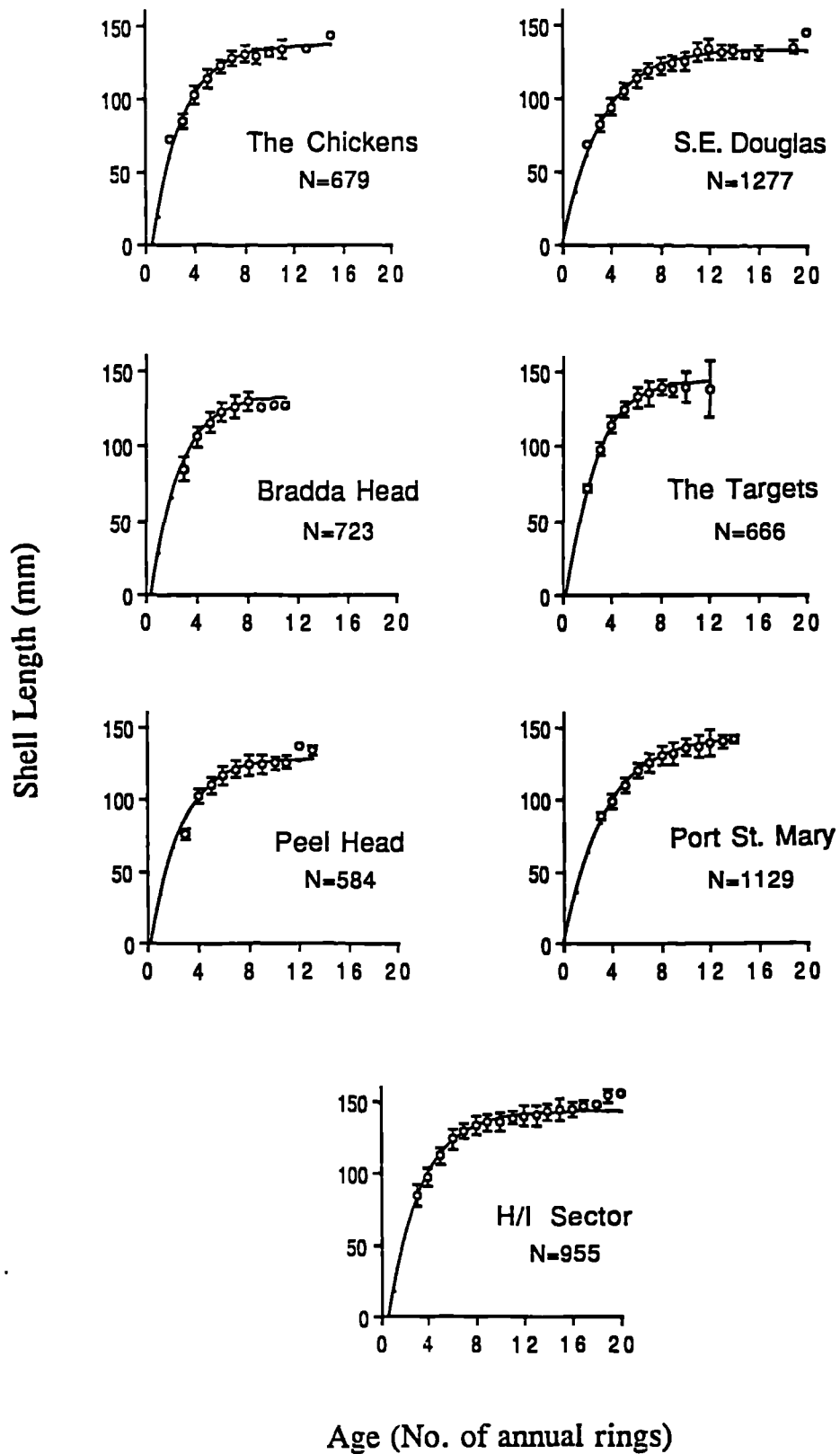


Fig. 3.4. Von Bertalanffy growth curves fitted to *Pecten maximus* length-at-age data from research vessel and commercial samples collected during the winters of 1986/7, 1987/8 and 1988/89. Standard deviations of the mean lengths-at-age are shown; sample numbers-at-age are given in Table 3.1.



**Fig. 3.5.** Von Bertalanffy growth curves fitted to *Pecten maximus* length-at-age data from commercial vessel samples collected during June, 1988. Standard deviations of the mean lengths-at-age are shown; sample numbers-at-age are given in Table 3.1.

Age (number of growth rings)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
<b>Area</b>																						
<b>a)</b>																						
CH	3	105	584	355	224	93	41	20	10	4	2	1										1442
BR	28	427	723	678	305	175	78	18	13	1	3											2449
PL		50	50	138	103	75	45	40	22	14	7	3	2									549
TG	32	152	141	110	75	44	22	6	1													583
P.A	1	16	10	22	24	29	17	13	8	7	12	5	4	5								173
RB	21	89	51	32	11	2	8	2		1												218
MG	1	9	10	58	20	17	47	23	22	12	3	1	1	1								225
SED	2	34	163	279	276	291	239	182	127	70	43	33	17	13	6	2	7				1	1785
PSM		19	28	17	90	54	28	18	13	8	3	4	4	4	1	1						288
H/I		9	36	21	68	100	85	75	41	40	42	38	23	10	9	4	3	2	1			607
<b>b)</b>																						
CH	1	24	247	243	68	44	44	21	19	4	6			1								679
BR		16	390	113	133	46	22	1	1	1	1											723
PL		5	188	88	137	76	51	20	12	4	4	1	2									584
TG		3	52	319	66	171	35	11	4	3	2											666
SED	1	30	197	128	214	158	111	51	22	22	22	7	9	4	5	2	1					1276
PSM		10	141	382	239	166	67	33	40	30	8	6	4									1126
H/I		5	24	26	48	236	204	101	48	56	63	57	41	23	8	6	3	3	1			953

**Table 3.1.** Numbers at age in *Pecten maximus* length-at-age samples used for fitting VBGFs a) winter samples (January 1987-November 1989) b) June 1988 samples.

AREA	N	r <sup>2</sup>	L <sub>∞</sub>	k	t <sub>0</sub>	ω	φ'
<b>a)</b>							
CH	1439	0.829	136.20 (0.881)	0.472 (0.017)	0.167 (0.065)	64.35 (1.195)	3.942
BR	2421	0.807	130.41 (0.672)	0.546 (0.017)	0.224 (0.048)	71.27 (1.837)	3.968
PL	549	0.785	127.48 (0.861)	0.485 (0.026)	-0.038 (0.116)	61.80 (2.928)	3.897
TG	551	0.832	144.40 (1.504)	0.518 (0.035)	-0.097 (0.119)	74.84 (4.348)	4.033
PA	172	0.868	144.49 (1.041)	0.460 (0.031)	-0.120 (0.161)	66.50 (4.118)	3.982
RB	218	0.874	134.60 (1.907)	0.522 (0.035)	-0.335 (0.097)	70.23 (3.905)	3.976
MG	224	0.606	126.41 (0.981)	0.501 (0.056)	-0.594 (0.343)	63.32 (6.636)	3.903
SED	1783	0.806	133.74 (0.559)	0.331 (0.010)	-0.542 (0.096)	44.31 (1.192)	3.772
PSM	288	0.877	138.09 (1.213)	0.415 (0.022)	0.222 (0.109)	57.26 (2.613)	3.898
H/I	598	0.765	141.96 (0.690)	0.349 (0.018)	-0.358(0.188)	49.55 (2.298)	3.847
<b>b)</b>							
CH	679	0.773	137.03 (1.293)	0.413 (0.024)	0.635 (0.138)	56.66 (2.810)	3.890
BR	707	0.596	134.28 (2.744)	0.445 (0.077)	0.468 (0.449)	59.70 (9.109)	3.904
PL	584	0.697	128.39 (1.313)	0.422 (0.041)	0.249 (0.292)	54.16 (4.784)	3.842
TG	666	0.782	144.77 (1.421)	0.447 (0.028)	0.472 (0.139)	64.66 (3.478)	3.972
SED	1276	0.825	134.06 (0.778)	0.311 (0.012)	0.031 (0.120)	41.66 (1.374)	3.747
PSM	1126	0.790	143.24 (1.142)	0.301 (0.015)	0.062 (0.161)	43.14 (1.183)	3.791
H/I	953	0.679	143.39 (0.550)	0.357 (0.014)	0.623 (0.154)	51.18 (1.865)	3.866

Table 3.2. Parameters of the VBGF and growth performance indices (with standard errors) calculated from *Pecten maximus* length-at-age data. a) November-March data (January 1987-November 1989) b) Tag release data, June 1988.

Area	Age (number of growth rings)								Total	
	0	1	2	3	4	5	6	7		8
TG	3	149	482	251	108	20	4		1	1018
PA	16	142	251	114	43	10	2	1		578
RB	2	164	220	56	10	4				457
MG	3	73	131	53	7	1		1		268
LX		112	102	62	16	5	12	1	1	243
ED	1	4	53	54	67	298	36	8	1	1908
SED	2	67	202	658	637	49	8	2		200
PSM		8	24	31	76	115	41	9		739
H/I		19	144	258	153					

**Table 3.3.** Numbers-at-age, *Chlamys opercularis* winter length-at-age samples, 1987-89, used for fitting VBGFs.

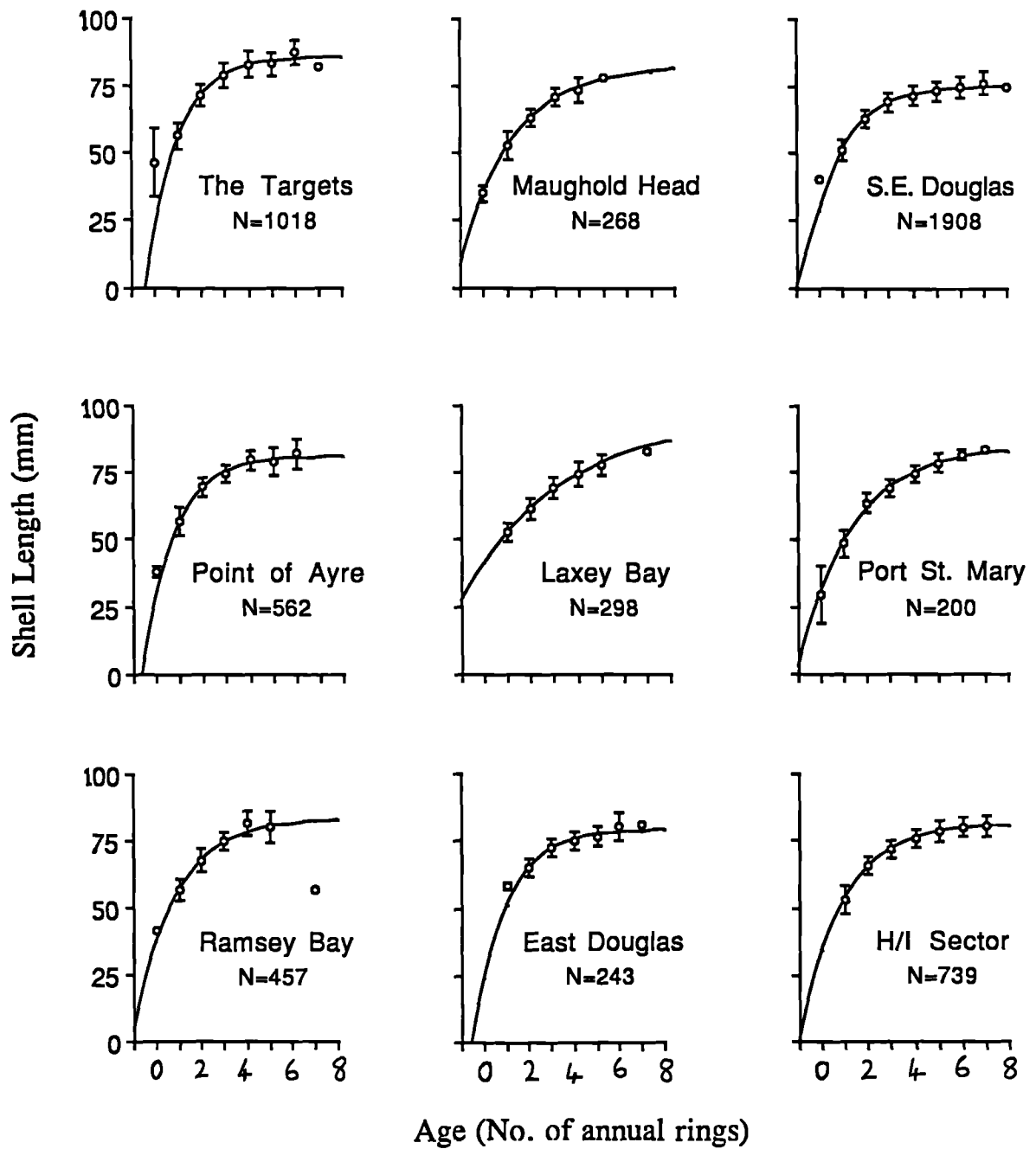


Fig. 3.6. Von Bertalanffy growth curves fitted to *Chlamys opercularis* length-at-age data from research vessel samples collected during the winters of 1986/7, 1987/8 and 1988/89. Standard deviations of the mean lengths-at-age are shown; sample numbers-at-age are given in Table 3.3.



AREA	N	r <sup>2</sup>	L <sub>∞</sub>	k	t <sub>0</sub>	ω	φ'
TG	1015	0.764	85.74 (0.651)	0.753 (0.037)	-0.421 (0.063)	64.59 (2.762)	3.743
PA	562	0.768	80.88 (0.904)	0.738 (0.057)	-0.642 (0.104)	59.66 (4.015)	3.684
RB	455	0.713	83.05 (2.123)	0.550 (0.072)	-1.092 (0.187)	45.70 (4.830)	3.579
MG	268	0.770	82.58 (3.056)	0.450 (0.065)	-1.253 (0.197)	37.12 (4.067)	3.487
LX	298	0.792	95.33 (6.963)	0.232 (0.051)	-2.470 (0.398)	22.14 (3.270)	3.324
ED	243	0.624	78.91 (1.035)	0.687 (0.126)	-0.534 (0.405)	54.19 (9.275)	3.631
SED	1908	0.639	75.13 (0.277)	0.693 (0.026)	-0.683 (0.068)	52.05 (1.759)	3.592
PSM	200	0.850	84.98 (1.409)	0.418 (0.035)	-1.082 (0.150)	35.51 (2.439)	3.480
H/I	739	0.699	81.04 (0.578)	0.553 (0.035)	-0.989 (0.143)	44.80 (2.564)	3.560

Table 3.4. Parameters of the VBGF (with standard errors) and growth performance indices calculated from *Chlamys opercularis* length-at-age winter data (January 1987–November 1989).

length distribution for this age class.

The VBGF curves from the Port St. Mary, Ramsey Bay and Maughold Head areas show a tendency to reach an asymptote, although data for older age classes is limited. The values of  $t_0$  obtained from these grounds are rather low ( $< -1$ ) due either to unrepresentative sampling of younger age classes, lack of older individuals in the population, or a combination of the two factors. The fitted curve is likely therefore to have overestimated  $L_\infty$  and underestimated  $k$  and  $t_0$  for these grounds. Values of  $t_0$  may be means of a fairly wide distribution, as queens have a protracted spat settlement period, spanning most of the summer growing season (Paul, 1978; Brand *et al.*, 1980). The growth curve fitted to length-at-age data of Laxey Bay queens does not show any tendency to reach an asymptote within the range of observed data, and it must be concluded that the VBGF is not appropriate for this data. A full list of parameter values of the VBGF for queen length at age are given in Table 3.4.

All the models provide a realistic fit to the observed data and correct estimates of the length-at-age for the age range best represented in the population and in commercial catches. Erroneous extrapolation to ages not represented in commercial catches are not important in the use of these models in Y/R analysis. It is, however, of paramount importance to appreciate that where extrapolation beyond the limits of the data are required for fitting growth curves, the parameter estimates should not be attributed with any biological significance, and comparison of such estimates with those from other grounds are of doubtful validity.

The use of the  $\omega$  parameter does, however, protect against errors in estimation of  $k$  or  $L_\infty$  to a certain extent, as the two parameters are negatively correlated. The degree of compensation for errors in one parameter with errors in the other will depend on the correlation coefficient between the two: if the correlation is perfect ( $r = 1$ ), the  $\omega$  parameter will be correct regardless of the compensatory errors in one or the other of the parameters. Correlations between  $k$  and  $L_\infty$  are generally high ( $> 0.9$ ) so errors will be largely compensated for.

Comparison of  $\omega$  values for scallops, grouped by area (Fig. 3.7) shows that although there are differences between areas, with the off-shore grounds to the south of the Isle of Man having generally lower  $\omega$  values, many of the 95% CI of  $\omega$  overlap, even between areas where the differences in  $\omega$  are quite large. The highest values are found on the inshore grounds of The Targets, Bradda Head and

Ramsey Bay. The lowest are obtained from two of the off-shore grounds (S.E. Douglas and the H/I Sector).

Where the 95% CI of  $\omega$  estimates are rather wide sample sizes were generally small (< 300) and older age classes were not well represented, leading to a large error in the estimation of  $L_{\infty}$ , and therefore  $\omega$ .

The data for the 1988 tag releases confirmed the pattern of differences in  $\omega$  values (Fig. 3.8), but CI were generally wider than for the winter data and the CI of the  $\omega$  value for the Bradda ground spanned all other estimates. This was due to a lack of younger scallops (< 3) in the samples, and fewer older individuals in the June 1988 sample.

The  $k - L_{\infty}$  pairs estimated from the winter length-at-age data for scallops from each ground are plotted to determine if there is any correlation between the two model parameters (Fig 3.9). Other growth studies have generally found a negative relationship between  $k$  and  $L_{\infty}$  (Pauly, 1987) but no such relationship is evident between growth parameters on different fishing grounds within the North Irish Sea population. Extreme values of  $\omega$  are provided by S.E. Douglas scallops which have a low growth rate and small  $L_{\infty}$ , and The Targets where both  $k$  and  $L_{\infty}$  are large.

$\phi'$  values perform similarly to  $\omega$  as growth indicators, although slight differences do occur in the rank order of  $\omega$  and  $\phi'$  between grounds, and the correlation between the two growth indices is not perfect (Fig 3.10.)

$\omega$  values and 95% CI calculated from queen winter length-at-age data indicate that some significant differences in growth performance occur between grounds, although again the differences are relatively small (Fig 3. 11). The Targets and Point of Ayre have the highest  $\omega$  values for both scallops and queens. A test of the relationship between  $\omega$  values for queens and scallops from the same grounds (with  $H_0$  = no correlation and  $H_A$  = positive correlation) indicated no significant linear correlation ( $r = 0.363$ ,  $0.5 < P_{\alpha 1} < 0.25$ ). The same test on  $\phi'$  values for scallops and queens also showed no significant difference at the pre-selected 95% probability level ( $r = 0.553$ ,  $0.10 < P_{\alpha 1} < 0.05$ ) although a relationship is suggested, with the Targets and Point of Ayre grounds being favourable to growth of both species, and some of the off-shore grounds to the south of the I.o.M. showing lower growth rates, but high asymptotic lengths in

Fig. 3.7

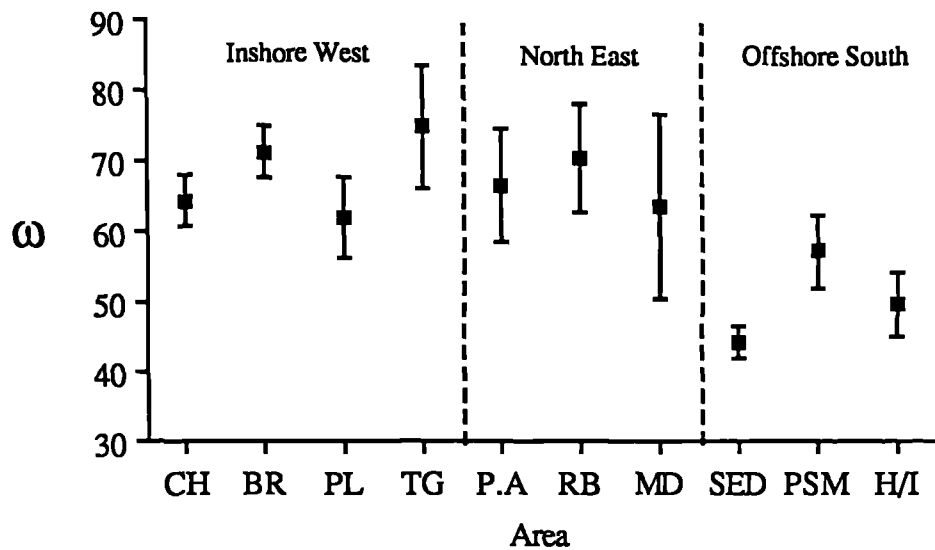
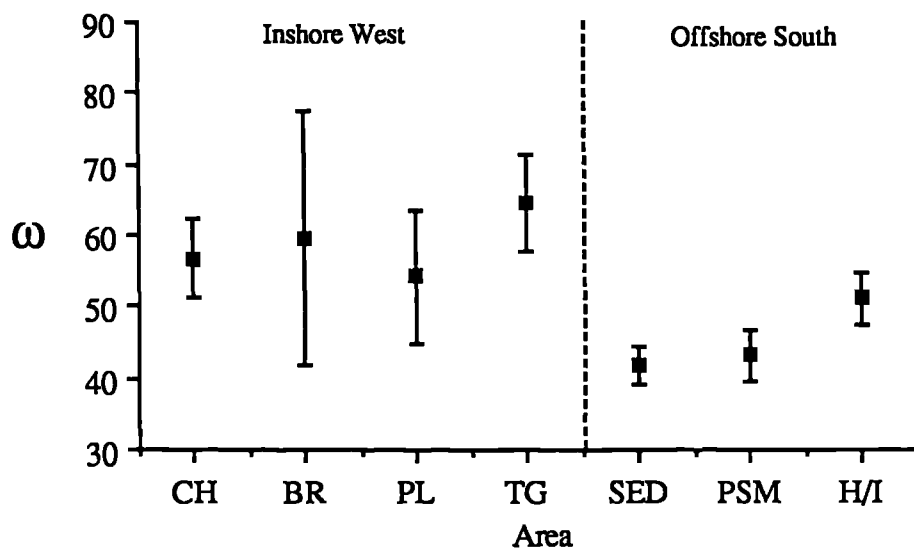


Fig. 3.8



**Figs 3.7 & 3.8.**  $\omega$  values (with 95% CI) calculated from VBGFs fitted to *Pecten maximus* length-at-age data collected during the winters of 1986/7, 1987/8 and 1988/9 (Fig. 3.7) and during June 1988 (Fig. 3.8).

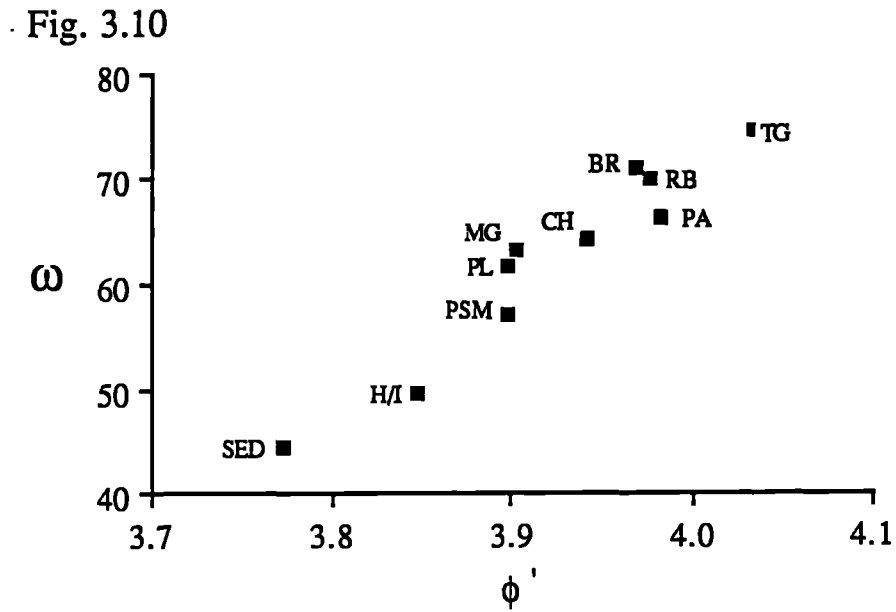
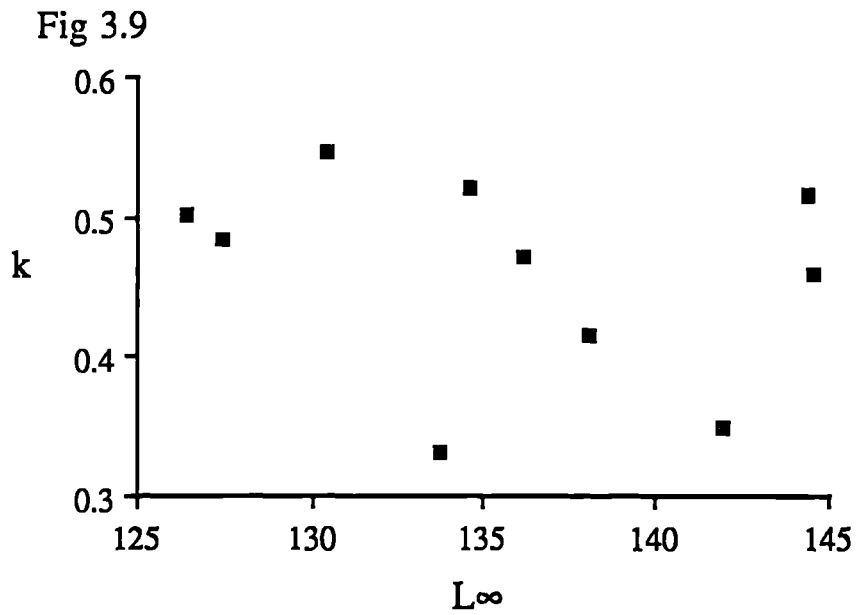


Fig. 3.9.  $K - L_{\infty}$  pairs from winter samples of *Pecten maximus*, showing no correlation between  $k$  and  $L_{\infty}$  values of scallops from different grounds.

Fig. 3.10. Comparison of  $\omega$  and  $\phi'$  values calculated from VBGFs for winter samples of *Pecten maximus*. Although the two indices are closely correlated, growth performance of scallops from different grounds are ranked in different orders by the two indices.

Fig. 3.11

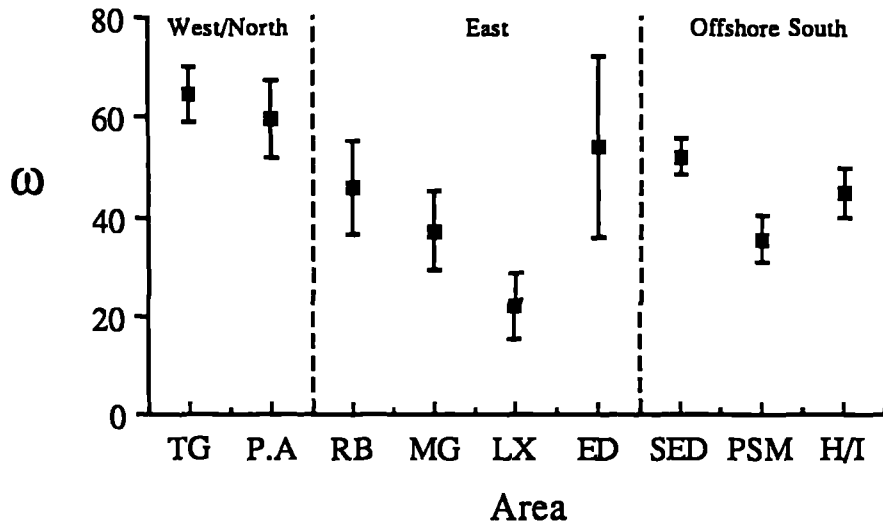


Fig. 3.12

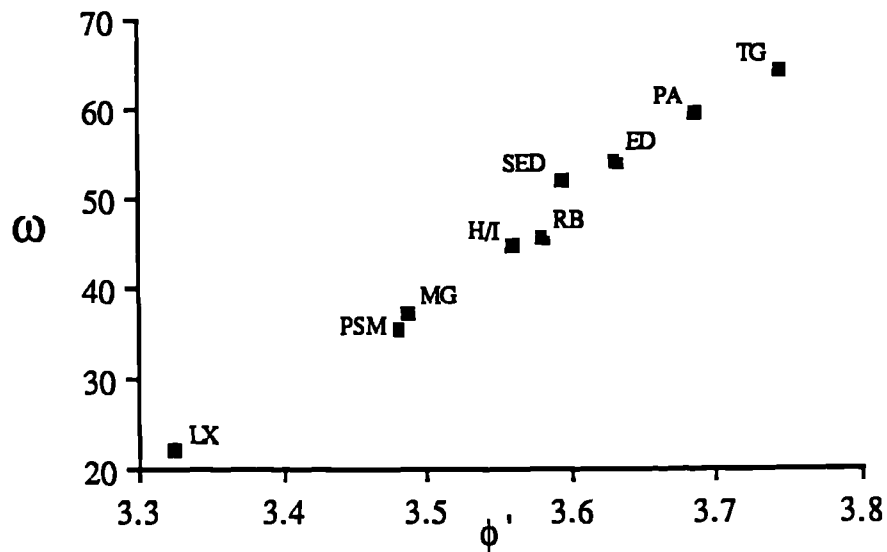


Fig. 3.11.  $\Omega$  values (with 95% CI) calculated from VBGFs fitted to *Chlamys opercularis* length-at-age data collected during the winters of 1986/7, 1987/8 and 1988/9.

Fig. 3.12. Comparison of  $\Omega$  and  $\phi'$  values calculated from VBGFs for winter samples of *Chlamys opercularis*. The two growth performance indices are closely correlated and rank the growth performance of queens from different grounds in same order.

both species (H/I sector and PSM). The relationship appears to break down on the other grounds where both species are found, and data from a larger number of grounds would be required to validate these findings.

The  $k$ ,  $L_{\infty}$  pairs for queens have not been plotted as some of the estimates of the individual parameters are of doubtful validity due to extrapolation of fitted curves to limited data, leaving too few areas for meaningful comparison. The two growth performance indices rank the grounds in the same order of relative growth performance (Fig 3.12) indicating that either parameter may be used for comparing growth performance between areas.

The statistical comparison of the  $\omega$  values and qualitative comparison of  $\phi'$  values for both scallops and queens have established that differences in growth performance are evident between the different scallop and queen grounds in the north Irish Sea, presumably due at least partially to differing environmental conditions on the fishing grounds. The only environmental data available are the mean depth of each sampling area and substrate categories based on British Geological Survey seabed sediment maps (Table 3.5). The effects of density on growth have not been considered as data are only available from commercial CPUE figures, which do not include the density of the first 3 or 4 year classes of scallops, and the 0+ year class in queens. As these are the most numerous on many grounds, a comparison of growth between areas based on densities which exclude these year classes could be misleading.

Lack of detailed data on substratum type limits the value of the investigation; substratum composition is only available by category, but there is a suggestion of a relationship between substrate composition (% gravel or % sand) and growth performance in *Pecten maximus*, with highest growth performance taking place in areas where the substratum is categorised as gravely sand (Fig. 3.13a). Areas with higher sand content (Peel Head) or predominantly gravely sediments are associated with lower growth performance. Depth is also implicated as a factor affecting growth, with a negative relationship between depth and growth performance in *P. maximus* (Fig. 3.13b). The covariance among environmental variables and lack of suitable quantitative data on substrate-composition urge caution in the interpretation of these relationships. No relationship was observed between *Chlamys opercularis*  $\omega$  or  $\phi'$  values and depth or substratum type.

### 3.3.2. Length/weight relationships

Table 3.6 gives the estimates of the parameters of the functional regressions between scallop length and yield ( $u$  and  $v$ ) and their standard errors for all November- March samples from which both length and weight were recorded during the January 1987 - October 1988 sampling period.

The traditional weight/length exponent of 3 only falls within the 95% CI of the estimate of  $v$  for the Port St. Mary scallop ground. All other values are significantly ( $p < 0.05$ ) higher. This suggests that the adductor muscle and gonad increase in weight faster than the other body tissues as the exponent of the total weight/length relationship is close to 3 (Murphy, 1986).

The hypothesis of no significant difference in the exponent of the length/weight regression between areas was rejected at the 95% level of significance by pair-wise comparisons using Clarke's t-test and the Bonferroni approximation for multiple paired comparisons, with each individual comparison being made at a significance level of  $p = 0.05/15 = 0.003$ , as the number of pair-wise comparisons necessary to test all pairs among 6 areas is 15. The highest length/weight exponents are from the Bradda, Targets and Chickens grounds, indicating that the growth of the edible yield on these grounds is greatest relative to the increase in shell length. At this significance level, the length/weight relationships on the Bradda and Port St. Mary grounds were significantly different to each other and to all other grounds. Differences among the other grounds were not significant at the stringent significance level used, but type II errors are likely in this type of comparison, so pooled slopes were not computed. No statistical test of the differences among the intercepts was made, as none was readily available (see Clarke, 1980).

Functional regressions of queen length/yield and length/adductor muscle weight are given for both winter (November - March) and summer (June - October) data (Tables 3.7, 3.8, 3.9 and 3.10). The latter period is included as it is the major queen-fishing season, and the former the time when seasonality is less pronounced (with no increase in shell length) allowing inter-area comparisons of the regression parameters between samples taken on different dates.

The length/weight relationship in queens is lower than in scallops, with the value of the exponent being generally close to 3, indicating that the growth of the



Area	Depth Range (m)	Mean Depth (m)	Substrate grade	% Gravel (median)	% Sand (median)	$\phi$ - value (Sand)
CH	49-67	58	gS	18	75	1.50
BR	33-38	35	gS	18	75	1.25
PL	28-38	33	S/mS	3	92	1.25
TG	23-33	28	gS/sG	35	55	1.25
PA	49-54	52	gS/sG	35	55	1.00
RB	14-24	19	S/gS/SG	8	85	1.25
MG	24-29	27	gS	18	75	1.25
ED	29-39	33	sG	50	38	0.75
SED	46-52	49	sG	50	38	1.50
PSM	48-62	56	gS	18	75	1.50
H/I	56-67	62	sG	50	38	1.50

**Table 3.5.** Depth (admiralty chart datum + tidal correction to approximate mean tidal level) and substrate type (from BGS 1:250 000 Sea Sediment series) on North Irish Sea scallop and queen fishing grounds. Substrate types are classified according to Folk's (1954) scale. Values of % composition of sand and gravel and the  $\phi$  value of the sand fraction are taken as the medians of the percentages defining the substrate-type boundaries.

Fig. 3.13a

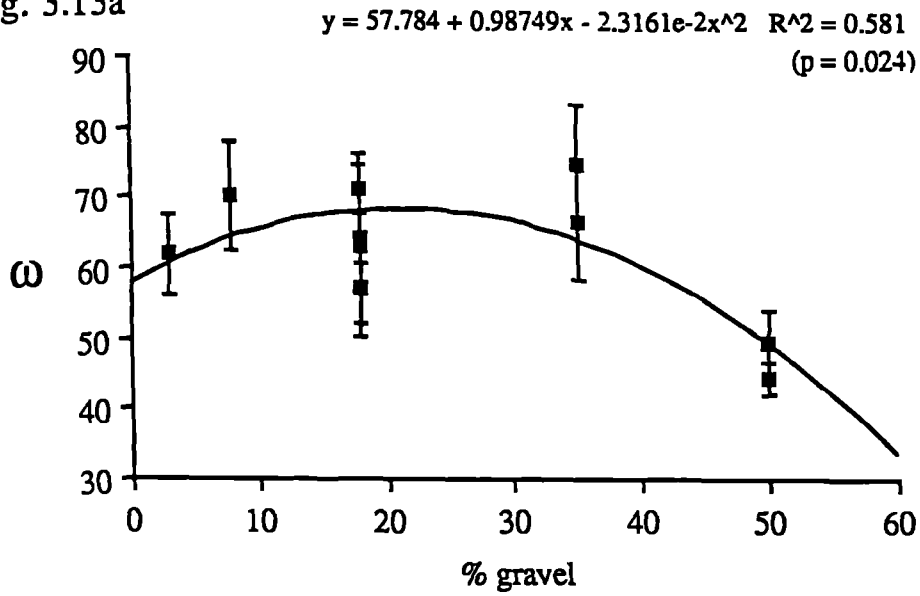
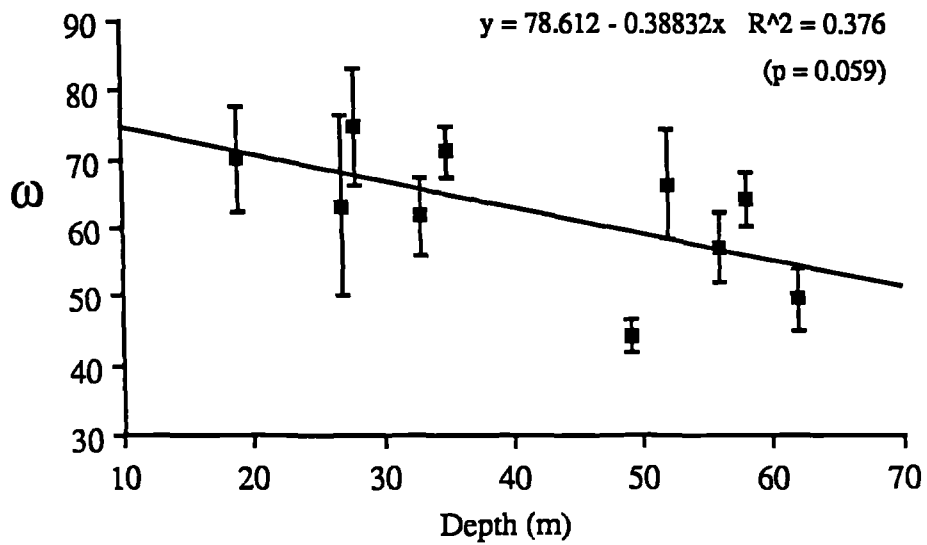


Fig. 3.13b



**Fig. 3.13a.** Relationship between growth performance ( $\omega$ ) of *Pecten maximus* and the substrate type (represented by % gravel) found on the fishing grounds (determined by British Geological Survey).

**Fig. 3.13b.** Relationship between growth performance ( $\omega$ ) of *Pecten maximus* and the depth of the fishing grounds.

AREA	N	r <sup>2</sup>	v		ln(u)	
CH	178	0.901	3.83	(0.091)	-14.850	(0.424)
BR	665	0.920	4.18	(0.046)	-16.416	(0.213)
TG	214	0.947	3.88	(0.062)	-14.944	(0.290)
SED	607	0.903	3.79	(0.048)	-14.599	(0.227)
PSM	116	0.812	3.23	(0.132)	-12.078	(0.627)
H/I	336	0.828	3.63	(0.082)	-13.868	(0.868)

**Table 3.6** Parameters of length/weight functional regression relationships (with standard errors); *Pecten maximus* winter (November-March) samples. Yield = adductor muscle + gonad weight.

**Table 3.7** Length/yield.

AREA	N	r <sup>2</sup>	v		ln(u)	
TG	249	0.783	3.29	(0.098)	-11.924	(0.417)
LX	135	0.884	3.11	(0.092)	-11.214	(0.375)
ED	40	0.671	3.17	(0.294)	-11.624	(1.236)
SED	536	0.534	3.49	(0.103)	-12.762	(0.411)
PSM	99	0.750	2.83	(0.143)	-10.084	(0.607)
H/I	145	0.738	3.16	(0.135)	-11.496	(0.868)

**Table 3.8** Length/adductor muscle.

AREA	N	r <sup>2</sup>	v		ln(u)	
TG	249	0.764	3.23	(0.100)	-11.860	(0.428)
LX	137	0.899	2.96	(0.081)	-10.838	(0.330)
ED	40	0.691	3.11	(0.280)	-11.505	(1.177)
SED	582	0.546	3.84	(0.107)	-14.445	(0.456)
PSM	99	0.767	2.82	(0.139)	-10.284	(0.589)
H/I	145	0.789	3.13	(0.121)	-11.538	(0.515)

**Tables 3.7 and 3.8.** Parameters of length/weight functional regression equations (with standard errors), *Chlamys opercularis* winter (November-March) samples. Yield weight = adductor muscle weight + gonad weight.

**Table 3.9** Length/yield.

AREA	N	r <sup>2</sup>	v	ln(u)
CL	95	0.897	2.54 (0.085)	- 8.628 (0.352)
ED	490	0.843	3.19 (0.057)	-11.207 (0.236)
SED	703	0.588	2.87 (0.070)	-10.105 (0.391)
H/I	165	0.516	2.69 (0.146)	- 9.315 (0.623)

**Table 3.10** Length/adductor muscle.

AREA	N	r <sup>2</sup>	v	ln(u)
CL	95	0.869	2.49 (0.094)	-8.646 (0.389)
ED	490	0.870	2.84 (0.046)	-10.005 (0.190)
SED	703	0.564	2.82 (0.070)	-10.016 (0.298)
H/I	165	0.446	2.72 (0.158)	-9.683 (0.673)

**Tables 3.9 and 3.10.** Parameters of length/weight functional regression equations (with standard errors), *Chlamys opercularis* summer (June - October) samples. Yield weight = adductor muscle weight + gonad weight.

adductor muscle and gonad of queens is close to isometric with respect to increase in overall size of the organism. Winter samples of length/yield and length/adductor muscle regression slopes showed significant differences between the highest and lowest values at  $p = 0.003$ , indicating that the hypothesis of no significant difference between areas is rejected at the  $p < 0.05$  level. No other differences between areas were found at the more stringent level for individual paired comparisons, but common regression equations were not computed as type II errors seem likely, and the intercepts have not been compared statistically.

Summer samples were more variable between areas, with the following differences suggested:

<u>ED</u>	SED	CL	H/I
_____	_____	_____	

Underscores link grounds which did not have significantly different length-weight relationships.

Variability in the length/yield relationship is clearly present within the North Irish Sea stocks of both scallops and queens, indicating that energy budgets differ between areas. The limitations of the statistical testing procedures do not at present allow any more detailed investigation.

### 3.3.3. Growth in Weight.

VBGFs were fitted to weight-at-age data for scallop samples taken from November-March during the winters of 1986/7 and 1987/8. The exponent  $v$  of the functional regression equation relating length to weight was calculated from the same data, and the appropriate value was used in the VBGF for each ground.

The VBGF fitted to scallop yield-at-age data (Fig 3.14) show that the fit is reasonably good ( $r^2$  0.73 - 0.82) but the data are highly variable, particularly in the older year classes, where estimates are based on small sample sizes, especially in samples from Bradda, The Chickens and The Targets where there are few scallops > 8 years old in the population (Table 3.11).

Yield-weight does tend towards an asymptotic value on all grounds,

although for the three mentioned above, the values have large statistical uncertainty. There is also a suggestion of decrease in weight in the oldest age classes of scallops from the H/I ground. The Targets and H/I grounds have the highest  $Y_{\infty}$  values, and the S.E. Douglas ground has the lowest. All other grounds have values similar to each other (Table 3.12).

The fit of the VBGF to winter weight-at-age data from queen samples is generally poor, ( $r^2$  0.21 - 0.70) due to a high degree of variability in the data. The shape of the fitted growth curves shows considerable variability between areas (Fig. 3.15). It is unlikely that growth curves will differ in form within the same species *living in the same geographical area*. High individual variability and differences in sample size and population structure (Table 3.13) are probably responsible for the differences in the form of the curves.

The growth curves fitted to winter samples from E. Douglas, S.E. Douglas, The Targets and the H/I ground, and all the weight curves fitted to summer (June - October) data (Fig 3.16), show reasonable concordance with the von Bertalanffy form, with an inflexion in the growth curve at approximately  $W_{\infty}/3$  (Beverton & Holt, 1957; Ricker, 1975b) and a clear asymptote. Of the grounds where the model assumptions appear to be met, the Targets ground has the highest  $Y_{\infty}$  and  $M_{\infty}$  as well as high  $k$ -values, indicating that this ground has the highest growth performance in terms of weight as well as length.

The data from Port St. Mary and Laxey Bay do not conform precisely to the form of the VBGF, and the  $k$  and  $t_0$  values are likely to be underestimates, while the  $L_{\infty}$  values are overestimates.

The curves fitted to yield (gonad + adductor muscle) and adductor muscle only are both shown, and parameter values tabulated (Tables 3.14, 3.15, 3.16 and 3.17). Standard errors of the parameter values are not given as the error on the exponent  $v$  has not been included in the fit of the model, so that the values for standard error derived from the NLR procedure are misleading.

Parameters of the VBGF for weight have also been calculated by using the VBGF-predicted winter lengths-at-age (from Fig. 3.4 and Fig. 3.5) and the exponent of the appropriate functional regression equation (Tables 3.6 - 3.10) to compute theoretical weight-at-age data. The VBGF for weight was fitted to these data, to give an alternative set of parameter estimates derived from the larger

		Age (number of growth rings)																					
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Area																							
CH				6	90	45	22	12	2		1												178
BR		2	127	225	145	88	44	27	3	3		1											665
TG		5	40	82	26	36	14	8	3														214
SED			11	76	63	106	134	61	63	38	25	11	12	5	2			1					608
PSM			1	6	12	38	16	13	7	7	5	3	4	3	1								116
I/I			2	22	9	36	86	44	23	9	25	31	23	13	4	4	2	2		1			336

Table 3.11. Numbers-at-age, *Pecten maximus* in winter samples used for fitting von Bertalanffy growth curves to weight (yield).



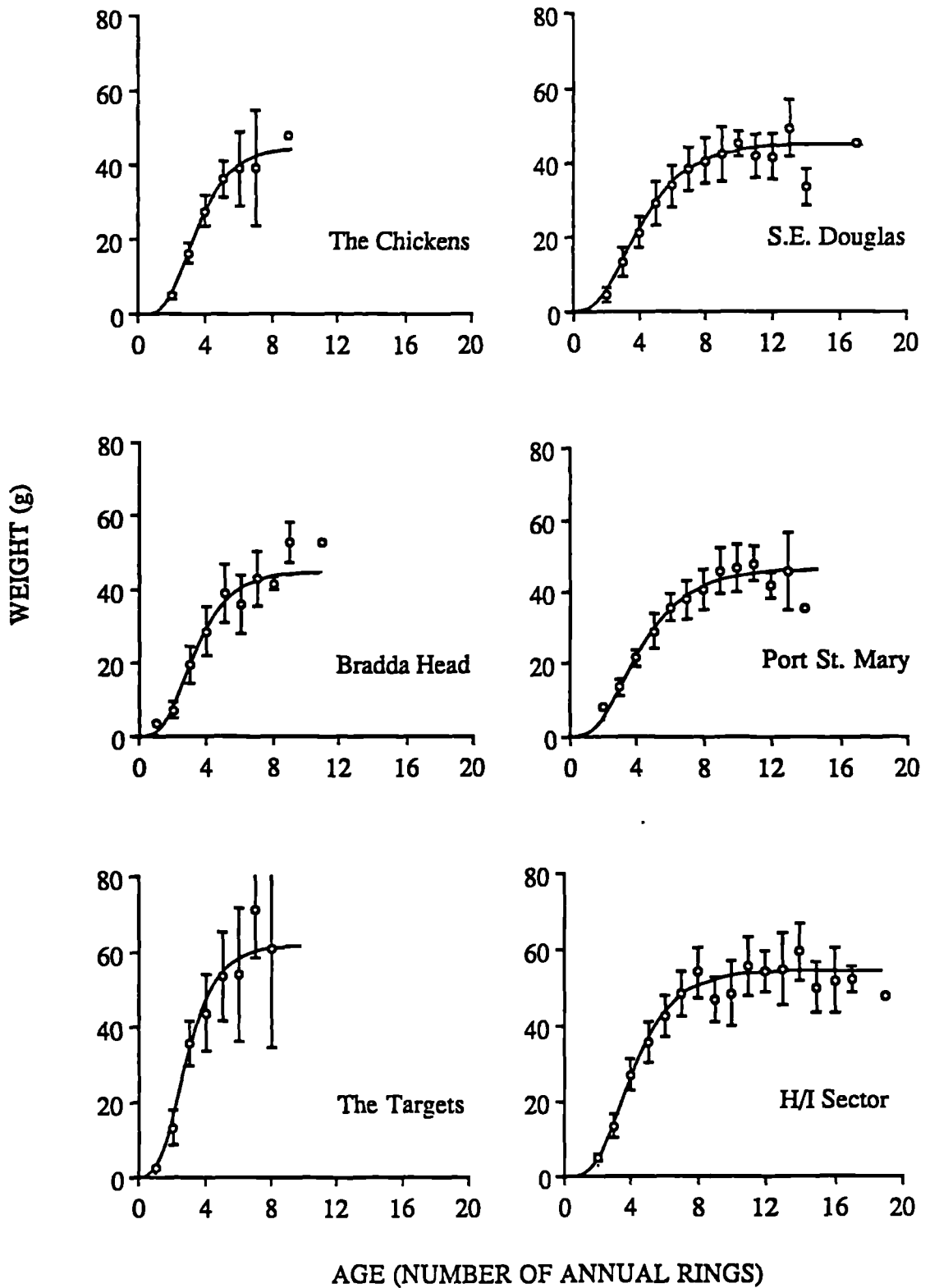
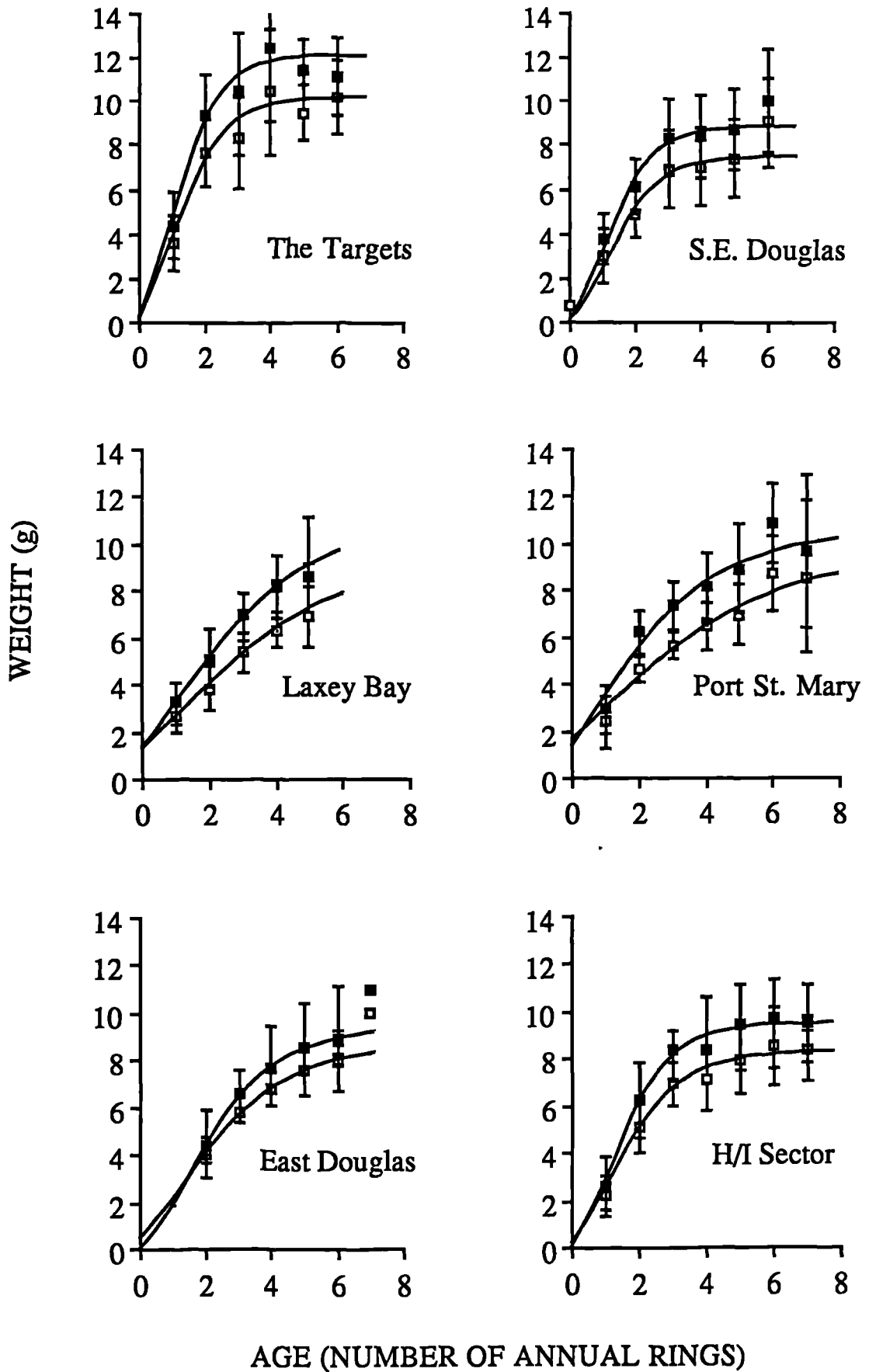


Fig. 3.14. VBGF for weight fitted to winter weight-at-age data, *Pecten maximus*. Standard deviations of weight-at-age are shown, sample numbers are given in Table 3.11.

AREA	N	r <sup>2</sup>	V	Y <sub>∞</sub>	k	t <sub>0</sub>	Y <sub>∞</sub> '	k'	t <sub>0</sub> '
CH	178	0.82	3.83	44.6	0.68	0.86	53.0	0.47	0.16
BR	665	0.77	4.18	44.4	0.66	0.42	51.4	0.55	0.23
TG	214	0.73	3.88	61.5	0.77	0.44	77.6	0.52	-0.10
SED	608	0.77	3.79	44.7	0.46	0.26	54.4	0.33	-0.50
PSM	116	0.76	3.23	46.2	0.45	0.51	46.5	0.42	0.23
H/I	336	0.75	3.63	54.3	0.54	0.90	61.6	0.35	-0.36

**Table 3.12** VBGF parameters calculated from *Pecten maximus* winter (November-March) yield-at-age data (January 1987 -March 1988; columns 2 to 7) and parameters calculated from winter length-at-age data (January 1987 - November 1989) and the slope of the length/weight regression relationship (columns 8 to 10).



**Fig. 3.15.** VBGF for weight fitted to winter weight-at-age data, *Chlamys opercularis*. Growth curves are fitted to data on adductor muscle weights (open plot symbols) and yield-weights (shaded symbols). Standard deviations of weight-at-age are shown; sample numbers are given in Table 3.13.

## Age(number of growth rings)

	0	1	2	3	4	5	6	7	8	Total
Area										
a)										
TG		22	130	49	42	3	2			249
ED			3	8	12	11	5	1		40
SED	1	11	66	236	176	82	10			582
PSM		5	10	12	36	27	6	2		98
H/I		6	25	29	27	39	15	4		145
b)										
CL		7	15	27	22	18	5			95
ED	2	88	251	98	38	9	4			490
SED		26	52	115	339	124	39	7	1	703
H/I			6	48	48	29	27	5	2	165

**Table 3.13.** Numbers-at-age of *Chlamys opercularis*, used to calculate VBGF curves for yield and adductor muscle growth a) winter samples (November - March), b) summer samples (June - October).

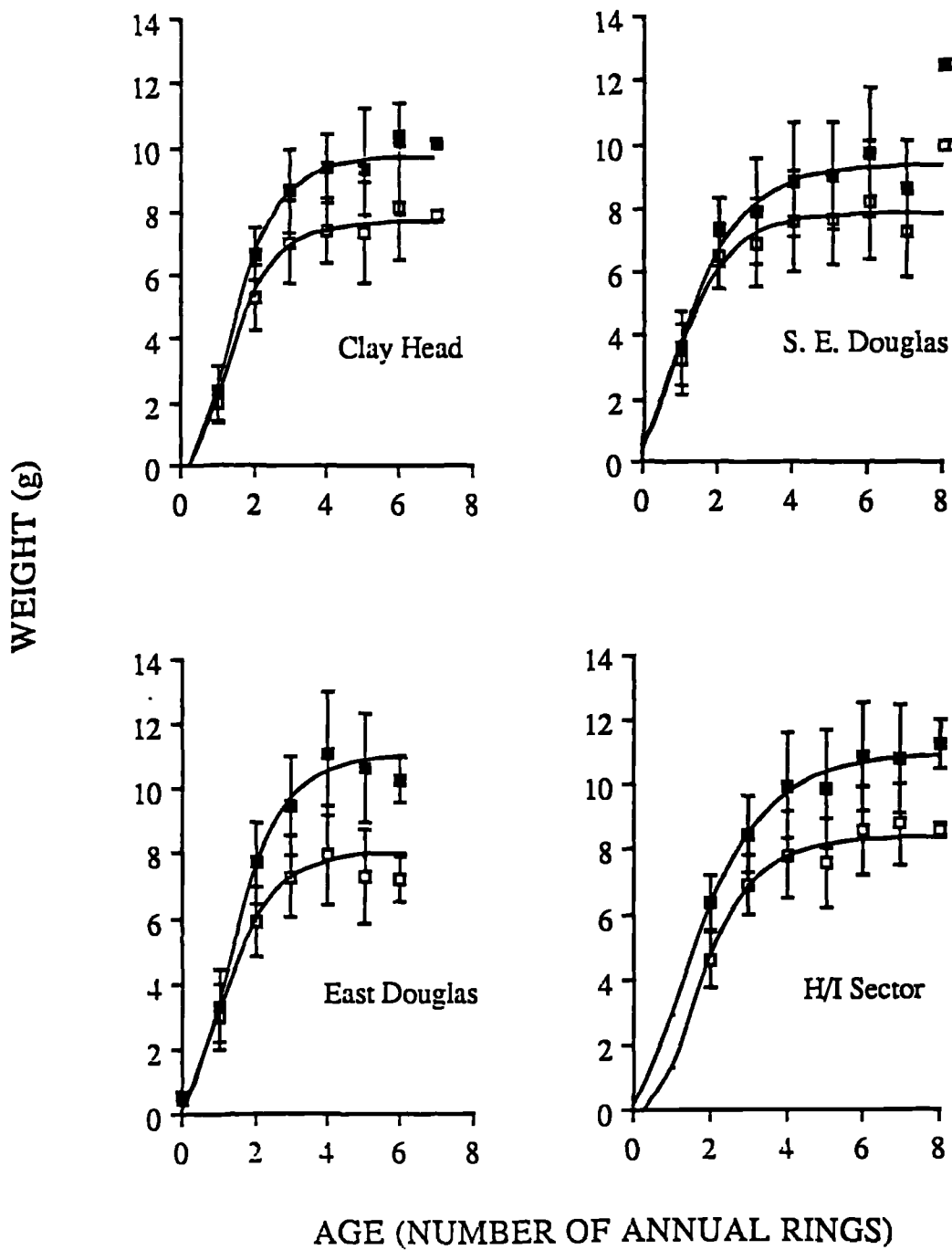


Fig. 3.16. VBGF for weight fitted to summer weight-at-age data, *Chlamys opercularis*. Growth curves are fitted to data on adductor muscle weights (open plot symbols) and yield-weights (shaded symbols). Standard deviations of weight-at-age are shown; sample numbers are given in Table 3.13.

Table 3.14. Yield.

AREA	N	r <sup>2</sup>	v	Y <sub>∞</sub>	k	t <sub>0</sub>	Y <sub>∞</sub> '	k'	t <sub>0</sub> '
TG	249	0.40	3.29	12.2	1.16	-0.17	15.3	0.75	-0.43
LX*	137	0.70	3.11	11.3	0.41	-1.72	19.3	0.23	-2.45
ED	39	0.36	3.17	9.4	0.63	-0.46			
SED	527	0.21	3.49	8.8	1.19	-0.14	10.1	0.69	-0.68
PSM	99	0.52	2.83	10.6	0.47	-1.41	12.1	0.42	-1.09
H/I	145	0.51	3.16	9.5	0.95	-0.19	11.2	0.55	-1.00

Table 3.15 Adductor muscle only.

AREA	N	r <sup>2</sup>	v	M <sub>∞</sub>	k	t <sub>0</sub>	M <sub>∞</sub> '	k'	t <sub>0</sub> '
TG	249	0.40	3.23	10.2	1.06	-0.27	12.5	0.75	-0.43
LX	137	0.69	2.96	9.9	0.33	-2.12	14.4	0.23	-2.51
ED	39	0.36	3.11	8.7	0.52	-0.98			
SED	572	0.21	3.84	7.5	1.12	-0.22	8.5	0.70	-0.68
PSM	99	0.56	2.82	9.8	0.31	-2.40	9.5	0.42	-1.09
H/I	145	0.56	3.13	8.3	0.79	-0.41	9.2	0.55	-1.00

Tables 3.14 and 3.15. VBGF parameters calculated from *Chlamys opercularis* winter yield-at-age data (January 1987 - March 1988; v, Y<sub>∞</sub>, k, t<sub>0</sub>) and parameters calculated from winter length-at-age data (January 1987 - November 1989) and the exponent (v) of the length/weight regression equation (Y<sub>∞</sub>', k', t<sub>0</sub>').

**Table 3.16.** Yield, *Chlamys opercularis*.

---

AREA	N	r <sup>2</sup>	v	Y <sub>∞</sub>	k	to
CL	95	0.71	2.54	9.7	1.15	0.27
ED	490	0.75	3.19	11.0	1.06	-0.10
SED	703	0.30	2.87	9.3	0.90	-0.49
H/I	165	0.32	2.69	10.9	0.74	-0.27

---

**Table 3.17.** Adductor muscle, *Chlamys opercularis*.

---

AREA	N	r <sup>2</sup>	v	M <sub>∞</sub>	k	to
CL	95	0.61	2.49	7.7	1.12	0.29
ED	490	0.65	2.84	8.0	1.08	-0.13
SED	703	0.26	2.82	7.8	1.06	-0.30
H/I	165	0.29	2.72	8.3	0.99	-0.30

---

**Tables 3.16 and 3.17.** VBGF parameters calculated from *Chlamys opercularis* yield and adductor muscle at age data collected during the queen fishing seasons (June - October) of 1987 and 1988.

length-at-age data-sets, which included more old scallops and were subject to less variability than the weight-at-age data. The derived values are also given in Tables 3.12, 3.14 and 3.15 for comparison with estimates from the actual weight-at-age data.

The length-derived values for  $M_{\infty}$  and  $Y_{\infty}$  for both scallops and queens are higher and  $k$  values are lower than the values calculated from the fit of the model to the actual weight-at-age data. Investigation of the reason for this discrepancy revealed that length-at-age differed between the large length and age data-set and its length, yield and age subset. The main length and age data-set covered the period January 1987 - November 1989, whereas the length, yield and age data-set covered only January 1987 - October 1988. Examination of annual variability in growth rates (see 3.3.5) revealed differences in the growth rates, with generally higher length-at-age of both scallops and queens in the winters of 1988/9 and 1989/90 than in the 1986/7 and 1987/8 winters.

The discrepancies between the two sets of estimates may also be due to the fact that there were more data for older scallops in the larger data set, and less variability, making more reliable the estimation of  $L_{\infty}$ , and hence calculated  $M_{\infty}$  and  $Y_{\infty}$  and its correlated parameters. For the purposes of Y/R assessments carried out as part of this study (Chapter 6), the parameters determined from length-at-age data and the length/weight regression are used for scallops. For the assessment of the East Douglas stock of queens, the values derived from weight-at-age data during the fishing season (June - October) are used.

#### **3.3.4. Seasonal growth patterns**

Monthly samples of scallops from the Bradda and S.E. Douglas grounds yielded growth in length curves which showed a seasonal pattern, with growth proceeding in a series of steps: a plateau corresponding to the winter cessation in shell growth (October - March), exponentially increasing length in spring/early summer, slowing down through August/September to reach another asymptote the following winter.

The pattern was only really visible in scallops aged 2-5 years in the Bradda Head samples (Fig 3.17a). Between-sample variability masked the seasonal pattern in older age classes where the annual increment is much less and sample sizes

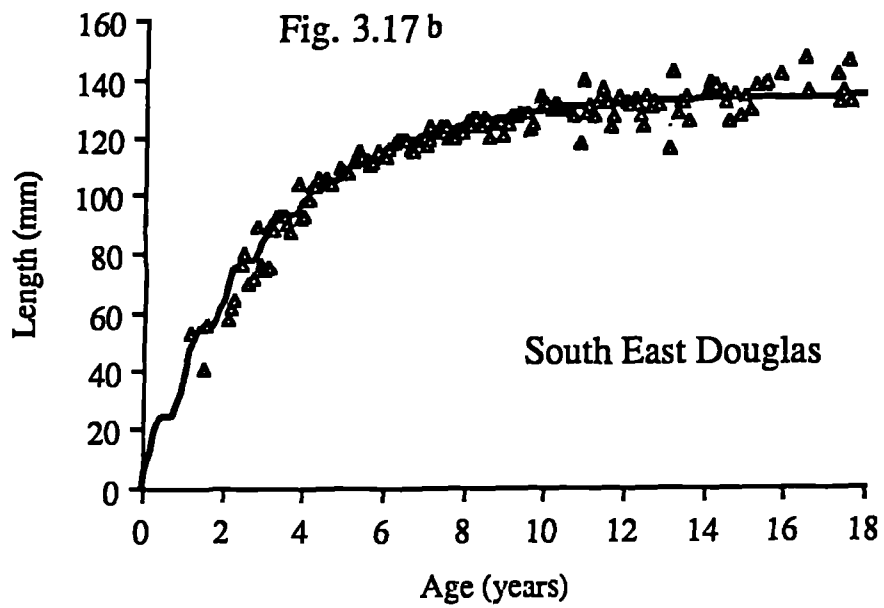
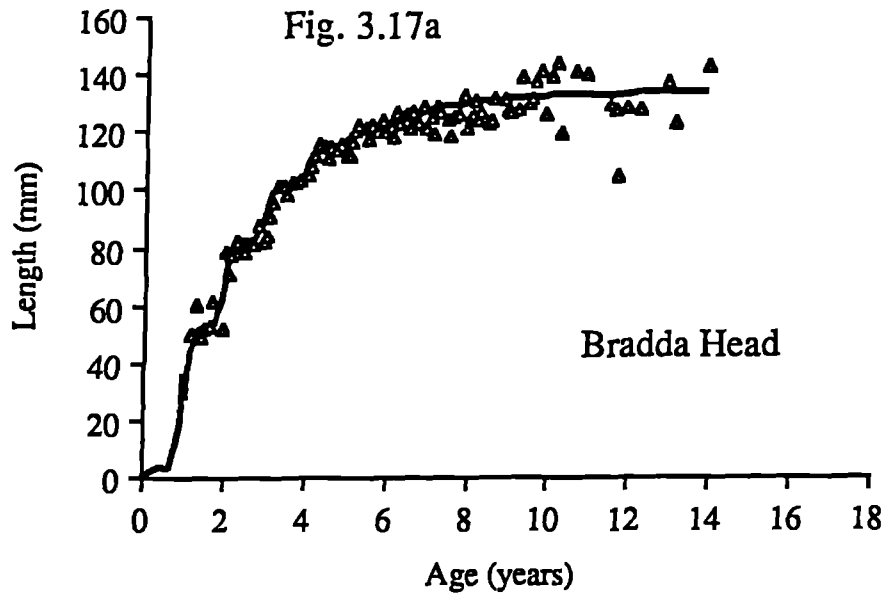


smaller. The S.E. Douglas samples show visible seasonal growth discontinuities up to age 8+ (Fig 3.17b) reflecting the different growth pattern on this ground, where successive growth increments decrease in size more slowly (lower  $k$  value). The fit of the seasonal VBGF is good on both grounds and the pronounced seasonal discontinuity is reflected in the high values of the seasonality parameter  $C$  (Table 3.18). The fact that  $C$  exceeds 1 produces an apparent slight decrease in length during the winters. This is likely to be due to the mathematical form of the curve, which simulates a wave-form rather than a series of flat-topped discontinuities, together with variability in the data, which are pooled from the 3 year sampling programme.

Queens from S.E. Douglas monthly samples showed strong seasonality (Fig 3.18a). The data set from the East Douglas ground was more limited but less variable, and the seasonal discontinuities are also readily discernible although the many missing months make it difficult to fit a seasonal curve without the prior assumption of growth cessation during the winter. The curve has been fitted by constraining  $C$  to 1 to simulate the winter cessation of growth (Fig. 3.18b). The curve was fitted using the CNLR procedure in SPSSX. As the two procedures (NLR and CNLR) use different algorithms and convergence criteria, direct comparison of parameter estimates from the S.E. Douglas and E. Douglas grounds should be undertaken with caution.

The seasonal weight cycle is of more direct commercial relevance than the seasonal length growth pattern. It is also more pronounced. The seasonal VBGF for length was converted to a seasonal VBGF for weight using length-weight relationships. The functional relationships between length and gonad weight and length and adductor muscle weight were calculated for each sample of scallops from Bradda Head and South-east Douglas, and for samples of queens from South-east Douglas and East Douglas. Weight data and length-weight relationships calculated from samples taken during 1987 and 1988 were pooled, in all but one case, to give a single series of data covering most months of the year. The exception was for data from South-east Douglas queen samples, which showed significantly different weight-at-age and length-weight relationships in samples collected during the same months in different years. Only the data collected in 1988 were used for analysis of seasonal changes. Data are presented in Tables A2.1 - A2.8, Appendix 2.

The parameters of the length-weight relationships show considerable



**Fig. 3.17.** VBGF with seasonal oscillation fitted to *Pecten maximus* length-at-age data from two fishing grounds. Absolute ages in months were calculated from the number of growth rings and date of sampling, assuming a July 1st 'birthday'.

Fig. 3.18a

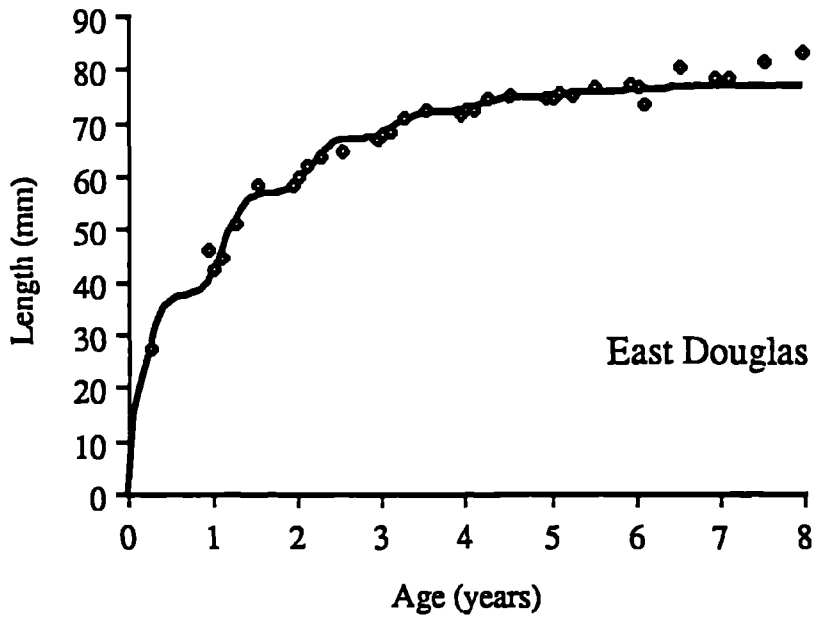


Fig. 3.18b



Fig. 3.18. VBGF with seasonal oscillation fitted to *Chlamys opercularis* length-at-age data from two fishing grounds. Absolute ages in months were calculated from the number of growth rings and date of sampling, assuming a July 1st 'birthday'.

Table 3.18. Parameters of seasonally oscillating von Bertalanffy growth models (with standard errors) fitted to *Pecten maximus* and *Chlamys opercularis* length-at-age data by non-linear least squares regression.

Species & Area	N	r <sup>2</sup>	L	k	t <sub>0</sub>	t <sub>s</sub>	C
<i>P. maximus</i> , Bradda	4120	0.807	133.68 (0.535)	0.466 (0.010)	0.280 (0.041)	0.524 (0.010)	1.192 (0.071)
<i>P. maximus</i> , SED	2758	0.805	133.92 (0.478)	0.329 (0.008)	0.009 (0.042)	0.558 (0.021)	1.049 (0.159)
<i>C. opercularis</i> , SED	3153	0.637	75.42 (0.216)	0.696 (0.020)	-0.149 (0.029)	0.428 (0.014)	1.356 (0.014)
<i>C. opercularis</i> , ED*	4927	0.856	77.05 (0.230)	0.678 (0.011)	-0.189 (0.086)	0.665 (0.019)	1.000 (0.081)

SED = Southeast Douglas

ED = East Douglas

\* Seasonality parameter (C) constrained to 1 for model fitting.

variability and large standard errors (Figs 3.19 - 3.22). This is not unexpected; the weight of individual scallops is variable, and wet weight is difficult to measure accurately and consistently. Short-term variability, especially of gonads during summer spawning periods also accounts for inconsistencies between successive samples. The pooling of two years' data may also increase variability, but was considered necessary in order to obtain data for as many months of the year as possible and to increase the likelihood that values were generally applicable, rather than specific to a single year.

In order to proceed with the analysis, smoothing of the variability was achieved by fitting a sine-wave model to the data. The model provides a reasonable fit to all but the data for South-east Douglas queen length/gonad weight parameters (Figs 3.19, 3.20, 3.21a & 3.22) but cannot simulate short-term changes or multiple spawning peaks within a single year. It may be possible to simulate multiple spawning peaks by superimposing two sine-wave models of different wavelengths (and possibly of different amplitudes), but better quality data would be required.

For scallops from the Bradda Head ground, the model predicts the maximum values of the exponent of the length/adductor muscle weight and length/gonad weight relationships to occur in early January, with the minimum therefore occurring in June. The values of the intercepts of the length/weight relationship show the inverse pattern (Figs 3.19a & 3.19b).

The exponents of the length/adductor muscle weight and length/gonad weight relationship for scallops from the South-east Douglas ground, predicted by the sine-wave model, are at a maximum in early December and a minimum in May. The inverse pattern is observed for the intercepts of the regression equations between length and weight (Fig. 3.20a & 3.20b).

Queens from the South-east Douglas ground have a maximum exponent of the length/adductor muscle weight relationship in late February, according to model predictions (Fig. 3.21a). The minimum therefore occurs in August, if the sine-wave model provides a reasonable simulation. The parameters of the length/gonad weight equation for South-east Douglas queens do not show clear seasonality (Fig. 3.21b) so no sine-wave model has been fitted.

Seasonal data from the East Douglas ground is limited, but a sine-wave model is fitted to the data to provide monthly estimates of the length/weight

parameters and to enable a seasonally oscillating model to be fitted to the observed weight-at-age data (Figs 3.22a & 3.22b).

The parameters of the fitted sine-wave models shown in Figs 3.19 - 3.22 are given in Table 3.19.

The growth of *Pecten maximus* gonads and adductor muscles in samples taken from Bradda Head (Fig. 3.23a) and S.E. Douglas (Fig. 3.24a) both show strong seasonality. The models fitted, which are von Bertalanffy growth equations with seasonal perturbations (calculated from the seasonal variability in length-weight relationships), are a generally good fit to the data. There are slight overestimation of adductor muscles of scallops aged 2 - 2.5 years, and underestimation of the weight of adductor muscles of scallops from S.E. Douglas of ages 4.9 - 5.3 years. Data for the mean weight of muscles and gonads from older year classes are more scattered, and the fit of the predicted curve is poorer for ages beyond 6 in Bradda Head scallops and 10 in S.E. Douglas scallops.

The gonad shows clear seasonality in weight gain and loss, with annual weight maxima being reached in March/April, and minima in September, after the autumn spawning. The adductor muscle weights gain annual maxima in October and minima in May. Beyond the age of 4 years, the seasonal fluctuation in the weight of both the adductor muscle and gonad exceeds the annual growth increment; it is the dominant feature of the growth pattern of older scallops. The annual increase in weight of gonads is slow in scallops from Bradda Head beyond the age of 5 years, and no annual increase in the weight of gonads is observed in scallops greater than 8 years old from South-east Douglas. Both shell length ( see Figs 3.17a & 3.17b) and adductor muscle weight continue to increase slowly over the whole age range sampled.

The seasonal cycles of weight change in adductor muscles and gonads vary out of phase (approximately 160°), and the seasonality of total yield is thus dampened to some extent (Figs 3.23b & 3.24b). For scallops from Bradda Head, the annual maxima occur in February to March, while gonad weights are increasing and close to the maxima, and adductor muscle weights are decreasing. Lowest yields are found in September when the gonad is generally spent and the adductor muscle is still increasing in weight. Between the ages of 3 and 4.6 years, when the yield is increasing most rapidly and the scallop is becoming vulnerable to exploitation, there is little or no seasonal decrease in yield. However, a period of

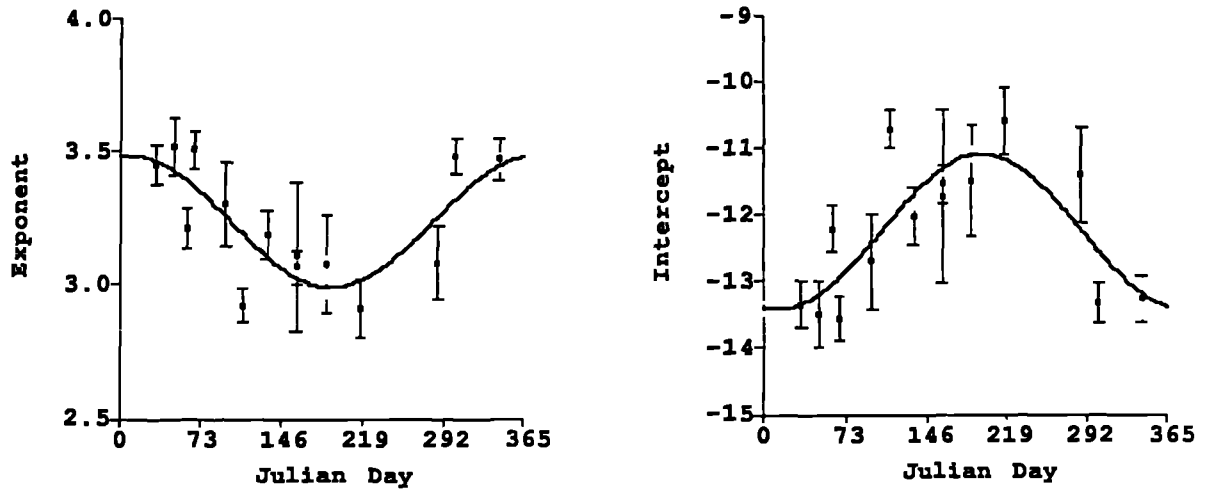


Fig. 3.19a. Seasonal variation in the exponent and intercept of the functional relationship between shell length and adductor muscle weight in *Pecten maximus* from Bradda Head. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

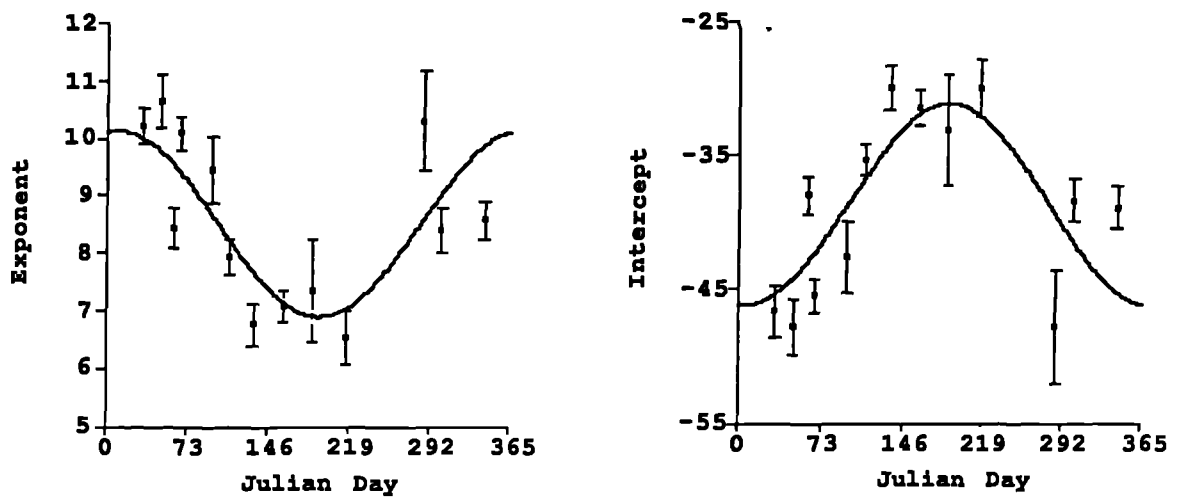


Fig. 3.19b. Seasonal variation in the exponent and intercept of the functional relationship between shell length and gonad weight in *Pecten maximus* from Bradda Head. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

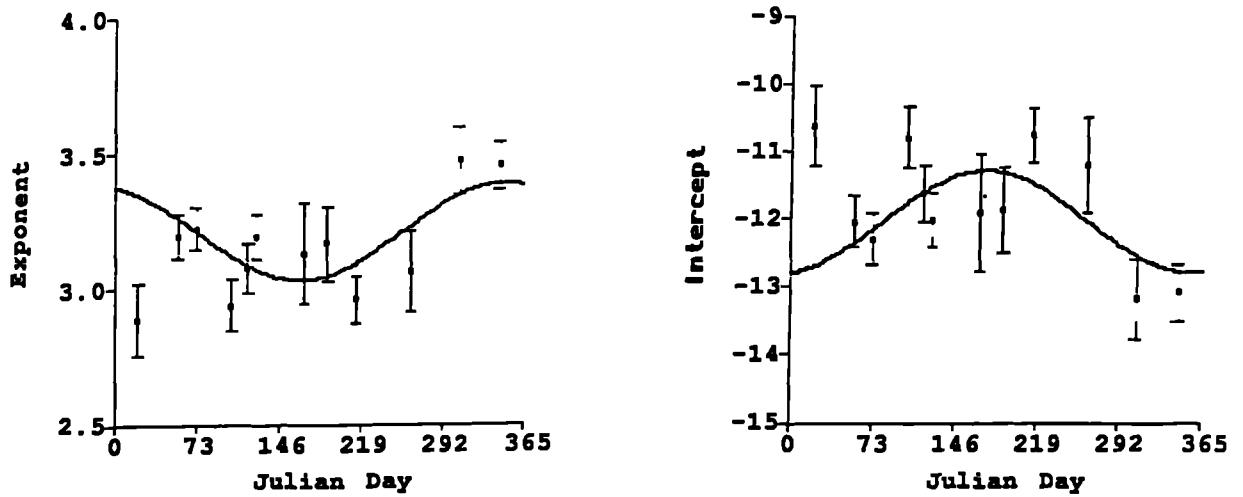


Fig. 3.20a. Seasonal variation in the exponent and intercept of the functional relationship between shell length and adductor muscle weight in *Pecten maximus* from S.E. Douglas. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

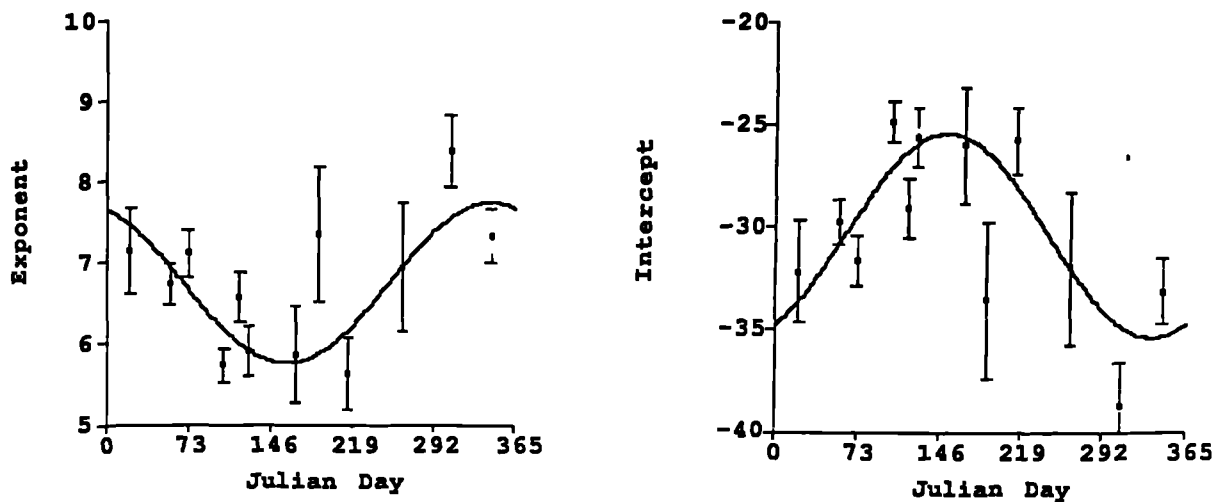


Fig. 3.20b. Seasonal variation in the exponent and intercept of the functional relationship between shell length and gonad weight in *Pecten maximus* from S.E. Douglas. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.



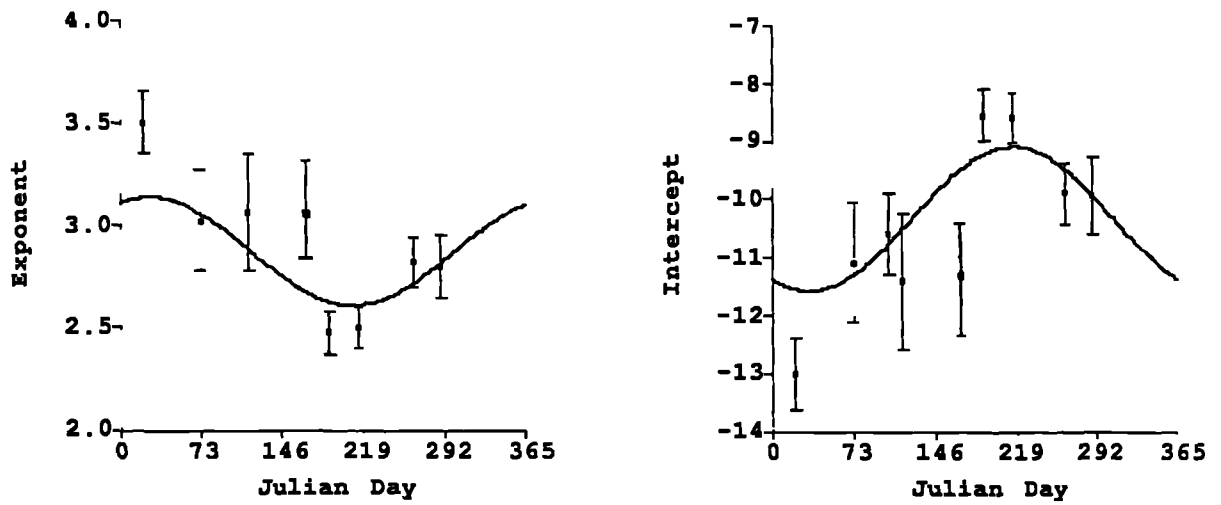


Fig. 3.21a. Seasonal variation in the exponent and intercept of the functional relationship between shell length and adductor muscle weight in *Chlamys opercularis* from S.E. Douglas. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

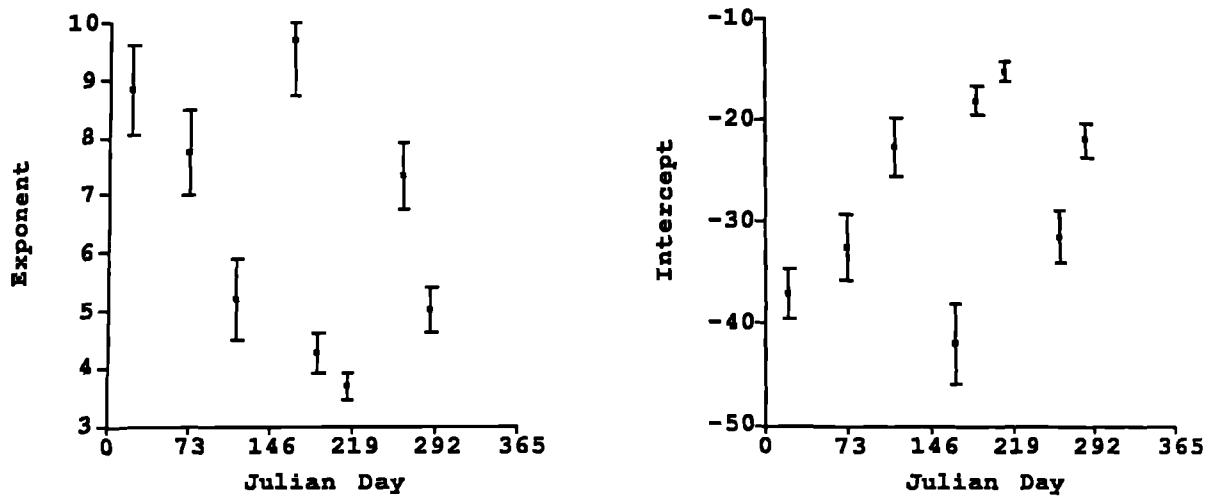


Fig. 3.21b. Seasonal variation in the exponent and intercept of the functional relationship between shell length and gonad weight in *Chlamys opercularis* from S.E. Douglas. Standard errors of the functional regression parameters are shown. No model is fitted to the data, as no clear seasonal pattern can be detected.

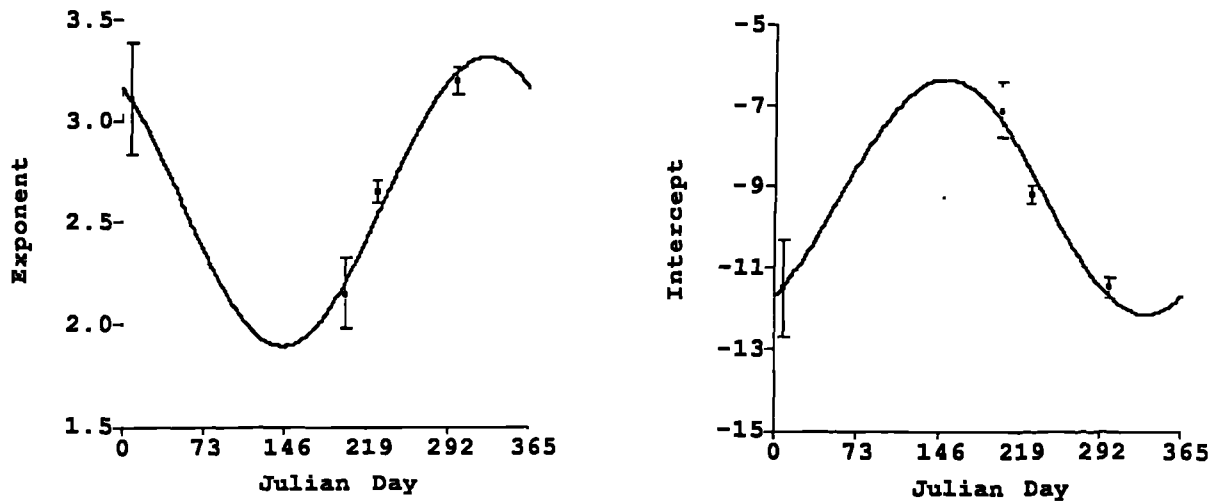


Fig. 3.22a. Seasonal variation in the exponent and intercept of the functional relationship between shell length and adductor muscle weight in *Chlamys opercularis* from East Douglas. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

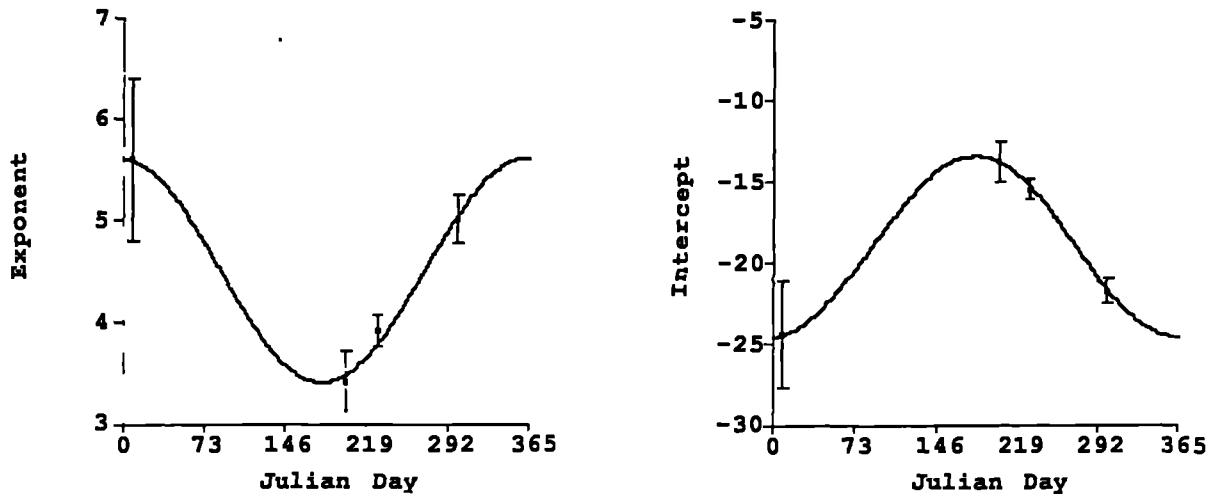


Fig. 3.22b. Seasonal variation in the exponent and intercept of the functional relationship between shell length and gonad weight in *Chlamys opercularis* from East Douglas. Standard errors of the functional regression parameters are shown, and a sine-wave model is fitted to the data.

**Table 3.19.** Parameters for sine-wave models of seasonal variability in the exponent and intercept of functional length-weight regression relationships for scallops and queens. The equation for the model is:

$$Y = M + A \cos(2\pi/T - (t-t_0))$$

Where Y = exponent or intercept of functional regression equation

M = mesor (mean level) of variable Y

A = amplitude of oscillation of Y

$2\pi/T$  = period of oscillation =  $2\pi/365$  days

t = time (days)

$t_0$  = day when Y is maximised

The equation was fitted to calculated regression parameters by nonlinear least squares.

a) Length : adductor muscle weight.

Species & Area	Exponent (v)					Intercept (u)				
	M	A	$t_0$	$r^2$	d.f.	M	A	$t_0$	$r^2$	d.f.
Scallops, Bradda	3.24	0.247	8	0.640	13	-12.24	1.161	195	0.626	13
Scallops, SE Douglas	3.21	0.176	347	0.507	10	-12.05	0.751	172	0.438	10
Queens, SE Douglas	2.88	0.265	26	0.680	6	-10.34	1.234	215	0.711	6
Queens, E Douglas	2.61	0.713	326	0.974	4	-9.25	2.889	149	0.998	4

b) Length : gonad weight.

Species & Area	Exponent (v)					Intercept (u)				
	M	A	$t_0$	$r^2$	d.f.	M	A	$t_0$	$r^2$	d.f.
Scallops, Bradda	8.52	1.619	9	0.615	12	-38.63	7.525	187	0.605	12
Scallops, SE Douglas	6.74	0.989	342	0.717	10	-30.40	4.975	152	0.746	10
Queens, SE Douglas										
Queens, E Douglas	4.51	1.102	361	0.993	4	-18.93	5.571	179	0.999	4

cessation in growth of yield does occur in scallops of between 3.2 and 3.75 years old. In older scallops, the seasonality in yield is marked.

Scallops from S.E. Douglas show a similar seasonal pattern in growth of the edible yield portions (Fig. 3.24b). Maxima occur in March, minima in September. Seasonality is damped up to age 6 years, but still shows cessation of growth over periods of up to 6 months in each year. Above age 6, there are significant annual decreases in yield. These are worthy of consideration on this fishing ground, where over 50% of the exploitable population is aged 6 years or over (Chapter 2, Fig. 2.1i).

The limited data-set for queens, *Chlamys opercularis*, from the East Douglas fishing grounds indicates an increase in both muscle weight and gonad weight during the late spring and early summer. Gonad weights reach maxima in July to August, and adductor muscle weights peak in September to October. Total yield is maximised in September. Gonad weights are at their minima in January, although the data suggest this minima is in fact reached in October the previous year. Gonad weights probably do not increase and decrease sinusoidally, which will account for the inability of the model to simulate rapid build-up of gonads and sharp decrease due to spawning. Adductor muscle weights are better predicted by the model, for queens from both the East and South-east Douglas fishing grounds (Figs 3.25 & 3.26).

Queen weights for the S.E. Douglas ground (Fig. 3.26) show strong seasonal cycles in adductor muscle weight, the seasonal change in weight exceeding the annual growth increment in queens older than 24 months. Maxima occur in September - October, minima in February - March. The model tends to underestimate muscle weights of queens aged 2 - 2.5.

The gonad cycle is more variable than that of scallops, possibly due to multiple spawning peaks and rapid recovery of gonads in this species. It was not possible to simulate seasonal changes in gonad weight (and therefore in total yield) from these data using the modelling approach applied to scallops and queens from the East Douglas ground. Gonad weight is generally higher in spring and early summer, with lower adductor muscle weights during the same period. The gonad makes up a relatively small proportion of the yield, and the yield therefore follows the pattern of adductor muscle growth closely. Maxima occur in August-September, minima in February.

Samples of scallops from Bradda and S.E. Douglas indicate that > 80% of gonads are of marketable condition throughout the winter, with a suggestion of slower recovery from the autumn spawning of S.E. Douglas scallops in 1987 (Fig.3.27). Fairly complete spawning took place in both the summers for which data were available (1982 and 1988) with the lowest percentages of marketable gonads in July and August, suggesting a main summer spawning.

Marketable gonads of S.E. Douglas queens are more variable, with three apparently minor spawnings in March/April, June/July and August/September suggested from the data (Fig 3.28).

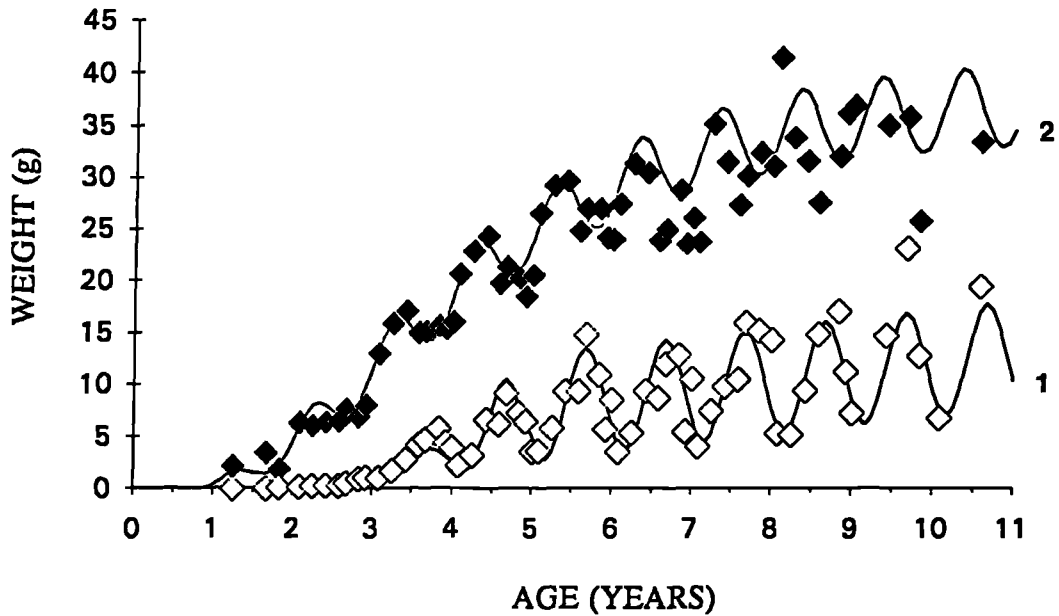
Spawning in these populations is known to vary spatially and annually (A.R. Brand, personal communication, 1990) and more detailed and long-term data are required to better understand the spawning cycle and its variability.

Detailed studies of the reproductive cycles for these populations are given by Mason (1958) for scallops and Aravindakshan (1955) and Soemodihardjo (1974) for queens. These and other studies of scallop and queen spawning suggest that marketable gonads are present predominantly from November to March in scallops, and at most times of year in queens, due to incomplete spawning and rapid recovery of the gonad in this species (Aravindakshan, 1955; Soemodihardjo, 1974).

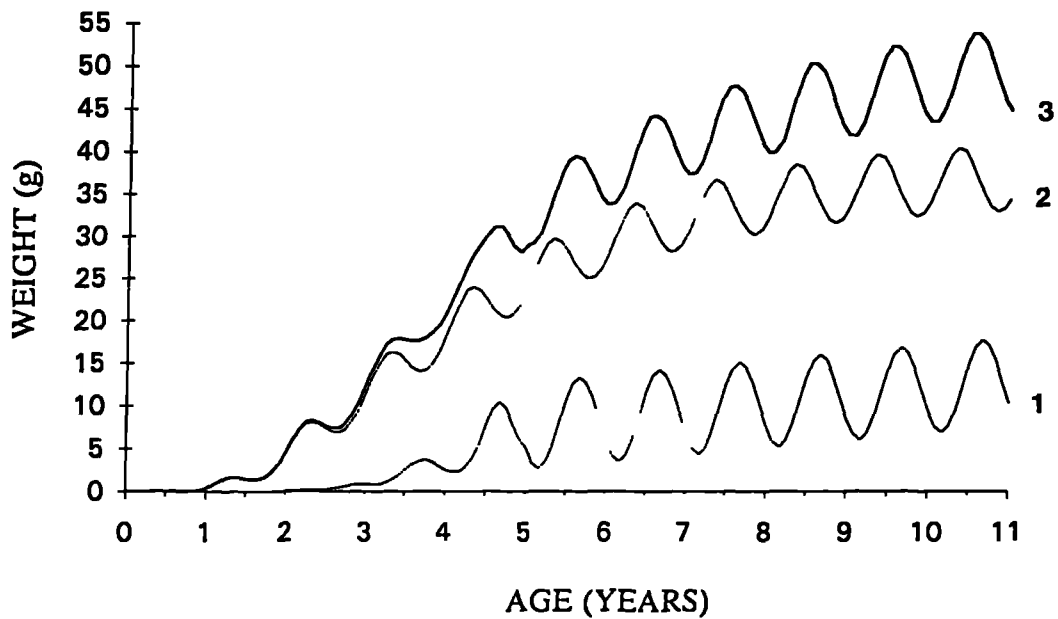
### **3.3.5. Long-term variability of growth in *Pecten maximus*.**

Comparison of the parameters of the VBGF fitted to length-at-age data from the Bradda Head ground reveal large differences in the pattern of scallop growth over the last 53 years (Table 3.20). The differences do not, however, show any underlying trend. It seems likely that the large differences found between studies are due to inconsistency in techniques used for age-determination. This is known to be true in the case of the 1981-83 data, where Murphy (1986) chose to discount the first growth ring to determine the age of the scallop, proposing that it could not be identified consistently. The data collected between 1966 and 1974 contained few younger scallops, and it seems likely that only the larger fractions of the size-distribution of these age-classes were retained by the sampling gear. Thus  $k$  is underestimated and  $t_0$  occurs at the unrealistic ages of -2.6 (1966-70) and -1.8 (1970-74).

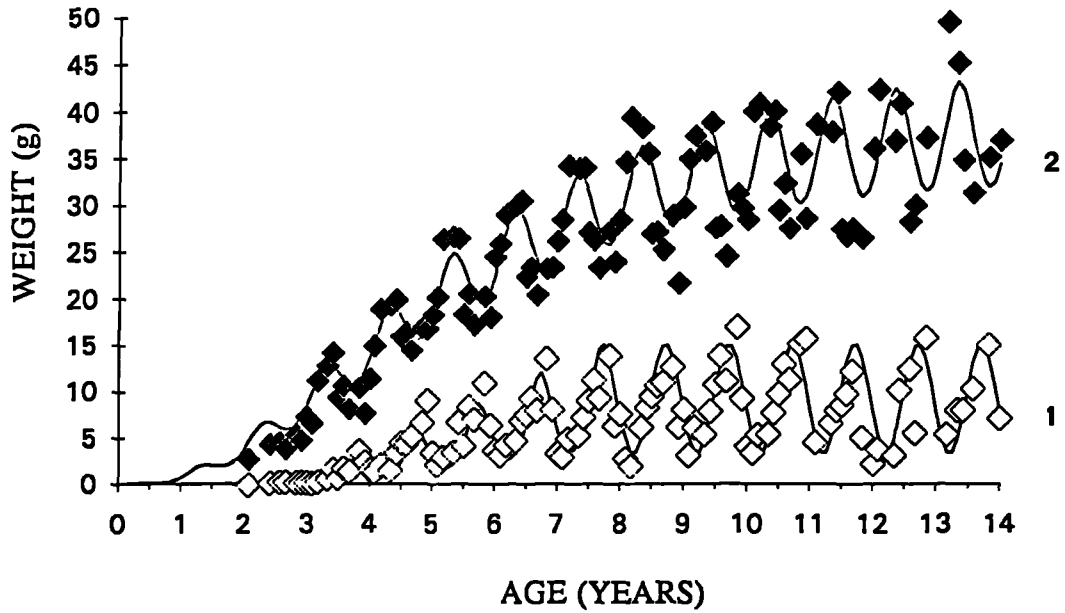
**Fig. 3.23a.** Mean gonad (1) and adductor muscle (2) weights-at-age of *Pecten maximus* from the Bradda Head fishing ground, with fitted VBGFs incorporating seasonal oscillations. Growth pattern for gonads of scallops aged 5+ has been modelled empirically from the observed data. Ages were calculated to the nearest month, assuming a July 1st 'birthday'.



**Fig. 3.23b.** Growth in weight of gonads (1), adductor muscles (2) and total edible yield (3) of *Pecten maximus* from the Bradda Head fishing ground, predicted by VBGFs incorporating seasonal oscillations.



**Fig. 3.24a.** Mean gonad (1) and adductor muscle (2) weights-at-age of *Pecten maximus* from the Southeast Douglas fishing ground, with fitted VBGFs incorporating seasonal oscillations. Growth pattern for gonads of scallops aged 8+ has been modelled empirically from the observed data. Ages were calculated to the nearest month, assuming a July 1st 'birthday'.



**Fig. 3.24b.** Growth in weight of gonads (1), adductor muscles (2) and total edible yield (3) of *Pecten maximus* from the Southeast Douglas fishing ground, predicted by VBGFs incorporating seasonal oscillations.

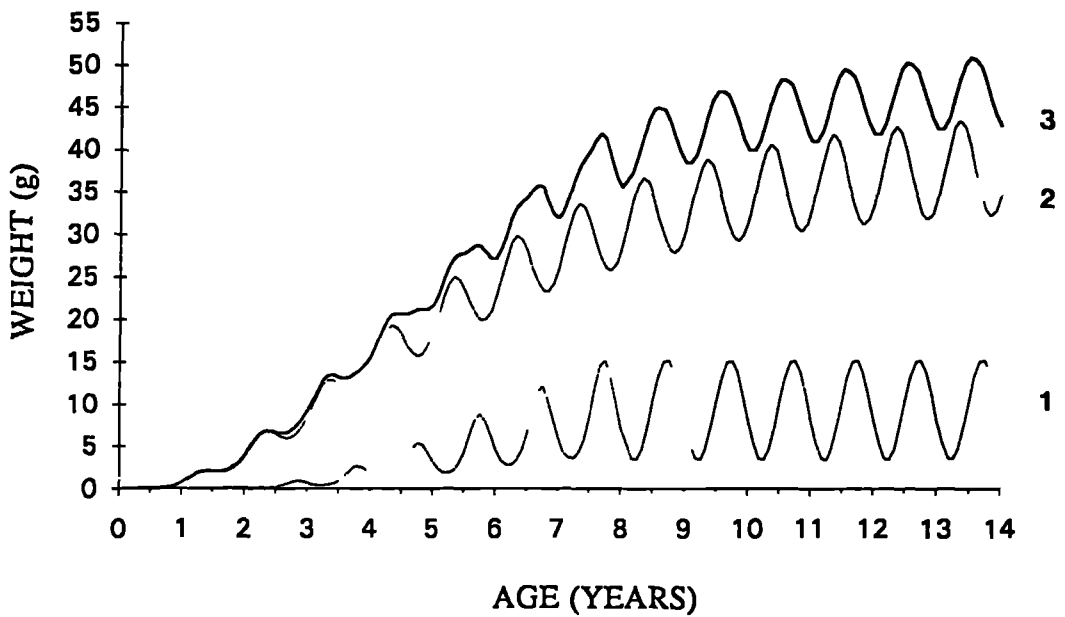


Fig. 3.25. East Douglas.

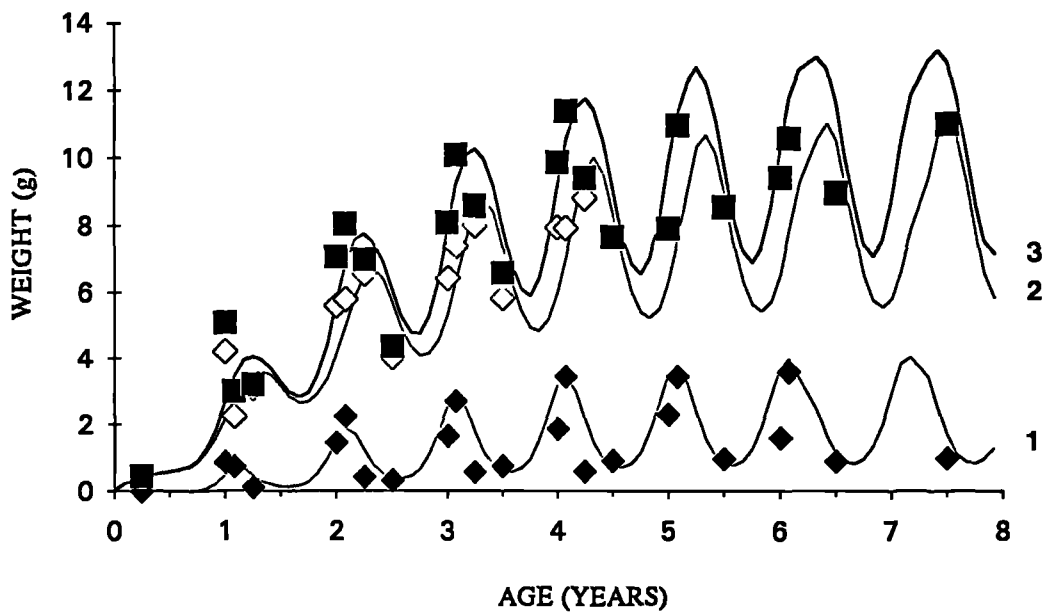
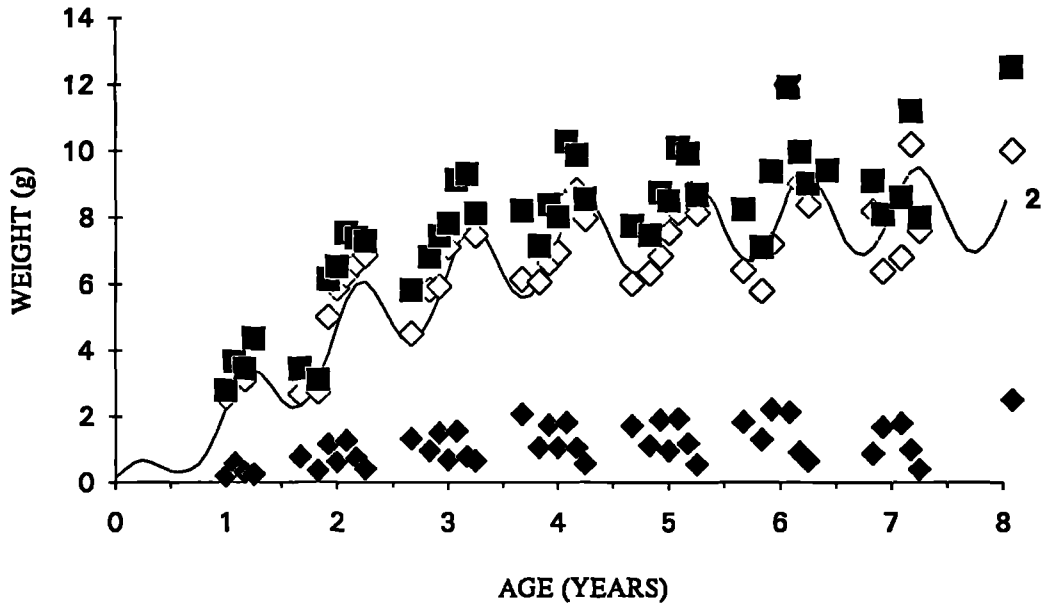


Fig. 3.26. South-east Douglas.



**Figs 3.25 & 3.26.** VBGFs incorporating seasonal oscillation fitted to mean weight-at-age of *Chlamys opercularis* gonads (1), adductor muscles (2), and total yield (3), from two fishing grounds off Douglas. Ages were calculated to the nearest month, assuming a July 1st 'birthday'. No model has been fitted to S.E. Douglas gonads or total yield, as these data were too variable. All samples were collected between January and November 1988. Data from 1987 were excluded as consistent differences in weights-at-age were observed for the same months in the two different years.



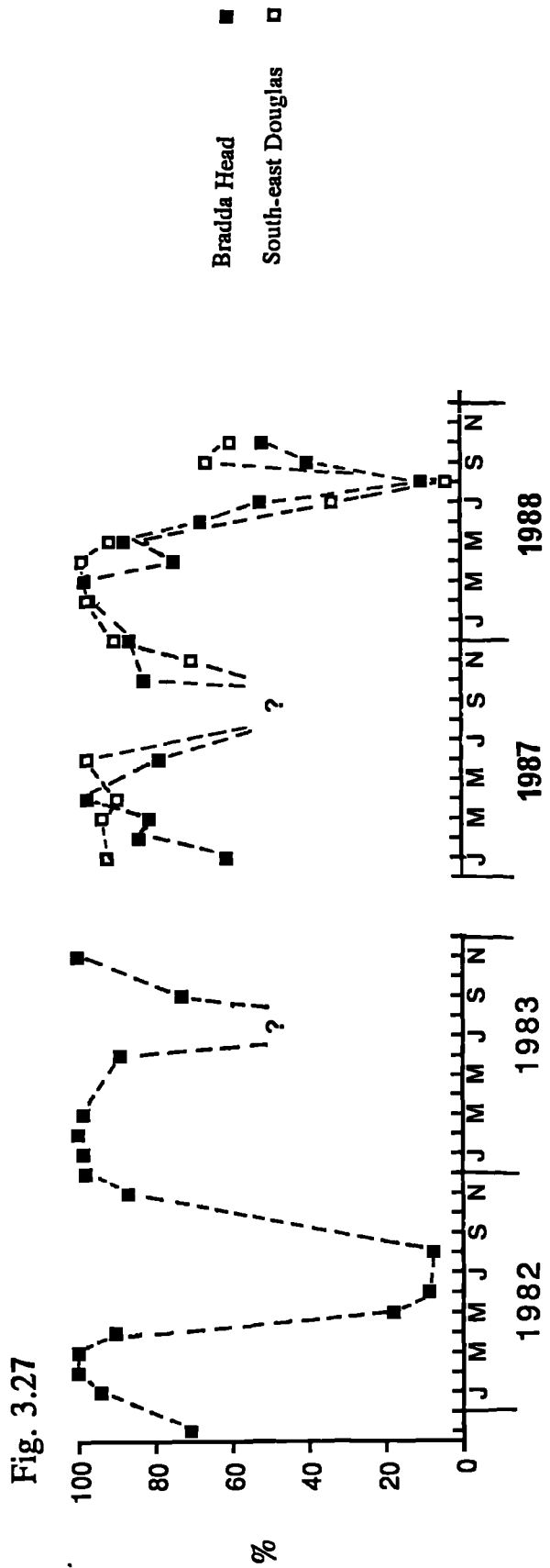
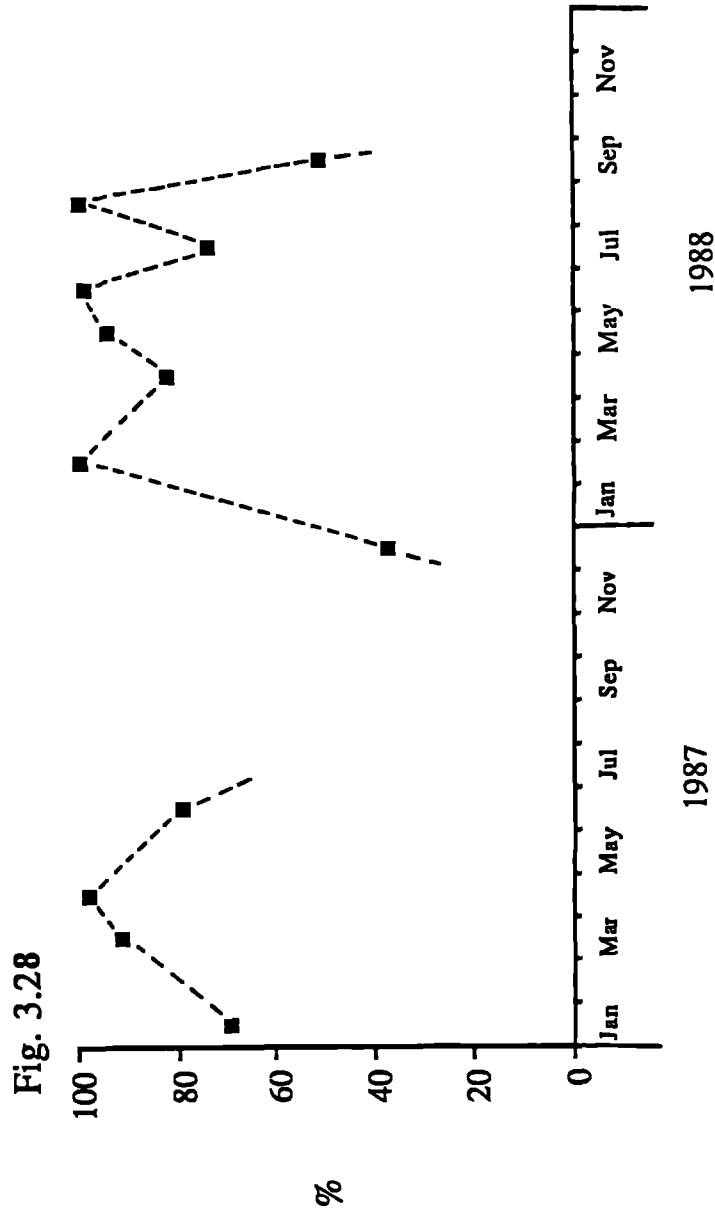


Fig. 3.27

Fig. 3.27. Percentage of scallops, *Pecten maximus*, with marketable gonads. Samples were taken from the Bradda Head ground November, 1981 - November 1983 (data from Murphy, 1986) and January 1987 - October 1988, and from the S.E. Douglas ground, January 1987 - October 1988.



**Fig. 3.28.** The percentage of queens, *Chlamys opercularis*, with marketable gonads. Samples were taken from the S.E. Douglas ground between January 1987 and October 1988.

The only parameter estimates I consider to be reliable are those from 1937/38, 1950-52, 1974-78 and 1987-89. These data do show a consistent trend in the parameters of the VBGF, and indicate that the asymptotic size of scallops on the Bradda ground has decreased from values of 144 mm in 1937/8 and 147 mm in 1950-52, to 131 mm in 1974-78 and 130 mm in 1987-89. There has been a reciprocal change in the growth constant  $k$ , which had values of 0.37 - 0.42 during the early years of the fishery, and has latterly had values of 0.53 - 0.55. This is a large change in the growth pattern - if it is an actual change, rather than the effect of inconsistencies in age determination methods. It seems likely to be an actual change, as the same age-determination techniques as those used by Tang (1941) and Mason (1953, 1957) were used in this study, although there is some discrepancy with the work of the latter author in the interpretation of spring-spawned scallop ages (see Chapter 1 for discussion).

Assuming the pattern of change to be real, the change in parameter values indicate that size-selective fishing has led to an alteration in the growth pattern of scallops on the Bradda head ground: early growth is faster and maximum size is reduced.

Comparison of the length-at-age of scallops with 4 annual rings reveals that little systematic change in the mean length of this age-class has taken place over the last 25 years (Fig. 3.29). The variation in mean size is quite large, ranging from 108 - 122 mm shell length. Ageing inconsistencies are unlikely, as both A.R. Brand (who collected the data from 1966 - 1978) and I follow the same methods of age determination.

The data are not sufficient to show any relationship between the 3 year running mean temperature and mean size of 4-ring scallops. However, the increase in temperature between 1987 and 1990 has been mirrored by an increase in mean length over the same period, and high temperatures during the mid 1970s coincided with large mean sizes. Missing data points for the period 1979 to 1983 reduce the value of the comparison. Data was collected during this period and will shortly become available. It may then be possible to examine the relationship between growth and temperature statistically by cross-correlating the two series in a time-series analysis (see Fogarty, 1988, for details of the methodology). Both series are being maintained as part of the continuing research programme.

### 3.4. DISCUSSION

#### 3.4.1. Model fit and statistical methods.

The VBGF proved to be an appropriate growth model to fit to length-at-age data of both scallops and queens for all areas where sufficient data over enough of the age range were available.

The VBGF is still standard in fishery-orientated growth studies, and has previously been shown to give a satisfactory fit for shell growth of *Pecten maximus* (Antoine *et al.*, 1979; Franklin & Pickett, 1980; Mason & Pope, 1980; Murphy, 1986) and *Chlamys opercularis* (Broom, 1976; Taylor & Venn, 1978) as well as other pectinids (e.g. Brown *et al.*, 1972; Conan & Shafee, 1978; Williams & Dredge, 1981; Heald & Caputi, 1981; MacDonald & Thompson, 1985a; Orensanz, 1986; Gwyther & McShane, 1988; Shumway & Schick, 1987; Schick *et al.*, 1988; Thouzeau *et al.*, 1991a). In heavily exploited populations, where older age-classes are absent, care must be taken in extrapolating data to compute  $L_{\infty}$ , especially as it is highly negatively correlated with  $k$  (Bayley, 1977; Pauly 1979). Forcing the model to fit the data by constraining  $t_0$  to a value of 0, or  $L_{\infty}$  within biologically reasonable limits is possible if data are lacking from younger and older age-classes, but it is preferable in these circumstances to use back-calculated ages from growth rings to obtain data for younger age classes or fit other model types. Forcing may be unavoidable in some circumstances but should be considered as a last resort. Where no data on older age-classes are available, or the shape of the growth curve suggests indeterminate growth, other growth models which do not force asymptotic behaviour may be more appropriate (Roff, 1980; Schnute, 1981). The overwhelming body of evidence suggests, however, that the VBGF is appropriate for the description of growth in length in these and other exploited scallop populations.

The use of the VBGF persists despite past criticism for its inflexibility and the difficulty of fitting the curve and comparing the parameters statistically (Roff, 1980; Schnute, 1981). While these criticisms have not been entirely banished, the availability of nonlinear curve fitting routines in most standard statistical software and new studies in the fisheries literature on the statistical comparison of non-linear curves or their parameters (Allen, 1976; Gallucci & Quinn, 1979; Kimura, 1980; Kapenmann, 1981; Misra, 1980; 1986; 1987; Welch & McFarlane, 1990; Chen *et al.*, 1992) have contributed to overcoming some of the previous theoretical and

Year	N	r <sup>2</sup>	L <sub>∞</sub>	k	t <sub>0</sub>	ω'	φ'	Reference
1937-38	296	0.945	144.97 (1.273)	0.417 (0.051)	0.071 (0.325)	60.45	3.943	Tang, 1941
1950-52	4049		147	0.372 (0.000)	0.620 (0.000)	54.68	3.905	Mason, 1953
1966-69	2470	0.410	132.89 (0.926)	0.327 (0.023)	-2.638(0.289)	43.46	3.762	Brand, unpubl. data
1970-74	1458	0.755	134.42 (1.119)	0.312 (0.015)	-1.820(0.142)	42.09	3.751	"
1974-78	1029	0.751	131.22 (0.750)	0.532 (0.025)	0.033 (0.100)	69.80	3.962	"
1981-83	1240		142.6	0.397 (0.065)	0.273	56.61	3.907	Murphy, 1986
1987-89	2421	0.807	130.41.(0.672)	0.546.(0.017)	0.224 (0.048)	71.20	3.968	This study

Table 3.20 Parameters of the VBGF fitted to *Pecten maximus* length-at-age data from the Bradda Head ground, 1937-89. Parameters were calculated as follows:

1937-38 NLR model fitted to length-at-age data published by Tang (1941).

1950-52 Ford-Walford plots fitted to mean length-at-age of autumn-spawned scallops (data from Mason, 1953) by Pope and Mason (1980).

1966-78 NLR model fitted to raw length-at-age data collected by A.R. Brand (unpublished).

1981-83 FORTRAN programme used to fit the curve to mean growth ring diameters at age by Murphy, 1986). L<sub>∞</sub> has been calculated using the functional length/breadth relationship established by Murphy (1986).

1987-89 NLR model fitted to raw length-at-age data.

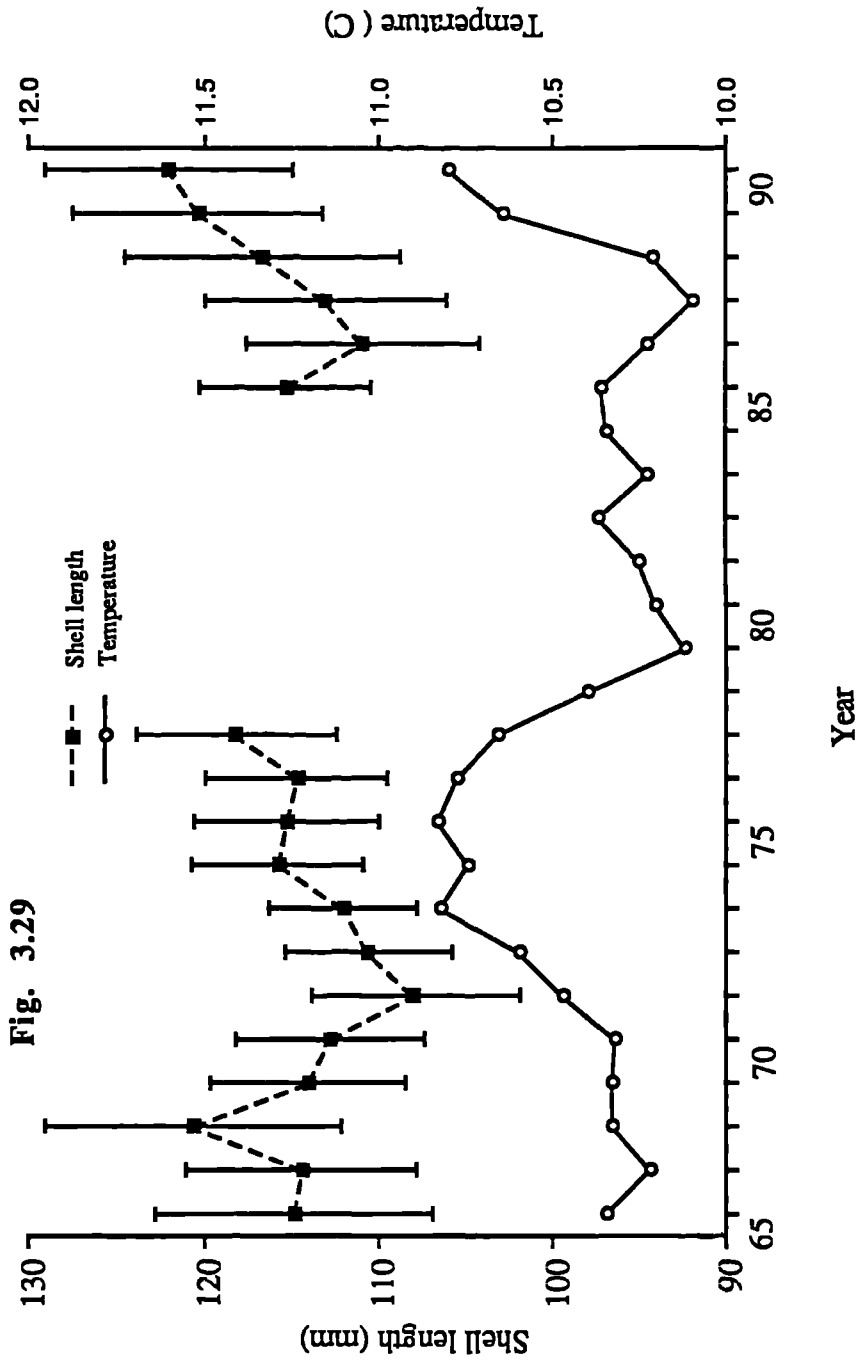


Fig. 3.29. Fluctuation of the mean size of 4-ring *Pecten maximus* from the Bradda Head ground, 1966-1990, and 3-year running annual mean water temperatures over the same period (from Slinn, 1974 and unpublished data). Error bars on mean shell length are one standard deviation. Sample numbers for each year are given in Table A3.1, Appendix 3.

practical difficulties with its use.

The attraction of the use of the VBGF rather than the more generalised curve-fitting procedures, such as polynomial regression, is that it is derived from the principles of growth physiology. The interpretation of the parameters in terms of growth physiology require, however, that certain biological assumptions be met (see von Bertalanffy, 1938; 1964; Taylor, 1962; Pauly, 1979 and Misra, 1980; 1986). The major assumptions are that the growth follows the VBGF throughout the life-span, and that growth is related to physiological surface area by a  $2/3$  power law, often measured by oxygen consumption/body size experiments, with oxygen consumption taken to represent metabolism. These experiments have found that the exponent of the oxygen consumption/body size relationship in marine bivalves has an overall mean value of approximately 0.7 (Bayne & Newell, 1983) suggesting the biological assumptions of the VBGF as used in this study are reasonable.

The formula is also only strictly applicable to the growth of individuals, not populations (Sainsbury, 1980). If parameter values for populations are required, they should be calculated from the means of all  $L_{\infty}$ ,  $k$ ,  $t_0$  vectors determined from the growth of individuals. Bias in parameter estimation from population samples is, however, more likely where growth increment data is used rather than size-at-age data (Sainsbury, 1980; 1982).

The VBGF is used here as an empirical model, where the main priority is to describe mathematically the growth of scallops as accurately and appropriately as possible. The parameter estimates have also been interpreted biologically, as indicators of growth rates and growth patterns which may be under environmental control, but slight deviations from the physiological assumptions of the model are not likely to greatly affect parameter estimates and their relative differences between areas.

The use of the VBGF as a purely empirical model is not without problems. Debate continues on the best method of fitting the equation to data (Vaughn & Kanciruk, 1982; Sundberg, 1984; Moreau, 1987; Stamatopoulos & Caddy, 1989; Welch & McFarlane, 1990). The method of fitting may influence parameter estimates, but is more likely to lead to differences in the calculated variances associated with the estimates.

The VBGF has also been used as the basis for fitting growth curves which

include seasonal patterns of growth. Scallops and queens do not grow during the winter (Mason, 1983) so the growth pattern is actually best described as a von Bertalanffy-type growth curve incorporating the annual cessation of growth during winter. The linkage between seasonal temperature fluctuation and growth was pioneered by Ursin (1963), who incorporated temperature in the VBGF and found that the sinusoidal seasonal temperature fluctuations were found to correspond with the seasonality of the growth pattern. Lockwood (1974) found that juvenile plaice showed strong growth seasonality which could be described by fitting a separate VBGF to each year's data. The seasonality of growth has since been simulated by incorporating a sine-wave function in the VBGF (e.g. Pitcher & MacDonald, 1973; Cloern & Nichols, 1978; Pauly & Gaschultz, 1979; Antoine *et al.*, 1979; Hanumara & Hoenig, 1987; Somers, 1988; Soriano & Jarre, 1988 and Hoenig & Hanumara, 1990). The version used in this study, developed by Pauly & Gaschultz (1979), modified by both Somers (1988) and Hoenig & Hanumara (1990) gives the best description of the seasonal oscillation with respect to the unbiased estimation of  $t_0$ .

In this study the seasonal VBGF model was easily fitted to length-at-age data by nonlinear regression. No constraints were necessary on parameters, but reasonable starting values were required to obtain realistic fits.

While the recent literature abounds with studies of the fitting of seasonally oscillating VBGFs for length (thanks to the incorporation of this growth curve in recent versions of ICLARM's ELEFAN routine for extracting growth parameters from length-frequency data) little work has been done on seasonal patterns of growth in weight. This is despite the fact that the seasonal patterns of growth in weight are of potentially greater importance. Only Shul'man (1974) has presented growth functions which incorporate seasonal patterns of weight loss and gain. Recent interest in this problem has led Sparre (1991) to develop a method of Y/R analysis which incorporates seasonality of growth and mortality. Sparre (1991) suggests that seasonal weights should be calculated from length-weight relationships and the seasonally oscillating VBGF for length - essentially the same approach as that used in this study. These techniques are due to be incorporated in the new ICLARM/FAO fisheries assessment software package (FiSAT).

The techniques used here to model seasonal weight changes are mathematically inelegant, and the models lack an error structure. In some cases, post-hoc modifications were made in order to improve the fit of the model to



growth of the gonad. Improvements could be made in one of two ways: The VBGF for weight, modified to include seasonality in the values of  $k$ ,  $L_{\infty}$  and the slope and intercept of the functional length/weight regression equation could be fitted directly. Fitting this model by non-linear regression requires the simultaneous iterative fit of data to a model containing at least 9 unknown parameters. In the case of scallop gonads in particular, the high value of the power function relating gonad weight to length leads to computer 'crashes' as iterations lead to values outside the numerical range of most statistical software. This direct-fit approach may work better with straight-forward data from whole finfish. The second approach is to jettison the VBGF and treat the data as a Fourier series, composed of two or more sine-functions (see Chatfield, 1984). The model could then be fitted empirically. The disadvantage of this undoubtedly simpler method is that the parameters have no biological significance.

The literature on the fitting and comparison of growth curves in bivalves appears to have favoured fitting the VBGF by nonlinear least squares using the Marquardt algorithm (e.g. Gallucci & Quinn, 1979; Appeldoorn, 1983; Choinard, 1984; MacDonald & Thompson, 1985a; Orensanz, 1986; Schick & Shumway, 1987; Jones *et al.*, 1990) and statistical comparison of growth curves using the  $\omega$  parameter and its 95% CI (Gallucci & Quinn, 1979; Appeldoorn, 1983; Orensanz, 1986; Jones *et al.*, 1990). These were the methods chosen for this study. The choice was made for reasons of convenience in fitting and the ability to incorporate variability in length and weight within age-classes in the fitting and testing procedures.

The estimates of the standard errors of parameter values derived from nonlinear regression analyses which utilise a linearisation algorithm have recently been criticised by Donaldson & Schnabel (1987) who found that supposed 95% CI had coverages of as little as 12%, depending on the degree of nonlinearity in the equation, but the method continues to be widely available and often used. The findings of this study should therefore be regarded as the best estimates available at this time. Future investigation of the effects of different fitting methods on parameter estimates and their variances would be useful. Two alternative approaches worth trying are the maximum likelihood method (e.g. Sainsbury, 1982; Welch & McFarlane, 1990) and the new algorithm proposed by Stomatopoulos and Caddy (1989) which allows the equation to be fitted by linear regression based on initial optimisation of  $k$ , rather than  $L_{\infty}$  as used by the older graphical fitting methods (see Ricker, 1975a).

An alternative method of statistical comparison of growth between areas is Hotelling's  $T^2$  test of the differences in the parameter vectors of two curves (e.g. Bernard, 1981; Hanumara & Hoenig, 1987). The advantage of this test is that all three parameters (or five parameters in the seasonal VBGF) can be compared in one test, rather than the separate comparisons of one or two of the parameters. Its main disadvantage is that it is a two sample test, and cannot be used for multiple comparisons, although the Bonferroni approximation (Neter *et al.*, 1983) will reduce the possibility of making type I errors by dividing the significance level by the number of pair-wise comparisons made. The penalty for maintaining an overall significance level of 95% (or whatever level is chosen) is that individual comparisons will be subject to more stringent significance levels, thereby increasing the likelihood of a type II error (incorrect acceptance of the null hypothesis when it is false). The procedure cannot be recommended in cases where the number of pair-wise comparisons is large. Chen *et al.* (1992) have recently proposed the use of Ratkowsky's (1983) analysis of residual sum of squares for non-linear regressions. This method, analogous to analysis of covariance but with less restrictive assumptions, provides a method of comparing several VBGF's. No *a posteriori* paired-sample test is suggested by the authors.

The linear fitting procedure of Stomatopoulos and Caddy (1989) has the advantage that conventional statistical comparisons of the slopes of the regressions can be made by analysis of covariance.

There are also several growth performance indices in the literature. The one used in the present study for statistical comparisons, the  $\omega$  parameter, is more sensitive to differences in  $k$  than differences in  $L_{\infty}$ , and Gulland (1983) considered that it is therefore less useful for describing differences in growth of older year classes, which are the commercially important ones. Similar comments apply to the analogous  $P$ - parameter of Pauly (1979), where  $P = \text{Log}_{10}(W_{\infty}k)$ .

The other commonly used indicator is  $\phi'$  (Pauly & Munro, 1984) which is defined as  $\phi' = 2\text{Log}_{10}L_{\infty} + \text{Log}_{10}k$ . This growth indicator has found favour for the non-statistical comparison of growth performance in many studies comparing the growth of tropical fish stocks (see Moreau *et al.*, 1986 and recent editions of "Fishbyte" magazine, published by ICLARM), and seems to allay Gulland's criticism of  $\omega$  by providing more weighting to  $L_{\infty}$ . No method of calculating the variance of  $\phi'$  has yet been developed (D. Pauly, ICLARM, Manila, Philippines, personal communication, 1991) so statistical comparisons of differences cannot be

made using this index. The two indices gave only slight differences in rankings of growth performance in the present study, but the two indices perform very differently when comparing the growth of scallops and queens from France and the British Isles (see Tables 3.21 & 3.22).

The general principal of all the above indices is to take account of the importance of the negative correlation between  $k$  and  $L_{\infty}$  and to provide a single comparable parameter which compensates for reciprocal errors in the estimation of the two individual parameters.

The use of the geometric mean or functional regression (Teissier, 1948; Ricker, 1973; 1975a; 1975b; Laws & Archie, 1981) rather than ordinary predictive regression is the other non-standard method used in this study. Ordinary least squares regression minimises the sum of squares of the Y - variable, assuming that X is not subject to error or natural variability. In length/weight relationships, where both variables are random, there are therefore two possible regression lines: the slope of weight on length, or the slope of length on weight. The functional relationship between two such variables is best given by the geometric mean of the two possible slopes (Ricker, 1973). Because they describe the functional relationship between the two variables, the parameters of the geometric mean regression have biological significance (Ricker, 1973; Calder, 1984). Jensen (1986) has argued that if the requirement of the regression model is to predict say, weight from length, then the ordinary predictive regression can be used. If, however, it is important to establish the functional relationship between length and weight, the geometric mean or functional regression slope should be used.

The length/weight relationship is of importance as part of a stock assessment study, to convert measured lengths to weights, especially in fisheries like the north American *Placopecten magellanicus* fishery, where regulations are enforced according to meat weights, but designed to control the age and size of first capture. In these cases the predictive regression can be used, as it has been in most of the working papers cited in Worms & Davidson (1986) and Schick *et al.* (1988). If the regression is calculated in a study of growth physiology or energetics, the functional regression should be used, as in Murphy (1986) and Bricelj *et al.*, (1987a). The functional regression is chosen here as the regression coefficient is used both in the fitting of growth curves for weight and as a means of comparing allometric relationships among areas and between the two pectinid species.

The use of the functional regression (otherwise known as the geometric mean, Model II or reduced major axis regression) in biology has probably been restricted by the fact that no commonly available statistical package can compute this type of regression and the functional regression is not readily extendible to problems where there are more than two variables. The major drawback to its use at present, however, appears to be the lack of a suitable multivariate statistical test to compare the parameters of more than two regression equations.

The lack of well-developed statistical methods for many of the comparisons made in this study, and the unsuitability of standard textbook methods for some of the analyses have hampered the process of hypothesis testing and precluded the pooling of samples from areas which may not differ significantly in some of the tested parameters. A more detailed statistical treatment may be worthwhile in deciding on the extent of future sampling programmes to assess spatial variability.

### 3.4.2. Spatial growth differences.

In scallops, the inshore fishing grounds off the west and north-east coasts of the Isle of Man show the highest growth rates ( $k$  values), with the *exception of the Peel Head ground*. The asymptotic lengths and weights are more variable, and no relationship between  $k$  and  $L_{\infty}$  or  $W_{\infty}$  is observed.  $L_{\infty}$  and  $k$  values calculated from individuals are generally negatively correlated (Sainsbury, 1980), which indicates that individuals with faster growth rates do not attain as large a maximum size as individuals with lower initial growth rates. This is evidently not the case at the population or sub-population level in scallops; populations whose mean initial growth rates are high do not necessarily have smaller asymptotic lengths, or vice versa.

The growth of organisms is generally thought to be the result of the expression of genotype modified by environment (e.g. Beaumont, 1991; Beaumont & Zouros, 1991). Differences in growth rate between reproductively isolated stocks may reflect genetic differences between the stocks. The North Irish Sea stocks of *Pecten maximus* and *Chlamys opercularis* were previously thought to be single populations (Beaumont, 1982; Beaumont & Beveridge, 1984; MacLeod *et al.*, 1985; Duggan, 1987) but Lewis (1992) has shown that *Chlamys opercularis* from east and west of the Isle of Man have different allozyme frequencies at particular gene loci, and are therefore likely to be at least partially reproductively

isolated. Differences in growth rates between areas are thus potentially due to genetic differences between stocks. However, studies which indicate no relationship between growth and heterozygosity (Beaumont *et al.*, 1985 for *Pecten maximus*; Lewis, 1992 for *Chlamys opercularis*) and experiments showing that young Irish and Scottish *Pecten maximus* spat transplanted to Brittany did not retain the growth characteristics of the parent stocks (Huelvan, 1985) indicate that growth in these species is not under strong genetic control (Ansell *et al.*, 1991). Environmental rather than genetic differences are thus likely to be the cause of spatial variability in growth rates within the North Irish Sea populations.

Growth performance in scallops, as measured by either  $\omega$  or  $\phi'$ , is at least partly due to or correlated with differences in depth and substrate type. Reliable parameter estimates are available for too few queen grounds to establish a relationship between growth and environment in this species, although some similarity in growth performance between queens and scallops is suggested.

Depth is often implicated as a factor influencing many aspects of the biology of scallop species, including growth rate in terms of shell length (Mason, 1957; Baird, 1966; Posgay, 1979b; MacDonald & Thompson, 1985a; Shumway & Schick, 1987; Schick *et al.*, 1988; Thouzeau *et al.*, 1991a), weight of somatic tissues (MacDonald & Thompson, 1985a; 1985b), allometric relationships between length and weight (Haynes, 1966; Haynes & McMullin, 1970; Schick & Shumway, 1986; Worms & Davidson, 1986) and fecundity and reproductive effort (MacDonald & Thompson 1985b; MacDonald *et al.*, 1987; Barber *et al.*, 1988). The effect of depth on production and other aspects of scallop ecology are indirect; temperature and food availability are affected by depth, and it is these factors which influence scallop population dynamics (see Brand, 1991 and Bricelj & Shumway, 1991, for reviews).

Differences in depth, substrate type and current flow-rate variations are likely to be an important influence on the growth of these filter feeding bivalves as these factors affect food availability and feeding efficiency. It is not known to what extent scallops and queens rely on phytoplankton for food or make use of benthic food sources. Christensen and Kanneworff (1985) have suggested that *Chlamys opercularis* living at 30m depth in the Oresund, Denmark were reliant principally on sedimenting phytoplankton for food. In the Irish Sea *C. opercularis* appears to be confined to hard substrata (hard sand and gravel) in areas of high current velocity and complete mixing of the water column, at depths of 10 - 70m. Queens

lie on, rather than recessed in the substrate, and it is likely that they are suspension feeders (Vahl, 1972), making relatively little use of benthic food sources, which in any case will be scarce in areas where detritus does not accumulate readily due to fast bottom currents. The scallop, *Pecten maximus*, by contrast, is generally found recessed into the substrate, with the top shell covered with a layer of sediment (Baird & Gibson, 1956; Baird, 1958; Mason, 1983). It is found on a wide range of substrata, from muddy sand to rocky gravel (Mason, 1983; Brand, 1991), and is recessed wherever the substrate is not too hard. Recession may be an adaptation to take advantage of benthic food sources (Baird, 1958). Studies on north American *Placopecten magellanicus*, which has a similar recessing habit and substrate requirements, indicated that benthic organisms and detritus form an important part of the diet in this species, with the contribution of benthic food sources increasing with depth (Shumway *et al.*, 1987). Reduction in growth performance with depth in *Pecten maximus* may therefore reflect the differing energetic values of benthic and phytoplankton food resources (or differing energetic cost of processing them) rather than differences in the quantity of food available.

Sand or shell-gravel, found on the Bradda, Targets and Ramsey Bay grounds would appear to be the type of substrate most suited for rapid growth of *Pecten maximus*. This substrate is found on the shallower grounds adjacent to the Manx and Northern Ireland coasts in the Irish Sea, so the effects of depth, substrate and location-specific differences in current flow rate are difficult to separate. Slower growth in areas where mud is present in the substrate has been observed in some stocks and is probably due to reduced water flow in these areas (which would reduce the availability of suspended food) coupled with the detrimental effects of fine silt on respiration and feeding efficiency (Vahl, 1980; Wallace & Reinsnes, 1985). Gruffydd (1974b) has found a relationship between maximum size and the silt content of the substrate in North Irish Sea *Pecten maximus*, and Murphy (1986) found that the off-shore fringes of the grounds to the west of the Isle of Man had reduced growth associated with muddier substrata towards the *Nephrops* grounds between the Isle of Man and Northern Ireland. Reduced growth of scallops in hard substrate areas (gravel, rocks) may be due to reduction in benthic food sources. Difficulty in recessing will subject the scallop to very high current velocities above the benthic boundary layer in some areas, which may inhibit feeding and growth (Kirby-Smith, 1972; Wildish *et al.*, 1987; Wildish & Kristmanson, 1988).

Tidal water currents vary with location of sampling areas and may be an important factor in determining both the differences in substrate type and growth

performance of scallops and queens on the grounds studied. The patterns of current flow in the Irish Sea are complex and variable (Bowden, 1980), and detailed bottom current measurements are not available. Tidally-induced frontal systems which separate stratified and mixed water masses during the summer months are located in the region around the south-west of the Isle of Man (The Chickens and Bradda Head grounds), and possibly over the Targets ground also (Ramster & Hill, 1969). Studies on the front to the south-west of the Isle of Man have indicated higher primary, secondary, microbial and benthic productivity in the frontal region than in the adjacent mixed and stratified zones (Fogg *et al.*, 1985). Growth rates and other aspects of scallop production may be similarly enhanced in frontal regions. The Chickens, Bradda and Targets grounds, which show fairly rapid growth rates despite depth differences are all located in regions where seasonal fronts occur.

Temperature discontinuities are also associated with frontal regions, and temperature affects metabolic rate, including growth rate. Incursions of colder bottom water from the summer-stratified area to the west of the Isle of Man (Ramster & Hill, 1969; Bowden, 1980) over the Peel Head ground may explain the anomalously low growth performance of scallops on this ground in comparison with the adjacent Bradda and Targets grounds. Muddier substrata in this area also indicate slower bottom currents than surrounding areas, possibly due to summer stratification. Most scallop grounds, however, will be subject to similar bottom temperatures, as the depth differences are relatively small, there is rapid exchange of water and the water column is fully mixed at most times of year. Differing nutrient content of water masses around the Isle of Man (Slinn, 1974) leading to localised differences in primary and secondary production may also affect growth rates. Growth rate differences in *Chlamys tehuetcha* on fishing grounds within the San Jose Gulf, Argentina, have recently been shown to occur as a result of spatial differences in food availability, due to variability in primary production (Ciocco, 1991). The same study showed that density differences did not correlate with growth rate differences.

Food availability, and therefore growth, may, however, be affected by population density in some cases. Many sedentary bivalves have been shown to exhibit density dependent growth: e.g. *Cardium edule* (Hancock, 1973; Brock, 1980), *Mytilus edulis* (Bayne, 1976) and *Spisula solidissima* (Murawski & Serchuk, 1984), but demonstrations of density dependent growth are less common in natural populations of the semi-mobile Pectinidae (but see Gruffydd, 1974b; Vahl, 1982 and Orensanz, 1986). The effect of density on growth has not been investigated in

this thesis. Density of scallops and queens changes from year to year (and from month to month in heavily exploited areas) and the effect on growth can only be assessed by relating specific growth increments to density in a particular year. Assessing the effect of density on maximum length, as Gruffydd (1974b) has done, implies that the density of scallops on each ground is constant over periods of up to 20 years. This implies constant recruitment and mortality, which may have been the case in the unfished populations surveyed by Gruffydd (1966) but is certainly not the case now, when fishing mortality and recruitment have been shown to vary annually, as has CPUE; all of which imply density variations.

The effect of density on growth could be investigated using growth increment data. These data have been collected, but are not presented in this thesis. The validity of such comparisons will be questionable, as data on the density of pre-recruit scallops and queens is not available due to the size-selectivity of fishing gear. Since the pre-recruit year classes may form a substantial part of the population on some grounds but not on others, their exclusion would diminish the value of any spatial comparison. The density of scallops is in any case very low on even the most productive grounds in the north Irish Sea (1 scallop per 10-50 m<sup>2</sup> of seabed), making density dependent differences in growth unlikely. Queens, however, may occur in high-density aggregations. Density is highly variable in this species, so the effects on growth are again difficult to ascertain. The density of other filter feeders may also affect growth of these species. All these intraspecific and interspecific competitive factors remain unknown, and could account for some of the unexplained spatial variability in growth rates of scallops and queens. Orensanz (1986) and Orensanz *et al.*, (1991) discuss the difficulties in evaluating and demonstrating competitive interactions in semi-mobile species whose densities are highly variable over small spatial scales. It is likely that controlled experimental studies will be of more value in assessing the effects of density on growth than crude observations based on commercial catch rates and mean population growth rates.

The effects of fishing activity on growth are also unknown. Dredging and trawling operations re-suspend benthic detritus, possibly increasing the availability of food but they also re-suspend quantities of silt, probably reducing feeding efficiency. The response of scallops to clouds of silt generated by fishing activity appears to be to close the two shell valves tightly (unpublished underwater video pictures, SOAFD {Scottish Office Agriculture and Fisheries Department, Aberdeen}). Heavy fishing may therefore reduce the time the scallop spends in



filter feeding, thereby reducing energy intake. Scallops on heavily fished grounds frequently have disturbance or shock rings on the shell, due largely to the effect of encounters with fishing gear (Merril *et al.*, 1966; Caddy, 1989b). These rings, which indicate growth discontinuities, clearly affect the growth of the individuals concerned. Mean population growth rate may be reduced on grounds where many scallops have shock rings. These rings are commonly visible in Irish Sea scallops, but no data on their frequency have been collected. I have not seen shock rings on queen scallops, presumably their greater fragility reduces their chances of surviving an encounter with fishing gear.

The exact causes of spatial growth variability in these species remain unclear due to lack of data on many of the factors discussed above. The relationship between the growth performance of the two species on grounds where they co-exist is also not clear. There is certainly no negative relationship, so it seems unlikely that where they co-exist one species out-competes the other in terms of growth performance, but it is not possible to determine whether their co-existence causes a reduction in growth rate in either or both species. There is a paucity of *in situ* experimental and observational work on the feeding and energetics of both *Pecten maximus* and *Chlamys opercularis*, and it has not been determined to what extent the two species compete for the same food resources.

These studies of spatial growth rate variations in *Pecten maximus* agree closely with the findings of Murphy (1986), who studied growth on many of the same grounds, despite the fact that he used a slightly different ageing method by not counting the first growth ring (E.J. Murphy, British Antarctic Survey, Cambridge, personal communication, 1987). This is a good indication that consistency is possible in ageing of the scallops on these grounds by visual assessment of the growth rings. Only the parameter  $t_0$  will differ substantially according to the method used (see Dare & Deith, 1991 and Chapter 1).

Growth in weight (of adductor muscles and total edible yield) and length/weight relationships also show spatial variability; the latter indicating that the relative energy investment in growth of different tissues varies between areas. The Bradda ground had the highest yield/length exponent, indicating that the relative increase in weight of marketable yield per unit increase in length is greatest on this ground, which suggests that a large amount of energy is available for storage and reproduction. On the Port St. Mary ground, the length/yield relationship is lower, suggesting that surplus energy for storage and reproduction is

lower. It is noteworthy that the differences in asymptotic yield-weight of queens are due largely to differences in gonad weights, as asymptotic muscle weights are very similar on all grounds. This implies that the amount of energy invested in reproduction is under environmental control. Under sub-optimal environmental conditions, the amount of surplus energy remaining for reproduction after maintenance and growth requirements have been met is reduced (Bayne *et al.*, 1983; Barber *et al.*, 1988) and reproductive output is correspondingly reduced. This has led some authors to conclude that sub-populations living in unfavourable environmental conditions may not produce sufficient viable gametes to be self-sustaining or provide a significant reproductive input to the population as a whole (Schick & Shumway, 1987; Barber *et al.*, 1988).

A large quantity of data has been generated by intensive studies of shell and somatic tissue allometry and its seasonal and spatial variability. These data have not been presented in this thesis, but could provide more detail on energy budgets in these species if analysed further in future. The approaches to determination of energy budgets outlined in Thompson and MacDonald (1991) should be consulted.

The ultimate aim of these studies on spatial growth variability is to produce growth estimates for yield models based on the 5 Nautical mile<sup>2</sup> statistical sub-units (grid squares) for which fishery statistics are collected. This investigation has produced estimates for most of the major scallop and queen fishing grounds in the North Irish Sea, many of which cover more than one grid square. If the relationship between growth, the environment, density and fishing activity can be elucidated, growth parameters for squares not sampled could be calculated. For preliminary modelling exercises, grid squares fished by the commercial fleet but not sampled for growth studies could be allocated the same growth parameters as the nearest ground (geographically and in terms of depth and substrate type) for which parameter estimates are available. Errors generated will be of minor consequence, as those areas not sampled tend to be fringe areas, which do not contribute substantially to overall catches.

### **3.4.3. Seasonal growth patterns.**

The seasonality of growth in pectinids, correlated with annual water temperature cycles, is well known (Ansell, 1974; Comely, 1974; Taylor & Venn, 1979). Growth of the shell and increase in body mass ceases during the winter

months, due either to the effects of lower temperature on metabolic rate, or to insufficient food during the winter to maintain metabolic requirements (Broom & Mason, 1978). The resumption of growth of the shell and increase in total weight each spring is triggered by rising temperature or increase in food supply after the spring phytoplankton bloom (Broom & Mason, 1978; Vahl, 1980).

The seasonal pattern of growth in length has been modelled using the seasonalised VBGF. The model simulates the growth pattern of scallops and queens effectively, with the strong seasonal discontinuities clearly seen in younger scallops. Models for seasonal growth cycles of the gonad and adductor muscle also fit well. The two constituents of the yield vary 160° out of phase; while the gonad weight decreases due to spawning in the summer months, the adductor muscle is increasing in weight. During the winter, the adductor muscle loses weight and the gonad gradually fills, reaching a maximum weight in the spring. The large adductor muscle acts as the main storage site for metabolic reserves in *Pecten maximus*, and weight loss in winter is due to mobilisation of reserves to contribute to metabolic requirements and development of the gonad (Comely, 1974; Lubet *et al.*, 1987b; Epp *et al.*, 1988; Ansell *et al.*, 1988; Le Pennec *et al.*, 1991; Faverit & Lubet, 1991; Barber & Blake, 1991).

It has been postulated (Lubet *et al.*, 1987a, 1987b; Dorange & Le Pennec, 1989) that gonads can provide a source of energy to fuel the autumn increase in muscle weight. It is suggested that lysis of oocytes occurs, and the products of this lysis are resorbed as a source of energy. This raises the possibility that the autumn spawning (see Chapter 1 and Mason, 1983) of Irish Sea scallops, which occurs after the main spatfall has already taken place (Brand *et al.*, 1991a), is not actually a spawning event, but a mass lysis of oocytes which have been formed over the late summer, at a time when food supply is plentiful and metabolism high. This spawning or lysis coincides with a period of rapid increase in adductor muscle weight, and may have evolved as a strategy of storing excess energy for transfer to the adductor muscle, which acts as the main energy storage site over the winter. This has not yet been demonstrated experimentally in scallops, but the transfer of the products of oocyte lysis to the somatic tissues of the mussel, *Mytilus edulis*, has been demonstrated by tracing radioactively labelled proteins (Pipe, 1987).

Spawning of *P. maximus* appears to take place in the summer months (June - August). Only one major spawning per year has been observed in this study, but the more detailed studies of Mason (1958) indicated that two peaks in spawning

were evident in Isle of Man *P. maximus*. Reproductive cycles appear to be highly variable in scallops, and variations in the frequency and timing of spawning activity occur from year to year and between areas (Kergariou *et al.*, 1980; Fegan *et al.*, 1985; Paulet *et al.*, 1988; Ansell *et al.*, 1988; 1991; Barber & Blake, 1991). Reproductive cycles in *Pecten maximus* from around the British Isles and Northern France appear to be controlled both by localised environmental conditions (temperature and food availability) and genetic adaptation of self-recruiting reproductively isolated stocks (Ansell *et al.*, 1991). The mechanism triggering spawning is not known, and factors such as water temperature, lunar phase and day-length have been proposed (Paulet & Boucher, 1991, for review).

Spawning in *Chlamys opercularis* appears to occur sporadically, with rapid recovery of the gonad. There may be two or three peaks of spawning activity each year in North Irish Sea queens (Aravindakshan, 1955; Soemodihardjo, 1974; Paul, 1978; Duggan, 1987). The seasonal fluctuation in the weights of the adductor muscles follow a pattern similar to that in *Pecten maximus*. Minima occur in spring, maxima in autumn.

Seasonal variations in the length/weight relationship are the obvious consequence of seasonal weight variation and shell growth discontinuities. The isometric length/weight regression relationship is often used as an index of the condition of the animal (Ricker, 1975a), where low condition at certain times of the year may indicate seasonally increased vulnerability to predation and environmental stress (starvation, disease or anoxia). Post-spawning deterioration in condition and increased mortality have been reported in the short-lived bay and tehuelche scallops *Argopecten irradians concentricus* Say and *Chlamys tehuelcha* (Barber & Blake, 1983; Orensanz, 1986; Bricelj *et al.*, 1987b), indicating that natural mortality may show seasonal pulses. More detailed biochemical analyses of seasonal cycles would help to indicate if scallops and queens showed similar seasonal deterioration in condition and consequent increased liability to mortality.

#### **3.4.4. Long-term changes in growth**

Subject to reservations regarding the consistency of data collected in different studies, there appears to have been a considerable change in the growth pattern of scallops on the Bradda Head ground since 1937, when the ground was first fished. This change in growth pattern could be caused by environmental

change or by the selective pressure generated by size-selective fishing.

The only environmental changes that have occurred are a change in scallop density (Brand *et al.*, 1991b) and a possible change in benthic community structure as a result of dredging. These are likely to affect growth performance, rather than alter the growth pattern. Size-selective fishing, however, could generate the selection pressure required to alter the pattern of growth in scallops; fishing pressure has already been implicated in causing reduction in size at first sexual maturity and growth rate in cod (Jørgensen, 1990; Law & Grey, 1988), change in life-history of Pacific Salmon (Ricker, 1981) and loss of genetic diversity in New Zealand stocks of Orange roughy (Smith *et al.*, 1991).

The Bradda Head ground has consistently remained one of the most productive scallop grounds in the Irish Sea, in terms of recruitment. This regularity of recruitment, and its accessibility, has ensured that it has been heavily fished every year for the last 55 years (with the exception of the years 1940-45). Throughout this period, a minimum legal landing size of between 110 and 114 mm has operated. This continuous, heavy, size-selective fishing may have influenced the growth pattern of the scallops; asymptotic length has decreased, and growth rate has increased. It is by no means assured that this change is caused by genetic selection - it is possible for example, that scallops which settle on the Bradda ground originate from a parent stock on other, less heavily exploited grounds where the selective pressure due to fishing is much reduced. Size-selective mortality also provides an alternative explanation to the apparent change in growth pattern. Size-selective mortality due to fishing could lead to enhanced survival of slow growing individuals. Thus  $k$  (the rate at which length reaches an asymptote) is increased and scallops which could potentially reach a large size never survive long enough to do so. The weakness in this argument is that the majority of a cohort of scallops become vulnerable to fishing at the same time (there is no protracted recruitment over several seasons) and all scallops are equally vulnerable to capture on reaching 110 mm (see Chapter 4).

The question of whether size-selective mortality or genetic change are responsible for the observed differences in growth patterns could easily be resolved by monitoring the growth of scallops in the part of the Bradda ground which has recently (1989) been closed to fishing. If the change is genetic, removing fishing pressure from this part of the stock for a short time would have no effect on growth pattern, whereas if the change were due to selective mortality of the faster growing individuals in the population, without genetic modification, the unexploited part of

the population would revert to the pattern of growth observed in the early years of the fishery.

Mean size of scallops with 4 annual rings has not shown any systematic trend over the last 25 years, but large annual fluctuations occur. These fluctuations may be correlated with mean temperatures over the life-span of the scallop, with higher mean size-at-age occurring during periods of higher annual mean temperatures. Correlations between temperature and growth rate are fairly common (e.g. Cushing, 1975, 1982; Le Cren, 1958) and may be due to the direct effect of temperature on metabolic rate, the effects of temperature on primary production (and therefore food supply) or variations in the movements of water masses (which may influence nutrient availability and therefore production) which are detectable as temperature fluctuations.

#### **3.4.5. The effects of spatial and temporal variability in growth on fishing strategy, and the implications for assessment and management.**

The scallop fishery is currently legislated by a minimum legal landing size of 110 mm shell length. Variations in growth rate mean that age at first recruitment differs between grounds. The recruitment ogives presented in Chapter 2 illustrate that the proportion of each age class reaching 110 mm varies between grounds. This may be beneficial in some respects as a particularly strong year class will not all recruit to the fishery in a single season, reducing the risk of 'boom and bust' cycles. Instead, recruitment of each year class is spread over 2-3 years. In some scallop fisheries, fishermen exploit the grounds where the scallops grow fastest and recruit earliest in the first year, and move to other grounds in the following years (Bull, 1989). This situation may be currently occurring in this scallop fishery, where a strong 1987-spawned year class was heavily fished in the early part of the last scallop season (1990/91) as 3+ year olds on the Targets ground. This year class will probably be targeted as 4+ year olds on other grounds in the current (1991/92) season. This type of exploitation strategy may lead to boom and bust cycles for particular grounds, but stabilise the fishery as a whole.

Queen fisheries are not legislated by minimum size at present, but the fishing gear used is size selective, so ogives of recruitment to fishing gear will differ between grounds. These differences in the proportion of a year class which recruits to the fishery, caused by growth rate differences, must be taken into

account when comparing year-class strength between grounds using commercial CPUE statistics. Queens are also subject to a processor-mediated minimum commercially acceptable size, for reasons of the economics of manual shucking of queen 'meats' (see below). This size may be reached at different ages on different grounds due to spatial variation in shell growth rate and the shell/yield relationship.

Spatial variability of growth equation parameters is of particular importance for Y/R assessments, with the optimum age at first capture for maximising Y/R being related to the growth rate. Y/R will therefore have to be calculated separately for each major fishing ground, requiring the availability of area-specific estimates of fishing and natural mortality rates. The growth parameter  $k$  and natural mortality are related in fish species, as the parameter  $k$  can be interpreted as 'the rate at which an organism lives' (Pauly, 1980). Differences in  $k$  between areas therefore indicate that natural mortality may also vary between areas. The calculation of mortality rates for the major North Irish Sea scallop grounds, and one important queen ground are presented in Chapters 4 and 5.

Seasonal growth and reproductive cycles are also of great importance in determining both yield and fishing strategy in these fisheries, particularly as the gonad forms part of the edible yield. *Scallops can only be fished from November 1st - May 31st under current legislation. Analysis of seasonal growth patterns suggests that this is close to the optimum time of year for fishing this species with a seven month fishing season. The previous year's growth has been completed and total yield remains relatively constant, despite relative changes in gonad weight and adductor muscle weight. The gonads of > 80% of scallops are full throughout the season, and muscle weight is high until the latter part of the season. There is some indication that spawning takes place earlier and more extensively in inshore scallops, with the fleet moving off-shore in the latter part of the season (April-May) partly to avoid catching scallops which have spawned (which would contravene a Manx fishery bylaw) and partly because inshore grounds have normally been depleted by the end of the season. Better weather at this time of year also allows off-shore grounds to be exploited more frequently. The spawning cycle appears to vary considerably from place to place and year to year, and scallops landed the same day by different boats can have markedly different yields according to the condition of the gonads (A.R. Brand, Port Erin Marine Laboratory, personal communication, 1987). Provided that natural mortality does not show strong seasonality, the current scallop season would optimise Y/R for any given age at first capture. The seasonality of natural mortality is potentially important in determining*

optimum fishing times and in running Y/R models; most models require the user to choose whether natural mortality occurs before or after fishing mortality. More detailed examinations of the effect of seasonality on Y/R could be performed if monthly or quarterly fishing and natural mortality rates can be calculated. This would help to determine the optimum time of year for harvesting of re-stocked scallops or closed areas, where shorter periods of harvesting may be legislated. It would also help determine the optimality of the current fleet strategy of exploiting inshore grounds first, followed by off-shore grounds in the latter part of the season. Looking at the timing of maxima in the seasonal yield-growth curves (Figs 3.23-3.24) suggests that the maximum yield from an individual scallop is taken in February-March on the inshore Bradda ground, and March on the off-shore S.E. Douglas ground. If a later start to the fishing season is contemplated, or if particular grounds are opened for short periods only, the gains due to increase in weight must be balanced against the losses due to mortality during the period prior to allowing fishing, bearing in mind that no new recruits enter the fishery over the winter.

Queens tend to be fished in the closed season for scallops (Brand & Allison, 1987) and the yield from an individual queen is maximised in the latter part of this season (*late August - September*), when the adductor muscle is in peak condition. *The shell of the queen grows rapidly during the early summer (June-July)*, and the 1+ age class does not recruit to the fishery until the latter part of the season on most grounds. In E. Douglas queens the attainment of a minimum commercially acceptable size of approximately 55 mm shell length occurs during the second growth season (age 1+), but not until the third growth season (age 2+) in S.E. Douglas queens (Fig. 3.18). Low meat yields for a given shell length and apparently lower catchability of trawled queens during spring and early summer (due to reduced swimming ability correlated with seasonal energy storage cycles; Brand, unpublished data) mean that fishing for queens in the early part of the season is a barely viable concern. The option of extending the scallop season into June or July is not tenable, as scallop gonads are spent or partially spent during this period, and therefore unacceptable to the market; meat weights are also low. At present, tying up the boat is the fisherman's only option in the early summer. White fish, herring or *Nephrops* could provide alternative fisheries during this period, but the Manx fleet and marketing system for these fisheries do not appear to be competitive with the larger-scale industries in the other nations bordering the Irish Sea (I.o.M Government, 1983; Brand *et al.*, 1991b).



An additional consideration in maintaining a closed season for scallops is to protect vulnerable stages of the life-cycle, such as spawning and spat settlement. The current closed season for scallops includes the periods of spawning and spat settlement, which are thought to take place mainly in June and July (Brand *et al.*, 1980; Duggan, 1987; Brand *et al.*, 1991a). Queen fishing on grounds where the two species co-exist continues during this period, and becomes heavier in August - October, when the spat are small, fragile, and liable to mortality due to siltation resulting from dredging and trawling activity (Stevens, 1987). The importance of fishing activity on the survival of spat or the 'receptiveness' (Orensanz, 1986) to settlement of the substratum has not been evaluated in any scallop population, but factors affecting the settlement and survival of young scallops are the focus of continuing studies by the M.A.F.F. Laboratory, Lowestoft (Dare, 1987; Anon, 1989). Queen spat are larger and more robust than scallop spat (Mason, 1983; Paul, 1985) and are likely to suffer less from disturbances due to fishing activity.

The seasonal and spatial variations in growth, length/weight relationships and the timing of reproduction are clearly appreciated by fishermen, who may adapt their exploitation strategy according to their perception of these patterns. In the queen fishery for example, processors set a maximum meat count (number of 'meats' per pound) because their factory workers are paid at higher rates per pound when they shuck for higher meat counts; profitability therefore decreases as the mean size of the catch decreases. The minimum acceptable commercial size of queens ( about 55 mm shell length) corresponds approximately to the maximum acceptable meat count, but this varies according to area and season, so fishermen may have to make decisions about where to fish partially on this basis, leaving areas where queens are abundant but small for later in the season. Gonad weights also vary between areas in queens, and the decision to land queens roe-on or roe-off (both are currently acceptable to the market) must be made on the basis of whether the increase in total landed weight of edible flesh will compensate for the reduced price per pound paid by processors for the roe-on product. It will therefore only be advantageous to land queens roe-on from grounds where the roes are relatively large. Decisions of this type may have to be made a few days in retrospect, when the returns from the shore-based shucking operations have been communicated to fishermen.

In the North American *Placopecten magellanicus* fishery, which is regulated by control of the meat count (maximum number of meats per pound weight), the variability in growth rates and shell length/adductor muscle weight

relationships has far-reaching implications for management, and has consequently received considerable attention (Worms & Davidson, 1986 and Schick & Shumway, 1987, for reviews). In this fishery, there is a requirement to consider the importance of these factors relative to the importance to fishing strategy of spatial differences in recruitment and abundance, weather patterns and relative costs of exploiting particular grounds from a given 'home port'. This is best achieved by simulation modelling, with sensitivity analysis to determine which factors have the greatest effect on model predictions (see Clark, 1989, for a review of bio-economic modelling methods).

The long term effects of fishing on the life-history of exploited stocks, first noted in Ricker's (1981) studies on Pacific Salmon, has come under increasing attention recently ( Law & Grey, 1989; Law, 1991). There are indications that heavy size-selective fishing can alter the life-history tactics of exploited stocks, by genetic selection favouring faster initial growth rates and lower maximum sizes, together with reduction in the age and size of first sexual maturity (e.g. Jorgensen, 1990 for Norwegian cod). This phenomena has also been demonstrated experimentally in a selectively harvested population of *Daphnia magna* (Edley & Law, 1988).

In The Australian scallop *Pecten alba* (Tate) growth rate changed significantly over a 20-year exploitation period (Gwyther & McShane, 1988), as a result of size-selective fishing. There appears to have been a change in the growth pattern of scallops from Bradda Head also, where a minimum legal landing size has operated since the start of the fishery, 55 years ago. What effect the minimum legal landing size is having is not precisely known. Further increase in the minimum legal landing size is contemplated (Chapter 6). Will this increase the selection pressure on scallops to 'live fast and die young'? The growth patterns of scallops should continue to be carefully monitored, to avoid the situation where a population which does not grow large enough to reach the minimum legal landing size is selected (Law, 1991). Analysis of the long-term data-set to identify any changes in the size at first sexual maturity would also be of interest. A decrease in size of first sexual maturity may increase spawning-stock biomass, but may also be correlated with a reduction in growth rate, as energetic resources are diverted into reproduction rather than growth.

### **3.4.6. Comparisons of growth rates between scallop and queen stocks around the British Isles.**

Growth data for a number of stocks of scallops and queens from around the British Isles and Northern France have been published, or have been collected by fishery management organisations (Tables 3.21 & 3.22). The growth parameter estimates obtained from this study fall within the range of values found elsewhere.  $L_{\infty}$  values from this study range from 127-145 mm shell length, while the overall range from published data is 107-158 mm. Values of  $k$  found within the North Irish Sea in this study (0.33-0.55) range almost as widely as the overall range of values found for this species (0.25-0.66). There is no evidence of a geographical trend in growth performance from south to north in either species, but a number of large differences are found, even between geographically adjacent stocks, suggesting that local environmental differences are more important in determining growth performance than genetic differences between stocks, or biogeographic factors such as latitudinally correlated temperature differences. Antoine *et al.* (1979) noted large variations in asymptotic length in stocks from north-west France, and large differences in asymptotic size but similar  $k$  values are observed in east and west Channel stocks (Dare & Deith, 1991). It is reasonable to assume that the differences in growth performance indicate actual differences in growth, although some of the variability will be due to the different methods of curve-fitting being used by each author, and differences in the quality of the original data. The majority of stocks have  $k$  values and asymptotic length values of a similar order of magnitude to north Irish Sea grounds, but current legal size-limits differ. The EEC - enforced minimum legal landing size is 100 mm, while the north Irish Sea size limit is 110 mm. Dare & Deith (1991) argue on the basis of their recent reassessment of the growth of Channel scallop stocks that these stocks would benefit from an increase in minimum size to bring them into line with the Irish Sea stocks, which have enjoyed relative stability under their current management regime. I would endorse the recommendations of Dare & Deith (1991), and suggest further that a similar size limit could be imposed for most stocks around the British Isles. Growth does vary between areas, however, and in order to optimise yield from each stock or even from each sub-stock, different minimum size regulations could be imposed locally, as they are in U.K. crab fisheries (Edwards, 1989). The major problems of differential size limits are in enforcement. This would be particularly difficult for the stocks in the off-shore areas in the Channel and Irish Sea. The

different Irish Sea legislation may already be causing problems for Irish Sea scallop management, with frequent allegations that Scottish vessels are fishing the north Irish Sea, landing outside the area and declaring the catches (which include substantial quantities of scallops of 100-109 mm long) to be from other areas. Any proposed increase in size limits in local areas within the north Irish Sea would exacerbate these problems, unless they were rigidly enforced.

The parameter estimates from queen stocks are highly variable, with problems in curve fitting to few age classes probably causing some of the differences. For stocks for which the data indicate realistic parameter estimates, the Shetland and Yorkshire coast stocks appear to have the highest growth performance (Table 3.22). The stocks on some of the Irish Sea grounds (The Targets, Point of Ayre), also appear to be amongst the highest performers in terms of growth. Again no latitudinal trend in growth performance is observed. Values of  $k$  from this study range from 0.42 - 0.75 (excluding the Laxey ground), and  $L_{\infty}$  from 75 - 86 mm. The range of values obtained for the species throughout the range where it is commercially exploited are  $k$ : 0.31 - 0.89 and  $L_{\infty}$ : 71-101 mm (excluding the parameter estimates for North Irish Sea queens obtained by Mason *et al.*, (1979), which fall outside this range due to problems in extrapolating from the limited age range of a commercial sample). Better growth rate assessments are required for many queen scallop stocks. Major problems with past studies are due to selective sampling gears and incorrect interpretation of growth rings.

Locality	$L_{\infty}$	k	$\omega$	$\phi'$	Reference
<b>The Channel</b>					
Armen	107.1 (3.54)	0.52 (0.08)	55.69	3.776	Antoine <i>et al.</i> , 1979.
Brest	106.8( 0.91)	0.66 (0.02)	70.49	3.877	"
St.Brieuc	124.6 (0.77)	0.56 (0.01)	69.78	3.939	"
Baie de Seine	139.8 (2.15)	0.56 (0.03)	78.29	4.039	"
	5 135.4 (2.95)	0.58 (0.03)	78.53	4.027	"
	6 138.9 (2.02)	0.48 (0.06)	66.67	3.967	"
Dieppe	123.5 (1.95)	0.53 (0.03)	65.46	3.908	"
W. Channel *	116.5	0.34			Dare & Deith, 1991.
E. Channel *	134.2	0.36			"
<b>North Irish Sea</b>					
Holyhead Hbr. §	158.3 (1.46)	0.44 (0.02)	69.65	4.042	Baird, 1966.
Irish Sea *	126.7	0.28			Dare & Deith, 1991.
N. Ireland *	128.0	0.25			Briggs, 1980.
S.W.Chickens	140.2	0.41 (0.03)	57.48	3.906	Murphy, 1986.
Bradda Head	142.6	0.40 (0.14)	57.04	3.910	"
Peel Head	131.6	0.45 (0.02)	59.22	3.892	"
S.E. Douglas	139.8	0.40 (0.05)	55.92	3.893	"
PSM Inshore	144.9	0.42 (0.00)	60.86	3.945	"
PSM Offshore	139.8	0.41 (0.03)	57.32	3.904	"
N. Irish Sea	124.6	0.52	64.79	3.907	DAFS, unpubl. data
<b>Scotland</b>					
East Clyde	141.3	0.49	69.24	3.990	DAFS, unpubl. data
West Clyde	125.8	0.46	57.87	3.862	"
West Kintyre	133.0	0.38	50.54	3.827	"
North West	120.7	0.43	51.90	3.797	"
Shetland	127.3	0.49	62.38	3.900	"
North East	136.7	0.33	45.11	3.790	"

\* asymptotic size values are calculated from shell breadth, not length.

§ curve fitted to values interpolated from published graph.

**Table 3.21.** VBGF parameters for *Pecten maximus* stocks from France and the British Isles. Values of  $t_0$  are not reported as they are dependent on whether absolute or relative ages were used, and will vary according to the time of spat settlement and sample collection if relative ages are used.

Data from Scotland are length-at-age measurements of market samples, supplied by T. Howell of DAFS, Aberdeen. I have fitted the VBGF to mean winter length-at-age data (October - March) for each area, with  $t_0$  constrained to a value of - 0.5 as younger age classes are absent or subject to size-selectivity. Unconstrained fits to these data give unrealistic parameter values ( $t_0 < -2$ ,  $L_{\infty} > 160$ , low k-values).

Locality	$L_{\infty}$	k	$\omega$	$\phi'$	Reference
Guernsey *	60.3	1.10			Askew <i>et al.</i> , 1973.
Irish Sea					
10' S Kilmore	74.1	0.48	35.57	3.421	Lee, 1973.
11' S Carnsore Pt.	70.6	0.53	37.42	3.422	"
Kish Bank	74.8	0.74	55.35	3.617	Rolfe, 1973.
Port Erin, I.o.M.	76.7	0.68	52.16	3.602	Aravindakshan, 1955.
" *	69.8	0.63	14.16	3.223	Soemodihardjo, 1974.
N. Irish Sea	118.0	0.12	26.38	3.351	Mason <i>et al.</i> , 1979.
Skerries #	85.1	0.31	41.53	3.496	Watson, 1971.
Clyde					
Millport	75.5	0.55	41.43	3.496	Aravindakshan, 1955.
Area 1 #	73.1	0.56	40.94	3.476	Taylor & Venn, 1978
Area 2 #	73.1	0.51	37.28	3.435	"
Area 3 #	78.2	0.45	35.20	3.440	"
Clyde grounds	75.0	0.89	66.75	3.670	Mason <i>et al.</i> , 1979.
North Sea					
Dogger Bank	78.0	0.65	50.70	3.597	Ursin, 1956.
Yorkshire Coast #	88.7	0.80	70.96	3.799	Taylor & Venn, 1978.
Aberdeen	73.5	0.75	55.13	3.608	Aravindakshan, 1955.
S. Kattegat, Danish Sound					
	73.1	0.64	46.78	3.534	Ursin, 1956.
Shetland	101.0	0.89	89.89	3.958	Mason <i>et al.</i> , 1979.
Faroes	70.0	0.54	37.8	3.423	Ursin, 1956.

\* values are calculated from shell breadth, not length.

# curve fitted to length-at-age data given by the authors.

**Table 3.22.** VBGF parameters for *Chlamys opercularis* stocks, taken from the published literature. Parameters from pre-1975 references are those calculated by Broom (1976) with the exception of Watson (1971).

## **CHAPTER 4 - ESTIMATING MORTALITY RATES OF NORTH IRISH SEA *PECTEN MAXIMUS* .**

### **4.1. INTRODUCTION**

Estimates of the rates of mortality due to fishing (F) and to natural causes (M) are required in all commonly used stock assessment models. The simplest surplus production models (e.g. Schaefer, 1954; Pella & Tomlinson, 1969) require only implicit knowledge of these rates in the form of fishing effort data (assumed proportional to F) and the assumption that M does not change over time. Yield per recruit models (e.g. Beverton & Holt, 1957; Thompson & Bell, 1934) require estimates of F and M for the exploited population, while Virtual Population Analysis (e.g. Pope & Shepherd, 1982) requires a vector of M-at-age values to generate F-at-age estimates from a catch-at-age time-series.

Total mortality rate (Z, the sum of F and M) can generally be obtained relatively simply from abundance-at-age in a sample or series of samples, but M is often difficult to measure directly (except in virgin stocks), and is usually obtained indirectly from estimates of total and fishing mortalities. Error in the estimation of one rate therefore leads directly to bias in the estimate of the other. Such errors in the estimation of mortality rates are the cause of much of the uncertainty in stock assessments. All the commonly used fishery models are sensitive to the choice of the input value of M;  $Y_{\max}$  in Yield per Recruit models changes in linear proportion to changes in M, and errors in M may have significant effects on estimates of population size and fishing mortality rate in cohort models (Vetter, 1988; Sims, 1984).

This study draws together all previous work on the estimation of mortality rates on North Irish Sea *Pecten maximus* stocks, with the aims of establishing the range of possible values, quantifying the sources of bias in the techniques used to estimate them, and providing appropriate values of F and M for stock assessment studies. Particular emphasis is given to the use of mark-recapture techniques for the estimation of mortality rates.

Most of the methods of estimating mortality rates commonly used in fish stock assessments have been applied to scallop stocks. Catch-curves (Chapman & Robson, 1960; Robson & Chapman, 1961) of various types have been used to estimate M or Z (e.g. Posgay, 1962; Golikov & Scarlato, 1970; Gruffydd, 1974a;

Broom, 1976; Posgay, 1979a; Del Norte, 1986; Orensanz, 1986; Thouzeau & Lehay, 1988). Estimates of fishing mortality have been obtained from cohort analysis in the Canadian fishery for *Placopecten magellanicus* on Georges Bank (e.g. Mohn *et al.*, 1989) and in some Scottish fisheries for *Pecten maximus* (Mason *et al.*, 1991) or have been calculated from catch-effort data (e.g. Caddy, 1979; Naidu *et al.*, 1982; Wolff, 1987).

The observation that mortality rate correlates with other life-history parameters (which are easier to measure) has been used by several authors to derive empirical relationships for the prediction of mortality from, for example, growth parameters, longevity and age at sexual maturity (Vetter, 1988, for review). Some of these relationships have been used to estimate  $M$  in studies on tropical scallop species (e.g. Del Norte, 1986; Wolff, 1987). The hypothesis underlying these empirical models is often derived from basic  $r$ - $K$  selection theory (e.g. Pianka, 1970; Gundersen, 1980), *i.e.* fast growth, small maximum size, young age at sexual maturity and large investment in reproduction is associated with species which have high mortality rates ( $r$ -selected) and slow growth, large asymptotic size, late sexual maturity and low energetic investment in reproduction imply low mortality rate ( $K$ -selected).

Most of the empirical relationships between mortality and other life-history parameters have been derived from fin-fish stocks and, although the physiological processes and ecological theory is applicable to scallops also, the regression constants may differ for different taxonomic groups, so opinion is divided as to whether they should be applied (see Caddy, 1986, for discussion).

Tagging is well established as a technique in studying scallop population dynamics (e.g. Tubb, 1946; Dickie, 1955; Posgay, 1963; Gwyther & McShane, 1988) and has been used to study the dynamics of *Pecten maximus* in the North Irish Sea (Mason & Colman, 1955; A.B. Bowers {reported in Colman, 1956; 1957; 1958}; Gruffydd, 1972; Murphy, 1986; Murphy & Brand, 1992; Brand & Murphy, 1992; Allison *et al.*, 1989) and elsewhere (Gibson, 1953; 1956; Franklin & Rolfe, 1976; Howell & Fraser, 1984).

Most of the tagging studies cited above are based on the analysis of simple single-release experiments, designed to give approximate rates of exploitation over short time periods or to study small-scale dispersal and migration patterns. Few have provided reliable estimates of mortality rates of exploited populations. The



exception is the experiment carried out by Murphy and co-workers (references above), who used a two-release experiment to derive mortality rate estimates for ten scallop fishing grounds within the North Irish Sea.

The sedentary or semi-sedentary nature of scallops presents both problems and opportunities in carrying out tagging experiments. Problems arise in satisfying the requirements that the tagged and untagged individuals in the population being studied should be equally liable to capture. In experiments on mobile animals, it can often be assumed that the marked individuals become evenly mixed among the unmarked individuals after a given period of time (see Ricker, 1975a and Jones, 1977). Adult scallops, however, do not move more than a few metres a year (Baird & Gibson, 1956; Hartnoll, 1967; Howell & Fraser, 1984) and will therefore not mix in with the untagged population. In order for tagged and untagged scallops to be equally liable to capture the tagged scallops should therefore be distributed such that their density reflects the spatial density distribution of the population. Exploitation rates are density-dependent at a spatial scale perceptible to fishermen (Chapter 2) and the recapture rates of tags distributed evenly or randomly over a whole population are unlikely to result in unbiased estimates of the exploitation rates on the population (Cranfield & Allen, 1979). In the experiments carried out in the North Irish Sea by Murphy (1986) and myself, tagged scallops have been distributed over a number of known fishing grounds within the population, so that the extent of intra-population differences in exploitation and mortality rates can be investigated. It was not possible to distribute tags in proportion to within-ground density of scallops, but by recording the release positions of each batch of scallops within each ground, it was possible to investigate whether all released scallops within a ground were equally liable to recapture. The sedentary nature of scallops thus provides the opportunity to study exploitation patterns at two spatial scales: between fishing grounds and within each individual fishing ground.

The fact that tags can be recovered from dead individuals when their shells are recaptured also provides the opportunity to assess post-tagging mortality, which is generally an unknown source of bias in tagging experiments.

Recent scallop tagging studies include good examples of carefully designed experiments which have overcome many of the practical and theoretical difficulties involved in mark-recapture experiments to provide useful data on population sizes and mortality rates (e.g. Dredge, 1985; Murphy, 1986; Naidu, 1988).

Two major tagging experiments have recently been carried out on North Irish Sea scallops to obtain estimates of exploitation and mortality rates for different scallop beds around the Isle of Man, independently of catch statistics. These experiments were designed to use Ricker's two-release method (Ricker, 1975a), with scallops tagged in two consecutive years, 1982 and 1983, repeated in 1987 and 1988. The first of these releases was carried out by Murphy (1986), the second set of releases were made as part of this study. Use of the Ricker two-release experimental design allowed estimates of mortality to be made at the end of the second fishing season after each tagging experiment started (Murphy, 1986; Murphy and Brand, 1992). Tagged scallops released in 1982 and 1983 have continued to be returned from the fishery in subsequent fishing seasons and it is now possible to estimate mortality rates from log-linear regression analysis of the declining number of annual returns (Beverton & Holt, 1957). The present work compares estimates of total, fishing and natural mortalities obtained from the 1982/3 release, using these two different methods of analysis, with results from the more recent two-release experiment (1987 and 1988) and then goes on to compare tagging-based estimates with those obtained from age-structures and commercial catch per unit effort data. Both tagging and age-frequency based methods have been used to investigate patterns of mortality rates-at-age. Finally, empirical and 'rule of thumb' methods have been used for comparison, and for analysis of their suitability for studies on scallops.

## **4.2. MATERIALS & METHODS**

### **4.2.1. Mark-recapture experiments**

The first in a series of mark-recapture experiments on North Irish Sea scallops took place in 1982 and 1983 (reported in Murphy, 1986 and Brand & Murphy, 1992). Scallops were tagged in 11 areas in 1982, identified as major scallop beds within the North Irish Sea fishery. In 1983, the tagging operation was repeated on 10 of these beds, on the basis of first year recaptures, with another 2 beds being included in order to consider the dynamics of populations farther offshore (Fig. 4.1). The scallops were all tagged in the early part of the annual closed season to scallop fishing, which runs from June to November inclusive, with the exception of 700 scallops tagged on the Peel ground in October, 1982. This allowed the scallops time to recess back in to the sediment before the start of the fishing season. Scallops were released as far as possible evenly over the grounds (one scallop per 183 m along the vessel track) resulting in overall densities similar to those used in previous scallop tagging experiments (1 scallop per 1,000-100,000 m<sup>2</sup>; Murphy, 1986, for review). A total of 5,850 scallops were marked and released in 1982, and 6,150 were released in 1983.

The scallops were marked with plastic Petersen discs and a number of ancillary experiments were designed to give estimates of the rate of tag loss, reporting efficiency and mortality due to tagging. A full account of the marking and release procedure for this experiment is given in Murphy (1986) and Brand & Murphy (1992). Tagged scallops from the 1982 and 1983 releases continued to be returned throughout the period of study. The rate of decline of annual recaptures have been used to estimate mortality rates for the period 1983-1991.

In 1987 and 1988, the two-release experiment was repeated on 7 major scallop fishing grounds (Fig. 4.1). A total of 9,973 scallops were released; 5,088 in 1987 and 4,892 in 1988. Table 4.1 gives the number released on each ground in both years, together with the release area and mean density of tagged scallops on each ground. Release densities were generally higher than in Murphy's (1986) experiment (1 scallop per 2,200 - 5,900 m<sup>2</sup>) as these latest experiments aimed to obtain sufficient returns to calculate age-specific mortality rates.

The findings of these subsequent tagging studies have been used to reassess some of the conclusions based on the earlier work, and mortality rates calculated from the earlier experiment have been modified in the light of more recent findings.

#### 4.2.1a. Marking and release procedures, 1987/8 experiment

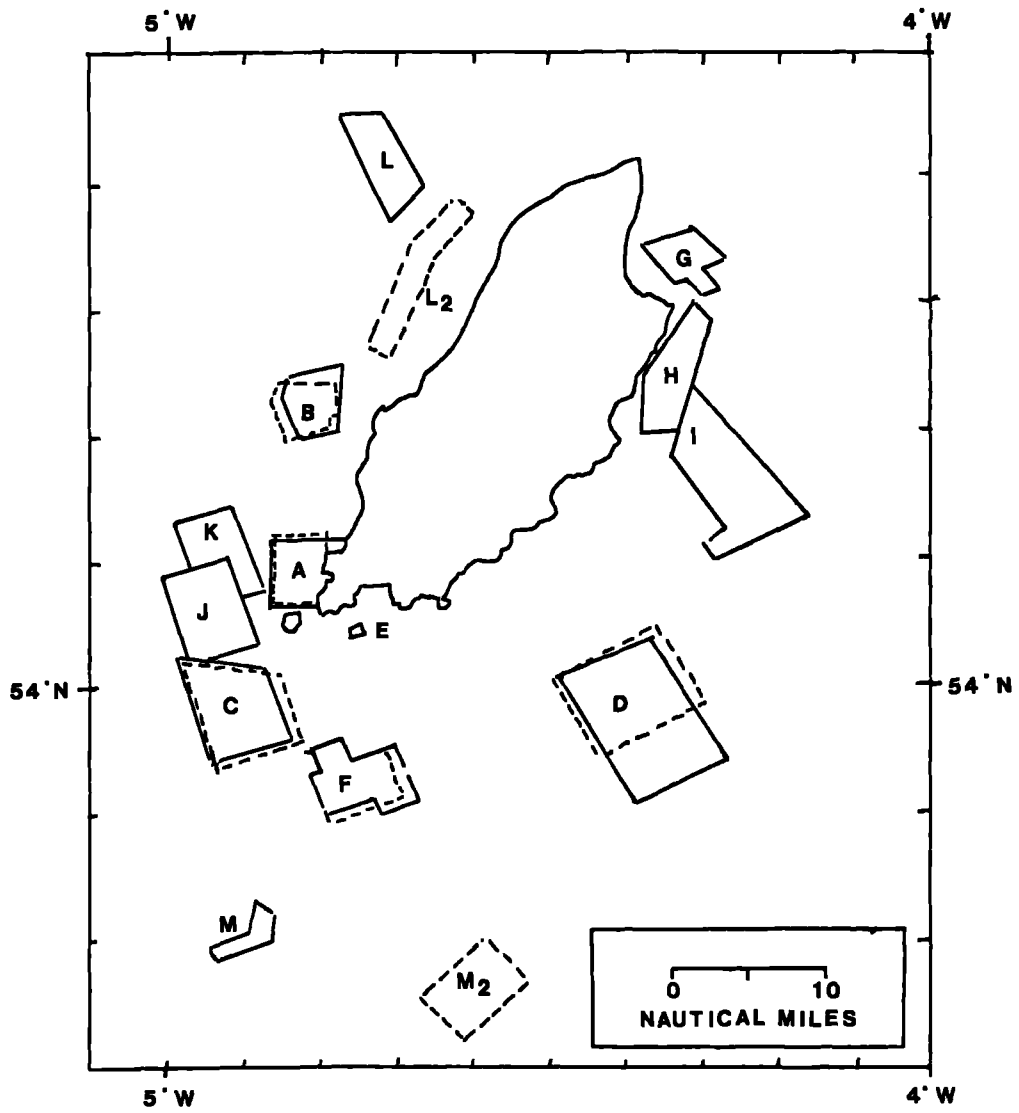
Scallops for marking were caught by a chartered commercial scallop vessel, the M.F.V. 'Mathilde' (CT100). The 'Mathilde' fished with twelve 2'0" (0.75 m) spring-loaded scallop dredges in 1987. In 1988 twelve 2'6" (0.83m) dredges were used. The vessel was chartered for the periods 30th June-9th July 1987 and 7-14th June 1988. Capture, marking and release of tagged scallops took place simultaneously within this period, with the R.V. 'Cuma' working together with the 'Mathilde'. The release periods were chosen to coincide with the period of least fishing activity on the grounds (most boats are having their annual repaint at this time), ensuring the minimum disturbance to the marked individuals and sufficient time for the scallops to recess back into the substrate before becoming liable to exploitation.

The M.F.V. 'Mathilde' fished within the designated release area, hauling the gear at hourly intervals. The scallops were then sorted by size on the 'Mathilde', and only those graded as being above 100 mm shell length were tagged. It was assumed, based on a knowledge of scallop growth rates, that most of these will have recruited to the commercial fishery (reached shell length 110 mm) by the start of the following fishing season. This eliminated the complication of having an 'open' population, where tagged scallops would recruit to the exploited population over a period of one or more years and recruit numbers would need to be considered (Murphy, 1986; Brand & Murphy, 1992).

The scallops for marking were transferred to the R.V. 'Cuma' after each tow, where they were kept in flowing seawater before marking. The tagging operation was performed on a tagging table on the deck of the 'Cuma', on which a high-speed electric drill was mounted. Each scallop was drilled through the anterior auricle (left lobe) of the left (flat) shell valve, using 2.5 mm high speed drill bits, following the procedure of Murphy (1986). A 10 cm length of 0.375 mm hard-drawn stainless steel wire was inserted through each hole, and a 15 mm yellow or red plastic Petersen disc with 1.5 mm centre hole was threaded onto the wire. Each tag bore a 4-figure serial number and the letters I.o.M. The tags from the two

**Fig. 4.1.** Scallop fishing grounds in the North Irish Sea on which tagged scallops were released in 1982, 1983, 1987 and 1988. Listed below are the names of the fishing grounds, together with the abbreviations used to refer to them in subsequent tables and figures.

A	Bradda Head	BR
B	Peel Head	PL
C	South-west Chickens	SWC; 1982/3, CH; 1987/8
D	South-east Douglas	SED
E	Port St. Mary Inshore	PSMI
F	Port St. Mary Main	PSMM; 1982/3, PSM; 1987/8
G	Ramsey Bay	RB
H	Maughold-Laxey	ML
I	East Douglas	ED
J	West Calf	WC
K	Offshore Bradda	OB
L	The Targets - offshore	TGO
L <sub>2</sub>	The Targets	TG
M	High SW Chickens	HSWC
M <sub>2</sub>	H/I Sector	H/I



 **TAGGED 82/83**

 **TAGGED 87/88**

Table 4.1. Areas where tagged scallops were released in June/July 1987 and June 1988. Release densities are calculated based on both the uncorrected number of scallops tagged and released (T1, T2) and the numbers corrected for tag-loss (T1', T2'). This gives the planned release densities (D1, D2) and the resultant densities (D1', D2').

Area name	Area (km sq.)	T1	T1'	T2	T2'	D1 m sq./tag	D1'	D2 m sq./tag	D2'
Bradda Head	28.71	535	488	518	472	5 366	5 884	5 542	6 077
Peel Head	14.74	600	547	487	444	2 457	2 694	3 027	3 319
The Targets	17.85	797	727	582	531	2 240	2 456	3 067	3 363
S.E. Douglas	59.40	999	911	1 002	914	5 946	6 520	5 928	6 500
H/I sector	50.00	927	845	864	788	5 394	5 914	5 787	6 345
Port St. Mary	32.00	858	782	876	799	3 730	4 089	3 653	4 005
The Chickens	13.96	480	438	555	506	2 908	3 189	2 515	2 758
Total	216.66	5 196	4 739	4 884	4 454	4 170	4 572	4 436	4 864

different years were distinguished by being marked with parallel lines above and below the serial number in the second year. Once the wire was threaded through the scallop and tag, the ends of the wire were twisted firmly together with pliers, and the excess wire cut to leave a tail of 6-10 mm length. Suppliers of equipment used for tagging scallops (and quccens; Chapter 5) are given in Murphy (1986) and Murphy & Brand (1992).

Each scallop was inspected for signs of damage from the capture operation and only undamaged scallops were marked and released. Prior to release, each scallop was measured (shell length or antero-posterior axis) and the number of growth rings recorded. The whole tagging procedure, from drilling to release, was carried out by a team of 4-6 people. Releases were made during the tagging procedure, while the vessel was steaming at full speed in variable directions over the fishing grounds. One scallop was released at approximately 10 second intervals, depending on the speed of the tagging operation. At a vessel speed of 9 knots (16.5 km h<sup>-1</sup>), this corresponds to a release every 46 m. A record of the release pattern, in the form of the vessel tracks on a Decca-plotter, was kept by the vessel skipper. In the 1988-release, the skipper marked the vessel position after the release of every 50 scallops, allowing investigation of the within-ground spatial pattern of subsequent tag recaptures (assuming the released scallops did not move great distances) to test the assumption of equal vulnerability of all marked individuals in the tagged population (Ricker, 1975a).

Other assumptions of tagging experiments (no tag-induced mortality, 100% reporting efficiency, no tag-shedding) were tested by Murphy (1986), who concluded: (i) reporting efficiency was of the order of 97-99%, based on experiments where the catch was seeded with known quantities of tagged scallops, and on other more subjective criteria; (ii) Tagging induced mortality was of the order of 10%, based on observations of tagged scallops held in large seawater tanks in the laboratory; (iii) Tag loss, assumed instantaneous, was also of the order of 10%, based on double-tagging experiments.

In the 1987/8 experiment, non-reporting was assumed to be negligible. The experiment was well publicised in the local media (radio, newspapers and television), efforts were made to contact as many fishermen as possible, and all scallop processors handling Irish Sea scallops were informed of the experiment, via letters and posters. A £3-00 reward was offered for the return of each tagged scallop. The tags were highly visible to both fishermen and processor, both of



whom handle each individual scallop caught in the on-board sorting and shore-based manual processing operations. The experiment was favourably regarded by most fishermen, who showed interest in the results - deliberate withholding of tags is thought to have been unlikely.

Although non-reporting was assumed negligible in the 1987/8 experiment, both tag-loss and deaths associated with the tagging procedure were investigated.

#### 4.2.1b. Estimation of tag-shedding, 1987/8 tagging experiment

Tag losses were calculated by double-tagging scallops on the Bradda Head ground in 1987, and The Chickens ground in 1988. The second tag was attached to the right auricle in the same way as for single tagged scallops (4.2.1a). Tag-shedding was estimated following the analytical methods of Seber (1982) and Murphy (1986);

$$p_L = \frac{R_R}{R_R + R_{LR}} \quad (4.1)$$

$$p_R = \frac{R_L}{R_L + R_{LR}} \quad (4.2)$$

$$p_{LR} = p_L p_R \quad (4.3)$$

where  $p_L$  = probability of loss of the left tag

$p_R$  = probability of loss of the right tag

$p_{LR}$  = probability of loss of both tags

$R_L$  = number of double-tagged scallops recaptured with just the left tag present

$R_R$  = number recaptured with just the right tag present

$R_{LR}$  = number recaptured which retained both tags.

It is assumed that the tags are independent of each other (i.e. double tagging does not affect the probability of an individual tag being lost), rate of tag-loss is independent of age, and that tag loss is instantaneous, i.e. occurs between release

and the first recapture period after tagging, and not progressively during the first and subsequent recapture periods.

#### 4.2.1c. Estimating deaths due to tagging, 1987/8 experiment

Tag-induced mortality was estimated by examining scallops which were dead when recaptured. It was established which of the dead recaptures were likely to have died as a result of tagging by observing whether or not the shell had grown over the hole drilled in the auricle. If the shell had not started to grow to cover the drilled hole, it is likely that the scallop died as a result of the tagging process, as shell growth over the hole was observed in live scallops recaptured within 2 weeks of release. It is assumed that the only mortality associated with tagging is that which occurs immediately following release, and that tagged scallops which survive the tagging procedure are no more or less vulnerable to death than untagged scallops.

In the absence of information from fishermen, scallops which were dead on recapture were distinguished from live scallops by the presence of bryozoans and other encrusting organisms on the inside of the shell.

The numbers of scallops which died as a result of tagging on each ground ( $T_{DT}$ ) are given by:

$$T_{DT} = \frac{R_{DT}T}{R} \quad (4.4)$$

where  $R_{DT}$  = number of scallops recaptured during the first fishing season after release which had died at the time of tagging  
 $R$  = total recaptures during the first fishing season after release  
 $T$  = total number tagged and released.

While scallops dying naturally around the time of release will be included in the numbers assumed to have died as a result of tagging, tending to overestimate the tagging-induced deaths, the capture and reporting efficiency of dead scallops relative to live ones is likely to be lower, tending to underestimate tagging-induced deaths. The more heavily exploited grounds, with higher values of  $R$ , will yield more reliable estimates of  $T_{DT}$ .

Similar estimates of  $T_{DT}$  were calculated for the 1982/3 experiment and used to recalculate the survival and mortality rates of post-recruit scallops previously reported by Murphy (1986). Murphy had assumed a uniform tagging-induced mortality of 10%, based on observations of the survival of tagged scallops in large, circulating seawater tanks.

#### 4.2.1d. Calculating survival and mortality rates by Ricker's two-release method

Mortality rates for the year between the two releases were calculated at the end of the second fishing season using Seber's (1982) modification of Ricker's two-release method (Ricker, 1975a):

$$\text{Survival Rate, } S_1 = \frac{R_{12}(T_2 + 1)}{T_1(R_{22} + 1)} \quad (4.5)$$

$$\text{Total mortality rate, } Z = -\log_e(S) \quad (4.6)$$

$$\text{and variance of } S_1, \sigma^2(S_1) = S_1^2 - \frac{R_{12}(R_{12} - 1)(T_2 + 1)(T_2 + 2)}{T_1(T_1 - 1)(R_{22} + 1)(R_{22} + 2)} \quad (4.7)$$

where,  $T_1$  = number of scallops marked at the start of year 1.  
 $T_2$  = number marked at start of year 2.  
 $R_{11}$  = recaptures of 1st year marks in year 1.  
 $R_{12}$  = recaptures of 1st year marks in year 2.  
 $R_{22}$  = recaptures of 2nd year marks in year 2.

Survival rate during the year between releases ( $S_1$ ) is therefore the ratio of recaptures of year 1 and year 2 marks caught in the second year, weighted by the numbers marked. The only difference between the numbers recaptured from the two tagged populations should be due to the tagged individuals from the first year release having been at liberty (and hence dying) for the period between the two releases. Age-specific estimates of survival and mortality rates were calculated using this procedure.

Total mortality rate in the fishing season following the first release,  $Z_1$ , can then be partitioned into fishing and natural mortality rates ( $F_1$  and  $M_1$ ) by utilising the exploitation rate  $u_1$  (see Ricker, 1975a);

$$\text{where } u_1 = \frac{R_{11}}{T_1} \quad (4.8)$$

$$\text{and } u_1 = \frac{F_1 A_1}{Z_1} \quad (4.9)$$

$$\text{where } A_1 = \text{annual mortality rate} = 1 - e^{-Z_1} \quad (4.10)$$

$$\therefore u_1 = \frac{F_1 (1 - e^{-Z_1})}{Z_1} \quad (4.11)$$

Rearranging equation 4.11 to give  $F_1$ :

$$F_1 = Z_1 \frac{u_1}{(1 - e^{-Z_1}) Z_1} \quad (4.12)$$

as  $Z_1 = F_1 + M_1$ , and both  $Z_1$  and  $F_1$  have been calculated from equations 4.6 and 4.12, the value of  $M_1$  can be calculated by rearranging the above equation:

$$M_1 = Z_1 - F_1 \quad (4.13)$$

It must be noted that the values of  $T_1$  and  $T_2$  (the numbers marked) need to be adjusted to take account of tagging-induced mortality and tag shedding, or estimates of  $u$  (and hence of  $F$ ) will be underestimated and, correspondingly,  $M$  will be overestimated. Survival rate estimates and hence  $Z$  (from equations 4.5 & 4.6) will only be biased if tagging mortality and tag loss differ between the two releases. A further loss from the tagged population which must be taken into account is the capture, while fishing for queens, of tagged scallops during the closed season immediately following the release operation. These recaptures are excluded from total recapture statistics used to calculate exploitation rates, and are instead subtracted from the release numbers as they would not be available for recapture (either dead or alive) at the start of the fishing season. The bias caused by the exclusion of closed-season recaptures (which were subject to natural mortality during their time at liberty) will be less than that incurred by their inclusion in estimates of exploitation rate. Pre-season recaptures were included for the purpose of calculating tagging-induced mortality rates. Closed season recaptures were only significant on offshore grounds to the south of the Isle of Man.

The calculations of  $F$  and  $M$  given above assume that all fishing mortality is accounted for by scallops that are caught and landed. In fact there will be a component of fishing mortality which does not result in the capture and landing of the scallops. This incidental or non-yield fishing mortality ( $F_i$ ) will be erroneously included in the estimates of  $M$  derived from equation 4.13. It is desirable that  $F_i$  be subtracted from the apparent values of  $M$  obtained above, and either be added to  $F$ , or included as a separate parameter, so that  $Z = M + F + F_i$ . Although these experiments cannot quantify  $F_i$  directly, an indirect estimate of  $F_i$  can be obtained from the relationship between total mortality rates ( $Z$ ) and exploitation rates ( $u$ ). It is assumed that when  $u=0$ ,  $Z=M$ , so that  $M$  can be calculated from a regression of  $Z$  on  $u$ . The exploitation rate ( $u$ ), expressed as a percentage, is first log-transformed so that  $u$  is linearly proportional to  $Z$ . A  $(\log_e u + 1)$  transformation allows calculation of the intercept for  $u=0$ . For the relationship to be valid, it must be assumed that  $M$  values are either the same on all grounds, or their variability is random and normally distributed. All estimates of  $Z_1$  and  $u_1$  from both the 1982/3 and 1987/8 tagging are combined to calculate an overall mean value of  $M$  for unfished populations from:

$$Z = M_0 + \log_e (u + 1) \quad (4.14);$$

where  $M_0$  = value of  $M$  when  $u = 0$  and  $\therefore F = 0$ . This is essentially Gulland's (1983, p113-115) approach to estimating  $M$  from  $Z$  and  $f$  (nominal fishing effort) by regression analysis, except  $u$  is used in place of  $f$  and the different values of  $Z$  come from different areas and years, rather than just different years. Exploitation rate is preferred to fishing effort because total effort values can only be calculated by extrapolation of sample fleet effort to total fleet effort, with a large degree of uncertainty in the raising factors.

Estimates of  $M$ , which will, however, include  $F_i$ , were also obtained from recaptures of dead shells bearing tags. The scallops dead on recapture were separated into those which had died as a result of tagging ( $R_{TD}$ ) and those which had died subsequently ( $R_{TM}$ ), either from natural or fishing-related causes. The ratio of  $R_{TM}$  to total recaptures ( $R$ ) in the year following each release is equivalent to  $n$ , the conditional rate of natural mortality (Ricker, 1975a) and as  $n = 1 - e^{-M}$  :

$$M = -\log_e (1 - n) \quad (4.15).$$

The assumptions required are that the capture efficiency, rate of tag-loss and reporting rate of dead shell is the same as for live tagged scallops.

Estimates of fishing mortality for the year after the second tagging may be obtained by utilising the  $F_1$  value calculated from equation 4.12 and fishing effort data (gear width  $\times$  hours fished) from sample fleet statistics obtained from logbooks (see Data Collection Methods), assuming that effort ( $f$ ) is proportional to  $F$  (Ricker, 1975a). It is also assumed that the difference in sample fleet effort for a particular ground is reflected in total effort for that ground. There is no requirement for sample-fleet to total fleet raising factors to be the same for all grounds.

$$\frac{F_1}{F_2} = \frac{f_1}{f_2}, \therefore F_2 = \frac{F_1 f_2}{f_1} \quad (4.16)$$

Some of the above methods were previously applied by Murphy (1986) and Murphy & Brand (1992) in the analysis of the 1982/83 tagging programme. Murphy's estimates (for post-recruit scallops only) have been recalculated using the above methods, so that estimates of mortality rates obtained from the two tagging programmes can be compared directly.

#### 4.3.1e. Mortality rates from log-linear regression

Mortality rates for the period 1983-1991 were obtained from the rate of decline of recaptures of tagged scallops released in 1982 and 1983.

$$R_t = R_0 e^{-Zt} \quad (\text{Beverton \& Holt, 1957}) \quad (4.17)$$

The above equation is transformed to give:

$$\log_e (R_t + 1) = \log_e (R_0 + 1) - Zt \quad (4.18)$$

where,  $R_t$  = number of recaptures in the period  $t$   
 $R_0$  = number of tags released

Plotting  $\log_e(\text{recaptures})$  in each year against time and fitting a straight line, either by eye or by least-squares regression, is recommended as a first analysis by Ricker (1975a) and Gulland (1983), but several more recent papers (reviewed in Farebrother, 1992) advocate weighted regression, using the number of recaptures as weights, to give more efficient and less biased estimates. In either case, if the points fit a straight line, this suggests that survival rate has been uniform over the period covered by the experiment and  $Z$  can be estimated from the slope, in this case, of the weighted regression. The transformation used is  $\log_e(R_t + 1)$ , so that years when no recaptures were recorded are not excluded from the regression. Weights ( $W_t$ ) are  $R_t + 1$ .

The time period  $t$  used here is the fishing season. Recaptures are grouped by fishing season and  $t$  represents the mid-point of the November-May scallop fishing season (February 14th). Note that the length of the first time interval, between release and the mid-point of the first fishing season, is not =1. In most cases releases were in June-July, so this is taken into account in utilising the intercept on the y-axis (number of returns) to calculate  $F$  from  $Z$  (see below).

Deviations from linearity of the log-transformed recaptures is indicative of variations in mortality rate; if these deviations are large, it may be necessary to weight recaptures by some measure of  $F$  (Jones, 1976; 1977), the disadvantage being the reliance on fishing effort data, which introduces additional error.

In this study, the Beverton and Holt deterministic or log-linear model (Beverton, 1954; Beverton & Holt, 1957) fitted by weighted least-squares gave a very good fit to the data for the total tag returns and for most of the individual grounds, particularly the main, regularly fished areas. The fit was not so good for those grounds where the number of returns was low and exploitation sporadic. In most instances there was therefore no requirement for weighting by fishing effort, which would in any case defeat one of the objectives of the study (to provide mortality rates independent of fishery statistics).

The slope of the log-linear regression gives  $-Zt$ , and  $F$  and  $M$  can then be calculated from the value of  $R$  at the time of release ( $R_{1t}$ ) and the number of scallops tagged ( $T$ );

$$F = \frac{Z e^{(R_u - Zt)}}{T(1 - e^{-Zt})} \quad (\text{after Gulland, 1983}) \quad (4.19)$$

Separate estimates of Z were obtained from the recaptures of scallops tagged in 1982 and 1983. The first season's returns have been excluded from the regression analysis of the scallops tagged in 1982 as there are strong indications that fishing mortality in 1982/83 was lower than in subsequent years (see Murphy, 1986 and Murphy & Brand, 1992). Removing the first point from this analysis also makes the two regressions directly comparable as they then cover the same time period. The slopes (and therefore the total mortality rates) of the regressions based on the recaptures of scallops tagged in 1982 and 1983 were compared using t-tests. Only pairs of slopes from the same ground were compared. If the slopes of the regressions of 1982 and 1983-released tags did not differ ( $p \leq 0.05$ ), a common value of Z was calculated for that ground. Analysis of covariance (ANCOVA) was used for multiple comparisons of Z among areas (see p124).

The main advantage of estimates of Z from log-linear regression is that they are independent of tagging mortality and initial tag loss, factors which must, however, be taken into account in utilising T (the number tagged) to partition Z into F and M (equation 4.19). T', the number tagged corrected for tag-loss (10%) and deaths due to tagging (area and year specific values calculated from first-year dead-shell returns) is used in all cases.

These mortality rate estimates, together with the calculation of mortality rates from the 1987/8 Ricker two-release experiment, provide further validation of Murphy's earlier studies (Murphy, 1986) as well as providing contemporary estimates for comparison with those obtained from abundance-at-age or CPUE-at-age data.

#### 4.3.1f. Spatial variability in survival, mortality and exploitation rates

The significance of the spatial variability of survival rates ( $S_1$ ) from the 1982/3 and 1987/8 Ricker two-release experiments were investigated by computing variance-weighted  $\chi^2$  statistics (Sokal & Rohlf, 1981):



$$\chi^2_{(n-1)} = \sum_{i=1}^n \frac{1}{\sigma^2(S_i)} (S_i - \bar{S})^2 \quad (4.20)$$

$S_i$  = survival rate for the  $i$ th area

$\bar{S}$  = pooled estimate of survival rate

$n$  = number of areas compared

The null hypothesis is that there are no significant differences in survival rates of scallops between the ten fishing grounds studied in 1982/3, and between the seven grounds studied in 1987/8.

Ordinary  $\chi^2$  tests were also used to compare exploitation rates (separate comparisons of spatial differences of  $u_1$  and  $u_2$  in 1982, 1983, 1987 and 1988), with  $H_0$  = no significant difference in recapture rates.  $\chi^2$  values were calculated using recaptures as observed frequencies, with expected recaptures calculated from the ratio of pooled recaptures to pooled release numbers and the numbers released on each ground.

An analysis of covariance (ANCOVA) was used for comparisons among the slopes of the log-linear regression equations fitted to tag returns from different grounds for the 1983-1991 fishing seasons. The null hypothesis tested was that the slopes ( $-Zt$ ) of the regressions were equal, and that therefore there were no significant differences in mortality rates between areas. Separate comparisons were run for the recaptures from the two different releases. Tukey tests were used to ascertain where the differences lay (see Zar, 1984, p186-190).

#### 4.2.2. Mortality rate estimates from age-composition data

Age-composition of catches or samples can be used to construct a catch-curve (e.g. Chapman & Robson, 1960) where mortality is estimated from the relative abundance of successive year-classes, using the basic survival rate equations  $N_2/N_1 = S$  and  $Z = -\log_e S$ . The basic catch-curve, in which a single estimate of  $Z$  is calculated from the slope of an ordinary least squares linear regression of  $\log_e(N)$  against age (the predictor variable) of a single sample or pooled samples, assumes constant recruitment and constant mortality rate with age for the range of age-classes used. A relatively high degree of recruitment variability precludes the application of catch-curve methods to these stocks in most cases, and only one such

mortality rate estimate has been calculated. This was obtained from the catch-curve in Gruffydd (1974a), whose data are from grounds to the south of the Isle of Man (Port St. Mary and H/I sector) which were unfished at the time of sampling (1966), so  $Z=M$ . The effects of recruitment variability were found to be much reduced by pooling samples from different areas, which is indicative of fairly constant recruitment to the region as a whole. Age-specific estimates of  $M$  were calculated, as the catch-curve ( $-\log_e$  plotted against age) was not linear.

As part of this study, a linear regression equation has been fitted to log-transformed age-frequency data from Tang (1941). These data were collected during the 1937/8 winter on the Bradda ground. As the ground had not been fished prior to this year, the resultant estimate of  $Z$  approximates to  $M$ .

More recent estimates of  $Z$  from exploited populations on most of the major scallop fishing grounds in the North Irish Sea were obtained using abundance-at-age estimates from successive years. Two data-sets were used; the abundance-at-age matrices calculated from research vessel age-structure data and commercial fleet catch per unit effort (Chapter 2, Tables 2.9a-2.9c), covering the periods 1986/7 - 1989/90, and catch/effort data and age-composition of catches from the M.F.V 'Mathilde' during the periods of her charter for the tagging experiments (30th June-9th July 1987 and 7th-14th June 1988). Abundance-at-age values were log-transformed prior to analysis, as suggested by Jensen (1985). Untransformed CPUE data from the 'Mathilde' were used for the calculations. Total mortality-at-age values were calculated from:

$$S = \frac{{}_{a+1}N_2}{{}_a N_1} \quad (4.21)$$

$$\therefore Z = -\log_e \frac{{}_{a+1}N_2}{{}_a N_1} \quad (4.22)$$

where  ${}_a N_1$  ,  ${}_{a+1}N_2$  = abundance or CPUE of age  $a$  scallops in year 1 and abundance of the same year class the following year, at age  $a+1$ .

Total mortality rates, averaged over all fully exploited year-classes, were also calculated by Heinke's method (Heinke, 1913), which is a weighted least-squares estimator of the geometric mean  $Z$  (Ricker, 1975a; Gulland, 1983).

$$Z = -\log_e \frac{{}_a N_2 + {}_{b+1} N_2 \dots {}_{i+1} N_2}{{}_a N_1 + {}_b N_1 \dots {}_j N_1} \quad (\text{after Heinke, 1913}) \quad (4.23)$$

More abundant age-classes, where changes in number between successive years are likely to be better estimated, are given greater weighting. Only exploited age-classes are used, so  $a$  is the age-class at which >50% of individuals are  $\geq 110$  mm shell length (from Chapter 2, Table 2.2).

Estimates from abundance-at-age (from Chapter 2) cover the period from the mid-point of one fishing season to the midpoint of the following (February - February), whereas the estimates from the 'Mathilde' catch data cover the period July 1987 - June 1988, and include only the 1987/8 fishing season.

#### 4.2.3. Empirical and life-history methods

Empirical relationships between mortality and growth parameters, longevity, age at sexual maturity and temperature, found in the published literature, were used to calculate values of  $Z$  and  $M$ . Many of these relationships are derived from fish-stocks only, but the underlying physiological theory also applies to invertebrates. It is therefore justifiable to apply them to scallop stocks (Caddy, 1987), at least to obtain order-of-magnitude estimates or test their applicability by comparison with other methods. The following regression equations (given in the authors' notation) have been used to derive mortality rate estimates for comparison with those obtained from mark-recapture and age-composition methods:

$$M = 1.5 \text{ to } 2.5k \quad (\text{Beverton \& Holt, 1959}) \quad (4.24)$$

$$M = \frac{2.996}{0.95L_\infty} \quad (\text{Taylor, 1960, for bivalves}) \quad (4.25)$$

$$\log_{10} M = -0.0066 - 0.279 \log_{10} L_\infty + 0.6543 \log_{10} k + 0.4634 \log_{10} T$$

$$(\text{Pauly, 1980, from 175 fish stocks}) \quad (4.26)$$

$$M = \frac{1.521}{(t_{m50})^{0.720} - 0.155} \quad (\text{Rikhter \& Efanov, 1976}) \quad (4.27)$$

$$M = 0.03 + 1.68(\text{WGSI})$$

(Gunderson & Dygert, 1988, from 24 fish stocks) (4.28)

$$\log_e(Z) = 1.23 + -0.832(\log_e(t_{max})) \quad (\text{Hoenig, 1983, for molluscs}) \quad (4.29)$$

where: M = Instantaneous rate of natural mortality

Z = Instantaneous rate of total mortality

$L_{\infty}$  = asymptotic length (in cm)

k = Brody/Bertalanffy growth coefficient

T = annual mean environmental temperature

$t_{m50}$  = age at 50% sexual maturity (months)

$t_{max}$  = age of oldest fish in sample (years)

$$\text{WGSI} = \text{Wet-weight gonado-somatic index} = \frac{\text{wet gonad wt. (g)}}{\text{total wet wt. (g)}}$$

Each of the above equations have been applied to data from all sub-stocks for which growth and maturity data are available (see Chapter 3). Von Bertalanffy growth parameters have been calculated from length-at-age data,  $t_{m50}$  is calculated from size at maturity (gonad stage >2) for scallops sampled at the start of the reproductive season (March - May) in 1987 and 1988, and  $t_{max}$  is taken as the mean age of the 10 oldest individuals in samples of 100+ scallops (Hoenig, 1983). Separate estimates are generated for each area sampled. Biometric data from 1987-89 are pooled to provide a mean estimate for the period January 1987 - November 1989. Estimates of M are also calculated for the Bradda Head ground when it was unfished, using the data of Tang (1941). Mean environmental temperatures (for the application of Pauly's multiple linear regression equation) are taken from bottom temperature measurements made at the 'Cypris' station (54°05'50 N, 4°50'00 W on the Bradda Head scallop ground (Slinn, unpublished data). A three-year mean (January 1987 - December 1989) is used (10.4° C), together with estimates of k and  $L_{\infty}$  calculated from pooled length-at-age data collected during the same period. The Pauly equation (Pauly, 1980) is applied to all grounds, although bottom temperatures on other fishing grounds are likely to differ by up to 1° C.

Temperature differences of this magnitude only have a small effect on estimates of M.

All statistical tests and mortality rate calculations (with the exception of the regression equations) were implemented on Microsoft EXCEL spreadsheets. Regression equations were fitted by weighted least squares using SYSTAT.

The estimates generated by the different methods were used to select the appropriate ranges of M and F for use in population assessments (Chapter 6).

## **4.3. RESULTS**

### **4.3.1. Mark-recapture experiments**

Both the 1982/3 and 1987/8 recapture experiments were characterised by high rates of returns relative to most tagging experiments on commercially exploited fish populations (e.g. Jones, 1979). During the period of this study (June 1982 to May 1991), a total of 4,221 of the 12,006 scallops tagged and released in 1982 and 1983 were returned. On some grounds, recaptures in the first year after release were as high as 55% of the number released. Of the 10,080 tagged scallops released in July 1987 and June 1988, 2,538 were recaptured before May 31st 1989. Subsequent recaptures from this experiment are not reported here. The high rates of return are immediately suggestive of intense fishing on the stocks. High recapture rates of live scallops, together with relatively low numbers recaptured dead, are also indicative of the suitability of mark-recapture experiments for quantifying the levels of exploitation in this fishery. Survival and mortality rates can also be calculated, provided that the major sources of bias in the calculations can be identified. Potential sources of bias are quantified in 4.3.1a - 4.3.1d.

#### **4.3.1a. Tag-loss**

The loss of tags will affect estimates of recapture rates (and therefore fishing and natural mortality rates) but will not bias survival rate estimates from the two-release experiments unless the proportion of tags lost differs between the two releases. For the 1982/3 experiment, a probability of tag-loss of 0.10 for both releases was used to correct for bias in the estimation of recapture rates, based on the results of a double-tagging experiment carried out by Murphy (1986). For the 1987/8 experiment, the probability of shedding the left (anterior) tag was 0.098 in both years (Table 4.2). This loss rate is used to correct release numbers of single-tagged scallops, as all single-tagged individuals bore the tag on the left auricle. The probability of loss of the right tag was higher (0.226 in 1987 and 0.114 in 1988) and was likely to have been due to the greater difficulty of attaching the tag to the right auricle of the scallop, which tends to be smaller. In all cases loss-rates were assumed to have taken place at the time of tagging (type I tag loss of Davis & Reid, 1982), so release numbers were adjusted to reflect the decrease in numbers of tags available for recapture. Progressive loss of tags during the recapture period (type II tag-loss) were thought to be negligible; tag attachment strengthened with time as the shell grew over the drilled hole, fixing the wire and threaded tag more firmly.

Probabilities of losing both tags (0.019 for the 1987 release and 0.011 for the 1988 release) were used to adjust the release numbers for the double-tagged releases.

In the double-tagging experiment carried out in 1987, all recaptures of double-tagged scallops from one vessel were excluded from the analysis, as deliberate removal of one tag from double-tagged scallops followed dispute over the fact that the same £3-00 reward was offered for both single and double-tagged scallops.

#### 4.3.1b. Tagging-induced mortality

The proportion of tagged scallops which appear to have died as a result of the capture and tagging process was highly variable, both between years and between grounds (Table 4.3). In the 1982/3 tagging, few dead tagged shells were returned. In 1982 the majority of these were from the Port St. Mary ground (Table 4.3a). Assuming that the catchability and reporting efficiency of dead scallops was the same as for live scallops, it is calculated that 28.5% of scallops released on this ground died as a result of tagging. Tagging induced mortalities on the S.E. Douglas ground were also high (13%). Estimates from other grounds are low (0-2% of the number released). Tagging-induced mortalities from the 1983 release were again relatively high for the Port St. Mary ground (9.2%) but relatively low for all other grounds (0 - 5.1%; Table 4.3b).

These figures will tend to be underestimates as the capture and reporting efficiencies for dead tagged shells are likely to be lower than for live ones. The relative differences in calculated tagging-induced deaths between areas and between years should not be seriously affected by lower reporting rates. The large difference in tagging-induced deaths on the Port St. Mary and South-east Douglas grounds, where more of the scallops died following release in 1982 than in 1983, means that the assumption of a uniform mortality of 10% (Murphy, 1986) will lead to overestimation of mortality rate on these grounds for the 1982/3 season. Murphy (1986) reported total mortalities of 1.15 and 0.53 for these grounds, whereas if the differences in tagging-induced mortalities are taken into account, values of 0.91 and 0.42 are obtained. Reducing the release numbers also affects exploitation rate estimates, which would be underestimated by Murphy in cases where tagging-induced deaths were > 10% and overestimated when tagging-induced deaths were < 10%.

**Table 4.2.** Calculation of tag-losses from the first season's recaptures of double-tagged scallops released in 1987 and 1988. Values in brackets exclude returns from one vessel where some tags were thought to have been removed and discarded.

	Bradda Head 1987	The Chickens 1988
Number of double-tagged scallops released, $T_{LR}$	219	405
Number recaptured with just the left tag present, $R_L$	14 (9)	20
Number recaptured with just the right tag present, $R_R$	9 (4)	17
Number recaptured which had retained both tags $R_{LR}$	47 (37)	156
Probability of loss of the left tag, $P_L$	0.161 (0.098)	0.098
Probability of loss of the right tag, $P_R$	0.226 (0.196)	0.114
Probability of loss of both tags, $P_{LR}$	0.036 (0.019)	0.011



**Table 4.3.** Calculation of the number of post-recruit scallops which died as a result of tagging ( $T_{DT}$ ) in the 1982/3 and 1987/8 tagging experiments.

$R_{DT}$  = number of scallops recaptured dead, with no shell-growth over the hole drilled in the auricle, during the year following release.

$T$  = number of scallops marked and released (adjusted to account for tag loss).

$R$  = total number of recaptures (live and dead) in the season following release (a measure of the exploitation rate, and therefore the probability of capture of any scallop, live or dead).

Scallops recaptured dead which appeared to have died naturally some time after tagging are also tabulated ( $R_{DM}$ ). These have been used to calculate natural mortality rate ( $M'$ , see Table 4.8).

a) 1982 release.

AREA	T	$R_{DM}$	$R_{DT}$	R	$T_{DT}$	Tag death (%)
Bradda Head	383	4	0	102	0	0.0
Peel Head	455	0	1	74	6	1.3
Ramsey Bay	180	0	0	15	0	0.0
Maughold/Laxey	366	1	0	31	0	0.0
East Douglas	336	0	0	26	0	0.0
S.E. Douglas	805	3	3	23	105	13.0
Port St. Mary	351	5	12	42	100	28.5
S. W. Chickens	661	3	1	88	8	1.2
West Chickens	396	0	1	57	7	1.8
Offshore Bradda	460	1	1	74	6	1.3

a) 1983 release.

AREA	T	$R_{DM}$	$R_{DT}$	R	$T_{DT}$	Tag death (%)
Bradda Head	131	4	1	73	2	1.5
Peel Head	260	0	0	49	0	0.0
Ramsey Bay	92	0	0	18	0	0.0
Maughold/Laxey	149	0	1	31	5	3.4
East Douglas	161	0	0	41	0	0.0
S.E. Douglas	534	2	1	29	18	3.4
Port St. Mary	293	1	3	32	27	9.2
S. W. Chickens	272	1	1	94	3	1.1
West Chickens	118	1	2	37	6	5.1
Offshore Bradda	199	1	2	55	7	3.5

c) 1987 release.

AREA	T	R <sub>DM</sub>	R <sub>DT</sub>	R	T <sub>DT</sub>	Tag death (%)
Bradda Head	507	4	3	194	8	1.6
Peel Head	541	0	0	134	0	0.0
The Targets	719	5	84	309	195	27.1
S.E. Douglas	901	1	15	95	142	15.8
H/I sector	836	5	10	69	121	14.5
Port St. Mary	771	7	16	203	61	7.9
The Chickens	442	0	10	193	23	5.2

d) 1988 release.

AREA	T	R <sub>DM</sub>	R <sub>DT</sub>	R	T <sub>DT</sub>	Tag death (%)
Bradda Head	477	2	4	108	18	3.8
Peel Head	439	3	3	126	10	2.3
The Targets	525	5	29	101	151	23.0
S.E. Douglas	904	4	15	90	151	16.7
H/I sector	779	1	10	42	185	23.7
Port St. Mary	790	7	34	232	116	14.7
The Chickens	536	4	6	237	14	2.6

Table 4.4. Numbers of tagged scallops returned during the closed seasons of 1987 and 1988. Closed-season recaptures were not included in calculations of exploitation rates. Scallops tagged in June/July 1987 which were recaptured before 1st November 1987 (R<sub>11</sub> ') and scallops tagged in June 1988 which were recaptured before November 1st 1988 (R<sub>22</sub> ') were subtracted from the release numbers. Tags released in June/July 1987 and recaptured between June 1st 1988 and October 31st 1988 (R<sub>12</sub> ') were excluded from recaptures used to calculate exploitation rates but were not subtracted from release numbers.

Area	R <sub>11</sub> ' live	R <sub>11</sub> ' dead	R <sub>12</sub> ' live	R <sub>12</sub> ' dead	R <sub>22</sub> ' live	R <sub>22</sub> ' dead
Bradda Head	0	0	0	0	1	0
Peel Head	0	0	1	0	0	1
The Targets	1	1	0	0	1	1
S.E. Douglas	2	0	1	1	1	0
H/I Sector	25	14	6	4	10	3
Port St. Mary	2	3	6	1	10	1
The Chickens	0	0	0	0	3	0

The number of dead-shell returns was generally higher in 1987/8 than in 1982/3, despite the use of the same capture, handling and tagging procedure in the two tagging programmes. In 1987 between 0 and 27.1% of released scallops died soon after release (Table 4.3c). The offshore grounds to the south of the Isle of Man again appeared to suffer higher tagging-induced mortalities (7.9 - 15.8%) than inshore grounds (0 - 5.2%, excluding the Targets fishing ground). The reason for this difference is not clear. The grounds have different age-structures (see Chapter 2) with off-shore grounds being dominated by older scallops, but no trend in capture-induced mortality with age was observed. The high tagging-induced mortality on the Targets fishing ground, which like the other inshore grounds is dominated by recruiting year-class scallops, would also appear to negate the theory that older scallops are less likely to survive the capture and release procedure. Differences in substrate type occur between grounds (Chapter 3, Table 3.5) and may affect the condition of the captured scallops. The offshore grounds tend to be stony. Dragging scallops along a boulder-strewn sea-bed in a stone-filled, heavy iron dredge for up to one hour may well have affected their condition. Variation in the number of predators may also have affected survival of newly released scallops, which would be in a weakened condition and less able to resist the predatory advances of crabs, starfish and whelks. No data were collected on abundance of predators.

The same four fishing grounds suffered high post-tagging mortality in 1988 (Table 4.3d). This implies that it is some factor(s) specific to these fishing grounds that affects survival of released scallops, rather than, for example, variation in the weather conditions on the day the scallops were tagged.

Determination of the absolute numbers which died at the time of tagging allows correction for bias in the calculation of exploitation rates ( $u$ ) and hence  $F$  and  $M$ . Determination of the differences in deaths between years allows correction for bias in the calculation of survival rate ( $S$ ) and total mortality rate ( $Z$ ). The number of tagging-induced deaths are subtracted from the tagged population after correction for tag-losses (4.3.1a) have been applied.

#### 4.3.1c. Pre-season recaptures

More than half the recaptures from the offshore H/I sector fishing ground were taken during the closed seasons following the 1987 and 1988 releases (Table

4.4). Closed-season recaptures were also relatively high on the Port St. Mary ground. Both these fishing grounds support large queen (*Chlamys opercularis*) populations, and the tagged scallops were taken incidentally while fishing for this species. Recaptures prior to the first fishing season were insignificant on other fishing grounds (Table 4.4). Pre-season recaptures were subtracted from the release numbers and excluded from exploitation rate calculations.

#### 4.3.1d. Non-reporting rate

Non-reporting rates for the 1982/3 experiment were set at 5%, following Murphy (1986), who found non-reporting rates of the order of 1-3% by seeding catches with tagged scallops at processing factories and who assumed further non-reporting of 2-4%, based on subjective assessment of shipboard and other losses. Non-reporting rates are used to adjust exploitation rate estimates, rather than to modify release numbers.

For the 1987/8 experiment, and for log-linear regressions of tag-returns for the period 1982-1991, non-reporting was assumed to be negligible. The majority of tags (>70% in the 1987/8 and 1988/9 fishing seasons) were returned by the fishermen that caught them, indicating their high visibility. Of those returned from processing factories, many were deliberately left on top of the landed bags of scallops for factory workers (often wives of fishermen) to find. A third check for tags was made by companies handling scallop shells for export. Only 6 tags were located at this third stage of processing. A small number of tags were returned from fish-processing factories and fishery officers from England, Scotland, Wales, Northern Ireland and Eire. The reporting rate of these are not known, but due to the wide publicity of the experiment in the area, the number of recaptures which were not reported are assumed to be negligible.

#### 4.3.1e. Survival, exploitation and mortality rates calculated from Ricker two-release experiments

Survival rates ( $S_1$ ) for the year July 1982 - June 1983 range from 0.45 - 0.71, giving a range of total mortality rates ( $Z_1$ ) of 0.35 - 0.91 for the different fishing grounds (Table 4.5). The highest estimate, for the offshore ground of Port St. Mary South, is based on low numbers of returns ( $R_{12}$ ,  $R_{22}$ ). This high estimate

Area	Tagged year 1 (T1)	T1 corrected	Tagged year 2 (T2)	T2 corrected	Recaptured year 1 (R11)	Recaptured year 2, tagged year 1 (R12)	Recaptured year 2, tagged year 2 (R22)	Survival rate (S)	s.dev.(S)	Total mortality rate (Z)
BR	426	383	145	129	98	93	68	0.457	0.056	0.782
PH	506	449	289	260	73	39	49	0.453	0.089	0.791
RB	200	180	102	92	15	26	18	0.707	0.189	0.347
ML	407	366	165	144	30	47	30	0.601	0.124	0.510
ED	373	336	179	161	26	45	41	0.517	0.098	0.661
SED	894	700	593	516	17	24	26	0.657	0.177	0.421
PSM	390	251	326	266	25	11	28	0.403	0.136	0.908
SWC	661	653	302	269	84	134	92	0.596	0.068	0.518
WC	440	389	131	112	56	57	34	0.473	0.087	0.748
OB	511	454	221	192	72	57	52	0.457	0.077	0.783
Total	4808	4161	2453	2141	496	533	438	0.625	0.037	0.470

Table 4.5. Summary table of the results of the 1982/3 tagging experiment. Included in the table are tag releases (year 1 = released in 1982, year 2 = released in 1983), tag releases corrected for tag loss (10%) and area-specific tagging mortality. Also shown are recaptures and calculated survival and mortality rates.

may be due to an underestimation of the level of tagging-induced mortality on this ground (see 4.3.1.c), as the low exploitation rate estimates lead to low fishing mortality rates and unrealistically high natural mortality rates.

With the exception of the Port St. Mary ground, the highest mortality rates were on the inshore grounds to the west of the Isle of Man (i.e. Inshore Bradda, Offshore Bradda, Peel Head, West Calf), with  $Z$  values of 0.75 - 0.79. Mortalities were generally lower on grounds to the south and east of the Island. The estimates given here differ only slightly from those given in Murphy (1986), with the exception of the SE. Douglas and Port St. Mary grounds, where the estimates calculated here are substantially lower.

The 1987/8 experiment indicates that survival rates on the major fishing grounds were generally low (0.26 - 0.66; Table 4.6). The highest mortality rate estimate ( $Z = 1.35$ ) was obtained from the offshore H/I sector ground, and was again based on low return rates. A large number of dead shells were returned from this ground and tagging-induced mortality rates may once again have been underestimated. Again, with the exception of this ground, the highest mortalities came from the inshore-west grounds of Bradda Head, Peel Head, The Targets and The Chickens ( $Z = 0.76 - 1.02$ ), with the lowest estimate (0.42) coming from the South-east Douglas ground. Most of the estimates were based on high numbers of returned tags and have fairly low standard deviations.

Fishing mortality rates for the 1982/3 fishing season ( $F_1$ ), calculated from estimates of  $Z_1$  (Table 4.5) and exploitation rates corrected for non-reporting are in the range 0.03 - 0.39 (Table 4.7). The highest  $F_1$  values are those for the inshore-west fishing grounds. Calculated natural mortality rates ( $M_1$ ) seem high (0.24 - 0.75) and are likely to include indirect fishing mortality ( $F_{1i}$ ) and losses associated with the tagging experiment which were not fully accounted for.

Using the relationship between exploitation rate ( $u$ ) and estimated total mortality rate (Fig. 4.2), back-calculated mortality at  $u = 0$ , when  $Z = M$ , is estimated at  $0.12 \pm 0.173$  (s.e.). The confidence limits for the estimate are wide, and probably reflect spatial variability in the natural mortality rate and differences in vulnerability to indirect fishing mortality as well as experimental error. Using the derived value for natural mortality in the absence of fishing ( $M_0$ ), estimates of indirect fishing mortality range from 0.12 to 0.63. With the exception of the Port St. Mary ground, indirect mortality is, as expected, higher on more heavily fished

grounds. For grounds with lower fishing mortality rates, however, indirect fishing mortality exceeds fishing mortality. If the above relationships are valid, the major cause of mortality on the grounds to the south and east of the Isle of Man is incidental damage during fishing operations.

Fishing mortality rates for the 1983/4 fishing season ( $F_2$ ), calculated from exploitation rates ( $u_1, u_2$ ) and change in sample-fleet fishing effort ( $f_1, f_2$ ), are generally higher than for the 1982/3 season (Table 4.7), particularly on the inshore-west fishing grounds where a very strong year-class had just recruited to the fishery (Murphy, 1986). Errors in estimates are likely to arise when the change in sample-fleet fishing effort for a particular ground does not reflect the actual change in total effort for that ground. This is likely to have been the cause of the apparently huge increase in fishing mortality rate on the Offshore Bradda ground (0.24 in 1982/3, 4.55 in 1983/4).

Fishing mortality rates in 1987/8 and 1988/9 were also higher than in 1982/3 in most cases (Table 4.8). Estimates of  $F_1$  ( $F$  for 1987/8) of 0.40 - 0.64 for inshore-west grounds compare with estimates of 0.15 - 0.39 for the same grounds in 1982/3. The relatively high estimates of  $F$  for inshore grounds in both fishing seasons contrast with estimates for offshore grounds to the south and east in the same season (0.03 and 0.16 for the two offshore grounds in 1982/3, 0.07 - 0.35 for offshore grounds in 1987/8).

Fishing mortality rates for 1988/9 ( $F_2$ ) are similar to those in 1987/8. The only large difference is the apparent increase in  $F$  on the H/I sector fishing ground. The estimate is based on relatively low tag returns and effort statistics for only 2-3 boats.

Calculated values of  $M_1$  for 1987/8 are highly variable, but generally lower than those for 1982/3, with the exception of the H/I sector and Peel Head grounds ( $M_1 = 1.27$  and  $0.63$  respectively). Values of  $M_1$  for other grounds range from 0.16-0.40. Estimates of  $M$  ( $M'$ ) from dead shell returns ( $R_{DM}$  from Table 4.3c) appear unrealistically low (0.013 - 0.040, excluding the estimate for the H/I-sector ground) and suggest that the capture and reporting efficiency of dead shells may be considerably lower than live ones, resulting in the underestimation of tagging-induced mortality rate. This implies that exploitation rates and fishing mortality rates will tend to be underestimated and natural and indirect fishing mortalities will tend to be overestimated.

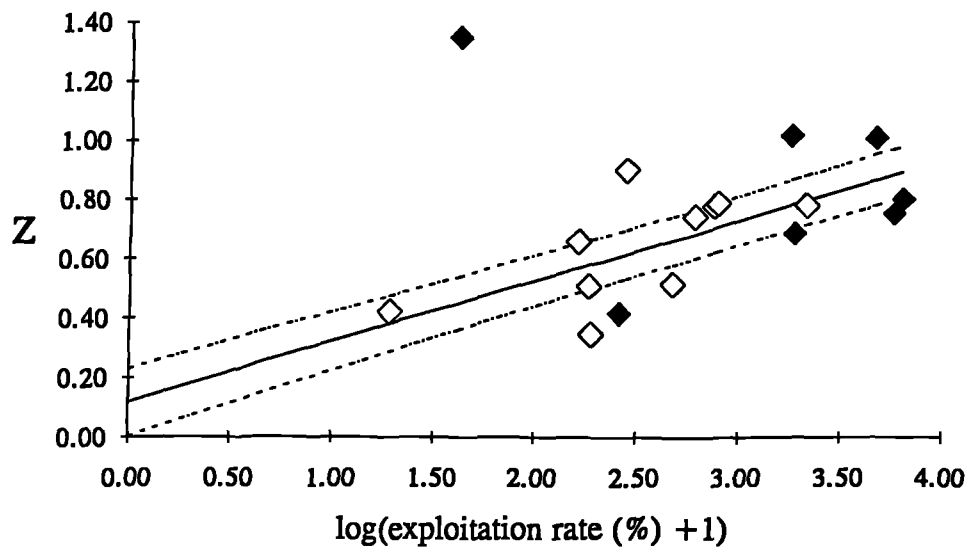
Area	T1	T1'	T2	T2'	R11	R12	R22	S1	s. d. (S1)	Z1
BH	535	490	518	458	187	40	102	0.364	0.063	1.011
PH	600	541	487	428	134	55	120	0.361	0.054	1.020
TG	797	524	582	374	219	44	66	0.470	0.085	0.755
SED	999	759	1002	753	77	47	70	0.658	0.118	0.419
H/I	927	715	864	594	29	10	31	0.260	0.092	1.347
PSM	858	703	876	649	178	99	181	0.503	0.056	0.687
CH	480	417	555	518	183	82	227	0.447	0.049	0.805
Total	5196	4149	4884	3774	1007	377	797	0.430	0.025	0.844

Table 4.6. Summary table of the results of the 1987/8 tagging experiment. Included in the table are tag releases, uncorrected (T1, T2), and tag releases corrected for tag loss (9.8%), area-specific tagging mortalities and pre-season recaptures (T1', T2'). Also shown are recaptures (R11, R12, R22) and calculated survival (S1) and mortality rates (Z1) for the year between the two releases.



Area	Z1	u1	u2	f1 (m-hrs)	f2 (m-hrs)	F1	F2	M1	F1i ( $M_0=0.12$ )
BR	0.78	0.27	0.55	4849.6	6346.9	0.39	0.51	0.39	0.27
PL	0.79	0.17	0.20	2220.5	4851.0	0.25	0.54	0.54	0.42
RB	0.35	0.09	0.21	3196.2	1793.1	0.10	0.06	0.24	0.12
ML	0.51	0.09	0.22	1041.9	1006.2	0.11	0.11	0.40	0.28
ED	0.66	0.08	0.27	1714.4	1850.4	0.11	0.12	0.55	0.43
SED	0.42	0.03	0.05	2033.2	4409.1	0.03	0.07	0.39	0.27
PSM	0.91	0.11	0.11	473.2	486.0	0.16	0.16	0.75	0.63
SWC	0.52	0.14	0.36	3253.8	3589.3	0.17	0.19	0.35	0.23
WC	0.75	0.15	0.32	1557.4	3159.3	0.22	0.44	0.53	0.41
OB	0.78	0.17	0.28	86.4	1637.6	0.24	4.55	0.54	0.42
Total	0.47	0.13	0.22	20426.6	29128.9	0.16	0.22	0.31	0.19

Table 4.7. Summary of exploitation rates (u1, u2) and mortality rates of North Irish Sea scallops, calculated from a two-release mark-recapture experiment carried out in 1982/3. Estimates relate to the 1982/3 and 1983/4 fishing seasons, and have been corrected for tag-loss (10%), non-reporting (5%) and differential mortality at tagging. Estimates of indirect fishing mortality (F1i) are calculated assuming  $M=0.12$  in an unexploited population (see Fig. 4.3).



**Fig. 4.2.** Relationship between log-transformed % exploitation rates ( $u$ ), calculated from tag returns during the 1982/3 and 1987/8 fishing seasons, and total mortality rates ( $Z$ ) calculated from Ricker-two release tagging experiments.

The regression equation is:  $Z = 0.118 + \log_e(0.205(u+1))$ ,  $r^2 = 0.456$ . Confidence bands (95%) are also shown. Open plot symbols are estimates from the 1982/3 season, closed symbols from the 1987/8 season; the outlying point was excluded when fitting the equation. The intercept, an estimate of  $Z$  when  $u = 0$  and therefore  $F = 0$ , provides an estimate of  $M$ .

Area	Z1	u1	u2	f1	f2	F1	F2	M1	M1'	F1i
BR	1.01	0.38	0.22	7414	7843	0.61	0.64	0.40	0.022	0.28
PL	1.02	0.25	0.28	3257	4541	0.40	0.55	0.63		0.51
TG	0.76	0.42	0.18	1643	1461	0.60	0.53	0.16	0.023	0.04
SED	0.42	0.10	0.09	2443	968	0.12	0.05	0.29	0.013	0.17
H/I	1.35	0.04	0.04	427	2377	0.07	0.41	1.27	0.189	1.15
PSM	0.69	0.25	0.28	4624	5262	0.35	0.40	0.34	0.040	0.22
CH	0.80	0.44	0.44	11673	10608	0.64	0.58	0.17		0.05
Total	0.844	0.243	0.209	31481	33060	0.359	0.377	0.485	0.022	0.28

Table 4.8. Summary of exploitation rates and mortality rates of North Irish Sea scallops, calculated from a Ricker two-release mark-recapture experiment carried out in 1987/8. Estimates relate to the 1987/8 and 1988/9 fishing seasons and have been corrected for tag-loss (9.8%), differential mortality at tagging and recaptures during the closed season. Indirect fishing mortality rate has been calculated assuming M for unexploited populations = 0.12. Natural mortalities calculated from dead-shell returns (M1') are also shown.

Taking  $M_0=0.12$  (from Fig. 4.2),  $F_{ii}$  values for 1987/8 are generally low (0.04-0.28) with the exception of the Peel and H/I grounds (0.51 and 1.15). These  $F_{ii}$  values will also be overestimates if  $F$  has been underestimated.

Fig. 4.3. shows the spatial and annual variability in exploitation rate of scallops on the major North Irish Sea fishing grounds in the four years following tag releases. Exploitation rates on most fishing grounds doubled between 1982/3 and 1983/4. The high levels of exploitation on inshore-west fishing grounds have been maintained in 1987/8 and 1988/9, while exploitation rates on the offshore grounds to the south have increased further. Exploitation rates within the 3 mile limit are generally  $>20\%$  and as high as 55%. The major grounds to the south and east within the 3-12 mile band have exploitation rates of between 3- 28%. The ground farthest offshore (H/I sector), outside the 12 mile limit, is not heavily exploited for scallops (4%) although it is heavily fished during the summer queen-fishing season.

Breakdown by age of tag returns and calculated survival, exploitation and mortality rates show that the age-distribution of recaptures is similar to the release age-distribution, indicating little age-class selection in post-recruit scallops (Table 4.9). Resultant age-specific survival and mortality rates are, however, highly variable. Many negative values are computed. The age-specific total mortality rates and exploitation rates obtained from tagging experiments are further discussed and compared, in Section 4.3.3, with estimates derived using age-composition methods.

Differences in survival rate ( $S_1$ ) and exploitation rates ( $u_1, u_2$ ) between areas were tested statistically with  $\chi^2$  tests. Spatial differences in  $S_1$  for 1982/3 were significant (variance-weighted  $\chi^2$  test,  $0.005 > p > 0.001$ ,  $v = 9$ ), but differences in  $S_1$  for 1987/8 were not ( $0.10 > p > 0.05$ ,  $v = 6$ ). Ordinary  $\chi^2$  tests indicated highly significant ( $p < 0.001$ ) differences in exploitation rates in 1982/3, 1983/4, 1987/8 and 1988/9. The tests compared observed tag returns with returns expected if exploitation rates were equal on all grounds. Taken overall, the evidence from these tagging experiments indicate that significant differences in survival and mortality rates occur between fishing grounds.

#### 4.3.1f. Calculation of mortality rates from weighted log-linear regression models

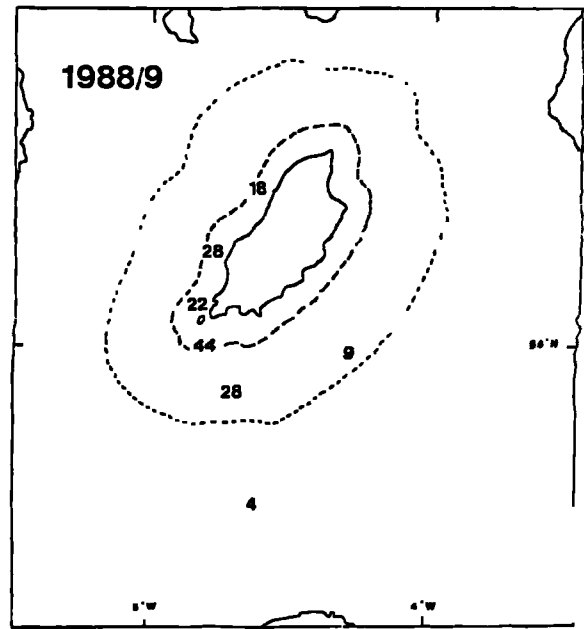
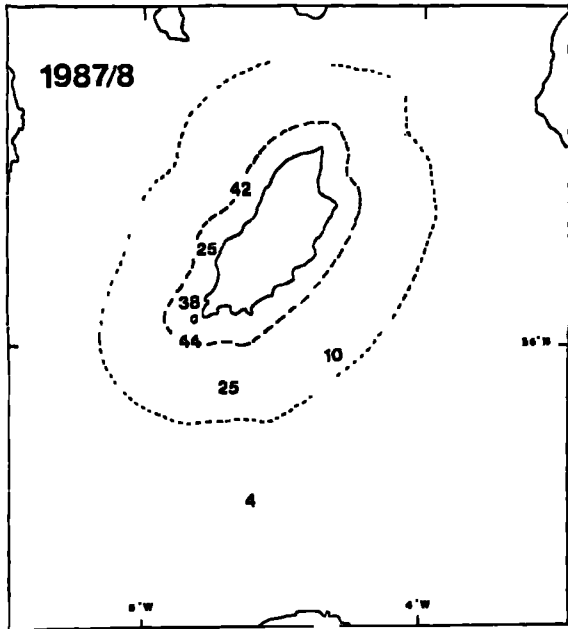
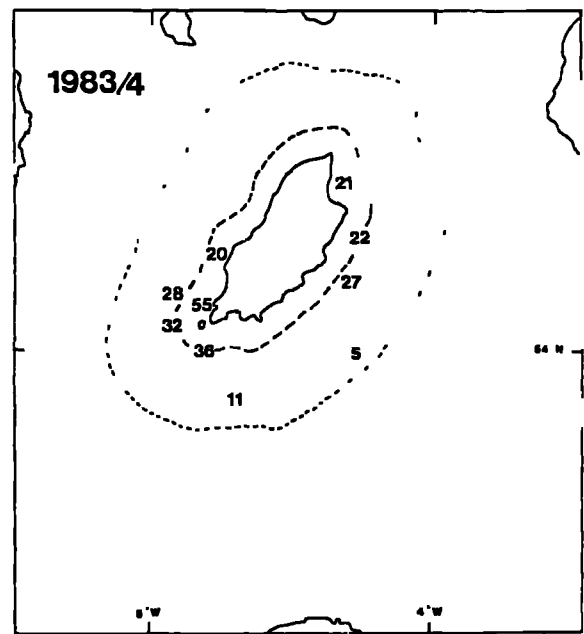
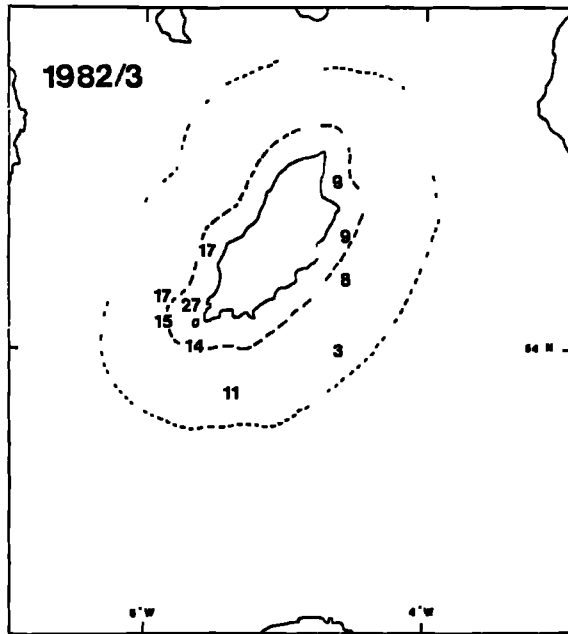
Tags released in 1982 and 1983 continued to be recaptured throughout the period of this study. Tag-recaptures, grouped by fishing season, are given in Table 4.10. Total mortality rate estimates for the period 1983-91, obtained by regression of log-transformed recaptures (live), were calculated separately for the 1982 and 1983 tag releases.

The fit of annual recaptures to the weighted log-linear model was generally good (Fig. 4.4 & Table 4.11), indicating that exploitation, and therefore mortality rates, were relatively uniform over the period 1983 - 1991. The first years' recaptures from the 1982-release were generally lower than recaptures the following season, due to the increase in fishing mortality rate that occurred between the 1982/3 and 1983/4 fishing season (see section 4.3.1e). As mortality rate was known to differ substantially between these two seasons, first year recaptures from the 1982 release were not used in fitting the log-linear regression models. Estimates of mortality rates from both the 1982 and 1983 release therefore apply to the same time period, and are thus directly comparable.

High recapture rates on the inshore-west fishing grounds lead to steep decline in numbers of tags returned (Fig. 4.4) and no live recaptures were made in the 1990/91 season from these grounds. Recaptures from eastern and offshore-south fishing grounds are lower and more variable from year to year, indicating substantial variability in fishing activity on these grounds. A small number of live tags continued to be returned from some of these grounds in the 1991/2 fishing season. All regression models provide a significant fit to the data ( $p < 0.05$ ) but the use of significance levels is not strictly valid as one of the basic assumptions of regression, independence of the data points, is not strictly met (see Discussion).

Total tag returns from the North Irish Sea for the period 1983 - 1991 show a very good fit to the log-linear regression model (Fig 4.5), indicating that mortality rate of scallops in the area as a whole has been fairly uniform over the last 8 years.

Estimates of total mortality rate from the slopes of the log-linear regression (Table 4.11) are similar to the two-release estimates for 1987/8 (Table 4.8) and some of the estimates from 1982/3 (Table 4.7). Estimates of  $Z$  for the offshore Port St. Mary ground (0.32 & 0.39) are considerably lower than the Ricker two-release estimates from the 1982/3 ( $Z = 0.91$ ) and 1987/8 ( $Z=0.69$ ) experiments.



**Fig. 4.3.** Exploitation rates (% per fishing season) on major scallop fishing grounds in the North Irish Sea. Exploitation rates were calculated from recaptures of tagged scallops released in 1982, 1983, 1987 and 1988. The 3 and 12 mile limits are shown on the maps.

**Table 4.9. Age-specific survival, exploitation and mortality rates of scallops from 7 fishing grounds in the North Irish Sea, 1987/8 fishing season. Values are calculated from a Ricker two-release tagging experiment. Release numbers have been corrected for tag-loss, tagging-induced mortality (both age-independent) and pre-season recaptures (age-specific).**

BRADDA HEAD

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	20	18	2	2	7	0	0				0.390		
4	129	118	272	241	47	0	50				0.399		
5	237	217	82	72	85	9	18	0.175	0.065	1.740	0.391	0.826	0.914
6	68	63	109	96	22	15	22	0.928	0.334	0.075	0.350	0.364	-0.289
7	60	56	34	30	21	8	7	0.382	0.166	0.962	0.375	0.584	0.377
8	12	11	17	15	1	5	5	0.843	0.483	0.170	0.090	0.097	0.073
9	4	4	1	1	2	3	0	0.829	0.233	0.188	0.552	0.606	-0.418
10	1	1	0	0	0	0	0				0.000		
>10	4	3	1	1	2	0	0				0.731		
Total	535	490	518	458	187	40	102	0.364	0.063	1.011	0.382	0.607	0.405



PEEL HEAD

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	10	9	0	0	3	0	0				0.333		
4	67	60	147	129	15	0	39				0.248		
5	191	172	74	65	45	8	20	0.180	0.068	1.714	0.261	0.546	1.168
6	117	106	118	104	24	13	26	0.428	0.137	0.848	0.227	0.337	0.511
7	119	107	70	62	30	17	17	0.584	0.192	0.538	0.279	0.361	0.176
8	50	45	45	40	11	10	10	0.835	0.387	0.180	0.244	0.266	-0.087
9	12	11	16	14	1	2	3	0.603	0.445	0.505	0.092	0.118	0.388
10	13	12	10	9	3	2	2	0.257	0.181	1.359	0.256	0.468	0.891
11	10	9	4	4	1	0	2				0.111		
12	8	7	1	1	1	1	0	0.191	0.191	1.655	0.139	0.283	1.371
13	2	2	2	2	0	2	1	1.109		-0.103	0.000	0.000	-0.103
14	0	0	0	0	0	0	0						
15	1	1	0	0	0	0	0						
Total	600	541	487	428	134	55	120	0.361	0.054	1.020	0.248	0.395	0.625

THE TARGETS

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	212	139	30	19	62	0	2				0.445		
4	149	98	286	183	45	11	30	0.438	0.166	0.825	0.459	0.675	0.150
5	316	208	59	38	81	8	9	0.259	0.106	1.350	0.390	0.711	0.640
6	63	41	155	100	14	21	14	1.828	0.646	-0.603	0.338	0.246	-0.849
7	21	13	32	21	10	4	5	0.623	0.324	0.473	0.770	0.967	-0.494
8	16	11	11	7	2	0	3				0.190		
9	8	5	4	3	3	0	3				0.570		
10	2	1	3	2	1	0	0				0.760		
>10	5	4	2	1	0	0	0				0.000		
?	5	5	0	0	1	0	0						
Total	797	524	582	374	219	44	66	0.470	0.085	0.755	0.418	0.595	0.160

SE DOUGLAS

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	0	0	0	0	0	0	0						
4	24	18	30	23	0	0	2				0.000		
5	186	142	113	85	15	0	6				0.106		
6	262	198	197	148	13	15	18	0.951	0.312	0.050	0.066	0.067	-0.017
7	155	118	299	225	17	9	17	0.762	0.315	0.272	0.144	0.164	0.108
8	138	105	146	109	11	7	10	0.533	0.240	0.630	0.105	0.141	0.489
9	62	47	105	79	2	4	9	2.952	2.298	-1.083	0.042	0.023	-1.106
10	56	43	45	34	6	4	0	0.412	0.244	0.888	0.141	0.212	0.676
11	36	26	22	17	4	1	3	0.322	0.322	1.132	0.153	0.256	0.876
12	32	24	21	16	3	2	1	0.257	0.199	1.358	0.123	0.225	1.133
13	16	12	7	5	4	3	1	1.357	1.026	-0.306	0.328	0.281	-0.586
14	11	8	6	5	0	1	0	0.254	0.254	1.369	0.000	0.000	1.369
15	19	14	10	8	2	1	3	0.069	0.069	2.672	0.138	0.397	2.276
?	2	0	1	0	0	0	0						
Total	999	759	1002	753	77	47	70	0.658	0.118	0.419	0.101	0.124	0.295

H/I SECTOR

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	1	1	0	0	0	0	0				0.000		
4	9	7	6	4	0	0	0				0.000		
5	94	72	24	17	2	0	1				0.028		
6	249	192	44	30	9	1	1	0.079	0.079	2.537	0.047	0.129	2.408
7	211	161	220	151	11	3	9	0.303	0.191	1.194	0.068	0.117	1.077
8	71	56	188	129	1	1	7	0.616	0.616	0.484	0.018	0.023	0.462
9	41	33	98	68	1	2	1	0.609	0.472	0.496	0.031	0.039	0.457
10	68	52	42	29	2	1	2	0.364	0.364	1.010	0.038	0.061	0.949
11	56	59	54	37	1	0	1				0.017		
12	48	38	55	38	0	1	3	0.999	0.999	0.001	0.000	0.000	0.001
13	36	26	54	37	2	1	0	0.357	0.357	1.031	0.076	0.123	0.908
14	20	16	39	27	0	0	2				0.000		
15	21	16	39	27	0	0	1						
?	2	1	1	1	0	0	0						
Total	927	715	864	594	29	10	31	0.260	0.092	1.347	0.041	0.074	1.273

PORT ST. MARY

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	2	2	0	0	1	0	0	0.000	0.000		0.602		
4	128	105	76	58	21	0	7	0.000	0.000		0.200		
5	298	246	301	232	59	14	56	0.186	0.053	1.680	0.239	0.494	1.186
6	182	151	199	153	47	37	46	0.588	0.107	0.531	0.311	0.401	0.130
7	93	77	136	105	19	14	43	0.666	0.223	0.406	0.246	0.299	0.107
8	39	32	56	43	9	12	11	1.153	0.423	-0.142	0.278	0.259	-0.401
9	39	32	27	21	8	7	6	1.034	0.480	-0.034	0.247	0.243	-0.277
10	32	27	36	28	4	6	5	0.703	0.320	0.353	0.151	0.179	0.174
11	22	18	27	21	4	1	6	0.350	0.350	1.051	0.219	0.354	0.697
12	8	7	7	5	1	2	0	0.846	0.620	0.168	0.151	0.164	0.004
13	7	6	6	5	3	0	1				0.516		
14	3	2	2	2	0	4	0	1.606		-0.474	0.000	0.000	-0.474
15	2	2	0	0	0	2	0	1.205		-0.186	0.000	0.000	-0.186
?	3	0	3	0	1	0	0						
Total	858	710	876	674	178	99	181	0.517	0.058	0.659	0.251	0.342	0.317

THE CHICKENS

Age	T1	T1'	T2	T2'	R11	R12	R22	S1	s.d.(S1)	Z1	U1	F1	M1
3	4	3	0	0	1	0	0				0.287		
4	87	76	173	161	42	0	63				0.555		
5	72	63	230	216	26	10	97	0.342	0.109	1.072	0.415	0.677	0.395
6	138	120	64	59	39	15	27	0.231	0.064	1.465	0.325	0.619	0.846
7	52	45	42	40	22	26	21	1.070	0.258	-0.068	0.486	0.470	-0.538
8	47	41	19	18	20	10	9	0.550	0.202	0.598	0.489	0.650	-0.052
9	30	26	18	17	10	7	7	0.651	0.346	0.430	0.383	0.472	-0.042
10	24	21	4	4	13	7	1	0.435	0.169	0.833	0.623	0.918	-0.085
11	12	10	3	3	4	2	2	0.192	0.128	1.652	0.383	0.783	0.869
12	11	10	0	0	5	1	0	0.205	0.205	1.584	0.523	1.042	0.542
13	1	1	1	1	0	2	0	2.300	4.789	-0.833	0.000	0.000	-0.833
14	2	2	0	0	1	1	0	1.128	1.128	-0.121	0.575	0.541	-0.662
15	0	0	1	1	0	1	0						
Total	480	417	555	518	183	82	227	0.447	0.049	0.805	0.438	0.638	0.167

Table 4.10. Recaptures of scallops tagged and released in July 1982 and June 1983. Recaptures are grouped by fishing season (November 1st - May 31st). Both live (l) and dead (d) recaptures are recorded.

a) Tagged and released in July 1982.

Season recaptured	BR		PL		RB		ML		ED		SED		PSMM		PSMI		SWC		WC		OB		Total	
	l	d	l	d	l	d	l	d	l	d	l	d	l	d	l	d	l	d	l	d	l	d	l	d
82/83	121	3	83	3	16	0	31	1	30	0	17	3	27	15	5	0	84	1	58	3	76	3	548	34
83/84	135	5	54	2	33	1	53	2	54	2	25	4	13	10	4	0	152	10	58	3	58	3	639	42
84/85	30	0	30	1	15	1	29	3	14	2	31	5	17	11	18	0	74	11	43	2	30	2	331	36
85/86	8	2	11	1	4	0	12	1	6	0	9	4	10	6	9	0	39	6	8	6	11	1	123	23
86/87	5	1	7	0	1	0	7	1	13	0	15	7	5	5	0	0	21	7	6	4	3	2	83	27
87/88	2	1	1	0	0	1	2	0	0	0	7	1	4	5	5	0	10	2	2	1	2	2	35	13
88/89	0	0	0	1	2	0	4	1	0	1	2	1	1	3	2	1	2	0	2	0	0	1	15	9
89/90	0	1	0	0	0	0	6	0	1	0	1	1	0	0	0	0	0	0	0	0	0	2	8	4
90/91	0	1	0	0	1	0	2	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	4	3
Total to	301	14	186	8	72	3	146	9	118	5	108	26	77	55	43	1	382	38	177	19	180	17	1786	191

b) Tagged and released in June 1983.

Season recaptured	BR		PL		RB		TGO		ML		ED		SED		HSWC		PSMM		SWC		WC		OB		Total	
	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d
83/84	241	5	99	0	40	0	4	0	54	2	93	1	33	1	1	0	35	1	187	3	119	3	133	5	1039	21
84/85	64	3	66	2	8	1	1	0	30	1	46	0	49	4	5	0	47	6	113	13	81	3	64	1	562	34
85/86	21	6	25	2	5	1	0	0	8	2	12	1	12	1	2	1	28	3	66	5	25	2	30	3	225	25
86/87	4	2	9	1	4	0	2	0	14	0	12	1	13	1	13	2	9	1	22	5	11	1	9	1	126	17
87/88	3	3	4	0	1	0	1	1	4	0	2	0	9	0	1	0	11	7	16	6	4	2	2	0	60	19
88/89	2	0	1	1	1	0	9	1	2	1	1	0	8	3	0	0	14	5	4	9	3	0	3	1	48	21
89/90	0	1	1	0	3	0	0	0	3	0	0	1	3	6	0	0	3	4	1	3	1	0	2	0	17	15
90/91	0	0	0	0	1	0	6	0	0	1	0	0	0	0	2	1	3	1	0	0	0	0	0	0	12	3
Total to 31-May-91	335	20	205	6	63	2	23	2	115	7	166	4	127	16	24	4	150	28	409	44	244	11	243	11	2089	155



**Fig. 4.4.** Log-linear regression models (weighted by number of recaptures) fitted to returns of tagged scallops, 1982 - 1991. The scallops were released in 1982 and 1983. Recaptures have been grouped by fishing season (e.g. 83 = 1982/3 fishing season, midpoint February 14th 1983). Fitted regression lines are extrapolated back to the time of release in both cases. First-season recaptures from the 1982 release were excluded when fitting the regression model. Regression parameters and statistics are given in Table 4.11.

-----◇----- 1982 release  
———◆——— 1983 release

Fig.4.4.

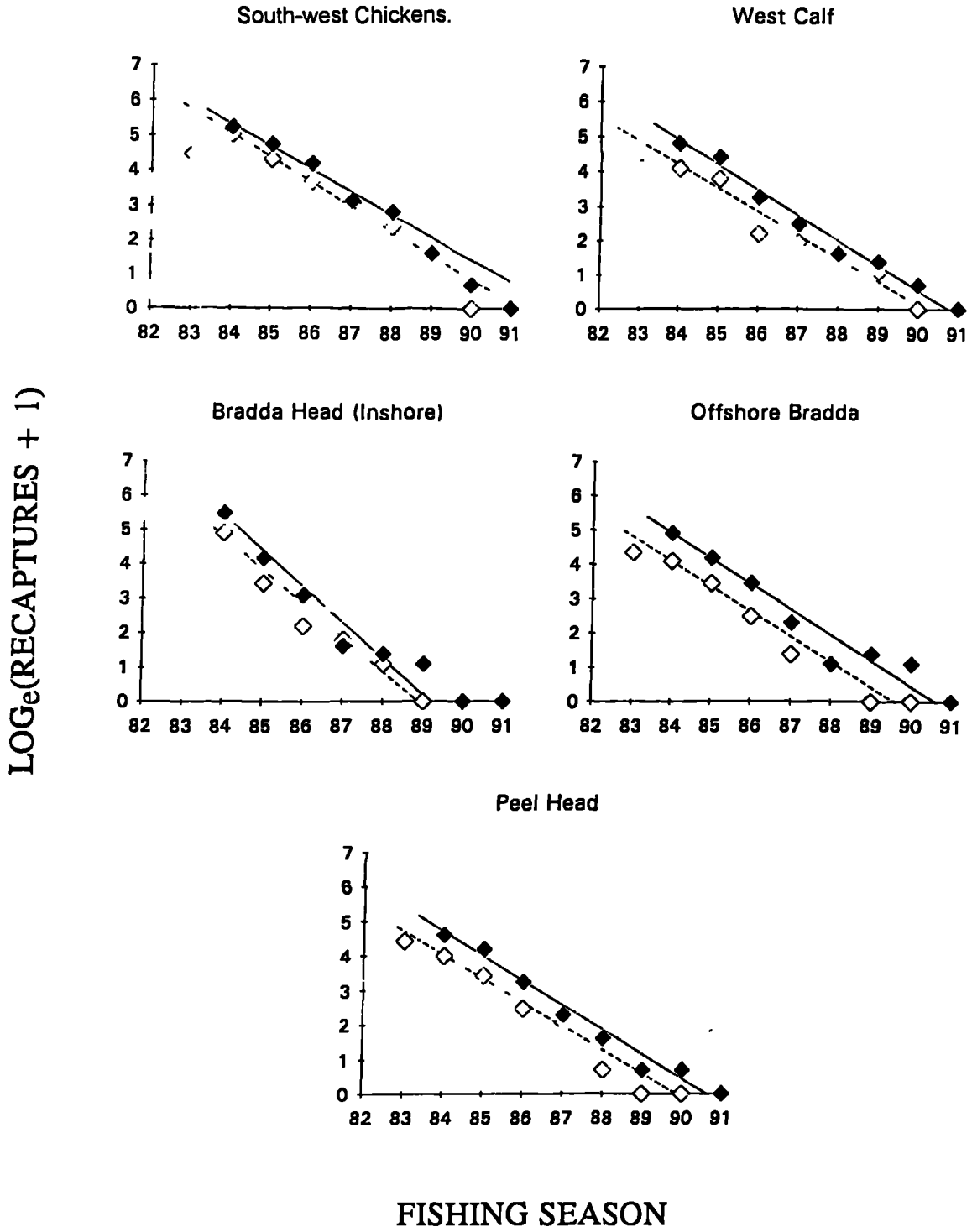
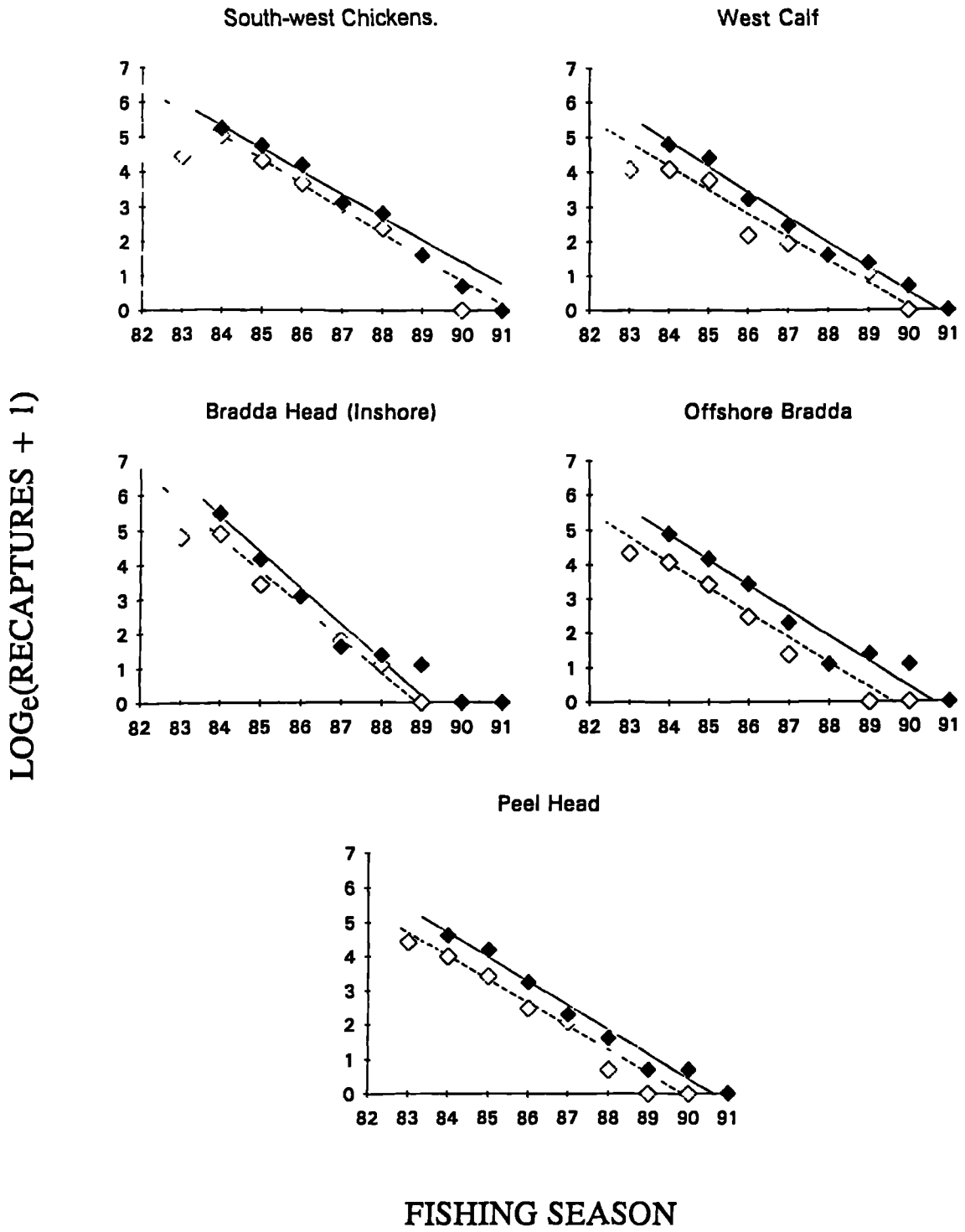
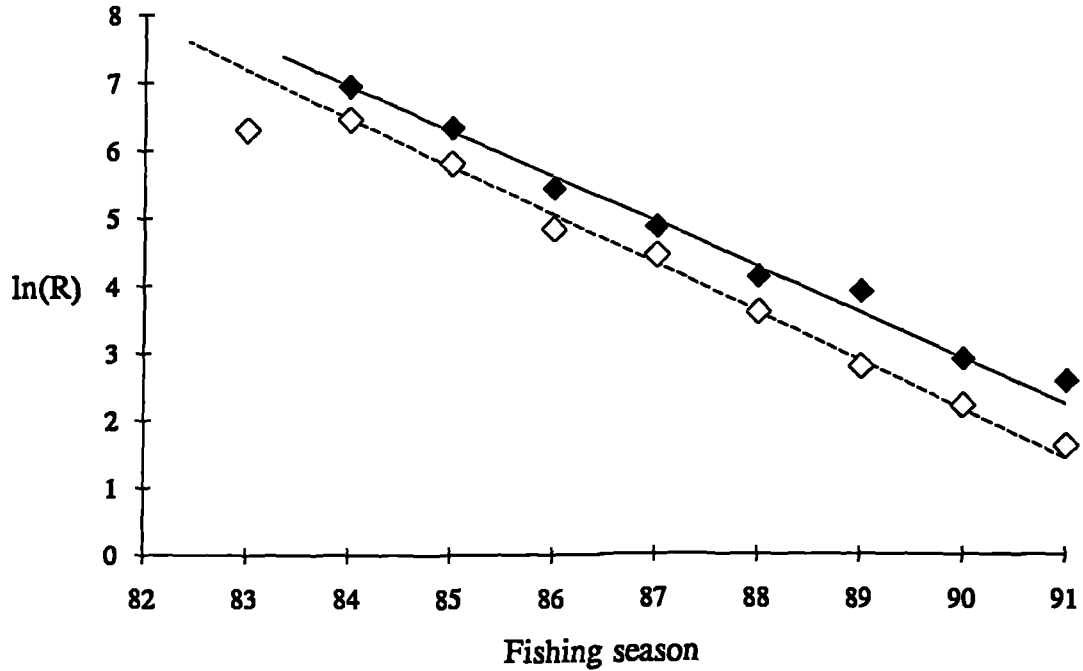


Fig.4.4.



### North Irish Sea



**Fig. 4.5.** Weighted least squares regression equations fitted to log-transformed tag recaptures. Tags were released in July 1982 and June 1983. Recaptures are grouped by fishing season (e.g. 83 = 1982/3 fishing season, with midpoint February 14th 1983). Open plot symbols are recaptures from the 1982 release, with the hatched line indicating the fitted regression. The first years returns were excluded when fitting the regression. Closed plot symbols are recaptures from the 1983 release, with the solid line indicating the fitted regression. Lines are extrapolated back to the time of release. Regression statistics are given in Table 4.11.

Table 4.11. Mortality rates of scallops, calculated from weighted log-linear regression of tag returns from successive fishing seasons, for the period 1983-1991.

a) 1982 release.

Area	Regression parameters									
	r-sq.	.-Zt	Ro	tt	Rtt	T1	T1'	Z	F	M
BR	0.934	-0.986	6.780	0.42	6.366	665	599	0.99	0.57	0.42
PL	0.974	-0.687	5.400	0.67	4.940	705	627	0.69	0.15	0.53
RB	0.853	-0.535	4.451	0.42	4.228	241	217	0.54	0.24	0.30
ML	0.882	-0.436	4.729	0.42	4.547	458	412	0.44	0.18	0.25
ED	0.825	-0.598	5.066	0.42	4.817	501	451	0.60	0.20	0.40
SED	0.785	-0.379	4.303	0.42	4.145	1000	765	0.38	0.07	0.31
PSM	0.843	-0.389	3.794	0.42	3.632	425	273	0.39	0.11	0.28
SWC	0.987	-0.697	6.434	0.42	6.144	726	646	0.70	0.50	0.20
WC	0.922	-0.675	5.523	0.42	5.242	449	397	0.68	0.33	0.34
OB	0.973	-0.731	5.538	0.42	5.233	553	491	0.73	0.26	0.47
Total	0.993	-0.720	7.907	0.42	7.605	5723	4878	0.72	0.28	0.44

b) 1983 release.

Area	Regression parameters									
	r-sq.	.-Zt	Ro	tt	Rtt	T2	T2'	Z	F	M
BR	0.963	-1.045	6.468	0.33	6.123	650	583	1.05	0.44	0.60
PL	0.967	-0.709	5.408	0.33	5.172	700	630	0.71	0.19	0.52
RB	0.801	-0.491	3.953	0.33	3.789	251	226	0.49	0.15	0.34
ML	0.918	-0.515	4.470	0.33	4.298	450	398	0.52	0.14	0.37
ED	0.967	-0.750	5.288	0.33	5.038	501	451	0.75	0.23	0.52
SED	0.759	-0.387	4.275	0.33	4.146	889	777	0.39	0.07	0.32
PSM	0.768	-0.315	4.205	0.33	4.100	426	351	0.32	0.15	0.17
SWC	0.970	-0.647	5.955	0.33	5.739	699	626	0.66	0.35	0.30
WC	0.960	-0.723	5.608	0.33	5.367	475	420	0.72	0.35	0.38
OB	0.978	-0.741	5.633	0.33	5.386	550	488	0.74	0.30	0.44
Total	0.990	-0.674	7.619	0.33	7.394	5591	4950	0.67	0.23	0.44

r-sq. = coefficient of determination

.-Zt = slope of regression, where  $t = 1$  year

Ro = Intercept at  $t = 0$

tt = time at which scallops were tagged (years)

Rtt = intercept at  $t - tt$ .

T1 = number marked

T1' = number marked, corrected for tag loss and tagging mortality.

c) Z from common slopes, computed after t-tests found no significant differences ( $p=0.05$ )

Area	Z
OB	0.74
PH	0.70
RB	0.52
SED	0.38

The lower values of Z calculated from log-linear regressions for the offshore grounds which suffered high post-tagging mortality in 1982 are consistent with low exploitation rate estimates and the age-composition of the grounds; both the Port St. Mary and SE. Douglas grounds have a wide range of age-classes and a high proportion of older scallops (Chapter 2, Fig. 2.1), consistent with lower mortality rates than for the inshore-west grounds where few scallops survive more than 2-3 years in the fishery.

The consistency between most of the values of Z obtained by the different methods increases confidence in the estimates, as well as providing further evidence of relatively uniform mortality rates over the period studied.

Slight differences in the slopes of regressions fitted to tag returns from 1982 and 1983 were observed (Fig. 4.4, Tables 4.11a & b). Paired-sample t-tests of the regression lines obtained from the 1982 and 1983 taggings in each area showed significant differences in slope ( $p < 0.05$ ) in 6 out of 10 comparisons. These differences may be manifestations of statistical problems with small sample sizes (fitting regression lines to few points) or may indicate differences in distribution, and therefore vulnerability to capture, between the two releases. Common values of Z are computed for those grounds where slopes did not differ significantly between the two years (reported in Table 4.11c).

The estimates of fishing mortality for the period 1983-91, from the two regression analyses (Table 4.11), generally show remarkably good agreement with the two-release estimates for 1983/4 (Table 4.7), with values of F of between 0.26 - 0.57 for the inshore west grounds (with the exception of Peel; 0.15 & 0.19) and  $< 0.25$  for the eastern and offshore grounds. M-values are also higher on the more heavily fished inshore grounds (0.40 - 0.60) and are likely to reflect higher indirect fishing mortality rates on these grounds.

Comparison of the estimates of regression-estimates of Z by analysis of covariance (ANCOVA) indicate significant differences in Z between areas ( $p < 0.05$ ). Tukey tests comparing each pair of areas in both years (Table 4.12) indicate that in most cases the differences are highly significant, but that adjacent areas often have similar mortality rates (e.g. Port St. Mary and SE. Douglas, West Calf and SW. Calf). Given the large number of comparisons and a relatively restricted range of possible values for Z, similarities between areas that are not adjacent are likely to occur coincidentally.

#### 4.3.1g. Spatial differences in exploitation rates within fishing grounds

Variability in survival, mortality and exploitation rate between fishing grounds in the North Irish Sea have been quantified above. Differences in capture-vulnerability of tagged scallops also occur within fishing grounds (Fig. 4.6 & Table 4.13). Records of the 1988 release-tracks and subsequent recaptures from those tracks indicate that significant spatial variation in exploitation rate occur within five of the seven fishing grounds over which tagged scallops were released. The only grounds which did not show significant within-ground differences in vulnerability to capture were the Peel Head and SE. Douglas grounds. Examination of  $\chi^2$  values indicate that rejection of the null hypothesis of no significant difference in exploitation rates is usually due to higher or lower values for 2 or 3 of the 10-21 marked tracks over which the scallops were released on each ground. These 2-3 tracks are often situated in proximity to one another, indicating that specific parts of a ground may be liable to differing exploitation rates than the rest. This appears to be the case for the Bradda Head and Chickens grounds.

The differences in vulnerability to capture within fishing grounds will not bias estimates of total mortality rate providing the distribution of both tags and fishing effort is the same in both years. Exploitation rate estimates and therefore fishing and natural mortality may, however, be affected.

#### 4.3.2. Mortality rates from age-compositions

Estimates of natural mortality rate ( $M$ ) from unfished populations have been calculated from catch-curves. A catch-curve was fitted to log-transformed numbers-at-age in samples taken by Tang (1941) on the Bradda Head ground during the winter of 1987/8 (Fig. 4.7). As scallops had not been exploited before that winter, the decrease in numbers-at-age is due to natural mortality only, assuming recruitment levels were constant or varied without trend during the 20 years prior to sampling. The calculated slope of 0.303 is therefore an estimate of natural mortality for the Bradda Head ground when it was unfished.

Age-specific estimates of  $M$  are calculated from the catch-curve in Gruffydd (1974a). The catch-curve is based on samples taken during a survey of previously unfished grounds to the south of the Isle of Man in 1966. All areas sampled were pooled to reduce the effects of small-scale recruitment variability. The area which

Table 4.12. Multiple comparison tests (Tukey-type) of differences in total mortality rates rates of scallops from different fishing grounds. Z values were calculated from the rate of decline of recaptures of tagged scallops in successive fishing seasons. The tags were released in 1982 and 1983 and recaptured during the period 1983-1991. ANCOVA indicated significant differences in regression coefficients between areas.

Ho= no significant difference in regression coefficients (=Z) between each pair of areas tested.

Ha= regression coefficients differ between areas.

Degrees of freedom for each test are > 120 in all cases, so the critical value of the q-distribution, p=0.05, k= 10, is approximately 4.500 (Zar, 1984, table B.5).

a) 1982 release.

	BR	PL	RB	ML	ED	SED	PSM	SWC	WC	OB
BR										
PL	***									
RB	***	***								
ML	***	***	*							
ED	***	**	NS	***						
SED	***	***	***	NS	***					
PSM	***	***	***	NS	***	NS				
SWC	***	NS	***	***	***	***	***			
WC	***	NS	***	***	NS	***	***	NS		
OB	***	*	***	***	***	***	***	*	NS	

b) 1983 release.

	BR	PL	RB	ML	ED	SED	PSM	SWC	WC	OB
BR										
PL	***									
RB	***	***								
ML	***	***	NS							
ED	***	NS	***	***						
SED	***	***	NS	***	***					
PSM	***	***	***	***	***	NS				
SWC	***	**	***	***	***	***	***			
WC	***	NS	***	***	NS	***	***	***		
OB	***	NS	***	***	NS	***	***	***	NS	

\* = significant difference (p < 0.05)

\*\* = significant difference (p < 0.01)

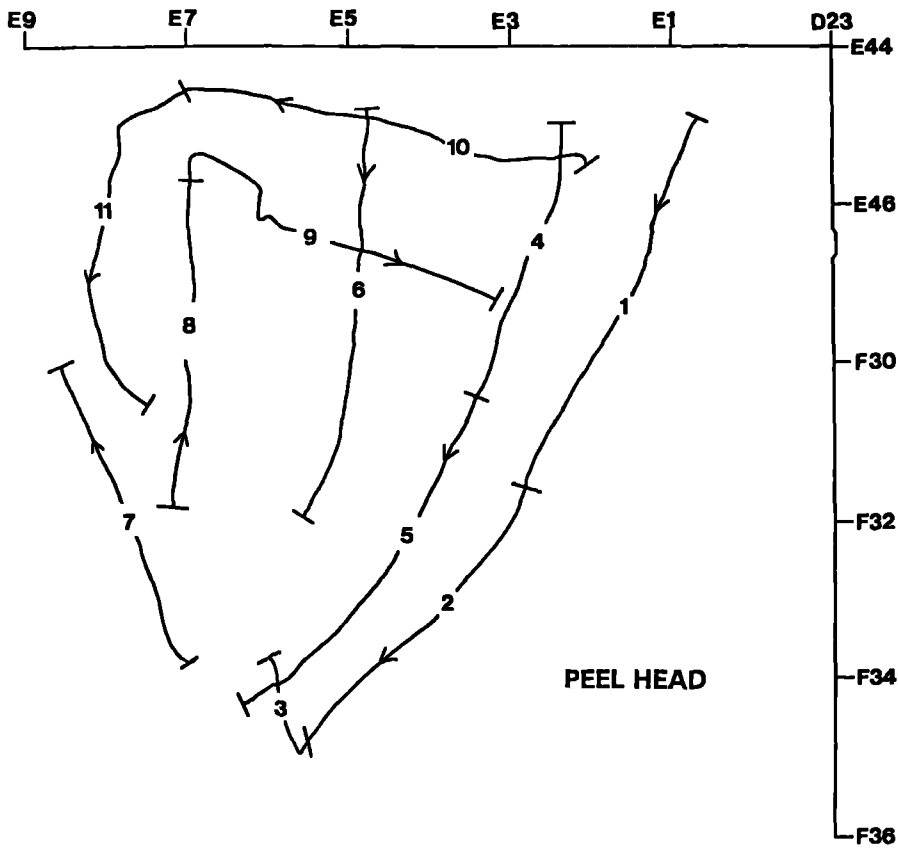
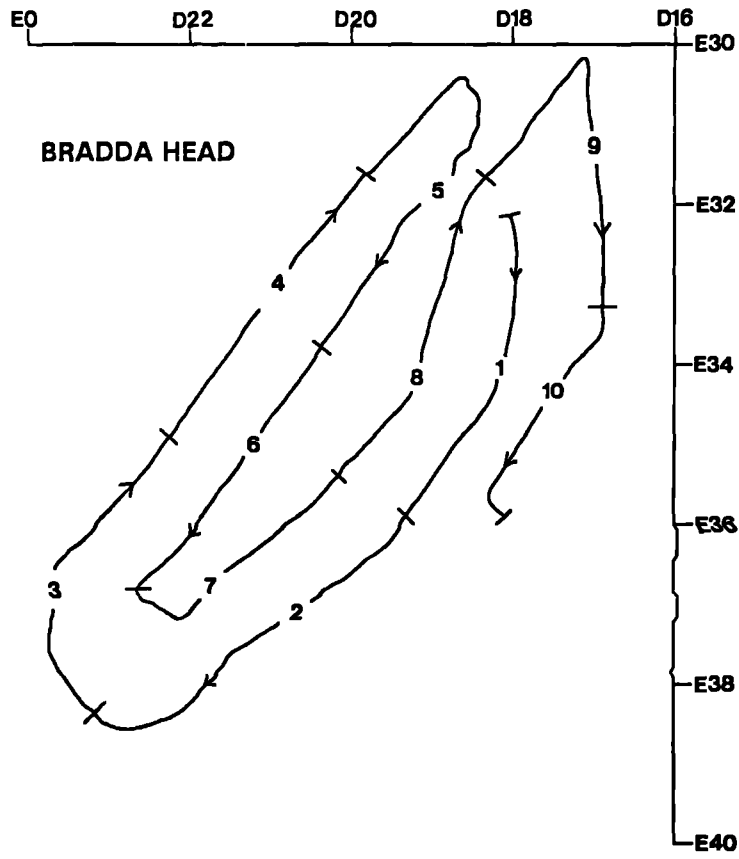
\*\*\* = significant difference (p < 0.001)

NS = no significant difference (p > 0.05)



**Fig. 4.6.** The distribution patterns of tagged scallops released over North Irish Sea fishing grounds in June 1988, recorded as the tracks of the R.V. "Cuma" during the release procedure. The tracks were recorded on a chart-plotter connected to the Decca radio-navigation system. Decca readings for Red (numbered 0-24) and Green (numbered 30-48) lanes are shown. The maps were drawn directly from the chart-recorder, but have been reduced by different scales. (Actual release areas and mean densities of release are given in Table 4.1.). Vessel tracks were marked after the release of every 50 scallops, and are numbered to identify the release positions of each successive batch of releases.

**Table 4.13.** Recaptures of 1988-tagged scallops during the 1988/9 fishing season. Numbers released ( $T_2$ ) between marks on the vessel tracks (Fig. 4.6) and recaptures from those track-segments ( $R_{22}$ ) are shown. The null hypothesis, that recapture frequencies (equivalent to exploitation rates) are equal between track-segments within each ground, is tested. Rejection of the null hypothesis implies differences in vulnerability to capture of scallops within the fishing ground.  $\chi^2$  statistics are computed for grounds with high-recapture rates; log-likelihood ratios (G-statistic) were computed for the S.E. Douglas and H/I sector grounds, where return rates were too low to run  $\chi^2$  tests without bias.



### BRADDA HEAD

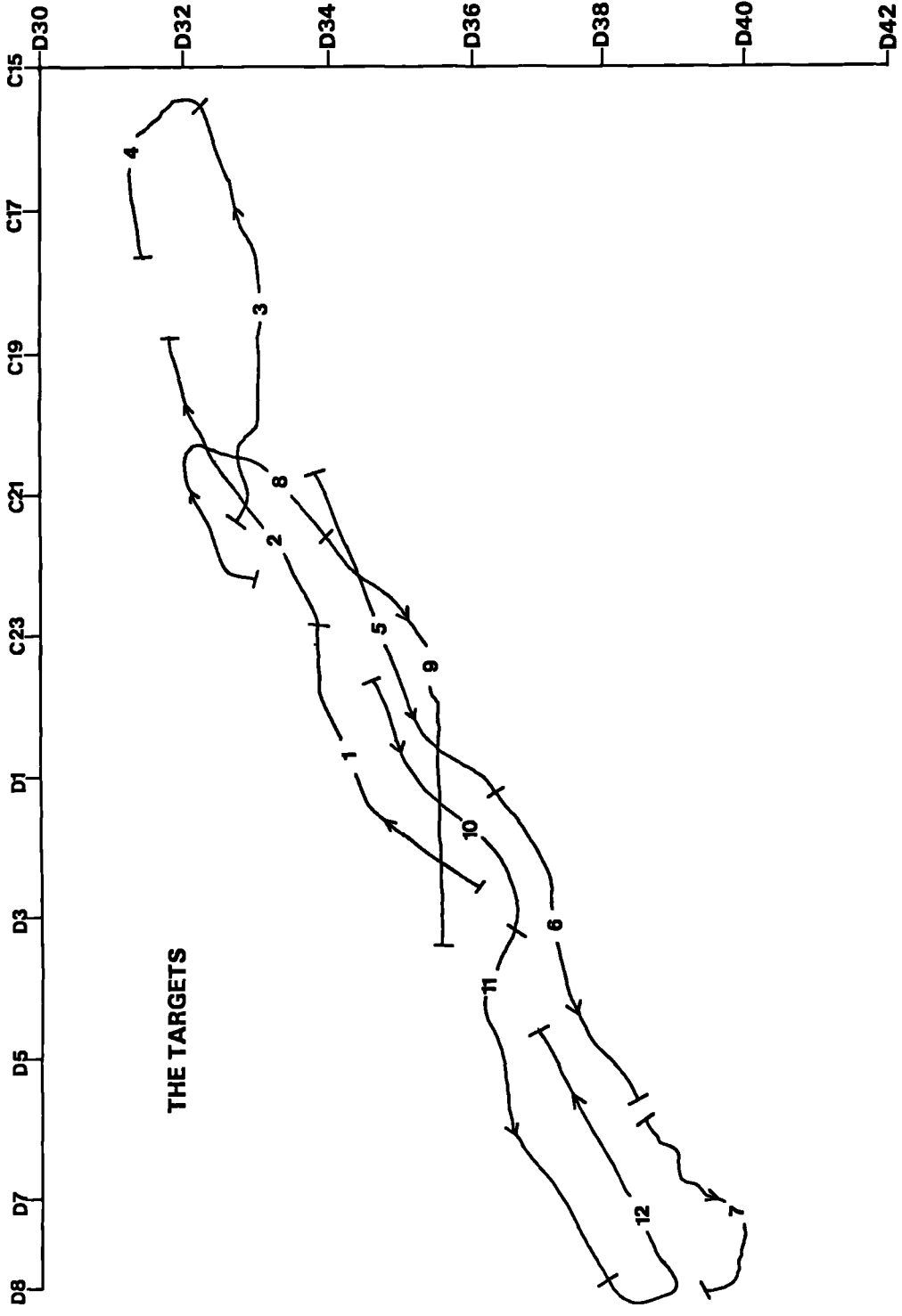
Track No.	T2	R22	Expected R22	Chi-squared
1	50	18	10.41	5.537
2	50	4	10.41	3.946
3	24	0	5.00	4.996
4	50	15	10.41	2.025
5	51	14	10.62	1.078
6	41	6	8.54	0.753
7	49	12	10.20	0.317
8	49	2	10.20	6.593
9	50	12	10.41	0.243
10	50	15	10.41	2.025
11	50	9	10.41	0.191
Sum:	514	107	107.00	27.704

critical value (p0.05, 10 d.o.f.)= 18.307  
therefore reject Ho:  $0.005 < p < 0.001$

### PEEL HEAD

Track No.	T2	R22	Expected R22	Chi-squared
1	50	15	13.12	0.269
2	50	17	13.12	1.148
3	50	12	13.12	0.096
4	50	14	13.12	0.059
5	50	17	13.12	1.148
6	50	7	13.12	2.855
7	50	19	13.12	2.635
8	50	14	13.12	0.059
9	50	10	13.12	0.742
10	34	2	8.92	5.370
Sum	484	127	127.00	14.380

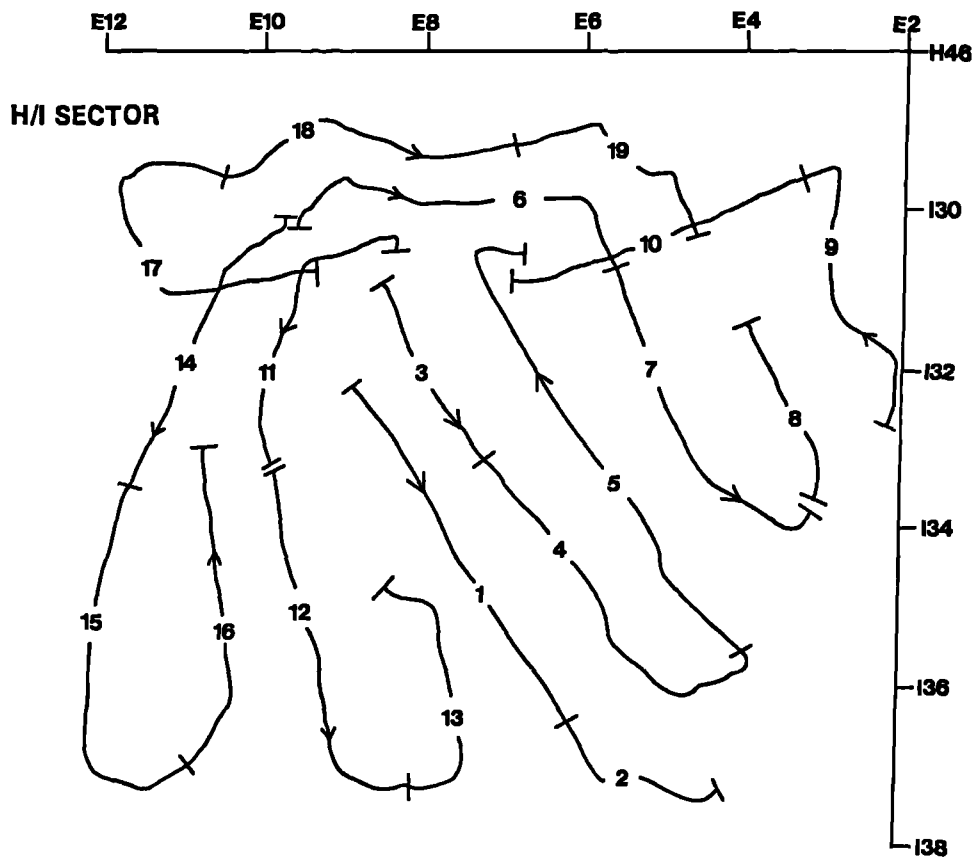
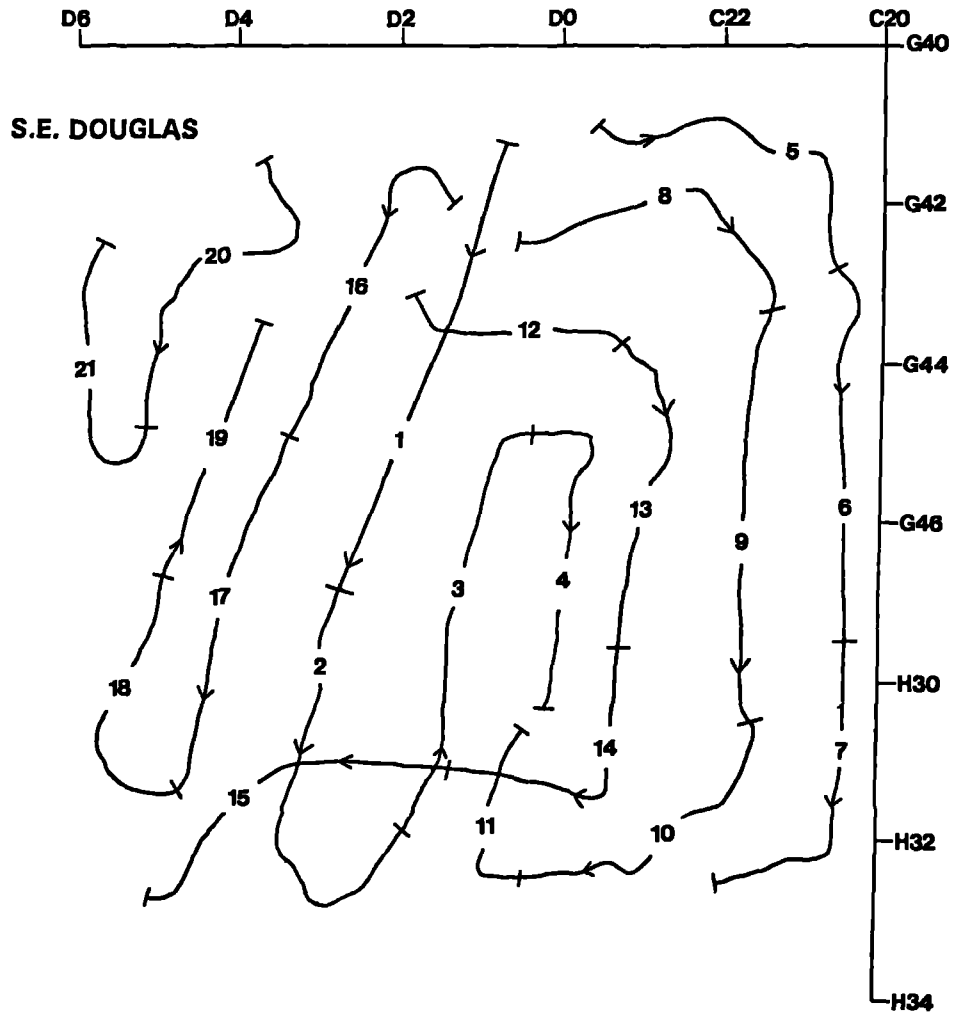
critical value (p0.05, 9 d.o.f.) = 16.919  
therefore accept Ho:  $0.25 < p < 0.10$



## THE TARGETS

Track No.	T2	R22	Expected R22	Chi-squared
1	50	10	8.54	0.251
2	50	9	8.54	0.025
3	50	17	8.54	8.391
4	27	4	4.61	0.081
5	48	7	8.20	0.174
6	50	2	8.54	5.005
7	34	2	5.80	2.494
8	50	7	8.54	0.277
9	59	18	10.07	6.238
10	50	9	8.54	0.025
11	50	6	8.54	0.754
12	56	7	9.56	0.686
<b>Sum:</b>	<b>574</b>	<b>98</b>	<b>98.00</b>	<b>24.400</b>

critical value (p0.05, 11 d.o.f.)=19.675  
therefore reject Ho:  $0.01 < p < 0.025$



**SOUTH-EAST DOUGLAS**

Track No.	T2	R22	Expected R22	R22*ln(R22)	R22*ln(ExpR22)
1	50	7	4.26	13.6214	10.1424
2	50	2	4.26	1.3863	2.8978
3	50	2	4.26	1.3863	2.8978
4	46	5	3.92	8.0472	6.8277
5	50	9	4.26	19.7750	13.0403
6	50	12	4.26	29.8189	17.3871
7	47	1	4.00	0.0000	1.3870
8	50	6	4.26	10.7506	8.6935
9	51	2	4.34	1.3863	2.9374
10	50	2	4.26	1.3863	2.8978
11	25	3	2.13	3.2958	2.2673
12	50	3	4.26	3.2958	4.3468
13	50	4	4.26	5.5452	5.7957
14	50	4	4.26	5.5452	5.7957
15	57	3	4.85	3.2958	4.7398
16	50	5	4.26	8.0472	7.2446
17	50	5	4.26	8.0472	7.2446
18	50	1	4.26	0.0000	1.4489
19	31	2	2.64	1.3863	1.9418
20	50	4	4.26	5.5452	5.7957
21	41	3	3.49	3.2958	3.7514
<b>Sum:</b>	<b>998</b>	<b>85</b>	<b>85</b>	<b>134.8577</b>	<b>119.4813</b>

G=30.75285

critical value (p0.05, 20 d.o.f.) = 31.410

therefore accept Ho: 0.05 < p < 0.10

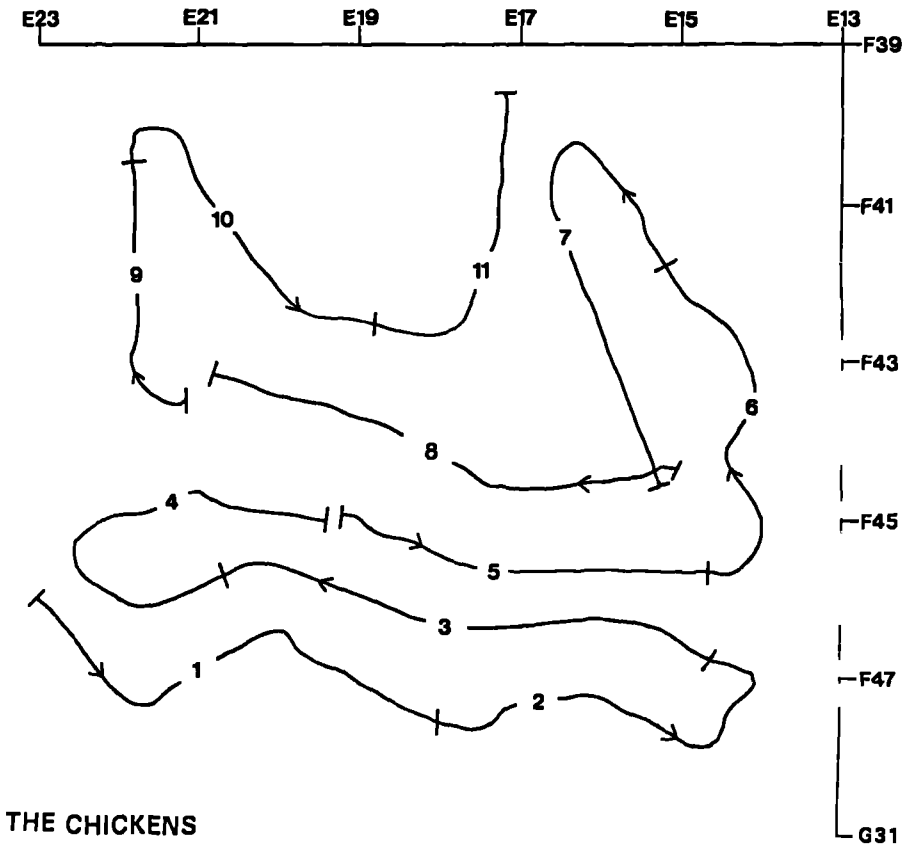
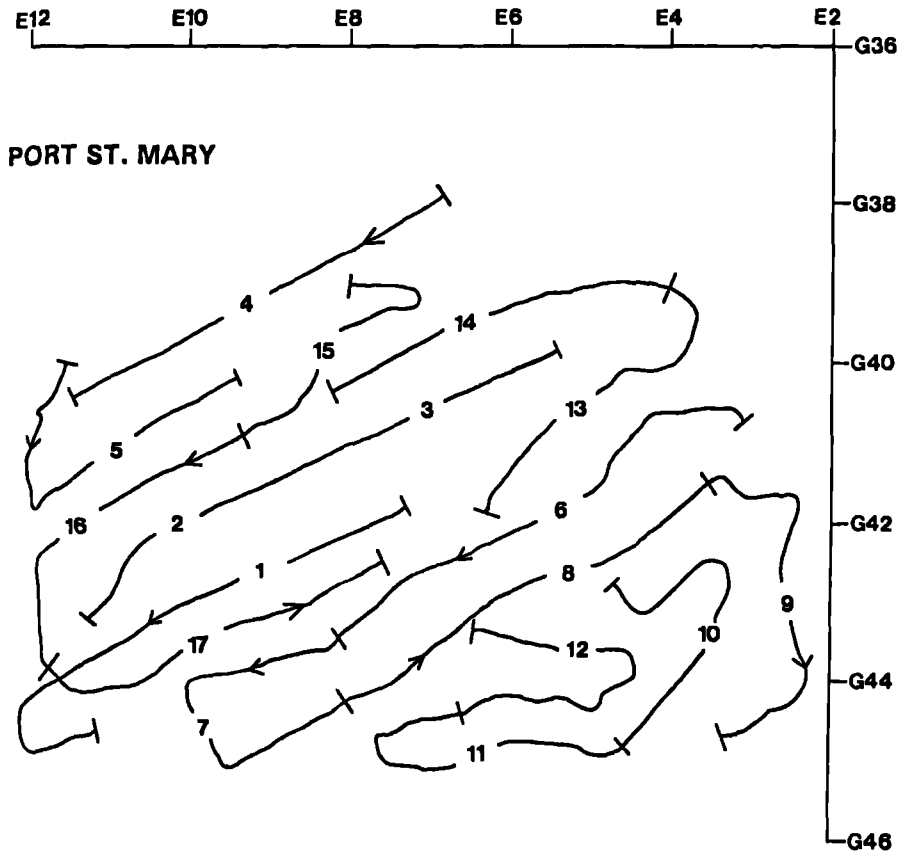
**H/I SECTOR**

Track No.	T2	R22	Expected R22	R22*ln(R22)	R22*ln(ExpR22)
1	42	0	1.47	0.0000	0.0000
2	22	0	0.77	0.0000	0.0000
3	28	1	0.98	0.0000	-0.0200
4	50	4	1.75	5.5452	2.2391
5	65	2	2.28	1.3863	1.6443
6	50	0	1.75	0.0000	0.0000
7	50	1	1.75	0.0000	0.5598
8	32	1	1.12	0.0000	0.1135
9	49	10	1.72	23.0259	5.3958
10	50	2	1.75	1.3863	1.1196
11	50	2	1.75	1.3863	1.1196
12	50	1	1.75	0.0000	0.5598
13	41	2	1.44	1.3863	0.7227
14	48	1	1.68	0.0000	0.5190
15	51	1	1.79	0.0000	0.5796
16	44	0	1.54	0.0000	0.0000
17	50	0	1.75	0.0000	0.0000
18	50	1	1.75	0.0000	0.5598
19	35	1	1.23	0.0000	0.2031
<b>Sum:</b>	<b>857</b>	<b>30</b>	<b>30</b>	<b>34.1162</b>	<b>15.3155</b>

G=37.601

critical value (p0.05, 18 d.o.f.)=28.869

therefore reject Ho: 0.01 > p > 0.005





**PORT ST. MARY**

Track No.	T2	R22	Expected R22	Chi-squared
1	50	14	12.67	0.139
2	50	12	12.67	0.036
3	43	13	10.90	0.405
4	55	21	13.94	3.574
5	66	8	16.73	4.555
6	53	16	13.43	0.490
7	47	5	11.91	4.012
8	48	16	12.17	1.208
9	50	8	12.67	1.723
10	50	18	12.67	2.239
11	50	6	12.67	3.514
12	50	14	12.67	0.139
13	51	14	12.93	0.089
14	51	17	12.93	1.283
15	50	20	12.67	4.235
16	50	8	12.67	1.723
17	50	9	12.67	1.065
<b>Sum:</b>	<b>864</b>	<b>219</b>	<b>219.00</b>	<b>30.429</b>

critical value (p0.05, 16 d.o.f.)=26.296  
therefore reject Ho:  $0.01 < p < 0.025$

**THE CHICKENS**

Track No.	T2	R22	Expected R22	Chi-squared
1	50	19	21.79	0.358
2	50	30	21.79	3.089
3	50	17	21.79	1.055
4	55	27	23.97	0.382
5	50	31	21.79	3.888
6	50	20	21.79	0.148
7	50	21	21.79	0.029
8	50	36	21.79	9.258
9	41	20	17.87	0.253
10	50	12	21.79	4.402
11	50	5	21.79	12.942
<b>Sum:</b>	<b>546</b>	<b>238</b>	<b>238.00</b>	<b>35.804</b>

critical value (p0.05, 10 d.o.f.)=18.307  
therefore reject Ho:  $p < 0.001$

Gruffydd's (1974a) estimates relate to includes the Port St. Mary, H/I Sector and High South-west Chickens grounds (see Fig. 4.1.). An increase in  $M$  with age is seen, with  $M=0.164$  at age 7, rising to  $M= 1.136$  at age 19 (Table 4.14).

More recent abundance-at-age data have been used to calculate age-specific total mortality rates ( $Z$ ) for major grounds, as well as a geometric mean estimate of  $Z$  for all exploited year classes, using the method of Heinke (1913).

Catch per unit effort (CPUE) values from the M.F.V. 'Mathilde' were taken to represent abundance, for scallops  $> 100$  mm shell-length (Table 4.15a). The ratios of the CPUE values for successive age-classes one year apart give estimates of  $S$ , from which  $Z$  is calculated (Table 4.15b). Estimates are variable, as sample sizes are relatively small (tens to hundreds of scallops per age-class). The younger year-classes tend to give negative values of  $Z$ , indicating that they may not have been fully recruited in the first of the two years compared. Heinke estimates of  $Z$  based on successively older ages at first exploitation ( $a$ ) provide running geometric mean estimates, which show increasing  $Z$  with age for most grounds. The exception is the H/I sector ground, where no increase in  $Z$  with age is observed and older age-classes were well represented in samples. Heinke estimates of  $Z$ , with  $a = 4$  or  $5$ , depending on the ground, generally provide lower estimates of  $Z$  than the estimates based on the 1987/8 Ricker-two release experiment which covers the same time period. The Heinke-estimate of  $Z$  ( $a=5$ ) for the H/I sector ground ( $Z=0.38$ ) is more realistic than the tagging-based estimate ( $Z=1.27$ ), and is consistent with the low exploitation rate estimates. The reliability of the CPUE based estimates cannot be assessed, but if they are unbiased then they suggest that the tagging-based estimates of  $Z$  may be too high.

A second set of abundance-at-age based estimates of  $Z$  have been calculated from sample-fleet CPUE and the age-composition of research-vessel samples (from Chapter 2, Table 2.9). These estimates relate to the period from the mid-point of one fishing season to the midpoint of the next. Total mortality-at-age values are again highly variable (Table 4.16). Only a few age-classes are represented as scallops  $> 10$  years old were pooled for calculations of abundance-at-age.

Heinke estimates of  $Z$  for the Bradda Head ground increase from 0.45 to 0.92 between 1987 and 1990 (Table 4.16). The estimate for the Peel Head ground is unrealistically low ( $Z=0.21$  for 1989/90). Negative estimates are obtained for the Targets and Maughold Head and SE. Douglas grounds for the same year,

suggesting either that the differences in CPUE data between the two years did not properly reflect changes in abundance, or age-composition data were not consistent between the two years. Estimates for 1987/8 on the SE. Douglas ground and 1988/9 on the H/I sector ground give realistic values ( $Z = 0.38$  and  $Z = 0.28$  respectively). Estimates for the Chickens ground are similar for all years but probably too low if age at first recruitment is taken as 4.

#### 4.3.3. Variation in total mortality and exploitation rate with age

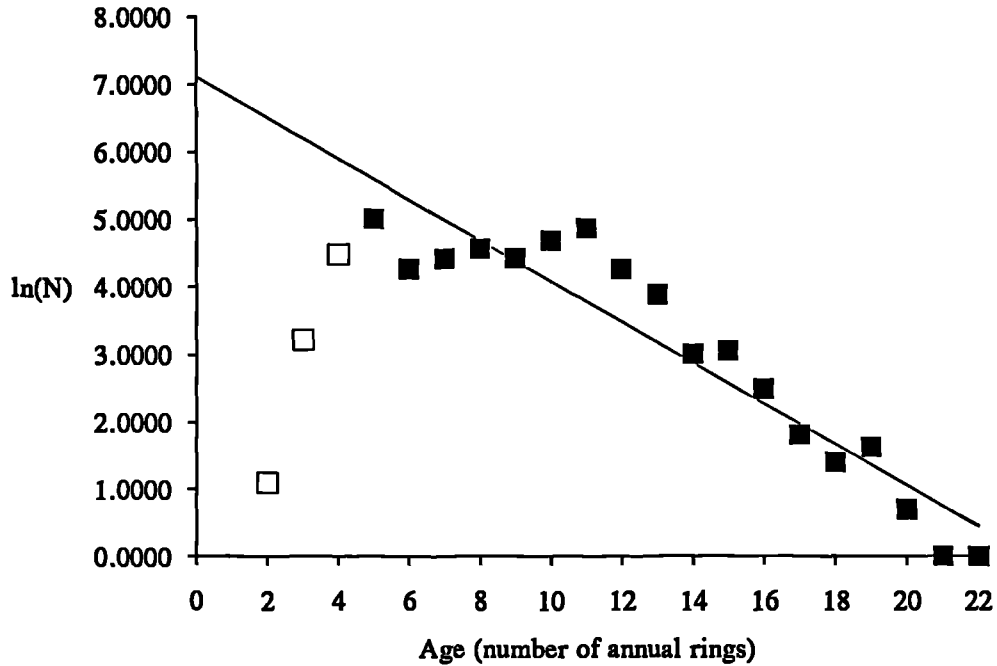
Estimates of  $Z$ -at-age from mark-recapture experiments and age-composition data, although highly variable, show a trend towards increasing mortality rate with age on most fishing grounds (Fig. 4.8a). The Port St. Mary ground provides the exception. All year-classes shown are fully vulnerable to the fishery, so the increase does not reflect recruitment to the fishing gear. Exploitation rates-at-age (Fig. 4.8b) do not show any systematic increase with age. Estimates for the oldest year-classes on each ground are highly variable, reflecting the low numbers on which the estimates were based, but in most cases exploitation rate-at-age is remarkably constant.

$Z$  increases with age, but  $u$  (which is proportional to  $F$ , and probably to  $F_i$  also) does not; the increase is therefore attributable to an increase in  $M$  with age.  $M$ -at-age values calculated from the 1987/8 Ricker two-release experiment confirm this observation for the Peel Head and SE. Douglas grounds, but estimates from other grounds are too variable to determine any trend (Table 4.9).

#### 4.3.4. Estimates of $M$ and $Z$ from empirical models

Calculation of  $M$  from its empirical relationships with various life-history parameters result in a wide range of estimated values (Table 4.17). Beverton & Holt (1959) proposed that  $M/k$  generally took values of 1.5-2.5. This relationship suggests that for North Irish Sea scallops,  $M$  has a range of values of 0.50 - 1.37. These values are clearly too high, so it can be concluded that this fish-derived 'rule of thumb' is not appropriate for use with scallops. Taylor's (1960) relationship between asymptotic length and  $M$  yields estimates of 0.022 - 0.025, which appear too low. Although this relationship was derived for bivalves, some of the larger bivalves studied by Taylor were very slow-growing and long-lived, whereas

**Fig. 4.7.** Catch-curve fitted to log-transformed age-frequencies of *Pecten maximus* in samples taken from the Bradda Head ground, winter 1937/38 (data from Tang (1941) total sample size = 1024). Open plot symbols indicate partially recruited year-classes which were excluded in fitting the regression equation. The regression equation is  $\ln(N) = 7.11 - 0.303 \cdot \text{Age}$  ( $r^2 = 0.89$ ). As the population was previously unfished, the slope of the regression approximates to  $-M$ .



**Table 4.14.** Age-specific natural mortality rates ( $M$ ) of *Pecten maximus* from offshore-south grounds in 1966, calculated from age-composition data (from Gruffydd, 1974a).

Age	$M$
7	0.164
8	0.178
9	0.187
10	0.207
11	0.238
12	0.263
13	0.281
14	0.335
15	0.367
16	0.475
17	0.642
18	0.868
19	1.136

**Table 4.15.**

a) Summary of catch-effort statistics obtained from the M.F.V. "Mathilde" during the period of her charter for the 1987/8 tagging programme. Estimates pertain to catches of scallops  $\geq 100$  mm shell-length only.

b). Age-specific survival (S) and total mortality (Z) rate estimates for the 1987/8 season (July 1987 - June 1988) for seven North Irish Sea scallop fishing grounds. The estimates were calculated from CPUE-at-age values obtained from the M.F.V "Mathilde". Heinke estimates of Z are also reported.

1987

1988

Area	Catch	Effort	CPUE	Catch	Effort	CPUE
	> 100mm	(m-hrs)		> 100mm	(m-hrs)	
BR	565	36.15	15.63	666	36.60	18.20
PL	588	28.92	20.33	554	27.45	20.18
TG	839	50.61	16.58	714	45.75	15.61
SED	1051	50.61	20.77	1150	50.33	22.85
H/I	1043	50.61	20.61	916	64.05	14.30
PSM	938	28.92	32.43	1046	45.75	22.86
CH	507	21.69	23.37	786	27.45	28.63

## Bradda Head

Age	Freq 87	Freq 88	CPUE	CPUE	S	Z	Heinke Z	
			87	88			a	Z
3	20	2	0.57	0.05				
4	131	352	3.76	9.59	16.72	-2.82	4	0.28
5	241	111	6.91	3.02	0.81	0.22	5	0.71
6	72	132	2.06	3.60	0.52	0.65	6	0.82
7	61	46	1.75	1.25	0.61	0.50	7	1.23
8	12	22	0.34	0.60	0.34	1.07	8	1.95
9	4	1	0.11	0.03	0.08	2.54		
10	1	1	0.03	0.03	0.24	1.44		
11	1	1	0.03	0.03	0.95	0.05		
12	1	0	0.03	0.00	0.00			
13	0	0	0.00	0.00	0.00			
14	1	0	0.03	0.00				
15	0	0	0.00	0.00	0.00			
Total	545	668	15.629	18.200				

## Peel Head

Age	Freq 87	Freq 88	CPUE	CPUE	S	Z	Heinke Z	
			87	88			a	Z
3	10	0	0.32	0.00				
4	69	165	2.21	5.42	16.93	-2.83	4	0.33
5	207	85	6.63	2.79	1.26	-0.23	5	0.58
6	120	138	3.84	4.53	0.68	0.38	6	0.71
7	128	76	4.10	2.50	0.65	0.43	7	0.90
8	53	51	1.70	1.68	0.41	0.89	8	0.92
9	13	20	0.42	0.66	0.39	0.95	9	0.88
10	13	12	0.42	0.39	0.95	0.05	10	1.55
11	10	4	0.32	0.13	0.32	1.15		
12	8	1	0.26	0.03	0.10			
13	3	2	0.10	0.07	0.26			
14	0	0	0.00	0.00				
15	1	0	0.03	0.00				
Total	635	554	20.33	18.20	20.18			

The Targets

Age	Freq 87	Freq 88	CPUE 87	CPUE 88	S	Z	Heinke a	Z
3	218	30	4.29	0.73			3	0.10
4	155	316	3.05	7.73	1.80	-0.59	4	0.53
5	342	66	6.73	1.61	0.53	0.64	5	0.50
6	66	171	1.30	4.18	0.62	0.48	6	0.58
7	23	35	0.45	0.86	0.66	0.42	7	0.81
8	17	11	0.33	0.27	0.59	0.52	8	1.08
9	8	4	0.16	0.10	0.29	1.23	9	0.95
10	3	3	0.06	0.07	0.47	0.76	10	1.17
11	2	0	0.04	0.00	0.00			
12	3	2	0.06	0.05	1.24	-0.22		
?	5							
Total	842	638	16.58	15.61				

South-east Douglas

Age	Freq 87	Freq 88	CPUE 87	CPUE 88	S	Z	Heinke a	Z
3	0	30	0.00	0.62				
4	25	31	0.49	0.65	4.97	-1.60		
5	192	118	3.80	2.46	1.17	-0.15	4	-0.04
6	279	213	5.52	4.43	1.18	-0.17	5	0.06
7	164	313	3.24	6.51	1.01	-0.01	6	0.11
8	142	158	2.81	3.29	0.82	0.20	7	0.29
9	65	111	1.29	2.31	0.83	0.19	8	0.45
10	58	51	1.15	1.06	0.40	0.92	9	0.64
11	38	22	0.75	0.46	0.61	0.50	10	0.87
12	33	22	0.65	0.46	0.22	1.50	11	0.85
13	17	7	0.34	0.15	0.56	0.59	12	1.07
14	11	9	0.22	0.19	0.38	0.96	13	0.87
15	12	4	0.24	0.08	0.44	0.82	14	1.05
16	6	5	0.12	0.10			15	1.09
17	4	0	0.08	0.00				
18	0	0	0.00	0.00				
19	0	2	0.00	0.04				
20+	2	1						
?	2	1						
Total	1050	1098	20.77	22.85				

## H/I sector

Age	Freq 87	Freq 88	CPUE	CPUE	S	Z	Heinke Z	
			87	88			a	Z
3	1	2	0.02	0.03				
4	10	10	0.20	0.15	1.93	-0.66		
5	101	25	2.00	0.38	0.37	1.00	4	0.37
6	285	48	5.63	0.73	0.65	0.44	5	0.38
7	229	238	4.52	3.63	0.69	0.37	6	0.40
8	80	204	1.58	3.11	0.98	0.03	7	0.35
9	50	101	0.99	1.54	0.74	0.30	8	0.31
10	79	48	1.56	0.73	0.55	0.60	9	0.28
11	61	56	1.21	0.85	0.80	0.23	10	0.35
12	59	63	1.17	0.96	0.75	0.29	11	0.35
13	38	57	0.75	0.87	0.83	0.18	12	0.27
14	22	41	0.43	0.63	0.81	0.21	13	0.29
15	12	23	0.24	0.35	0.51	0.66	14	0.29
16	8	8	0.16	0.12	0.58	0.55	15	0.39
17	6	6	0.12	0.09	0.39	0.95		
18	1	3	0.02	0.05	2.32	-0.84		
19	1	3	0.02	0.05				
20+	0	1						
Total	1043	937	20.61	14.30				

## Port St. Mary

Age	Freq 87	Freq 88	CPUE	CPUE	S	Z	Heinke Z	
			87	88			a	Z
3	2	2	0.07	0.05				
4	132	80	4.63	1.94	1.58	-0.46		
5	316	302	11.08	7.31	0.44	0.81	4	0.35
6	200	203	7.01	4.92	0.53	0.64	5	0.44
7	102	153	3.58	3.71	0.49	0.72	6	0.72
8	40	72	1.40	1.74	0.52	0.66	7	0.66
9	46	30	1.61	0.73	0.63	0.46	8	0.67
10	34	42	1.19	1.02	0.59	0.53	9	0.64
11	25	29	0.88	0.70	0.41	0.88	10	0.63
12	10	15	0.35	0.36	0.62	0.48	11	0.75
13	9	9	0.32	0.22	0.31	1.18	12	0.93
14	5	4	0.18	0.10			13	0.98
15	3	0	0.11	0.00			14	1.62
?	1	3					15	
Total	925	944	32.43	22.86				



The Chickens

Age	Freq 87	Freq 88	CPUE 87	CPUE 88	S	Z	Heinke a	Z
3	4	0	0.18	0.00				
4	92	180	4.24	8.86	2.77	-1.02	4	0.16
5	77	239	3.55	11.76	0.94	0.06	5	0.86
6	143	68	6.59	3.35	0.33	1.11	6	1.19
7	56	44	2.58	2.16	0.40	0.92	7	1.25
8	47	21	2.17	1.03	0.43	0.84	8	1.43
9	32	19	1.48	0.93	0.13	2.01	9	2.00
10	26	4	1.20	0.20	0.21	1.58	10	2.00
11	14	5	0.65	0.25			11	2.61
12	11	0	0.51	0.00	0.10	2.33	12	1.95
13	1	1	0.05	0.05			13	1.32
14	3	0	0.14	0.00	0.36	1.03	14	1.03
15	0	1	0.00	0.05				
16	1	0	0.05	0.00				
<b>Total</b>	<b>507</b>	<b>582</b>	<b>23.37</b>	<b>28.63</b>				

**Table 4.16.** Survival (S) and total mortality (Z) rates-at-age calculated from abundance-at-age values from successive fishing seasons. Abundances were calculated from research vessel age-composition data and sample-fleet catch/effort statistics (Chapter 2). Heinke estimates of Z are also given. For some fishing grounds Z is calculated using more than one value of  $\alpha$ , the first recruited year class. These are areas where recruitment occurs over more than one year.

BRADDA HEAD

Age	1986/87	1987/88	1988/89	1989/90	S1	S2	S3	Z1	Z2	Z3
2	0	0	0	0						
3	67 561	210 244	166 444	406 672						
4	1 493 879	834 303	1 479 069	1 880 018	12.35	7.04	11.30	-2.51	-1.95	-2.42
5	620 226	1 011 422	462 863	713 567	0.68	0.55	0.48	0.39	0.59	0.73
6	732 006	250 847	482 149	103 611	0.40	0.48	0.22	0.91	0.74	1.50
7	166 728	309 001	97 456	103 611	0.42	0.39	0.21	0.86	0.95	1.54
8	21 747	37 080	112 843	25 903	0.22	0.37	0.27	1.50	1.01	1.33
9	21 747	24 730	30 775	103 611	1.14	0.83	0.92	-0.13	0.19	0.09
10+	0	12 360	20 517	0						
Heinke's Z (a=4):								0.45	0.72	0.92

PEEL HEAD

Age	1986/87	1987/88	1988/89	1989/90	S3	Z3
2	0		0	0		
3	0		0	0		
4	444 540		759 967	190 532		
5	577 523		345 986	1 230 249	1.62	-0.48
6	921 549		501 628	193 268	0.56	0.58
7	443 734		243 942	352 837	0.70	0.35
8	287 840		312 659	298 831	1.23	-0.20
9	80 595		137 432	298 831	0.96	0.05
10+	161 191		206 149	219 623		
Heinke's Z (a=5):					0.21	

THE TARGETS

Age	1987/88	1988/89	1989/90	S2	S3	Z2	Z3
2	0	0	0				
3	3 128 663	986 466	820 895	0.73	0.36	0.31	1.04
4	781 368	2 299 410	350 198	0.46	1.76	0.77	-0.57
5	1 302 279	361 064	4 047 992	0.62	0.52	0.48	0.65
6	386 483	804 477	188 279	0.62	1.37	0.47	-0.32
7	302 465	240 710	1 106 137	0.19	0.78	1.67	0.25
8	84 018	57 010	188 279	0.38	0.00	0.98	
9	0	31 672	0				
10+	0	0	0				
Heinke's Z (a=3):						0.46	-0.21
Heinke's Z (a=4):						0.65	-0.39

MAUGHOLD HEAD

Age	1988/89	1989/90	S3	Z3
2	0	0		
3	328 950	53 511		
4	2 052 892	243 232	0.74	0.30
5	182 750	1 817 084	0.89	0.12
6	475 150	486 463	2.66	-0.98
7	1 541 192	608 079	1.28	-0.25
8	438 600	1 330 620	0.86	0.15
9	511 700	972 927	2.22	-0.80
10+	438 600	729 695		
Heinke's Z (a=4):			-0.11	

SE DOUGLAS

Age	1986/87	1987/88	1988/89	S1	S2	Z1	Z2
2	0	0	0				
3	0	11 072	7 333				
4	1 011 694	185 389	266 378				
5	2 171 769	1 111 993	908 490	1.10	4.90	-0.09	-1.59
6	1 432 109	2 049 239	1 339 009	0.94	1.20	0.06	-0.19
7	1 348 925	740 184	1 953 835	0.52	0.95	0.66	0.05
8	1 229 020	832 535	1 132 377	0.62	1.53	0.48	-0.43
9	599 522	626 547	873 548	0.51	1.05	0.67	-0.05
10+	1 258 997	866 867	1 348 068				
Heinke's Z (a=5)						0.38	-0.11

H/I SECTOR

Age	1987/88	1988/89	1989/90	S2	S3	Z2	Z3
2	0	0	0				
3	0	0	53 511				
4	239 359	580 187	243 232				
5	990 451	814 215	1 817 084	3.40	3.13	-1.22	-1.14
6	3 861 579	732 794	486 463	0.74	0.60	0.30	0.52
7	2 122 394	3 361 547	608 079	0.87	0.83	0.14	0.19
8	1 179 108	907 269	1 330 620	0.43	0.40	0.85	0.93
9	280 038	1 186 428	972 927	1.01	1.07	-0.01	-0.07
10+	4 451 133	3 466 232	729 695				
Heinke's Z (a=5):						0.28	0.54

THE CHICKENS

Age	1986/87	1987/88	1988/89	1989/90	S1	S2	S3	Z1	Z2	Z3
2	0	0	0	0						
3	458 770	49 495	17 513	236 791						
4	1 743 989	2 419 111	2 061 432	395 136	5.27	41.65	22.56	-1.66	-3.73	-3.12
5	1 922 178	1 172 593	1 021 583	1 516 702	0.67	0.42	0.74	0.40	0.86	0.31
6	731 372	785 977	235 388	623 898	0.41	0.20	0.61	0.89	1.61	0.49
7	349 064	223 048	273 050	130 583	0.30	0.35	0.55	1.19	1.06	0.59
8	33 244	106 213	183 602	130 583	0.30	0.82	0.48	1.19	0.19	0.74
9	33 244	63 728	56 493	96 728	1.92	0.53	0.53	-0.65	0.63	0.64
10+	0	42 485	37 662	101 565						
Heinke's Z (a=4):								0.43	0.47	0.46
Heinke's Z (a=5):								0.69	0.37	1.17

Fig. 4.8a.

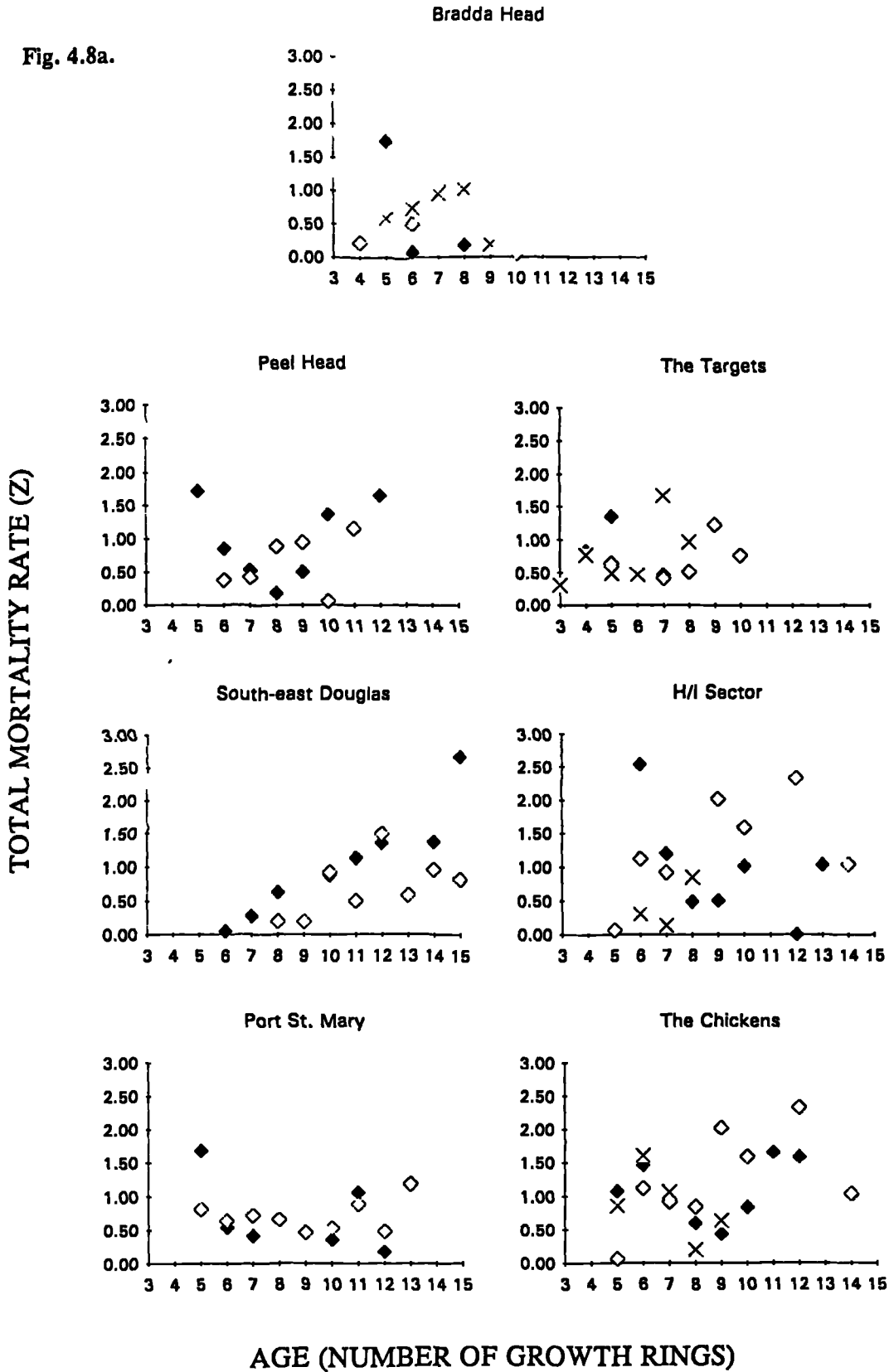


Fig. 4.8a. Total mortality rate (Z) at age values calculated from Ricker two-release tagging experiments ( $\blacklozenge$ ), CPUE-at-age values from the M F V. "Mathilde" ( $\diamond$ ) and abundance-at-age values from research vessel age-structures and sample-fleet CPUE ( $\times$ ). Estimates all relate to 1987/8.

Fig. 4.8a.

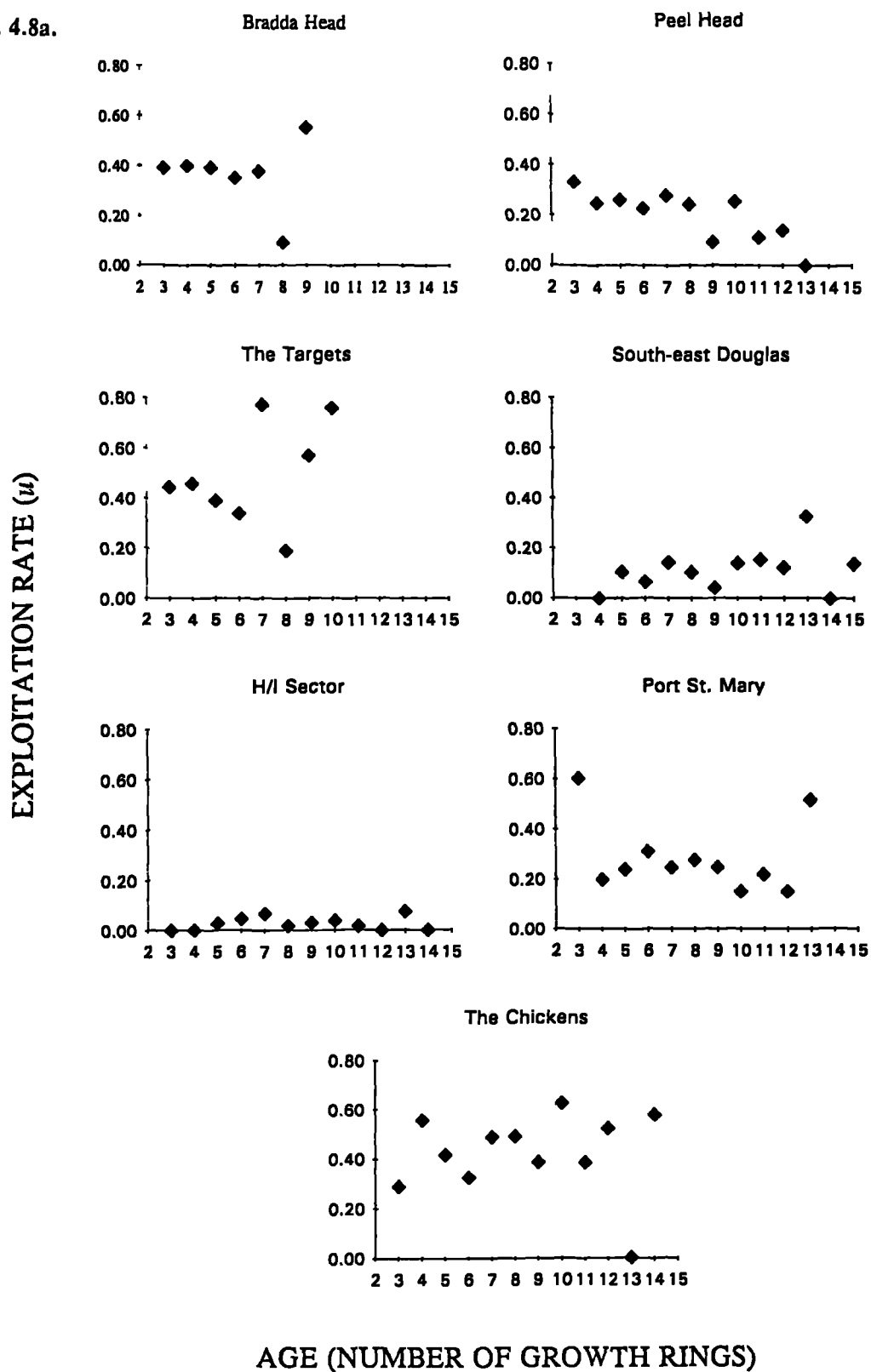


Fig. 4.8b. Exploitation rate ( $u$ ) at age estimates for the 1987/8 fishing season, calculated from the Ricker two-release tagging experiment.



Table 4.17. Natural mortality rate (M) and total mortality rate (Z) of scallops, estimated from empirical models. Data required to generate the estimates are also shown. Estimates relate to the period 1987-89, except BR37/8, which relates to the winter of 1937/8.

Area	L <sub>inf.</sub>	k	t <sub>max</sub>	tm50	WGSI	Beverton & Holt (1959)		Taylor (1960)		Pauly (1980)		Rikhter & Efanov (1976)		Gunderson & Hoening (1983)	
						lower M	upper M	M	M	M	M	M	M	M	Z
BR37/8	144.97	0.42	18	30		0.63	1.04	0.022	0.41	0.13				0.31	
BR	130.41	0.55	9	28	0.042	0.82	1.37	0.024	0.50	0.14		0.10		0.55	
PL	127.48	0.49	11	28		0.73	1.21	0.025	0.47	0.14				0.47	
TG	144.40	0.52	7	16	0.056	0.78	1.30	0.022	0.47	0.21		0.12		0.68	
PA	144.49	0.46	13	28	0.081	0.69	1.15	0.022	0.43	0.14		0.17		0.40	
RB	134.60	0.52	7	16	0.054	0.78	1.31	0.023	0.48	0.21		0.12		0.68	
MG	126.41	0.50	10			0.75	1.25	0.025	0.48					0.50	
SED	133.74	0.33	14	40	0.049	0.50	0.83	0.024	0.36			0.11		0.38	
H/I	141.96	0.35	15	40	0.061	0.52	0.87	0.022	0.36			0.11		0.36	
PSM	138.09	0.42	12	40	0.040	0.62	1.04	0.023	0.41			0.11		0.43	
CH	136.20	0.47	9	28	0.058	0.71	1.18	0.023	0.45			0.14		0.55	

L<sub>inf</sub> = asymptotic length, from VBGF  
k = Brody-Bertalanffy growth coefficient  
t<sub>max</sub> = age of oldest fish in sample (years)  
tm50 = age at 50% sexual maturity (months)  
WGSI = wet-weight gonado-somatic index

scallops, although relatively long-lived, grow fast during the first 5-6 years of life and approach their asymptotic size at a relatively young age (see Chapter 3). Estimates of  $M$  from Pauly's (1980) widely used model linking  $M$  to von Bertalanffy growth parameters and water temperature have a range 0.36 - 0.50. These values are once again too high, and it must be concluded that relationships between growth and mortality derived from fish will overestimate mortality rates in scallops, and that growth-mortality relationships from bivalves are equally inapplicable.

The two methods which link mortality to reproductive effort (Rikhter & Efanov, 1976; Gunderson & Dygert, 1988) appear to give reasonable values ( $M = 0.11 - 0.21$  and  $M = 0.10 - 0.17$  respectively), although they are derived from fish. This indicates that such models may be more generally applicable than those based on growth parameters, as the measures of reproductive investment are less arbitrary and shape-dependent than linear measurements.

Estimates of  $Z$  from longevity (Hoenig, 1983) give reasonable estimates; the value of  $Z=0.31$  for the Bradda Head ground in 1937/8 compares closely with that derived from a catch-curve (0.303, Fig. 4.7) and estimates for 1987-89 (0.36 - 0.68) are plausible for offshore grounds but underestimates for inshore grounds. The drawbacks of Hoenig's method are that it relies on accurate determination of the age of the oldest individuals in a population, which is difficult for scallops, and that it is dependent on the age chosen to represent the oldest in the population.

#### 4.4. DISCUSSION

Tagging experiments and age-composition data have provided estimates of mortality rates for most of the major scallop-fishing grounds in the North Irish Sea. The tagging-based estimates have shown that significant spatial variation in mortality rates occurs between fishing grounds. In most cases the differences are consistent with what is known about the distribution of fishing effort over the grounds. The inshore fishing grounds to the west of the Isle of Man are known to be heavily exploited, and tags released on these grounds have the higher probability of being recaptured. Recapture rates of tagged scallops from grounds to the south and east of the Isle of Man are lower, reflecting less intense exploitation in these areas. High mortality rates are not always associated with high recapture rates, indicating either that capture is not the main source of mortality on some fishing grounds, or that some of the tagging-based estimates may be biased. Estimates of mortality rates from the two different analytical techniques (Ricker two-release and log-linear model) shed some light on where bias may arise.

Ricker (1975a) has placed the factors which cause errors in tagging-based estimates of mortality rates into three categories (Type A, B & C). Type A errors affect estimates of  $F$  (and therefore  $M$ ), but not  $S$  or  $Z$ . The causes of Type A errors are loss of tags at the time of release or before the first recapture period, tagging-induced mortality, and incomplete reporting. Note that under certain circumstances (e.g. in multiple-release experiments where tag-loss, tagging mortality and non-reporting differ between releases) estimates of  $S$  and  $Z$  will be affected, as well as estimates of  $F$  and  $M$ .

In these experiments, reporting of recaptures can be assumed to be complete or nearly complete (95-100%). Tag-shedding appears to have been fairly constant at around 10% for all four releases (1982, 1983, 1987 and 1988) but tagging-induced mortality shows considerable variation. The proportion of tagged scallops which appear to have died as a result of tagging is not related to the age-structure of the tagged population or the weather conditions at the time of tagging. Certain fishing grounds (Port St. Mary, H/I Sector, SE. Douglas and The Targets) appear to have suffered high post-tagging mortalities on all the occasions when tagged scallops were released on them. The causes of the high post-tagging mortality are not known, but possibilities include differences in the incidence of predators or the effect of different substrate-types on the degree of stress suffered during capture. Predators may be able to take advantage of newly released scallops, which are

likely to be in a weakened condition. Adult scallops (> 75 mm shell height) are not vulnerable to crab predation (Lake *et al.*, 1987) and are seldom eaten by starfish (Briggs, 1983). The latter, together with the predatory gastropods *Buccinum undatum* and *Neptunea rugosa* may, however, be attracted to weakened prey. Scallops too weak to recess back into the substrate may also be more liable to predation. Substrate-type may play a part in determining survival of released scallops. Scallops dredged from smooth sand are likely to have suffered less stress during capture than those dredged from either muddy or rocky grounds (Caddy, 1968; Naidu, 1988).

Tagging-induced mortality, unless accounted for, will cause F from log-linear models to be underestimated, but will not affect Z. In two-release estimates, F will always be underestimated if any tagging-mortality has occurred, but Z will also be affected if the tagging-mortality differs between the two releases. Tagging-induced mortalities for each release have been estimated from the recapture of dead shells which bear tags but show no sign of shell growth over the drilled hole. Although the number which died is likely to be underestimated (due to the likely lower recapture and reporting rate of dead tagged shells), the magnitude of the differences between years for the same ground should be unaffected. Estimates of Z will therefore be unbiased, but F is likely to be underestimated. Of Ricker's 'Type A' errors, this is the only one which may cause significant bias in estimates.

Type B errors are those which affect Z, but not F. They arise when the following occur and are not detected: (1) progressive loss of tags during the recapture period, (2) additional mortality of tagged individuals and (3) emigration from the stock. None of these errors are thought to affect mortality estimates in these experiments. Tag losses are likely to have occurred soon after tagging, when any tags not properly affixed to the shell will have been lost. The hole drilled in the shell soon becomes covered with new shell growth, so that the tag becomes firmly fixed after 1-3 months. Examination of the several thousand tagged scallops which had been recaptured revealed only two instances where tags were potentially being lost; due to erosion of the shell by the wire of a loosely attached tag in one case, and due to the wire cutting through the plastic tag in the another case. Both Dredge (1985) and Murphy (1986) found that, whereas initial tag-losses were significant, subsequent losses were negligible. This may not be the case for dead scallops which bear tags. Shell erosion and disintegration will tend to accelerate the rate of tag loss.

Emigration of scallops from the area over which they were distributed is unlikely to have occurred. All the available evidence on scallop movements indicate that adult *Pecten maximus* move only a few metres a year, with no substantiated records of large-scale movements over periods of several years (Brand, 1991, for review).

Type C errors affect first-year recaptures only (or more generally, the early part of the recapture period) and arise when tagged animals behave abnormally after tagging, or are not distributed randomly within the population into which they are released, becoming mixed only after some time. Type C errors affect estimates of  $Z$ , and where significant, are usually corrected by excluding the data from the first recapture period.

Newly released scallops may be abnormally vulnerable to capture as they are physiologically stressed and thus unable to escape capture by rapid muscle adduction and shell-valve closure (the escape reaction; Brand, 1991, for review). Scallops are also normally recessed into the substrate (Baird & Gibson, 1956) and have to be dug out using toothed dredges; newly released scallops will be unrecessed and unable to recess until they have regained sufficient energy to carry out the vigorous movements associated with recessing (see Baird & Gibson, 1956, for description). Unrecessed scallops lying on top of the seabed are likely to be captured with greater efficiency. In the experiments described here, tagging scallops early in the closed season allowed plenty of time for them to become recessed into the substrate before the start of the fishing season. Only in the case of the 1982 release on the Peel Head ground were scallops tagged just prior to the start of the fishing season, and Murphy (1986) considered that the high mortality rate estimate obtained from his analysis of recaptures over two years was due to higher catchability during the first fishing season.

The problem of non-random distribution will not just affect recapture rates during the early part of the experiments. If the scallops are not initially distributed at random within the population (or part of the population being studied) their distribution will remain non-random for the duration of the experiment. This is not therefore a typical 'Type C' source of error, which can be avoided by excluding early recaptures from the analysis.

Of the many potential errors which can arise in tagging experiments (reviewed in Ricker, 1975a; Jones, 1977; 1979), these experiments are only

subject to significant errors from two: the quantification of tagging-induced deaths, and bias stemming from the distribution pattern of releases relative to the spatial distribution of the population.

Underestimation of tagging-induced deaths for some grounds may have biased some of the estimates of  $F$  and  $Z$  calculated from the two-release experiments. The very high  $Z$  values calculated for the Port St. Mary, SE. Douglas and H/I sector fishing grounds, which all had low exploitation rates, may have been caused by underestimation of the difference between the two years in the number dying after tagging. Estimates of  $Z$  for Port St. Mary and SE. Douglas calculated from log-linear regression, estimates which are independent of the initial number of tags, are much lower than the two-release estimates and are consistent with observed population structure on these grounds.

The spatial distribution of releases relative to the distribution of the population and the distribution of fishing effort on that population are the most important considerations in the design of tagging experiments on immobile shellfish. In the first of the two tagging experiments carried out (1982 & 1983 releases) the areas over which tags were distributed were chosen based on information provided by fishermen on the location and extent of the fishing grounds which they habitually fished. Scallop stocks appear to be fairly persistent at the scale of the fishing ground in this population, and the major grounds are consistently exploited each year. The cycles of intense exploitation followed by a period of years when the ground lies fallow, prevalent in other scallop fisheries (Caddy, 1975; Young & Martin, 1989) do not appear to occur on these grounds. Most of the fishing grounds in the North Irish Sea receive regular recruitment, and the recruiting year class often replenishes the stock taken the previous year, stabilising stock size to some extent over long time periods (Brand *et al.*, 1991b, for review). Stability in stock size and distribution leads to relative stability in the distribution of fishing effort from year to year (Murphy, 1986). Returns of tagged scallops from the periods 1983-90 show that fluctuation of fishing effort between years is minimal for the major fishing grounds. The persistence and regularity of the distribution of exploitable scallop-fishing grounds simplify the choice of areas for distribution and the subsequent analysis and interpretation of the results. The estimates of exploitation rates, subject only to uncertainty over the number of tagging-induced deaths, should be applicable to the areas over which tagged scallops were distributed. Some uncertainty remains over the within-ground pattern of exploitation.

Analysis of the spatial pattern of recaptures of 1988-released scallops in the 1988/9 fishing season indicated that some of the fishing grounds over which tags were distributed were not evenly fished throughout. The within-ground differences are subtle, however. There are no cases of large parts of a ground being completely unexploited. This patchiness in the distribution of fishing effort, which at least partially reflects differences in scallop density perceptible to fishermen, will always cause  $F$  to be underestimated (Cranfield & Allen, 1979).

It has already been noted that fishing effort on the main scallop grounds is reasonably consistent from year to year. It would be interesting to examine the distribution of 1988-tagged scallops in recaptures from subsequent fishing seasons. This should establish if the exploitation pattern within grounds is also consistent, *i.e.* if high-density aggregations within grounds are spatially persistent, or if patches within a ground are sequentially exploited, leading to a different spatial distribution of fishing in each season as fishermen locate and deplete high-density aggregations (e.g. Caddy, 1975; Orensanz, 1986; Robert & Jamieson, 1986).

The un-quantified sources of bias in these experiments can be investigated by comparison of the results of the two-release analysis and the log-linear regression analysis. The two types of experiment and analysis are subject to different types of bias, and comparison between them is thus instructive.

Although estimates of  $Z$  from the regression analysis are free from 'Type A' errors and unlikely to be significantly affected by 'Type B' errors in this particular case, as the time from release increases the tagged population becomes less representative of the population as a whole. The age structure of the tagged population shifts towards the older age-classes, which may have a higher natural mortality rate (Gruffydd, 1974a) and lower catchability (Chapman *et al.*, 1977; Mason *et al.* 1979a), so systematic bias in the estimation of  $Z$  from regression can occur. If the increase in  $M$  over time was exactly balanced by the decrease in  $F$  due to decreasing catchability,  $Z$  would remain unbiased. Exploitation rates-at-age appear, however, to be fairly uniform, indicating that all scallops of commercial size are equally vulnerable to capture.  $Z$  has been shown to increase with age, indicating that  $M$  increases with age. It is therefore most likely that estimates of  $Z$  from log-linear regressions will tend to be overestimates. This problem is reduced to a great extent by giving more weighting to the early recaptures (using the number of recaptures, usually higher in the early years after tagging, as weights). A systematic change in mortality over time would be difficult to detect with few points

in the regression and the methods of Sandland (1982) of looking at trends in residuals are not really applicable in such cases.

Many of the assumptions of linear regression modelling are violated in the application of log-linear models to a closed population such as the tagged population studied here. The tagged population can only decrease, through recaptures and natural mortality, so a negative relationship between recaptures and time is inevitable. The higher the rate of losses, the more linear the relationship is likely to be, i.e. successive points in the regression are not independent of one another. Statistical comparisons between estimates are therefore of doubtful validity. Despite the reservations on the statistical validity, the log-linear model provides useful estimates of mortality rates, and is still widely used (e.g. Sandland, 1982; Gulland, 1983; Farebrother, 1985; 1992).

Having applied corrections to estimates of mortality and exploitation rates, the F and M values calculated from the two-release method indicated that natural mortality exceeded fishing mortality, even for grounds known to be heavily fished. Similar high values of M were obtained from the two regression estimates. The values obtained are unrealistically high. The high values of M estimated in this study will include indirect fishing mortality, which has been shown to be very important in some other scallop species (Medcof & Bourne, 1964; Caddy, 1968; 1973; Naidu, 1988; Smolowitz & Serchuk, 1989; McLoughlin *et al.*, 1991), particularly where heavy dredges are used for fishing. In extreme cases, such as in one of the Australian stocks of *Pecten fumatus* Reeve 1852 studied by McLoughlin *et al.*, (1991), 12-22% of the initial stock was harvested - the rest wasted due to high numbers of incidentally damaged scallops dying and decaying on the seabed. A bacterial infection followed and the entire stock was lost within 9 months. The loss of entire stocks in this way, following brief periods of intense exploitation by dredgers, is apparently not uncommon in Australian scallop fisheries (Young & Martin, 1989).

The available evidence suggests that incidental fishing mortalities are significant in *Pecten maximus* fisheries also. Estimates of M (averaged over all year-classes) from unfished populations are of the order of 0.3 (see 4.3.2) but unfished populations contain many older individuals which have a higher mortality rate (Gruffydd, 1974a). Values for exploited populations, which consist mainly of scallops aged 4-8, are expected to be lower. The relationship between exploitation rate and total mortality rates from tagging experiments on the North Irish Sea



populations, used to calculate  $Z$  at  $u=0$ , gives an estimate of  $M$  of 0.12, which is close to the conventionally assumed value of 0.15 (Mason *et al.*, 1980; 1991; Murphy, 1986; Murphy & Brand, 1987; Bannister, 1986) and the value for 7-year old scallops (0.16) in an unfished population calculated by Gruffydd (1974a). Estimates of  $M$  for other long-lived scallop species are of the order of 0.1 - 0.2 (reviewed in Orensanz *et al.*, 1991). Estimates based on empirical models relating fecundity to mortality (see 4.3.4.) also give estimates of  $M$  in the range 0.1-0.2.

In contrast to the low expected values of  $M$  for this species, tagging studies on exploited populations lead to much higher estimates of  $M$  (Gruffydd, 1972; Murphy, 1986, and this study). With  $M$  obtained indirectly by subtraction of  $F$  from  $Z$ ,  $F$ , is indistinguishable from  $M$ . The apparently high values of  $M$  are due to the erroneous inclusion of  $F$ .

The causes of indirect fishing mortality have been reviewed by Caddy (1989b), McLoughlin *et al.* (1991) and Orensanz *et al.* (1991). In this fishery, the greatest source of incidental fishing mortality is likely to occur due to damage of scallops which come into contact with dredges but are not caught by them. Some damage may also occur to scallops which were caught and discarded because they were undersized, or were caught as a by-catch to queen fishing during the scallop closed season.

Mortality caused incidentally during fishing is potentially quantifiable (e.g. Naidu, 1988). More difficult to detect are the indirect effects of fishing on a population. The effects of fishing on mortality may be subtle; fishing may alter the dynamics of the benthic community, which may in turn affect natural mortality rates. Examples of the potential effects of fishing on population and community dynamics are: changes in populations of predators and competitors (Orensanz *et al.*, 1991), increased susceptibility to changes in environmental conditions due to the stress of intensive fishing (Dare, 1974) and increased susceptibility to disease (McLoughlin *et al.*, 1991).

Any such change in 'natural' mortality which is caused by the indirect effects of fishing activity should strictly be excluded from  $M$  in fishery models;  $M$  (or  $M$ -at-age) is used as a constant in yield equations and must not vary with  $F$ . For the purposes of yield per recruit analysis (Chapter 6), a conventional value of  $M=0.15$  is chosen, but the effect of varying  $M$  between 0.10 and 0.30 is also investigated. All reasonable values of  $M$  lie within this range, with estimates for

the age-classes predominant on these grounds being at the lower end of the range. Age-specific  $M$  calculated from tagging and age-composition data is highly variable, but tends to increase with age. The age-specific values calculated from the catch curve of Gruffydd (1974a) are the most consistent data available, and could be used if age-specific  $M$  is required for cohort analysis.

In order to show the status of the fishery on each ground relative to  $F_{\max}$  and  $F_{0.1}$  (in the yield per recruit analysis),  $F$  values covering the range of estimates generated by the Ricker two-release tagging experiments are chosen. The values used exclude  $F_t$ , which is highly variable, and are applicable to the period 1987-1989, when contemporary estimates of growth rates are available (Chapter 3).

Although this study is the most exhaustive work available on mortality rates of *Pecten maximus*, further analysis of the tagging data is still possible. Hearn *et al.* (1987) describe a method of obtaining  $M$  from completed tagging experiments (when no more live tags are returned) which requires only the time at liberty of all recaptures and is not affected by fluctuations in  $F$  or incomplete mixing of tagged individuals in the population. The only disadvantage of the method is that it will give values of  $M$  calculated from an ageing population. Refinements to the regression analysis are also possible; Lucas (1975) presents equations for obtaining maximum likelihood estimates of  $F$  and  $M$  when fishing varies with time, as it does seasonally in this fishery. Joint confidence intervals for the parameters can also be calculated. Furthermore, sufficient data has been collected to fit regression models to recaptures from the 1987 and 1988 releases once the more recent data is made available for analysis. It is also possible to combine tag returns with catch-effort data to produce estimates of  $F$  and  $Z$  (Dickie, 1955; Murphy, 1986) or estimate  $F$  from cohort models. An entirely different approach, used in several North American scallop fisheries, calculates natural mortality rates using the ratio of dead, paired shells ('cluckers' or 'clappers') to live shells in the catch (Caddy, 1989b, for review). The assumption that 'cluckers' and live shells are equally catchable is required. Also required are estimates of the time taken for the two shell-valves to become disarticulated (probably several months) and the number of 'cluckers' which disarticulate in the dredge during the fishing operation. The experimental closed area off Bradda Head provides a useful area to try the 'clucker method'. The area could also be used for direct observation of mortality rates, with scope for manipulative experiments to investigate mortality at different densities or with removal of particular predators.

#### 4.5. CONCLUSIONS

1. Differences in mortality rates between areas illustrate the importance of studying the dynamics of scallop fisheries on a spatial basis.
2. High post-tagging mortality may have affected estimates of Z, F and M for some areas, indicating the importance of testing the survival of tagged scallops in natural rather than laboratory conditions.
3. Total mortality rates on all scallop beds studied were greater during the period 1983-91 than in 1982-83, due to an increase in fishing mortality which occurred between the 1982/3 and 1983/4 fishing seasons and was maintained in subsequent years. Fishing mortality rates on the major grounds were consistent from year to year during the period of study.
4. Estimates of Z from tagging experiments are higher than corresponding estimates from age-composition data, but it is not certain which of the estimates is biased. Estimates of Z, F and M from log-linear regression are similar to those obtained from two-release experiments in most cases. Where they are not, it is likely that the two-release estimates were biased by underestimation of post-tagging mortality.
5. Natural mortality rate appears to increase with age, whereas exploitation rates, and therefore F appear to be uniform for all recruited age-classes. This implies that there is no age-class selection (see also Chapter 2) in the exploited population, with all recruited age-classes equally vulnerable to fishing.
6. On some scallop grounds, fishing is not evenly distributed. Targeting of high-density patches may occur on some grounds, but on others patchiness may not occur at a scale perceptible to fishermen.
7. Natural mortality rate estimates from tagging experiments are higher than the value of 0.15 commonly used in scallop stock assessments, but will include losses associated with tagging experiments and indirect or non-yield fishing mortality caused by dredging.
8. Empirical models relating M to growth parameters are not appropriate for use with *Pecten maximus*. Models relating reproductive investment to mortality are more promising.

## CHAPTER 5 - MARK-RECAPTURE EXPERIMENTS ON QUEEN SCALLOPS, *CHLAMYS OPERCULARIS* L.

### 5.1. INTRODUCTION

Tagging experiments on the great scallop, *Pecten maximus*, have been successful in providing estimates of fishing and natural mortality rates for several exploited areas within the North Irish Sea (Murphy, 1986; Murphy & Brand, 1992; Allison *et al.*, 1989, and Chapter 4). The experiments described in this chapter investigate the potential utility of similar tagging experiments for obtaining estimates of exploitation, fishing and natural mortality rates, population size, and large-scale movements of queen scallops or 'queens' (*Chlamys opercularis*). Mortality rates have also been estimated from age-structure data and from empirical relationships between natural mortality rate and other life-history parameters.

Although many aspects of the biology of *C. opercularis* have been investigated in some detail (see Chapters 1,2 & 3 for review) few estimates of natural mortality rate ( $M$ ) have been produced; Orensanz *et al.* (1991) use the age-frequency data of Ursin (1956) to calculate values of  $M=0.76$  for queens from the Kattegat and  $M=1.05$  for North Sea populations and Askew *et al.* (1973) produce estimates of 1.65-1.98 from age-frequencies on unfished queen beds off Guernsey. The only previous stock assessment study on this species (Mason *et al.*, 1979c) used an assumed value of  $M=0.70$  for North Irish Sea, Clyde and West of Kintyre stocks. Fishing mortality rates in Mason *et al.* (1979c) were calculated from catch statistics based on declared landings (cohort analysis).

The often-presumed ability of queen scallops to undertake large-scale directed migrations is not well studied either, being based on either purely anecdotal evidence (e.g. Rolfe, 1973) or on experimental studies of swimming behaviour and theoretical hydrodynamic calculations (Thomas, 1976). No demonstrations of such migrations have been reported in the scientific literature.

Mark-recapture studies have been previously attempted on this species in the English Channel (Franklin & Rolfe, 1976) but the results were never published or made generally available, however, pectinid species of similar size and active swimming habit have been successfully tagged elsewhere (e.g. Dredge, 1985, on *Amusium japonicum balloti* Bernardi in northern Queensland, Australia). Dredge's

study provided growth and mortality rate estimates for use in yield per recruit models, without using catch/effort data from the fishery.

This study aims to provide the basic data required for input into a dynamic pool model (Chapter 6) to make a preliminary assessment of management options for the North Irish Sea queen fishery, while catch-effort data series become sufficiently well established to use in more refined stock assessments.

## 5.2. MATERIALS & METHODS

### 5.2.1. Tagging experiments

The experiment was initially designed as a Ricker two-release experiment (Ricker, 1975a; Seber, 1983) where queens would be released on known fishing grounds in two consecutive years and survival rate estimates would be calculated from the ratio of year 1 to year 2 marks in the recapture period following the second release (see Chapter 4). However the results of the first year's experiment necessitated subsequent re-evaluation of the analytical methodology.

The scope of the experiment was necessarily limited, as a larger (and relatively expensive) mark-recapture experiment on *Pecten maximus* was being carried out simultaneously. It was agreed that only 2,000 tagged queens would be released, calculated on the basis of the projected costs of payment of rewards for scallop tags and any tagged queens that would be returned. Given the limited number of tags and the large area of the north Irish Sea which is fished for queens (see Introduction, Fig. 2b) it was planned to release all the tagged queens on a single fishing ground in order to ensure adequate returns for a meaningful assessment of the technique.

#### 5.2.1a. 1987 release

On May 28th 1987, queens were caught by dredging with two 2'9" (0.83m) dredges towed from the R.V. 'Cuma'. The dredges were fitted with 2½" (64 mm) diameter steel belly-rings, and 2½" (64 mm) long teeth, spaced 3" (76 mm) apart along a spring-loaded toothbar. Two one-hour tows were made, yielding 700 queens, 600 of which were tagged and released the same day. The following day, 400 more queens were tagged and released, these having been caught in the R.V. Cuma's otter trawl.

The tagging method used was essentially the same as that used for tagging scallops (see Chapter 4), but the hole drilled in the shell to affix the tag was made with a smaller drill bit (1.5 mm, instead of 2.1 mm) and the Petersen Disk tag used was smaller (10 mm, instead of 15 mm diameter). The smaller tag was thought necessary due to the smaller auricle of the queen scallop, and the possibility that the larger disk tag would interfere with valve opening. The shells were kept in 50 litre

tanks on board the vessel, with a constant flow of pumped seawater, before and after tagging. Releases were made within 15 minutes of tagging, with each shell being checked for damage both before and after tagging, and rejected if necessary. Each queen was measured to the nearest mm (shell-length), and the age recorded by counting the annual rings (see Chapter 1). The 1,000 tagged queens were released over the area where they had been caught, to the south-east of Douglas (Fig. 5.1). Information received from fishermen indicated that this ground was likely to be fished by many of the smaller inshore boats.

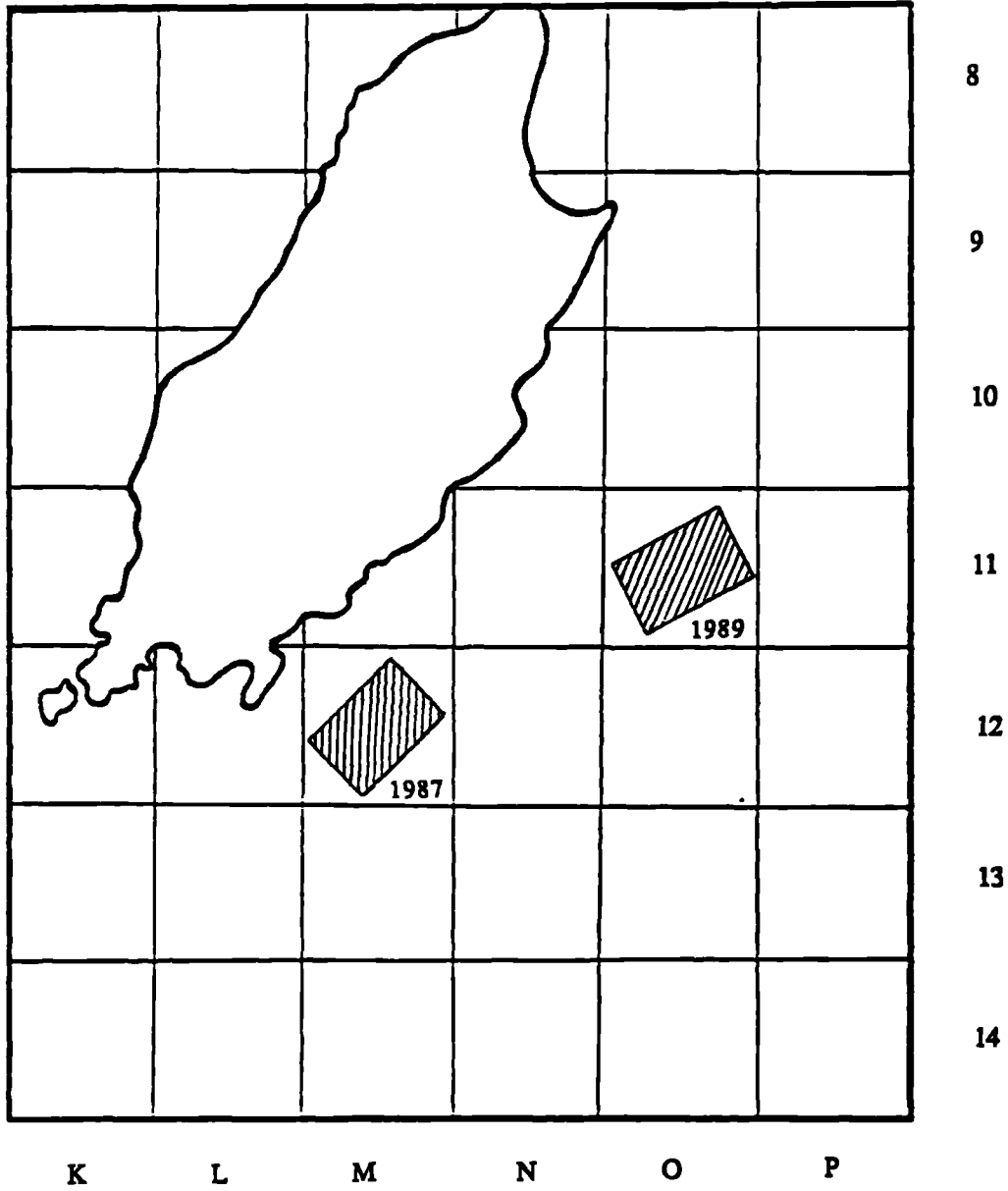
During the 1987 summer fishing season, only one tagged queen was returned, and only two queens have been returned subsequently (one live and one dead) from the 1987 release. In retrospect, it seems likely that the tag was not visible enough to be seen in the factories (where it was intended to be recovered), especially as many queens were being processed by machine rather than by hand at this time. It is also likely that the area was not as intensively fished as had been anticipated. A repetition of the same experiment was not deemed worthwhile, and several modifications were made to the experimental design before making another attempt in May 1989.

#### 5.2.1b. 1989 release

The R.V. Cuma was again used to catch queens for tagging and release. A better knowledge of the distribution of queen stocks and fishing effort led to the choice of a different release area (Fig 5.1), also to the south-east of Douglas but further offshore. The area was known to be fished throughout, with no wrecks, cables, brittle star beds or other obstructions to restrict the spatial distribution of fishing within the ground. Sampling this ground from commercial vessels the previous summer revealed an abundance of 1+ year class queens, likely to be fished heavily the following season.

Non-reporting of tags was thought to be a problem with the first tagging experiment, so for the 1989 release, streamer tags were used in addition to the numbered Petersen Disks. Streamers were cut from rolls of bi-coloured "Duoglo" plastic surveyors tape (fluorescent yellow and orange) supplied by local highway contractors Colas Ltd., Balthane Industrial Estate, Ballasalla, I.o.M. The streamers were 1 cm wide and 7-10 cm long. A hole was punched near one end of the streamer using a punch plier, and a brass eyelet was inserted into each streamer, and

**Fig. 5.1.** Fishing grounds over which tagged queens were distributed in 1987 and 1989 (shaded areas). Five nautical mile grid-squares are also shown.





crimped on using a combination eyelet plier (punch and eyelet pliers supplied by Mann Industrial Ltd., brass eyelets supplied by DTP Supplies, both of Spring Valley Industrial Estate, Isle of Man). The stainless steel wire used to affix the tag to the shell was then threaded through the Petersen Disk and the streamer tag, before threading it through the hole drilled in each shell. The brass eyelet was intended to prevent the wire cutting through the tape and losing the streamer. The tag was fastened through the anterior (right) auricle of the upper (ventral) valve of the shell.

Different capture and handling methods were also used to investigate some aspects of possible capture and tagging induced mortality. Queens were caught by both dredging and trawling, using the same fishing gear as in 1987. Some queens were tagged and released the same day as captured, and some dredged queens were transported from the fishing ground to the laboratory, where they were kept in circulating seawater for 32-36 hours. These were then tagged and returned to circulating seawater for a further 18-22 hours, after which they were transported back to the fishing grounds (2.5 hours steaming, during which the queens remained in pumped, circulating seawater). Moribund queens were removed before and after tagging, and before release. A summary of the capture and release data for both the 1987 and 1989 tagging experiments is given in Table 5.1.

#### 4.2.1c. Assessing tag loss, reporting rate and tagging-induced mortality

In order to assess the rate of tag loss, 100 queens tagged in 1989 were double tagged. The method of tagging was the same as for the single tagged animals, but the additional tag was attached to the left (posterior) auricle of the upper (left) valve. Loss of tags was assumed to occur immediately after release, with subsequent tag shedding considered to be negligible. Analytical methods were the same as those used in the analysis of the double-tagging experiment in Chapter 4.

No experimental work on reporting rate was carried out; the high visibility of the tag, together with the incentive of a £3.00 reward and extensive advertising by poster, letter, radio and TV was deemed sufficient to ensure that non-reporting of tags would be negligible. Fishermen were asked to record date and area of capture, the name of their vessel and whether the queen was alive or dead when they recaptured it. Poster advertising and personal communication were used to establish these information requirements, and recording sheets were sent to all

fishermen active in the queen fishery. Tags were collected personally from fishermen, or were brought to the laboratory or Fisherman's Association shop, together with completed recording sheets (sometimes).

Tagging-induced mortality was assessed by examining the shells of queens which were dead on recapture. If the hole where the shell was drilled did not show signs of shell growth, and the shell increased in length, the queen was assumed to have died as a result of tagging. Live queens recaptured between 7 and 10 days after release had already laid down new shell. All queens which were dead on capture during the first week were assumed to have died as a result of tagging. As the number of queens recaptured dead will depend on the exploitation rate, the numbers of queens which died as a result of tagging ( $T_{DT}$ ) are calculated from:

$$T_{DT} = \frac{R_{DT} T}{R} \quad (\text{Chapter 4, eqn. 4.4}) \quad (5.1)$$

Where  $R_{DT}$  = number of queens recaptured dead and assumed to have died as a result of tagging,  $R$  = total recaptures and  $T$  = total number tagged and released, corrected for tag loss.

#### 5.2.1d. Calculating exploitation rates, mortality rates and population size

In order to obtain a population size estimate from a single season's data following a single release, the Petersen or single census method is used (Ricker, 1975a, p77-78). Exploitation rate ( $u$ ) is estimated from:

$$u = \frac{R'}{T'} \quad (5.2);$$

where  $T'$  = number of fish marked (corrected for tag shedding and tagging induced mortality) and  $R'$  = number of recaptures (corrected for non-reporting).

An unbiased estimate of the population size at the time of release ( $N$ ) is given by:

$$N = \frac{(T'+1)(C+1)}{(R'+1)} \quad (5.3);$$

where C = catch or sample taken for census, in this case the total catch of queens taken by boats fishing the area where marked queens were released, obtained from sample fleet logbooks. Catches are reported in bags; samples taken from the M.F.V. 'Mathilde' on the same fishing ground from July-October 1988 contained approximately 1200 queens per bag. This figure is used to calculate sample fleet catch in numbers of queens. Sample-fleet catches ( $C_s$ ) are converted to total catches (C) for the area using the proportion of tagged queens which were recaptured by the sample fleet ( $R'$ :  $R'_s$ ):

$$\frac{C}{C_s} = \frac{R'}{R'_s}, \quad \therefore C = \frac{C_s R'}{R'_s} \quad (5.4)$$

The assumptions required are that there is no immigration, recruitment or emigration, that there is random mixing of marked and unmarked queens and that the catches of both tagged and untagged queens and the distribution of fishing effort of the sample fleet are representative of the whole fleet. Catch data are reported on the basis of a 5 Nautical mile square grid, and therefore correspond to the grid square within which the tagged scallops were distributed (the O11 square: see Data Collection Methods, p16 & Fig. 4). The estimates of catch and abundance apply to the whole square, not the area over which tags were distributed.

The variance of the exploitation rate ( $\sigma_u^2$ ) can be calculated from:

$$\sigma_u^2 = \frac{R'(C - R')}{T'^2 C} \quad (\text{Leslie, 1952}) \quad (5.5)$$

Confidence limits (95%) for N are obtained by assuming  $R'$  is distributed as a Poisson variable and using the tables in Ricker (1975a, Appendix II):

$$\alpha_{0.05}(N) = N + 1.92 \pm 1.960\sqrt{(N+1.0)} \quad (5.6)$$

Total, fishing and natural mortality rates (Z, F & M) are calculated from the rate of decline of recaptures (R) over the five months of the queen fishing season (June-October inclusive) using the log-transformation of the Beverton-Holt deterministic model (see Chapter 4) with the recapture period  $t = 1$  month.

$$\log_e(R'_t) = \log_e(R'_0) - Zt \quad (5.7)$$

Where the recapture period was not known within one month, the recaptures were partitioned according to the proportions of known-time recaptures during the possible months of recapture. Recaptures from November and December were not included in the regression as the majority of boats cease fishing for queens at the start of the scallop fishing season on November 1st (Brand & Allison, 1987). The regression of log-transformed recaptures on recapture period was weighted by the un-transformed recapture numbers (see Farebrother, 1992 and Chapter 4). The slope of the regression gives  $-Zt$ .  $F$  is calculated from the slope, intercept ( $R_0$ ) and the number of queens tagged and released, adjusted for tag-loss, non-reporting and tagging-induced mortality ( $T'$ ):

$$F = \frac{Z e^{(R_0 - Zt)}}{T'(1 - e^{-Zt})} \quad (\text{after Gulland, 1983}) \quad (5.8)$$

$M$  is then simply  $Z-F$ , although this will include  $F_i$  (indirect fishing mortality).

### 5.2.2. Total mortality rates from age-frequency distributions

The age-frequency distribution of queens captured for the tagging programme are used to provide rough estimates of total mortality rate ( $Z$ ) for the periods May 1986-87 and May 1988-89 by fitting a catch-curve to log-transformed frequencies of those age-classes fully recruited to the sampling gear.

### 5.2.3. Mortality from empirical models

Empirical models relating natural mortality to growth parameters, longevity, age at sexual maturity and temperature, found in the published literature, were used to calculate values of  $Z$  and  $M$  for queens from different fishing grounds in the North Irish Sea. The sources of the models and the equations themselves are given in 4.2.3, pp126-127. Growth parameter estimates were obtained from research vessel samples from the period January 1987-November 1989 (see Chapter 3). Age at maturity and gonado-somatic indices are obtained from samples taken at the start of the reproductive period (March-May) in 1987 and 1988. A bottom temperature of 10.4° C is assumed (see p127, Chapter 4).

**Table 5.1.** Date of capture, tagging and release and methods of capture for each batch of tagged queens. Batches released with different capture 'treatments' for the 1989 experiment are numbered 1-4.

Capture method	No.	Date caught	Date tagged	Date released	No. released	Tag numbers
Dredge		28 May 1987	28 May 1987	28 May 1987	600	0001-0600
Trawl		29 May 1987	29 May 1987	29 May 1987	400	0601-1000
Trawl	1	31 May 1989	31 May 1989	31 May 1989	520	1001-1520
Dredge	2	2 June 1989	2 June 1989	2 June 1989	80	1521-1600
Dredge	3	2 June 1989	4 June 1989	5 June 1989	272	1601-1872
Dredge	4	5 June 1989	5 June 1989	5 June 1989	128*	1873-2100*

\* includes 100 double tagged shells.

**Table 5.2.** Releases and recaptures of 1989-tagged queens, by capture treatment.

Batch No.	No. released	No. recaptured live	No recaptured dead
1	520	107	13
2	80	15	1
3	272	56	7
4	128*	25	9

\* includes 100 double tagged shells.



## 5.3. RESULTS & DISCUSSION

### 5.3.1. Tagging experiments

From 995 tagged queens released between May 31st and June 5th 1989, a total of 233 were recaptured during the 1989 fishing season (June - December). Of these, 203 were recaptured alive. In order to distinguish live from dead shells we relied partly on information supplied by fishermen, and partly on identifying the presence of epifauna on the inside of the shell (see Discussion, Chapter 4). Many of the recaptures were made soon after release, before epifauna would have colonised the inside of the shells, so fishermen's statements could not be independently checked in some cases.

Small-scale (less than 2 km) movements could not be investigated as information on the exact location of recaptures was not available. Recapture positions supplied by fishermen were generally only given to the nearest Decca sector (six by twelve nautical miles, or approximately 11 by 22 km, in this area), and tows made in this area generally last 2-3 hours, covering up to 6 km. No queens were reported as being recaptured further than 2 km from the release area, indicating no large-scale movement. The recapture of consecutively numbered tags in the same tows, even 2-3 months after release further indicate that active movement and dispersal of queen populations is unlikely. The tag was not thought to affect swimming ability; tagged queens held in large circulating seawater tanks in the laboratory were observed to swim as frequently as un-tagged animals. No difference in swimming ability (number of adductions, distance travelled) was noted. The tag, brass eyelet, streamer and wire weighed approximately 0.9 g - much less than the weight of epifauna commonly found on the shells of queens, which have been demonstrated to affect swimming ability (*Chapman et al.*, 1979).

Tags were returned by 24 vessels during the season. This represents approximately half the Manx queen-fishing fleet at the time, reflecting the importance of this ground to the queen fishery during the 1989 season. All but one of the tags were returned directly by the boats that recaptured them, confirming the high visibility of the tag. Only one was returned through a processing factory. Of these 24 boats, 5 had completed logbooks of their queen-fishing activities during the 1989 fishing season.

Exact day of recapture of returns was reported for 73 tags, the return date of 116 tags were reported to within one calendar month, with the return period for the remaining 44 tags being reported to within periods of 6 weeks to three months.

#### 5.3.1a. Estimation of reporting rate, tag-losses and tagging-induced mortality

The high visibility of the tag, the incentive of the £3.00 reward and the generally co-operative attitude of the Manx fishermen to tagging experiments conducted over the last 9 years all contribute to a high reporting rate. It is likely that the only tags caught by the Manx boats which we did not receive are those that were lost accidentally. The principal cause of loss was due to herring gulls taking tags from the deck while the catch was being sorted; reports were received of between 5 and 10 tags being lost in this way, so, with recaptures of 233 queens being recorded, reporting efficiency can be taken as 96-98%. No tagged queens were returned from outside the Isle of Man, and it is not known whether Scottish and English vessels fished the East Douglas queen grounds, or if they had captured tagged queens, whether they would go to the trouble of returning them. Tagged *Pecten maximus* were received from outside the Isle of Man (see Chapter 4) but the reporting rate of these tags was not known.

Tag-loss was determined by double-tagging 100 of the 995 tags released. Of these, 26 were returned; 24 still carried both tags, the other 2 had lost the anterior tag. If this loss is considered to occur immediately after release, with negligible subsequent losses (a reasonable assumption, as the tag becomes more securely attached as new shell is laid down over the drilled hole) this gives a probability of loss of the anterior tag of 7.7%, and zero probability of loss of the posterior tag, and therefore of both tags. The small number of tags involved do not allow the conclusion that anterior tags are more likely to be shed than posterior tags. In calculating the number of tagged queens available at the start of the recapture period, 7.7% of single-tagged scallops are assumed to have been lost from the tagged population with no losses from the double-tagged population. Tag-losses were assumed to be independent of age.

In order to assess if the method of capture and subsequent treatment of each batch of tagged queens affected their rate of survival of the tagging process, the relative frequencies of the live and dead recaptures from each batch released were compared by a log-likelihood ratio (G-test: Zar, 1984) with the null hypothesis of



no difference in the relative frequency of live and dead recaptures among the four treatments, and the alternative hypothesis that the method of capture and subsequent handling affected the survival probability of the tagged queens. The null hypothesis was accepted ( $G = 5.750$ ,  $v=3$ ,  $p 0.10 < 0.25$ ) so estimates of mortality due to tagging were calculated on the basis of pooling all dead recaptures. Total release numbers, with dead and live recaptures, are given in Table 5.2.

Of 30 tagged shells dead on recapture, 26 died as a result of tagging (as defined above), 3 were returned without the shell (cause & time of death unknown), and 1 died towards the end of the fishing season, having completed the majority of one seasons' growth in shell length. With 995 tags released, and a total of 233 recaptures, tagging induced-mortality calculated from equation 5.1 is of the order of 11.2-12.5%. This is likely to be a minimum estimate as the capture efficiency of dead shells is probably lower than for live shells - especially for boats fishing with nets, where the fishing line of the net is above the substrate much of the time, taking only actively swimming queens or those thrown up by the pressure wave which precedes the arrival of the fishing line of the trawl. A figure of 11.9% is assumed for the calculation of the number of tags available at the start of the fishing season.

After taking into account the losses associated with the tagging process (tag-shedding and mortality due to tagging) the initial number of tagged queens used for calculating exploitation rates, mortality and population size was 824 (see Table 5.3). Recorded recaptures were increased by 3% to account for non-reporting.

#### 5.3.1b. Exploitation rate, mortality and population size estimates

Calculated exploitation rates by age are given in Table 5.3. No trend in exploitation rate with age is noted, and the population structures of the marked and recaptured samples are not significantly different (comparison of medians test, Mood, 1950;  $p < 0.05$ ). Overall exploitation rate is calculated as 25.4% for the season (June-December). Variances are low, as recapture rates are high.

The sample fleet catch for square 011 during June - December 1989 was estimated as 1 641 100 queens and as the sample fleet captured 32 of the 203 live recaptures (33 of 209, when non-reporting is taken into account) the total-fleet catch is estimated as 10 393 600. The size of the population in statistical square 011 in

June 1989 is calculated as 40 832 000 queens  $\pm$  12 526 (Table 5.3). This gives a mean density of 0.47 queens  $m^{-2}$ . This density is lower than estimates of queen density over fishing grounds off Guernsey (5.7-6.1  $m^{-2}$ ; Askew *et al.*, 1973) and SW England (1-4  $m^{-2}$ ; Pickett & Franklin, 1975b). It is likely that not all areas of the square will support commercially exploitable populations, so actual densities within the fished parts of the square (area unknown) are likely to be higher. Pickett & Franklin (1975b) report densities of 20 queens  $m^{-2}$  on dense beds within fishing grounds. Without more detailed survey data, however, assessments in this fishery will have to be made on the basis of the 5 nautical mile square grid.

The confidence limits on N are small, but may be misleading; they are calculated with the assumption that C is known exactly, which is not the case in this experiment. The calculated value of C is sensitive to the assumed number of queens per bag landed, which may vary between boats, and to correct reporting of catches. Examination of data from logbooks in conjunction with tag-returns show many discrepancies between reported tag-recapture areas and dates, and dates and fishing areas reported in logbooks, indicating that one or both datasets are incorrectly recorded by fishermen.

Recaptures of tagged queens in each month, used for the calculation of mortality rates, are given in Table 5.4. Recaptures in the early part of the season are high, with a large drop between July and August, probably reflecting a reduction of fishing effort as the heavy exploitation of the ground early in the season causes boats to move, either to different parts of the same ground, or to other areas. Only 5 vessels from the sample fleet fished the area during the 1989 fishing season, and the data from some of these vessels show inconsistencies. Weighting recaptures by fishing effort to calculate mortality rates (Jones, 1977) was not possible as the data are not sufficient. Mortality rates calculated from the log-linear regression model, weighted by recaptures (Fig. 5.2.) are  $Z=0.41 \text{ month}^{-1}$ ,  $F = 0.21$ ,  $M = 0.20$ . The estimate of M is probably too high, as it will include indirect or non-yield fishing mortality ( $F_i$ ; see Chapter 4 for discussion). Extrapolation to annual instantaneous rates is problematical as F, and therefore the  $F_i$  component of the calculated M, are highly seasonal (Brand & Allison, 1987). If all fishing is assumed to occur in the June - October period,  $F (\text{year}^{-1}) = 1.06$ , and if M is assumed to be constant throughout the year, a very high value of  $M = 2.37$  is obtained. The latter value is clearly unrealistic for a species which lives to an age of 6-8 years (Hoenig, 1983) and indicates that either M ( $\text{month}^{-1}$ ) is overestimated or  $F_i$ , included in M, is both substantial and highly seasonal.

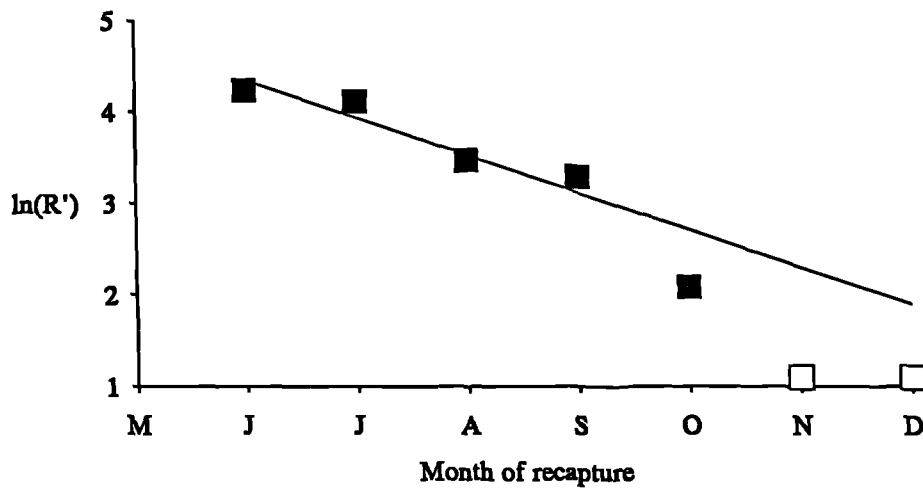
**Table 5.3.** Age-specific estimates of population size and exploitation rates, from sample fleet catch statistics and recapture of tagged queens, June-November 1989. The data shown are: tag releases (T), releases corrected for tag-loss and tagging induced mortality (T'), tagged queens recaptured dead (R<sub>D</sub>), live recaptures by the sample fleet (R<sub>S</sub>' - corrected for non reporting; 3%) and total recaptures (R, R' - corrected for non-reporting), sample fleet catches (C<sub>S</sub>) and estimated total fleet catches (C), estimated exploitation rate  $\mu$ , and initial population size (N). The variance of  $\mu$  and 95% confidence interval for N are also shown.

AGE	T	T'	R <sub>D</sub>	R <sub>S</sub> '	R	R'	C <sub>S</sub>	C	$\mu$	$\sigma^2(\mu)$	N	95%CI (N $\pm$ )
1	9	7	1	0	2	2	15 704	99 460	0.286	0.0408	265 230	1 011
2	450	372	9	13	85	88	690 988	4 376 256	0.237	0.0006	18 340 942	8 396
3	345	286	10	12	73	75	588 910	3 729 764	0.262	0.0009	14 084 769	7 358
4	142	118	6	6	35	36	282 677	1 790 287	0.305	0.0026	5 757 952	4 705
5	37	31	2	1	5	5	39 261	248 651	0.161	0.0052	1 326 144	2 259
6	11	9	2	0	3	3	23 556	149 191	0.333	0.0370	372 979	1 198
7	1	1	0	0	0	0			0.000			
Total	995	824	30	33	203	209	1 641 096	10 393 608	0.254	0.0003	40 832 035	12 526

**Table 5.4.** Recaptures of tagged queens by month, June - December 1989.

Month	No. Recaptures (R)
June	69
July	61
August	32
September	27
October	8
November	3
December	3

**Fig. 5.2.** Log-transformed tag-returns plotted against month of recapture, 1989. The fitted line is the weighted (tag numbers as weights) regression line of slope  $(-Zt) 0.409$ , and intercept  $(R_0) 4.554$ ;  $r^2 = 0.869$ . Returns from November and December are not used in the fitting of the regression equation.



### 5.3.2. Total mortality rates from age-frequency distributions.

Values of  $Z$  ( $\text{year}^{-1}$ ) calculated from age-frequency distributions are 0.43 for queens aged 3-6 and 1.83 for ages 6-8 for queens from the fishing ground in the M12 grid-square (see Fig. 5.1), south-east of Douglas ( Fig. 5.3a). The increase in mortality rate at age 6 suggests the onset of senescence: other short-lived scallop species also show senescent mortality beyond certain ages (Bricelj *et al.*, 1987a; 1987b). The relatively low annual instantaneous rate of total mortality for ages 3-6 suggests that fishing mortality was very low on this ground during the previous year, and that the value of  $Z$  approaches that of  $M$ . This implies that the high value of  $M$  obtained from the tagging experiment is not realistic.

The 'offshore' Douglas ground was fished regularly by several boats during the 1988 fishing season, and this is reflected in the higher total mortality rate for ages 3-6, obtained from the age-frequency distribution of samples taken in May-June 1989 (Fig 5.3b). The value of  $Z = 1.17$  is similar to the calculated  $F$  ( $\text{year}^{-1}$ ) from the tagging experiment, but it is likely that fishing effort on this ground was less in 1988 than in 1989. The calculated value of  $M$  from tagging experiments ( $2.37 \text{ year}^{-1}$ ) exceeds both age-frequency derived estimates of  $Z$  and is likely to be grossly overestimated.

The problems encountered in obtaining estimates of population size and mortality rates are due to difficulties in getting accurate catch and effort data, rather than any shortcomings in the marking and release procedure. The method of tagging used in 1989 appears to be suitable for use on this species; rates of returns were high and rates of tag-loss, non-reporting and tagging-induced mortality are all relatively low. Multiple release methods which place less reliance of catch and effort data (Ricker, 1975a; Seber, 1982, for reviews) may provide more reliable estimates of mortality rates.

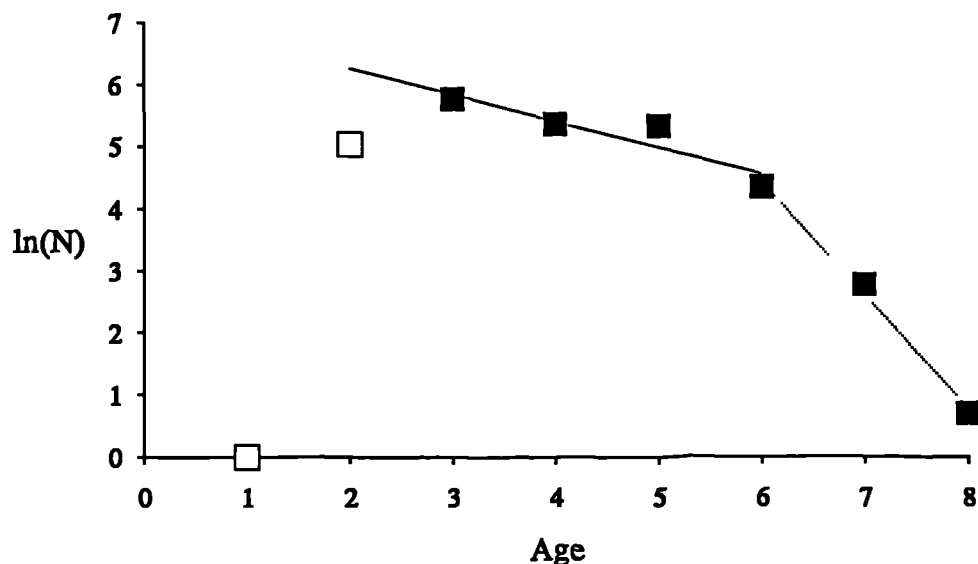
### 5.3.3. Mortality rates from empirical models

Values of  $M$  from empirical models show large variation (Table 5.5). The highest values, in the range 0.68 - 1.88, are given by the Beverton & Holt (1959) model relating  $M$  to the von-Bertalanffy growth coefficient  $k$ . The lowest estimates (0.037 - 0.042) are those from the model of Taylor (1960), relating maximum size to  $M$  in molluscs. The Pauly model (Pauly, 1980) gives values in the range 0.48 -

0.70. This model gave unrealistically high values of M for *Pecten maximus* (Chapter 4), but the values of M calculated here accord with previously assumed or estimated values for *Chlamys opercularis* (see 5.1). Models based on the linkage between reproductive investment and mortality (Rikhter & Efanov, 1976; Gunderson & Dygert, 1988) give lower estimates of M (0.09 - 0.30). These models provided realistic values of M for *P. maximus*, but provide estimates lower than any previously suggested for *C. opercularis* species. The large range of estimates generated here, and paucity of reliable estimates in the literature, make the choice of a value of M for use in assessments problematical.

**Fig. 5. 3.** Catch-curves fitted to log-transformed age-frequency distributions from two queen fishing grounds off Douglas. Data are research vessel samples collected for queen tagging experiments.

a) East Douglas 'Briar' ground, May 31st 1987. Regression equations are fitted to ages 3-6 and 6-8, as mortality increases with age; mortality rates are obtained from the slope of the regression. The equation for ages 3-6 is  $N_t = 7.119 - 0.425 \cdot \text{Age}$  ( $r^2 = 0.768$ ) and the equation for ages 6-8 is  $N_t = 15.430 - 1.832 \cdot \text{Age}$  ( $r^2 = 0.988$ ).



b) East Douglas 'offshore' ground, May 31st - June 5th 1989. The regression equation, fitted to ages 3-6 is  $N_t = 9.459 - 1.168 \cdot \text{Age}$  ( $r^2 = 0.990$ )

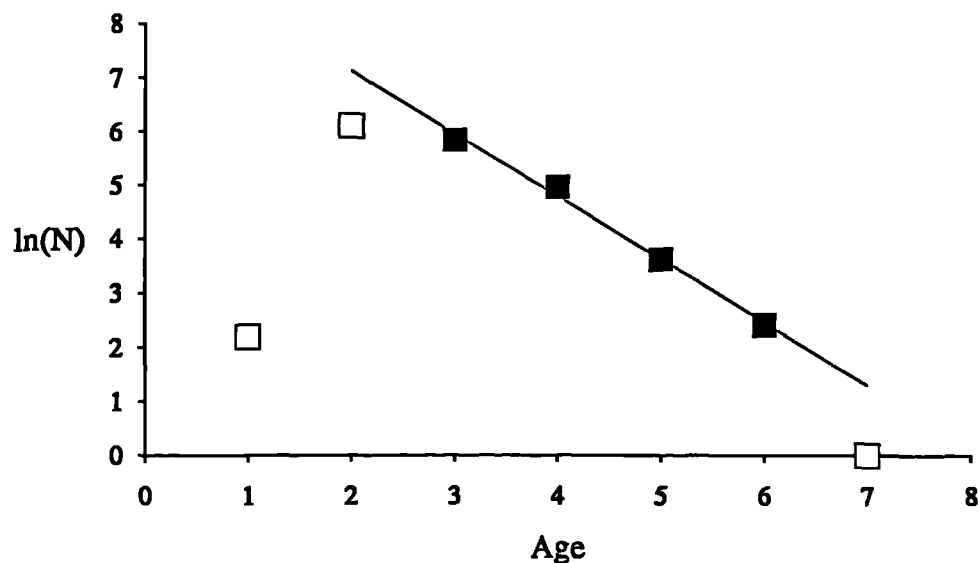


Table 5.5. Natural mortality rate (M) and total mortality rate (Z) of queens, estimated from empirical models. Data required to generate the estimates are also shown. Estimates relate to the period 1987-89.

Area	L <sub>inf</sub>	k	tmax	tm50	WGSI	Beverton & Holt (1959)		Taylor (1960)	Pauly (1980)	Rikhter & Efanov (1976)	Gunderson & Hoenig (1983)	
						lower M	upper M				M	Dyggert (1988)
TG	85.74	0.753	6	10	0.045	1.13	1.88	0.037	0.70	0.30	0.11	0.77
PA	80.88	0.738	6	10		1.11	1.85	0.039	0.70	0.30		0.77
RB	83.05	0.55	5	10	0.043	0.83	1.38	0.038	0.57	0.30	0.10	0.90
MG	82.58	0.45	4	10		0.68	1.13	0.038	0.50	0.30		1.08
ED	78.91	0.687	5	10		1.03	1.72	0.040	0.67	0.30		0.90
SED	75.13	0.693	7	10	0.034	1.04	1.73	0.042	0.69	0.30	0.09	0.68
H/I	81.04	0.553	7	10		0.83	1.38	0.039	0.58	0.30		0.68
PSM	84.98	0.418	6	10	0.039	0.63	1.05	0.037	0.48	0.30	0.10	0.77

L<sub>inf</sub> = asymptotic length from Von Bertalanffy growth function

k = Brody-Bertalanffy growth coefficient.

tmax = age of oldest queens in samples

tm50 = age at which 50% of queens are mature (months)

WGSI = wet-weight gonado-somatic index.



## 5.4. CONCLUSIONS

1. The capture, handling and tagging procedures used in the 1989 experiment are appropriate for use in large-scale mark-recapture experiments on this species, as evidenced by the high recapture rates and apparently low rates of non-reporting, tag-losses and tagging-induced mortalities.
2. The failure of the 1987 experiment is ascribed to the low visibility of the Petersen Disk tag, and to the choice of an inappropriate release area.
3. No large-scale directed migration of queens has been observed.
4. During the 1989 fishing season, 25.4% of the initial stock on the 'Offshore' Douglas queen-fishing ground was caught and landed.
5. Estimates of population size from the Petersen or single-census method are dependent on the reliability of the commercial catch-statistics, particularly on catches and fishing effort being assigned to the correct grid-square.
6. Estimates of mortality rates from the decline of recaptures over the fishing season, weighted by the number of recaptures, give an estimate of  $F = 0.21 \text{ month}^{-1}$  or  $1.06 \text{ year}^{-1}$ . Calculated values of  $M$ , which will include  $F_t$ , are unrealistically high ( $M = 0.19 \text{ month}^{-1}$ ,  $2.37 \text{ year}^{-1}$ ). Short-term fluctuations in fishing effort are likely to have a significant effect on recapture rates and it would be better to weight recaptures by monthly fishing effort. Sample fleet fishing effort data were not sufficient to undertake the analysis.
7. Age-frequency distributions show that beyond age six, there is an increase in mortality rates, possibly due to the onset of senescence.
8. Empirical models give widely fluctuating estimates of  $M$ , and the choice of a value of  $M$  for stock assessments is difficult. Values in the range  $0.2 - 0.5 \text{ year}^{-1}$  have been chosen, based on: the value of  $Z = 0.43$  obtained from a catch-curve for a lightly exploited ground, the fact that the longevity of queens is approximately half that of scallops (so the mortality rate should be about double), and the range of values obtained from empirical models.

## **CHAPTER 6: ASSESSING THE STOCKS OF *PECTEN MAXIMUS* AND *CHLAMYS OPERCULARIS* IN THE NORTH IRISH SEA.**

### **6.1. INTRODUCTION**

The assessment of stocks of shellfish is conventionally thought to present especial problems which render the application of conventional fishery models inappropriate (Hancock, 1973; 1979; Caddy, 1989a; Orensanz *et al.*, 1991). There are various aspects of shellfish biology which complicate assessments. Many shellfish species have limited mobility and are patchily distributed, with fishing concentrated on the high-density patches (Caddy, 1975; Allen, 1975), rather than at random over the stock. Molluscs and crustaceans often have protracted pelagic larval phases which tends to result in a high degree of recruitment variability, both temporal and spatial (e.g. Dickie, 1955; Rothlisberg *et al.*, 1983; Fogarty, 1988). The density-dependence of population processes such as recruitment, growth and mortality (e.g. Murawski & Serchuk, 1984; Gruffydd, 1974b and Orensanz, 1986), and the dependence of these processes on locally variable environmental factors (e.g. substrate type, temperature and salinity) compound the variability. Within a stock, which conventional fishery models would assume to be homogenous ('dynamic-pool' assumptions), the basic parameters of recruitment, growth, natural and fishing mortality are thus likely to be highly heterogeneous.

Despite widespread recognition of the problems in applying dynamic pool models to shellfish populations, most of the world's major scallop stocks are assessed using these conventional fishery models (Dao *et al.*, 1975; Serchuk *et al.*, 1979; Naidu *et al.*, 1982; Caddy, 1989b; Mohn *et al.*, 1989; Mason *et al.*, 1991). The apparently diverse array of assessment methods that have been applied to scallop and other shellfish stocks (see Caddy, 1989a, for review) are, without exception, simply methods of accounting for heterogeneity in the input parameters required for conventional dynamic-pool or cohort analyses.

Although no new class of models has arisen from the now extensive body of work on shellfish stock assessment, quantifying and modelling spatial and temporal heterogeneity in shellfish populations has led to a greater understanding of the mechanisms of population regulation in exploited invertebrates (e.g. the work of Caddy (1975) on the great scallop *Placopecten magellanicus*, Allen (1979) on the dredge oyster, *Ostrea lutaria*, Sluczanowski (1984) on *Haliotis* (abalone) species, Orensanz (1986) on *Chlamys tehuelcha* d'Orbigny, and Phillips and Brown (1989)

on the Western Australian rock-lobster). This improved understanding of shellfish fishery and population dynamics has been helpful in translating the results of stock-assessments into management action (see Jamieson & Bourne, 1986 and Caddy, 1989a for reviews and case-studies).

In this work, spatial heterogeneity of dynamic processes is taken into account in the application of conventional stock assessment techniques. First, total landings statistics for the Manx and U.K. pectinid fisheries in the North Irish Sea are collated, and compared with other European scallop fisheries. Spatial distribution patterns of scallop catches and fishing effort, obtained from fishermen's logbooks (see p 15-17) are then examined to establish the location of major fishing grounds and to monitor the distribution of fishing activity by the Manx fleet. Catch rates (catch per unit effort or CPUE) by area are analysed as indicators of changes in stock-abundance on the major fishing grounds. Estimates of total catch and effort by the Manx scallop fleet and stock abundance of scallops are calculated from sample-fleet catches (catches from boats completing logbooks) and from tag-recaptures. Also included is an analysis of how catch-effort data could be used to develop yield-models and cohort models for application to these fisheries.

Yield per recruit (Y/R) and spawning-stock biomass per recruit (SSB/R) are used together with auxiliary information on catch-rates to make recommendations for the management of the stocks of scallops and queens in the North Irish Sea. By applying separate models to individual fishing grounds within the stock, the spatial heterogeneity of growth rates can be included in the assessment, and information on the spatial variations in fishing mortality rate are used to suggest an appropriate overall management strategy.

The type of data-collection programme and analysis being undertaken on the North Irish Sea scallop stocks is similar in many respects to the scallop assessments carried out on the *Amusium japonicum balloti* Bernardi stocks in northern Queensland, Australia (Dredge, 1985; 1988; Williams & Dredge, 1981) where biometric sampling and tagging studies support a fishermen's logbook data collection system which does not provide complete and accurate records. The stock is managed using recommendations resulting from Y/R analysis (Dredge, 1985) and monitoring of stock-size from log-book and survey catch-per-unit-effort (Dredge, 1988).

The *Placopecten magellanicus* fishery on the Canadian portion of Georges Bank, probably the best documented scallop stock in the world, is assessed through a logbook programme (all boats complete logbooks) and extensive annual research-vessel surveys (Robert & Jamieson, 1986; Mohn *et al.*, 1988; 1989). Assessment studies in this stock use research-vessel surveys to contour abundance-at-age values over the whole of the fishing area. Logbook data and port-samples of landed, shucked scallops are used together with the age-structure data to obtain catch-at-age matrices by area, which are then summed and used in a cohort analysis (VPA) to calculate F-at-age. The pattern of F-at-age is used to calculate Y/R and spawning-stock biomass per recruit (SSB/R) which are then coupled with estimates of recruitment and biomass from research vessel surveys to forecast yield and biomass under different management regimes.

The most advanced scallop fishery assessments in Europe are those on the largest stocks. The French stocks of *Pecten maximus* are assessed by annual surveys of the grounds which are used together with Y/R and SSB/R models and economic data from the fishing fleet to set target values of fishing mortality for the next fishing season (Dao *et al.*, 1975; Ansell *et al.*, 1991). Mason *et al.* (1991) have recently published a VPA assessment of the *P. maximus* stocks off Kintyre, Scotland, which does not account for spatial heterogeneity in the catches-at-age or other parameters. The data requirements for the model are limited (catch and age-structure data for the whole stock), but estimates of F appear reasonable.

Of the other stocks of scallops around the world, many are sporadic and are managed on an *ad-hoc* basis. Assessments are normally restricted to identifying the presence of strong year-classes in the fishery from research-vessel samples, or occasional stock surveys to locate concentrations of scallops (e.g., Young & Martin's, 1989, review of Australian scallop fisheries). For stocks which are persistent and provide reasonably regular catches, Y/R analysis (without the prior application of VPA) of varying sophistication is the primary assessment method (e.g. Mason *et al.*, 1979c; Serchuk *et al.*, 1979; Naidu *et al.*, 1982; Lanteigne *et al.*, 1986; Murphy & Brand, 1987).

The previous assessment studies on North Irish Sea scallops reflect the relative importance of the stock to the nations assessing it. The small, localised Northern Ireland stocks are surveyed occasionally, and research-vessel CPUE is used as an index of abundance (Briggs, 1987; 1991). The short-lived but valuable Cardigan Bay fishery was surveyed by MAFF (Franklin & Connor, 1980), and a

Y/R analysis was applied retrospectively by Bannister (1986). The research programme funded by the Isle of Man Department of Agriculture and Fisheries has led to a detailed study of the Manx fishery in 1981-84 by Murphy (1986) and a Y/R analysis for five Manx fishing grounds carried out by Murphy and Brand (1987). Earlier work on these stocks (see Introduction, pp 2-4, for review) estimated many of the parameters useful for stock assessments, but no assessment models were used.

Stocks of queens (*Chlamys opercularis*) were surveyed in 1972 by Soemodihardjo (1974) who summarised catch-rates at sample stations throughout the North Irish Sea. A Y/R assessment of the North Irish Sea fishery, based on sampling catches from the Scottish fishery, was carried out by Mason *et al.* (1979c).

The Y/R analyses on scallops presented here are updates and refinements to the analyses of Murphy (1986) and Murphy and Brand (1987). The changes made for this analysis include the use of the total edible yield (adductor muscle + gonad), rather than the weight of the adductor muscle only, the use of a recruitment ogive rather than the assumption of knife-edge recruitment, and the use of maturity-at-age data so that spawning stock biomass per recruit can be calculated, rather than biomass per recruit as an approximation to it.

The Y/R analyses are used to assess the state of the major scallop fishing grounds (and one queen-fishing ground) in the North Irish Sea scallop stocks, and make recommendations for the management of the fishery. In making recommendations on optimum fishing mortalities from Y/R analyses, two target-levels of fishing mortality are referred to:  $F_{max}$  (Beverton & Holt, 1957), the level of fishing mortality that maximises yield per recruit for a given size at first capture; and  $F_{0.1}$  (Gulland & Boerma, 1973; Gulland, 1984), approximately defined as the level of  $F$  which has a catch rate of one-tenth of the theoretical rate for a virgin fishery (Mohn, 1986). Fishing at  $F_{max}$  is thought to lead to recruitment overfishing (Deriso, 1987), so  $F_{0.1}$  is normally recommended as the level of  $F$  to aim for to obtain high yield per recruit, while maintaining reasonably high spawning stock biomass and stock abundance (and therefore catch-rates).  $F_{0.1}$  is always lower than  $F_{max}$ , and although it has no explicit biological significance, it is thought to take approximate account of likely stock-recruitment relationships, and arguably, of economic factors (Gulland & Boerma, 1973).  $F_{0.1}$  is used as a target fishing mortality rate in many important fisheries world-wide (Patterson, 1991, for review) including the Canadian Georges Bank scallop fishery (Mohn *et al.*, 1989).

## 6.2. METHODS

### 6.2.1. Analysis of fishery statistics

An overview of the status of the Isle of Man-based fisheries for *Pecten maximus* (scallops) and *Chlamys opercularis* (queens) is provided by summaries of catch-statistics for these species. Landings (in tonnes liveweight) to the Isle of Man for the years 1969-89 were obtained from statistics collected by the Isle of Man Department of Agriculture and Fisheries, based on sales of scallop meats declared by fish processors (see Data Collection Methods, p15). All catches landed to the Isle of Man were caught in ICES area VIIa (the Irish Sea, from latitude 52 ° N to 55 ° N). Scallops and queens caught in area VIIa and landed to England & Wales, Scotland, Eire and Northern Ireland were obtained from the ICES Bulletin Statistique (1987) - the latest edition available, as of July 1992. Catches for Ireland (N. Ireland and Eire combined) are available for 1972-86 and catches from Scotland, England and Wales are available for 1974-87. Prior to 1974, landings of scallops and queens were not recorded separately by these nations.

Total landings of scallops and queens to the ICES area (the Western European continental shelf) by country are also summarised to show the importance of the Manx and area VIIa fisheries relative to other fisheries for these species.

### 6.2.2. Sample fleet catch-effort data

Since 1981, catch-effort statistics have been collected from the Isle of Man fishing fleet by the distribution of log-books which are returned on a voluntary basis with a small financial incentive for satisfactory completion. Details of the information recorded are given in the Data Collection Methods, pp 15-16.

Annual summaries of *P. maximus* catches (tonnes liveweight), fishing effort (m of dredge towed × hours fished) and catch per unit effort (scallops m<sup>-1</sup>hr<sup>-1</sup>) have been calculated for each grid square fished by the sample fleet (those boats completing logbooks) for all fishing seasons from 1981/2 to 1989/90. The data are used to identify major scallop fishing grounds, monitor changes in stock abundance through changes in catch per unit effort (CPUE), and assess changes in the spatial distribution of fishing activity and stock sizes from year to year.

Annual summaries of queen catches from 1981-89 are also presented, providing the first indication of the location of major queen fishing grounds in the North Irish Sea.

### 6.2.3. Population size estimates, *Pecten maximus*

Estimates of population size for 5 nautical mile grid-squares encompassing major scallop fishing grounds have been calculated for the 1986/7, 87/8, 88/9 and 89/90 fishing seasons using CPUE-based density estimates. Mean scallop densities in a grid square were calculated from:

$$\text{Density} = \frac{\text{CPUE} / \text{Gear efficiency}}{\text{Distance covered in 1 hr fishing}} \quad (6.1)$$

CPUE was obtained from log-books, a value of 20% gear efficiency was assumed, and a towing speed of 1.5 Kts (2.78 km hr<sup>-1</sup>) was used to calculate the distance covered in 1 hr fishing (see Chapter 2, section 2.2.4, pp 31-32). Calculated densities were used to estimate stock abundance per grid square, using the area of each square (86 x 10<sup>6</sup> m<sup>2</sup>). Densities and abundance-at-age have already been presented in Chapter 2, Tables 2.8 and 2.9.

CPUE-based estimates, which assume even distribution over the whole grid square, are compared with Petersen estimates of population size obtained from catch data and tag returns:

$$N = \frac{(T'+1)(C+1)}{(R+1)} \quad (6.2)$$

Estimates of population size (N) for grid-squares over which tagged scallops were distributed are obtained for the 1987/8 and 1988/9 fishing seasons from first-year recaptures (R') of scallops marked and released in July 1987 and June 1988 (T'). Release numbers are corrected for tagging-induced mortality and tag-loss; non-reporting of recaptures is considered to be negligible. Total catch (C) is estimated from sample-fleet catches and the ratio of tag recaptures by the sample fleet to tag recaptures by the rest of the fleet (see Chapter 5, 5.2.1d, pp 156-157).

#### 6.2.4. Yield per recruit and biomass per recruit analyses

Yield per recruit (Y/R) and spawning stock biomass per recruit (SSB/R) analyses were carried out on six *Pecten maximus* sub-stocks and one *Chlamys opercularis* sub-stock. The areas chosen are major fishing grounds for which growth and mortality data are available. The yield per recruit equation chosen for the analysis was the Thompson-Bell formulation of the yield equation (Thompson & Bell, 1934; Pitcher & Hart, 1982):

$$Y/R = \sum_i \left[ 1 - \exp^{-Z_i} \frac{F_i}{Z_i} \bar{W}_i \right] \quad (6.3)$$

$$SSB/R = \sum_i \left\{ \exp[-\sum_i Z_i] \bar{W}_i \right\} \quad (6.4)$$

A BBC microcomputer program (programmed by A.B. Bowers) was used to calculate Y/R and SSB/R for fishing mortality rates in the range  $F = 0.0 - 2.0$ , with a step value of 0.1.  $F$  values were adjusted by a recruitment ogive to give  $F$  for each age class ( $F_i$ ). The required inputs for the Y/R and SSB/R models were: the recruitment ogive (the proportion of each age-class  $\geq$  the chosen size of first capture), the maturity ogive (the proportion of each age-class which had attained sexual maturity), the mean weight-at-age  $\bar{W}_i$ , and a single age-independent value of  $M$  (the instantaneous rate of natural mortality). Also required for the calculation of SSB/R were the proportion of  $F$  and  $M$  which took place before spawning each year. As spawning takes place mainly during June to August and the scallop fishing season takes place from November to May, it was assumed that all fishing took place before spawning, *i.e.* the spawning stock biomass was calculated at the end of each fishing season. For queens, the majority of fishing takes place immediately after the main spawning season, so 90% of fishing was assumed to occur after spawning.  $M$  was assumed to occur simultaneously with  $F$  in both cases.

For this analysis, the proportions of each age-class recruited to the fishery were calculated from length-age data collected by the R.V. "Cuma" during 1987-1989. Empirical data were used directly; no recruitment curve or ogive was fitted. Maturity-at-age data were also taken from research vessel samples, with gonad



stages 5-7 representing mature scallops, and stages 4-6 representing mature queens (see Chapter 3, Fig. 3.2).

Weights-at-age for scallops were calculated from von Bertalanffy growth function (VBGF) parameters fitted to length-at-age data from the winters of 1987/8, 1988/9 and 1989/90, and the length-weight relationship (see Chapter 3). For the assessment of the East Douglas stock of queens, weights-at-age were derived from a VBGF fitted directly to weight-at-age data collected during the 1988 fishing season (June-October). Although the Thompson-Bell equation allows the use of empirical weight-at-age data, values derived from growth curves were used here. Growth curves fitted the data well, and use of these values has the effect of smoothing irregularities in the Y/R curves which would occur if the empirical data were used. For scallops, the weights-at-age used are total edible yield (gonad + adductor muscle weights). For queens, both total edible yield and adductor muscle weights have been used as this species is marketed either roe-on or roe-off.

A value of  $M = 0.15$  was chosen for scallops (see Chapter 4), but values in the range 0.10 - 0.30 are used to examine the effect of different values of  $M$  on the Y/R and SSB/R calculations. For queens, a value of  $M = 0.30$  is chosen (see Chapter 5), and a range of values from 0.20 - 0.50 is used to examine the effect of different values of  $M$  on the Y/R and SSB/R calculations.

For each area, Y/R and SSB/R curves for scallops are calculated for sizes of first capture of 100, 105, 110 (the current minimum legal size of first capture), 115 and 120 mm. These values cover the range of minimum first-capture sizes likely to be acceptable to the fishing industry, should any change be suggested. The lower end of the range represents the EEC minimum legal landing size for scallops. A range of minimum landing sizes of 40-65 mm is used for queen scallops, with 55 mm queens being the size considered to be the minimum currently acceptable to Manx processors.

All input data on the proportions of each year class that are recruited to the fishery at different sizes of first capture on each fishing ground are listed in Table 6.1. The proportions of mature scallops and queens in each age-class are also shown. Input weight-at-age data for each fishing ground are given in Table 6.2.

The output Y/R and SSB/R curves, together with estimates of  $F_{\max}$  and  $F_{0.1}$ , are used to assess the optimum size at first capture for each fishing ground studied.

Table 6.1. Maturity and recruitment ogives (proportions) for input into YPR and BPR, 1987-89 data (Lc = length of 1st capture (mm)).

Bradda Head - scallops.

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120	Lc=125
1	0	0	0	0	0	0	0
2	0.25	0	0	0	0	0	0
3	0.95	0.61	0.31	0.10	0.02	0	0
4	1	0.97	0.92	0.76	0.48	0.23	0.07
5	1	1	0.99	0.96	0.85	0.58	0.30
6	1	1	1	0.99	0.90	0.75	0.49
7	1	1	1	1	0.96	0.87	0.58
8	1	1	1	1	1	0.96	0.61
9	1	1	1	1	1	1	0.85
10	1	1	1	1	1	1	0.95
11	1	1	1	1	1	1	0.99
12+	1	1	1	1	1	1	1

The Targets - scallops.

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120	Lc=125
1	0	0	0	0	0	0	0
2	0.70	0.30	0.08	0.02	0	0	0
3	1	0.98	0.95	0.84	0.58	0.28	0.06
4	1	1	1	0.97	0.94	0.79	0.94
5	1	1	1	1	1	0.98	0.99
6	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1
12+	1	1	1	1	1	1	1

South-east Douglas - scallops.

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120	Lc=125
1	0	0	0	0	0	0	0
2	0.20	0	0	0	0	0	0
3	0.87	0.15	0.01	0.01	0	0	0
4	0.97	0.79	0.49	0.19	0.05	0	0
5	1	0.99	0.94	0.75	0.36	0.11	0.10
6	1	1	0.97	0.95	0.74	0.40	0.14
7	1	1	0.99	0.99	0.89	0.69	0.36
8	1	1	1	1	0.96	0.80	0.53
9	1	1	1	1	0.98	0.92	0.69
10	1	1	1	1	0.99	0.95	0.81
11	1	1	1	1	1	0.96	0.88
12+	1	1	1	1	1	0.97	0.91

Table 6.1 (cont).

## H/I sector - scallops

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120	Lc=125
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	1	0.31	0.08	0.03	0	0	0
4	1	0.95	0.95	0.62	0.19	0.05	0
5	1	1	1	0.97	0.82	0.62	0.29
6	1	1	1	1	1	0.89	0.59
7	1	1	1	1	1	0.99	0.87
8	1	1	1	1	1	1	0.97
9	1	1	1	1	1	1	0.98
10	1	1	1	1	1	1	0.99
11	1	1	1	1	1	1	1
12+	1	1	1	1	1	1	1

## Port St. Mary - scallops.

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0.83	0.33	0.17	0	0	0
4	1	0.92	0.83	0	0	0
5	1	1	1	0.92	0.76	0
6	1	1	1	1	1	0.88
7	1	1	1	1	1	0.99
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12+	1	1	1	1	1	1

## The Chickens - scallops

Age	Maturity	Lc=100	Lc=105	Lc=110	Lc=115	Lc=120	Lc=125
1	0	0	0	0	0	0	0
2	0.35	0.02	0	0	0	0	0
3	0.99	0.49	0.17	0.04	0.01	0	0
4	1	1	0.97	0.84	0.55	0.19	0.04
5	1	1	1	0.99	0.92	0.68	0.34
6	1	1	1	1	0.99	0.93	0.70
7	1	1	1	1	1	0.98	0.83
8	1	1	1	1	1	1	0.95
9	1	1	1	1	1	1	0.99
10	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1
12+	1	1	1	1	1	1	1

Table 6.1 (cont).

East Douglas - queens, June-October 1988.

Age	Maturity	Lc=40	Lc=45	Lc=50	Lc=55	Lc=60	Lc=65
0	0	0	0	0	0	0	0
1	0.29	0.76	0.42	0.11	0.02	0	0
2	0.95	1	1	1	0.96	0.68	0.15
3	1	1	1	1	1	1	0.87
4	1	1	1	1	1	1	0.99
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7+	1	1	1	1	1	1	1

Table 6.2. Weights-at-age (g) of the edible parts of scallops and queens from each area, for input into YPR and BPR models.

Age	Scallops						Queens	
	BR	CH	TG	SED	PSM	H/I	ED (yld)	ED (am)
0	0.07	0.04	0.00	0.00	0.28	0.80	0.00	0.00
1	3.96	2.88	1.22	0.00	4.28	5.28	2.36	2.00
2	14.23	11.25	11.36	0.04	11.97	13.15	6.99	5.36
3	25.73	21.69	27.83	1.49	20.38	22.30	9.47	7.03
4	34.97	31.09	43.60	6.03	27.71	31.04	10.45	7.66
5	41.34	38.31	55.66	12.85	33.41	38.53	10.81	7.88
6	45.39	43.41	63.91	20.44	37.56	44.54	10.93	7.96
7	47.86	46.84	69.22	27.63	40.48	49.17	10.98	7.99
8	49.34	49.08	72.53	33.85	42.48	52.63	10.99	8.00
9	50.20	50.53	74.56	38.92	43.83	55.17		
10	50.71	51.44	75.78	42.89	44.73	57.02		
11	51.00	52.02	76.51	45.92	45.33	58.34		
12	51.17	52.39	76.95	48.20	45.73	59.29		

yld = weight of adductor muscle + gonad

am = weight of adductor muscle only

Estimates of mean  $F$  for each fishing ground from mark-recapture experiments (Chapters 4 & 5) are compared with calculated values of  $F_{\max}$  and  $F_{0.1}$ . Incidental or non-yield fishing mortality on scallops is not included for this analysis, as estimates are highly variable (see Chapter 4); the mean  $F$ -values used here should be taken as minimum estimates.

## 6.3. RESULTS

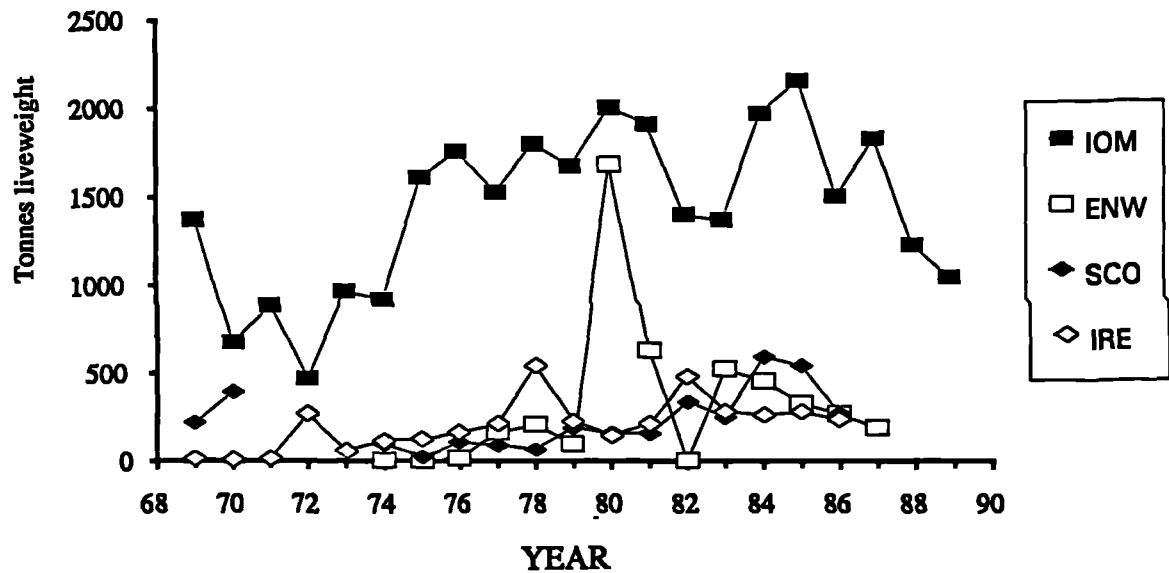
### 6.3.1. Fishery statistics

Analysis of total landings of scallops to area VIIa shows that the Isle of Man has the most important fishery in the area (Fig. 6.1a). Annual landings to the Isle of Man between 1969 and 1989 were in the range 470 - 2060 tonnes liveweight ( $\bar{x}$  = 1434t), making up between 50 and 90% ( $\bar{x}$  = 69%) of the scallops caught in area VIIa annually. Landings generally increased between 1972 and 1984, but have been declining since then. Between 1972 and 1987, landings to Scotland, Ireland and England & Wales were low (below 500 tonnes) with the exception of recorded landings of over 1600t to England & Wales in 1980 - the majority of these scallops were from the 'boom and bust' Cardigan Bay fishery (Franklin & Conner, 1980). More recent data are not available, but it is likely that landings to England & Wales and Scotland have increased in the last five years, as a number of new purpose-built scallopers have been built for the port of Kirkcubright, and several large beam trawlers, previously fishing for sole, switched to fishing scallops from Fleetwood and Holyhead in the late 1980s (communicated by R. Banham, MAFF, Lowestoft, August, 1988, and established from reports in 'Fishing News').

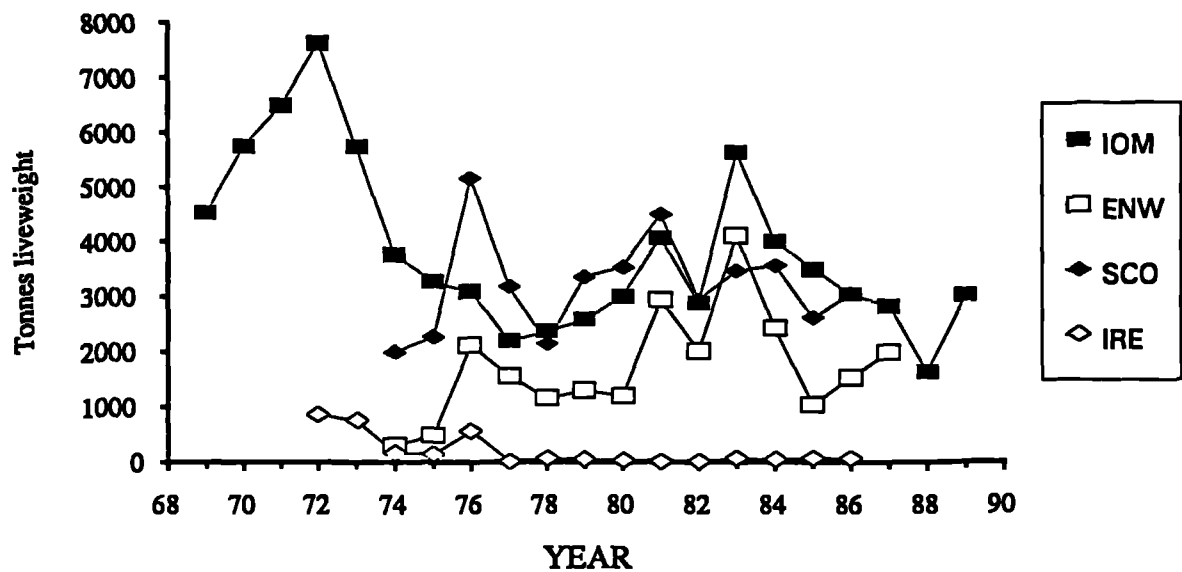
The Manx fishery for queens was the largest in area VIIa in the early 1970s and again in 1982-86 (Fig. 6.1b). The high Manx landings (up to 7 600 tonnes) in the early 1970s were the result of strong markets for queens and high catch rates in the developing fishery, which was unexploited in this area until 1969 (Brand & Allison, 1987; Brand *et al.*, 1991b). Landings declined in the mid 1970s due to a switch to the herring fishery (Brand *et al.*, 1991b), increased through the late 1970s and early 1980s to peak again at 5 600t in 1983, when catch rates of both scallops and queens were good and the Manx fleet was comparatively large (60-70 vessels). Queen catches have declined since 1983 due to poor markets and reduction in the fleet size following low catch rates and hence profits (43 active boats in 1992). Between 1974 and 1986 the Manx fleet accounted for between 22 and 38% ( $\bar{x}$  = 28%) of annual queen landings from area VIIa. The Scottish fishery in area VIIa has been of similar size to the Manx one during the same period. Substantial quantities of queens were also landed to England & Wales (1 000 - 4 000t per annum between 1976 and 1987). Fluctuations in catches by the three main fishing nations tend to show similar patterns between 1974 and 1986, as all fleets in the area sell to the same markets and fish many of the same grounds.

**Fig. 6.1.** Catches of scallops and queens in ICES area VIIa (North Irish Sea and Cardigan Bay) by country of landing: IOM = Isle of Man, ENW = England and Wales, SCO = Scotland. Catches landed in Eire and Northern Ireland have been combined (IRE).

**a. Scallops, *Pecten maximus*.**



**b. Queens, *Chlamys opercularis*.**



The scallop and queen fisheries in ICES area VIIa are among the most important for these species. Between 1974 and 1986, ICES area VIIa accounted for between 4 and 16% ( $\bar{x} = 11\%$ ) of total landing of scallops reported in the ICES area (western European Continental shelf). Both the proportion and total landings of scallops from area VIIa increased over the period specified, whilst total landings of this species have been declining (Fig. 6.2a).

The queen fisheries in area VIIa are the largest in the ICES region (which spans the range of commercially viable populations of this species) by an order of magnitude (Fig. 6.2b). The annual landings of 5, 000 - 13, 000 tonnes per year make up between 65 and 80% ( $\bar{x} = 71\%$ ) of ICES landings. Other important areas are the West of Scotland (area VIa) and the Faeroes. Total landings fluctuate greatly, reflecting variability in markets and in catch rates in area VIIa.

To put the Manx fisheries for scallops and queens into perspective, catches landed to each of the major fishing nations are shown as fractions of the total ICES catches (Fig. 6.3a & 6.3b). The Manx scallop fishery, at around 1 000 to 2 000 tonnes per year, averages 7% of the total scallop catch in ICES, making the Isle of Man the fourth-largest scallop fishing nation. The French fishery, based offshore in the Channel and along the Normandy and Brittany coasts, is the largest, but has been declining, while Manx, Scottish and English & Welsh catches have remained relatively stable. The major fishing areas for scallops are the Channel, the west coast of Scotland and the North Irish Sea.

The Manx queen fishery is the second largest in ICES, making up between 22 and 38% ( $\bar{x} = 28\%$ ) of the total annual queen landings of 8 000 - 17 000 tonnes per year. The Scottish fishery, based mainly in the North Irish Sea, the Clyde and west of Kintyre (Mason, 1983) is the largest fishery for this species. The total landings of queens fluctuate considerably, but were generally increasing between 1978 and 1986.

### 6.3.2. Sample fleet catch-effort data

The distribution of sample-fleet scallop catches by grid-square is shown in Fig. 6.4. The area inshore to the south-west of the Isle of Man has consistently been a major catching area for the Manx fleet during the last 10 years. These grounds, off Peel, Bradda Head and the Chicken Rock, have all been important to

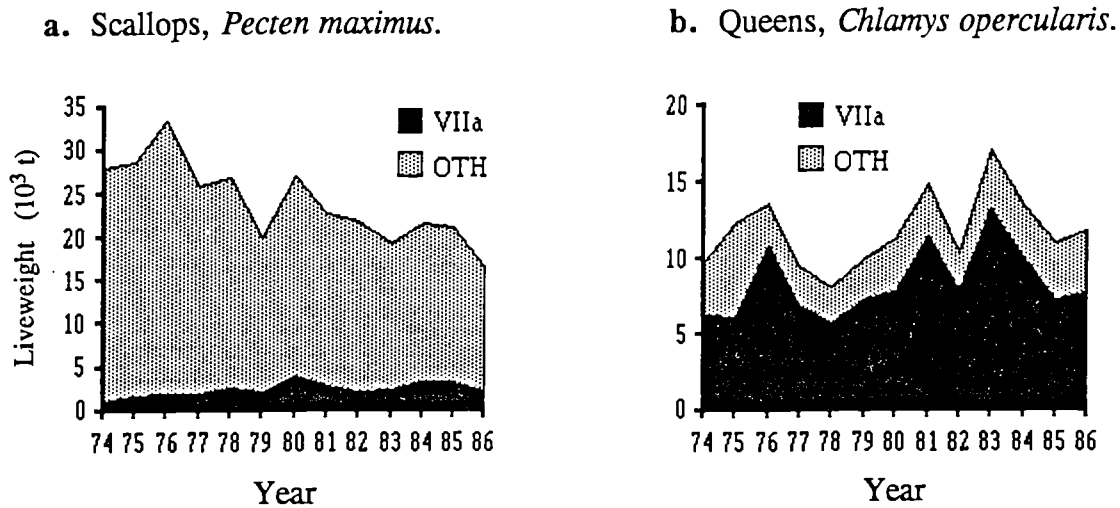


the fishery for over 30 years (Brand *et al.*, 1991b). The distribution of catches over other squares is more uneven, dependent on the location of high-density unexploited patches and the distribution of fishing effort. The area to the south of the Isle of Man has provided an increasing proportion of the sample-fleet catch, as is also evident from the increase in returns of tagged scallops from these areas between 1982 to 1984 and 1987 to 89 (see Chapter 4). Grounds to the east and south-east of the Isle of Man are sporadically important, perhaps reflecting more variable or lower levels of recruitment than to the major grounds inshore to the west and south of the Isle of Man (see Chapter 2 for discussion). From 1984 to 1988, wide areas of the North Irish Sea were exploited, as traditional fishing grounds had been subjected to intense fishing to the detriment of catch rates. The fleet was reduced in size between 1987 and 1990 due to falling catch rates and low market prices, and the majority of catches from the remaining boats in the 1989/90 season came from traditional fishing grounds.

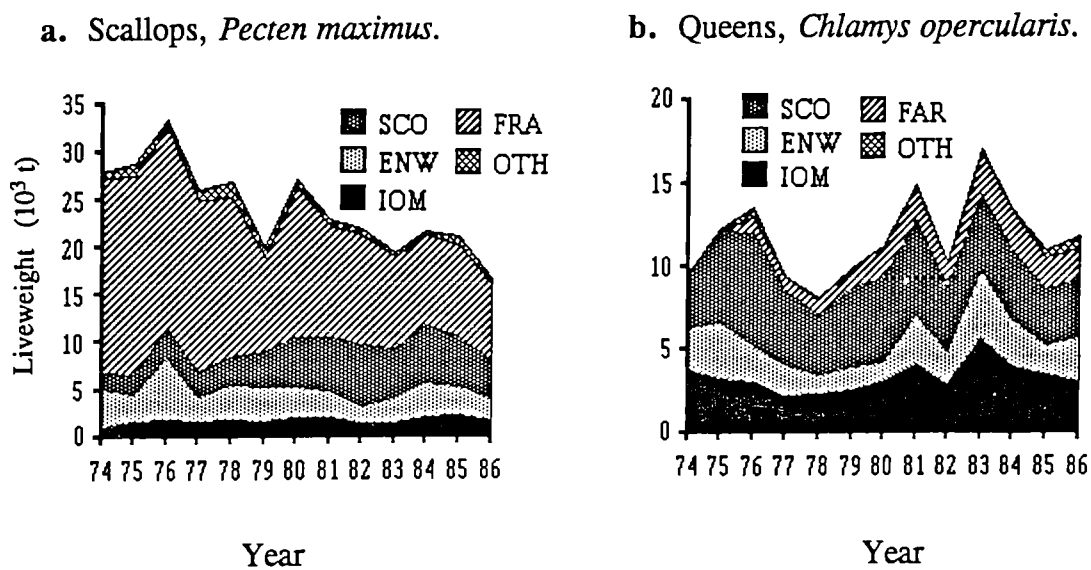
The distribution of fishing effort shows that the areas inshore to the west and south of the Isle of Man consistently provide high catches due to high fishing effort (Fig. 6.5). Recent high levels of fishing effort offshore to the south reflect the increasing importance of these grounds to the Manx fleet. Although scallop catch-rates are not always high, substantial queen by-catches are often taken in these areas. Relatively high levels of fishing effort have also been expended on the grounds off the north-west coast of the Isle of Man recently (grid squares K8, K9, L8, L9; the Targets fishing ground) for apparently low catches. Although the catches in these areas are low in number, individual scallops are large and have exceptionally high yields (see Chapter 3).

The areas of highest CPUE (Fig. 6.6) are not necessarily the most heavily exploited. Areas which have been subjected to low fishing effort may contain small high-density patches which are quickly fished out, leading to high catch rates with low fishing effort and low overall catches compared to major grounds which provide lower catch rates over larger areas, more consistently. Weather and distance from home port play a major part in determining the level of exploitation of fishing grounds, so that for much of the season, fishermen may not be fishing to optimise their catch rates (Murphy, 1986) but may be close to optimising their catch per unit cost under constraints to vessel safety caused by adverse weather conditions.

**Fig 6.2.** Total catches of scallops and queens in the ICES area, showing the proportion caught in area VIIa (OTH = all other areas combined).



**Fig. 6.3.** Catches of scallops and queens in the ICES area, by country of landing. (SCO = Scotland, ENW = England & Wales, IOM = Isle of Man, FRA = France, FAR = Faroes, OTH = others: Eire, N. Ireland, Spain & Belgium)



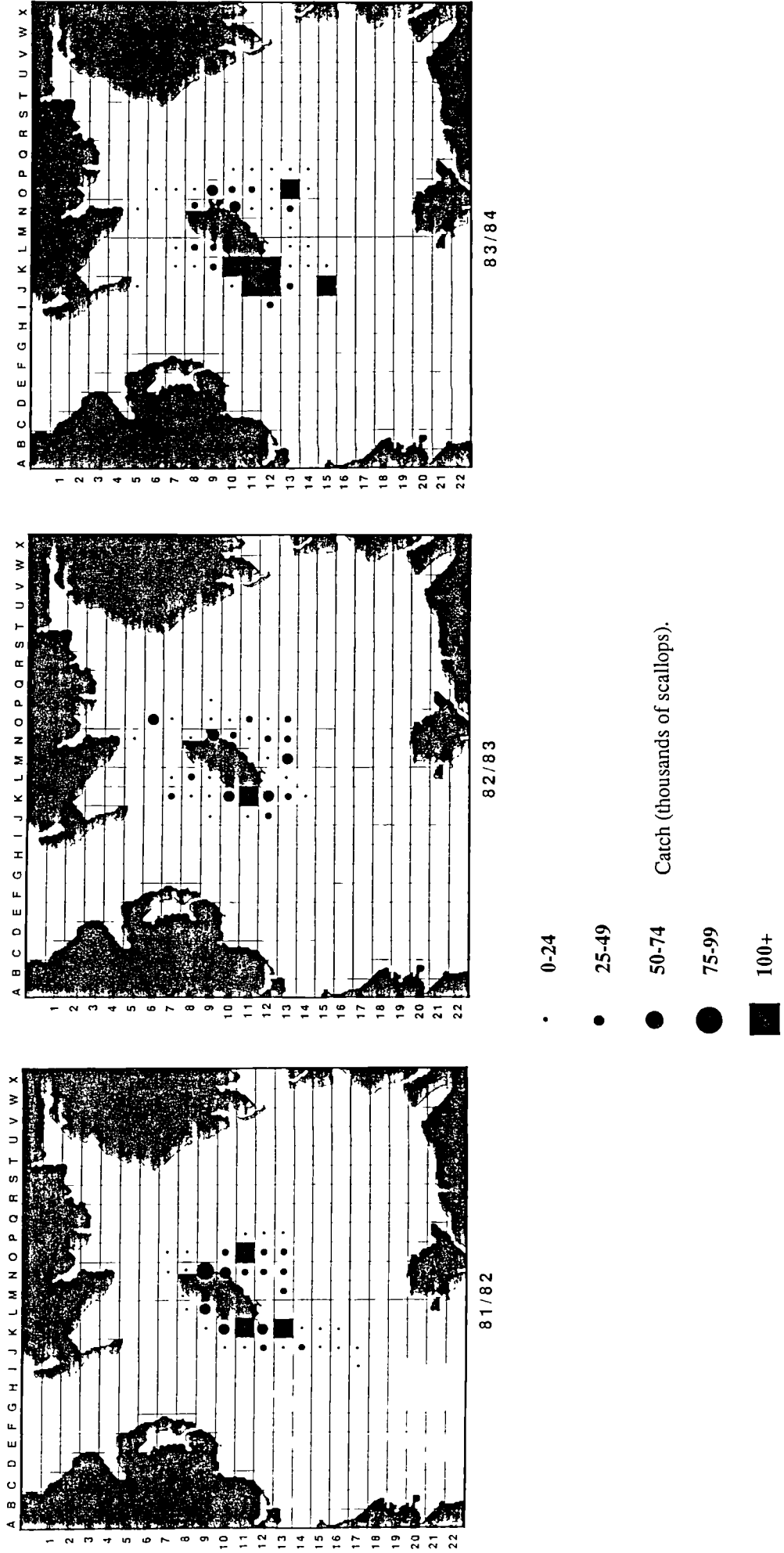
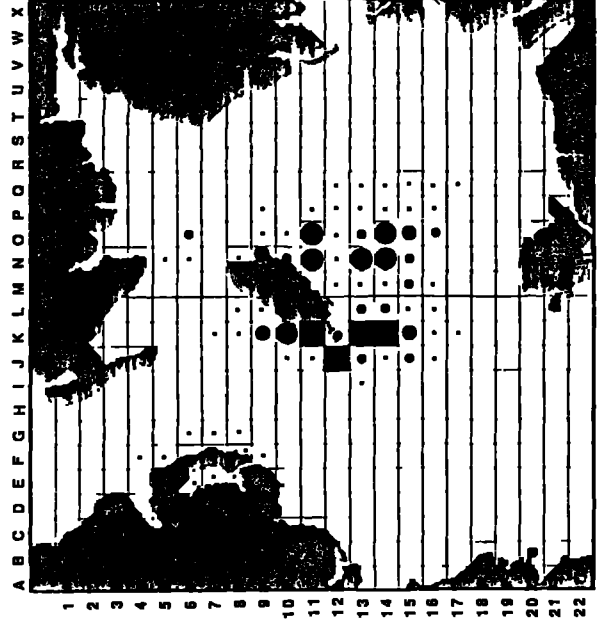
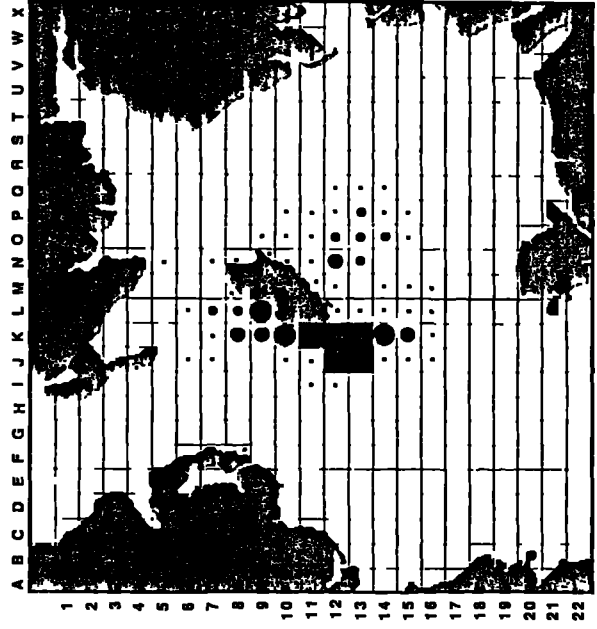


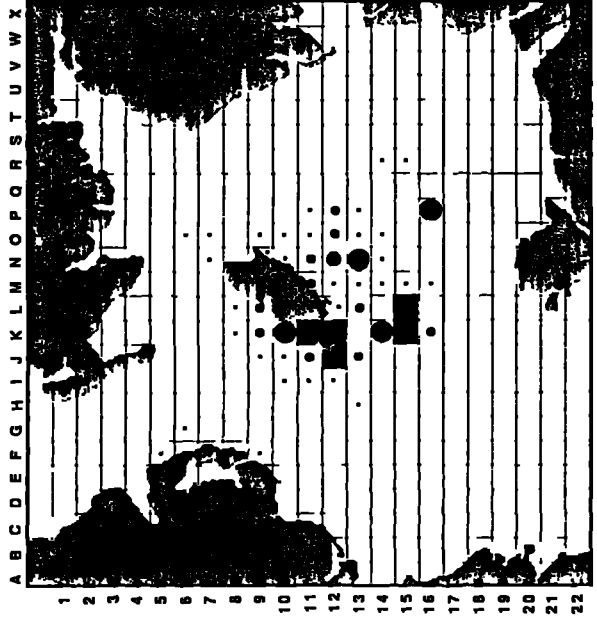
Fig. 6.4 The distribution of scallop catches by the sample fleet in the North Irish Sea, 1981 - 90.



86/87



85/86



84/85

- 0-24
  - 25-49
  - 50-74
  - 75-99
  - 100+
- Catch (thousands of scallops).

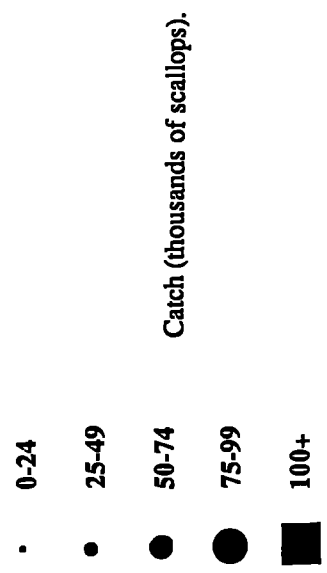
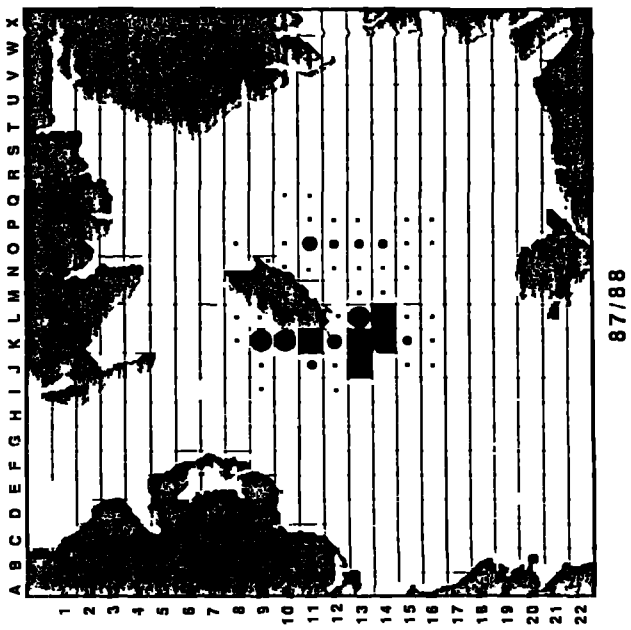
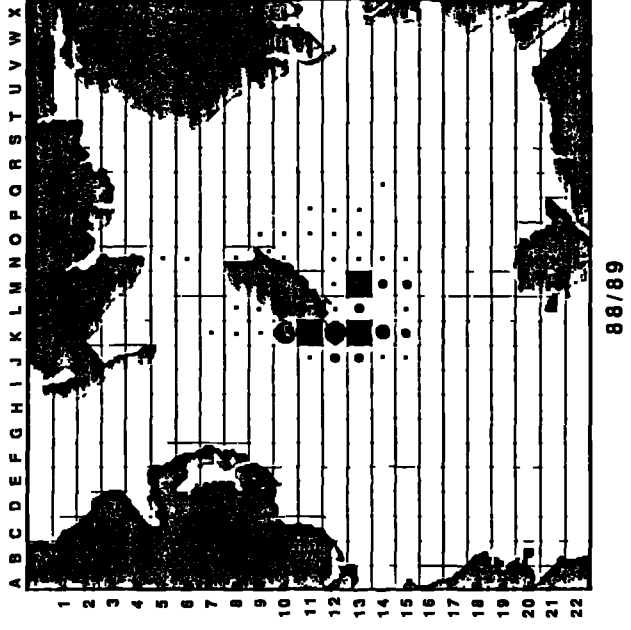
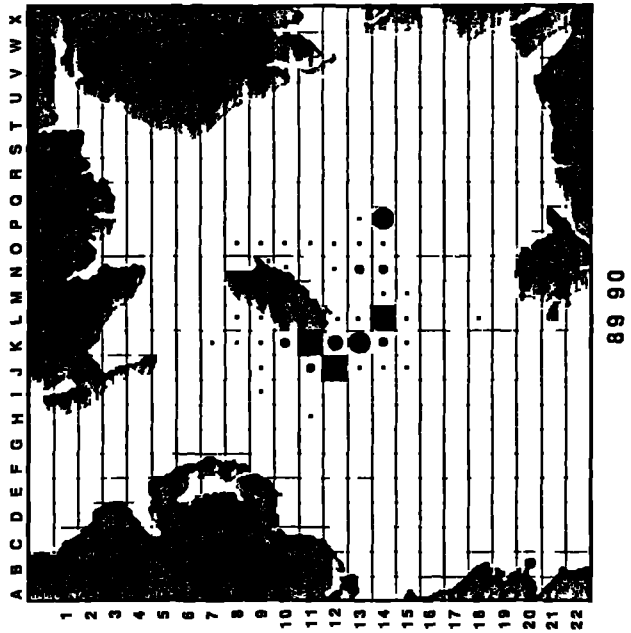
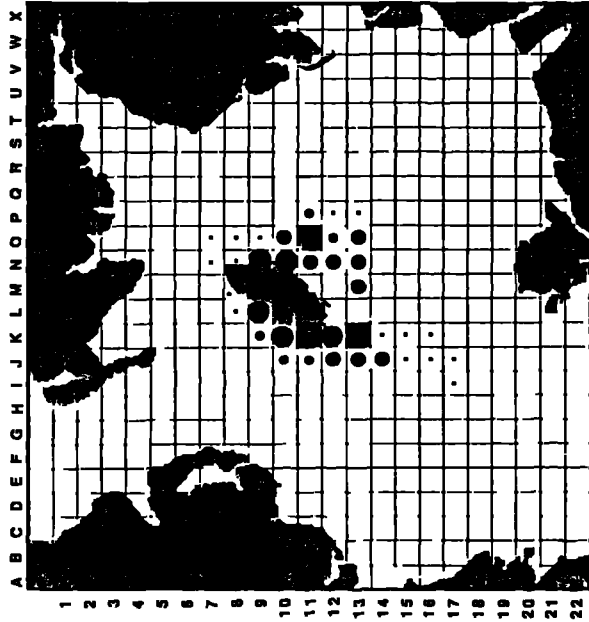
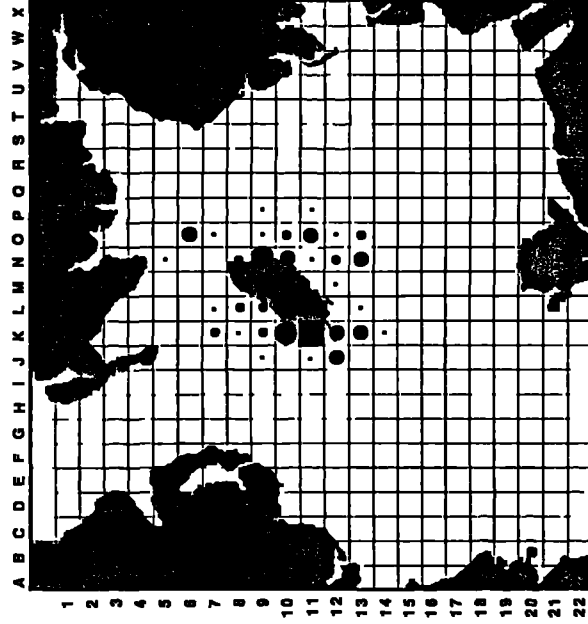


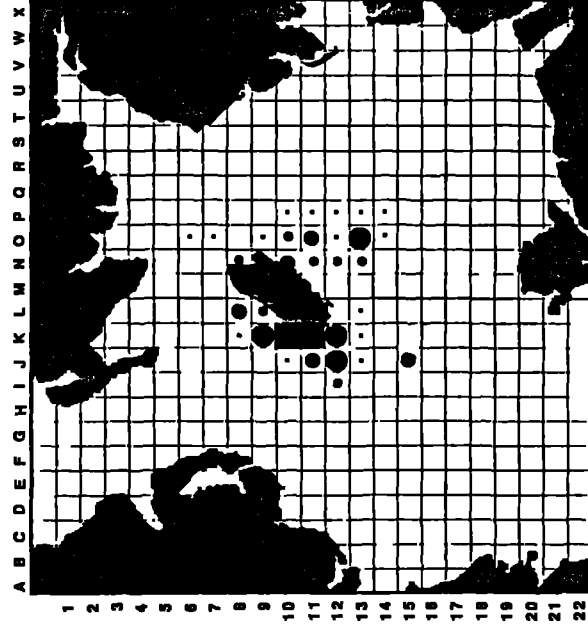
Fig. 6.4 (Cont'd) The distribution of scallop catches by the sample fleet in the North Irish Sea, 1981 - 90.



81/82



82/83



83/84

• 0-499

● 500-999

● 1000-1999

● 2000-3999

■ 4000+

Fishing effort - number of hours spent towing 1 metre width of scallop dredge ( $m^{-1}h^{-1}$ ).

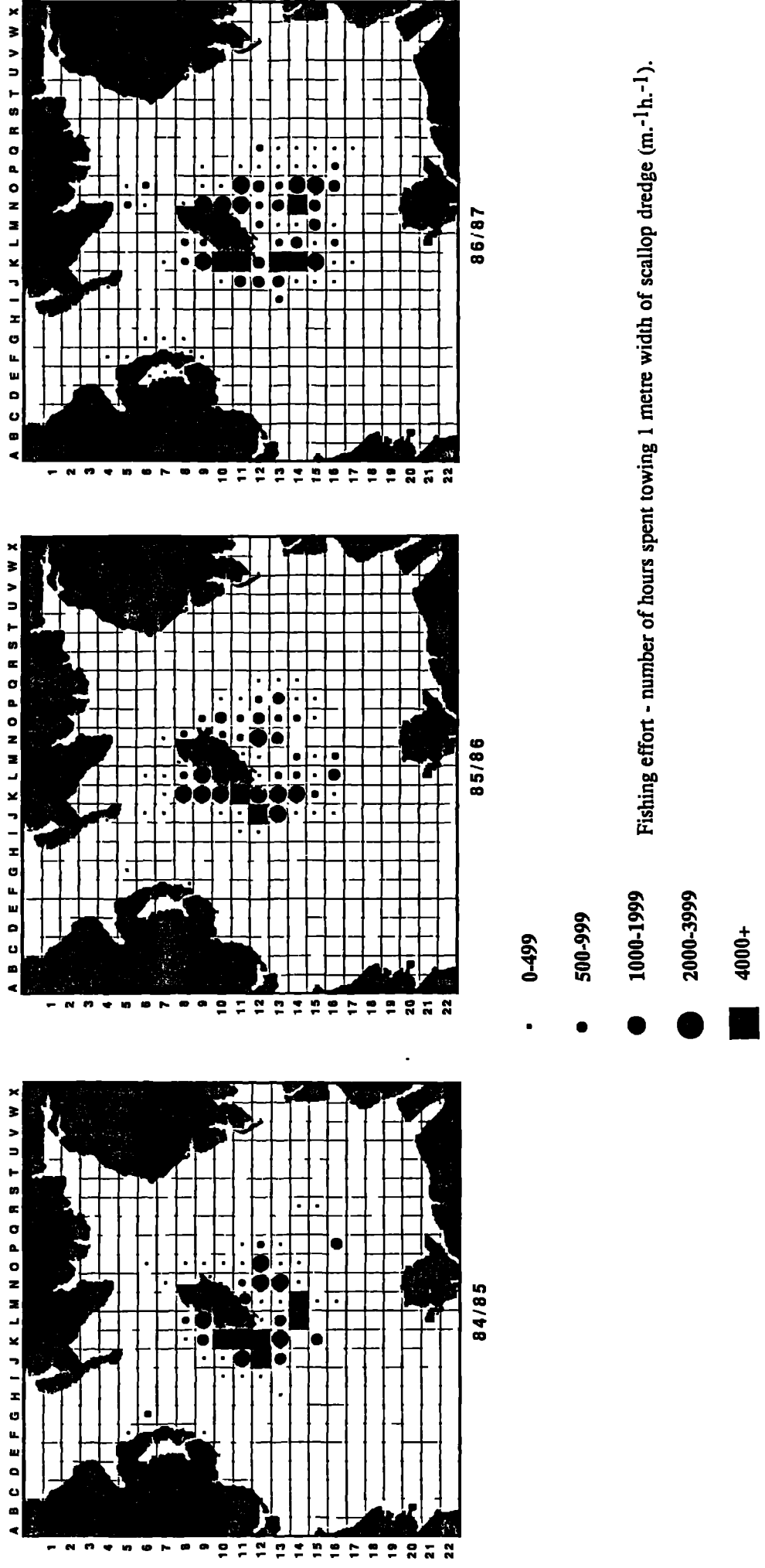
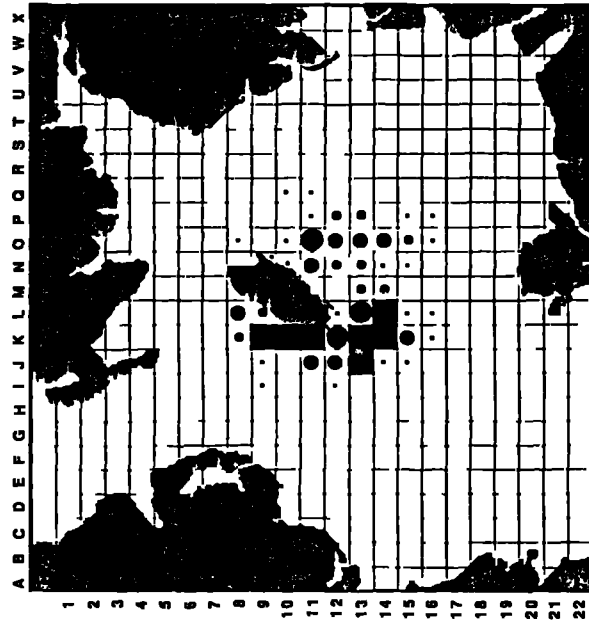
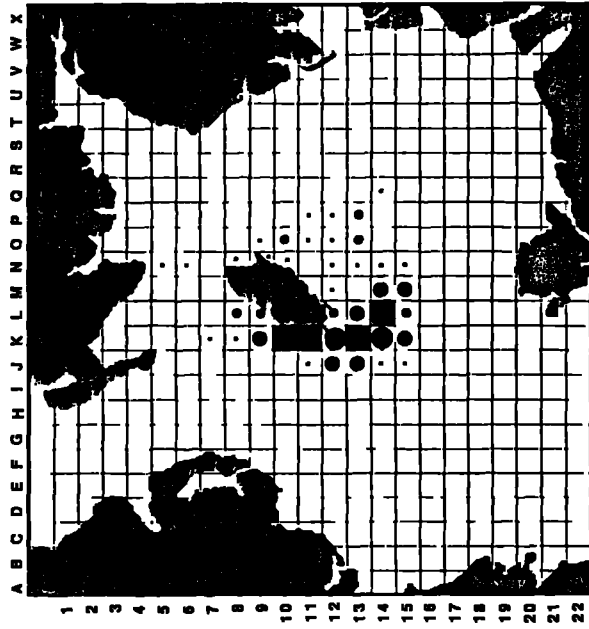


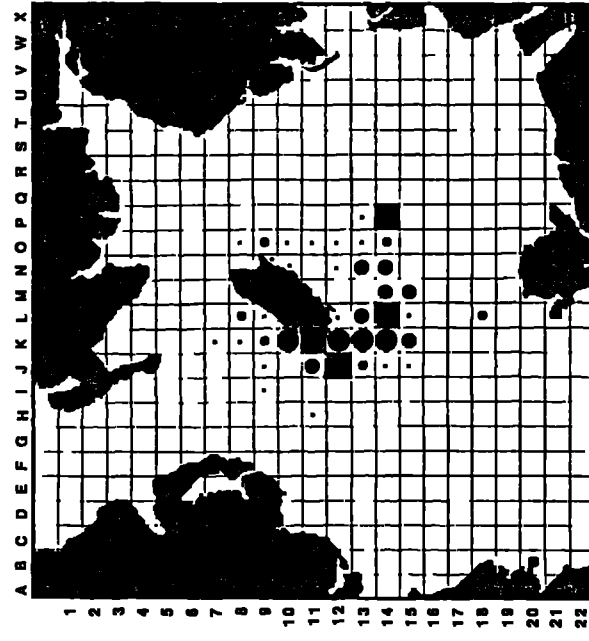
Fig. 6.5 (Cont'd) The distribution of fishing effort on scallops by the sample fleet in the North Irish Sea, 1981-90.



87/88



88/89



89/90

• 0-499

• 500-999

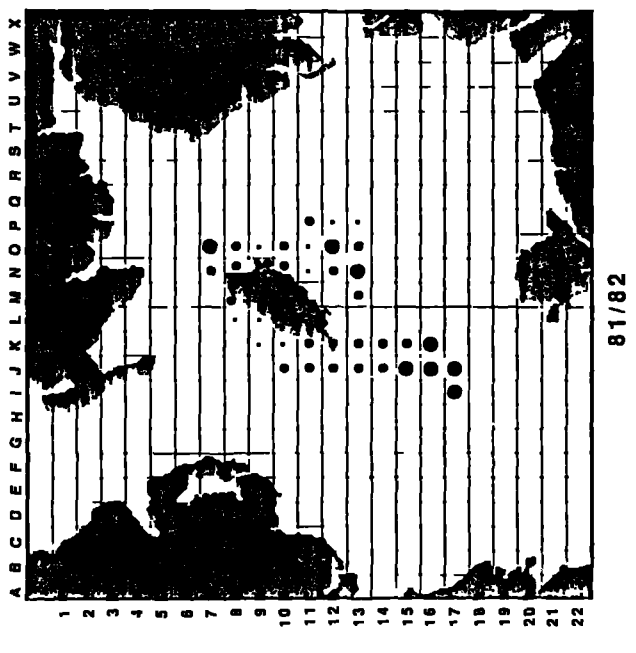
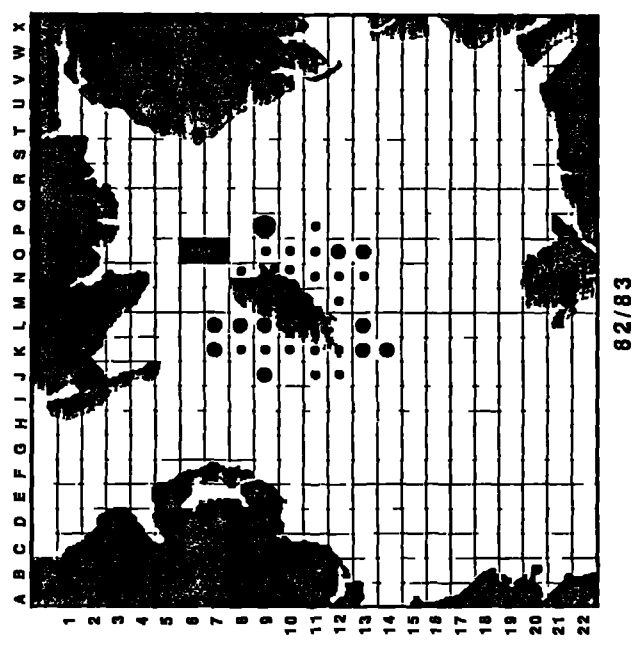
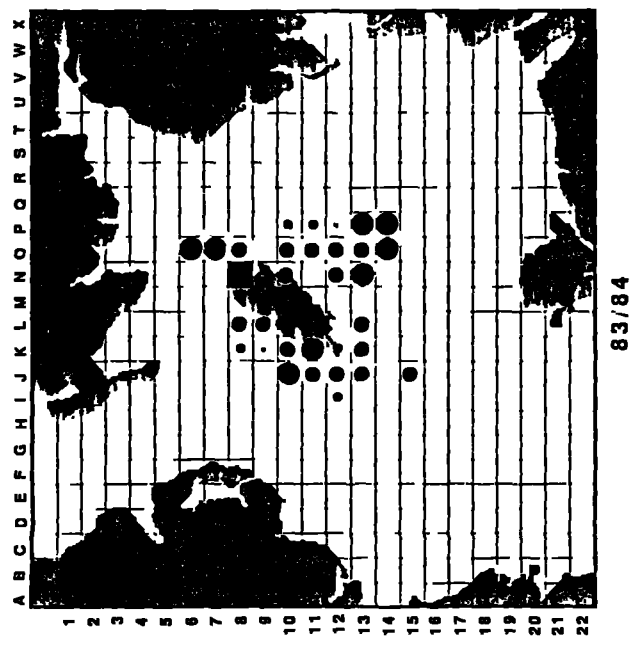
● 1000-1999

● 2000-3999

■ 4000+

Fishing effort - number of hours spent towing 1 metre width of scallop dredge (m.-1h.-1).





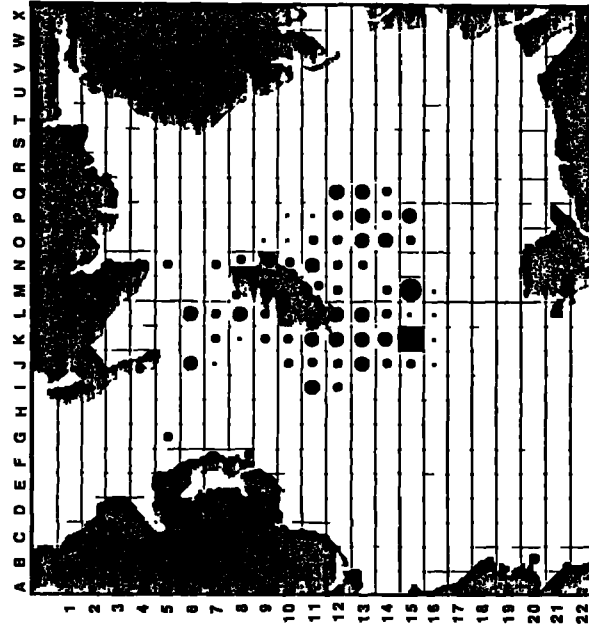
- 0-19
- 20-29
- 30-39
- 40-49
- 50+

CPUE = number of scallops caught per hour spent towing 1 metre width of dredge (N.m.<sup>-1</sup>h.<sup>-1</sup>).

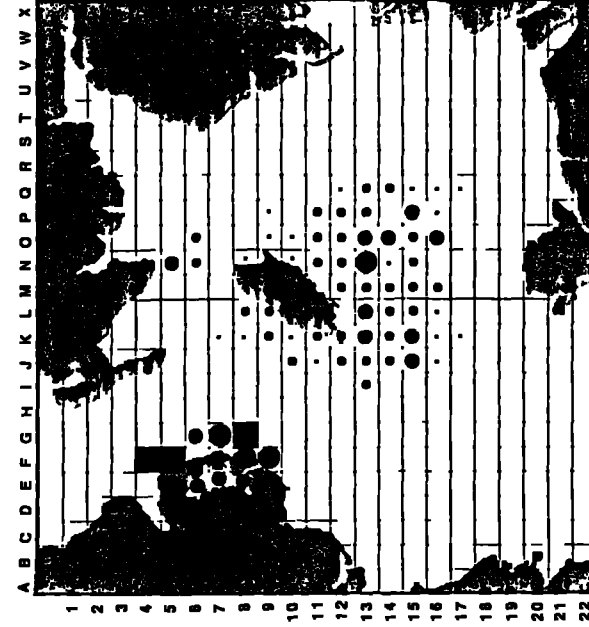
Fig. 6.6 The distribution of catch per unit effort (CPUE) on scallops by the sample fleet in the North Irish Sea, 1981-90.



84/85



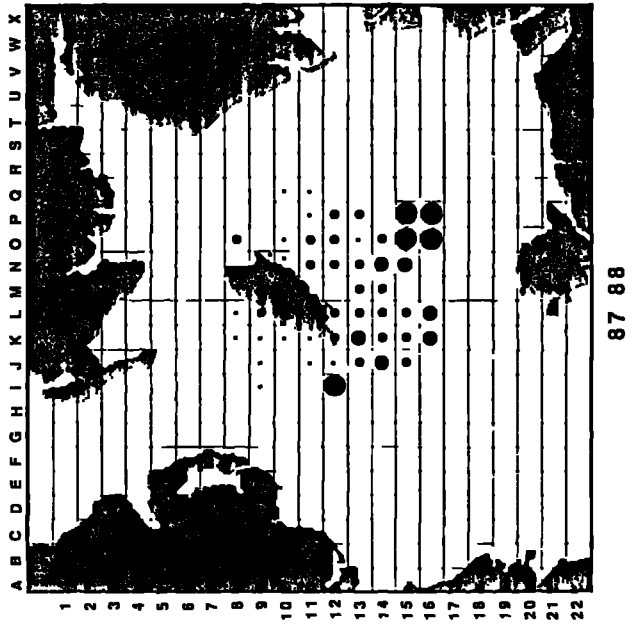
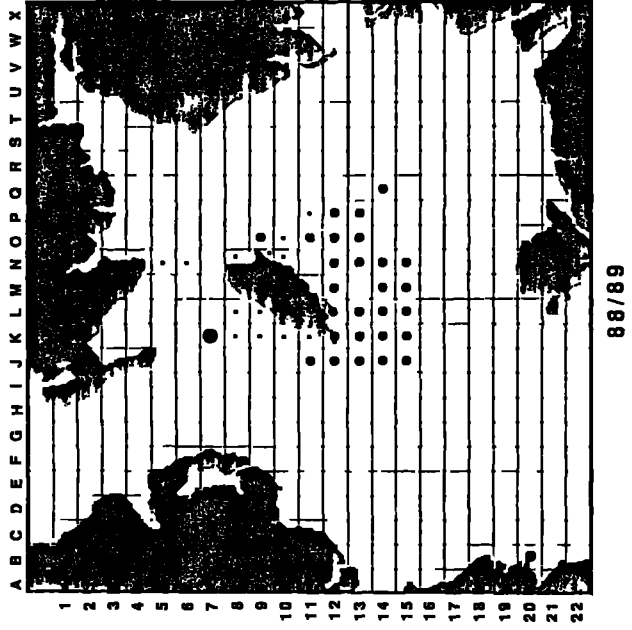
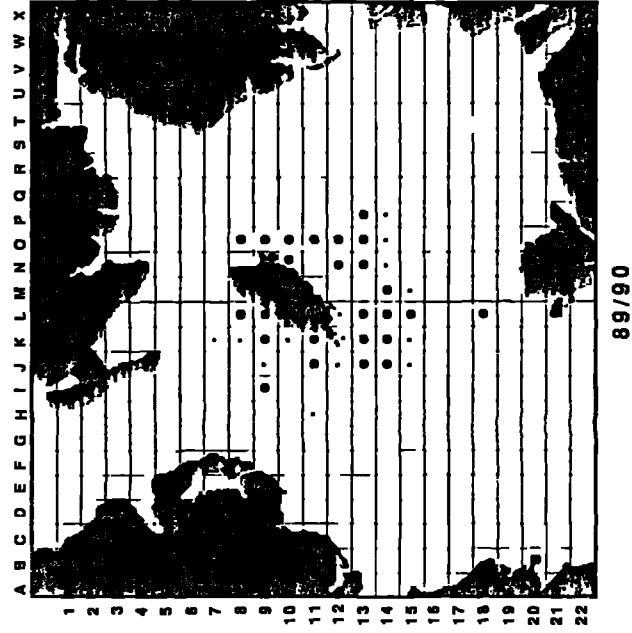
85/86



86/87

- 0-19
- 20-29
- 30-39
- 40-49
- 50+

CPUE = number of scallops caught per hour spent towing 1 metre width of dredge (N.m.-1h.-1).



- 0-19
- 20-29
- 30-39
- 40-49
- 50+

CPUE = number of scallops caught per hour spent towing 1 metre width of dredge (N.m. <sup>-1</sup>h. <sup>-1</sup>).

Fig. 6.6 (Cont'd) The distribution of catch per unit effort (CPUE) on scallops by the sample fleet in the North Irish Sea, 1981-90.

CPUE tends to be highest on offshore grounds, but is highly heterogeneous. Catch rates have fallen over the period studied, and have become homogeneously low over the whole fishing area since 1987/8 (Fig. 6.6).

The changes in CPUE on all major fishing grounds over the period 1981 - 1990 are shown in Fig. 6.7. Catch rates actually increased on most grounds between 1981 and 1983 or 1984, but have tended to decrease since then. The pattern of change is very similar on all the inshore grounds off the west coast of the Isle of Man (Bradda, Peel, the Targets). On grounds covering more than one grid-square variations in catch rates followed similar patterns. If CPUE is taken to represent abundance (see Chapter 2), this indicates that the factors affecting abundance (fishing mortality, recruitment) act over the fishing ground as a whole, rather than differing over smaller spatial scales. Catch rates in 1989/90 were uniformly low, at around 20 scallops  $m^{-1} hr^{-1}$ .

The catch rates reported during the period 1981 to 1990 are substantially lower than catch rates reported during the early development period of the fishery (see Brand *et al.*, 1991b, for review). Catch rates of over 100 scallops  $m^{-1} hr^{-1}$  in the 1950s contrast with catches of around 20 scallops  $m^{-1} hr^{-1}$  for the same grounds in the late 1980s.

The distribution of queen catches in the North Irish Sea has not previously been examined in any detail. The major catching areas appear to change from year to year (Fig. 6.8). Sample-fleet catches in 1982 were uniformly low (0-50 tonnes per grid square), but in 1983 large catches were made inshore off the east coast of the Isle of Man and offshore to the north east. In 1984 catches were more evenly distributed, with the grounds off the south of the Isle of Man providing a large proportion of the sample-fleet catches. In 1985 the majority of catches came from the Targets ground off the north-west coast of the Isle of Man, with some concentration of catches 20 nautical miles south of the Isle of Man also. From 1986 to 1988 sample-fleet catches were low as little queen fishing was taking place due to poor markets. In 1989 reasonable markets led to a revival in queen fishing, with the grounds offshore to the south and east of the Isle of Man providing the majority of the catches.

Obtaining estimates of total catches and fishing effort and their spatial distribution from sample-fleet catch-effort statistics can be problematic (see Discussion, 6.4.2). Preliminary estimates of total-fleet catches and fishing effort

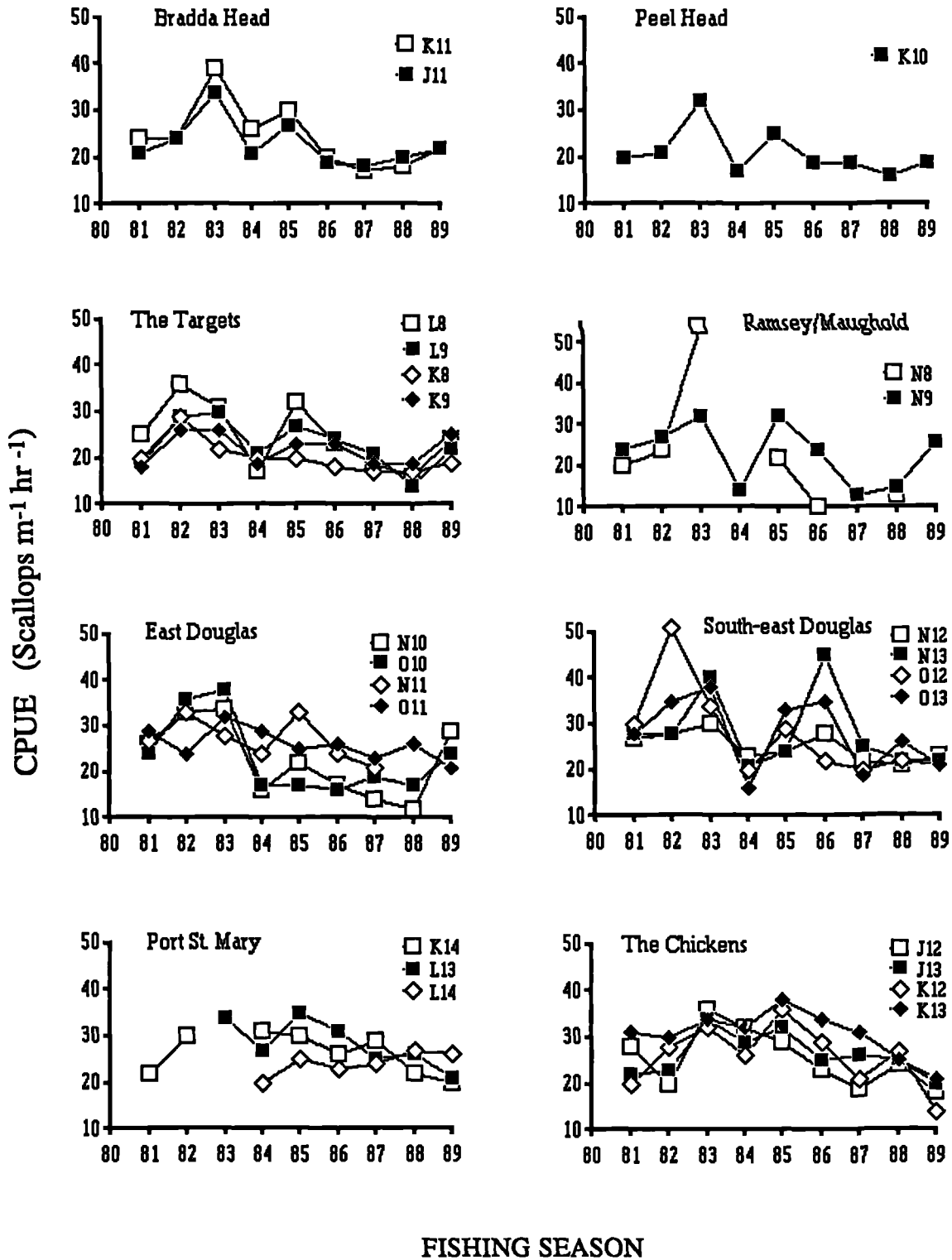
have been made by assuming that the sample fleet is representative of the fleet as a whole, in terms of the fishing power of the vessels, the effort expended in a fishing season and the catching efficiency. Total-fleet catches and effort for each fishing season can then simply be obtained by scaling up sample-fleet statistics using the relative numbers of vessels in the sample and total fleets (Table 6.3). No attempt is made to scale up catches in individual grid squares, as the distribution of fishing effort is related to a number of factors, for example, home port, size of vessel and skippers fishing strategy, which all need to be taken into account to provide an accurate extrapolation of sample-fleet to total-fleet catch and effort spatial distribution.

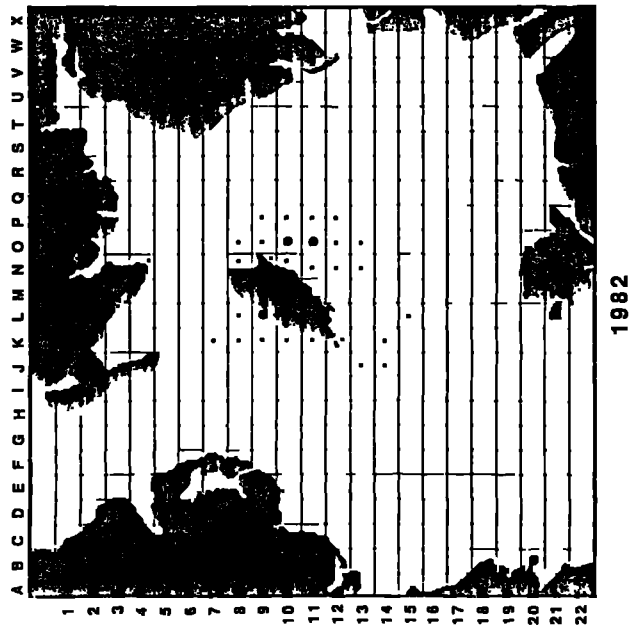
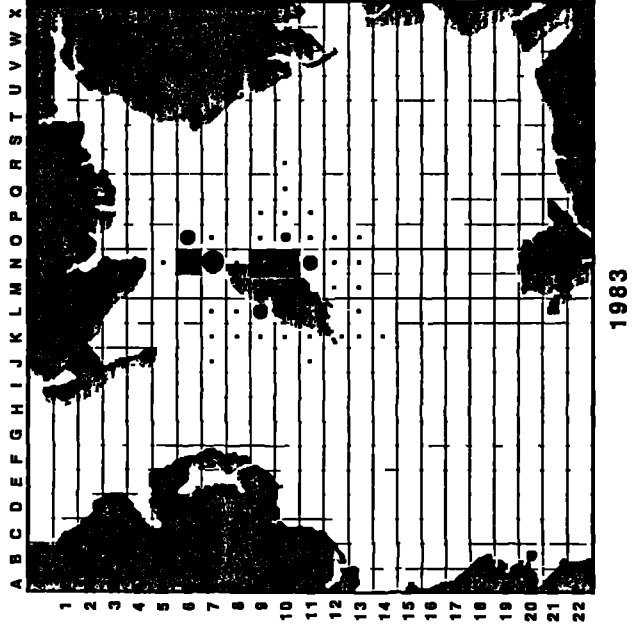
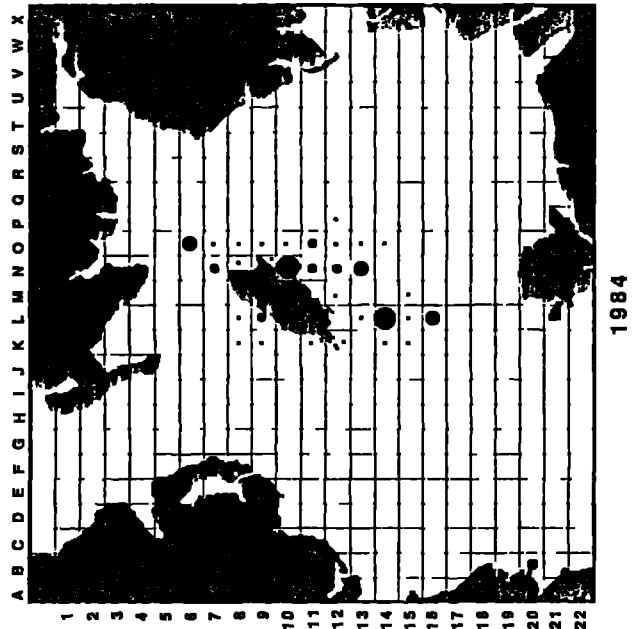
The sample fleet has varied from between 13 to 21 boats from a fleet of 48 to 65 boats (Table 6.3), making up 24 - 34% of the total fleet size each year. Total catches for each season (in tonnes liveweight) are calculated by scaling up sample-fleet catches in numbers and assuming 200 scallops weigh 40 kg (the number and weight per bag landed). The calculated total catches for each season are, on average, 20% lower than annual catches reported by the Isle of Man Department of Agriculture and Fisheries. This implies that the sample fleet, on average, catch fewer scallops per boat than the fleet as a whole. The most likely reason for this is a bias towards smaller boats in the sample fleet (unpublished data). Calculated total-fleet effort is therefore also likely to be underestimated. If monthly landings data can be obtained from the Department of Agriculture and Fisheries, total landings by fishing season can be produced. Total numbers can then be calculated directly from these data, and scaling factors for conversion of sample-fleet effort to total effort can be calculated assuming the CPUE of the sample fleet is the same as that of the fleet as a whole. It may also be possible to calculate the fishing power (total width of dredges towed) of the total fleet in past seasons from relationships between dredge-width and vessel length, horsepower and age, obtained from vessels in the sample fleet (unpublished data). Fishing power in future seasons should be obtained simply by going round all the fishing ports during bad weather and counting the number of dredges on each boat.

### **6.3.3. Population size estimates, *Pecten maximus***

Petersen estimates of population size per 5 Nautical mile grid square are, in general, considerably lower than estimates calculated from CPUE and the assumption that the CPUE value for a square is derived from the whole area of that

**Fig. 6.7.** Sample-fleet catch per unit effort (scallops  $m^{-1}hr^{-1}$ ) on major North Irish Sea fishing grounds, 1981/2 to 1989/90 fishing seasons. CPUE values are calculated for each statistical square covered by the fishing grounds.

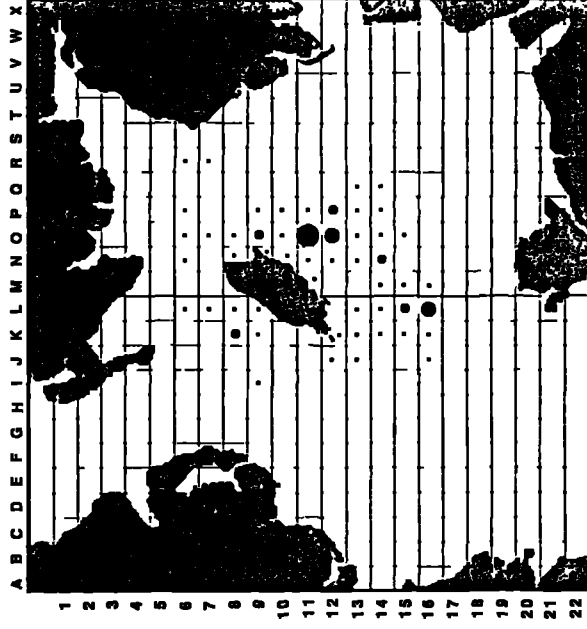




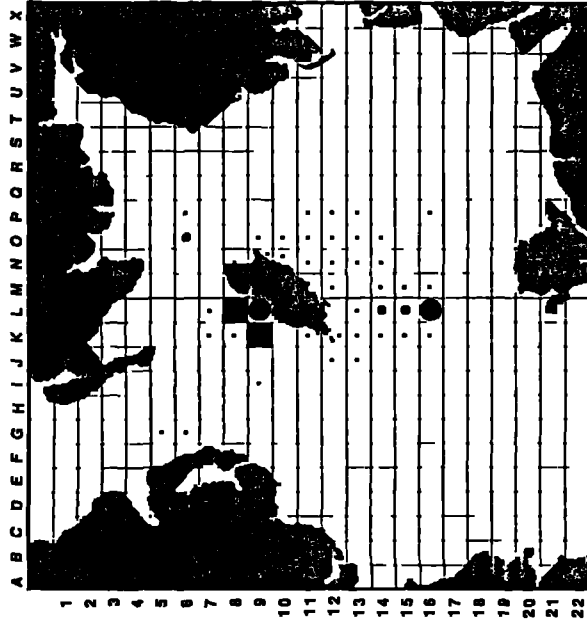
- 0-24
- 25-49
- 50-74
- 75-99
- 100+

Catches (tonnes liveweight, 1 bag = 50 kg).

Fig. 6.8 The distribution of queenie catches by the sample fleet in the North Irish Sea, 1982-90.



1986



1985

- 0-24
- 25-49
- 50-74
- 75-99
- 100+

Catches (tonnes liveweight, 1 bag = 50 kg).



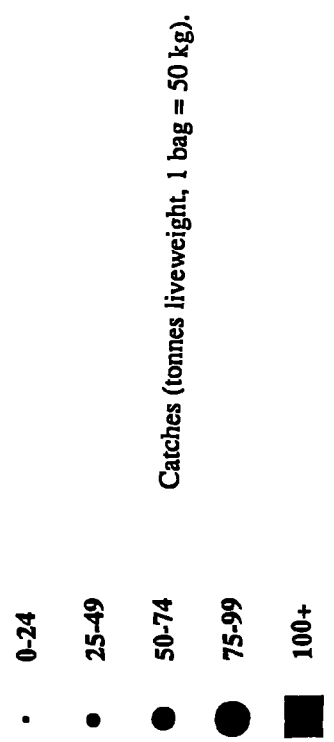
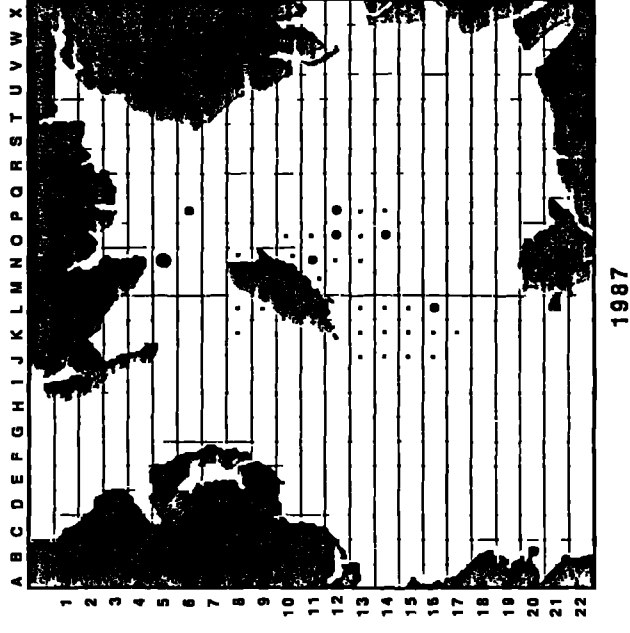
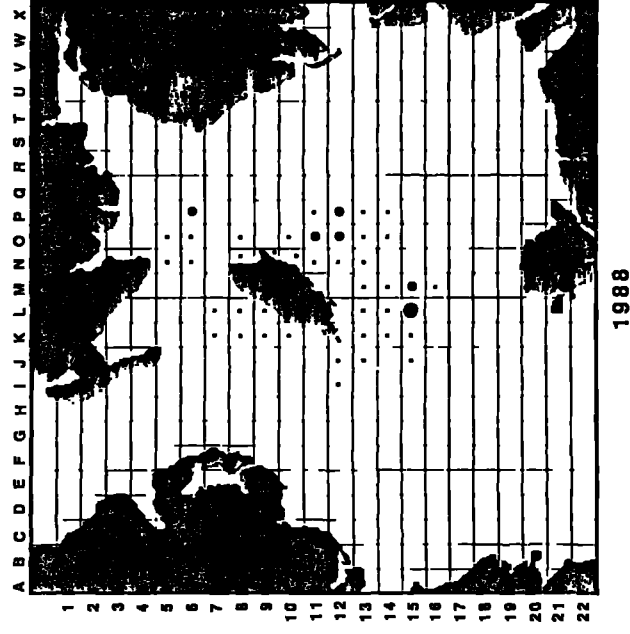
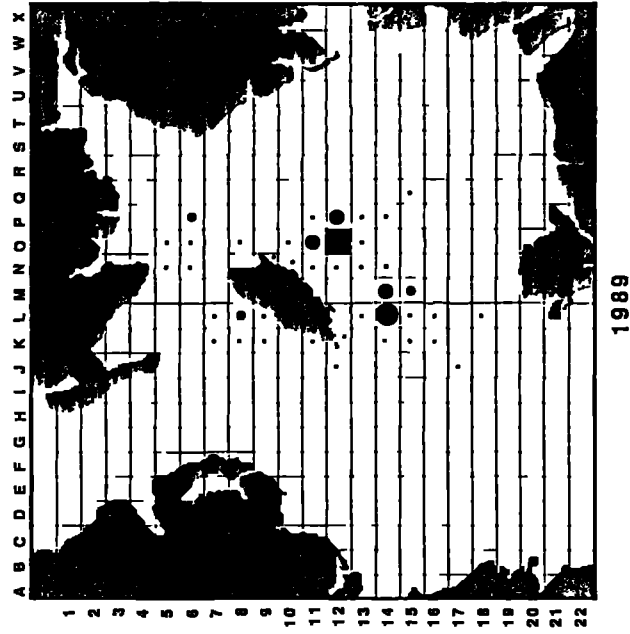


Fig. 6.8 (Cont'd) The distribution of queenie catches by the sample fleet in the North Irish Sea, 1982-90.

**Table 6.3.** Summary of sample and total fleet catches and fishing effort in the North Irish Sea, 1981-1990. The number of boats completing logbooks (the sample fleet) and the estimated number of active fishing boats in the Manx fleet are also shown. Landings in tonnes liveweight are calculated assuming 200 scallops (1 bag) weigh 40 kg.

Fishing season	Sample-fleet catch (No of scallops)	Total catch (No. of scallops)	Total catch (t liveweight)	No. of boats in sample fleet	Total number of Manx boats	Sample fleet CPUE	Sample fleet fishing effort (m-hrs)	Total fleet fishing effort (m-hrs)
1981/82	1 224 613	3 961 983	792	17	55	27.1	45 229	146 329
1982/83	870 142	3 294 109	658	14	53	28.1	30 920	117 054
1983/84	2 299 653	9 729 301	1 946	13	55	32.0	71 864	304 040
1984/85	1 895 585	5 686 755	1 137	19	57	26.6	71 378	214 134
1985/86	1 849 243	6 010 040	1 202	20	65	28.0	65 997	214 490
1986/87	2 239 098	6 610 670	1 322	21	62	25.2	88 997	262 753
1987/88	1 677 793	5 625 541	1 125	17	57	23.2	72 234	242 196
1988/89	1 217 909	4 871 636	974	13	52	22.7	53 634	214 536
1989/90	1 001 261	3 696 964	739	13	48	19.4	51 557	190 364

square (Fig. 6.9). The only instances in which the stock-size estimates are comparable are for the south-east Douglas and H/I-sector fishing grounds in the 1987/8 season (Fig. 6.9a). Both Petersen and CPUE-based estimates for these grounds are based on very small catches by the sample fleet. Estimates for grounds where sample-fleet catches were high and large proportions of tag-recaptures were made by the sample fleet lead to Petersen estimates of population size that are an order of magnitude lower than the CPUE-based estimates.

The discrepancy in population size estimates is most likely to be due to the invalidity of the assumption that CPUE (and therefore scallop density) reported for grid-squares applies to the whole grid-square. For most grid-squares, it appears that fishing activity only occurs over relatively small proportions of the square. The CPUE-based stock-size estimates for a fishing ground are likely to be most severely overestimated in the case where the fishing ground is located around the intersection between four grid-squares, so that CPUE from that ground will be assumed to apply to the whole of four squares.

Although the tagging-based estimates of population size will be subject to some error, due both to violation of the assumptions required for tagging experiments (see Chapter 5) and to the necessity of obtaining total catches by extrapolation, they are unlikely to be severely biased. The Petersen estimates of abundance (Table 6.4) are therefore used in preference to the CPUE-based estimates reported in Chapter 2 (Table 2.9). Numbers-at-age should be recalculated accordingly. The use of CPUE as an index of stock abundance, and of CPUE of the recruiting age-class as a recruit index (Chapter 2) for particular grounds will be unbiased only if the stock covers the same area each fishing season. CPUE per grid square cannot be used to compare stock-sizes or recruitment between grid-squares without information on the area of the square that the stocks cover.

Petersen estimates of population size (Table 6.4) indicate that the populations on some of the traditionally fished inshore grounds (Inshore Bradda, Peel Head and the Targets) are fairly small. The Targets ground is estimated to support a population of only 0.25 million scallops of commercial size, and the Bradda and Peel grounds support populations of between 0.6 and 1.3 million scallops. These are estimates of the size of the exploitable population; relatively large numbers of scallop may be present, scattered over extensive areas at densities insufficient to merit their exploitation. These estimates of population size also exclude the number of scallops < 110 mm shell-length, which may make up the

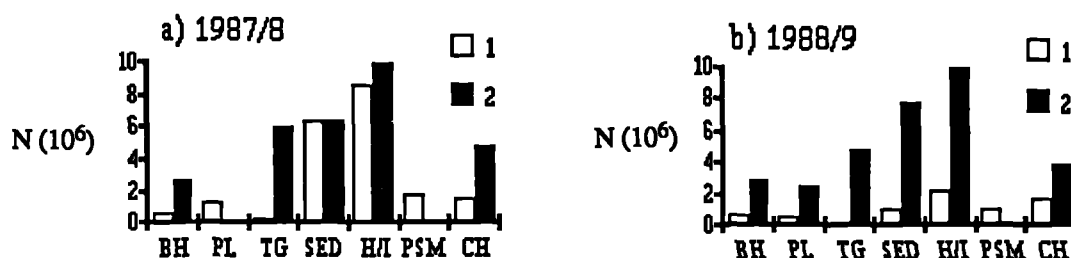
majority of the spawning stock, as well as being numerically dominant, on heavily fished inshore grounds (see Chapter 2).

Population sizes on grounds further offshore (the Chickens, south-east Douglas, Port St. Mary, H/I-sector) are of the order of 1 to 2 million, with the exception of very high estimates of 6.4 and 8.6 million scallops on the SE Douglas and H/I grounds in 1987/8. These latter estimates were based on low sample-fleet catches, and the recapture of only a few tagged scallops, so they may not be reliable. The largest sub-population, in terms of numbers of commercial size scallops per grid-square, is found in square L14, south of Port St. Mary (1-1.8 million scallops).

The ratio of sample-fleet to total fleet tag-recaptures also provides an estimate of total-fleet catch. The catches of 5.1 million scallops in 1987/8 and 3.6 million in 1988/9, calculated from tag-recapture ratios (Table 6.4) are comparable with estimates of 5.6 million and 4.9 million calculated from vessel-number ratios (Table 6.3). If the multiplier used to convert from numbers to tonnes is correct (200 scallops = 1 bag, which weighs 40 kg) both methods provide lower estimates of total annual catch than those published by the Isle of Man Department of Agriculture and Fisheries, which are calculated by converting meat yields to liveweight.

Total catches by grid-square or group of grid-squares, calculated from tag-recapture ratios (Table 6.4) show that the catches per individual grid-square are greatest for the Port St. Mary and Chickens fishing grounds, and lowest for the Targets and H/I grounds. The proportion of the catch made by the sample fleet differs between areas, indicating that the spatial distribution of fishing activity by the sample fleet is not always representative of the spatial distribution of fishing activity by the fleet as a whole. For example, in 1987/8 the sample fleet accounted for 32 and 34% of catches on the Bradda and Chickens grounds, but only 3 and 7% of catches on the south-east Douglas and the H/I-sector grounds. In 1988/9 the sample fleet accounted for 40% of catches on the Bradda ground, and only 15% on the south-east Douglas ground. The proportion of catches made by the sample-fleet on other grounds was fairly uniform at between 19 and 27% of total catches in both years. There appears to be a slight bias in the sample fleet towards boats fishing the inshore grounds off the south-west coast of the Isle of Man, leading to over-estimation of the relative importance of these grounds to the fishery as a whole (see Fig. 6.4 & 6.5).

**Fig. 6.9.** Total stock size estimates (millions of scallops) for major North Irish Sea fishing grounds calculated by two methods: (1) Petersen estimates from total catches and tag returns and (2) estimates from the relationship between CPUE and scallop density, assuming calculated densities apply to the whole of one or more 5 nautical mile grid squares.



**Table 6.4.** Total fleet catch (*C*) and effort (*f*) and Petersen estimates of population size (*N*), calculated from sample fleet catch-effort statistics ( $C_s, f_s$ ), tag releases, corrected for tag-loss and non-reporting (*T'*) and the ratio of tags recaptured by the sample fleet ( $R_s$ ) to the number recaptured by the total fleet (*R*).

a) 1987/8.

Area	Grid-squares	T'	$R_s$	R	$C_s$	C	$f_s$	f	N
BH	K11	490	87	187	129 155	277 609	7 406	15 918	727 428
PL	K10	541	32	134	75 792	317 379	4 076	17 070	1 281 359
TG	L8, L9	524	66	219	31 755	105 369	1 637	5 432	252 116
SED	N13, O13	759	6	77	50 657	650 098	1 437	18 411	6 408 111
H/I	L15/16, M15/16	715	1	29	12 075	350 173	426	12 357	8 633 625
PSM	L14	703	44	178	111 527	451 177	4 624	4 624	1 781 897
CH	J13/K13	417	93	183	342 417	673 788	11 673	11 673	1 535 354
Total	All fished	4 149	329	1 007	1 677 793	5 135 372	72 234	221 093	21 158 551

b) 1988/9.

Area	Grid-squares	T'	$R_s$	R	$C_s$	C	$f_s$	f	N
BH	K11	458	69	102	144 456	225 415	7 834	12 234	727 042
PL	K10	428	39	120	73 801	230 628	4 535	14 172	564 051
TG	L8, L9	374	21	66	22 473	66 811	1 454	4 322	227 160
SED	N13, O13	753	12	70	25 431	175 025	1 013	6 971	1 126 444
H/I	L15/16, M15/16	594	11	31	48 203	152 025	1 985	6 259	2 202 506
PSM	L14	649	54	181	142 957	444 755	5 262	16 371	1 030 879
CH	J13/K13	518	66	227	299 909	996 472	11 962	39 746	1 670 461
Total	All fished	3 774	272	797	1 217 909	3 568 652	53 634	157 156	16 898 487

Total size of the North Irish Sea scallop stock is estimated as 21.2 million commercial-sized scallops at the start of the 1987/8 fishing season, and 16.9 million at the start of the 1988/9 fishing season (Table 6.4).

#### 6.3.4. Yield per recruit and spawning-stock biomass per recruit

Yield per recruit and spawning-stock biomass per recruit for *Pecten maximus*, calculated for a range of fishing mortality rates (with  $M = 0.15$  and length of first capture = 110 mm), differ substantially between fishing grounds (Fig. 6.10). The Y/R curves reflect differences in scallop growth rates and growth patterns between areas (see Chapter 3). The highest growth rates are found on the Targets ground, which also has the highest Y/R values. The lowest Y/R values are found on the south-east Douglas fishing ground, which has the lowest growth rates.

The shape of the Y/R curves also differ, with curves for the Targets and south-east Douglas grounds reaching maxima at fairly low values of  $F$ . On other fishing grounds there is no  $F_{max}$  for the chosen  $M$  and length of first capture, and the Y/R curves tend towards an asymptote at  $F > 2$ .

Spawning stock biomass per recruit (SSB/R) also differs between fishing grounds (Fig. 6.10; note that SSB/R is abbreviated further to B/R on some graph axes). All SSB/R values decrease rapidly at fairly low values of  $F$  ( $F < 0.5$ ). The off-shore grounds (H/I sector and south-east Douglas) have lower SSB/R than other areas, indicating that the potential reproductive output per recruited scallop is less on these grounds. The more productive fishing grounds off the south and west coasts of the Isle of Man have higher SSB/R at all levels of fishing mortality.

Y/R and SSB/R curves are sensitive to the rate of natural mortality ( $M$ ) used (as a component of the total mortality,  $Z$ ) in the yield and biomass equations (equations 6.3 & 6.4). Fig. 6.11 shows Y/R and SSB/R curves for six *Pecten maximus* fishing grounds, calculated with values of  $M$  ranging from 0.10 to 0.30. The lowest assumed mortality rate results in the highest Y/R and SSB/R at all values of  $F$ .  $F_{max}$  and  $F_{0.1}$  are shifted towards higher values of  $F$  if higher values of  $M$  are used (Table 6.5). A value of  $M = 0.15$  has been chosen for all comparisons of spatial differences in Y/R and SSB/R, and for the analysis of management strategies based on changing  $F$  and length of first capture ( $L_c$ ).

The effects of changing  $L_c$  are shown in Fig. 6.12. At current fishing mortality rates, decreasing  $L_c$  to 100 mm (the EEC minimum legal landing size, applicable to all areas except the North Irish Sea) would decrease both Y/R and SSB/R on the majority of fishing grounds. The only exceptions are the slight increases in Y/R that would occur on the offshore grounds, where growth rates are slow and fishing mortality rates are very low.

Increasing  $L_c$  to 115 mm would increase SSB/R slightly on all fishing grounds and would also increase Y/R at current  $F$  on the Targets grounds. The change in  $L_c$  would make little difference to Y/R for most other fishing grounds, at current  $F$ . A larger increase to an  $L_c$  of 120 mm would further increase SSB/R, but would only significantly increase Y/R on The Targets ground. With  $L_c = 120$  mm, Y/R at current levels of  $F$  would decrease substantially on the Bradda Head, south-east Douglas and Port St. Mary grounds.

The management options for each fishing ground and suggested management strategy for the fishery as a whole, based on Y/R and SSB/R modelling, are analysed and discussed further in section 6.4.3.

Y/R and SSB/R curves for *Chlamys opercularis* from the East Douglas fishing ground, calculated for values of  $M$  from 0.2 to 0.5 ( $L_c = 55$  mm) are all asymptotic, rather than domed, over the range of  $F$  values examined (Fig. 6.13). Y/R and SSB/R curves calculated for roe-off (adductor muscle only) and roe-on (adductor muscle + gonad) queens are of the same shape. The value of  $F = 1.06$ , calculated from a mark-recapture experiment (Chapter 5) results in a Y/R close to the asymptotic Y/R for all values of  $M$ . SSB/R is low at this high value of  $F$ .

The differences in Y/R and SSB/R curves (Fig. 6.13) and  $F_{0.1}$  and (Table 6.5) calculated with different values of  $M$  are large. Given the uncertainty in the value of  $M$  (see Chapter 5), this assessment must be regarded as a preliminary one.

The minimum size of queens landed to the Isle of Man is currently around 55 mm shell-length. The effects of changing  $L_c$  on Y/R and SSB/R are shown in Fig. 6.14. Decreasing  $L_c$  to 40 or 45 mm shell length would result in a large decrease in both Y/R and SSB/R at current levels of  $F$ . Increasing  $L_c$  to 60 mm would slightly increase SSB/R with no effect on Y/R. Similarly, a fairly large increase in SSB/R and no change in Y/R would result from raising the size of first capture to 65 mm shell length.

Fig. 6.10. Y/R and SSB/R (grammes per recruit) for six *Pecten maximus* fishing grounds (M=0.15, length of first capture = 110 mm).

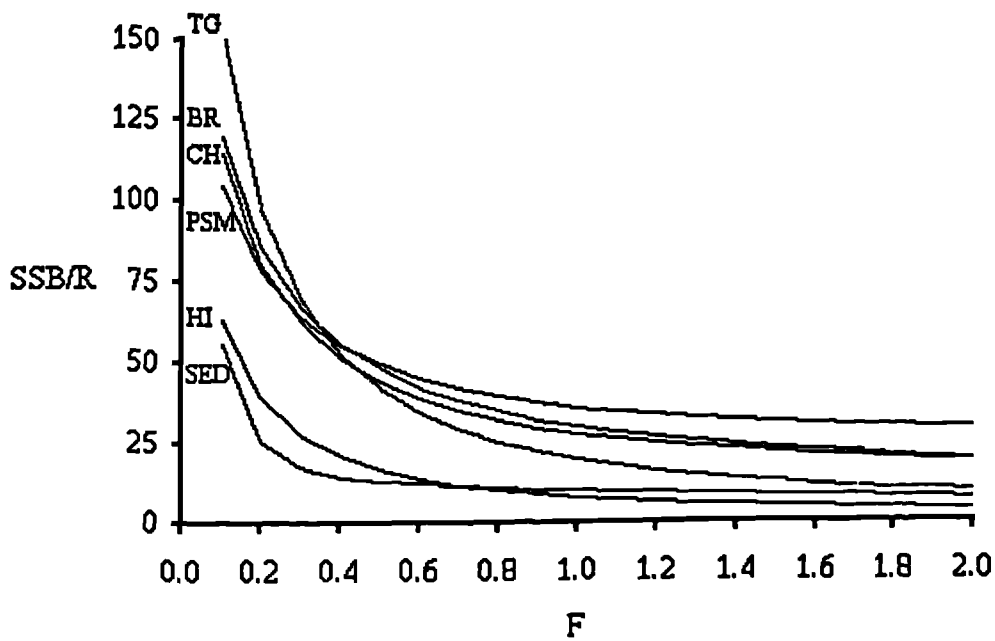
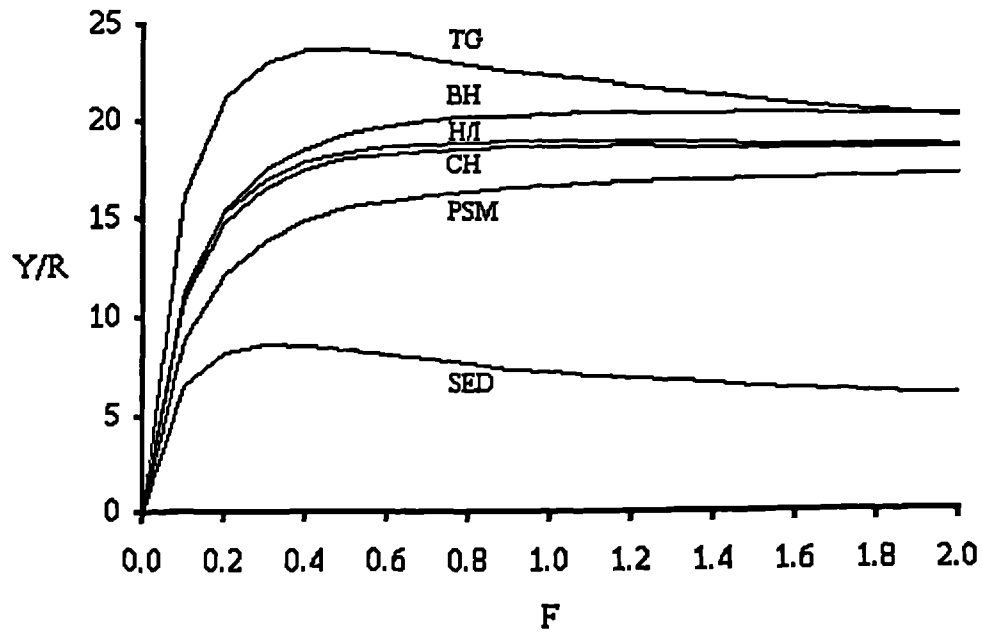
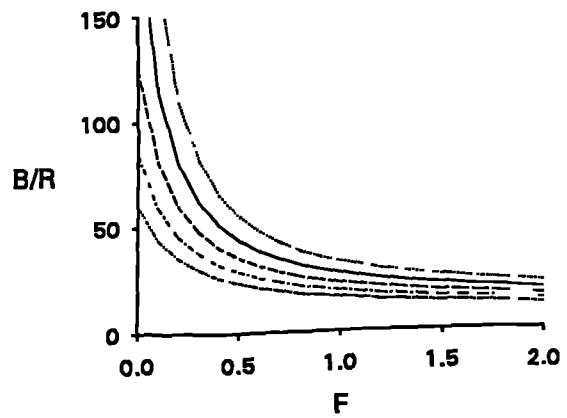
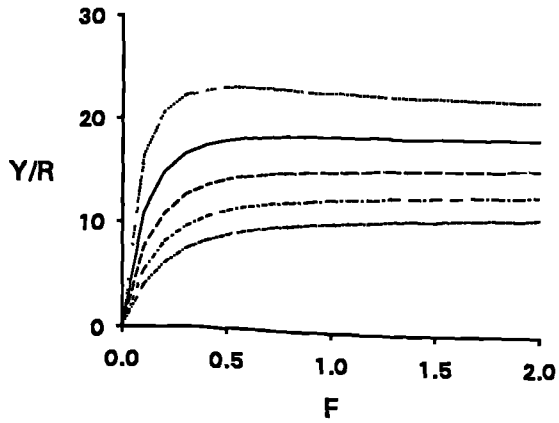


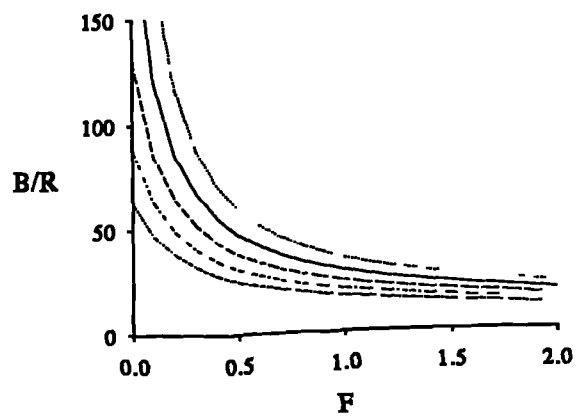
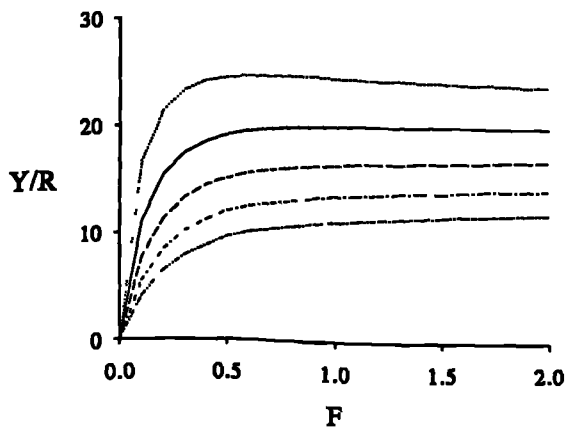


Fig. 6.11. Yield per recruit and spawning-stock biomass per recruit (grammes per recruit) curves calculated using values of  $M = 0.10, 0.15, 0.20, 0.25, 0.30$ . The lowest value of  $M$  gives the curve with the highest  $Y/R$  and  $B/R$ , and the highest value of  $M$  gives the curve with the lowest  $Y/R$  and  $B/R$ . Length of first capture is 110mm.

a) The Chickens.



b) Bradda Head.



c) The Targets.

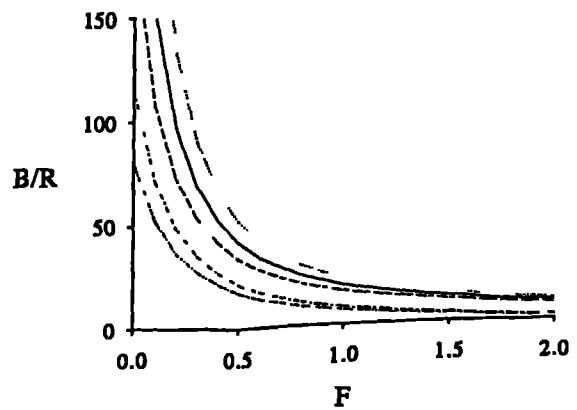
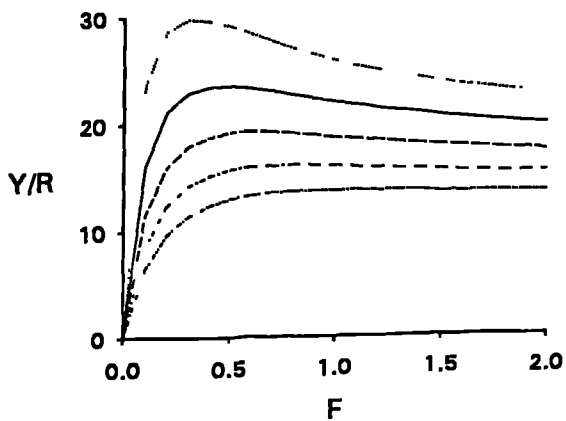
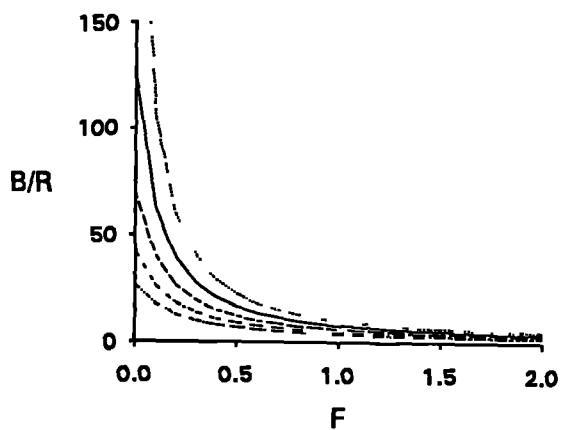
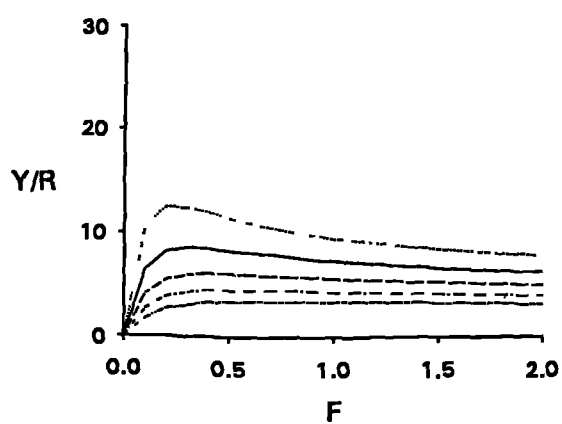
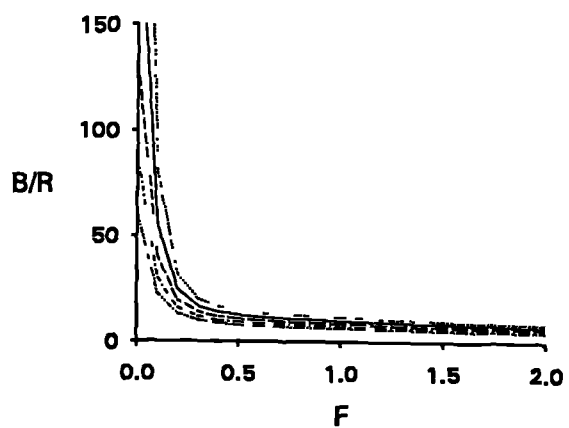
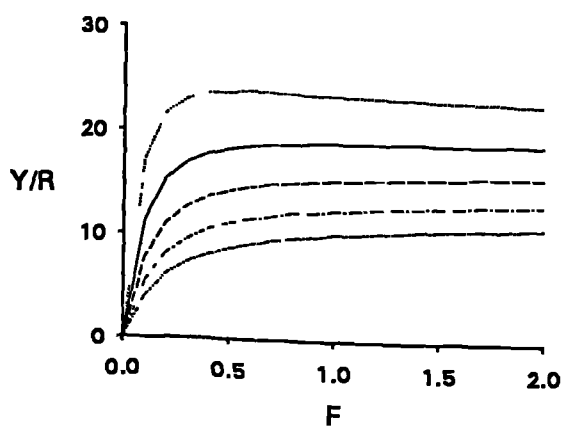


Fig. 6.11 (cont.)

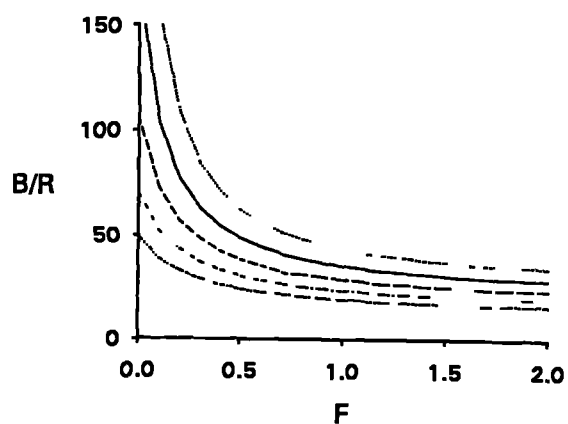
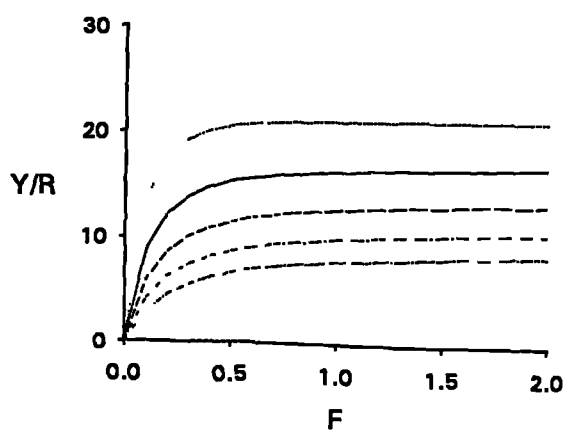
d) South-east Douglas.



e) H/I sector.



f) Port St. Mary.

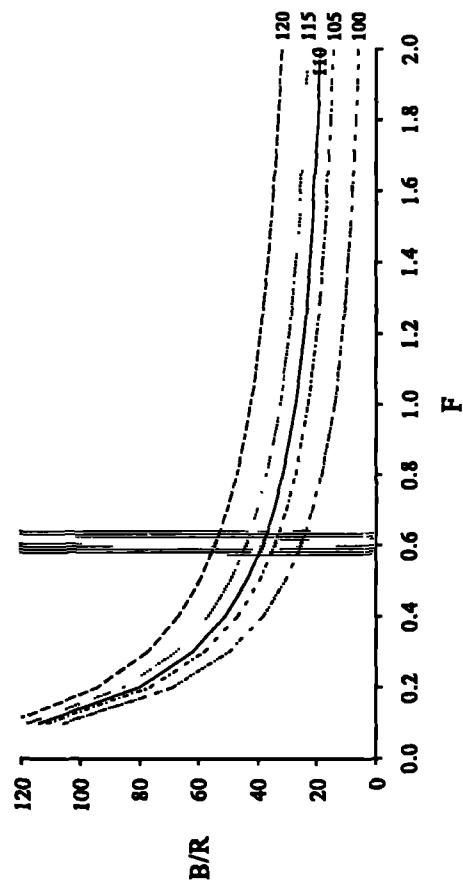
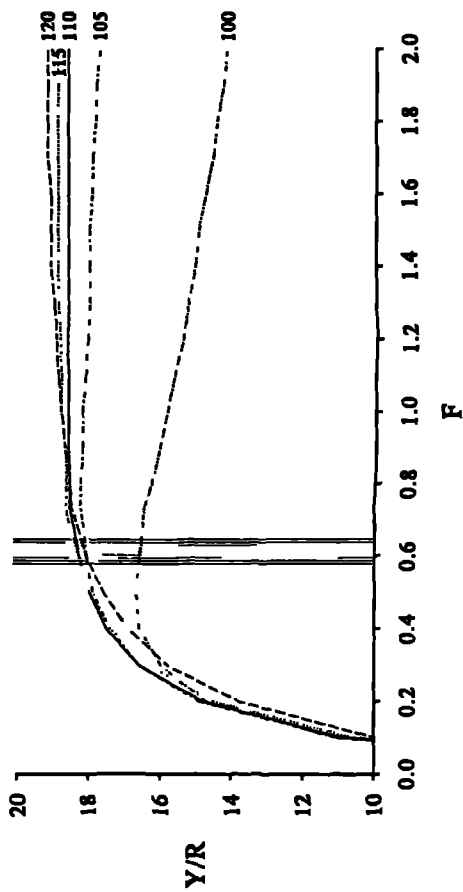


**Table 6.5.**  $F_{\max}$  and  $F_{0.1}$  calculated from Y/R analysis using different values of M. Missing values are for cases where  $F_{\max} > 2.00$ .

AREA	M	$F_{\max}$	$F_{0.1}$
<i>Pecten maximus</i>			
Bradda Head	0.10	0.83	0.18
	0.15	1.58	0.26
	0.20	-	0.34
	0.25	-	0.43
	0.30	-	0.52
The Chickens	0.10	0.63	0.16
	0.15	1.23	0.24
	0.20	-	0.31
	0.25	-	0.39
	0.30	-	0.47
The Targets	0.10	0.33	0.14
	0.15	0.47	0.19
	0.20	0.63	0.25
	0.25	0.86	0.31
	0.30	1.21	0.36
H/I-sector	0.10	0.56	0.16
	0.15	1.10	0.23
	0.20	-	0.30
	0.25	-	0.38
	0.30	-	0.46
Port St. Mary	0.10	-	0.18
	0.15	-	0.27
	0.20	-	0.35
	0.25	-	0.44
	0.30	-	0.54
SE Douglas	0.10	0.24	0.12
	0.15	0.33	0.16
	0.20	0.43	0.21
	0.25	0.56	0.25
	0.30	0.71	0.30
<i>Chlamys opercularis</i>			
East Douglas (adductor muscle)	0.2	1.74	0.33
	0.3	-	0.48
	0.4	-	0.64
	0.5	-	0.81
East Douglas (adductor muscle + gonad)	0.2	1.37	0.32
	0.3	-	0.47
	0.4	-	0.62
	0.5	-	0.78

Fig. 6.12. *Pecten maximus* yield per recruit and spawning stock biomass per recruit for different sizes of first capture (mm shell-length). Current size of first capture is 110 mm shell length;  $M$  is set at 0.15. The ranges of  $F$ -values on each fishing ground in 1987 - 89, estimated from tagging experiments, are indicated by the shaded bands.

a) The Chickens.



b) Bradda Head.

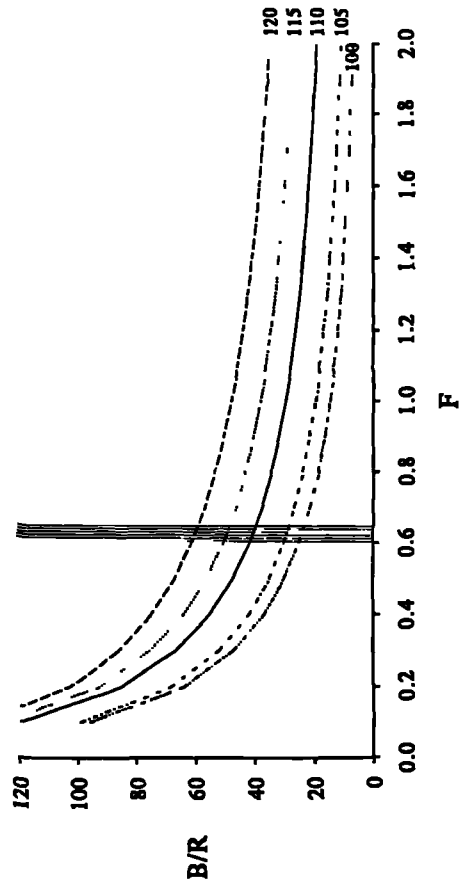
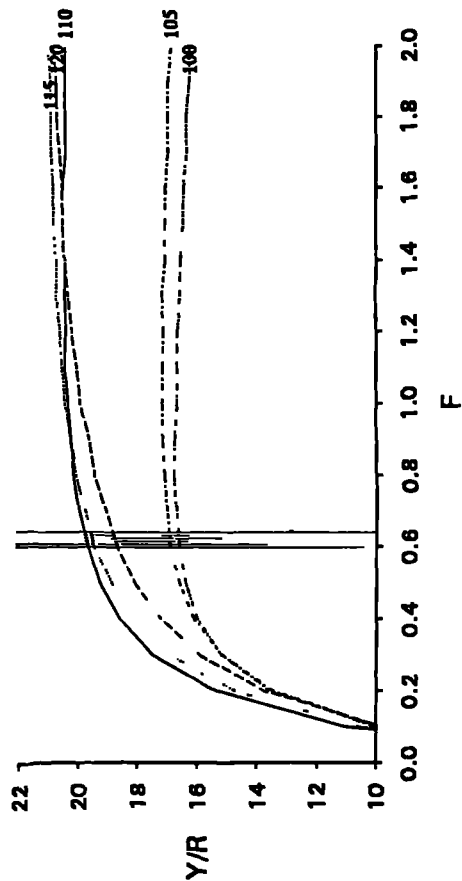
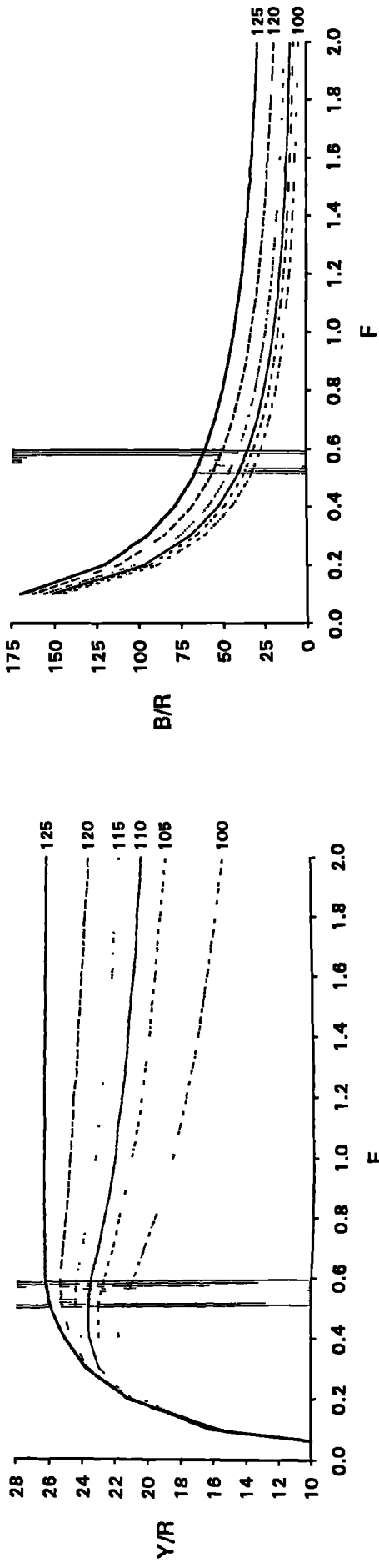


Fig. 6.12 (cont.)

c) The Targets.



d) South-east Douglas.

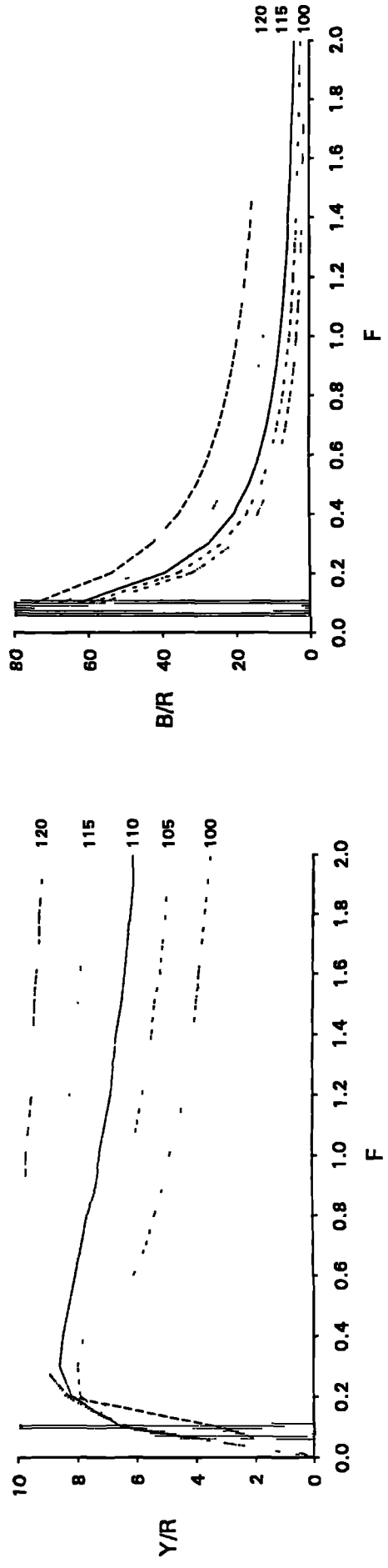
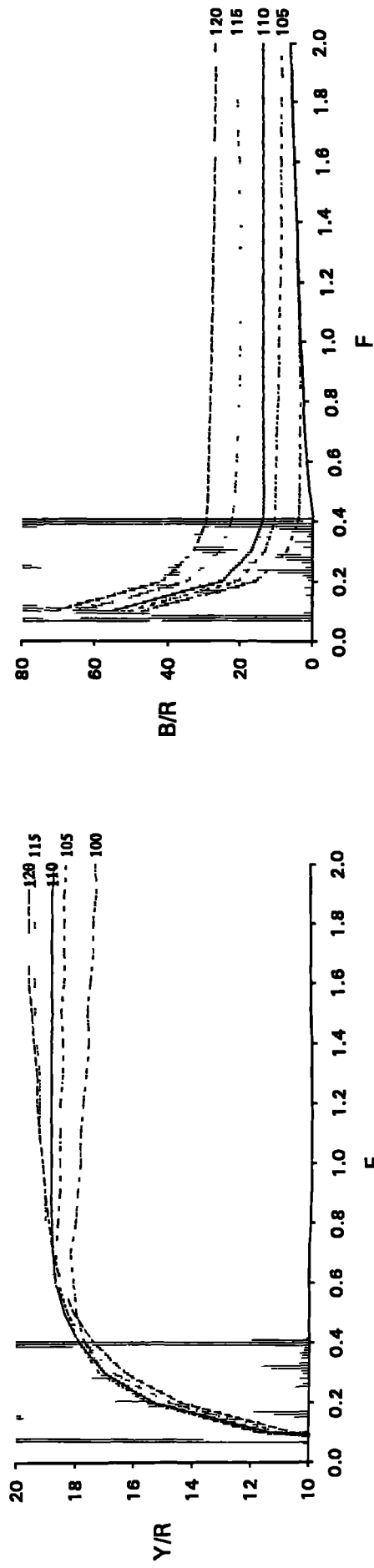
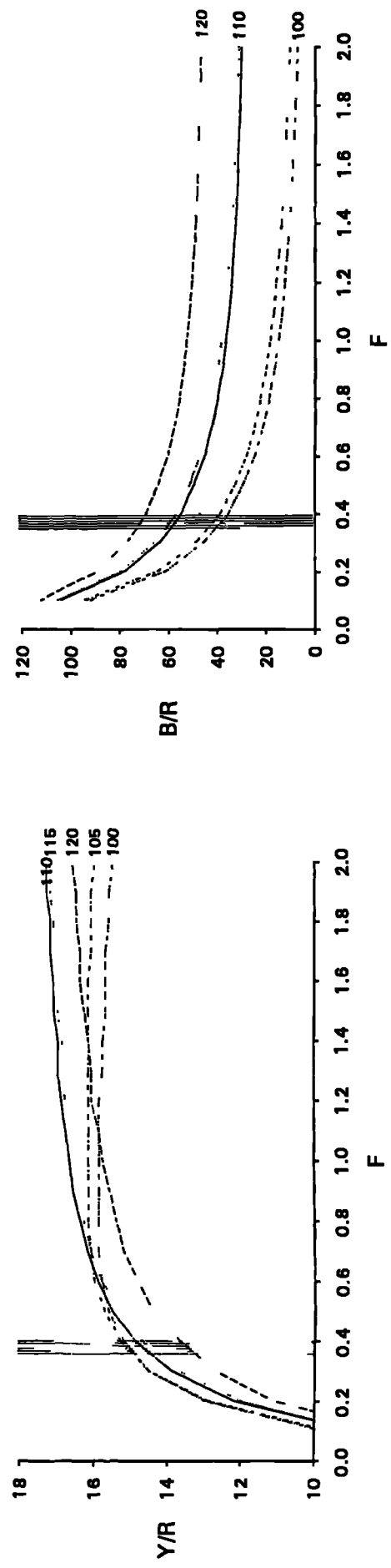


Fig. 6.12 (cont.)

e) H/I sector.

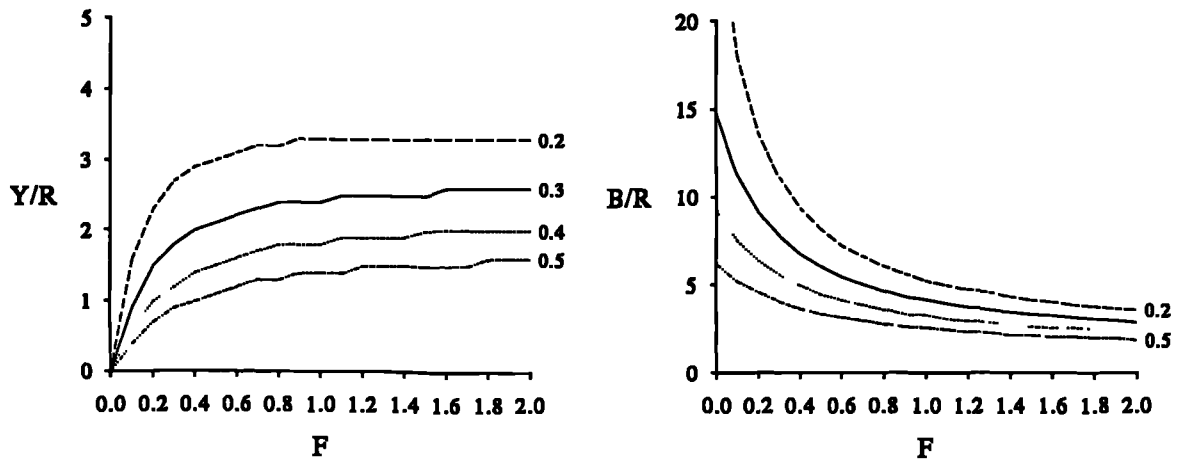


f) Port St. Mary.

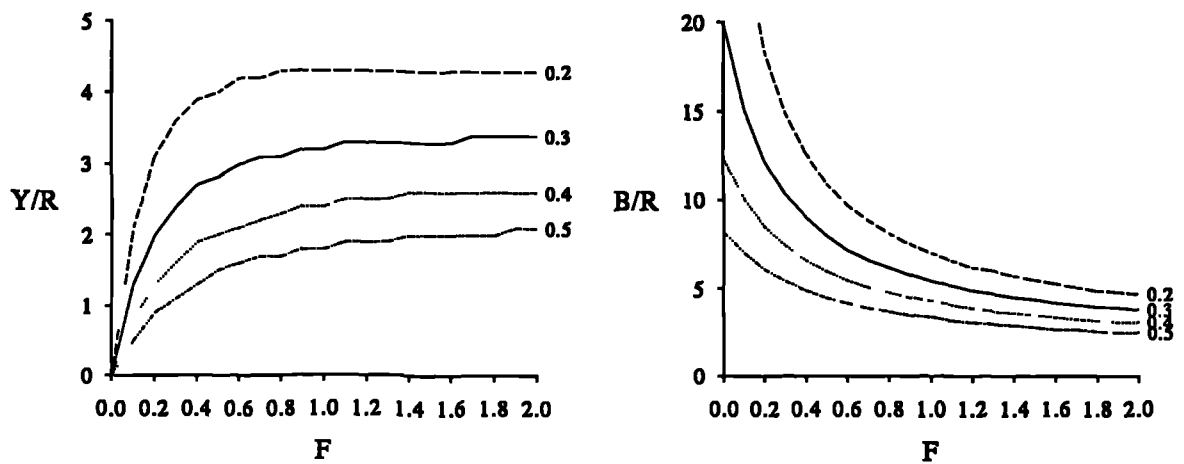


**Fig. 6.13.** Yield per recruit and spawning stock biomass per recruit for *Chlamys opercularis* from the east Douglas fishing ground, calculated for values of  $M$  ranging from 0.2 to 0.5 year<sup>-1</sup>.

**a) Adductor muscle only.**

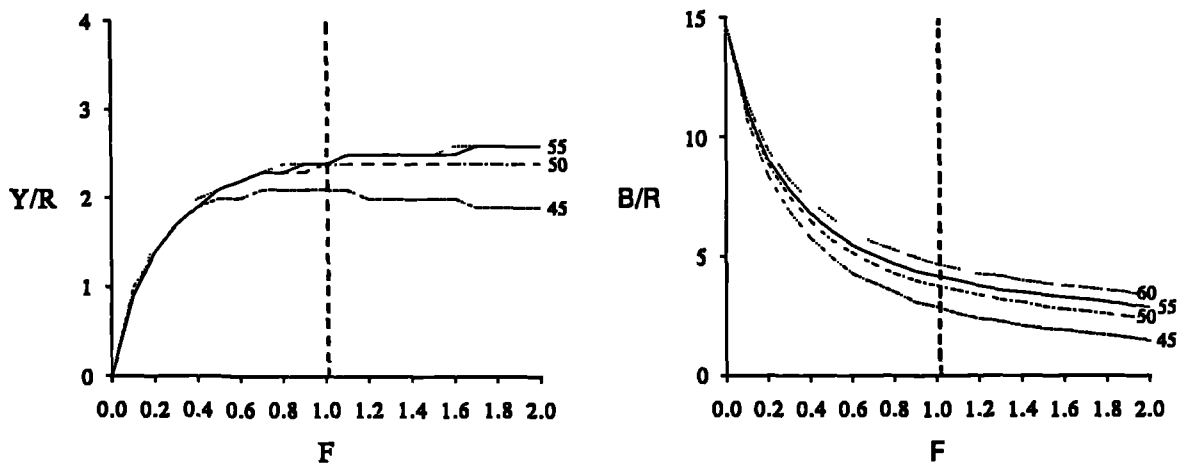


**b) Adductor muscle + gonad.**

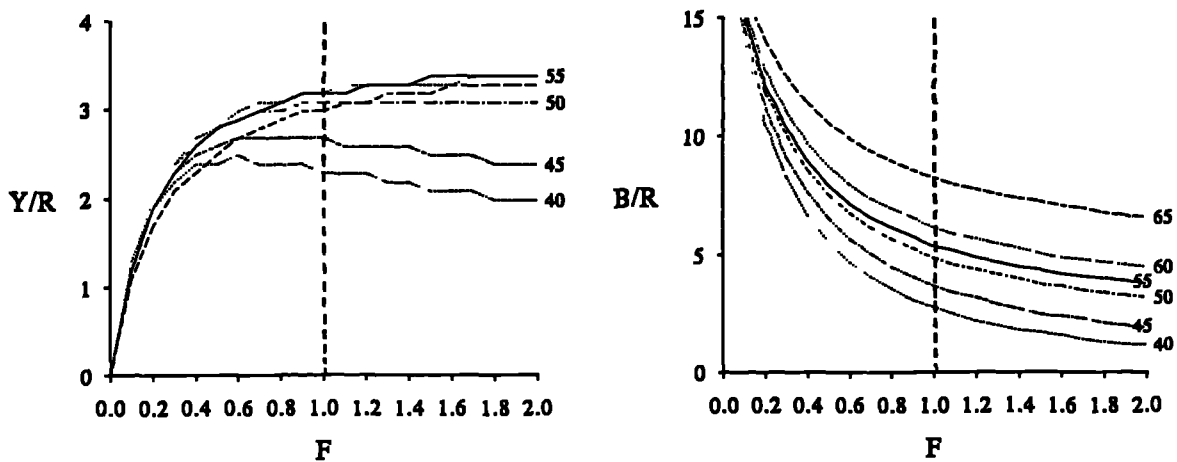


**Fig. 6.14.** Yield per recruit and spawning stock biomass per recruit for *Chlamys opercularis* from the east Douglas fishing ground ( $M = 0.3$ ), calculated for different sizes at first capture (mm shell-length). Fishing mortality rate ( $F$ ) in 1989, calculated from a mark-recapture experiment, is indicated by the vertical dotted line.

**a) Adductor muscle only.**



**b) Adductor muscle + gonad.**





## 6.4. DISCUSSION

### 6.4.1. The analysis of fishery statistics

The analysis of landings statistics in the ICES area shows that the Isle of Man has a major share of the European scallop market, particularly of that for queen scallops. The Isle of Man's market share of the *Pecten maximus* fishery has not decreased, despite recent decreases in landings, because some other major fisheries, notably the French one, have declined (see Ansell *et al.*, 1991, for review). In the French fishery, efforts to restock depleted grounds with artificially reared juveniles have been underway for some years, and scallop farming is well developed relative to other scallop-fishing nations. A similar, but smaller-scale research programme was recently initiated on the Isle of Man (Brand *et al.*, 1991a), and could, in the long term, assist in reviving the fortunes of the Manx fishing industry.

The Isle of Man-based fisheries for scallops and queens are not enjoying a boom period. The last large year-class of scallops entered the fishery in 1983, and catch rates have since declined to reach the lowest values recorded in 1989/90. Catch rates for the following two seasons were even lower (Brand, unpublished data). CPUE on several of the major fishing grounds is now less than 20 scallops  $m^{-1}hr^{-1}$  dredging. An economic analysis of the Northern Ireland scallop fishery by Briggs (1991) found that in 1985, catch rates of 25 scallops  $m^{-1}hr^{-1}$  were the lower limit of what was economically viable for the N.I. inshore scallop fishing fleet.

Market prices for scallops have shown no increase in real terms over the last 3 years, while the costs of exploiting them have continued to rise. The market and fishery for queens continues to be unpredictable, and the Manx fleet has not diversified substantially into other fisheries. The consequences of the worsening economic situation have been that many vessels have been sold over the last 5 years, and many more are currently (January 1993) up for sale.

Sample-fleet catch-effort statistics from commercial-vessel logbooks have provided a useful graphical impression of the distribution of fishing activity, assisting in locating the major fishing grounds for scallops and queens - information which has proved useful in the choice of areas used in population dynamics studies (Chapters 2-5). Total catches and fishing effort from the sample fleet have been

extrapolated by scaling up sample fleet statistics to the size of the whole fleet. The ultimate objective of the logbook data collection programme, however, is to derive accurate, area-specific estimates of fishing activity. This is problematic when less than 30% of the fleet complete logbooks.

The first stage in extrapolating sample-fleet to total fleet catches is to determine the fishing power (number of dredges towed) of the whole fleet. These can be obtained either from relationships (derived from the sample fleet) between dredge width and various vessel characteristics (e.g. length, horsepower, tonnage, age, type: ex-beamer, stern-trawler etc.) or from direct counts of the number of dredges.

The next step is to determine the number of days fished by each boat. Two sources of information may be useful: the Isle of Man Social Security Office, who *keep records of claims made by fishermen kept in port by bad weather*, and scallop processing factories, who keep records of catches landed each day for each boat landing to them. Both sources of information are sensitive, and it may not be possible to obtain full records. Recent attempts to obtain data from processors have been successful, however, and these data are particularly useful as they provide information on the catch per boat and an indication of the gross income per boat, as well as the days fished. They also provide a useful means of checking sample-fleet records from logbooks.

So, if sample fleet catch and effort are known, and the total fleet catch, fishing power and number of days fished can be obtained, the only remaining unknown is the spatial distribution of fishing activity. Straightforward extrapolation of sample-fleet catch/effort distributions is unlikely to be successful, given that the ratio of sample-fleet to total-fleet catches of tagged scallops was found to vary spatially (Section 6.3.3). It would be necessary to weight predictive relationships between sample-fleet effort and total-fleet effort by factors such as size of vessel (e.g. for offshore grounds, boats < 40 ft, which seldom fish outside the 3 mile limit, would get zero weighting), home port, and any known pattern of fishing or fishing habit (e.g. skipper tends to explore, or fishes with the majority of the rest of the fleet from the same port). Some validation data may be available from the occasional MAFF aerial surveys of fishing activity in the Irish Sea, if vessel names and positions are recorded on these surveys.

Another approach would be to use sample-fleet CPUE as a measure of scallop density, and to predict the distribution of effort using simulation models based on the assumption that fishermen will exploit the highest-density patches first, then search for the next densest patch when the first one is depleted, and so on. Other factors such as the relative cost of exploiting each ground (related to its distance from port) as well as more complex simulations (e.g. using the wind-speed and direction data as an additional determinant of the distribution of fishing effort or allowing a certain fraction of the effort to be allocated at random over the area occupied by the stock, to simulate exploration, or programming a tendency for boats from the same home port to fish as a fleet) could be built into the model. The basic approach to such problems is outlined in Hilborn & Walters (1987) and extensively discussed in a later publication (Hilborn & Walters; 1992). The theory comes from search and stock-depletion models (Mangel & Clark, 1983), which are based on optimal foraging theory (Pyke *et al.*, 1977 and Hughes, 1980; for reviews). Models could be validated, at least for 1987/8 and 1988/9, by checking predicted effort and catches against those obtained from recaptures of tagged scallops and sample-fleet catch statistics, which are probably the most reliable area-specific data currently available (section 6.3.3).

Before work on the queen fishery can progress to such a level of sophistication, it is necessary to explore further the choice of an appropriate unit of fishing effort for this mixed-gear fishery, and to carry out a bio-economic analysis of the fisheries using both gear-types. Brand and Allison (1987) discuss some of the factors which may determine whether a boat fishes with a trawl or dredges; these include the size and type of vessel (e.g. beam trawlers cannot tow nets, and larger vessels tend to exploit the offshore grounds to the south which are too rocky to fish with nets), the home port and the relative running costs of the two type of gear (dredges being more expensive to fish than trawls).

Many vessels fish with dredges in the early part of the queen season (June-July), switching to trawls later in the season (August-October) because the catchability of queens by the two different gears varies seasonally. Trawls rely on the escape reaction of queens to capture them (Chapman *et al.*, 1979). Tickler chains, or simply the approach of the trawl, cause the queens to rise from the substrate and swim by means of rapid adduction of the shell valves. The fishing line of the trawl is generally a few centimetres off the bottom, and the queens are thus caught while swimming up off the seabed. Fishermen maintain that the queens do not 'jump' in the early part of the season, and so are not caught in trawls. If the

queens do not swim as actively in the early part of the season, they are more likely to be caught in dredges. These will catch the queens which cannot escape from the path of the dredge, or pass over the top of the dredge, which is only a few centimetres above the substrate. Physiological evidence of seasonal variability in the swimming ability of pectinids supports the views of fishermen (Joll, 1989; and Brand, unpublished data).

The spread of trawls, and whether they are rigged to fish exclusively for queens or to take queens as a by-catch to demersal fish, are difficult to determine from fishermen's logbooks. This complicates the comparison of CPUE between different boats, or even the same boat at different times. In initial analyses, it may be better to use a less precise unit of effort than the 'metre width of gear  $\times$  hours fished' used for scallops. Boat-days are suggested as an alternative unit, perhaps weighted by vessel size or horsepower.

Data on catches of queens from sample-fleet logbooks suggest that the major grounds are persistent in location, but that the importance of a particular ground to the fishery varies from year to year. This pattern of exploitation, where high-density patches are located and fished down sequentially by the fleet, is typical of what is thought to occur in other fisheries for sessile and semi-mobile shellfish (Caddy, 1989a and Orensanz *et al.*, 1991, for reviews).

The scallop fishery is perhaps atypical of shellfish fisheries in that the major catching areas remain the same from year to year. The pattern of sequential stock depletion in the scallop fishery may, however, occur on a smaller time-scale; movement of the fleet from one ground to another may take place within the fishing season. Murphy (1986) examined the within-season patterns of effort distribution, in the North Irish Sea scallop fishery and found that boats tended to start fishing on inshore grounds and move offshore later in the season when catch-rates on the inshore grounds had fallen. The weather tended to obscure the pattern to a large extent. Murphy's work (*op. cit.*) indicates that simulations of fleet response to scallop density variations (Hilborn & Walters, 1987) would have to be made using a time-step of days or weeks in this fishery.

The fact that, in the scallop fishery, all high density-areas are exploited and depleted within a portion of a single fishing season, whereas in the queen fishery a few high-density areas support the fleet for the whole season, implies that the

overall level of exploitation in the North Irish Sea scallop fishery is higher than that in the queen fishery.

#### **6.4.2. Scallop abundance estimates**

The Petersen estimates of stock-abundance of commercial-size scallops on the Bradda Head ground in 1987 and 1988 are of the same order of magnitude as previous estimates of abundance of commercial-sized scallops on this ground: Mason and Colman (1955) used a short-term single-release tagging experiment to estimate a total of 144 000 marketable scallops in an area of 0.5 square miles. The same authors went on to estimate the total area dredged to be between 6 and 7 square miles, giving an abundance estimate of 1.7 - 2.0 million scallops on the Bradda Head ground in 1953. Gruffydd's (1972) single-release tagging experiment provided an estimate of 914 000 scallops in 1966, assuming the dredged area of the Bradda Head ground to cover 4.5 km<sup>2</sup>. Murphy (1986) calculated that 278 000 commercial-size scallops were present in an area of 7.5 km<sup>2</sup> in 1982/3 and 452 000 scallops in 1983/4. Estimates of abundance from tagging and commercial catch data in this thesis are 727 000 scallops in July 1987 and approximately the same number in June 1988, estimated independently of fished area.

The estimates of scallop abundance on the Bradda Head ground, derived independently of CPUE data, accord well with the historical changes in CPUE on this ground (see Brand *et al.*, 1991b). This suggests that CPUE may well be a reasonable index of abundance for grounds where the spatial extent of the stock is the same over long periods of time. For areas or fishing grounds where the spatial extent of the stock is highly variable, CPUE is not such a reliable measure of abundance. For this reason, CPUE cannot be used to compare absolute abundances of different fishing grounds, although it provides a useful measure of relative density over unspecified areas.

For the major, traditionally fished grounds such as the Bradda Head ground which are persistent in their location at a fairly small spatial scale (< 10 km<sup>2</sup>) and where changes in CPUE are therefore likely to reflect changes in overall abundance, the spatial extent of the fishing grounds need only be determined once before CPUE can be converted to abundance, without incurring the bias resulting from the assumption (apparently unreasonable) that scallop grounds cover the whole of the 5 nautical mile squares from which CPUE data are reported. CPUE could thus be used to provide annual abundance estimates for major grounds without the

requirement for an expensive annual research-vessel survey. Improved estimates of gear-efficiency and towing speed would enhance the accuracy of the conversion of CPUE to abundance (see Chapter 2). Murphy (1986) provides estimates of the area of some of the major scallop fishing grounds; estimates which require confirmation.

#### 6.4.3. Management recommendations based on Y/R and SSB/R analysis

Yield per recruit and spawning stock biomass per recruit curves for scallops differ between fishing grounds due to spatial variation in weight-at-age, age at recruitment and age at first sexual maturity. Fishing mortality rates also show considerable spatial variability (Murphy, 1986 and Chapter 4). Widely differing values of  $F$  within the North Irish Sea stock mean that the status of the fishery on each ground with respect to management targets such as  $F_{max}$  or  $F_{0.1}$  will differ considerably. In practical terms, if the same management target is set for each ground (to maximise yield per recruit, for example) the method of achieving that target will depend on whether the scallops on that fishing ground are fast or slow growing, or are lightly or heavily fished. Taking the *status quo* in the scallop fishery to be  $L_c = 110$  mm and  $F =$  the area-specific estimate for 1987-89 ( $F_{obs}$ ), Table 6.6 shows, as a percentage change from that status quo, Y/R and SSB/R of *P. maximus* for all combinations of 5 possible classes of management strategy. These management strategies are:

- i) Maintain  $F$  at recent or current levels (target =  $F_{stq}$ ) and change  $L_c$ .
- ii) Aim for  $F_{0.1}$  at current  $L_c$
- iii) Aim for  $F_{0.1}$ , also change  $L_c$
- iv) Aim for  $F_{max}$  at current  $L_c$
- v) Aim for  $F_{max}$ , also change  $L_c$

Note that  $F_{max}$  and  $F_{0.1}$  decrease with decreasing  $L_c$ . Conclusions from examining all possible management options within the range of values of  $F$  and  $L_c$  examined are:

- i) Aiming to maintain  $F_{stq}$  and decrease  $L_c$  to the EEC minimum legal landing size of 100 mm shell length would lead to decreases in Y/R (9-16%) on inshore grounds (The Chickens, Bradda Head and The Targets) and little change on the offshore grounds (3% decrease - 2% increase). Spawning stock biomass would decrease on all fishing grounds by between 10 and 47%.

**Table 6.6.** Changes in *Pecten maximus* Y/R and SSB/R resulting from different management scenarios. Listed are: the mean fishing mortality for 1987-89 ( $F_{obs}$ ), the calculated values of  $F_{0.1}$  and  $F_{max}$  for each length of first capture ( $L_c$ ), percentage changes in Y/R and SSB/R calculated for each  $L_c$  at different management targets ( $F_{stq}$ : F 'status quo'),  $F_{0.1}$  and  $F_{max}$ . Changes in Y/R and SSB/R are expressed as a % of the values of Y/R and SSB/R for  $F_{obs}$ ,  $L_c = 110$  mm).

Area	$L_c$	$F_{obs}$	$F_{0.1}$	$F_{max}$	Y/R ( $F_{stq}$ )	Y/R ( $F_{0.1}$ )	Y/R ( $F_{max}$ )	SSB/R ( $F_{stq}$ )	SSB/R ( $F_{0.1}$ )	SSB/R ( $F_{max}$ )
CH	100	0.61	0.20	0.51	-9	-19	-9	-42	59	-31
	105	0.61	0.23	0.87	-1	-16	0	-22	64	-38
	110	0.61	0.24	1.23	0	-15	3	0	81	-43
	115	0.61	0.25	1.64	0	-16	4	1	77	-42
	120	0.61	0.27	-	-1	-17	-	25	90	-
BH	100	0.63	0.23	0.83	-16	-29	-15	-40	45	-55
	105	0.63	0.24	1.04	-15	-30	-13	-28	52	-53
	110	0.63	0.26	1.58	0	-16	4	0	82	-67
	115	0.63	0.27	-	-1	-10	-	22	98	-
	120	0.63	0.30	-	-5	-18	-	48	111	-
TG	100	0.57	0.18	0.36	-12	-17	-8	-20	167	36
	105	0.57	0.19	0.42	-3	-13	-2	-9	164	25
	110	0.57	0.19	0.47	0	-12	0	0	173	20
	115	0.57	0.21	0.54	4	-9	4	15	167	19
	120	0.57	0.22	0.67	8	-7	8	41	184	21
	125	0.57	0.24	0.96	11	-5	13	68	194	-10
SED	100	0.09	0.13	0.23	-3	20	34	-10	-30	-59
	105	0.09	0.15	0.28	0	30	45	-4	-32	-62
	110	0.09	0.16	0.33	0	36	55	0	-30	-64
	115	0.09	0.19	0.44	0	48	66	14	-32	-64
	120	0.09	0.22	0.66	-51	53	79	34	-26	-63
HI	100	0.24	0.21	0.69	1	-2	14	-47	101	-94
	105	0.24	0.22	0.90	1	-1	17	-19	105	-71
	110	0.24	0.23	1.10	0	-1	19	0	126	-55
	115	0.24	0.24	-	7	-3	-	43	140	-
	120	0.24	0.25	-	5	-4	-	74	157	-
PSM	100	0.38	0.23	0.87	2	-8	9	-27	0	-70
	105	0.38	0.23	1.06	3	-9	14	-27	5	-70
	110	0.38	0.27	-	0	-9	-	0	19	-
	115	0.38	0.27	-	-1	-10	-	9	22	-
	120	0.38	0.29	-	-10	-14	-	30	37	-

Maintaining  $F_{stq}$  and increasing  $L_c$  to 115 mm would have little effect on Y/R: the largest change would be a 7% increase on the Targets ground. SSB/R would show little change on the Chickens and Port St. Mary grounds, but would increase by 43% on the H/I ground, and by between 14 and 22% on other grounds.

ii) Aiming for  $F_{0.1}$  while retaining the minimum legal landing size at 110 mm would decrease Y/R by 12-16% on the inshore grounds, and by 9% on the Port St. Mary ground. Note that to reach  $F_{0.1}$  on the inshore grounds, reductions of  $F$  (and therefore fishing effort, assuming constant catchability) of around 60% would be required. Y/R on the H/I ground would remain unaffected, as  $F_{obs}$  is close to  $F_{0.1}$ . Aiming for  $F_{0.1}$  on the SE Douglas ground would increase Y/R by 36% as  $F_{obs}$  is below  $F_{0.1}$ .

The mean  $F$  for 1987-89 ( $F_{obs} = 0.24$ ) on the H/I ground is likely to be an overestimate. The estimate of  $F = 0.07$  in 1987/8, derived from the Ricker two-release tagging experiment, is probably realistic, whereas the value of  $F = 0.41$  for 1988/9, derived from exploitation rates of tags and sample-fleet fishing effort data, is less reliable due to the fact that only one or two vessels in the sample fleet fished the area. Actual  $F$  on this ground during 1987-89 is likely to have been lower than  $F_{0.1}$  and therefore Y/R would increase if  $F$  was increased.

SSB/R would increase greatly on the heavily fished inshore grounds with the large reductions in  $F$  required to reach  $F_{0.1}$ . The decrease in Y/R on the south-east Douglas ground caused by the increase in  $F$  required to reach  $F_{0.1}$  is inevitable: maximum SSB/R occurs at  $F = 0$ .

iii) Aiming for  $F_{0.1}$  and decreasing  $L_c$  would lead to larger losses of Y/R and smaller gains in SSB/R than if  $L_c$  were kept at 110 mm. Aiming for  $F_{0.1}$  and increasing  $L_c$  to 115 mm or 120 mm would make little difference (to either Y/R or SSB/R) to retaining the current  $L_c$ .

iv) Aiming for  $F_{max}$  at  $L_c = 110$  would make little difference to Y/R on the Bradda and Chickens grounds, as Y/R approaches a maximum at  $F_{obs}$  on these grounds. Increases in Y/R would occur on the south-east Douglas and H/I grounds. Large decreases in SSB/R would be the consequence of aiming for  $F_{max}$  on most grounds. In the case of Bradda and the Chickens, the large decrease in SSB/R would occur with no significant increase in Y/R. Aiming for  $F_{max}$  in fisheries where the Y/R



curve is asymptotic will always result in a decline in catch rates, profitability and spawning stock biomass (Patterson, 1991).

Aiming for  $F_{\max}$  on the Targets ground would increase both Y/R and SSB/R because  $F_{\text{obs}}$  exceeds  $F_{\max}$ .

v) Aiming for  $F_{\max}$  and decreasing  $L_c$  to 100 mm would lead to losses of 9 - 15% of Y/R on inshore grounds, and gains on offshore grounds, albeit less than the gains that would occur by aiming for  $F_{\max}$  at the current  $L_c$ . Reductions of SSB/R would be greater than if  $L_c$  was maintained at 110 mm.

Increasing  $L_c$  to 115 mm or 120 mm and aiming for  $F_{\max}$  would result in larger gains in Y/R on the Targets and SE Douglas grounds than if no change in  $L_c$  was made. The effect on SSB/R for these grounds would be the same as if  $L_c$  was not changed. On other grounds,  $F_{\max}$  occurs at F-values  $> 2.00$  for lengths of first capture  $> 110$  mm, so the percentage change is not evaluated. Decreases in SSB/R resulting from a change of F from  $F_{\text{obs}}$  to  $F_{\max}$  would be very large.

There are two possible overall management strategies, depending on whether total management control can be assumed (the ideal situation), or if the degree of management control and legislative intervention is assumed to be limited (the realistic situation).

The ideal strategy would be to set differing management targets for each fishing ground. Fishing effort should be reduced on the inshore grounds (Bradda Head and The Chickens) by aiming towards  $F_{0.1}$ , rather than  $F_{\max}$  as fishing to  $F_{\max}$  will lead to low stock sizes, reducing individual profitability and increasing the likelihood of stock collapse due to low spawning stock biomass (Gulland & Boerma, 1973; Deriso, 1987). Some of the reduction in effort required may already have taken place through reduction in fleet size brought on by decreasing catch rates and profitability (A.R. Brand, personal communication, January 1993). No change in the minimum legal landing size is recommended for these grounds. In the case of the Targets ground, the minimum legal landing size would ideally be increased to 120 mm or more, and fishing effort cut by at least 20% to bring  $F_{\text{obs}}$  down to below  $F_{\max}$ ; a cut of 66% would be required to reach  $F_{0.1}$ . F and  $L_c$  should be maintained constant on the Port St. Mary ground, and F should be increased on the offshore SE Douglas and H/I grounds.  $L_c$  on the SE Douglas

ground could be increased to 115 mm, as the initial growth rate of scallops is slower than on other grounds, but the asymptotic length is reached at an older age.

The 'ideal strategy' would require tight management control and complete co-operation from fishermen, who would probably need to form co-operatives with sole rights to particular fishing grounds. Management of individual grounds could then incorporate rotational closure and stock enhancement schemes (Brand *et al.*, 1991a). The very fact that the Isle of Man government funds a stock-enhancement feasibility study (Brand *et al.*, 1991a) shows that this type of management is thought by some to be possible. In the short and medium term (the next decade) it is unlikely that stock enhancement will progress far beyond pilot experiments, and some simpler, administratively easier management option is required now to prevent a collapse in the fishery, if not the stock.

A realistic management strategy for the stock as a whole, based on the Y/R and SSB/R analysis, would be to maintain the current  $L_c$  and aim to decrease F on inshore fishing grounds, and encourage exploitation of under-fished offshore grounds. Recent evidence, however, (Brand, unpublished data) suggests that the increase in F on offshore grounds which occurred between 1983 and 1988 has continued since this work was completed, due to increasing fishing activity by Scottish, Welsh and English vessels. It is therefore likely that fishing activity on the inshore grounds will now have to be reduced without the possibility of redistributing effort by the Manx fleet to grounds further offshore. The possible means of reducing overall fishing effort are outlined in the General Discussion.

The results of this Y/R analysis differ slightly to those of Murphy (1986) and Murphy and Brand (1987). These authors indicated that an increase in the minimum legal landing size to 115 mm would be beneficial to the fishery as a whole, as it would increase Y/R slightly and SSB/R substantially on most grounds. My analysis, which uses a more realistic recruitment ogive (Murphy and Brand, 1987, assumed 'knife-edge' selection) shows that the benefits of increasing the minimum size would be insignificant on most grounds when compared to the benefits of reducing F.

Managing queen fisheries by aiming for a specific level of F on individual fishing grounds is probably not realistic for a fishery in which areas tend to be heavily exploited for one or two seasons, and left to recover for one or more seasons following exploitation (see Fig. 6.8). Y/R analysis is perhaps less

applicable to this fishery than to the North Irish Sea scallop fisheries, where fishing activity on the major grounds appears relatively constant from year-to-year (i.e. the equilibrium assumption is reasonable over the time periods to which Y/R is applied). Y/R analysis can, however, detect growth overfishing due to an inappropriate size of first capture. For the queen fishery on the East Douglas ground, the  $L_c$  of 55 mm seems appropriate for maximising Y/R over the range of fishing mortalities likely to be encountered. Reducing  $L_c$  and aiming for  $F_{stq}$  leads to losses in Y/R and SSB/R (Table 6.7). Increasing  $L_c$  reduces Y/R but increases SSB/R. The maintenance of high SSB/R is not, however, a priority in a fishery where the grounds will in any case usually be left to recover after one or two seasons of exploitation. The only concern would be that the stock remaining is sufficient to ensure future recruitment success. This cannot be easily determined without establishing the relationship between stock and recruitment. Given current knowledge, continuing to fish with the objective of maximising Y/R would seem to be the best management strategy. Values of Y/R close to the maximum are obtained from  $F_{obs}$ , and as the Y/R curve is flat-topped, there is little point in increasing  $F$  further. Current levels of  $F$  should therefore be maintained. Further intervention in the management of queen fisheries should await Y/R analyses for other fishing grounds and the analysis of queen catch-effort data. Estimates of fishing effort (and the distribution of that effort) exerted by the English, Welsh and Scottish queen fisheries in the region are also required.

In using Y/R models to explore different management options, the potential problems with the analysis must be borne in mind. Y/R analysis is sensitive to the choice of value of  $M$ , a quantity which may, in any case, be highly variable (Vetter, 1988, for review). The differences in Y/R, SSB/R,  $F_{max}$  and  $F_{0.1}$  for these scallop and queen fisheries, calculated using different values of  $M$ , are significant. The choice of an incorrect value of  $M$  could seriously undermine management recommendations based on Y/R and SSB/R modelling, and the problems in separating incidental fishing mortality from natural mortality (see Chapter 4) make the reliable estimation of  $M$  difficult.

The yield per recruit analysis performed here has not taken account of indirect fishing mortality ( $F_i$ ), which appears to be highly variable between grounds (see Chapter 4, Table 4.7). In certain circumstances,  $F_i$  can be a highly significant component of fishing mortality (Chapter 4, p147 - 149, for review and discussion). The exclusion of  $F_i$  will have underestimated the actual fishing mortality rate ( $F_{obs}$ ),

**Table 6.7.** Changes in East Douglas *Chlamys opercularis* Y/R and SSB/R resulting from different management scenarios. Listed are: the fishing mortality for 1989 ( $F_{obs}$ ), the calculated values of  $F_{0.1}$  and  $F_{max}$  for each length of first capture ( $L_c$ ), percentage changes in Y/R and SSB/R calculated for each  $L_c$  at different management targets ( $F_{stq}$ : F 'status quo'), and with fishing mortalities set at  $F_{0.1}$  and  $F_{max}$ . Changes in Y/R and SSB/R are expressed as a % of the values of Y/R and SSB/R for  $F_{obs}$ ,  $L_c = 55$  mm).

$L_c$	$F_{obs}$	$F_{0.1}$	$F_{max}$	Y/R ( $F_{stq}$ )	Y/R ( $F_{0.1}$ )	Y/R ( $F_{max}$ )	SSB/R ( $F_{stq}$ )	SSB/R ( $F_{0.1}$ )	SSB/R ( $F_{max}$ )
40	1.06	0.32	0.61	-29	-31	-24	-50	51	-13
45	1.06	0.37	0.78	-19	-25	-17	-33	71	-13
50	1.06	0.44	1.35	-5	-18	-5	-11	55	-22
55	1.06	0.47		0	-15		0	57	
60	1.06	0.50		-2	-14		13	67	
65	1.06	0.57		-6	-19		59	91	

and so will tend to underestimate the losses to Y/R incurred by aiming for  $F_{0.1}$ , and the reduction in fishing mortality required to achieve this target.

Despite potential errors which may arise due to variable  $M$  and the exclusion of  $F_i$ , the approach taken here of assessing Y/R for individual fishing grounds goes some way to nullifying criticism of the inappropriateness of dynamic pool assumptions in shellfish stock assessments (Hancock, 1979; Orensanz *et al.*, 1991) by applying the model at a spatial scale at which the assumptions can arguably be met. The equilibrium assumptions of the model are also reasonable for the formulation of broad management targets in the short to medium term.

The Y/R and SSB/R analyses described above have only been applied to six *Pecten maximus* sub-stocks, and one *Chlamys opercularis* ground. Application to more grounds is possible: growth, length-composition and age-maturity data are available for the Ramsey, Maughold and Point of Ayre scallop fishing grounds, and for the Targets, Maughold, Laxey, Point of Ayre, H/I Sector and SE Douglas queen-fishing grounds. Estimates of  $F$  are not available for these areas at present, but exploration of differences in Y/R over assumed ranges of  $F$  may be of some value.

Further refinements can be made to the Y/R analysis carried out in this study; the single value of  $M$  used here could be substituted for a vector of  $M$ -at-age values, perhaps starting with the values obtained from Gruffydd's (1974a) catch-curve. Allowing  $M$  to increase with age would result in lower Y/R and higher  $F_{0.1}$  and  $F_{max}$  for a given size at first capture.

Seasonal growth patterns (see Chapter 3) could be incorporated in the Y/R calculations (e.g. Dao *et al.*, 1975; Pitcher & Hart, 1982; Dredge, 1985; Mohn *et al.*, 1989). In the Thompson-Bell Y/R equation, empirical weight-at-age values are used, so seasonality of growth is incorporated by changing the time-step from years to, for example, quarters or months. Instantaneous mortality rates are re-expressed in terms of the new time-step, and seasonality of fishing mortality can be incorporated by modification of the  $F$ -at-age vector to include seasonal effects. Seasonal variations in  $M$  (e.g. post-spawning increase in mortality) could also be included given sufficient data. The seasonal model would allow exploration of the effects of varying three control variables:  $F$ ,  $L_c$  and the timing of the fishing season.

The usefulness of yield per recruit and biomass per recruit analysis can be increased greatly by the incorporation of the number of recruits in the year under consideration, or preferably, the stock-recruitment relationship ('modern dynamic pool modelling', Pitcher & Hart, 1982). The method was developed by Walters (1969) and examples of the application of this approach to yield prediction are found in assessments of the N.E. Atlantic cod fishery (Garrod & Jones, 1974) and the western mackerel stock (Lockwood & Shepherd, 1984). Similar models have been applied to shellfish stocks, modified to take account of some of the dominant features of the biology of the stocks they assess. For example, Murawski and Fogarty (1984) and Fogarty and Murawski (1986) describe a yield model which incorporates density-dependent growth of surf clams (*Spisula solidissima*) and Mohn *et al.* (1989) use a model for *Placopecten magellanicus* yield predictions which is based on F-at-age output from cohort models. The flexibility of the Thompson-Bell yield equation allows Mohn *et al.* (1989) to incorporate the unusual exploitation-at-age pattern which results from vessels attempting to maximise their yield within the restrictions of a regulated minimum scallop 'meat' count per unit weight landed.

Incorporating recruitment into the Y/R and SSB/R equations could be carried out in the North Irish Sea pectinid fisheries as an exploratory exercise, using available data on stock-size and number of recruits without explicit statement of an underlying stock-recruit model (Mohn, 1986; Bannister 1986; Sissenwine & Shepherd, 1987 and Gabriel *et al.*, 1989).

The improvements and extensions to Y/R and SSB/R analysis described above could be carried out fairly simply with the existing data, providing yield and biomass predictions for individual fishing grounds, while more sophisticated models incorporating the spatial distribution of recruits and fishing effort are developed to provide predictions applicable to the whole fishery. Spatial yield models, such as those described by Caddy (1975), Allen (1979) and Sluczanowski (1984) and the contouring of yield-isopleths from research vessel surveys and logbook data (Robert & Jamieson, 1986) are simply methods of generating the required data for the type of modelling described in the preceding paragraphs - although their usefulness in understanding the dynamics of stocks goes a long way beyond this basic function. Ultimately, these spatial models are used to predict yields and biomasses under different levels of F and at different sizes of first capture in the same way as the dynamic pool models of Pitcher & Hart (1982) and Lockwood & Shepherd (1984). The analysis of Georges Bank scallop stocks by Mohn *et al.*, (1989), is the best example of how the complex spatial dynamics of sedentary shellfish stocks can be

accounted for, and incorporated into, conventional stock assessments by cohort analysis and dynamic-pool modelling.

#### **6.4.4. Alternative assessment approaches**

In addition to dynamic-pool modelling, two other approaches to stock assessment are commonly used in fisheries: surplus-production models (e.g. Shaefer, 1954; 1957; Pella & Tomlinson, 1969; Fox, 1970) and cohort or virtual population analysis (e.g. Pope & Shepherd, 1982).

Surplus production models are typically used prior to dynamic-pool models, as they are less demanding on data, requiring only catch-effort data series. Production models sum the processes of recruitment, growth and mortality as changes in population biomass; a stock-recruitment relationship of unspecified form is implicit in the model. Production models are extensively used in tropical fisheries (see Sparre *et al.*, 1989) but are generally not useful (or at least reliable) until the stock has been overfished, after which the level of effort at which the overfishing started to occur ( $F$  at the maximum sustainable yield or ' $F_{MSY}$ ') can be identified with some confidence. Production models may be useful, however, in the assessment of shellfish stocks in which stock-recruit relationships may exist but have proved difficult to quantify explicitly (Caddy, 1986).

The fitting of surplus-production models to catch-effort data for the whole North Irish Sea stock of scallops and queens, using ICES landing statistics and rough measures of effort, such as total fleet size, is recommended, despite anticipated problems in collating the data. Catch-statistics go back to around 1969, with fragmentary data from the Manx fishery going back to 1937 (reviewed in Brand *et al.*, 1991b). This type of model cannot be usefully applied to only part of the fleet (e.g. using catch/effort data from Manx boats only) and so will require the collection of data on fleet sizes and scallop landings from MAFF (the U.K. Ministry of Agriculture and Fisheries), SOAFD (The Scottish Office Agriculture and Fisheries Division), DANI (The Department of Agriculture for Northern Ireland) and the Department of the Marine (Eire) also. If such data are unavailable, total mortality rate estimates ( $Z$ ) from the age-composition of catches or from tagging experiments can be used instead of nominal fishing effort data (Csirke & Caddy, 1983). The problem with using  $Z$ -values calculated from particular grounds is that a value for the whole stock is difficult to obtain.

In order to use cohort analysis to assess the North Irish Sea scallop and queen stocks on a spatial basis, total fleet catches for each grid-square would be required over at least a ten year series, together with the age-structures. Cohort analyses could then be run on individual squares, or catches-at-age summed to provide an unbiased analysis of fishing mortalities-at-age for the whole stock.

To obtain the catch-data required for cohort analysis, it would first be necessary to develop a model to extrapolate sample-fleet catches to total fleet level for the Manx fleet (see pp 184-187) - then the catches in each grid square for other fleets would have to be incorporated. Little information is available on the scallop fisheries of other nations exploiting the Irish Sea grounds, with the exception of some data from logsheets completed by Scottish boats for 1986-89 (supplied by D. Fraser, SOAFD, Aberdeen) and from one U.K. vessel, whose skipper made fishing records for 1987-88 available to me when I was on board, sampling catches. The data from Scottish log-sheets give only a general statement as to the area fished (e.g. 'off Douglas'), so catches are difficult to allocate to particular grid-squares.

The database on North Irish Sea scallop catches and nominal fishing effort and their spatial distribution should be contrasted with similar data for the Canadian part of Georges Bank, off the coast of Nova Scotia. In that scallop fishery, more than 90% of the fleet provide logbooks which are considered to be complete and reliable records of all days fished (Robert & Jamieson, 1986; Mohn *et al.*, 1989). The data from these logbooks enable Canadian scientists to contour stock abundances accurately based on catch/effort data from 1 minute squares. These data are also checked by extensive research-vessel surveys, which use the commercial-vessel logbook data to stratify their surveys, with CPUE as the stratification parameter. The research vessel surveys also provide area-specific age-structures. These data, together with extensive port-sampling of landed scallop meats (required for enforcement) and the use of a meat-weight/length/age key, enable catch-at-age matrices for each grid square to be constructed for cohort analysis.

As an alternative to the estimation of catches per grid-square, and given a knowledge of the area covered by the stock, abundance-at-age can be calculated from CPUE in successive years ( $N_1$ ,  $N_2$ ) so that total mortality ( $Z$ ) of each exploited age-class  $a$  can be calculated from:  $-\log e( {}_{a+1}N_2/{}_aN_1)$ , and a vector of  $F$ -at-age values can be estimated from  $Z$ - $M$ , using any assumed pattern of  $M$ -at-age.



This is perhaps the most feasible of the two options for obtaining the data required for cohort analysis. My opinion, however, is that to aim to assess these stocks, on a spatial basis, using cohort analysis will prove to be a fruitless task.

Given reasonable data on scallop catches and their age-structure from all fleets fishing ICES area VIIa, it should be possible to apply cohort analysis to the fishery as a whole, as Mason *et al.* (1991) have done for the Kintyre scallop stocks. Some age-structure data is available from Scotland, and spatially disaggregated data is available for Manx stocks, so some sort of analysis may be feasible. The difficulty lies in re-aggregating the dis-aggregated age-structure data. The quality of the assessments will be dependent on how representative the irregular port-samples of scallop age-structure are of the age-structure of catches from the whole fleet, for the whole area. While this type of assessment may be useful for calculating annual fishing mortalities for the whole stock and setting annual catch-quotas, this type of modelling provides little insight into the factors affecting populations, and is therefore of little value as a predictive tool.

My recommendation for the best way to proceed with the assessment of these stocks is to develop the yield-model approach as an extension to the current Y/R analysis. The models could then be used for forecasting yields and biomasses using different  $F$  and  $L_c$  values, for all grounds for which growth and mortality data are available. Concurrent attempts should be made to generate the data required to carry out an analysis for the whole stock (annual values of  $F$ -at-age for each grid-square) by modelling the distribution of fishing effort. Fishing effort ( $f$ ) can be converted to fishing mortalities given knowledge of the catchability coefficient ( $q$ ) from  $F=qf$ ; various methods of calculating  $q$  from data which has already been collected are given in Ricker (1975a) and Gulland (1983). The investigation of factors affecting recruitment patterns (in time and space) to the scallop and queen populations should be the priority of the biological research programme.



## GENERAL DISCUSSION

### I. Population dynamics of North Irish Sea pectinids: a conceptual model

The conceptual model shown in Fig. 1, drawn using Forrester's (1961) convention of symbols, provides a framework for a summary of the factors that act to regulate the populations of *Pecten maximus* and *Chlamys opercularis* in the North Irish Sea. Numbers, rather than biomasses, are used in the model to simplify discussion of the processes affecting survival rates. Integrals of rate-processes are given in the subsequent discussion, rather than differential equations, also for simplicity. It is unlikely that all rates and abundances (or biomasses) can be estimated, but as any of these life-history stages may be the 'critical period' (Hjort, 1914) in the life cycle, some knowledge of the order of magnitude of survival rate from one stage to the next would be useful.

Scallops and queens in the North Irish Sea appear to have a fairly protracted spawning season, during the summer, when a series of partial spawnings occur (see Chapter 1, and Chapter 3, 3.4.3, for review). Viable egg production ( $N_E$ ) for each spawning event can be given by the equation:

$$N_E = \rho \sum_i^{i=m} (N_i e_i v_i) \quad \text{EGG PRODUCTION} \quad (1)$$

where:  $\rho$  = the age-independent proportion by weight of eggs which are released at each spawning

$N_i$  = number of scallops in all  $i$  age-classes, starting from  $i = m$ , the age of first sexual maturation.

$e_i$  = matrix of mean egg numbers per gonad at ages  $\geq m$

$v_i$  = age-dependent proportion of viable eggs in the scallop gonad.

Numbers of mature scallops ( $N_i$ ) could be obtained from survey data, perhaps in combination with commercial catch-statistics and tagging experiments (see Chapters 2 & 6). The major drawback with using commercial catch statistics is that the number of scallops  $< 110$  mm is not known. On some grounds (e.g. Bradda Head) a large proportion of the spawning stock is below commercial size (Chapter 2), and therefore needs quantifying from pre-recruit surveys.

Mean number of eggs per gonad for each age ( $e_i$ ) is calculated by weighing ripe gonads, and combining with a measure of egg number per gram female gonad:

$$e_i = fw_i/n_e \quad (2)$$

where:

$f$  = female proportion of gonads (by weight)

$w_i$  = mean gonad weight at age (g)

$n_e$  = mean number of eggs per gramme female gonad tissue.

Overall egg production, egg size, quality, viability, and the proportion of eggs spawned may all be under environmental control (Sastry, 1975; Mackie, 1984; Mann, 1988) with the factors affecting food supply to the adult affecting viable egg production (temperature, water currents, depth, population density). External environmental cues such as temperature, day-length and lunar cycles may influence spawning intensity (Korringa, 1947; Sastry, 1975). If variability in egg production and quality is important in determining recruitment success, then the effects of environmental factors need to be incorporated in equations (1) and (2).

Alternatively,  $N_E$  can be calculated annually as above, and used directly as an input parameter in the model. If the spatial structure of the stock is to be taken into account, estimates of egg-production per 5 nautical mile square would need to be calculated.

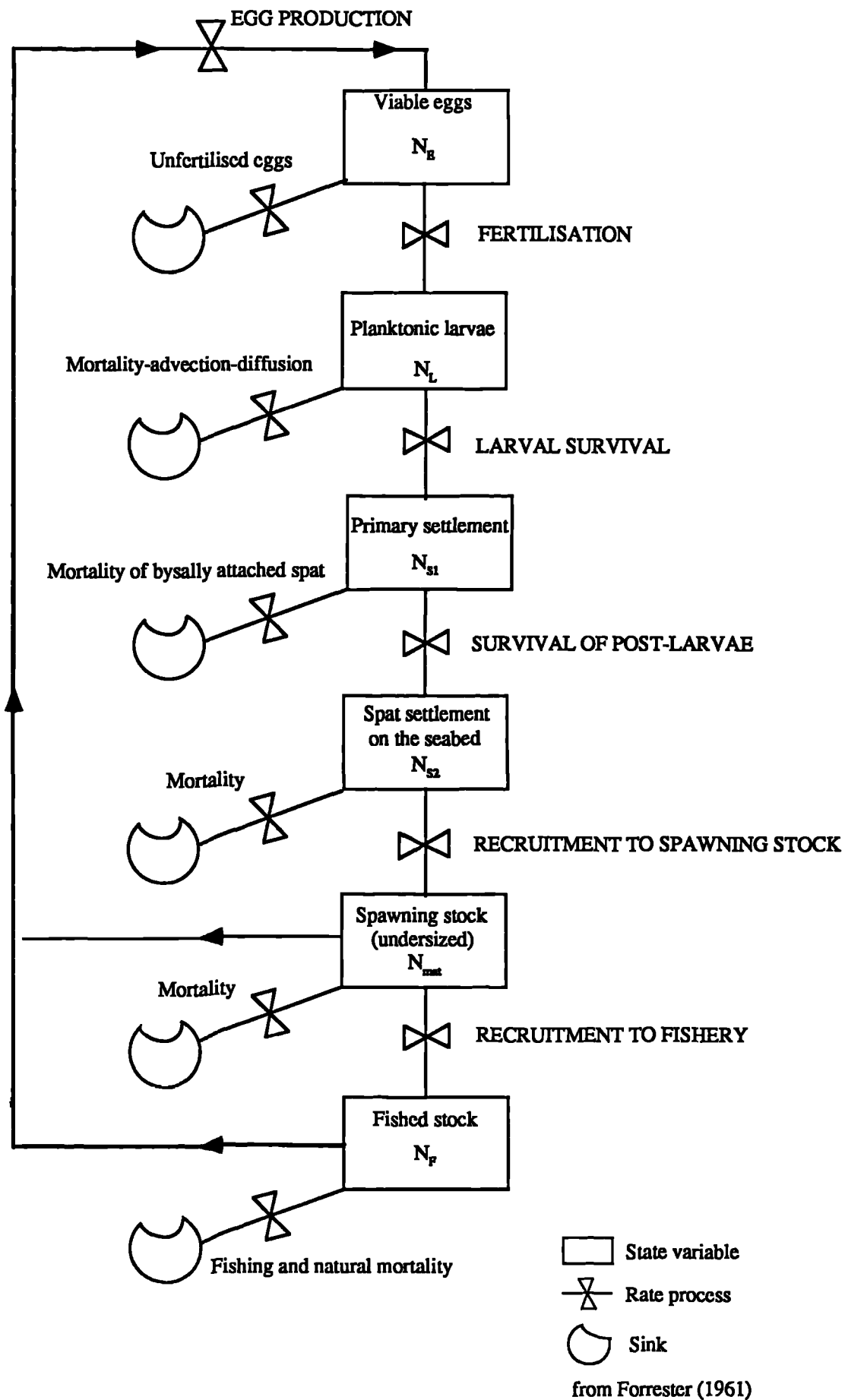
Total annual egg production would be difficult to estimate as not all eggs are released at once. There may be more than one spawning per year in both *Pecten maximus* (Mason, 1958; Brand et al., 1980) and *Chlamys opercularis* (Soemodihardjo, 1974), and eggs are constantly being produced and degraded.

Empirical evidence suggests that egg production may not be the most important factor affecting recruitment success. Spawning intensity does not always correspond with intensity of subsequent settlement (Paul, 1978; 1981; Wolff, 1988).

The number of larvae produced ( $N_L$ ), will depend on the viable egg production ( $N_E$ , from equation (1)), and the rate of fertilisation ( $\gamma$ ), which is equivalent to survival rate in the standard survival-mortality equation  $S = 1 - e^{-Z}$ ;

$$N_L = N_E (1 - e^{-\gamma t}) \quad \text{FERTILISATION RATE} \quad (3)$$

**Fig. 1.** Life-history model of pectinid recruitment in a self-sustaining population.



Fertilisation rate (encounter of viable gametes) is likely to depend principally on five factors which must be incorporated in equation (3):

- 1) The density of scallops or queens in the spawning area
- 2) The degree of turbulent mixing of the water column, affecting dispersal of gametes.
- 4) The degree of synchronicity of spawning within the population, at a scale relevant to fertilisation.
- 3) Predation on viable eggs.
- 4) The time (t) after release for which the eggs/sperm remain viable (temperature dependant?).

Orensanz (1986) argues that local or 'neighbourhood' densities (i.e.- within-patch densities) are important in determining fertilisation rate. Scallop fisheries operate by targeting high-density areas and depleting them. The scale they operate on, however, is larger than the scale at which fertilisation is likely to take place. Depletion of scallop beds, although resulting in reduced total egg production, may not cause large decreases in fertilisation rate if small-scale patches still exist within the depleted bed. Similarly, low-density 'fringe' areas of pectinid populations may provide a refuge for a substantial spawning stock, but will only form a significant contribution towards larval production if they are aggregated into high-density patches.

If small-scale patchiness is prevalent, and population numbers are sufficient to ensure that a critical patch-size and density can occur, high fertilisation rates may be maintained in populations of low overall density, such as the North Irish Sea *P. maximus* population.

Synchronicity of spawning is also important in ensuring fertilisation. If fertilisation only takes place between individuals within the same patch or bed, then synchronous spawning by the whole population is not required to ensure maximum fertilisation rate. Asynchronous spawning appears to take place within both the *P. maximus* and *C. opercularis* North Irish Sea 'megapopulations' (*sensu* Orensanz, 1986), with gonad conditions varying both between and within different fishing grounds. Such asynchronous spawning is sometimes thought to result in more stable populations than when mass synchronous spawning occurs (Paulet *et al.*, 1988). Mass spawning may occur where environmental conditions are stable or predictable from year to year, and may serve to maximise fertilisation rate and

minimise the losses of eggs and larvae to predators by satiating the predatory capacity (Harrison *et al.*, 1984; Babcock *et al.*, 1986). The North Irish Sea production cycle is unpredictable (Brander & Dickson, 1984), so spreading the risks of failure of larvae by trickle spawning over a protracted period may be a favourable reproductive strategy. The role of spawning stimuli may vary between populations according to the environmental conditions prevalent. It seems likely that 'ripe' pectinids in the North Irish Sea respond to local scale stimuli (stress, other scallops spawning) more readily than the strong environmental cues, such as lunar phase, which have previously been thought to elicit spawning in pectinid populations (Armithalingham, 1928; Tang, 1941) and demonstrably trigger mass synchronous spawning in other invertebrate broadcast spawners (Korringa, 1947; Babcock *et al.* 1986). Synchronising release with lunar phase is thought to provide a mechanism for ensuring release takes place during periods of low water movement (turbulent mixing), thereby reducing gamete dilution rate (Black *et al.*, 1991).

The number of larvae reaching the primary settler stage ( $N_{s1}$ ) are given by:

$$N_{s1} = N_L e^{-(M_L t_L)} \quad (4)$$

where:

$N_L$  = initial number of larvae produced, from equation (3)

$M_L$  = mortality rate of larvae (assumed constant)

$t_L$  = duration of larval phase (3-6 weeks).

Losses of larvae due to mortality are likely to be influenced by development rate (changes in  $t_L$ ), and the abundance of predators, food availability, and incidence of disease (which will affect  $M_L$ ), all of which are likely to be under environmental control and interlinked (Heath, 1992, for review). It is unlikely also, that  $M_L$  will be constant throughout the larval stage, but will change with size, and may show pulses of high mortality associated with potentially critical periods, such as the time the veliger larva begins to feed, having exhausted the contents of the yolk sac, and the time of metamorphosis prior to settlement, which is energetically expensive (see Shumway, 1991, for discussion).

To understand fluctuations in larval mortality rate it would be necessary to construct a model of the planktonic ecosystem. Before going to such lengths, it would be advisable to establish the relative importance of mortality and dispersive

larval losses. Interannual changes in mortality rate of larvae could be negligible compared to variation in advective and diffusive losses of larvae from the life-cycle closure site, (in this case the North Irish Sea megapopulation, or available suitable substrate within larval dispersive distance). Such losses have been termed 'larval vagrancy' in Sinclair's (1988) generalisation of his larval retention hypothesis (Iles & Sinclair, 1982; Sinclair *et al.*, 1985) which examines the mechanisms acting on marine populations with planktonic life-history stages to maintain their geographical and numerical stability.

The use of field studies of larval dispersal and of theoretical models to understand stock-recruitment relationships and recruitment variability has recently become widespread in fisheries research on benthic and nektonic organisms with a planktonic larval stage, e.g. prawns, (Rothlisberg *et al.*, 1983), North Irish Sea *Nephrops norvegicus* (White *et al.*, 1988; Hill, 1990; Hill & White, 1990), blue crabs, (Epifanio *et al.*, 1989; Goodrich *et al.*, 1989), abalone, (McShane *et al.*, 1988), demersal fish, (papers in Blaxter *et al.*, 1989), and pelagic fish (McGurk, 1989; Bartsch *et al.*, 1989). These last authors have found that interannual variability of recruitment to North Sea herring populations is largely affected by differences in advective losses of larvae, induced by wind-driven differences in residual circulation.

At the simplest level, it is necessary to add a term representing 'larval vagrancy, ( $\lambda$ )' (*sensu* Sinclair, 1988) into equation (4):

$$N_{s1} = N_L e^{-(M_L t_L + \lambda)} \quad \text{LARVAL SURVIVAL} \quad (5)$$

Hill (1990) gives advection-diffusion-mortality equations for the larval stages of *Nephrops norvegicus*, where the only physical oceanographic parameters required are  $k$ , the eddy diffusivity constant, and the speed and direction of advection, which can be determined from a residual circulation model (e.g. Davies & Jones, 1992). As these parameters will vary spatially, the megapopulation must be divided into a series of model compartments; the 5 Nautical mile grid used in these studies of the scallop fishery (Chapter 6) may provide an appropriate model mesh size, as measures of egg production, and therefore larval release, can be calculated at this scale. Dispersive losses and gains between squares can then be calculated, providing an initial idea on the fate of larvae spawned from each grid-square.



At present, the origin of the scallop spat which settle on the fishing grounds around the Isle of Man is not well known (Beaumont, 1991). The contradictory findings of studies on the current systems and movement of water masses in the North Irish Sea (see reviews by Bowden, 1980 and Dickson *et al.*, 1987) have hampered the development of a working hypothesis on pectinid larval origins. Dickson *et al.*, (1987) support Ramster and Hill's (1969) description of the circulation pattern in the Irish Sea which results in a net northward flow, passing to the east and west of the Isle of Man. This flow pattern suggests that recruitment of pectinids to the fishing grounds around the Isle of Man is from either the grounds to the south of the Isle of Man (south-east Douglas, Port St. Mary and H/I Sector (see Introduction, Fig. 2) or from the southern part of Irish Sea (the Kish Bank and Cardigan Bay scallop and queen grounds - see Mason 1983), depending on the assumed rate of transport and length of larval life. This has been the conclusion of previous workers on these stocks (Beaumont *et al.*, 1982; McLeod *et al.*, 1985; Murphy, 1986; Duggan, 1987).

Short-term circulation patterns may, however, show a different picture to the net long-term flow pattern. Much of the net transport of water out from the Irish Sea through the north Channel (Ramster & Hill, 1969) may occur in short periodic bursts, especially during the winter. Of more relevance to the study of pectinid recruitment is the residual circulation pattern during the months when *P. maximus* and *C. opercularis* larvae are in the water column in significant numbers, (June-July). The Backhaus model for the north European Shelf seas (Backhaus, 1985; Backhaus & Hambucher, 1987) indicates that both the surface layer (0-10 m) and the depth averaged residual mean flow in June and July is southward through the North Channel (J. Bartch, unpublished data, reported in Lewis, 1992), with flows through the North Irish Sea being generally slow ( $< 2.5 \text{ cm s}^{-1}$ ). This model is forced by monthly mean wind stress, monthly mean temperature and salinity, and the M-2 tide. Since the three primary forces responsible for the movement of water within the Irish sea are the weather, water-density differences and tides (Bowden, 1980), the model should be reasonably realistic.

Although the spatial resolution of the Backhaus model (20 km grid) is too large to consider circulation in detail, the predicted pattern of circulation, and the speed of tidal currents indicated are such that with a 3-6 week larval phase (Broom, 1976; Brand *et al.*, 1980; Le Pennec, 1982) and a mean drift velocity of  $2.5 \text{ cm s}^{-1}$  larvae could be advected between 45 and 90 km in total. As the current pattern will not take the larvae in a straight line in most cases, it is likely that the residual mean

advection distance will be considerably less. Distance advected could be reduced still further by byssus drifting of larvae (Beaumont & Barnes, 1992) or vertical migration through depth layers with opposing flows. The frontal systems which become established to the south-west and north-west of the Isle of Man as a result of summer stratification may also act as barriers to dispersive loss of larvae from the release area (see Pingree & Griffiths, 1978).

All the above evidence suggests that the North Irish Sea pectinid stocks are self-sustaining, as argued by Sinclair *et al.*, (1985). All hydrodynamic models and other studies (reviewed in Dickson *et al.*, 1987) agree on the fact that the residual transport of water in the North Irish Sea is slow (Backhaus, 1985; Dickson *et al.*, 1987; Nihoul *et al.*, 1989). Residence times of water in the North Irish Sea are of the order of several months, with an estimate of up to 16 months for the Liverpool Bay area, with gyres, particularly to the south and east of the Isle of Man (Nihoul *et al.*, 1989) acting as possible larval retention mechanisms. Semi-persistent gyres have previously been thought to act as larval retention mechanisms in scallop populations on Georges Bank (Posgay, 1979; Caddy, 1979), St. Pierre Bank (Naidu & Anderson, 1984), and most other major scallop fisheries in the North Atlantic (reviewed by Sinclair *et al.*, 1985).

Although it is reasonable to conclude from indirect evidence that the North Irish Sea *P. maximus* and *C. opercularis* populations are self-sustaining, nothing conclusive can be said about the within-population patterns of larval transport. The long-held assumption that larvae settling on beds around the Isle of Man were spawned 'somewhere to the south', based on Ramster & Hill's (1969) mean residual circulation pattern, is open to question. A further complication is posed by Lewis's (1992) finding that *C. opercularis* stocks to the east and west of the Isle of Man are genetically different, and may be partially or totally reproductively isolated. If this is the case, then more than one stock of each species may be present in the fishery. Establishing the source of recruits to the fishing grounds around the Isle of Man, and the fate of the larvae spawned on these grounds is a crucial question for management, particularly if restocking or protection of spawning stocks by rotational closed-area management is contemplated (Brand *et al.*, 1991a).

Following the pelagic larval phase, *P. maximus* and *C. opercularis* settle and become byssally attached to a range of substrates including algae, bryozoans and erect hydroids (Eggleston, 1962; Brand *et al.*, 1980; Dare, 1987) and artificial

'spat collectors' ( Beustel *et al.*, 1979; Brand *et al.*, 1980; Paul *et al.*, 1981). This is the primary settlement phase (see Fig. 1). The common function fulfilled by the range of primary settlement substrates seems to be the provision of a silt-free surface suitable for byssal attachment. If availability of substrates such as hydroids are a necessary pre-condition for successful settlement and byssal attachment of larvae (Dare, 1987), then the density of settlers may be determined by the abundance of hydroids. Hydroid (or other suitable substrate) abundance is therefore a possible 'bottleneck' restricting the success of scallop recruitment. The role of hydroids in recruitment could be investigated in the experimental closed area off Bradda Head (see Brand *et al.*, 1991a), where the effects of fishing on the availability of primary settlement substrata can be assessed. If fishing makes grounds harder by eroding soft substrates (Caddy, 1973) then hydroid growth may either be favoured by an increase in attachment sites, or may be inhibited by mechanical damage. The role of primary settlement requirements in determining the limits of distribution of pectinids to coarse substrates should also be examined (Thouzeau *et al.*, 1991b). Drifting of post-larvae, either using byssal threads (Dare, 1987, and Beukema & De Vlas, 1989, for reviews), or on detached hydroids may also act as secondary dispersal mechanisms. The duration of the byssal stage is not known, but *P. maximus* are capable of byssus formation for several months and *C. opercularis* can secrete byssal threads throughout their lives (Mason, 1983).

On leaving the pelagic environment, the pectinid spat become liable to a different suite of predators. The primary settlement phase may serve to reduce predation (Pohle *et al.*, 1991), as well as losses due to ingestion by filter feeding adults of the same or another species and inter-cohort competition for food or space (Hancock, 1973; Orensanz, 1986). In low density populations such as the North Irish Sea *P. maximus* population, inter-cohort competition is not likely to be significant. Predators will target high-density aggregations (Sih, 1984; Boulding & Hay, 1984), so mortality of primary settlers may have a density-dependent component, leading to the following relationship between the number of primary settlers ( $N_{s1}$ ) and number of spat settling on the bottom ( $N_{s2}$ ), assuming a linear relationship between mortality and density (after Holm, 1990):

$$N_{s2} = N_{s1} e^{-[(bD + M_{di})t_{s1}]} \quad \text{POST-LARVAL MORTALITY} \quad (6)$$

where:  $D$  = the density of settling spat,  $M_{di}$  = density-independent mortality and  $b$  is the slope of the linear relationship between density and total mortality ( $M_{s1}$ ), with

$M_{S1} = (bD + M_{di})$ .  $t_{S1}$  is the duration of the primary settlement phase (weeks?).

Although the density of *P. maximus* may not be high enough to affect either settlement and early survival of other *P. maximus* or of *C. opercularis* (the two-species co-exist on many fishing grounds), populations of the latter species can be very dense ( $> 100 \text{ m}^{-2}$ , Mason, 1983), and could be regulated by competitive interaction among early settlers. Some fishing grounds appear to favour recruitment of one pectinid species over the other, but the differential requirements are not known. Spat collection studies in the North Irish Sea have caught much larger quantities of *C. opercularis* spat than *P. maximus* spat, despite the fact that adult *P. maximus* are prevalent on the fishing grounds close to the areas where the studies were undertaken (Brand *et al.*, 1991a, for review).

Mortality of pectinids settling on the seabed after the byssal attachment phase is substrate or site-specific (Thouzeau & Leahy, 1985). Siltation may occur on soft substrates (Stevens, 1987), burial by shifting sediments is more likely in shallow or high bottom-stress areas (Tettelbach *et al.*, 1990), and predator abundance may be greater on inshore areas bordering rocky reefs (U.A.W. Wilson, personal communication).

Mortality rate will be reduced on attainment of sexual maturity, as at this size ( $> 85 \text{ mm}$  shell-length in the North Irish Sea), *P. maximus* become less vulnerable to some of their predators (Lake *et al.*, 1987). Size-related changes in *C. opercularis* predation rate are not known; they reach sexual maturity at approximately 40 mm shell length.. The numbers of spat settling on the seabed ( $N_{S2}$ ) which survive to reach sexual maturity ( $N_{mat}$ ) are given by:

$$N_{mat} = N_{S2} e^{-(M_{S2} t_{S2})} \quad \text{RECRUITMENT TO SPAWNING STOCK} \quad (7)$$

where:  $M_{S2}$  = the mortality rate of juvenile scallops

$t_{S2}$  = the time between settlement on the seabed and attainment of sexual maturity (approx. 2 years in scallops, up to 10 months in queens).

Pectinids in the size range between sexual maturity and age at first capture are liable to encounters with fishing gear, and may suffer damage on the seabed, or when discarded from fishing vessels (indirect fishing mortality rate, see Chapter 4, for review). The mortality of undersized discards of dredged *P. maximus*, and of *C. opercularis* caught in trawls may be quite low, but discarded dredge-caught *C. opercularis* are likely to suffer high losses, as they are often damaged or filled with

sand or gravel. The rate of damage by encounter with fishing gear remains an unknown, potentially high, source of losses to scallop fisheries (Naidu, 1988, McLoughlin *et al.*, 1991).

Losses to the fishable stock ( $N_F$ ) occur due to fishing mortality (both direct and indirect) and natural mortality (predation, burial, disease, starvation and senescence). For this model, where annual estimates of spawning-stock size ( $N_{mat} + N_F$ ) are used to calculate egg production (see Fig. 1 and equation (1)), mortality rates in the spawning stock need not be considered. In *P. maximus*, no fishing takes place during the spawning season, so fishing mortality (F) is zero. If only one spawning took place, or the spawning period was relatively short, natural mortality (M) would also be negligible; if spawning season is protracted then a mortality term must be added to calculate egg production. In *C. opercularis*, fishing takes place during spawning and the spawning stock size will change more rapidly during the spawning period, so estimation of fishing and natural mortality rates during this period are therefore more important. With the estimates of spawning stock biomass ( $N_{mat} + N_F$ ), the life cycle (Fig. 1) is completed.

Only a few of the processes and variables described have been quantified, or could be estimated from existing data. These include the size of the spawning stock, where estimates could be obtained from population age-structures (Chapter 2), the maturity ogive (Chapter 6, Table 6.1) and size of the fishable stock (Chapter 6, 6.2.3). Egg production could be estimated roughly from known gonad weights-at-age (Chapter 3). Spat settlement data are available (Brand *et al.*, 1991a, and U.A.W. Wilson, in preparation) from artificial collectors, but would be difficult to compare with natural settlement densities. Mortality rates are available only for the *adult stock*. *Advective and diffusive losses* of larvae could be simulated from models of water circulation and published knowledge on the larval life of pectinids (e.g. Darby & Durance, 1989). Setting up the model as a steady-state system, and testing the use of parameter values for rate-equations and numbers at each stage, using published, known or likely ranges of values, may provide useful insights into which processes are the most important in regulating recruitment to the fishable stock.

## II. Management of the scallop and queen fisheries - a summary of options

After a long period of relative stability (Brand *et al.*, 1991b) the last few years have seen a decline in scallop and queen catches in the North Irish Sea. Dwindling catch rates (Chapter 6) coupled with relatively poor markets, have led to economic hardship in the Manx fishing industry, and many people involved with the fishery are currently of the view that additional conservation measures are necessary to safeguard the pectinid stocks around the Isle of Man. The possibilities for new conservation measures are summarised below. Distinction is made between actions that could be taken within the 3-mile territorial limit, where the Isle of Man has sole jurisdiction, actions that could be taken within the 3-12 mile limit, where the Isle of Man must have the agreement of the U.K to impose new legislation, and actions that could be taken for the area outside the 12 mile limit, where the Isle of Man has no jurisdiction, but has a historical track-record of fishing activity.

The discussion that follows centres on fisheries for *P. maximus*, as *C. opercularis* fisheries tend to be governed by economic factors, particularly fluctuating prices, rather than stock size. For the last decade, there has been a world-wide surplus of small pectinid species, due to large catches from newly discovered stocks in South America, Australasia, the Arctic, and in deep water off the east coast of the USA (see Shumway, 1991, for review), and to the massive production of farmed scallops in Japan (Aoyama, 1989). The export market for *C. opercularis*, previously the USA (Mason, 1983) is now to the UK and Europe, where small scallops species are not highly prized.

Scallop abundance has declined on all grounds over the period for which we have good information from the fishery (since 1981). Heavy fishing over many years has resulted in stocks dominated by the recruiting year-class on many of the major fishing grounds (Chapter 2). Past records of population age structure over many years show that really strong year classes only occur periodically (Duggan, 1987; Brand *et al.* 1991b). The last strong recruitment to enter the fishery was in 1983/4. Stocks on many grounds now support a fishery for only a limited number of days each year before catches fall to uneconomic levels (Murphy, 1986). Yield from the fishery is comparatively high but this is achieved by high effort (Chapters 4 to 6), and therefore by incurring high costs.

The effect of the fishery on recruitment has not been demonstrated clearly. The difficulties in linking stock and recruitment have been discussed in Chapter 2, and the conceptual model in the first part of this discussion (Fig. 1) illustrates the complex suite of factors which regulate the size of pectinid populations. Heavily fished grounds still receive regular settlements of spat, but this does not in any way prove that fishing enhances recruitment (see Chapter 2 for discussion). Although a relationship between stock and recruitment has not been quantified beyond reasonable doubt, it is intuitive that there is a minimum spawning-stock biomass required for successful production of offspring. In some scallop fisheries (Dredge, 1988; Young & Martin, 1989) fishing can continue economically at stock densities which are too low to ensure adequate recruitment. With densities of scallops on the fishing grounds around the Isle of Man falling below 1 scallop per 30 m<sup>2</sup> of seabed, while still supporting a fishery, there is a danger of recruitment failure. There is an immediate requirement to consider measures to increase the overall spawning stock biomass - or create localised dense patches of spawning stocks by closure of areas which are likely to be net exporters of larvae to other fishing grounds (see Chapter 2, section 2.4, and General Discussion I).

An analysis of fishing mortalities on scallops in relation to target fishing mortalities commonly used in Y/R analysis ( $F_{max}$  and  $F_{0.1}$ , see Chapter 6) shows that the stocks on the inshore grounds would benefit from measures to reduce fishing. At the time the analysis was done (1990), it may have been possible to divert effort to the more stable offshore populations, which were relatively unexploited, but this option now appears to have been lost through an increase in the activity of large beamers and purpose-built scallopers from U.K fishing fleets on these grounds (Brand, personal communication).

With fishing mortality rate on all grounds approaching  $F_{max}$ , and therefore probably exceeding the sustainable yield from the fishery (Deriso, 1987), and little overall benefit apparent from changing the minimum legal-landing size in the scallop fishery (Chapter 6), it appears that there are no easy management options. Any measures which reduce fishing effort will result in an initial fall in yield from the fishery, but in the long term may lead to an increased yield or a more stable fishery. Similarly, an increase in minimum landing size may increase the spawning stock biomass on most grounds, but at the expense of both short and long-term loss in yield per recruited scallop. The management measures that could be applied to conserve the stocks are listed on the following pages.

## 1) Measures to increase size at first capture

### a) Increasing minimum legal landing size (MLLS)

The MLLS is currently 110 mm shell length. This has been an excellent conservation measure, ensuring that scallops spawn at least twice (only once on the Targets fishing ground) before entering the fishery. This has ensured the survival of a reasonable level of broodstock. Increasing the MLLS by 5-10 mm would result in little change in Y/R, but would increase spawning stock biomass, per recruit. The exceptions are the Targets and south-east Douglas grounds, where Y/R would increase significantly with an increase in the size of first capture (see Chapter 6, 6.4.3.). An increased MLLS would be difficult to enforce for the three mile limit only. It may be a valid conservation measure for the whole of the N. Irish Sea but is unlikely to be accepted by other fishing nations. The current EEC minimum size for scallops is 100 mm, and there are already problems with enforcement due to the discrepancy in minimum size between the Irish Sea and other areas where scallop growth rates are lower.

The ideal situation would be to have a different MLLS for each ground. The only possible way this could be achieved would be with rotational closed area management and tightly controlled harvesting strategies on re-opening the area.

### b) Increase dredge selectivity

The selectivity of dredges is highly variable, depending largely on the type of substrate and the length and spacing of the dredge teeth (unpublished data). The selectivity of different combinations of teeth/bellies has been little studied. Any increases are likely to affect queen by-catches which are significant on some offshore grounds. If the queen-catch decreased these grounds may no longer be economically viable and pressure on traditional scallop grounds closer inshore would increase. This would be detrimental to the fishery. The effects of changing gear specification need to be assessed before recommendations can be made. This would ideally be carried out by a commercial vessel, perhaps subsidised by Government to undertake fishing trials.

A final word of caution regarding further increases in size at first capture:



setting the size too high could lead to selective depletion of the faster growing individuals in the population. The removal of the scallops genetically 'programmed' to grow quickly could favour genetic selection for slow growth in the population (see Chapter 3 for discussion). We could end up with a population incapable of growing large enough to reach the MLLS.

## **2) Measures to reduce fishing effort**

Although fishing effort at present is approaching that appropriate for achieving the maximum yield per recruit from the fishery, it is unlikely that the maximum economic yield is being achieved, or that recent effort levels are sustainable. A similar annual yield could be taken with much less fishing effort, therefore increasing individual profitability. The dependence on the recruiting year class, leading to growth overfishing and considerable instability of catches from year to year would be reduced if fishing effort were reduced.

To reach a target of  $F_{0.1}$  in the scallop fishery, a level of fishing on the conservative side of the theoretical maximum sustainable yield (Gulland & Boerma, 1973), severe reductions on the present regulations or fishing practices would be required. The Y/R analysis in Chapter 6 indicates that fishing mortality would have to be reduced by 60% on inshore grounds. The methods of reducing fishing effort are generally interrelated, and if only one restriction is applied, it would be possible for the boats to nullify or reduce the overall effect by making compensatory changes to other factors.

### **a) Closed season to scallop fishing**

The closed season currently runs from 1st June to 31st October. This was initially introduced for marketing reasons but is very effective in limiting effort. A longer closed season within the 3-mile limit would further reduce effort on the overfished inshore grounds and force fishermen to exploit the offshore grounds at lower levels of profitability. This would be discriminatory against smaller boats and produce hardship during periods of bad weather when inshore grounds may be the only ones that boats can work on. A selective closed season for individual grounds would be even worse in this respect and very difficult to enforce.

An extended closed season for all grounds would probably not be desirable, as alternative fisheries will not support the fleet for longer than the current closed

season. Any extensions would amount to enforced tie-up periods.

b) Regulation of the number of boats

The number of boats permitted to fish for scallops is not at present limited in any way. A licensing scheme could be very effective. If the number of licences were restricted, control over fishing effort could be achieved, preventing overcapacity resulting from the arrival of too many boats in the fishery during 'boom' periods. Additional licences could be granted if stock size stabilizes at a higher level in future. A licensing scheme for non-Manx boats fishing within 3 miles could also control the fishing effort of these fleets. The control the Isle of Man Government would gain by this system would allow them to determine the level of fishing desirable for the best compromise between stock conservation and the socio-economic goals of fishery management. However, it would be discriminatory, with many administrative and political difficulties in having to deal with the UK and the EC.

c) Size of boats

The Manx fleet consists largely of boats less than 50 ft long, the maximum size now permitted to fish inside 3-miles. These are ideally suited to exploiting the inshore grounds, but have to be competitive with the large U.K. beamers and new, purpose-built scallops further offshore. It may be desirable to set a maximum vessel size for scallop fishing in the N. Irish Sea to prevent the arrival of large beamers in the fishery. The largest vessels operating in the area in 1990 were 79 ft. long. Other fishing nations would not, however, agree to this restriction. Further restriction *inside 3-miles is probably not desirable as effective fishing effort is more closely related to engine H.P. in vessels within the restricted 35 ft - 50 ft length category.*

d) Engine horsepower

Engine H.P. and vessel length are both closely related to a vessel's fishing power, although other factors, such as the amount of deck-space, winch capacity, and number of crew also play a part in determining the spread of dredges fished, the crucial factor in determining fishing effort. Restrictions on length and horsepower, however, could limit the number of boats that can turn temporarily to scallop fisheries, when, for example, sole quotas run out. It would only be

worthwhile if agreed by all fishing nations for the whole of the North Irish Sea. Restrictions of this type would limit efficiency, vessel speed and safety.

e) Spread of dredges

The most direct method of controlling the fishing power of individual vessels. A limit on the spread of gear to 10 ft. a side for vessels fishing within the 3 mile limit was introduced in 1992. In the three years prior to that a sample-fleet analysis shows that 45 % of the fishing effort within the 3 mile limit is accounted for by boats towing more than the proposed spread of gear. However, most of these boats were only towing one extra dredge per side (2.5 ft dredges) so the limitation would only reduce the overall effort by about 10%. Boats from the UK fishing close to the Isle of Man tend to tow more gear than the small Manx inshore boats and a greater reduction in total effort may have been achieved by limiting their activities. This restriction limits the efficiency of operation, and therefore increases costs and must be enforced by regular checks at sea. Its effectiveness at reducing fishing effort has not yet been evaluated.

None of the above regulations would be effective if fishing time increased to compensate for smaller vessels, increased minimum sizes, or decreased efficiency due to engine and gear restrictions.

f) Limit to the length of fishing day

The average time a Manx fisherman spends fishing (gear in contact with the seabed) is 8.5 hours a day. Restriction to a 8 or 9 hour fishing day would have little effect. Some fishermen do make longer trips but over a season, the average time fished is not much greater. The system would be inflexible, difficult to enforce, and considered discriminatory to larger vessels and vessels from non-Manx fleets, who make longer journey times to fish the scallop and queen grounds around the Isle of Man and therefore have to fish longer to recoup their expenses.

g) Limits on the number of fishing days per week, or no fishing on weekends

Not fishing at weekends would reduce fishing effort by around 5%. Most fishermen do not fish on Sundays and there are an average of two Saturdays a month suitable for fishing. The loss of a weekends fishing may be economically damaging after a period of bad weather. Stopping fishing at weekends would be easier to enforce than a limit to the length of the fishing day, but may be

insufficiently flexible.

h) Total allowable catches (TACs).

TACs, set using scientific advice provided by ICES, are currently used by the EC for fisheries management. The setting of annual TACs and their allocation requires a high level of confidence in stock assessments and would be costly to administrate. TAC management has been heavily criticised by the fishing press, the main objection being that it encourages the discarding of fish once quotas have been taken, having adverse effects on stock conservation. While these problems would be inapplicable to scallop stocks, which survive the discard process (as evidenced by our tagging programme, which used commercial fishing gear to capture the scallops for marking), I feel that the conservation-minded pattern of fishing that has evolved in the Manx fleet would be detrimentally affected. The Manx fleet normally fish a ground until catch rates start to fall and then move to new ground, exploiting a wide area without fishing out a bed completely. The introduction of quotas on scallops would lead to a scramble by boats to catch their share of the quota before anyone else did, and to do so in the cheapest and quickest possible way. This would probably increase effort on inshore grounds and promote instability in the fishery, rather than encourage it. It would also be extremely unpopular with fishermen.

Of the above possibilities for increased conservation measures, I would favour a restricted licensing scheme, with limits on the size and power of vessels able to gain a licence. The time to implement such a scheme is now, when the fleet has been reduced by natural economic wastage (and 3 recent sinkings). *Co-operation between UK, Irish and Manx administrations will be required to determine how many licences can be allocated to each fishing nation. These should be based on historical catch records, and on the relative importance of the scallop fisheries to each fishing nation. If the number of non-transferable licences are restricted to boats currently active in the fishery, no increase in effort would occur in the event of improved catches resulting from recent reductions in fishing effort. Catch rates and profits to boats remaining in the fishery would increase.*

3) Stock conservation and stock enhancement measures.

The alternative to negative, restrictive conservation methods lies in positive intervention to enhance natural stocks. Stock enhancement is currently undergoing

a resurgence of interest in Europe. Most of the biological problems associated with culturing juveniles for release into the wild are now known, and it is the management aspects of stock enhancement that require attention (Lockwood, 1991, for review). An Isle of Man Government funded re-stocking project is currently looking at the effects of closing an area of seabed to fishing for a period of natural recovery and at the biological feasibility of enhancing stocks on inshore grounds by the release of artificially reared juveniles (Brand *et al.*, 1991a). These two practices together have been highly successful in Japan (Ventilla, 1982; Aoyama, 1989) and are now being introduced in many other countries around the world (e.g. Dao *et al.*, 1985; Wieland & Paul, 1983; Shumway & Sandifer, 1991). The major biological problems in restocking depleted scallop grounds in the North Irish Sea are the low spatfall (Brand *et al.*, 1991a) and rapid aggregation of predators on the high-density patches of newly released scallops (U.A.W. Wilson, personal communication).

Stock enhancement of scallops in the North Irish Sea must, at present, be considered to be a long-term possibility. Management of stocks by rotational closure of fishing grounds coupled with restocking of the ground using cultured juveniles would require a radical change in the way that the inshore fishing grounds are administered and controlled. In order to be successful, the switch from an open access fishery to a system of extensive farming would require different methods of organisation and greater co-operation between fishermen than exists at present. It seems certain that the Manx fishing industry must continue to rely on the wild stocks of scallops and queens for some years to come, and accept that the stocks will have to be managed by increasingly restrictive management regimes.

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APPENDIX 1.

Dates and locations of scallop and queen samples used for analysis of growth, population structure and mortality rates, January, 1987 - November, 1989.

Date	Boat	Gear	Area	Decca readings				No. tows		Catch	
				Red	Green	From:	To:	(1hr)	(NR = not recorded)	Scallops	Queens
7-Jan-87	R. V. Cuma	2 x 3' dredges	Chickens	E15.0	E20.8	F44.0	G30.2	3	220	0	0
9-Jan-87	R. V. Cuma	Sample trawl	East Douglas	D00.3	D05.7	F41.3	F47.2	2	0	>500	>500
12-Jan-87	R. V. Cuma	2 x 3' dredges	Bradda	E00.7	E08.3	E45.1	F31.3	3	309	0	0
21-Jan-87	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.3	D04.5	G30.0	G30.7	3	295	>500	>500
1-Feb-87	R. V. Cuma	2 x 3' dredges	N.Peel/Targets	D02.4	D14.0	D32.7	D42.5	3	72	83	83
2-Feb-87	R. V. Cuma	2 x 3' dredges	Bradda	E0.00	E08.1	E45.6	F32.0	3	209	0	0
3-Feb-87	R. V. Cuma	2 x 3' dredges	Chickens	E13.6	E20.0	F45.0	G30.0	2	261	0	0
17-Feb-87	R. V. Cuma	2 x 3' dredges	Peel Head	D18.0	D20.5	E33.5	D33.5	3	228	0	0
20-Feb-87	R. V. Cuma	2 x 3' dredges	Port St. Mary	E01.5	E02.5	H31.0	H37.0	3	121	370	370
24-Feb-87	R. V. Cuma	2 x 3' dredges	Bradda	E00.5	E07.2	E45.2	F31.5	4	246	0	0
4-Mar-87	R. V. Cuma	Sample trawl	Laxey Bay	C06.0	C09.0	E40.0	E46.0	3	0	NR	NR
11-Mar-87	R. V. Cuma	Sample trawl	Bradda	D18.0	E01.0	E44.5	F32.0	3	0	50	50
13-Mar-87	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.0	D03.5	H30.1	H30.4	3	156	210	210
4-Apr-87	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C21.5	D00.8	H30.1	H30.7	3	97	NR	NR
6-Apr-87	R. V. Cuma	2 x 3' dredges	Bradda	E00.0	E07.1	E45.7	F31.6	4	239	0	0
8-Apr-87	R. V. Cuma	2 x 3' dredges	Chickens	E13.4	E20.4	F44.6	F46.6	4	375	0	0
28-Apr-87	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C20.5	D03.0	G47.1	H30.4	3	118	NR	NR
19-May-87	R. V. Cuma	2 x 3' dredges	Bradda	E01.6	E07.2	E45.4	F33.5	4	151	0	0

Date	Boat	Gear	Area	Decca readings				No. tows (~1hr)	Catch	
				Red From: To:	Green From: To:	Scallops	Queens			
22-May-87	M.F.V "J.T.S."	24 x 2'6" dredges	H/I sector/Anglesey	D07.0 D08.0	J43.0 J46.0	1	NR	NR		
23-May-87	M.F.V "J.T.S."	24 x 2'6" dredges	H/I sector/Anglesey	D05.0 D08.0	J37.0 J45.0	2	NR	NR		
23-May-87	M.F.V "J.T.S."	24 x 2'6" dredges	H/I sector/Anglesey	C17.0 D00.0	I32.0 I36.0	3	NR	NR		
23-May-87	M.F.V "J.T.S."	24 x 2'6" dredges	I-sector	E10.0 E19.0	I30.0 I34.0	2	NR	NR		
28-May-87	R.V. Cuma	2 x 3' dredges	East Douglas	C03.6 C10.4	F46.9 G30.6	2	5	750		
29-May-87	R.V. Cuma	Sample trawl	East Douglas	C03.6 C10.4	F46.9 G30.6	1	0	483		
9-Jun-87	R.V. Cuma	2 x 3' dredges	Bradda	E01.4 E05.1	E43.0 F33.0	4	216	0		
17-Jun-87	R.V. Cuma	2 x 3' dredges	S.E. Douglas	C19.8 D01.1	G47.9 H30.3	3	90	425		
30-Jun-87	M.F.V. Mathilde	12 x 2' dredges	Chickens	E21.0 F03.0	F45.0 F46.0	3	558	0		
30-Jun-87	M.F.V. Mathilde	12 x 2' dredges	Bradda	E00.0 E05.0	E45.0 F30.0	2	240	0		
2-Jul-87	M.F.V. Mathilde	12 x 2' dredges	H/I sector	E07.0 E09.0	I31.0 I32.0	7	1043	NR		
2-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Port St. Mary	E03.3 E06.0	G32.5 G41.5	1	151	NR		
3-Jul-87	M.F.V. Mathilde	12 x 2' dredges	S.E. Douglas	D00.0 D03.5	G41.0 G42.0	4	476	NR		
3-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Port St. Mary	E03.3 E06.0	G32.5 G41.5	4	673	NR		
8-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Bradda	E00.0 E05.0	E45.0 F30.0	3	325	0		
8-Jul-87	M.F.V. Mathilde	12 x 2' dredges	S.E. Douglas	D00.0 D03.5	G41.0 G42.0	3	475	NR		
9-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Peel	D17.5 D21.0	E30.0 E34.0	1	200	0		
9-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Targets	C15.0 D05.0	D31.0 D37.0	7	839	NR		
10-Jul-87	M.F.V. Mathilde	12 x 2' dredges	Peel	D17.5 D21.0	E30.0 E34.0	3	388	0		
21-Jul-87	R.V. Cuma	2 x 3' dredges	Douglas 'Briar'	D00.3 D05.7	F41.3 F47.2	3	182	NR		
22-Jul-87	R.V. Cuma	2 x 3' dredges	Chickens	E15.0 E22.5	F43.5 F46.1	3	197	0		
28-Oct-87	R.V. Cuma	2 x 3' dredges	Chickens	E13.5 E20.2	F44.5 F45.7	2	298	0		
29-Oct-87	R.V. Cuma	2 x 3' dredges	Bradda	E00.4 E06.5	E45.3 F31.7	4	365	0		

Date	Boat	Gear	Area	Decca readings				Catch		
				Red		Green		No. tows (~1hr)	Scallops	Queens
				From:	To:	From:	To:			
3-Nov-87	R. V. Cuma	2 x 3' dredges	S. E. Douglas	C20.9	D02.8	G47.0	H30.5	3	222	531
7-Dec-87	R. V. Cuma	2 x 3' dredges	Bradda	E00.6	E09.5	E45.0	F31.5	4	312	0
8-Dec-87	R. V. Cuma	2 x 3' dredges	Targets	C19.0	D01.0	D31.5	D39.4	4	120	243
9-Dec-87	R. V. Cuma	2 x 3' dredges	S. E. Douglas	C20.0	D03.5	G47.1	H30.5	3	139	325
10-Dec-87	R. V. Cuma	2 x 3' dredges	H/I Sector	E03.4	E10.6	I30.1	I32.1	3	159	71
11-Dec-87	R. V. Cuma	2 x 3' dredges	Chickens	E14.0	E21.5	F44.2	F46.6	3	240	0
1-Feb-88	R. V. Cuma	2 x 3' dredges	Bradda	E00.2	E06.5	E45.0	F31.5	3	314	0
17-Feb-88	R. V. Cuma	2 x 3' dredges	Chickens	E14.5	E21.5	F44.5	F46.6	2	118	0
25-Feb-88	R. V. Cuma	2 x 3' dredges	S. E. Douglas	C21.0	D04.0	G42.8	H30.2	4	243	354
4-Mar-88	R. V. Cuma	Sample trawl	Laxey Bay	C06.0	C09.0	E40.0	E46.0	2	0	NR
7-Mar-88	R. V. Cuma	2 x 3' dredges	Bradda	E00.1	E08.5	E45.2	F31.8	4	307	0
8-Mar-88	R. V. Cuma	2 x 3' dredges	H/I Sector	E02.2	E09.5	I30.3	I31.7	3	162	378
9-Mar-88	R. V. Cuma	2 x 3' dredges	Targets	C19.2	D04.7	D32.8	D37.5	5	137	195
10-Mar-88	R. V. Cuma	Sample trawl	Laxey Bay	C06.0	C09.0	E40.0	E46.0	2	2	NR
12-Apr-88	R. V. Cuma	2 x 3' dredges	Chickens	C14.5	C22.7	F43.6	F46.5	4	272	0
13-Apr-88	R. V. Cuma	2 x 3' dredges	Douglas 'Briar'	D00.5	D04.3	G40.5	H30.5	3	182	NR
14-Apr-88	R. V. Cuma	2 x 3' dredges	Bradda	E00.0	E07.7	E45.0	F33.7	4	356	0
20-Apr-88	R. V. Cuma	2 x 3' dredges	Bradda	D23.4	E05.4	E44.0	F31.6	3	315	0
4-May-88	R. V. Cuma	2 x 3' dredges	S. E. Douglas	C20.5	D04.7	G45.0	H30.0	3	172	>100
11-May-88	M.F.V. Golden Sceptre	8 x 2' dredges	Bradda	D21.6	E09.5	E40.5	F31.0	8	>1800	0
12-May-88	R. V. Cuma	2 x 3' dredges	Bradda	D07.0	D22.5	E43.5	F31.5	4	306	0
25-May-88	R. V. Cuma	2 x 3' dredges	Targets	C16.3	D09.5	C43.0	D36.2	4	41	500
25-May-88	R. V. Cuma	2 x 3' dredges	Ramsey Bay	B13.3	B15.5	D39.6	D45.0	3	17	>1000

Date	Boat	Gear	Area	Decca readings				Catch		
				Red		Green		No. tows (1hr)	Scallops	Queens
				From:	To:	From:	To:			
26-May-88	R. V. Cuma	2 x 3' dredges	P. of Ayre	A14.1	A17.5	C30.2	C46.7	4	95	> 2000
27-May-88	R. V. Cuma	2 x 3' dredges	Chickens	E15.2	E21.5	F44.8	F45.2	2	110	0
2-Jun-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C20.1	D02.7	G45.3	H30.3	4	145	NR
7-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	H/I sector	E07.0	E09.0	I31.0	I32.0	8	991	NR
8-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Bradda	E00.0	E05.0	E45.0	F30.0	4	822	0
8-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Port St. Mary	E03.3	E06.0	G32.5	G41.5	2	295	NR
10-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Chickens	E21.0	F03.0	F45.0	F46.0	3	882	0
10-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Port St. Mary	E03.3	E06.0	G32.5	G41.5	3	828	NR
13-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	S.E. Douglas	D00.0	D03.5	G41.0	G42.0	6	1302	NR
14-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Peel	D17.5	D21.0	E30.0	E34.0	3	585	0
14-Jun-88	M.F.V. Mathilde	12 x 2'6" dredges	Targets	C15.0	D05.0	D31.0	D37.0	5	743	NR
4-Jul-88	R. V. Cuma	2 x 3' dredges	Bradda	E00.8	E04.7	E41.1	F32.0	4	239	0
6-Jul-88	R. V. Cuma	2 x 3' dredges	Chickens	E15.5	E22.9	F43.5	F46.2	4	178	0
7-Jul-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.0	D05.1	G45.2	G46.5	3	128	NR
20-Jul-88	M.F.V. Manx Maid	10 fa queen trawl	East Douglas	C08.0	C11.0	G31.0	G33.0	5	0	26 bags
1-Aug-88	R. V. Cuma	2 x 3' dredges	Douglas 'Briar'	C21.5	D05.7	G41.2	G46.0	4	192	204
2-Aug-88	R. V. Cuma	2 x 3' dredges	Maughoid	B16.2	B20.0	D47.4	E35.2	2	127	128
2-Aug-88	R. V. Cuma	2 x 3' dredges	Clay Head	C01.0	C04.0	E47.7	F32.0	1	27	153
3-Aug-88	R. V. Cuma	2 x 3' dredges	Bradda	D16.0	E07.7	E44.1	F31.8	3	114	0
17-Aug-88	M.F.V. Maureen Patricia	10 fa queen trawl	East Douglas	C05.0	C08.0	F47.0	G30.3	6	0	25 bags
17-Aug-88	M.F.V. Silver Quest	8 x 3' dredges	East Douglas	C06.0	C10.0	G30.5	G33.0	6	0	23 bags
19-Aug-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C21.0	D03.6	G45.5	G46.0	3	216	NR
20-Sep-88	R. V. Cuma	2 x 3' dredges	Chickens	E12.7	E22.7	F45.0	F46.0	3	175	0

Date	Boat	Gear	Area	Decca readings				Catch		
				Red From:	Red To:	Green From:	Green To:	No. tows ("1hr)	Scallops	Queens
21-Sep-88	R. V. Cuma	2 x 3' dredges	Bradda	D23.3	E07.0	E44.3	F33.0	3	231	0
12-Oct-88	R. V. Cuma	2 x 3' dredges	Bradda	D15.5	E06.6	E38.0	F32.6	3	159	0
14-Oct-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.5	D03.7	G44.9	G46.9	4	287	NR
27-Oct-88	M.F.V. Maureen Patricia	10 fa queen trawl	E. Douglas	C05.0	C08.0	F47.0	G30.3	6	0	22 bags
27-Oct-88	R. V. Cuma	2 x 3' dredges	Chickens	E13.6	E21.0	F45.3	F46.0	1	96	0
31-Oct-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.5	D04.2	G45.6	G46.9	4	334	NR
10-Nov-88	R. V. Cuma	2 x 3' dredges	Peel Head	D19.0	D21.6	E33.0	E37.2	4	185	0
22-Nov-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C23.1	D04.5	G45.0	G46.6	3	296	NR
1-Dec-88	R. V. Cuma	2 x 3' dredges	Bradda	D23.6	E07.0	E42.0	F31.5	3	170	0
11-Dec-88	R. V. Cuma	2 x 3' dredges	S.E. Douglas	C22.6	D04.4	G45.0	G47.0	3	128	NR
31-Jan-89	R. V. Cuma	4 x 2'6" dredges	S.E. Douglas	C22.1	D04.0	G45.5	G46.3	2	421	209
1-Feb-89	R. V. Cuma	4 x 2'6" dredges	Bradda	D22.8	D05.5	E44.0	F31.8	4	380	11
3-Mar-89	R. V. Cuma	4 x 2'6" dredges	H/I Sector	E03.4	E10.1	I30.0	I31.4	3	131	165
15-Mar-89	R. V. Cuma	4 x 2'6" dredges	Maughold	B16.5	B23.1	E31.4	E36.3	3	165	153
15-Mar-89	R. V. Cuma	4 x 2'6" dredges	Ramsey	B13.7	B15.8	D39.4	D44.4	2	93	1377
16-Mar-89	R. V. Cuma	4 x 2'6" dredges	P. of Ayre	A14.4	A23.2	B46.9	C31.4	3	114	1771
17-Mar-89	R. V. Cuma	4 x 2'6" dredges	Chickens	E14.3	E22.5	F44.5	F46.5	3	262	0
6-Apr-89	R. V. Cuma	4 x 2'6" dredges	Peel	D18.1	D21.9	E30.2	E34.5	3	198	0
7-Apr-89	R. V. Cuma	4 x 2'6" dredges	Targets	C18.9	D15.0	D30.3	D38.0	3	210	293
19-May-89	R. V. Cuma	4 x 2'6" dredges	S.E. Douglas	C20.8	D03.5	G45.7	H30.1	2	173	NR
31-May-89	R. V. Cuma	Sample trawl	East Douglas	C03.6	C10.4	F46.9	G30.6	1	0	618
2-Jun-89	R. V. Cuma	4 x 2'6" dredges	East Douglas	C03.6	C10.4	F46.9	G30.6	3	0	458
5-Jun-89	R. V. Cuma	4 x 2'6" dredges	East Douglas	C03.6	C10.4	F46.9	G30.6	1	0	211



Date	Boat	Gear	Area	Decca readings			No. tows (~1hr)	Catch		
				Red	Green	Green		Scallops	Queens	
				From:	To:	From:	To:			
31-Jul-89	R. V. Cuma	4 x 2'6" dredges	S.E. Douglas	C23.0	D04.0	G45.6	G46.6	2	144	NR
10-Oct-89	R. V. Cuma	4 x 2'6" dredges	S.E. Douglas	D00.5	D04.6	G44.4	G46.5	2	228	NR
18-Oct-89	R. V. Cuma	4 x 2'6" dredges	Port St. Mary	E03.3	E06.0	G32.5	G41.5	2	173	2
18-Oct-89	R. V. Cuma	4 x 2'6" dredges	Chickens	E12.7	E22.7	F45.0	F46.0	1	100	3
23-Oct-89	R. V. Cuma	4 x 2'6" dredges	Chickens	E12.7	E22.7	F45.0	F46.0	1	66	0
23-Oct-89	R. V. Cuma	4 x 2'6" dredges	Bradda	D22.8	D05.5	E44.0	F31.8	2	202	21
25-Oct-89	R. V. Cuma	4 x 2'6" dredges	Peel Head	D14.0	D22.9	E30.8	E44.7	2	132	2
6-Nov-89	R. V. Cuma	4 x 2'6" dredges	H/I Sector	E02.0	E10.0	I30.1	I31.6	2	130	370
8-Nov-89	R. V. Cuma	4 x 2'6" dredges	S.E. Douglas	D00.6	D04.6	G44.6	G47.0	1	29	80
13-Nov-89	R. V. Cuma	4 x 2'6" dredges	Maughold	B16.7	C00.1	E32.7	E37.2	2	64	116
13-Nov-89	R. V. Cuma	4 x 2'6" dredges	P. of Ayre	A14.0	A18.0	B46.8	C31.4	2	61	1440
13-Nov-89	R. V. Cuma	4 x 2'6" dredges	Ramsey	B13.0	B15.4	D38.8	D38.8	1	48	49
14-Nov-89	R. V. Cuma	4 x 2'6" dredges	Ramsey	B13.5	B15.6	D38.4	D43.9	1	75	487
14-Nov-89	R. V. Cuma	4 x 2'6" dredges	Targets	C12.3	C21.2	D30.5	D34.5	2	129	452

APPENDIX 2:

Ordinary least squares (OLS) and functional regression parameters from scallop and queen length - weight relationships. All variables needed to calculate functional regression parameters and their standard errors (from the methods described in Chapter 3, section 3.2.2b) are included.

Table A2.1. Length - adductor muscle weight regression parameters, Bradda scallops.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(avMWT)	s.d.(MWT)	v	s.e.(v)	ln(u)	s.e.(u)
2-Feb-87	0.963	3.324	-12.754	146	4.639	0.155	2.668	0.536	3.452	0.077	-13.344	0.358
2-Mar-87	0.975	3.128	-11.843	88	4.624	0.189	2.619	0.605	3.208	0.076	-12.216	0.351
6-Apr-87	0.954	3.149	-11.987	41	4.658	0.147	2.680	0.486	3.301	0.159	-12.695	0.721
9-Jun-87	0.975	2.989	-11.185	119	4.612	0.156	2.600	0.478	3.066	0.064	-11.539	0.288
29-Oct-87	0.974	3.393	-12.896	147	4.665	0.160	2.932	0.560	3.484	0.065	-13.319	0.305
7-Dec-87	0.968	3.362	-12.744	137	4.651	0.157	2.891	0.545	3.473	0.076	-13.263	0.346
18-Feb-88	0.949	3.340	-12.671	104	4.623	0.135	2.772	0.474	3.519	0.110	-13.499	0.502
7-Mar-88	0.960	3.368	-12.896	190	4.658	0.157	2.790	0.549	3.508	0.071	-13.552	0.331
20-Apr-88	0.966	2.824	-10.262	158	4.623	0.171	2.796	0.499	2.923	0.060	-10.719	0.278
12-May-88	0.938	2.989	-11.104	149	4.702	0.123	2.950	0.393	3.187	0.091	-12.033	0.427
7-Jun-88	0.784	2.436	-8.545	50	4.739	0.073	3.001	0.225	3.107	0.279	-11.724	1.282
4-Jul-88	0.915	2.815	-10.300	49	4.705	0.109	2.994	0.335	3.077	0.181	-11.481	0.834
3-Aug-88	0.966	2.815	-10.133	50	4.689	0.126	3.066	0.368	2.914	0.108	-10.598	0.501
12-Oct-88	0.938	2.889	-10.501	50	4.723	0.110	3.142	0.335	3.080	0.138	-11.405	0.705

Table A2.2. Length-gonad weight relationships, Bradda scallops.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(av. GWT)	s.d.(GWT)	v	s.e.(v)	ln(u)	s.e.(u)
2-Feb-87	0.843	8.622	-39.211	146	4.639	0.155	0.783	1.457	10.228	0.309	-46.664	1.942
2-Mar-87	0.931	7.854	-35.497	88	4.624	0.189	0.995	1.434	8.436	0.342	-38.013	1.366
6-Apr-87	0.923	8.710	-39.230	41	4.658	0.147	1.345	1.390	9.437	0.583	-42.611	2.648
9-Jun-87	0.901	6.375	-28.254	119	4.612	0.156	1.146	1.104	7.075	0.284	-31.486	1.299
29-Oct-87	0.848	7.123	-32.559	140	4.665	0.160	0.794	1.169	8.400	0.379	-38.391	1.528
7-Dec-87	0.894	7.669	-34.655	137	4.651	0.157	1.014	1.346	8.578	0.332	-38.884	1.527
18-Feb-88	0.897	9.536	-42.795	103	4.623	0.135	1.326	1.374	10.631	0.467	-47.821	2.050
7-Mar-88	0.919	9.274	-41.758	186	4.658	0.157	1.510	1.501	10.091	0.294	-45.496	1.288
20-Apr-88	0.866	6.871	-30.427	155	4.623	0.171	1.439	1.084	7.934	0.321	-35.241	1.178
12-May-88	0.760	5.136	-22.329	149	4.702	0.123	1.820	0.834	6.758	0.362	-29.956	1.698
7-Jun-88				50	4.739	0.073	1.245	0.529				
4-Jul-88	0.548	4.032	-17.475	49	4.705	0.109	1.495	0.801	7.358	0.898	-33.123	4.133
3-Aug-88	0.870	5.689	-25.936	50	4.689	0.126	0.738	0.826	6.539	0.466	-29.924	2.144
12-Oct-88	0.789	8.138	-37.566	50	4.723	0.110	0.869	1.121	10.314	0.886	-47.846	4.183

Table A2.3. Length - adductor muscle weight relationship, SE Douglas scallops.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(avMWT)	s.d.(MWT)	v	s.e.(v)	ln(u)	s.e.(u)
21-Jan-87	0.950	2.744	-9.947	50	4.731	0.121	3.035	0.350	2.888	0.131	-10.630	0.604
13-Mar-87	0.968	3.120	-11.826	100	4.668	0.172	2.734	0.558	3.223	0.082	-12.312	0.380
28-Apr-87	0.952	2.931	-10.942	113	4.700	0.146	2.836	0.450	3.079	0.089	-11.634	0.417
17-Jun-87	0.929	2.908	-10.864	41	4.754	0.122	2.961	0.382	3.130	0.185	-11.920	0.861
3-Nov-87	0.903	3.133	-11.589	149	4.758	0.105	3.318	0.364	3.470	0.123	-13.190	0.581
9-Dec-87	0.955	3.294	-12.358	133	4.746	0.121	3.272	0.418	3.449	0.089	-13.098	0.422
25-Feb-88	0.940	3.004	-11.138	174	4.717	0.129	3.031	0.412	3.196	0.083	-12.043	0.390
13-Apr-88	0.924	2.714	-9.764	138	4.706	0.115	3.009	0.338	2.937	0.096	-10.814	0.450
4-May-88	0.950	3.037	-11.259	141	4.719	0.128	3.072	0.408	3.197	0.084	-12.014	0.396
7-Jul-88	0.959	3.038	-11.287	45	4.747	0.118	3.136	0.374	3.168	0.138	-11.902	0.636
1-Aug-88	0.979	2.896	-10.502	52	4.732	0.176	3.201	0.521	2.958	0.085	-10.797	0.396
19-Sep-88	0.939	2.872	-10.335	50	4.763	0.123	3.342	0.376	3.059	0.151	-11.226	0.708

Table A2.4. Length - gonad weight relationship, SE Douglas scallops.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(av. GWT)	s.d.(GWT)	v	s.e.(v)	ln(u)	s.e.(u)
21-Jan-87	0.855	6.112	-27.262	50	4.731	0.121	1.651	0.867	7.149	0.534	-32.169	2.487
13-Mar-87	0.915	6.504	-28.864	98	4.668	0.172	1.560	1.118	7.108	0.293	-31.621	1.237
28-Apr-87	0.865	5.683	-24.887	113	4.700	0.146	1.822	0.961	6.570	0.313	-29.057	1.461
17-Jun-87	0.764	4.475	-19.433	41	4.754	0.122	1.845	0.714	5.857	0.605	-26.001	2.804
3-Nov-87	0.762	6.378	-29.219	149	4.758	0.105	1.125	0.877	8.370	0.447	-38.700	2.109
9-Dec-87	0.845	6.178	-27.778	133	4.746	0.121	1.539	0.886	7.311	0.342	-33.160	1.612
25-Feb-88	0.871	5.855	-25.705	174	4.717	0.129	1.930	0.816	6.722	0.252	-29.778	1.112
13-Apr-88	0.901	5.159	-22.178	138	4.706	0.115	2.104	0.660	5.726	0.213	-24.842	0.998
4-May-88	0.788	4.650	-19.702	141	4.719	0.128	2.241	0.753	5.901	0.308	-25.606	1.440
7-Jul-88	0.678	4.982	-22.338	45	4.747	0.118	1.314	0.868	7.348	0.824	-33.567	3.827
1-Aug-88	0.842	4.734	-21.672	51	4.732	0.176	0.798	0.813	5.622	0.433	-25.807	1.652
19-Sep-88	0.612	4.243	-19.185	50	4.763	0.123	1.022	0.853	6.933	0.792	-32.000	3.696

Table A2.5. Length - adductor muscle weight relationship, Southeast Douglas queens.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(avMWT)	s.d.(MWT)	v	s.e.(v)	ln(u)	s.e.(u)
21-Jan-87	0.848	2.973	-10.755	161	4.237	0.085	1.840	0.298	3.506	0.147	-13.015	0.621
13-Mar-87	0.555	1.682	-5.407	105	4.219	0.064	1.691	0.194	3.031	0.248	-11.097	1.038
26-Apr-87	0.771	2.367	-8.445	50	4.244	0.075	1.600	0.229	3.070	0.283	-11.429	1.167
17-Jun-87	0.590	1.813	-5.925	100	4.263	0.054	1.804	0.165	3.073	0.251	-11.296	1.052
9-Dec-87	0.737	2.287	-7.619	155	4.272	0.075	2.150	0.231	3.095	0.168	-11.072	0.712
25-Feb-88	0.790	2.441	-8.615	161	4.237	0.086	1.728	0.266	3.090	0.150	-11.364	0.633
13-Apr-88	0.787	2.282	-7.998	117	4.237	0.087	1.672	0.252	2.900	0.167	-10.615	0.700
4-May-88	0.812	2.826	-10.310	103	4.265	0.074	1.746	0.259	3.480	0.202	-13.096	0.859
13-Jun-88	0.629	1.825	-5.931	140	4.276	0.058	1.872	0.167	2.901	0.192	-10.533	0.809
7-Jul-88	0.956	2.371	-8.113	49	4.184	0.154	1.807	0.383	2.480	0.106	-8.569	0.436
1-Aug-88	0.856	2.147	-7.095	171	4.255	0.111	2.041	0.279	2.508	0.100	-8.631	0.423
19-Sep-88	0.869	2.454	-8.345	128	4.248	0.102	2.079	0.289	2.824	0.124	-9.917	0.527
14-Oct-88	0.768	2.151	-7.169	134	4.252	0.083	1.973	0.236	2.801	0.156	-9.937	0.669

Table A2.6. Length - gonad weight relationships, Southeast Douglas queens.

DATE	OLS regression parameters					Functional regression parameters						
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(av. GWT)	s.d.(GWT)	v	s.e.(v)	ln(u)	s.e.(u)
21-Jan-87	0.256	2.262	-9.254	121	4.237	0.085	0.344	0.551	8.836	0.783	-37.094	2.414
13-Mar-87	0.229	1.777	-7.257	105	4.219	0.064	0.241	0.498	7.760	0.745	-32.498	3.119
26-Apr-87	0.400	2.077	-9.379	50	4.244	0.075	-0.562	0.388	5.193	0.687	-22.599	2.846
17-Jun-87	0.257	2.490	-11.272	100	4.263	0.054	-0.656	0.520	9.689	0.946	-41.959	3.968
9-Dec-87	0.472	3.325	-14.571	155	4.272	0.075	-0.367	0.580	7.044	0.569	-30.461	2.340
25-Feb-88	0.543	2.761	-11.201	161	4.237	0.086	0.497	0.438	5.085	0.339	-21.047	1.428
13-Apr-88	0.393	2.014	-8.885	117	4.237	0.087	-0.350	0.445	5.125	0.440	-22.063	1.843
4-May-88	0.445	3.068	-13.196	103	4.265	0.074	-0.108	0.512	6.894	0.614	-29.513	2.604
13-Jun-88	0.163	1.019	-3.851	140	4.276	0.058	0.504	0.360	6.252	0.525	-26.228	2.213
7-Jul-88	0.829	3.538	-15.096	49	4.184	0.154	-0.291	0.659	4.268	0.348	-18.147	1.431
1-Aug-88	0.608	2.242	-9.067	171	4.255	0.111	0.474	0.410	3.688	0.225	-15.216	0.955
19-Sep-88	0.413	3.027	-13.162	128	4.248	0.102	-0.301	0.752	7.329	0.595	-31.436	2.522
14-Oct-88	0.556	2.785	-12.523	115	4.252	0.083	-0.700	0.425	5.009	0.392	-21.998	1.688

Table A2.7. Length - adductor muscle weight relationships, East Douglas queens.

DATE	OLS regression parameters				Functional regression parameters							
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(avMWT)	s.d.(MWT)	v	s.e.(v)	ln(u)	s.e.(u)
9-Jan-87	0.831	2.586	-9.242	40	4.302	0.090	1.883	0.280	3.112	0.280	-11.504	1.177
20-Jul-88	0.716	1.542	-4.615	76	4.120	0.124	1.737	0.267	2.154	0.175	-7.136	0.711
17-Aug-88	0.939	2.486	-8.541	297	4.145	0.135	1.764	0.358	2.647	0.053	-9.210	0.219
27-Oct-88	0.977	3.130	-11.208	117	4.046	0.180	1.458	0.575	3.204	0.063	-11.504	0.255

Table A2.8. Length - gonad weight relationships, East. Douglas queens.

DATE	OLS regression parameters				Functional regression parameters							
	r	b	ln(a)	N	ln(av. L)	s.d. (L)	ln(av. GWT)	s.d.(GWT)	v	s.e.(v)	ln(u)	s.e.(u)
9-Jan-87	0.481	2.697	-11.872	40	4.302	0.090	-0.269	0.505	5.607	0.798	-24.391	3.347
20-Jul-88	0.660	2.252	-8.252	76	4.120	0.124	0.333	0.423	3.412	0.298	-13.725	1.212
17-Aug-88	0.742	2.905	-11.268	297	4.145	0.135	0.772	0.530	3.915	0.153	-15.456	0.633
27-Oct-88	0.874	4.379	-19.252	110	4.046	0.180	-1.426	0.716	5.010	0.235	-21.698	0.746



APPENDIX 3

Table A3.1. Mean length of scallops with 4 annual rings, sampled on the Bradda ground in the winters of 1966-1990. Data are from Brand (unpublished) Murphy (1986) and this study.

Three year running mean temperatures (from Slinn, 1974 and Slinn, unpublished) are also given. These temperatures represent the mean temperatures at which the 4-ring scallops have lived (a scallop with 4 rings is 3.4 - 3.9 yrs old in winter).

Winter	Mean L	S.dev(L)	N	s.e.(L)	T (3yr run. mean)
1966/67	114.83	7.921	286	0.028	10.34
1967/68	114.43	6.674	253	0.026	10.22
1968/69	120.62	8.479	130	0.065	10.33
1969/70	114.00	5.613	78	0.072	10.33
1970/71	112.80	5.503	173	0.032	10.32
1971/72	107.90	6.008	30	0.200	10.47
1972/73	110.67	4.861	157	0.031	10.59
1973/74	112.10	4.306	41	0.105	10.82
1974/75	115.85	4.859	66	0.074	10.74
1975/76	115.36	5.313	73	0.073	10.83
1976/77	114.74	5.206	41	0.127	10.77
1977/78	118.26	5.709	57	0.100	10.66
1978/79					10.40
1979/80					10.12
1980/81					10.20
1981/82					10.25
1982/83					10.37
1983/84					10.23
1984/85					10.34
1985/86	115.35	4.931	220	0.022	10.36
1986/87	111.01	6.718	193	0.035	10.23
1987/88	113.06	6.967	174	0.040	10.09
1988/89	116.66	7.945	268	0.030	10.21
1989/90	120.36	7.133	83	0.086	10.64
1990/91	122.06	7.005	31	0.226	10.80