THE POTENTIAL FOR CULTIVATION AND RESTOCKING OF *PECTEN MAXIMUS* (L.) AND *AEQUIPECTEN OPERCULARIS* (L.) ON MANX INSHORE FISHING GROUNDS

A thesis submitted in accordance with the requirements of the University of Liverpool for the degree of doctor in Philosophy

by

Ulric Anders Whitnell Wilson B.Sc.

Port Erin Marine Laboratory
Department of Environmental and Evolutionary Biology
University of Liverpool
Port Erin
Isle of Man

September 1994

THE POTENTIAL FOR CULTIVATION AND RESTOCKING OF *PECTEN MAXIMUS* (L.) AND *AEQUIPECTEN OPERCULARIS* (L.) ON MANX INSHORE FISHING GROUNDS

TABLE OF CONTENTS

CHAPTER 1
GENERAL INTRODUCTION

CHAPTER 2
THE ANALYSIS OF PECTEN MAXIMUS POPULATIONS AROUND THE ISLE OF MAN BY RESEARCH VESSEL SURVEY

CHAPTER 3
PECTINID SPAT COLLECTION AROUND THE ISLE OF MAN

CHAPTER 4
THE GROWTH OF *PECTEN MAXIMUS* AND *AEQUIPECTEN OPERCULARIS* IN SUSPENDED CULTURE

CHAPTER 5
EXPERIMENTAL RESEEDING OF THE GREAT SCALLOP, *PECTEN MAXIMUS* (L.)

CHAPTER 6
GENERAL DISCUSSION

The potential for cultivation and restocking of *Pecten maximus* (L.) and *Aequipecten opercularis* (L.) on Manx inshore fishing grounds

Ulric Anders Whitnell Wilson B.Sc. (Hons) Liverpool

ABSTRACT

There has been a directed fishery for *Pecten maximus* off the Isle of Man since 1937, and for *Aequipecten* (formerly *Chlamys*) *opercularis* since 1969. The combined first sale values of these two species account for more than 80% of the value of all fish landings to the Island. Catch rates of *P. maximus* have been in decline since 1983.

Research vessel surveys carried out at the beginning and end of the fishing season (1st November - 31st May) revealed large changes in the density of commercial size scallops over the period of the fishery; on the Bradda Inshore and Bradda Offshore fishing grounds scallop density was more than halved. Maximum densities of 3 commercial size scallops.100m^{-2} were recorded at Peel and Bradda Offshore. Comparison of scallop density estimates based on the area swept by research vessel dredges, with previous estimates based on catch per unit effort and assumed fishing boat towing speed, suggest that scallop density may have been over estimated in the past. Recruitment ogives constructed from age and length data from individual grounds showed marked changes in the proportion of scallops ≥110 mm shell length and hence the perceived age of first recruitment to the fishery. The continued decline in the fishery and in scallop densities provided the impetus for an investigation into the potential for scallop reseeding.

The first attempts at large scale pectinid spat collection in Manx waters were carried out at a site off the north coast of the Calf of Man, using Japanese longline techniques. Only modest numbers of spat were collected; the mean number of *P. maximus* spat per onion bag collector was never more than one tenth the minimum number considered economically viable for commercial spat collection. Extreme variations were recorded between the numbers of pectinid spat settling on collectors placed at locations on the east and west coasts of the Isle of Man. Collector bags sited on the east coast yielded almost no spat and differences between the spat collector communities suggested that there may be a common mechanism influencing the dispersal and recruitment of these species. It is hypothesised that differences in local hydrographic conditions may account for the paucity of spat settlement.

Trials using Japanese pearl nets confirmed that *A. opercularis* and *P. maximus* were both amenable to longline cultivation techniques. Shell heights at age were comparable to those published for trials in Scotland. The relative merits of different designs of culture equipment are discussed.

Adult *P. maximus* (mean shell height 92.3 mm) were reseeded onto the seabed and monitored by SCUBA diving periodically, over 286 days. 58% of the scallops were unaccounted for at the end of the experiment; they had dispersed out of the 30 m diameter area monitored. Survival of those accounted for was 14% at the termination of the experiment. Rapid aggregation of the predatory starfish *Asterias rubens* into the areas reseeded was followed by a slow disaggregation. Initial high mortality was attributed to *A. rubens* but over the full course of the trial crab predation was of greater impact.

A simple economic assessment of four different culture regimes for *P. maximus* suggested that, over a period of 10 cycles of spat input to harvest approximately 3.5 years later, reseeding onto the seabed was the most promising method. However, a net profit was only returned when cultivation was undertaken on a large scale (1 × 10^6 spat input annually).

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr A.R. Brand for his help and advice during the course of this work. Dr S.J. Hawkins co-supervised some of the more ecological aspects and provided an indefatigable stream of suggestions and comments, many of which were gratefully incorporated into the project. This study was undertaken during the tenure of a research assistantship funded by the Isle of Man Government and subsequent short-term contracts from a myriad of sources. Foremost among these were periods of re-employment by Andy Brand and innumerable projects funded by Steve Hawkins' 'contingency' fund. I would like to thank Dr R.G. Hartnoll and Mr D. Minchin who acted as examiners for this thesis.

I am thankful to Professor T.A. Norton for the provision of facilities at the Port Erin Marine Laboratory, and to the library, technical and administrative staff for all their help. Special thanks must go to the crews of the laboratory research vessels, who tried their best to accommodate my ideas despite their misgivings: Peter Crebbin, Gary Heaney, Roger Gillam, Will Cubbon and Richard Georgeson of the R.V. Cuma and latterly of the R.V. Roagan, and Al 'Bo' Johnson and Derek 'Scout' Kneen of the R.V. Sula and R.V. Corallina. It has been my pleasure to undertake a significant amount of my practical work underwater, a pleasure made safe by the skill and experience of the chief diver Mike Bates. During diving operations I have by coercion, black-mail, and in return for vague promises of reciprocated favours, had the assistance of a large number of divers. Prominent among these were: Mark 'Dicky' Whittington, Dave Pennington, Bruce McGregor, Rupert Lewis, Ben Hextall, Bill Sanderson, Dave MacDonald, Sarah Proud and many others.

All the members of the 'Scallop Group' contributed in some respect to this thesis, through discussion and suggestion or weeks spent helping me construct and later sort countless spat collectors. Thanks are due to Eddie Allison, Dicky, Dave, Tikiri Wanninayake, Jian Zhang, Kate Prudden and particularly Sara Lawrence.

It has been my good fortune to have had a series of fine house-mates, who have helped make life on the Isle of Man enjoyable: Andy Bryant, Simon Harding, Graham 'Splodge' McCathie, Bruce McGregor, Elaine Fisher, Bill Sanderson, Pol Fernandes, Chris Dawes, Helen Grieg, Debbie Jones and Graeme Cushnie. The many other postgraduates and undergraduates who have passed through the lab during my extended residence have all helped to keep life interesting.

My family provided much encouragement and continue to have high hopes that I will get 'a real job'. My greatest debt is to Julie Martin, for perseverence beyond all understanding through even the darkest days of my writing-up, without whose support this work would not have been completed. Finally, I would like to dedicate this work to the memory of my mother, Hilde Wilson (née Andersen).

NOMENCLATURE

In common with other taxonomic groups, the phylogenetic relationships of the Pectinidae continue to be elucidated, leading to changes in the nomenclature as species are reassigned to different genera. This trend is likely to continue as molecular genetic techniques develop and analysis of comparative morphology becomes increasingly sophisticated. The queen scallop *Chlamys opercularis* (L.) has been reassigned to the genus *Aequipecten* (Waller, 1991) and this name has been used throughout this thesis. Similarly, the Japanese scallop is referred to as *Mizuhopecten yessoensis* (Jay) rather than *Patinopecten yessoensis.*

Waller, T. R. (1991). Evolutionary relationships among commercial scallops (Mollusca: Bivalvia: Pectinidae). *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 1-73.

CHAPTER 1

GENERAL INTRODUCTION

The family Pectinidae contains some 400 extant species, found across all latitudes from polar regions to the tropics, and from the intertidal zone to abyssal depths greater than 3 000 m (Brand, 1991). Within this family (otherwise known as pectinids or scallops) several species are of economic importance both from traditional fisheries and more recently from the development of mariculture, e.g. *Mizuhopecten yessoensis* from the western North Pacific, *Placopecten magellanicus* and *Argopecten irradians* from the western North Atlantic, *Pecten maximus* from the eastern North Atlantic and *Pecten fumatus* from southern Australia (see Shumway, 1991).

Around the coasts of Europe (including the Mediterranean) there are 28 species of scallop, of which five are commercially significant: the "Great scallop", "Escallop" or "Clam" (in Manx fishermen's vernacular), *Pecten maximus*, the "Queen", "Queenie" or "Queen Scallop" *Aequipecten opercularis*, the "St .James' Scallop" *Pecten jacobeus*, the "Black Scallop" *Chlamys varia*, and the "Iceland Scallop" *Chlamys islandica* (Ansell *et al.*, 1991). Only the first two species are fished in the North Irish Sea with *P. maximus* the more valuable. Other locally occurring pectinids include: *Chlamys varia, C. distorta, C. tigerina, C. striata, C. furtiva* and *C. similis* (Bruce *et al.*, 1963).

1.1 History of the fishery

The abundance and distribution of *P. maximus* and *A. opercularis* around the Isle of Man was first reported in the 19th Century (Forbes, 1838; Darbishire, 1886; Herdman, 1886; 1895). The stocks were not subject to directed fishing until 1937, when local fishermen were informed of the commercial potential of the scallop beds off Bradda Head by a visiting Irish fisherman (Smith, 1938). Within one season scallops became the principal target of the Manx fleet as effort was switched from the fisheries for cod and plaice, which were no longer viable (Brand *et al.*, 1991a).

Queen scallops have been fished commercially in Manx waters since 1969, although they had previously been fished for use as bait in the longline fishery for cod, and for local consumption (Fullarton, 1888; Mason, 1983). The fishery developed rapidly to exploit US markets for frozen adductor muscle, aided by the presence of processing facilities on the island for the scallop fishery (Brand *et al.*, 1991a).

Legislation of the scallop fishery began almost at its inception, with the first closed season established by the Escallop Control and Maximum Prices Order 1943. This order closed the grounds to fishing from 1st May to 30th September, and also stipulated a minimum legal landing size of $4^1/_2$ inches 'across the broadest part of the shell' (Brand *et al.*, 1991a), equivalent to shell length. After some modification, the closed season currently extends from 1st June until 31st October, and since metrication in 1976 the minimum landing size of scallops has been reduced slightly to 110 mm shell length. This limit currently applies to the whole of the North Irish Sea, the area covered by ICES area VIIa. Fisheries outside this area (e.g. west coast of Scotland, English Channel) are governed by the EU minimum landing size of 100 mm. The full history of the Manx scallop and queen fishery has been documented by Murphy (1986), Brand *et al.* (1991a) and Allison (1993).

The first scallop dredges used around the Isle of Man were 3'6"-6'0" (1.07-1.83 m) wide, with a fixed tooth bar and triangular frame. Between 1 and 3 of these were towed by small motor boats (Mason, 1953; Mason, 1983). The spread of gear used increased with vessel size and engine power, and in 1972, spring tooth bar dredges were introduced (described by Chapman *et al.* (1977) and Mason (1983)). These were considered to be more efficient than dredges with a fixed tooth bar, although the work of Chapman *et al.* (1977) failed to confirm this. However, they remain the preferred gear design because the reduced quantity of trash they retain eases sorting of the catch (Murphy, 1986).

The trend since the early 1980s has been for increasing numbers of smaller dredges (2'-2'6"; 0.61-0.76 m) towed in 'gangs' from a heavy steel pipe fitted with solid rubber rollers. These are perceived to follow the contours of the seabed more closely than larger dredges, so that they spend more time fishing (Howell, 1983). This design of gear is maintained by fishermen to be more efficient on the rough ground around the Isle of Man, but as yet there has been no work to corroborate this. The gear studies of Mason (1970), Chapman *et al.* (1977) and Mason *et al.* (1979) were all carried out on clean, hard sand, whereas Dare *et al.* (1993) recently evaluated the performance of spring tooth bar dredges on differing substratum types, but did not compare gear types.

1.2 Current state of the fishery

Data regarding the landings of scallops and queens to the Island have been collated by the Isle of Man Government since 1969. Total landings of scallops rose slowly but erratically to a peak of 2 100 tonnes live weight in 1985 (back calculated from meat weights reported by the scallop processing factories), followed by a continuous decline (with the exception of 1987) to less than 650 t in 1992 and 1993 (Figure 1.1*a*). Landings of queens have been more variable due to fluctuations in the level of effort directed at the fishery, but landings have recently increased. The total first-sale value of the queen catch reached its highest recorded level in 1993 at £1.75 million from the previous peak of 1983. This was due to increased prices rather than a substantially higher catch. First sale values of scallops peaked in 1987 at £2.4 million but have since declined to less than a third of that value in 1993 (Figure 1.1*b*). The combined value of both species still accounts for the greatest proportion (82% in 1993) of the first sale value of all fish landed to the Isle of Man, although down on the 1987 figure of 95% (Brand *et al.*, 1991a).

Total scallop landings have been maintained at the cost of increasing effort, resulting in falling profitability. Increasing exploitation has reduced scallop abundance and catch per unit effort, increased fishing mortality and depleted the older year-classes and hence the available spawning stock. There is evidence of growth overfishing on the main inshore fishing grounds, and the success of the fishery has become dependent on the strength of the recruiting year class (Brand *et al.*, 1991a; Allison, 1993).

The size of the Manx fishing fleet fell from a maximum of approximately 70 boats in 1983/4, to some 48 actively fishing in 1990 (Allison, 1993). The majority of these were ageing vessels less than 15 m in length. There has been some recent investment, supported by the Isle of Man Industry Board, in larger and more up to date vessels capable of fishing grounds elsewhere in the British Isles and with the ability to convert to other fisheries. These newer vessels have generally replaced existing ones and the current (1994) size of the fleet is estimated to be approximately 50 vessels fishing scallops and/or queens (K. Prudden, Port Erin Marine Laboratory, personal communication).

Despite the current high value of queen landings, fishing around the Isle of Man, particularly for scallops remains in decline. Allison (1993) suggested a range of possible additional management measures that might be taken to protect the scallop fishery. His recommendation for a reduction in total effort and a subsequent limited entry licence scheme for the fishery would require considerable political will in the face of inevitable opposition. Similar measures were recommended ten years previously by an Isle of Man Government commission of inquiry into the fishing industry (Lyon-Dean *et al.*, 1983). Without further management, however, the future for the scallop fishery is likely to be one of considerable hardship for fishermen and a gradual reduction in the size of the fleet through progressive bankruptcies and boat sales.

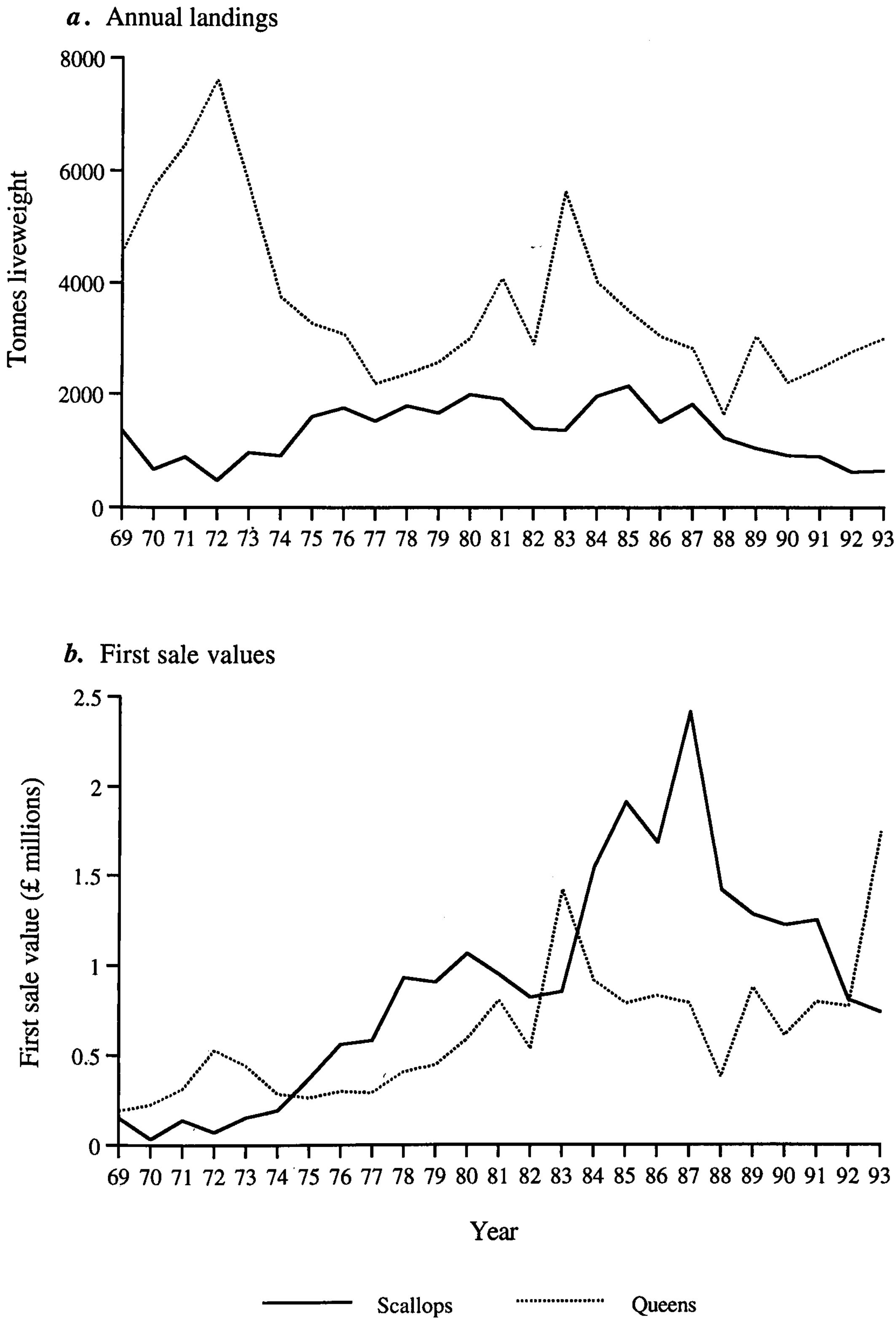


Figure 1.1 *a.* Total annual landings and *b.* first sale values of scallops, *Pecten maximus* and queens, *Aequipecten opercularis*, landed to the Isle of Man 1969-93. Data from the Isle of Man Department of Agriculture, Fisheries and Forestry.

The plight of the wild fishery has generated interest not only in further management measures but also in alternative strategies such as mariculture of scallops and rotational closure of fishing grounds (Brand *et al.*, 1991b). The success of scallop mariculture in Japan in response to declining fisheries provides an obvious model (Ventilla, 1982; Ito & Byakuno, 1988; Ito, 1991) and has led to the adoption of their techniques in many parts of the world (see Shumway, 1991 for reviews) .

1.3 Pectinid cultivation

Scallops and to a lesser extent queens are attractive prospects for mariculture, fulfilling as they do the essential criteria suggested by Wildish *et al.* (1988):

1. The species should yield a high-priced gourmet product for an established (e.g. salmon) or newly established (e.g. blue mussel) market.
2. The production capacity of the fishery supporting the established market should be unable to keep up with demand due to declining catches or increased demand.
3. Culture is biologically feasible at production costs which allow this to be a profitable venture.

Scallop cultivation techniques allow large numbers of individuals to be held in a confined area while maximising growth rate and minimising mortality. Elevating the scallops above the seabed in suspended nets improves the quality of the meats as well as their size relative to the shell (Wieland & Paul, 1983), as they are able to exploit a more plentiful supply of particulate food (Wildish *et al.*, 1988). Suspended culture also removes the scallops from benthic predators, reducing mortality. Further advantages of cultivation over fishing for natural populations include: assured high quality produce, in terms of freshness, purity, weight consistency and meat counts to pound, product specification may be established and fulfilled relatively easily by planned harvesting and cultured scallops may be made available all year round, thus ensuring continuity of supply (Wieland & Paul, 1983).

Cultivation provides the opportunity for the selection of faster growing scallops at various stages in the culture process, and it may be possible to genetically select fast growers by using them as hatchery brood stock. The scallop farmer also has the ability to regulate growth rate by the manipulation of stocking density, and if the farm is in a sheltered area may be able to maximise financial returns by harvesting during periods of adverse weather and short supply when prices may be higher.

There are three basic stages in *P. maximus* cultivation; procurement of a reliable and plentiful supply of spat, intermediate culture from the spat stage over winter to approximately 20-25 mm, followed by final culture to harvestable size.

1.3.1 Supply of spat

The source of spat for cultivation may be a hatchery where larvae are raised from captive broodstock (Comely, 1972; Gruffydd & Beaumont, 1972; Costello, 1973; Beaumont *et al.*, 1982; Beaumont, 1986; Bourne, 1991; Dabinett, 1991; Ballantyne & Williams, 1993; Millican, 1993) although for many species it is possible to obtain naturally occurring spat from artificial collectors (Slater, 1977; Buestel *et al.*, 1979; Brand *et al.*, 1980; Ventilla, 1981; Fegan, 1983; Goodwin *et al.*, 1985; Ruzzante & Zaixso, 1985; Paul, 1985a; Fraser, 1987; Hortle & Cropp, 1987; Roman & Cano, 1987; Aoyama, 1988; Bonardelli, 1988; Coleman, 1988; Ito & Byakuno, 1988; Miller, 1988; Bull, 1988a; Ambrose Jr & Peterson, 1989; Sumpton *et al.*, 1990; Burnell *et al.*, 1991; Ruiz-Verdugo & Caceres-Martinez, 1991; Brand *et al.*, 1991b; Young *et al.*, 1992).

1.3.1*a* Larval culture

Techniques for the hatchery production of pectinid spat have been established for some time (Castagna & Duggan, 1971; Comely, 1972; Costello, 1973) and some species have reached large scale commercial production; China produces 50 000 tonnes live weight of *Argopecten irradians* from hatchery produced seed (Chew, 1990; Zhang, 1991; Jian-Guang, 1993), and in Chile 1 million 10 mm *Argopecten purpuratus* spat are reported to be produced monthly from larval rearing (Flores-Briceño *et al.*, 1993). However, economic problems remain with hatchery production of spat for some species and the collection of naturally occurring spat may provide a more viable alternative (Ventilla, 1982; Cropp & Frankish, 1988; Bull, 1988b). Information on the rearing of *P. maximus* larvae is provided by Comely (1972) and Beaumont *et al.* (1982). The methods used are similar to those for other bivalves (Loosanoff & Davis, 1963), although pectinid larvae appear to be extremely sensitive to rearing conditions (Beaumont *et al.*, 1987; Cragg & Crisp, 1991).

1.3.1*b* Spat collection

The techniques currently used for scallop spat collection world-wide originated in Japan. The first attempts used cedar twigs as a settlement substratum, tied to nets made of rice straw rope (Kinoshita (1935) cited in Ventilla (1982)). In the 1960s the settling materials were, for the first time enclosed in a small mesh onion bag which retained the spat that detached at the end of the phase of byssal attachment. This development, in conjunction with the introduction of synthetic collector materials led to commercial spat collection by the late 1960s (Ventilla, 1982). The availability of a plentiful supply of spat provided the basis for the massive scallop culture industry in Japan frequently cited as a model for other nations; in 1984 1.8×10^9 spat were provided for aquaculture in Japan from spat collection (Ito, 1991) and total scallop production in 1988 was 341 618 t (Ito, 1992).

Spat collection techniques

Artificial spat collectors aim to provide an attractive surface for mature scallop larvae to settle on, to retain the developing spat if they detach from the settlement substratum and to maximise early survival. There has been extensive research into the factors affecting spat collector success, primarily collector design and materials, and the timing, location and depth of collector placement.

The Japanese ‘onion bag collector’ (a small mesh synthetic bag containing monofilament nylon netting) has been generally accepted as the standard design (Naidu & Scaplen, 1976; Buestel *et al.*, 1979; Brand *et al.*, 1980; Dix, 1981; Cropp, 1985; Hortle & Cropp, 1987; Dadswell *et al.*, 1988). However, different internal substrata have been tested, as have different mesh sizes for the outer bag; synthetic materials have replaced the cedar twigs and scallop shells initially used in Japan and nylon monofilament has proven most successful (Evans *et al.*, 1973; Phleger & Cary, 1983).

Recent developments have attempted to use more natural settlement substrata. The association of pectinid spat with hydroids as a primary settlement surface was first noted by Allen (1899) and juvenile scallops have since been commonly found on hydroids and other arborescent species on the seabed (Brand *et al.*, 1980; Paul *et al.*, 1981). Dare & Bannister (1987) hypothesised that *Pecten* might be dependent on certain hydroids for initial settlement offshore, following extensive sampling in the English Channel. Further, Harvey *et al.* (1993) found non-random distributions of newly settled *Chlamys islandica* with 20 times more post-larvae present on the perisarcs of dead *Tubularia larynx* than on live hydroids or red algal species. This work has now led to the potential use of hydroid species as a filling for artificial spat collectors and experimental trials have yielded very high numbers of spat (Legault *et al.*, 1993).

The mesh size of the onion bag containing the settlement material has been demonstrated to affect the yield of spat from the collectors; 45% of *Pecten fumatus* may be lost from collectors with a 4 mm mesh (Hortle, 1983) rising to 62% for a 7-8 mm mesh (Hortle & Cropp, 1987). Buestel *et al.* (1979) doubled the yield of *P. maximus* spat from collectors by reducing the outer mesh from 5 mm to 2 mm.

Naidu & Scaplen (1976) used a 1.5 mm mesh for *Placopecten magellanicus* but Brand *et al.* (1980) and Ventilla (1977a) favoured a 6 mm mesh for the collection of *P. maximus* as a means of reducing siltation of the collectors. The optimum choice of mesh size appears to be both species and location specific: the mesh must be small enough to retain the spat of the target species when they detach from the filling, but large enough not to restrict water flow (reducing both the supply of larvae and subsequently food to the developing spat) nor become choked by silt and fouling organisms.

The location of spat collectors in areas with a suitable larval supply is an obvious necessity for effective collection. The pelagic larval phase of many scallop species is of the order of weeks (Cragg & Crisp, 1991) and may potentially result in larvae travelling some distance. The intensity of settlement on collectors may thus not be directly associated with close proximity to areas of high adult density (Minchin, 1992; Robinson *et al.*, 1993) although Young *et al.* (1989) found a positive correlation between the size of the spawning stock of *P. fumatus* and the number of spat on artificial collectors. Studies carried out in the waters around the Isle of Man have placed collectors on the coastal margins of commercial scallop grounds (Paul, 1978; Brand *et al.*, 1980; Duggan, 1987; Brand *et al.*, 1991b). The best settlements of *P. maximus* and *A. opercularis* have been recorded on the north coast of the Calf of Man, off the southern tip of the Isle of Man (Duggan, 1987 and Coles, unpublished data summarised in Brand *et al.*, 1991b).

In order to maximise spat yield the deployment of collectors must be timed to coincide with the peak of larval settlement. This period may be relatively brief: Paul (1987) considered that *P. maximus* settlement was restricted to a 5 week period in the UK, from late June to late July, similar in timing to settlement in Manx waters (Paul, 1978; Duggan, 1987). Ventilla (1977a) found that on the west coast of Scotland in 1976 75% of the total *P. maximus* collected settled in the third week of July as well as 60% of the *A. opercularis* spat. Timing of collector placement may be of greater importance for the collection of *P. maximus* than *A. opercularis* as there is only a single annual settlement of this species (see Allison *et al.*, 1994 for a re-analysis and discussion of *P. maximus* settlement based on winter spat size, growth ring sizes and oxygen isotope analysis) around the Isle of Man. In contrast, settlement of *A. opercularis* occurs over an extended period with two or three pulses of higher settlement in Manx waters (Paul, 1978; Paul, 1981; Duggan, 1987) and off northern France (Buestel *et al.*, 1979).

The exact timing of peak settlement will inevitable vary between years due to the influence of both abiotic and biotic factors on gonad maturation and spawning in the adults and the larval lifespan and dispersal of the larvae. Ideally larval development and distribution should be monitored as a cue for collector deployment, as performed successfully in Mutsu Bay, Japan (Ventilla, 1982). However, the cost and complexity of such a monitoring programme were considered prohibitive by Bull (1988a), who favoured a trial and error approach over a wide geographical area.

The timing of spat collector deployment is further complicated by conflicting reports regarding whether onion bags are most efficient at collecting spat when fresh or whether their efficacy increases with the development of a biofilm (i.e. a period of 'conditioning'). Minchin (1992) considered that collectors should be set close to the time of settlement to avoid organic build-up. However, there is considerable evidence that settlement is better on surfaces that have been conditioned: *Chlamys hastata* prefers fouled surfaces (Hodgson & Bourne, 1988); the bay scallop, *Argopecten irradians*, has been induced to settle at different rates in response to different species of bacteria (Xu *et al.*, 1991) and settlement of the sea scallop *Placopecten magellanicus*, was significantly higher on collectors immersed some weeks before spatfall in order to develop a biofilm (Bonardelli, 1988; Parsons *et al.*, 1989; Parsons *et al.*, 1993). Higher numbers of *Mizuhopecten yessoensis* juveniles have been observed to attach to lightly fouled cultch and the presence of the biofilm also improved early growth (O'Foighil *et al.*, 1990). Conversely, Tritar *et al.* (1992) found that settlement of *P. maximus* was neither enhanced nor reduced by the presence of bacterial species that attracted oyster larvae (*Crassostrea gigas* and *Ostrea edulis*) and that it was equally competent at settling on clean, unfouled substrata.

If spat collector efficiency does improve after a period of immersion then to obtain maximum settlement, the collectors must be deployed a suitable time before the peak of larval settlement. To do this accurately would again require monitoring for early larval stages and so a pragmatic approach of setting the collectors on a fixed date prior to past peak settlement periods appears preferable (Bull, 1988a).

1.3.2 Suspended cultivation

The first stage of ongrowing, intermediate culture, is almost universally carried out in Japanese style pearl nets. Originally designed for the culture of pearl oysters, these pyramid-shaped nets are loaded with spat (the number dependent on the size of the scallops, but in general sufficient to cover 10-20% of the floor area of the nets) and tied together in strings suspended in the water column from longlines or rafts (Ventilla, 1982; Hardy, 1991). In the case of *P. maximus* cultivation this stage lasts from the autumn after settlement, when the collectors are sorted and the spat separated from the other settled organisms, until the following April/May when the spat are 20-25 mm in size (Wieland & Paul, 1983).

Scallops can be grown through to harvest size in suspended culture, for which there is a wide variety of equipment available (see Hardy, 1991 for a review of culture methods). The most common forms are Japanese style 'lantern nets' and 'ear hanging', where scallops are attached in pairs to strings by plastics ties through holes drilled through the shell. The capital costs of lantern nets escalate as the scallops grow and require more space, and the amount of labour required to maintain the nets and longlines can adversely affect the viability of cultivation. This has led to increasing interest in the potential for seabed cultivation or reseeding.

1.3.3 Reseeding

The costs involved in longterm suspended cultivation of scallops may be prohibitive, at least in countries where labour costs are high (Frishman *et al.*, 1980; Wildish *et al.*, 1988). Both of these studies suggested that extensive cultivation on the seabed was the only economically viable culture method. However, reseeding scallops onto the seabed has been used as more than a technique for final cultivation. Potential aims of reseeding include:

i) to introduce scallops to a suitable area which does not have a population.
ii) to increase the broodstock of an area as a means of increasing settlement on natural or artificial substrata.
iii) as a method of cultivation.
iv) as a means of direct fishery enhancement.

i) New introductions

The introduction of animals to an area which appears suitable but has no resident population has been carried out successfully in New Zealand with *Pecten novaezelandiae* (Bull, 1987). Three different techniques have been utilised: emptying spat collectors over suitable virgin ground which lacked a supply of larvae, allowing spat to fall to the seabed from settlement substrata without a mesh bag and redistributing the recently detached scallops using fine-mesh dredges, and the reseeding of scallops after three to six months in suspended culture. The latter method resulted in the best survival (44-75%) but the costs of intermediate culture cast doubt on its economic viability. 50% of the scallops survived the redistribution by dredging and survival rate at harvest was 22% (Bull, 1987).

ii) Brood stock enhancement

To increase the settlement of scallop larvae on spat collectors or natural substrata by the enhancement of the adult stock, clearly requires a close and predictable relationship between stock and recruitment. This correlation is highly site specific and in light of the dispersive, larval phase of the scallop life cycle, is primarily dependent upon local hydrography (Coleman, 1988). In the eastern United States there have been publicly funded projects to restock depleted populations of the bay scallop, *Argopecten irradians*, and create spawning stocks, although their efficacy remains unproven (Rhodes, 1991). Similar traditional practices for the hard clam, *Mercenaria mercenaria*, have been demonstrably unsuccessful (Kassner & Malouf, 1982). However, in Mutsu Bay, Japan, 300 scallop spat per collector was considered satisfactory in the early 1960s but as the size of the spawning population in the bay increased due to hanging culture and reseeding, this figure improved dramatically. Now up to 20 000 spat can settle on each collector because of the enhanced broodstock (Body & Murai, 1986). Kilkieran Bay and Mulroy Bay in Ireland have each been seeded in the hope of improved spat collection, in the latter case to make up for the effects of several years of zero recruitment caused by the use of organotin anti-fouling compounds (Burnell & Slater, 1989; Minchin & Ni Donnachada, 1991).

iii) Cultivation method

Reseeding as a means of bottom culture has been carried out extensively in Japan, accounting for more than half of total scallop production (Ventilla, 1982; Body & Murai, 1986; Aoyama, 1988; Ito, 1988; Ito & Byakuno, 1988; Cropp, 1988a; Ito, 1991). The growth of scallops in suspended culture is generally faster than those living on the seabed, and survival better, but production costs are far higher making reseeding an attractive prospect (Ventilla, 1982; Paul *et al.*, 1986; Wildish *et al.*, 1988). In particular, labour costs in the west have made suspended culture economically unattractive because of its high demands on manpower. Cultivation of the American bay scallop, *Argopecten irradians*, although hugely successful in China (Chew, 1990) has been delayed in the United States because of the lack of an economic grow out method (Rhodes, 1991). Both Frishman *et al.* (1980) and Wildish *et al.* (1988) considered that "benthic relaying" was the only method of cultivation likely to be economic. In Mutsu Bay the production costs of bottom culture are only 30% of those for suspended culture, reflecting the potential of this approach (Body & Murai, 1986).

iv) Fishery enhancement

Declining catches are a feature of scallop fisheries all over the world (see Shumway (1991) for review) and reseeding may provide a means of maintaining catches at economical levels. This is likely to be most profitable when combined with temporary closure to fishing of the areas reseeded. A system of rotational closure, allowing exploitation of some areas followed by closure and reseeding, as other areas are re-opened to fishing would produce the most efficient mechanism. This would allow harvesting of the open areas with a minimum of restriction and hence maximum efficiency, while providing maximum protection to the closed areas (Bull, 1988c). Manipulation of this kind could only be undertaken where access to the fishery is highly restricted, ensuring that the benefits of the enhancement go to those who funded it or to whom it was aimed.

1.3.4 Problems of reseeding

Three major problems threaten the success of reseeding; rights of ownership to the seabed and stock, and losses of seeded scallops due to either dispersal and/or predation.

1.3.4*a* Ownership

In Japan, scallop fisheries and aquaculture are carried out by co-operatives who have sole rights to areas of sea and seabed in their locality (Ventilla, 1982; Ito & Byakuno, 1988; Ito, 1991). This system removes the majority of competition between fishermen and hence problems of theft and security. Co-operatives are given protective rights over scallops in suspended culture but also to those native to or reseeded onto the seabed. There is thus no need to distinguish between reseeded scallops and the resident population at the time of harvest. Furthermore, to ensure that reseeded scallops are not wasted by dispersive losses to areas managed by other co-operatives, a buffer zone is left around the area actually seeded (Quéllerou, 1975).

Rights to coastal waters in the United Kingdom are controlled by the Crown Estates Commissioners (Hardy, 1991). Licences for aquaculture are granted by them after a consultative phase with other interested parties to consider objections. The basic licence only gives protection to scallops maintained in suspended culture and not to those reseeded onto the seabed. A further application is necessary for the granting of a "Several Order" which provides ownership of stock reseeded onto the bottom within the leased area.

Jurisdiction for Manx waters lies with the Isle of Man Government. They have exclusive control over the waters within the 3-mile fishing limit where any aquacultural development would be likely to take place and the "Sea Fisheries Amendment Act (1991)" empowers them to grant licences for aquaculture. In July 1991 jurisdiction was extended to the 3-12 mile zone, but any development or changes to legislation affecting this area must be taken with the 'concurrence' of the UK Government. There is currently no Manx equivalent to the UK Several Order, however, and hence no provision for the granting of rights to scallops reseeded onto the seabed. This would clearly need to be modified before scallop reseeding was carried out commercially, to provide some degree of protection to enhanced stocks. The tradition of Manx fishermen is very individualistic (even among boats landing to the same processor) and there is no history of co-operative fishing (c.f. Japan). The availability of sites for suspended culture and on-bottom cultivation in particular is likely to be extremely limited. The Manx coastline provides little in the way of sheltered bays and all areas are likely to be sensitive because of existing scallop fisheries, crab and lobster potting and navigational considerations. Objections would be strongest against a large area suitable for extensive reseeding. Unfortunately, scallop reseeding carried out in a small area would be liable to dispersive losses due to scallops swimming out of the designated area.

1.3.4*b* Dispersal

The Pectinidae are well known for their ability to swim (Baird, 1958; Hartnoll, 1967; Thomas, 1969; Moore & Trueman, 1971; Thomas & Gruffydd, 1971; Peterson *et al.*, 1982; Winter & Hamilton, 1985; Brand, 1991; Wilkens, 1991). *Pecten maximus* swims little compared to some other species of scallop, covering less than 1 mile (1.6 km) in 34 months (Baird & Gibson, 1956), and with 95% of tagged individuals being found within 5 miles of the release point (Franklin & Rolfe, 1976). Scallop swimming is also size-related; all sizes retain the ability to swim but intermediate sized animals tend to swim more often and farther (Gruffydd, 1976; Winter & Hamilton, 1985; Manuel & Dadswell, 1991; Orensanz *et al.*, 1991; Parsons & Dadswell, 1991a; Carsen *et al.*, 1993). *P. maximus* moves little under normal conditions, when recessed, and is unlikely to swim unless disturbed (Baird, 1958; Hartnoll, 1967; Thomas, 1969; Thomas & Gruffydd, 1971). Howell & Fraser (1984) recovered 60% of their tagged, dredge-caught scallops within 30 m of their release point after a period of 18 months. The scallops they used were of commercial size, mostly 110-130 mm, but still dispersed to the same density as indigenous scallops in the locale (Howell & Fraser, 1984). A rapid dispersal of scallops from areas seeded at high density has been common for various species of scallop: *Mizuhopecten* *yessoensis* (Quéllerou, 1975; Volkov *et al.*, 1982), *Argopecten irradians* (Morgan *et al.*, 1980; Tettelbach, 1986), *Pecten novaezelandiae* (Bull, 1988a).

Orensanz *et al.* (1991) suggested that a threshold level of some environmental parameter, when crossed, could induce swimming in scallops. Potentially significant parameters include: substratum, salinity, oxygen concentration, water currents and food supply.

High scallop density stimulates motor activity under otherwise neutral conditions and leads to the diffusion of artificial high density patches (Kalashnikov, 1991). Little is known, however, about the degree of perception by scallops of their neighbours or other competitors. Visual perception of static organisms is likely to be poor given the limited ability of the scallop eye, although detection of movement, even without the casting of a direct shadow over the scallop is sufficient to provoke a response (Wilkens, 1991). At high densities ("750 tagged scallops within 5 m of a central point") swimming by one scallop within a patch can elicit swimming in other scallops nearby; increased levels of activity continuing until the scallops are sufficiently dispersed for interactions between individuals to be reduced to more natural levels (Howell & Fraser, 1984). Similar chain reaction behaviour has been noted for *P. maximus* (Minchin & Mathers, 1982), *A. opercularis* (Chapman *et al.*, 1979) and *Chlamys islandica* (Vahl & Clausen, 1980). Visual cues may cause the chain reaction but the original stimulus to move is more likely to be attack from predators, or some environmental effect. Density may also be indirectly related to the dispersal of scallops, owing to the aggregation of predators on areas of high scallop density (Caddy, 1988).

Tidal currents have been suggested to increase the frequency of swimming in *Chlamys islandica* (Gruffydd, 1976), but such a response would appear counter-productive for a species like *Pecten maximus*, which commonly lives recessed. However, swimming behaviour, induced by whatever stimulus, will be influenced by tidal currents and may result in apparently directed movements, when the reality is a tidal influence on otherwise randomly directed swimming (Moore & Marshall, 1967; Imai, 1980; Posgay, 1981; Tettelbach, 1986; Caddy, 1988). Scallops swim typically in three phases: an initial take off phase when height is gained, an active horizontal phase followed finally by a passive descent to the seabed (Caddy, 1968; Chapman *et al.*, 1979; Morton, 1980; Brand, 1991). The swimming performances of several scallop species were reviewed by Brand (1991). No speed has been estimated for the performance of *Pecten maximus* or any plano-convex species of scallop, although 37 $cm.s^{-1}$ is quoted for 100 mm *Amusium pleuronectes*, a bi-convex lightweight scallop which is undoubtedly a superior swimmer (Morton, 1980). Assuming this figure to be the maximum of which scallops are capable, the contribution to the distance covered in any bout of swimming by tidal currents may be significant. Tidally influenced scallop movements have been reported by several authors (Moore & Marshall, 1967; Morgan *et al.*, 1980; Caddy, 1988; Orensanz *et al.*, 1991).

Localised depletion of food supply may also produce a swimming reaction. This can occur from the feeding activities of local suspension feeders - the "seston depletion effect" (Wildish & Kristmanson, 1979; 1984; 1985; 1988; Wildish *et al.*, 1987; 1988). Scallops, particularly when recessed, draw their food supply from the benthic boundary layer of water immediately adjacent to the seabed. This layer of water is slow moving due to frictional effects with the seabed, and mixing between it and the bulk layer of water above is limited (Fréchette & Bourget, 1985; Fréchette *et al.*, 1989). Where suspension feeders live at high densities, removal of food particles from the benthic boundary layer can outstrip their replenishment by advection from the bulk layer and resuspension from the sediment, resulting in seston depletion. Reductions in concentration of seston due to the suspension feeding of sponges and bryozoans have been found in the field (Buss & Jackson, 1981). Orensanz (1986) found *Chlamys tehuelcha* growth limited at high density (above 1 kg of scallops.m^{-2}) and a consistent maximum of 1.3 kg.m^{-2} dictated by food supply, implying density dependent movement to maintain spacing (dilution). Similar maxima are reported by Aoyama (1988) for *Mizuhopecten yessoensis* and Iribarne *et al.* (1991) for *C. tehuelcha*, equivalent to approximately 6 scallops.m^{-2} on the seabed. The use of the swimming response to escape from high density patches of conspecifics and other competitors, thereby lowering competition, was hypothesised by Peterson *et al.* (1982) but they were unable to demonstrate this in trials using the bay scallop *Argopecten irradians*. However, their experiments ran for only a matter of hours and may not have reached the threshold of seston depletion required to induce swimming.

At the current low densities of scallops on the fishing grounds around the Isle of Man (Murphy, 1986; Allison, 1993 and see Chapter 2) seston depletion seems unlikely. It might, however, be significant at the enhanced densities produced by reseeding, leading to a potential maximum reseeding density dictated by the supply of food.

1.3.4*c* Predation

The responses of scallops to predators (valve closure, jumping and swimming) are well known, although most of the work carried out on the subject has concentrated on responses to asteroid starfish (Dickie & Medcof, 1963; Thomas & Gruffydd, 1971; Morgan *et al.*, 1980; McClintock & Robnett, 1986; Pitcher &

Butler, 1987; Caddy, 1988). Some work has been carried out on gastropod predators (Ordzie & Garofalo, 1980a; 1980b; Peterson *et al.*, 1982), but research on crustacean predators has been directed towards size selectivity in predator feeding and not scallop escape responses (Tettelbach, 1986; Lake *et al.*, 1987; Minchin, 1991).

Caddy (1988) suggests that the swimming response is potentially significant as an agent of density regulation because of the aggregation of predators on high densities of scallops. He found that predators (whelks, *Buccinum undatum*, and starfish, *Asterias* spp.) congregated on seeded scallops within 48 hours in response to olfactory stimuli, and resulted in the dispersal of the large and otherwise inactive scallops. The diffusion of high density patches of *Mizuhopecten yessoensis* has been attributed to invasions of predators (Kalashnikov, 1991). Predator attacks, particularly from starfish, have been considered to be the most frequent and important triggers of swimming behaviour by several authors (Thomas & Gruffydd, 1971; Peterson *et al.*, 1982; Volkov *et al.*, 1982; Winter & Hamilton, 1985; Orensanz *et al.*, 1991), but the value of being able to discriminate between predatory and non-predatory species was pointed out by Thomas & Gruffydd (1971). They demonstrated this ability in *Pecten maximus*, and found that swimming was elicited by *Asterias rubens*, *Marthasterias glacialis* and *Astropecten irregularis* but not by the non-predatory species *Porania pulvillus* or *Henricia sanguinolenta*. Discrimination of this kind can save significant amounts of energy by avoiding unnecessary swimming activity, as well as the additional energetic costs of constructing a new depression in which to recess. The only anomaly of their work is that, as an intra-oral feeder, *Astropecten irregularis* would be unable to attack large adult *P. maximus*, although newly settled spat may be vulnerable. They also suggested that *Pecten maximus* will swim in response to extracts of other scallops, a self-preservation reaction to the detection of damage to its own species (Thomas & Gruffydd, 1971). Discrimination between predatory and non-predatory species has also been demonstrated in the bay scallop *Argopecten irradians* (Ordzie & Garofalo, 1980a).

Starfish are frequently cited as major scallop predators, causing large scale stock losses of reseeded scallops (Galtsoff & Loosanoff, 1939; Ito & Byakuno, 1988; Lake & MacMillan, 1991; Barbeau & Scheibling, 1993; Lake, 1993), and with crabs are considered to be major scallop predators around the Isle of Man (Brand *et al.*, 1991b). Briggs (1983), however, considered *A. rubens* an insignificant predator of commercial scallops. Other potential predators include octopus, lobsters and demersal fish although nothing is known of their impact locally.

Successful predation is dependent on the relative sizes of both animals and size selection of prey has been demonstrated in both starfish (Hancock, 1974; Paine, 1976; Anger *et al.*, 1977; Sloan, 1980; Allen, 1983; Blankley & Branch, 1984; Penney & Griffiths, 1984; McClintock & Robnett, 1986) and crabs (Elner, 1978; Elner & Hughes, 1978; Tettelbach, 1986; Ameyaw-Akumfi & Hughes, 1987).

The chemotactic sense of asteroids has been comprehensively reviewed by Sloan & Campbell (1982). Although there remained conflicting points of view, 73% of the papers they considered demonstrated an olfactory ability in starfish. However, estimates of the distance over which food can be perceived vary greatly, from zero (contact chemoreception) to 12 m (Smith, 1940 for *Asterias vulgaris* detecting mussels). Distance chemoreception by *Asterias forbesi* of upstream *Mercenaria mercenaria*, over distances of 0.5 - 0.7 m, has been clearly demonstrated in both the laboratory and the field (Doering, 1982).

Fundamental to the chemical detection of food in the marine environment is the speed and direction of water movement (Carthy, 1958; Lapointe & Sainte-Marie, 1992). The distance at which starfish can detect prey inevitably depends upon the direction of water movement relative to the predator and the prey, the concentration of perceptible matter, the diffusion coefficient of the chemical, and the sensitivity of the predator to it. In their review, Feder & Christensen (1966) noted that many authors reported starfish becoming excited immediately prey items were introduced to an aquarium, but they were subsequently unable to find the prey efficiently. This was attributed to the "uncontrolled water movements" in the tanks (leading to even mixing of the chemical attractants) causing the starfish to detect prey from several or all directions simultaneously. In 20 × 20 × 20 cm aquaria, Valentincic (1985) found that test and control solutions introduced gently at the water surface reached the furthest corners of the tank in less than one minute, and that dyes added became colorimetrically homogeneous after 2 minutes. For larger tanks (50 × 40 × 40 cm), the same author found that milk used as an indicator reached the furthest corners in 5 minutes and was fully dispersed in 10 minutes (Valentincic, 1973). If the attractants from prey disperse similarly, then the confusing results are unsurprising. Some assertions have been made that chemosensation is unimportant to starfish in the search for food, following experiments where animals were released 5 feet (1.53 m) from prey and then passed within 10 cm of the food without detecting it (Galtsoff & Loosanoff, 1939). However, the prey were in the tank prior to the starfish being added allowing homogeneity of the chemical attractants in solution and resulting in poor direction finding by a chemotactic predator. The significance of water movement was further confirmed by Valentincic (1973), who found experiments on the chemosensory abilities of *Marthasterias glacialis* more successful in flow through tanks than in closed systems.

Carthy (1958) indicated that current induced gradients gave directionality to chemical stimuli and so made them useful as a means of locating food. In the absence of water currents any stimuli from chemicals in the water will be short-lived, their duration dependent upon their diffusion coefficients (Mackie, 1975). Upstream chemotaxic aggregation on bait by *Buccinum undatum* has been clearly demonstrated by Lapointe & Sainte-Marie (1992), with whelks in a 20-60° arc downstream of the bait, up to 20 m away, being attracted.

Asteroids are extremely sensitive to low concentrations of chemical attractants; *Marthasterias glacialis* can detect certain amino acids at concentrations of 3×10^{-7} $mol.l^{-1}$, with some individuals able to detect levels 30-100 lower (Valentincic, 1985). Minute quantities of a chemical can release a sequence of feeding behaviour (Sloan & Campbell, 1982).

Rapid aggregation of predators can be caused by chemical cues and *A. rubens* can move at up to 5-8 $cm.min^{-1}$ having detected food (Feder & Christensen, 1966). Volkov *et al.* (1982) found that starfish aggregated readily in response to chemical stimuli. Following a very large and dense reseeding of *Mizuhopecten yessoensis*, starfish aggregated rapidly and their subsequent distribution followed that of the scallops, both spatially and temporally (Volkov *et al.*, 1982).

Crab predation can cause large-scale scallop mortalities similar to starfish predation (Elner & Jamieson, 1979; Paul *et al.*, 1986; Tettelbach, 1986; Lake *et al.*, 1987; Minchin, 1991; Scheibling *et al.*, 1991; Barbeau & Scheibling, 1993; Lake, 1993; Scheibling, 1993). Size selective behaviour has been demonstrated for several crab species (Elner & Hughes, 1978; Tettelbach, 1986; Ameyaw-Akumfi & Hughes, 1987). *Carcinus maenas* feeding on mussels demonstrates a definite size preference for smaller individuals which can be easily crushed. In a patch of mixed size prey, larger mussels are rejected in favour of the smaller and more easily handled individuals. However, if only large, sub-optimal prey are encountered consecutively then, after a time, these will be consumed. If the crab then encounters a small mussel, this will be eaten and the size bias in favour of small prey will be re-instated (Elner & Hughes, 1978; Ameyaw-Akumfi & Hughes, 1987). Similarly, *A. rubens* feeding on *M. edulis* will consume all size classes presented to it but shows a clear size preference for smaller prey. However, if denied the preferred size class, *A. rubens* feeds on progressively larger mussels (Hancock, 1974).

Size selection and optimal foraging experiments have not been carried out on *Cancer pagurus*. To date it has been shown that *C. pagurus* of all sizes eat more smaller scallops than larger scallops, and that the maximum size of scallop that can be eaten increases with increasing crab carapace width (Lake *et al.*, 1987). However, the crabs were only presented with one size class of scallop at a time and so were unable to actively select prey on the basis of size. Lake *et al.* (1987) suggested that at a size of 6-7 cm *P. maximus* achieved a size refuge from predation by *C. pagurus*. They demonstrated a change in crab handling technique with progressively larger scallops; a scallop of small size relative to the crab was crushed, but as the size of the scallop increased, more time consuming methods were employed, such as chipping of the shell margin to gain entry to the mantle cavity. A similar change in technique with increasing prey size has been observed in other crab species (Hughes & Seed, 1981; Tettelbach, 1986).

C. pagurus is a mobile predator and can range over considerable distances. Edwards (1979) details numerous tagging experiments with this species; most of the crabs recovered were within 5 miles (8 km) of the release point, although one exceptional crab was found a straight line distance of 230 miles (368 km) from its release site after just 52 weeks. Foraging over large areas has also been demonstrated in other cancrid crab species (Boulding & Hay, 1984).

Crabs have also been shown to be chemosensitive and able to react rapidly to dense aggregations of prey. *Cancer magister* is able to detect extracts of its infaunal bivalve prey at concentrations as low as 10^{-10} g.l^{-1}, using its antennules as distance chemoreceptors (Pearson *et al.*, 1979). Above this concentration, feeding behaviour is initiated. Minchin (1991) found predatory activity from crabs within minutes of reseeding, as they responded to chemical exudates from the scallops. As has been previously discussed, this ability to detect chemicals in the water, in concert with water movement to give a directional quality to scent, provides a mechanism for food location. As a result, predator distribution is greatly affected by small scale aggregations of dense prey (Auster, 1988).

Auster & Malatesta (1991) considered patch size to be a more important factor than prey density in its effect on predation on infaunal bivalves. Predation was higher in larger patches of prey, while prey density had little effect and there was no significant interaction between the two factors. However, crabs have been found to forage preferentially in areas of high prey density, as would be expected from Optimal Foraging Theory (Charnov, 1974; Hughes, 1980; Boulding & Hay, 1984).

Several factors influence predation success: predator density, prey density, predator choice/preference, ease of capture, handling time, energy content of prey and size related factors as well as prey conditioning and learned behaviour. The relationships between these factors have been modelled by various authors under the general title of Optimal Foraging Theory (Pyke *et al.*, 1977; Krebs, 1978; Hughes, 1980; Andersson, 1981; Hughes & Seed, 1981; Scheibling, 1981; Boulding & Hay, 1984; Campbell, 1984; Sih, 1984; McClintock & Robnett, 1986). A fundamental premise of Optimal Foraging Theory is that behaviour which maximises the net rate of energy uptake confers a selective advantage on the individual. This Energy Maximisation Premise is central to consideration of the animal's choice of prey, search method and foraging habitat.

Optimal foraging or optimisation of diet has been found in both crabs (Hughes & Seed, 1981; Dare *et al.*, 1983; Jubb *et al.*, 1983; Boulding & Hay, 1984; Davidson, 1986; Ameyaw-Akumfi & Hughes, 1987; Lake *et al.*, 1987; Auster & Malatesta, 1991), and starfish (Hancock, 1974; Anger *et al.*, 1977; Scheibling, 1981; Campbell, 1984; Penney & Griffiths, 1984; McClintock & Robnett, 1986). Areas of high prey density allow predators to reduce the time spent searching for prey to a minimum. With minimal searching time, energy intake is limited only by the efficiency of prey handling and ingestion. Aggregation to such areas of high prey density has been observed in both crabs (Auster, 1988; Auster & Malatesta, 1991; Minchin, 1991), and starfish (Brun, 1968; Ormond *et al.*, 1973; Warner, 1979; Scheibling, 1980; Sloan & Aldridge, 1981; Jangoux, 1982; Volkov *et al.*, 1982; Blankley & Branch, 1984; Sloan, 1984; Caddy, 1988).

The Marginal Value Theorem of optimal foraging suggests that a predator should stay within a patch until the net rate of energy intake from the patch falls to the average level for the habitat (Hughes, 1980). Where the prey are of uniform size the predator should move on to another area when the prey within a patch have been exploited down to nearfield densities (Auster & Malatesta, 1991). Such alternatives in foraging strategy do, however, imply capabilities of the predator to be conscious of the prey density, and to be able to retain a measure of the background density as a comparison on which to base any change in foraging strategy. Such a memory may be a threshold density set by previous foraging experience. Once in a high density patch the predator can maximise energy intake per unit of time by optimising handling time.

Scallop density is clearly of fundamental importance to the success of reseeding. By definition, reseeding will increase scallop density in the cultivation area relative to the background level and from an economic point of view, density should be maintained at the maximum sustainable for the area without incurring density dependent depression of growth through seston depletion (Wildish & Kristmanson, 1988; Wildish *et al.*, 1988). However, high densities have been shown to provoke aggregation of predators, both starfish (Warner, 1979; Sloan & Aldridge, 1981; Doering, 1982; Jangoux, 1982; Volkov *et al.*, 1982; Auster, 1988; Caddy, 1988) and crabs (Auster, 1988; Minchin, 1991), leading to high mortality rates.

1.4 Global reseeding experience

Scallop reseeding originated in Japan and has now been carried out on at least an experimental scale in France (Buestel & Dao, 1979), Britain (Howell & Fraser, 1984), Ireland (Burnell & Slater, 1989; Minchin, 1991; Minchin & Ni Donnachada, 1991), United States (Morgan *et al.*, 1980), New Zealand (Bull, 1991), Russia (Kalashnikov, 1991), Mexico (Felix-Pico, 1991), Canada (Naidu, 1991), Australia (Gwyther *et al.*, 1991), China (Lou, 1991) and Chile (Munita, 1988).

1.4.1 Japan

The first reseeding experiments were done in 1936 on the Okhotsk Sea coast of Hokkaido (Kinoshita (1949) cited in Ito (1991)) following spat collection trials in 1935. The trials were, however, unsuccessful because of very high mortality rates (Ventilla, 1982; Ito, 1988; Ito, 1991). In the late 1960s further large scale reseeding took place but this time after a period of intermediate culture so that the scallops were larger. Quantities of more than 20 million scallops were seeded annually, with survival rates of 54.7-98.0% over one year in the Tokoro region and 5.5-28.9% over two years in the Sarufutsu region (Ito, 1988; Ito, 1991). The resultant increase in the reproductive stock on the seabed was in turn reflected in heavier spatfalls on natural and artificial substrata and a stabilisation of the dredge fishery (Ventilla, 1982; Ito, 1988).

Japanese scallop production rose from 5 000 t in 1969 to 100 000 t in 1975, but was followed in Mutsu Bay by a period of mass mortalities due to over crowding, red tides and an overloading of the ecosystem (Ventilla, 1982; Aoyama, 1988). Annual spat input into Mutsu Bay is now restricted to 700 million shells in total, with 60 000-100 000 shells.ha^{-1} seeded onto the bottom and in some areas 60 000 shells.ha^{-1} above in hanging culture (Ventilla, 1982; Aoyama, 1988). In 1982 seed input around the Hokkaido coast was approximately 1 500 million scallops (Ito, 1991). In 1988 sowing culture and the wild fishery produced 159 689 t of scallops out of a national total of 341 618 t (Ito, 1992).

In Mutsu Bay, Honshu, 23 000 ha are used for sowing culture. Scallops are seeded at 30-50 mm at a density of 5-6 m^{-2} and retrieved by dredging 2.5-3.5 years later at 120 mm (Body & Murai, 1986; Aoyama, 1988). The optimum scallop sowing density was calculated from the maximum production of 1 200 $g.m^{-2}$ being equivalent to six scallops of 200g at market size (Aoyama, 1988), and from experience: in 1972 approximately 200 million second year scallops died in an area where 30-40 shells m^{-2} and up to 140 shells m^{-2} had been sown (Ventilla, 1982). Prior to reseeding the ground is prepared by intensive dredging to remove starfish, *Asterias amurensis* and *Destolasterias nippon* (Body & Murai, 1986). An area approximately five times greater than that to be seeded is cleared of predators and only the central portion sown. By the time commercial harvest size is reached the scallops will have dispersed to the margins of the area (Quéllerou, 1975).

In the Shibetsu region of Hokkaido scallops are seeded at 45 mm by tipping them over the side of a boat moving at 8 knots to give an approximate initial density of 7-13 shells m^{-2}. The ground is again prepared by intensive dredging to remove predators and the starfish are used onshore for fertiliser. Growth and survival are monitored by sample dredging and sledge mounted video. Harvest is by repeated dredging until the catches of scallops and starfish fall close to zero. In 1986/7 one area of 2 km^2 produced 650 t of scallops and 450 t of starfish (Cropp, 1988a). Over a four year rotational cycle 25-30% scallop survival is achieved, dredged with an 80% efficiency, giving a total recovery of 20% of the seeded stock (Ventilla, 1982). However, yield is difficult to calculate accurately because of natural scallop production (Ito, 1991).

1.4.2 Other Pacific countries

Artificial populations of the Japanese or Yezo scallop *Mizuhopecten yessoensis* have been seeded into Posiet Bay, Russia, since 1973 (Kalashnikov, 1985). These have contributed to the spawning population and since 1983 30 million spat have been produced annually from collectors, 70% of which are subsequently used for bottom culture (Kalashnikov, 1991). Scallops are seeded at 10-40 m^{-2} and are harvested 2-4 years later. Survival is dependent on the weather and predator activity but is between 5-50%. Harvesting can be done efficiently by divers because of the shallow depths involved (3-20 m), and a single diver can remove up to 4 000 shells per hour at a density of 10 m^{-2}, with an average of 500 per hour (Kalashnikov, 1991).

In China reseeding has been carried out with the native Jicon scallop (*Chlamys farreri*) and with the Japanese scallop (*Mizuhopecten yessoensis*) since the early 1980s (Lou, 1991). However, both of these species are relatively slow growing (3-4 years to harvest), and recent efforts have concentrated on the suspended culture of the Atlantic bay scallop *Argopecten irradians* introduced from the United States in 1982 (Chew, 1990).

Semi-commercial reseeding in collaboration with the Japanese, has been carried out in New Zealand with *Pecten novaezelandiae*. 70 million spat were seeded in the third year of the trial, using various release methods; the best survival was recorded from those on-grown in intermediate culture before reseeding (44 and 75% Bull, 1987).

The catarina scallop *Pecten circularis* has been seeded in shallow enclosed bays on the Pacific coast of Mexico, at a density of 30 m^{-2}, although no information is available on survival rates (Felix-Pico, 1991) .

1.4.3 Atlantic coasts

The American bay scallop *Argopecten irradians* has been the subject of experimental reseeding on the Atlantic coast of the United States (Morgan *et al.*, 1980). 47 000 scallops were introduced, of various sizes, but losses were very rapid, to both dispersal and predation.

The French have seeded *Pecten maximus* in shallow sea areas after predator removal. At an initial density of 4.3 m^{-2} survival was approximately 50% fourteen months after sowing, with commercial size attained four months later. Intermediate culture was recommended, to give a size at reseeding of 30-40 mm because of the vulnerability of the young spat to predators; losses through dispersal were low (Dao, 1979). On the basis of the results obtained it was suggested that bottom culture would be economically preferable to suspended culture (Buestel & Dao, 1979).

Reseeding to improve broodstock and hence natural settlement of *Pecten maximus* has been carried out in various bays on the Atlantic coast of Ireland (Berry & Burnell, 1981; Minchin, 1991; Minchin & Ni Donnachada, 1991). The North Water of Mulroy Bay has particular potential because as it has a low tidal amplitude (1 m) and is relatively enclosed; this provides a low rate of water exchange and the capacity to maintain larvae within the bay until metamorphosis. However, many factors affect the link between the adult stock and final recruitment; an exceptional natural spat settlement in 1979 produced few recruits to the adult population because of intense predation from the starfish *Asterias rubens* (Minchin & Ni Donnachada, 1991).

In the United Kingdom experimental reseeding has been carried out by the Sea Fish Industry Authority (formerly the White Fish Authority). Trials using *Pecten maximus* of 4.9 cm showed them to be vulnerable to crab predation; 137 mortalities were recovered from 200 scallops seeded, within the first two weeks. The majority of these showed signs of crab predation (Lake *et al.*, 1987).

1.5 The Isle of Man

It is no longer economical to drag heavy fishing gear over increasingly large areas of seabed in pursuit of scallops that have been reduced to extremely low densities by decades of exploitation (Allison, 1993). Against this background, interest in scallop cultivation was inevitable (Brand, 1976; Paul, 1978; Brand *et al.*, 1980; Paul *et al.*, 1981; Brand *et al.*, 1991b; Whittington, 1993), given the example set by the Japanese (Ventilla, 1982; Body & Murai, 1986; Aoyama, 1988; Ito, 1988; Ito & Byakuno, 1988; Cropp, 1988a; Ito, 1991). The coastline of the Isle of Man, however, has no sea lochs or embayments of any significance which might provide shelter for aquaculture operations and suspended culture systems would be limited in extent by the need for safe navigation. Suspended culture systems are unlikely to be viable under such conditions but the potential for scallop culture based on reseeding remains.

1.5.1 History of Manx pectinid spat collection and cultivation

Research into pectinid cultivation at Port Erin began in 1975 when a study was initiated to examine the biological feasibility of spat collection and culture of *Pecten maximus* and *Aequipecten opercularis* (Brand, 1976). This work continued with Paul (1978), and the potential for *A. opercularis* culture in trays held off the seabed was established (Brand *et al.*, 1980; Paul *et al.*, 1981). *P. maximus*, however, did not respond well to this form of cultivation and it was suggested that this species might require an alternative methodology (Paul *et al.*, 1981).

Small scale spat collection continued at Port Erin with Coles (unpublished data summarised in Brand *et al.*, 1991b) and Duggan (1987) in conjunction with studies on pectinid recruitment, although there was no further research into scallop cultivation. Research into the population dynamics of exploited scallop populations around the Isle of Man emphasised the dependence of the fishery on regular recruitment to the inshore fishing grounds, and highlighted the declining catch per unit effort (Murphy, 1986; Allison, 1993). As early as 1983 an Isle of Man Government commission recommended that "escallop cultivation ... be investigated" as a complement to the wild fishery (Lyon-Dean *et al.*, 1983).

1.6 General aims of this work

The objectives of this research were to assess the viability of scallop mariculture in the waters around the Isle of Man and the potential for the use of closed areas as a management strategy for conservation of the fishery. The state of the Manx scallop fishery revealed by the work of Murphy (1986) and Allison (1993), carried out during the 1980s, plus the decline in catches evident from Isle of Man Government statistics led to the interest in scallop mariculture and restocking. The initial stages of this research programme concentrated on the collection of spat and their subsequent culture, followed by experimental reseeding in an area closed to commercial fishing. The latter stage of this study returned to investigate the state of the local scallop fishing grounds, continuing and extending certain aspects of the theses of Murphy (1986) and Allison (1993), using research vessel surveys. This part of my research is presented before the cultivation work to provide a more natural progression (the poor state of the fishery leading to the investigation of cultivation and restocking) although this was not the chronological order in which the investigations were undertaken. However, the case for an investigation into the potential for pectinid mariculture around the Isle of Man was already well established (Lyon-Dean *et al.*, 1983; Murphy, 1986; Allison, 1993).

Chapter 2 aimed to produce estimates of the density of *Pecten maximus* on the major scallop fishing grounds around the Isle of Man, and the relative abundance of the major scallop predators. This information was obtained from replicate research vessel tows of known length and swept area, as an alternative to the previous estimates of scallop density based on commercial fleet catch per unit effort. Further estimates were made using direct observations made by SCUBA divers inside the scallop fishing Exclusion Zone.

The work presented in Chapter 3 investigated the potential for commercial scale scallop spat collection using large arrays of artificial spat collectors of various designs suspended from subsurface longlines. This aspect of the study also investigated the spatial distribution of pectinid spat settlement around the south of the Isle of Man by the use of experimental lines of onion bag collectors.

The objective of Chapter 4 was to investigate the potential for suspended culture of scallops and queens using Japanese style methodology and equipment adapted for local conditions and to assess the relative merits of the different equipment utilised.

Chapter 5 aimed to determine the survival and fate of adult *P. maximus* re-laid at high density onto the seabed in an area closed to fishing as a model of on-bottom cultivation or stock enhancement. Major considerations included the mortality and dispersal of the scallops, and the behaviour of the local predators to the introduction of high density patches of prey.

The final chapter presents an economic model of scallop and queen cultivation around the Isle of Man. Special emphasis is given to the relative costs of different cultivation methodologies and their requirements for space, capital and manpower. This is followed by suggestions for maximising the success of scallop culture under local conditions. Finally suggestions for further work arising from this thesis are presented.

CHAPTER 2

THE ANALYSIS OF *PECTEN MAXIMUS* POPULATIONS AROUND THE ISLE OF MAN BY RESEARCH VESSEL SURVEY

2.1 INTRODUCTION

The fishery for the scallop *Pecten maximus* around the Isle of Man began in October 1937 and rapidly became the principal target of the Manx fleet. Increasing size and sophistication of the scallop fishing fleet initially brought high yields but fishermen have long maintained that catch rates have fallen from previously high levels (Murphy, 1986; Brand *et al.*, 1991a).

A brief history of the Isle of Man fishery for scallops and queens was presented in Chapter 1 and more detailed accounts can be found in Brand *et al.* (1991a) and Allison (1993). Allison (1993) also provides a history of the pectinid research and data collection carried out at Port Erin and provides the latest contribution to this continuing research theme. His comprehensive approach utilised several techniques (tagging, Yield per Recruit analysis, Catch Per Unit Effort (CPUE) from fishermen's logbooks, regression analyses of population parameters) to consider the state of the Manx scallop and queen stocks, taking into account spatial variations between the fishing grounds around the Isle of Man. He estimated exploitation and mortality rates on a spatial basis and found that on the inshore west fishing grounds, up to 55% of the recruiting year-class could be removed by fishing in a single season. The fishery was shown to be heavily dependent on the incoming year-class of scallops on all of the major fishing grounds, leaving it vulnerable to collapse in the event of recruitment failure of a single cohort. North Irish Sea recruitment has been remarkably consistent from year to year compared to many other scallop fisheries (see Brand *et al.*, 1991a) with only small fluctuations in age-class strength observed in age-frequency analyses and recruitment indices (Allison, 1993). However, with declining scallop abundance and density, a catastrophic failure of recruitment remains a possibility.

The impact of sustained fishing on the age structures of the scallop populations from the Bradda Head, the Chickens and South-East Douglas fishing grounds has been clearly demonstrated by Brand *et al.* (1991a). On all grounds there has been a shift to increased reliance on the younger age-classes, with this trend most pronounced on the Bradda Head ground because of its long history of high exploitation.

Data collected from a sample of the Manx scallop fishing fleet via a voluntary logbook scheme has revealed a general decline in catch per unit effort (CPUE, scallops caught per metre width of dredge towed per hour), particularly on the inshore grounds (Murphy, 1986; Brand *et al.*, 1991a; Allison, 1993). These estimates of CPUE have generally been based on data from a whole season and not provided information on catch rate variation over the duration of a fishing season. Only Murphy (1986) analysed catches over a shorter period. He found that the CPUE of the fleet at the opening (first 350-450 hours fishing) of the season was substantially higher than the season average, especially on the inshore west grounds. Further, Murphy (1986) demonstrated that CPUE on individual grounds fell to low levels over a period of weeks, providing the impetus for the fleet to move on to other grounds, often further afield.

Estimates have been made of the average population density of commercial size scallops on the seabed off Bradda Head from tagging studies (Mason & Colman, 1955; Gruffydd, 1972), and also by combining CPUE figures from a sample of the fishing fleet with estimates of dredge efficiency and towing speed (Murphy, 1986; Allison, 1993). There appears to have been a decline in scallop density from 9.1-20 scallops.100m^{-2} in the 1950-60s (Mason & Colman, 1955; Gruffydd, 1972), to <6 scallops.100m^{-2} between 1981-83 (Murphy, 1986). However, Murphy (1986) recorded a recovery in density to 6-11 scallops.100m^{-2} in the 1983/4 season following a very good recruitment, although subsequent estimates for the Bradda Inshore ground from 1986-90 have been <4 scallops.100m^{-2} (Allison, 1993).

Aims of this work

The aim of this chapter was to build on the previous studies of North Irish Sea scallop fisheries, taking into account the bipartite nature of the fishing year for scallops, by sampling before and after the fishing season. It updates current knowledge about the state of the scallop fishery as the background against which interest in scallop cultivation has arisen, and provides an indication of the relative importance and abundance of the major scallop predators (crabs and starfish). Predation, particularly on scallops weakened or damaged by encounters with fishing gear may be a significant source of mortality (Medcof & Bourne, 1964). Three research vessel surveys were undertaken, two post fishing season and one pre-season on up to 10 scallop fishing grounds around the Isle of Man, and direct observations were made by SCUBA diving in the scallop fishing Exclusion Zone off Port Erin.

This work sought to provide contemporary estimates of the density of commercial size scallops on fishing grounds around the island and to re-evaluate the density estimates of Murphy,(1986) and Allison (1993). Scallop density estimates were based on the area of seabed dredged during research vessel surveys rather than on CPUE, and the implications of possible under-estimation of fishing boat towing speed on scallop density estimates by previous workers are discussed.

Research vessel catch per unit effort (CPUE) was compared within and between fishing grounds, both before and after the fishing season, to investigate seasonal trends in recruitment to the stocks and depletion of them by the prosecution of the fishery.

Age-specific instantaneous coefficients of total mortality Z (the annual rate of total mortality for the population), were calculated separately for the open and closed phases of the scallop fishing season using changes in age-class density estimates, in order to further assess the relative impact of the fishery on the grounds sampled. Heincke's Z, an estimate of mean total mortality for all fully exploited age-classes was also calculated, with the age at first full exploitation varied from 4-6 years of age to cover the period of scallop recruitment to the commercial fishery.

Recruitment ogives for the different fishing grounds were constructed for each survey, from the proportion of each year-class which was of commercial size (≥110 mm). The implications of the time of sampling on the perceived age of recruitment are discussed.

The population age structures, as sampled by scallop and queen dredges, were compared subjectively between fishing grounds and between surveys. This provided an alternative method of comparing the relative impact of the fishery on the scallop populations of the different fishing grounds and the degree of reliance of the fishery on the recruiting year-class.

The relative abundances of the major by-catch species of the scallop fishery were estimated for each fishing ground . The seasonal nature of the sampling regime provided information on the temporal variation in the abundance of the major scallop predators and the potential importance of these predators is discussed.

2.2 METHODS

2.2.1 Sampling

Dredge surveys were carried out in October, before the start of the scallop fishing season on 1st November, and in June, after the end of the season on 31st May on various Manx fishing grounds (Figure 2.1). Three surveys were carried out as part of this study; 8th-17th June 1992, 19th-30th October 1992 and 1-11th June 1993. The fishing grounds sampled are summarised in Table 2.1. Full details of the sampling programme can be found in Appendix 1.

Table 2.1. Summary of scallop fishing grounds sampled during pre- and post-season surveys.

Site	June 1992	October 1992	June 1993
Bradda	17/6/92	26/10/92	1/6/93
Chickens	16/6/92	21/10/92	2/6/93
Peel	12/6/92	19/10/92	11/6/93
SE Douglas	-	29/10/92	7/6/93
East Douglas	-	28/10/92	8/6/93
10' S Port St.Mary	8/6/92	20/10/92	3/6/93
20' S Port St.Mary	9/6/92	30/10/92	4/6/93
Targets	10/6/92	-	9/6/93
Point of Ayre	11/6/92	-	10/6/93
Ramsey	15/6/92	-	-
Maughold Head	15/6/92	-	-
Laxey	15/6/92	-	-

Dredge surveys were carried out from the R.V. Roagan (length overall 23.4 m, 600 HP) towing 4 x 2 foot 6 inch (0.762 m) spring-loaded dredges per side. One side carried 'scallop' dredges similar to those towed commercially for scallops while the other side carried 'queen' dredges, which have more, smaller teeth and smaller belly rings as used in the fishery for the smaller queen scallop, *Aequipecten opercularis* . The dredge specifications are summarised in Table 2.2. The dredges on each side of the vessel were towed in 'gangs' from a heavy steel pipe fitted with solid rubber wheels that run along the seabed. This is in line with normal commercial practice where gangs of up to 12 dredges per side are towed by boats fishing offshore.

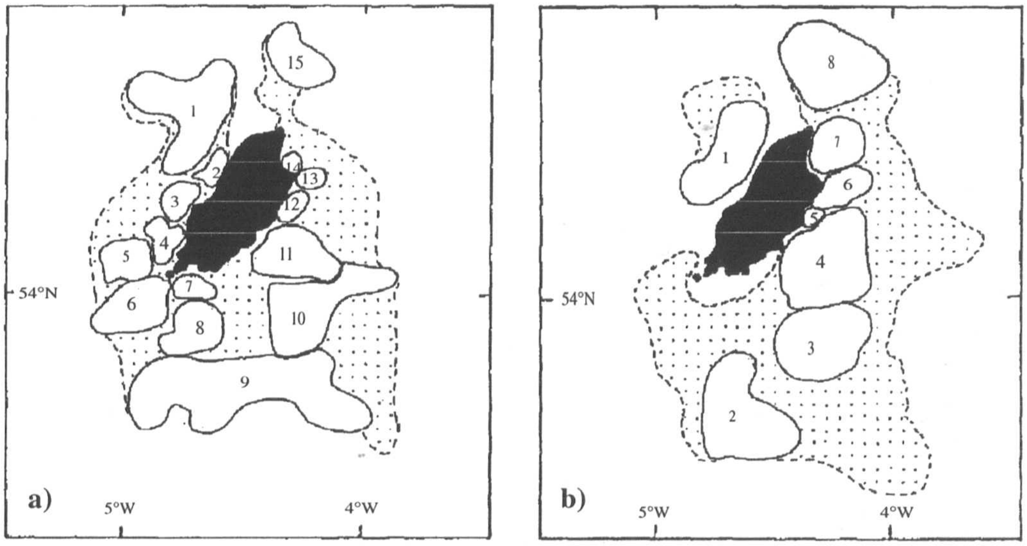


Figure 2.1 North Irish Sea scallop (*Pecten maximus*) and queen (*Aequipecten opercularis*) fishing grounds around the Isle of Man. Numbered areas bounded by solid lines are the major fishing grounds; hatching indicates areas where scallops occur and are occasionally fished. All boundaries are approximate and many grounds are contiguous. Primary source of information is voluntary logbook scheme.

a. Scallop fishing grounds: 1. The Targets; 2. Kirkmichael Bank; 3. Peel; 4. Bradda Inshore; 5. Bradda Offshore; 6. The Chickens; 7. Port St. Mary Inshore; 8. 10' South Port St. Mary; 9. 20' South Port St. Mary; 10. South East Douglas; 11. East Douglas; 12. Laxey Bay; 13. Maughold Head; 14. Ramsey Bay; 15. Point of Ayre.

b. Queen fishing grounds: 1. The Targets; 2. 20' South Port St. Mary; 3. South East Douglas; 4. East Douglas; 5. Laxey Bay; 6. Maughold Head; 7. Ramsey Bay; 8. Point of Ayre.

Taken from Allison (1993).

Table 2.2. Specifications of dredges used in pre- and post-season surveys of Manx fishing grounds.

Dredge type	No. in gang	Dredge width (m)	No. of teeth	Tooth spacing (cm)	Tooth length (cm)	Belly ring diameter (cm)
Queen	4	0.762	10	7.6	7.6	5.7
Scallop	4	0.762	9	8.6	11.0	7.0

Four tows of approximately 2 nautical miles (1 nautical mile = 1852 m) were made at each site, where time and weather permitted, at a towing speed of approximately 2.5 knots. The track of each tow, including details of start and finish times and depth were recorded on board the vessel by the Microplot/Roxann computer software linked to Decca and GPS navigational aids. Later analysis of the dredge tracks allowed accurate measurement of the length and average speed for each tow. The area covered by each tow was calculated by multiplying the number of active or 'successful' dredges by dredge width and tow length and used for the assessment of densities or for the comparison of relative abundances. The catch of individual dredges was excluded from calculations when the dredge did not perform successfully (i.e. the mouth of the dredge was blocked by a large rock, the tooth bar came loose or fouled by discarded rope etc. on the seabed). Complete tows were excluded when the fishing gear came fast on the seabed. Full details of the sampling programme can be found in Appendix 1.

The catch of each dredge was sorted individually and the numbers of the following species recorded: *Pecten maximus, Aequipecten opercularis, Cancer pagurus, Asterias rubens, Marthasterias glacialis, Buccinum undatum, Neptunea antiqua, Eledone cirrhosa*. The fish by-catch was also identified to species. All scallops were aged and measured and random samples of 300-400 queens from each dredge type were taken, when caught, and shell height (umbo to ventral shell margin) measured to the nearest millimetre using callipers.

2.2.2 Ageing of *Pecten maximus*

All *P. maximus* were aged by counting the rings laid down in the shell at the resumption of growth in spring (April/May). These rings have been shown to be laid down annually (Gibson, 1956; Mason, 1957; Dare & Deith, 1991). Ageing was performed by the author and one of two other co-workers to maintain consistency in age determination. Each 'ager' was responsible for two scallop dredges and two queen dredges to avoid systematic errors imposed by consistent ageing of scallops from one dredge type by any one individual. The shell length (the greatest dimension parallel to the hinge) of all *P. maximus* was measured to the nearest millimetre using specially made measuring boards (Mason, 1983).

2.2.3 Relative species abundance

Relative species abundance was compared as the numbers of each species collected per 100 m^2 of seabed covered by the dredges, which was considered to be a reasonable index of abundance for spatial comparisons. This assumed, however, that gear efficiency remained constant for each species on all grounds, and that it was independent of species density. By-catch comparisons were made using data from the successful queen dredges only as they retained far more benthic material.

Species abundance was calculated as:

$$\text{By catch} = \frac{\text{No. caught in successful dredges} \times 100}{\text{No. successful dredges} \times \text{dredge width} \times \text{tow length}}$$

(Equation 2.1)

where a dredge was considered successful if it sustained no damage to the tooth bar or mesh bag and did not become blocked during fishing operations, irrespective of the catch.

2.2.4 Catch Per Unit Effort (CPUE)

Stock assessment and fishery management measures are often based, in part, on consideration of Catch Per Unit Effort (CPUE) as they provide a standardised measure of fishing success on different grounds. In this study CPUE was calculated as the number of scallops caught per metre width of dredge per hour towed (scallops.m^{-1}.h^{-1}) after Murphy (1986) and Allison (1993).

Catch per unit effort for R.V. Roagan was calculated as:

$$\text{CPUE} = \frac{\text{No. scallops} / (\text{dredge width} \times \text{no. successful dredges})}{\text{tow duration}} \qquad \text{(Equation 2.2)}$$

2.2.5 Scallop density

In order to estimate the absolute density of scallops on the seabed for comparison with other studies, an allowance must be made for the efficiency of the dredges, or conversely the catchability of the scallops. A figure of 0.2 (or 20% efficiency) was employed based on published estimates (Rolfe, 1969; Gruffydd, 1974; Chapman *et al.*, 1977; Mason *et al.*, 1982; Iribarne *et al.*, 1991), and as used by Murphy (1986) and Allison (1993). Gear efficiency was also assumed to be the same on all grounds and independent of scallop density. Estimates of absolute scallop density were restricted to commercial size scallops (≥110 mm) caught in the scallop dredges.

The recent work of Allison (1993) also presented estimates of post-recruit scallop densities on the major fishing grounds. These were calculated from the CPUE estimates from logbooks and from age composition data from research vessel surveys. These were combined to provide density-at-age estimates but required the inclusion of an assumed fishing vessel speed while towing as well as dredge efficiency. Allison (1993) followed Murphy (1986) in taking a value of 1.5 knots for fishing speed and assumed a dredge efficiency of 20% but drew attention to the sensitivity of scallop density estimates to variation in these assumptions.

During the three surveys, the speed of the R.V. Roagan was observed to be maintained at between 2-3 knots over the ground. To provide comparisons with the work of Murphy (1986) and Allison (1993) scallop density has been re-calculated assuming speeds of 1.5, 2.0 and 2.5 knots and research vessel CPUE as well as absolute densities based on the known duration of each tow and hence swept area.

Scallop density from research vessel tows:

$$\text{Density} = \frac{\text{No. scallops}}{\text{No. active dredges} \times \text{dredge width} \times \text{tow length} \times \text{dredge efficiency}}$$

(Equation 2.3)

Scallop density at assumed speed:

$$\text{Density} = \frac{\text{CPUE / gear efficiency}}{\text{distance covered in 1 hour fishing}}$$

(Equation 2.4)

where:

distance covered in 1 hour in metres = assumed speed (knots) × 1852.

2.2.6 Density-at-age

The density of post-recruit scallops (of greatest relevance to the fishery) was calculated for individual age-classes using Equation 2.3 and the number of commercial size scallops caught within each age-class. Densities were expressed as the number of scallops per 100 m^2.

2.2.7 Recruitment ogives

Using data from both the scallop and queen dredges, recruitment ogives were constructed to define what proportion of each year-class had recruited to the fishery. An age-class was considered to have recruited if >50% of individuals had a shell length of 110 mm or greater.

2.2.8 Mortality rate estimation

Age-specific estimates of scallop survival rate S and instantaneous total mortality rate Z were computed for commercial size scallops ($\geq$110 mm) from each ground, caught in each dredge type, for the periods between successive surveys. Survival rate S_1 and mortality rate Z_1 were calculated for the closed season period from June 1992 to October 1992; S_2 and Z_2 apply to the fishing season period from October 1992 until June 1993. Survival rate estimates were extrapolated to annual rates in accordance with the number of days between samples.

Survival and mortality rate calculations were based on the abundance of each age-class expressed, for convenience, as the number of scallops collected per square kilometre. As S_1 and S_2 were based on ratios of abundance between successive samples the units cancel out and do not affect the calculated rates.

The annual growth ring in *Pecten maximus* is laid down in April/May just prior to the post-season survey in June. Hence changes in the abundance of a cohort of 4 year old scallops from June to October (S_1) will be reflected in the relative strength of the 4-ring age-class. However, the following June a further ring will have been laid down and so changes in cohort abundance must be considered between scallops 4 years old in October and scallops 5 years old the following June (S_2).

Hence survival rate S_1:

$$S_1 = \frac{1}{{}_aN_{t_1}} \times \left({}_aN_{t_1} - \left(\left(\frac{{}_aN_{t_1} - {}_aN_{t_2}}{t_2 - t_1} \right) \times 365 \right) \right) \qquad \text{(Equation 2.5)}$$

and survival rate S_2:

$$S_2 = \frac{1}{{}_aN_{t_2}} \times \left({}_aN_{t_2} - \left(\left(\frac{{}_aN_{t_2} - {}_{a+1}N_{t_3}}{t_3 - t_2} \right) \times 365 \right) \right) \qquad \text{(Equation 2.6)}$$

Where:
$t_2 - t_1$ = Time in days between first and second surveys
$t_3 - t_2$ = Time in days between second and third surveys
${}_aN_{t_1}$ = Abundance of year-class a scallops at t_1
${}_aN_{t_2}$ = Abundance of year-class a scallops at t_2
${}_{a+1}N_{t_3}$ = Abundance of year-class a+1 scallops at t_3

Instantaneous total mortality rate for the cohort is thus

$$Z_1 = -\left(\frac{365}{t_2 - t_1} \right) . \log_e \left(\frac{{}_aN_{t_2}}{{}_aN_{t_1}} \right) \qquad \text{(Equation 2.7)}$$

for the closed season period, and

$$Z_2 = -\left(\frac{365}{t_3 - t_2} \right) . \log_e \left(\frac{{}_{a+1}N_{t_3}}{{}_aN_{t_2}} \right) \qquad \text{(Equation 2.8)}$$

for the period covering the fishing season (Gulland, 1983).

Total mortality for all fully exploited age-classes was also calculated using the method of Heincke (1913). This produces a weighted least-squares estimation of the geometric mean Z (Ricker, 1975; Gulland, 1983). Greater weight is afforded to the more abundant age-classes where changes in abundance between successive samples are likely to be better estimated.

The method is only used on fully exploited year-classes, where 'a' is the first age-class fully recruited to the fishery, i.e. >50% of individuals ≥110 mm shell length. However, where exploitation is heavy and a large proportion of the recently recruited scallops are removed in their first year in the fishery, late recruitment from slow-growing scallops can have a significant effect on the size composition of the population. Thus Heincke's Z was computed for values of 'a' from 4-6 which covers the age of recruitment in scallop populations around the Isle of Man. The values of Heincke's total mortality estimate were also extrapolated to represent annual rates.

In general,

$$\text{Heincke's } Z = -\log_e \frac{{}_{a+1}N_{t_2} + {}_{b+1}N_{t_2} \cdots {}_{i+1}N_{t_2}}{{}_{a}N_{t_1} + {}_{b}N_{t_1} \cdots {}_{i}N_{t_1}}$$

after (Heincke, 1913)

(Equation 2.9)

Thus extrapolated to an annual rate for the period of S_1:

$$\text{Heincke's } Z = -\left(\frac{365}{t_2 - t_1}\right).\log_e \left(\frac{{}_{a}N_{t_2} + {}_{b}N_{t_2} \cdots {}_{i}N_{t_2}}{{}_{a}N_{t_1} + {}_{b}N_{t_1} \cdots {}_{i}N_{t_1}}\right)$$

(Equation 2.10)

and for the period of S_2:

$$\text{Heincke's } Z = -\left(\frac{365}{t_3 - t_2}\right).\log_e \left(\frac{{}_{a+1}N_{t_3} + {}_{b+1}N_{t_3} \cdots {}_{i+1}N_{t_3}}{{}_{a}N_{t_2} + {}_{b}N_{t_2} \cdots {}_{i}N_{t_2}}\right)$$

(Equation 2.11)

Where a, b ... *i* denote the different cohorts. The practical maximum for *i* was 9 for the period S_1 and 8 (as $i+1 = 9$) for the period S_2 as scallops with 10 or more rings were grouped as 10+ because they were generally very poorly represented.

2.2.9 SCUBA-diver surveys

Surveys to assess the density of *Pecten maximus* and their associated predators *Asterias rubens* and *Cancer pagurus* in the scallop fishing Exclusion Zone and within a comparable area off Bradda Head, were carried out by divers. Each sample consisted of a 200 m^2 line transect, 50 m long × 4 m wide, taken with the aid of a self-made 'survey pole' (Figure 2.2). This consisted of a standard 4 m length of 50 mm uPVC plumbing pipe with a freely-rotating plastic reel (discarded reel of welding wire) at its mid point, carrying 200 m of 4 mm diameter pre-stretched polyester rope. Experience proved 50 m to be the optimum length of line to use under the prevailing conditions, so the line was tied-off at this point. On either side of the reel was a centrally placed wooden board, faced with plastic laminate and marked out to provide a slate on which the divers kept a count of animals seen. Each slate had a compass mounted on it and a pencil on a length of wire.

The survey pole was used in conjunction with a heavy concrete shot-weight. The weight was deployed at the location (chosen using random numbers as ordinates

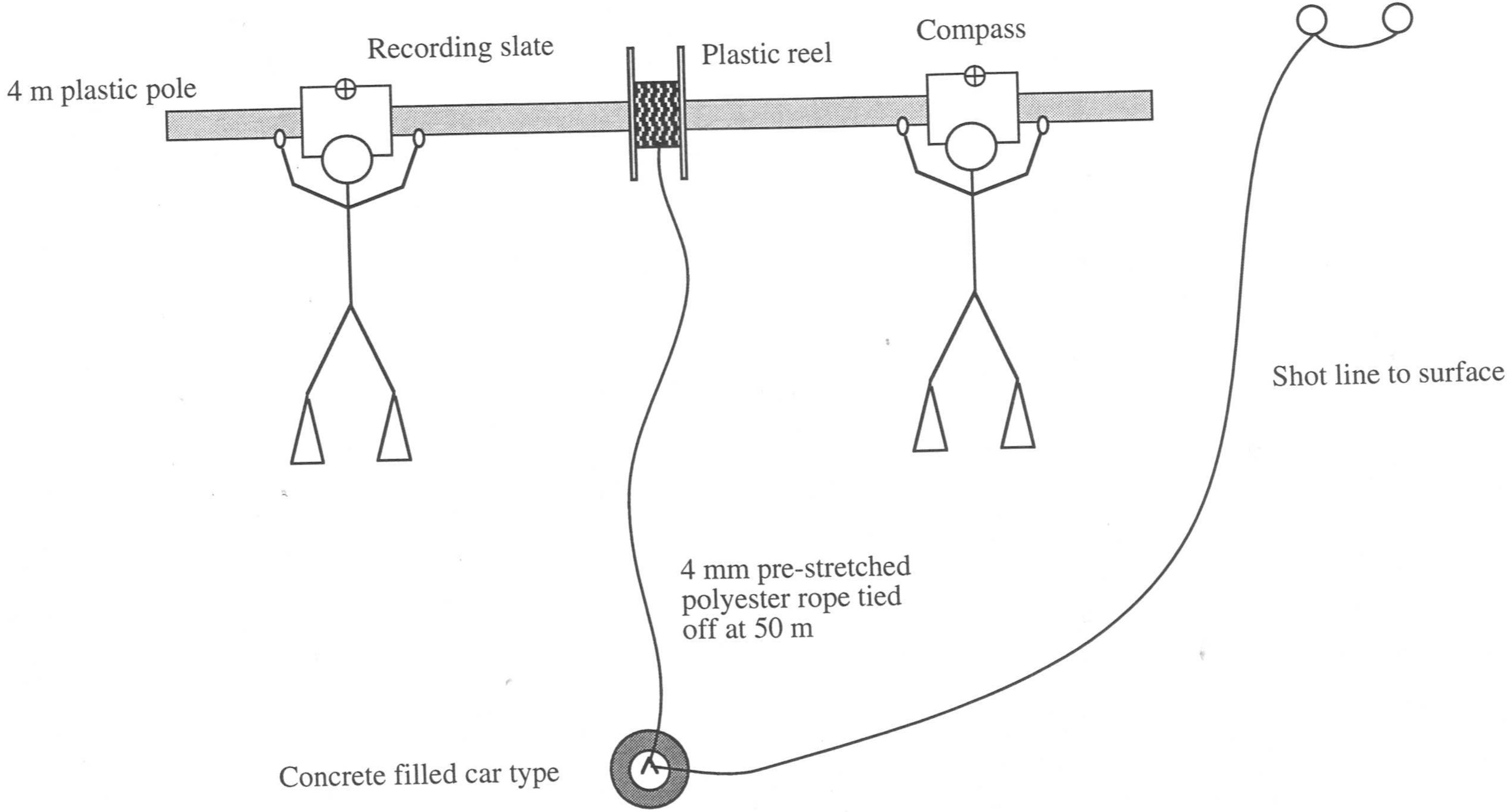


Figure 2.2 Diagram of SCUBA diver operated Survey Pole, used for abundance assessments of macrobenthos.

along the north-south and east-west sides of the Exclusion Zone and a similar sized area off Bradda Head) and divers descended the shot-line with the survey pole, the reel locked. The survey line was then clipped onto the weight and the divers set off along a bearing (decided by the divers in consideration of the prevailing current). The initial setting-up of the pole inevitably caused sediment to be re-suspended and so a ribbon marker was tied 5 m from the start of the line, with the line tied-off at 55 m to provide the 50 m transect length. Each diver had a 2 m width of seabed to monitor as it passed underneath the pole. Individual transects took approximately 10 minutes to carry out, with the divers shuffling along the seabed on their knees, into the current where possible to maintain visibility. At the end of the transect the pole was sent to the surface with an air-filled lifting bag with the divers ascending as normal. The dates of sampling are summarised in Table 2.3 and full details are presented in Appendix 2.

Table 2.3. SCUBA diver surveys of the scallop fishing Exclusion Zone and a comparable area of Bradda Head. Each dive represents a line transect of 200 m^2 area.

Location	Dates	No. of dives/transects
Exclusion Zone	30th Mar. - 12th Apr. 1989	8
	6th - 13th Sept. 1989	8
	8th Dec. 1989	8
	28th - 29th Nov. 1990	8
	8th Dec. 1992	4
Bradda Head	28th Apr. - 12th June 1989	8
	5th Dec. 1990	1
	10th Dec. 1992	1

2.3 RESULTS

2.3.1 Sampling area

The area of seabed that was sampled during the research vessel surveys varied between sites due to slight variations in the length of tow and the performance of the fishing gear. The effective area sampled, after the removal of unsuccessful tows and individual unsuccessful dredges is given in Table 2.4.

Table 2.4. Area of seabed (m^2) sampled on each fishing ground during research vessel surveys, after removal of unsuccessful tows/dredges.

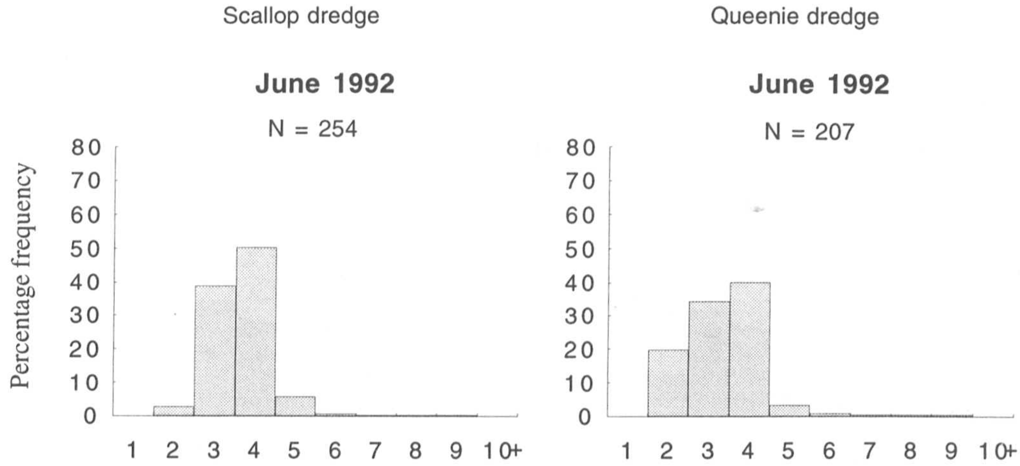
	June 1992		October 1992		June 1993	
Dredge type	Queen	Scallop	Queen	Scallop	Queen	Scallop
Targets	45 110	45 110			46 512	40 599
Peel	47 823	47 823	45 750	45 750	46 055	46 055
Bradda Offshore	11 460	11 460	11 460	11 460	11 460	11 460
Bradda Inshore	35 296	35 296	34 656	34 656	34 168	34 168
Chickens	46 086	46 086	46 695	46 695	46 634	46 634
10'S Port St.Mary	35 357	29 139	37 917	37 917	46 025	46 025
20'S Port St.Mary	34 686	34 686	32 522	35 418	35 631	32 545
SE Douglas	-	-	45 720	45 720	45 720	45 720
E Douglas	-	-	33 955	33 955	46 726	46 726
Point of Ayre	-	-	-	-	-	-

2.3.2 Population age structures

The age structures of the scallop populations on the various fishing grounds sampled are presented in Figure 2.3*a-m* as a series of age-% frequency histograms. The catches from the scallop and queen dredges have been plotted separately as the two dredges select differently. The characteristic truncation of the age-frequency distribution after recruitment, caused by the selective removal of commercial size scallops, was clearly visible on many of the fishing grounds but particularly those on the inshore/west coast, where exploitation rate was high. These populations had few old scallops as they rarely survive longer than 2-3 years after recruiting to the fishery.

On the inshore/west grounds (Targets, Peel, Bradda Inshore) there were few scallops over 8 years old and the populations were completely dominated by younger age-classes. Peel had the broader spread of age-classes but was still dominated by 4 and 5 year old scallops. The queen dredges retained a higher proportion of pre-recruit scallops, reflected in the better representation of year-

Targets



Targets not sampled in October 1992

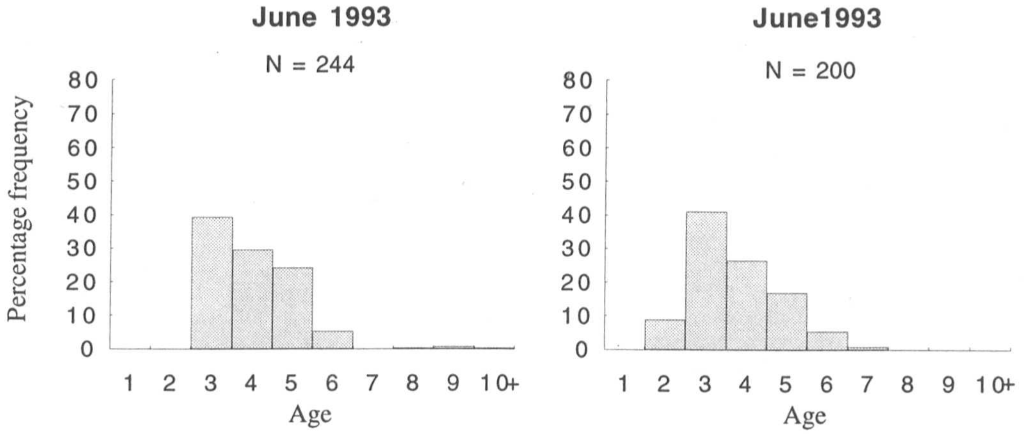


Figure 2.3*a*. Age-% frequency histograms of *Pecten maximus* from Targets sampled after the fishing season, 1992 and 1993. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

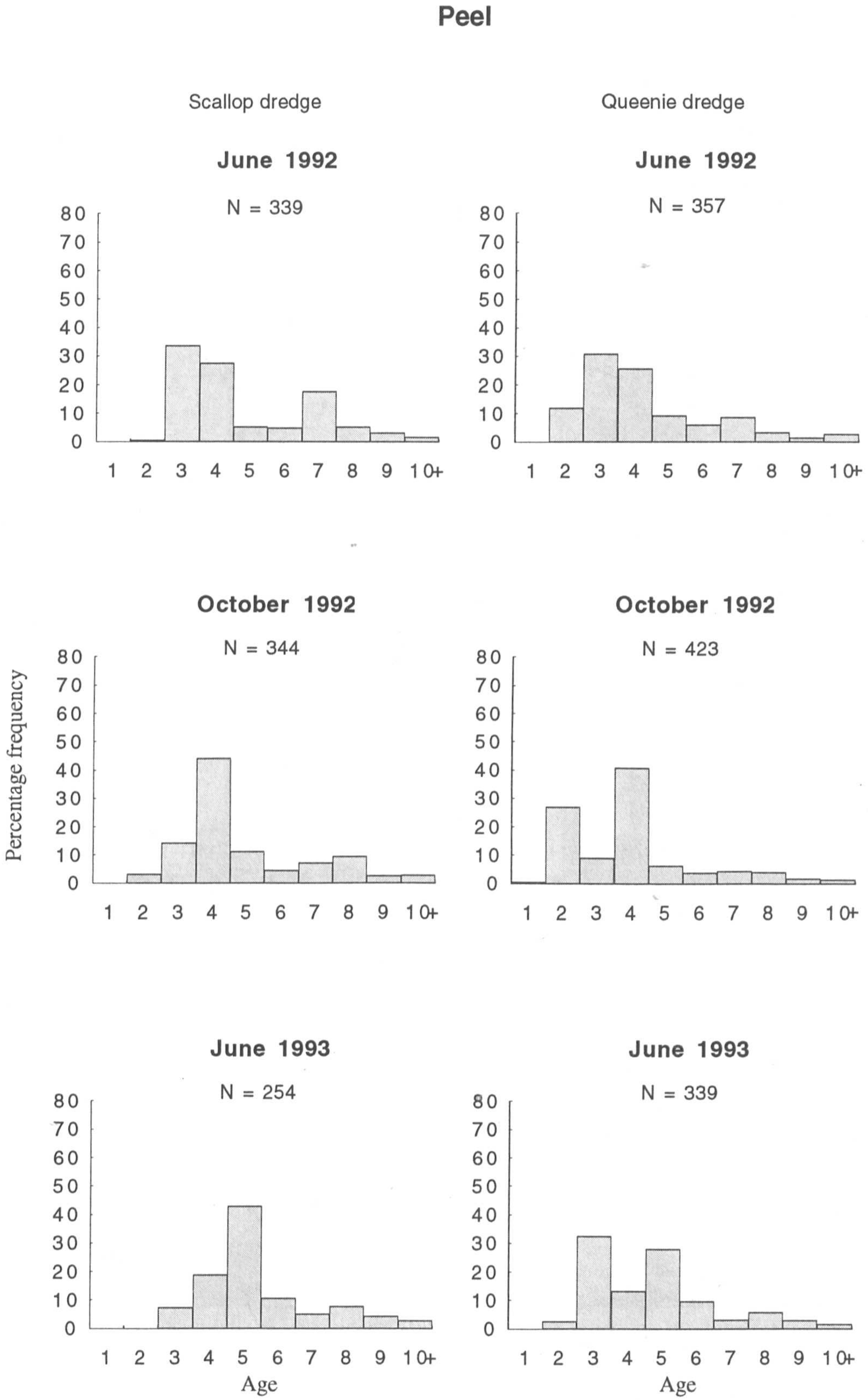


Figure 2.3*b*. Age-% frequency histograms of *Pecten maximus* from Peel sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

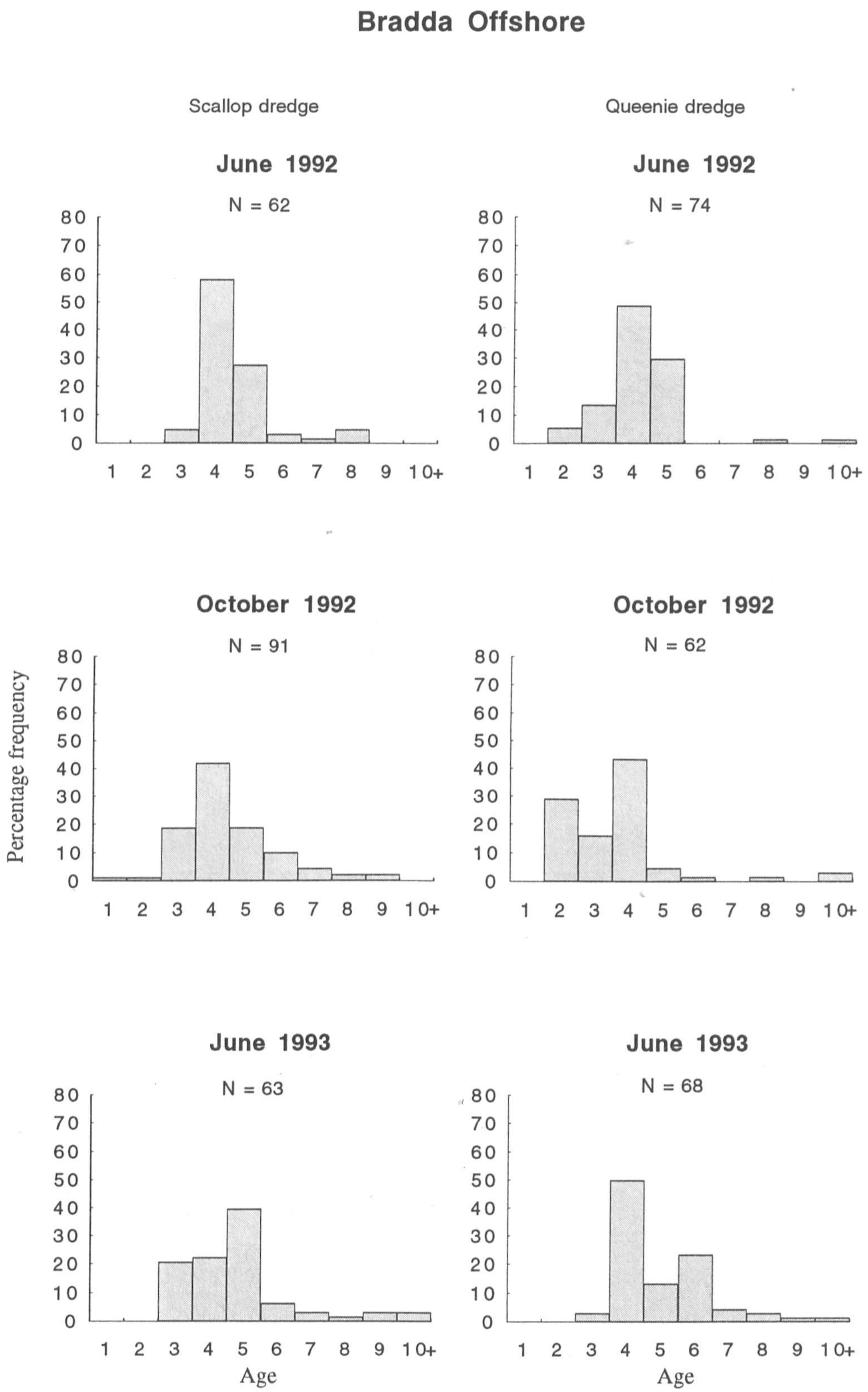


Figure 2.3*c*. Age-% frequency histograms of *Pecten maximus* from Bradda Offshore sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

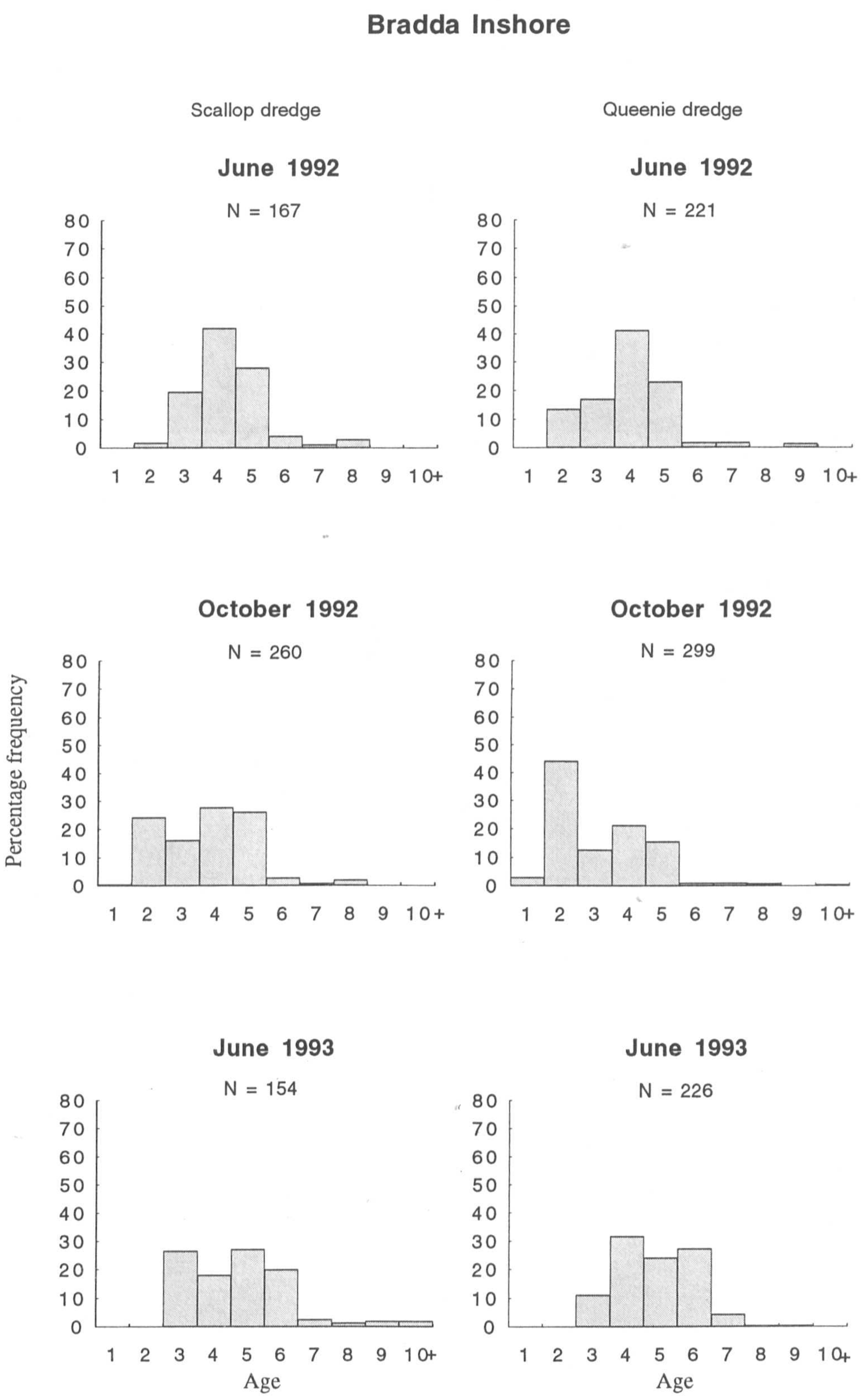


Figure 2.3*d*. Age-% frequency histograms of *Pecten maximus* from Bradda Inshore sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

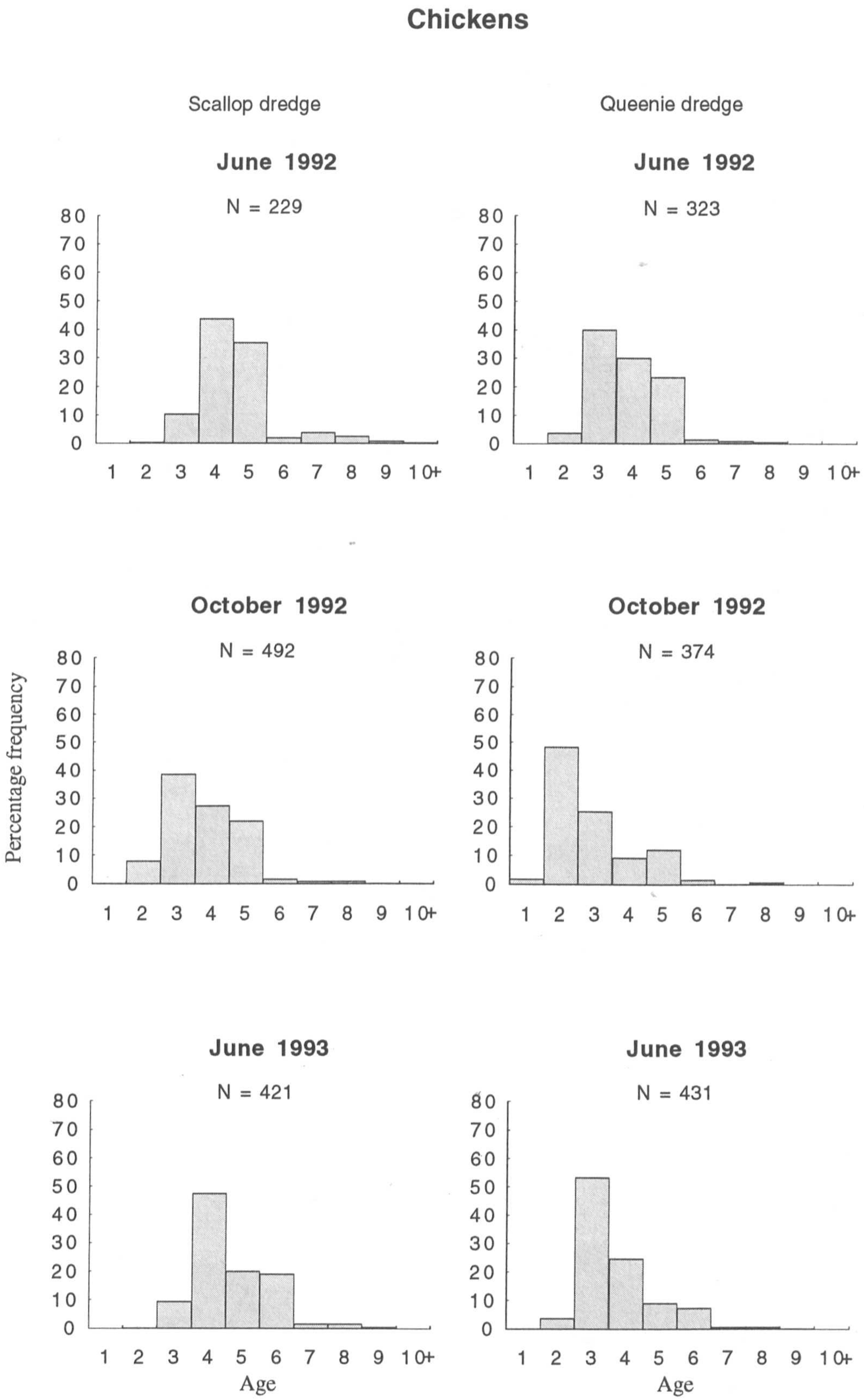


Figure 2.3*e*. Age-% frequency histograms of *Pecten maximus* from The Chickens sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

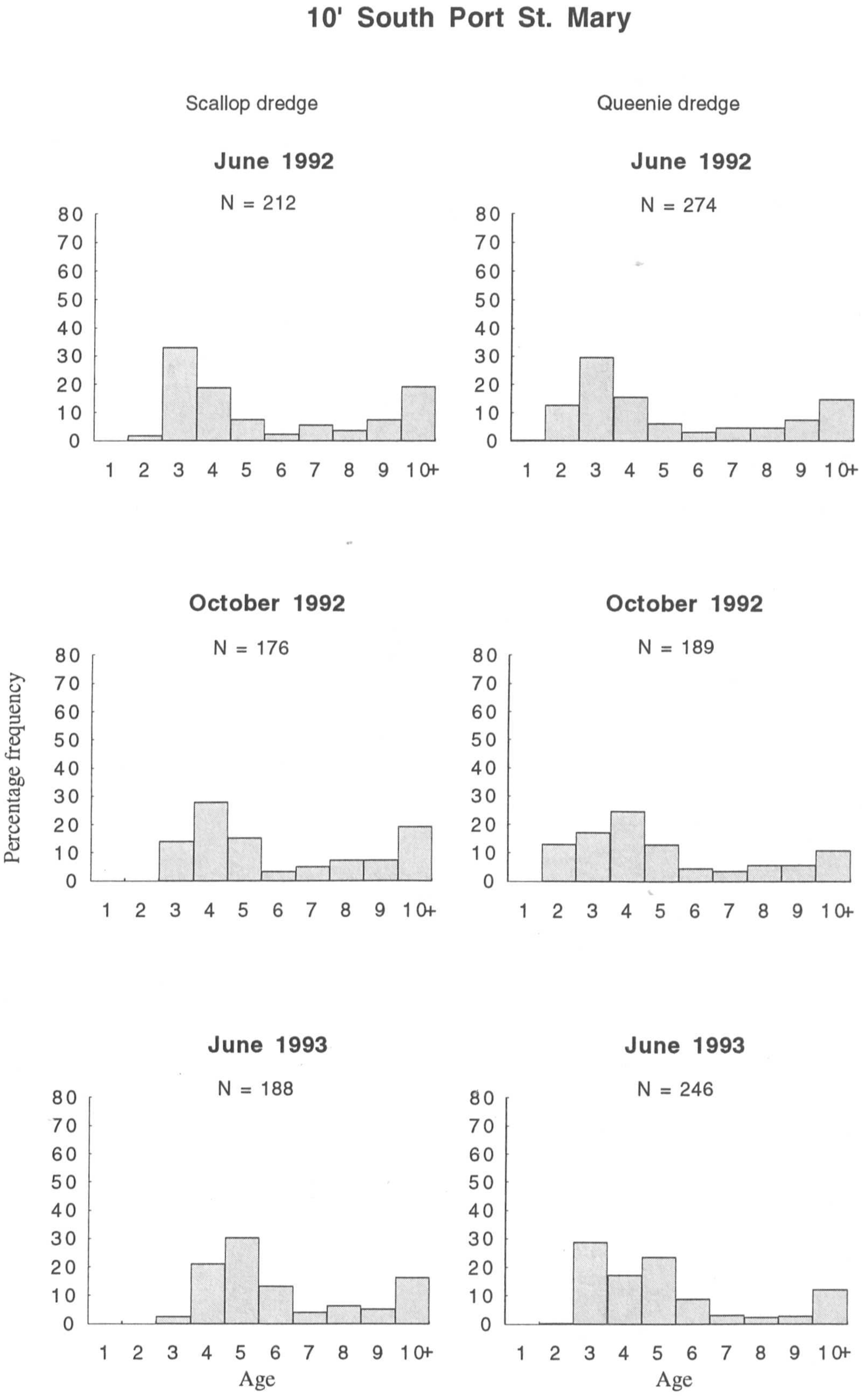


Figure 2.3*f*. Age-% frequency histograms of *Pecten maximus* from 10' South Port St.Mary sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

20' South Port St. Mary

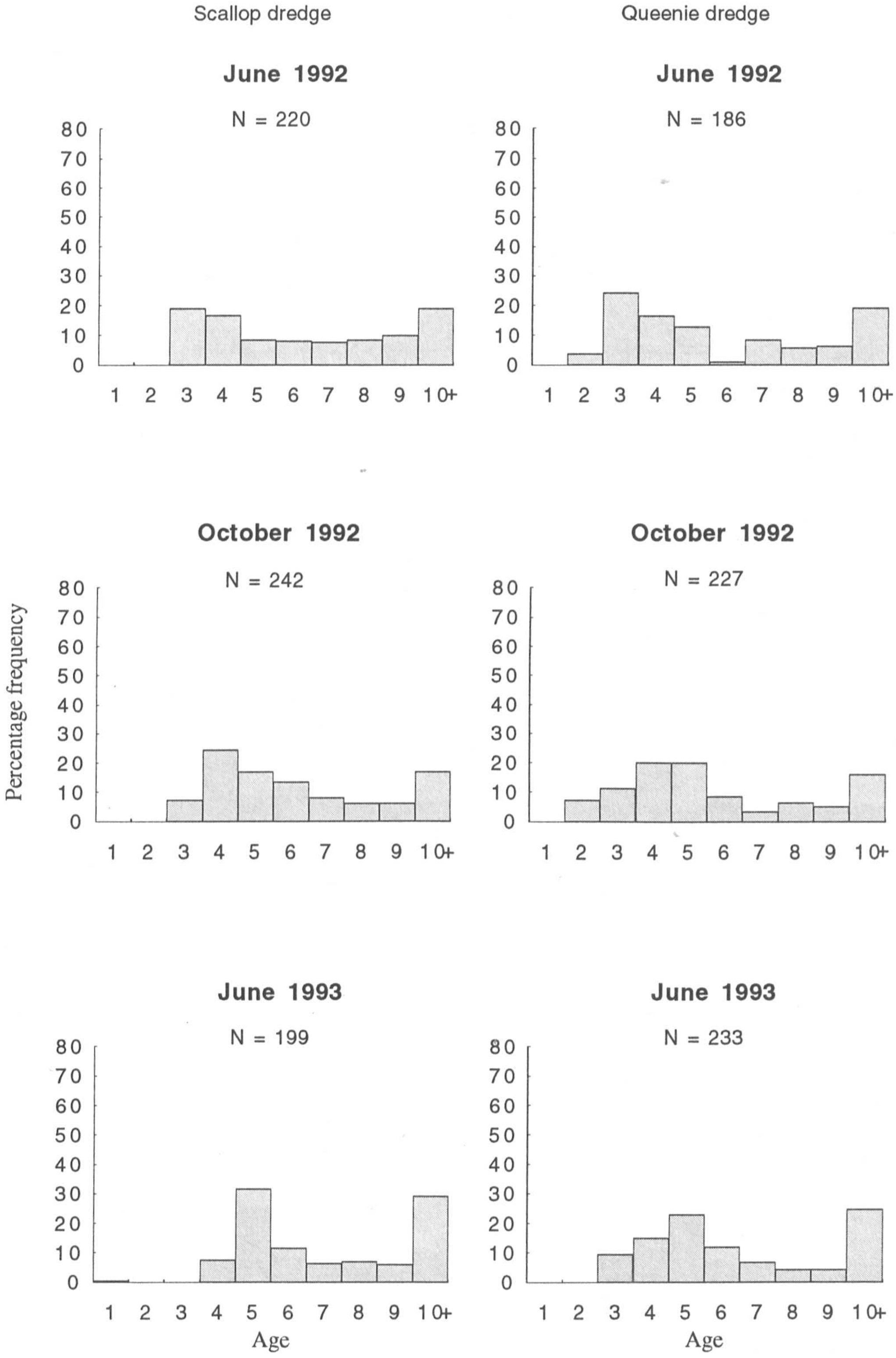


Figure 2.3*g*. Age-% frequency histograms of *Pecten maximus* from 20' South Port St.Mary sampled before and after the fishing season. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

South East Douglas

Scallop dredge

Queenie dredge

South East Douglas not sampled in June 92

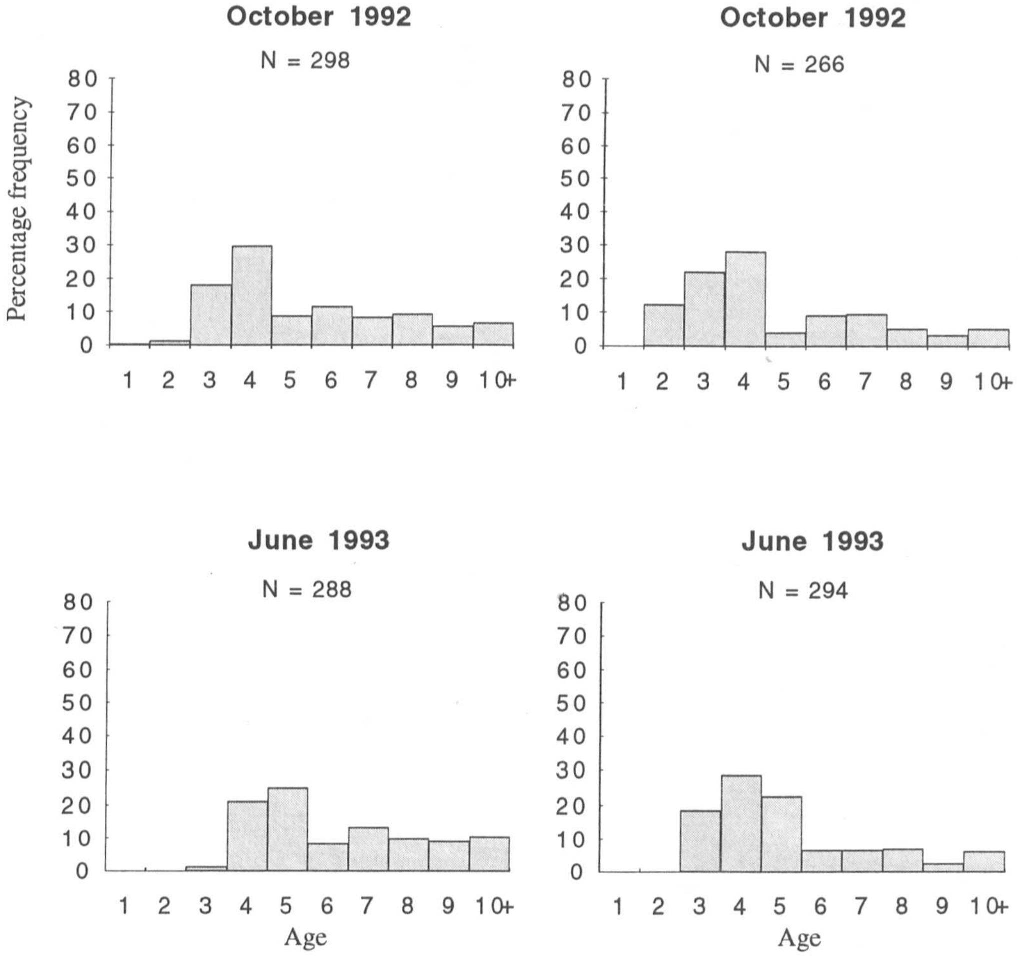


Figure 2.3*h*. Age-% frequency histograms of *Pecten maximus* from South East Douglas sampled before and after the fishing season, 1992/93. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

East Douglas

Scallop dredge

Queenie dredge

East Douglas not sampled June 1992

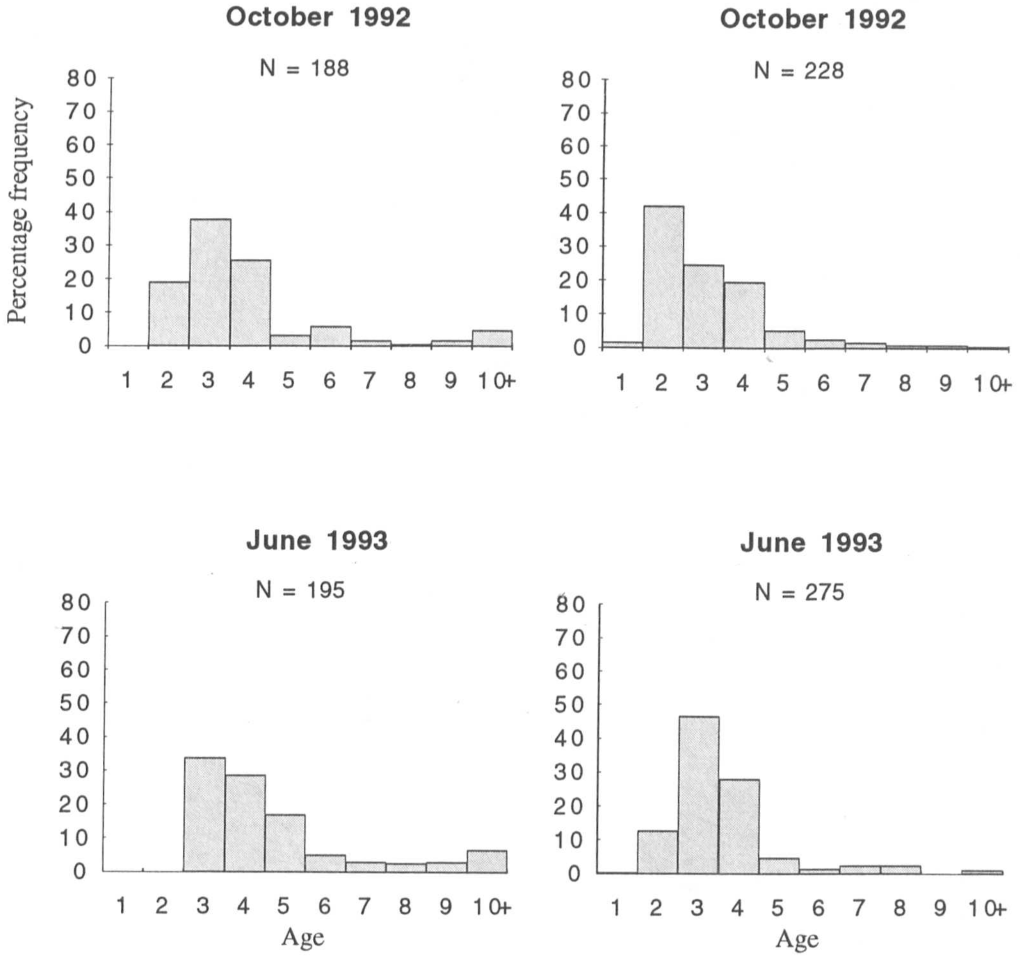
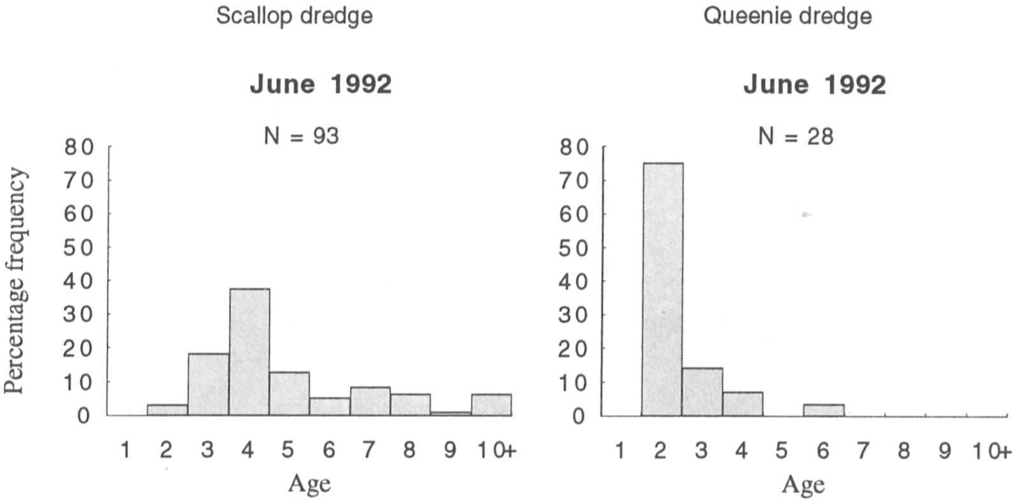


Figure 2.3*i*. Age-% frequency histograms of *Pecten maximus* from East Douglas sampled before and after the fishing season, 1992/93. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

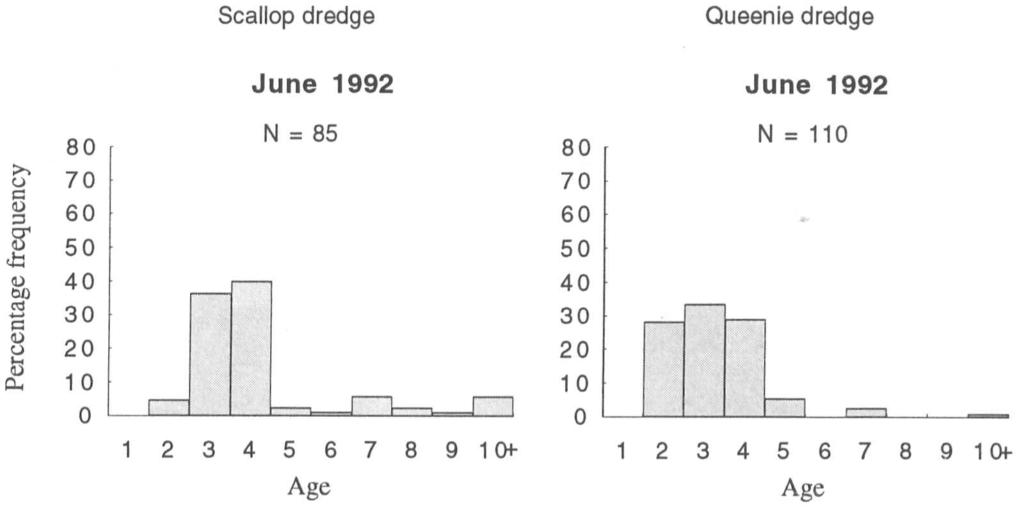
Laxey



Laxey not sampled October 1992 or June 1993

Figure 2.3*j*. Age-% frequency histograms of *Pecten maximus* from Laxey sampled after the fishing season, 1991/92. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

Maughold Head


Scallop dredge

June 1992

N = 85

Queenie dredge

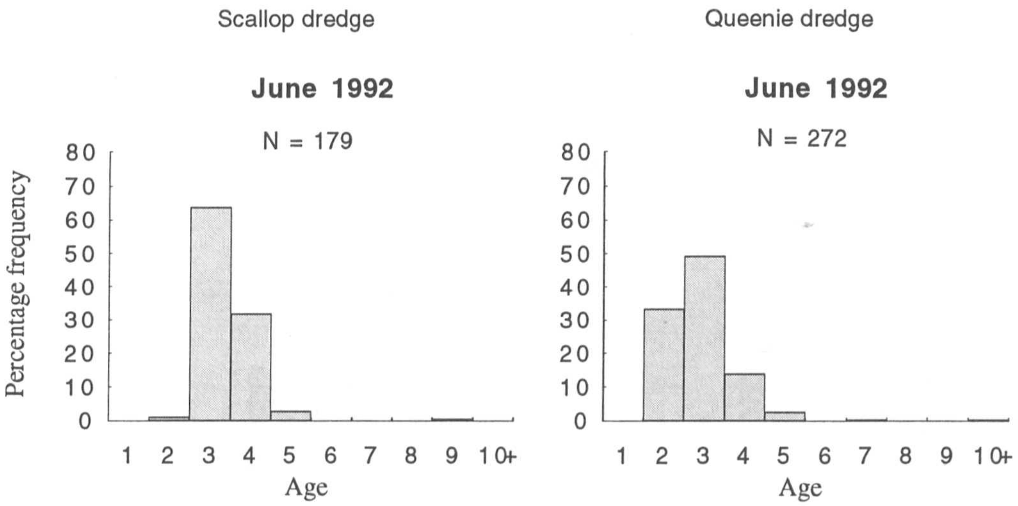
June 1992

N = 110

Maughold Head not sampled October 1992 or June 1993

Figure 2.3*k*. Age-% frequency histograms of *Pecten maximus* from Maughold Head sampled after the fishing season, 1991/92. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

Ramsey Bay


Scallop dredge

June 1992

N = 179

Queenie dredge

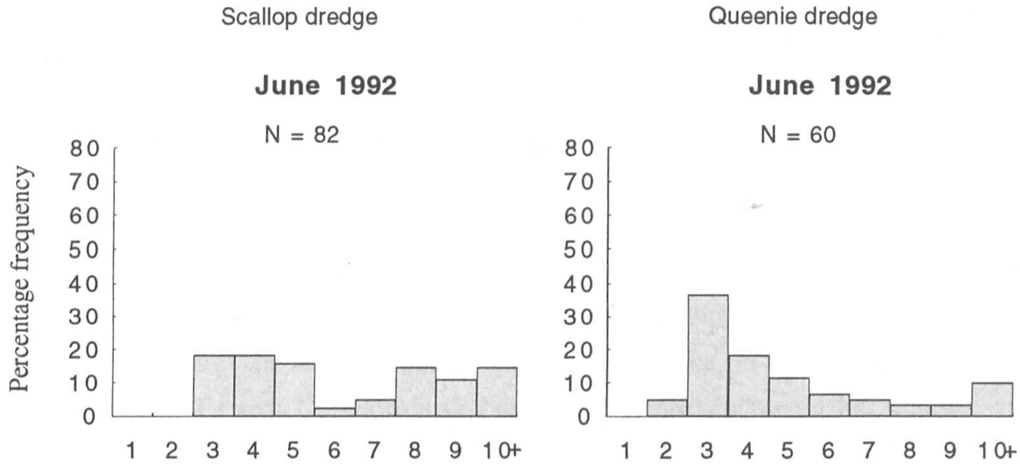
June 1992

N = 272

Ramsey Bay not sampled October 1992 or June 1993

Figure 2.3*l*. Age-% frequency histograms of *Pecten maximus* from Ramsey Bay sampled after the fishing season, 1991/92. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

Point of Ayre



Point of Ayre not sampled October 1992

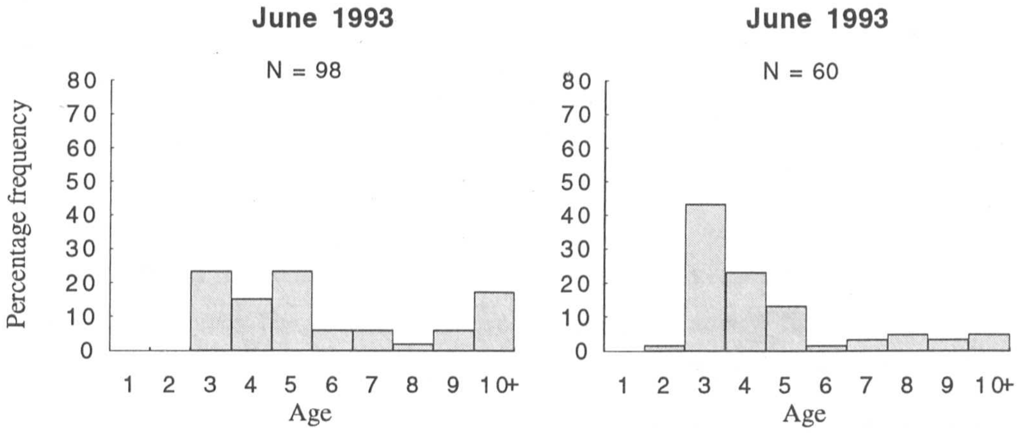


Figure 2.3*m*. Age-% frequency histograms of *Pecten maximus* from the Point of Ayre sampled after the fishing season, 1992 and 1993. Samples are from research vessel scallop and queenie dredges. Ages are given as no. of annual growth rings; ring formation is assumed to occur between March-May.

classes 2-4 in the catches from those dredges. There was a broadening of the age-class distribution of Bradda Inshore and Targets between the two June samples taken by the queen dredges. The age %-frequency distribution of Bradda Inshore from the scallop dredges showed a broadening of the age-class distribution over the summer as the recruiting scallops entered the fishery.

The Chickens ground, to the south-west of the Isle of Man, was also dominated by pre-recruit scallops, to an even greater extent than Bradda Inshore, reflecting the high exploitation rate of this fishing ground. At the Chickens, the severely truncated right hand tail of the distribution is indicative of a high exploitation rate, and the reliance of the fishery in this area on the recruiting year-class of scallops. Bradda Offshore had a strong 4+ cohort in June 1992 which remained dominant in June 1993 as the 5+ age-class. This continuing dominance in relation to the following year-class suggests that it may have been a strong age-class, although the queen dredges caught large numbers of 4 year old scallops in June 1993 of which only 20% had recruited.

The offshore/south fishing grounds (Bradda Offshore, 10’ South Port St.Mary, 20’ South Port St.Mary, South-East Douglas and East Douglas) all had a wide spread of age-classes represented. The exceptions were for East Douglas and Bradda Offshore, which had relatively few scallops over 6 years old. On the two Port St.Mary grounds the modal age-3 class became the age-4 class between June 1992 and October. This was an artefact of the difficulty in ageing scallops in June, when the ring has just been formed. Many shells had just laid down their fourth ring but were classed as age-3 scallops in June and only correctly identified as 4 year olds in October. The progress of this cohort as 5 year olds the following June was clearly evident from the scallop dredges, while the queen dredges revealed the strength of the pre-recruit 3 year olds. The modal year-class at East Douglas was a year younger than at the other offshore/south grounds at age-3 compared with age-4, reflecting the higher growth rate on this ground, and their earlier entry to the fishery and subsequent removal.

The ground to the north of the Point of Ayre had a relatively large number of older scallops whereas the grounds inshore to the east (Ramsey Bay, Maughold Head and Laxey) all had severely truncated age-% frequency distributions, suggesting heavy exploitation. At Laxey there was a very high proportion of two year old scallops in the queen dredge samples, but these were almost absent from the scallop dredges. The inshore grounds to the east of the Isle of Man, at Ramsey Bay, Maughold Head and Laxey, were heavily dependent on the recruiting year-class to provide the fishery. There was a very narrow range of age-classes represented.

These grounds are heavily exploited as they are readily accessible during periods of strong westerly winds. The Point of Ayre ground is less heavily fished for scallops, partly because of its degree of exposure, lying to the north of the Isle of Man, but it is a major queen fishing area.

2.3.3 Relative abundance of *Pecten maximus*

In comparing the catches of the two dredge types on the different grounds sampled as part of the assessment surveys, dredge efficiency was not quantified for *P. maximus* or *A. opercularis* or for the by-catch, and comparisons were made on the basis of the number of specimens collected per 100 m^2 of seabed covered by the dredges. Estimates of scallop dredge efficiency are available in the literature but to allow direct comparison with the catch of scallops from the queen dredges, the results are presented as uncorrected relative abundances (Figures 2.4 & 2.5). However, it remains implicit in this work that dredge efficiency remained constant between grounds and surveys, which is unlikely in the light of the work of Dare *et al.* (1993), but in the absence of information comparing dredge performance on these different grounds, the results must be accepted as an index of relative species abundance on the grounds sampled.

The abundance of *P. maximus* was estimated using the catch from both scallop and queen dredges. Post-recruit (≥110 mm) abundance was best estimated by the scallop dredges which were similar to those used in the commercial fishery and were optimised to select for post-recruits. The queen dredges, with their smaller, more closely spaced teeth and smaller diameter belly rings, retained a higher proportion of the pre-recruit scallops, and so the catch from both dredge designs was considered separately.

The numbers of scallops caught in the scallop and in the queen dredges per 100 m^2 was very low; the combined catch of pre- and post-recruits was only greater than 1 scallop per 100 m^2 at Peel and Bradda Inshore in October 1992. However, these values make no allowance for the efficiency of the dredges.

2.3.3*a* Pre-recruits (< 110 mm)

Scallops less than the minimum legal landing size were better sampled by the queen dredges, although some were retained in the scallop dredges. Variation in the abundance of pre-recruit scallops was slight on the inshore grounds (The Targets, Peel and Bradda Inshore) with the only consistent trend from the two dredge designs being an increase in pre-recruit abundance on the Bradda inshore ground from June 1992 to October 1992 (Figure 2.4). Offshore pre-recruit abundance was greatest at

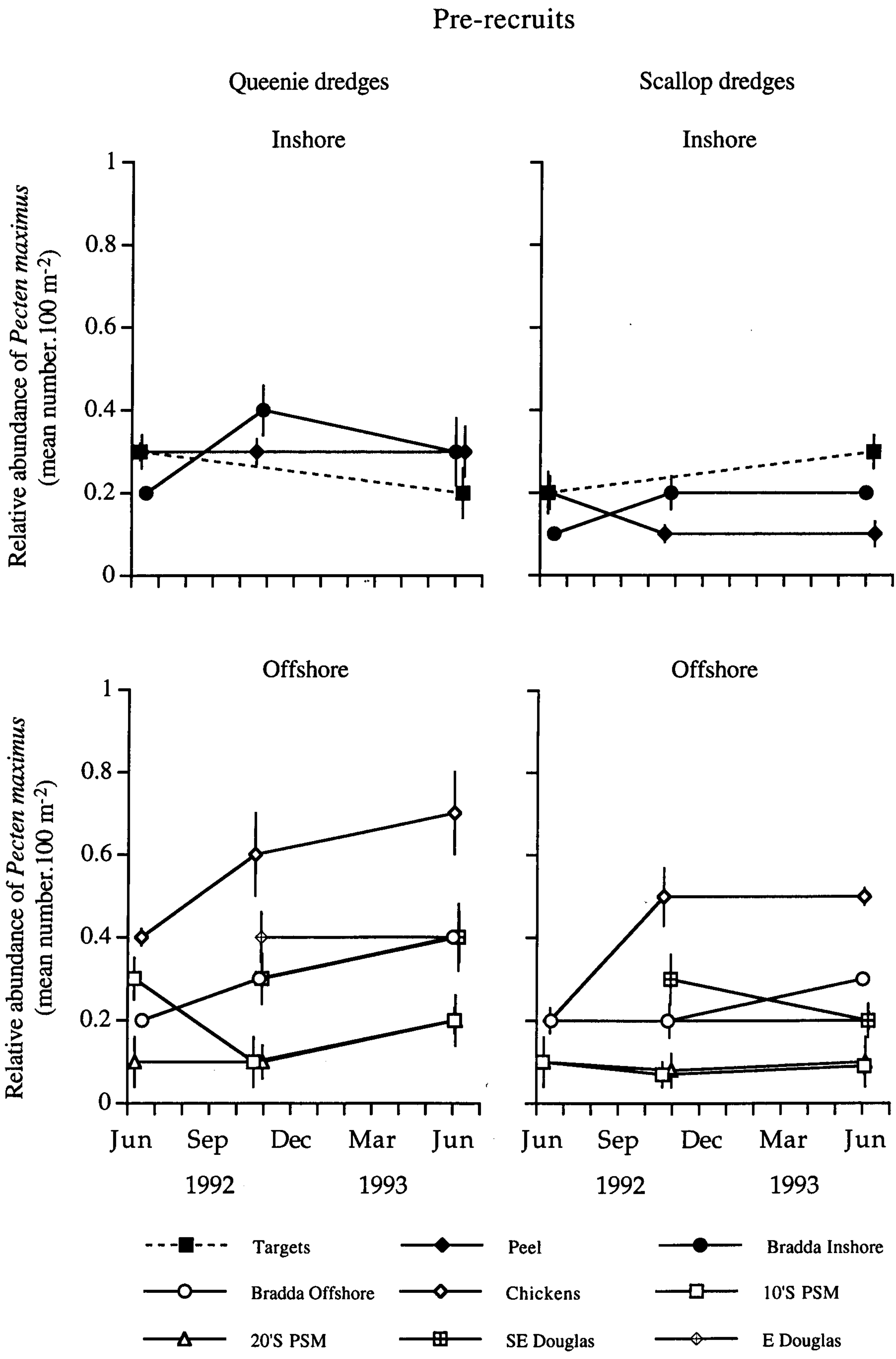


Figure 2.4. Relative abundance of pre-recruit (<110 mm) *Pecten maximus* caught in scallop and queen dredges on inshore and offshore grounds as mean numbers (±SE) per 100m^2 of sea bed. Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled.

the Chickens with a consistent increase in numbers indicated by the queen dredges over the period of the sampling. The other offshore grounds (Bradda Offshore, 10 and 20 miles South Port St.Mary, South-East Douglas and East Douglas) had similar abundances of pre-recruits to the inshore grounds.

Although the queen dredges retain smaller scallops than the scallop dredges they do not sample all sizes equally. There is a minimum size of scallop for which they are efficient and a ‘recruitment’ to the queen dredges by the pre-recruits prior to recruitment to the scallop dredges and the commercial fishery. The general increase in pre-recruit abundance on most grounds suggests that there were relatively strong settlements in recent years. The fall in abundance at 10’ South Port St.Mary from June 1992 to October 1992 suggests that the scallops that entered the adult fishery during that year were not replaced by younger age-classes, implying poor settlement and/or survival of scallops from the spawning three years previously. In general recruitment appears stronger offshore than inshore.

On the offshore grounds there was a general increase in the numbers of pre-recruits caught in the queen dredges over the winter period of the fishery, as well as over the summer when there was no scallop fishing and scallops were actively growing. At 10’ South Port St.Mary the number of pre-recruits fell sharply between June 1992 and October of the same year.

2.3.3*b* Post-recruits ($\geq$ 110 mm)

There was a seasonal variation in the abundance of post-recruit scallops on the inshore and offshore grounds (Figure 2.5). This was shown most clearly by the scallop dredges, with an increase in numbers between June 1992 and October 1992, followed by a decline in abundance from October 1992 to June 1993. This pattern was evident on all grounds except 20’ South Port St.Mary where there was a decline in post-recruits from June to October with no further change to June 1993, and 10’ South Port St.Mary where there was no change in post-recruit abundance. East Douglas and South-East Douglas were first sampled in October 1992 and while abundance remained unchanged at South-East Douglas and declined at East Douglas, it is not possible to discern any seasonal variation. Similarly, the Targets was only sampled on the two June surveys and the number of scallops collected per 100 m^2 was the same on both occasions.

The seasonal processes of recruitment to the fishing gear by growth over the summer and removal by the fishing gear over the winter were apparent both inshore and offshore on the grounds which are heavily exploited. On grounds which were

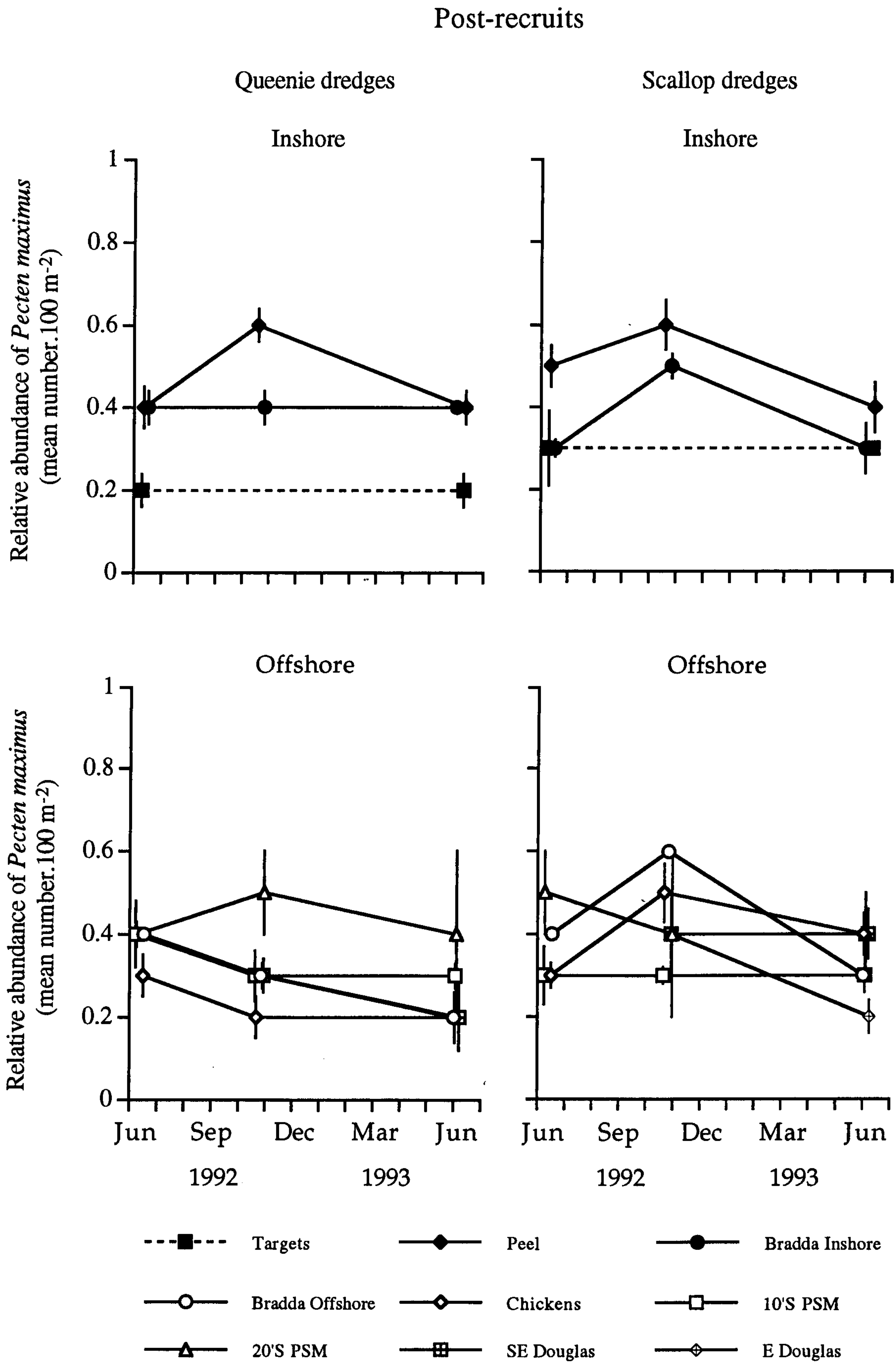


Figure 2.5. Relative abundance of post-recruit (≥110 mm) *Pecten maximus* caught by scallop and queen dredges on inshore and offshore grounds as mean numbers (±SE) per 100 m^2. Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled.

not fished heavily for scallops this trend was not seen. This is due in part to the fact that these grounds have a larger number of older scallops, and the relative increase in abundance from the recruiting year-class is smaller, in comparison to those grounds where the fishery is dependent on the recruiting year-class to replenish the grounds depleted over the previous season. The high between-tow variation at 20' South Port St.Mary included the heterogeneity of the fishing ground, but also a reduced sampling effort because of the exclusion of some dredges/tows due to frequent gear damage. Areas of low exploitation (i.e. 10' South Port St.Mary and South-East Douglas) had a very consistent number of scallops, even over the fishing season, but on the heavily fished grounds (Bradda Inshore, Bradda Offshore, Chickens, Peel) it was not unusual for the number of commercial sized scallops caught on the assessment surveys to halve between October 1992 and June 1993.

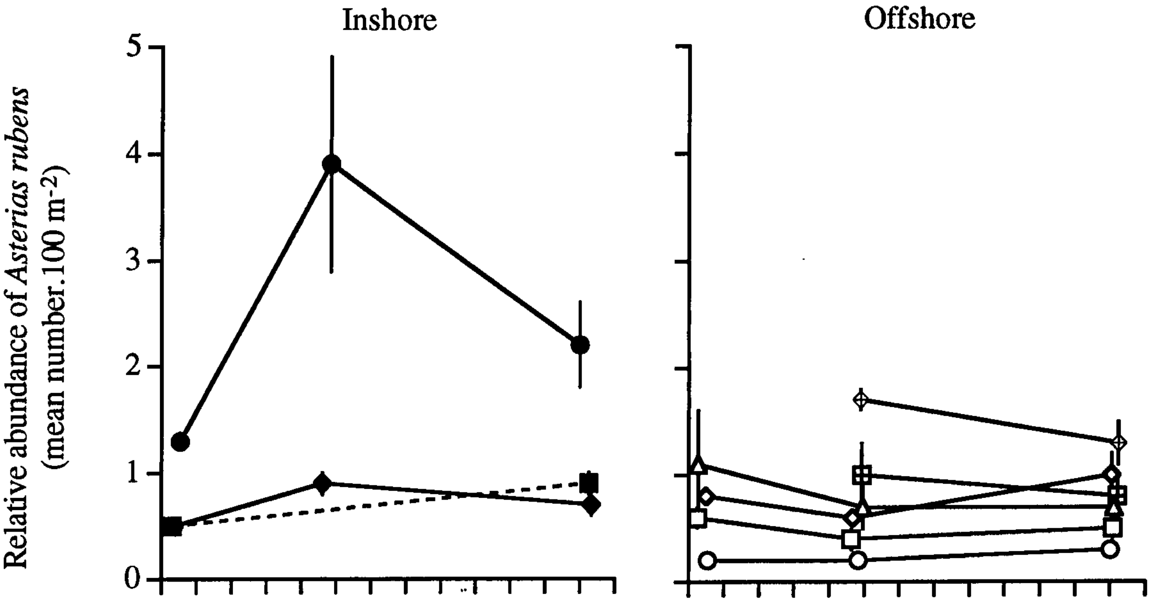
2.3.4 Relative abundance of by-catch species

The relative abundance of by-catch species between the grounds sampled, was estimated from the catch of the queen dredges only, as they invariably retained more by-catch material.

The common starfish, *Asterias rubens*, was ubiquitous to all tows on all the grounds sampled (Figure 2.6*a*). The abundance of this species was approximately similar on all the grounds, both inshore and offshore and between surveys, with the exception of Bradda Inshore. On this ground the numbers of *A. rubens* caught increased more than three-fold from June 1992 to October 1992. Contemporaneous observations showed that this increase was due to a very large proportion of small starfish; photographs and video recordings made of the catch on the deck did not appear to be dominated by starfish, re-inforcing the impression of many small individuals. By June 1993 the numbers of starfish at Bradda Inshore, had fallen considerably although they were still more abundant here than at any other site. The lowest numbers of *A. rubens* were recorded at Bradda Offshore on all three of the surveys, just three nautical miles west of Bradda Inshore, where numbers were highest.

The edible crab, *Cancer pagurus*, was rare in comparison to *A. rubens* but its abundance varied seasonally on the inshore grounds and at Bradda Offshore (Figure 2.6*b*). There was a three-fold increase in the numbers of *C. pagurus* caught at Bradda Inshore and Peel between June and October 1992, followed by a decline to initial levels by June 1993. A similar abundance was observed at Bradda Offshore in October 1992 although the initial catch in June was higher. By June 1993 the number of *C. pagurus* at Bradda Offshore had fallen to less than 0.025 per 100 m^2

a. Asterias rubens



b. Cancer pagurus

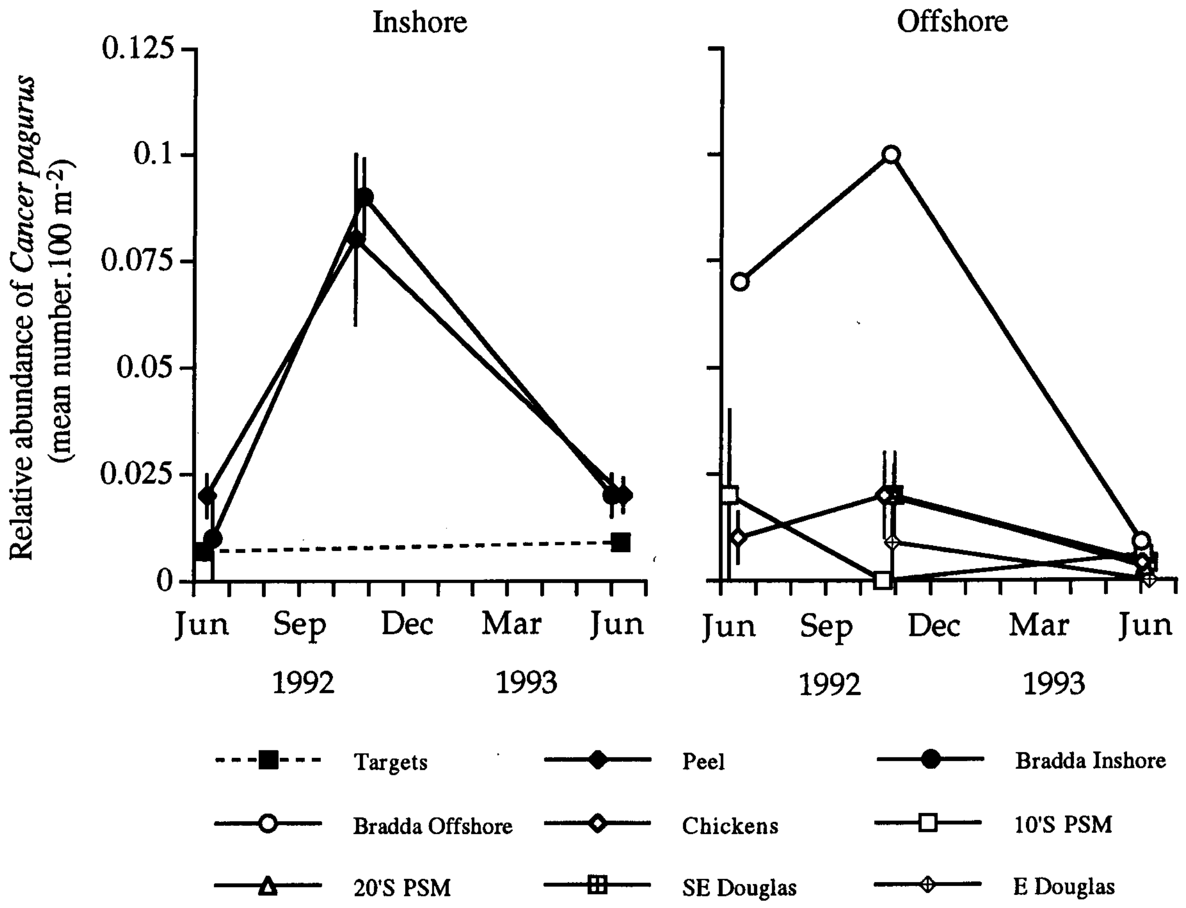


Figure 2.6. Relative abundance of by-catch species caught by queenie dredges on inshore and offshore fishing grounds, mean number (±SE) per 100 m^2 of sea bed covered. ***a.*** *Asterias rubens.* ***b.*** *Cancer pagurus.* Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled.

(equivalent to one crab per 4 000 m^2), similar to the other grounds. Unfortunately, Targets was not sampled in October 1992 so it is impossible to say if the seasonal variation was common to all of the inshore sites on the west coast of the Island. Crab abundance remained low on all of the other offshore grounds.

The abundance of the whelk species *Buccinum undatum* and *Neptunea antiqua* was only analysed from October 1992 onwards (Figure 2.7*a* & *b*). Both species were absent from Peel, despite their presence to the north at the Targets and of low numbers of *N. antiqua* at Bradda Inshore, to the south. *B. undatum* was absent from Bradda Offshore and the Chickens, but present in significant numbers at the other offshore grounds. Maximum numbers of *B. undatum* were found at South-East Douglas and East Douglas, with the abundance of *N. antiqua* greatest at East Douglas followed by South-East Douglas. At all the sites where whelks of either species occurred, there was an increase in abundance from October 1992 to June 1993.

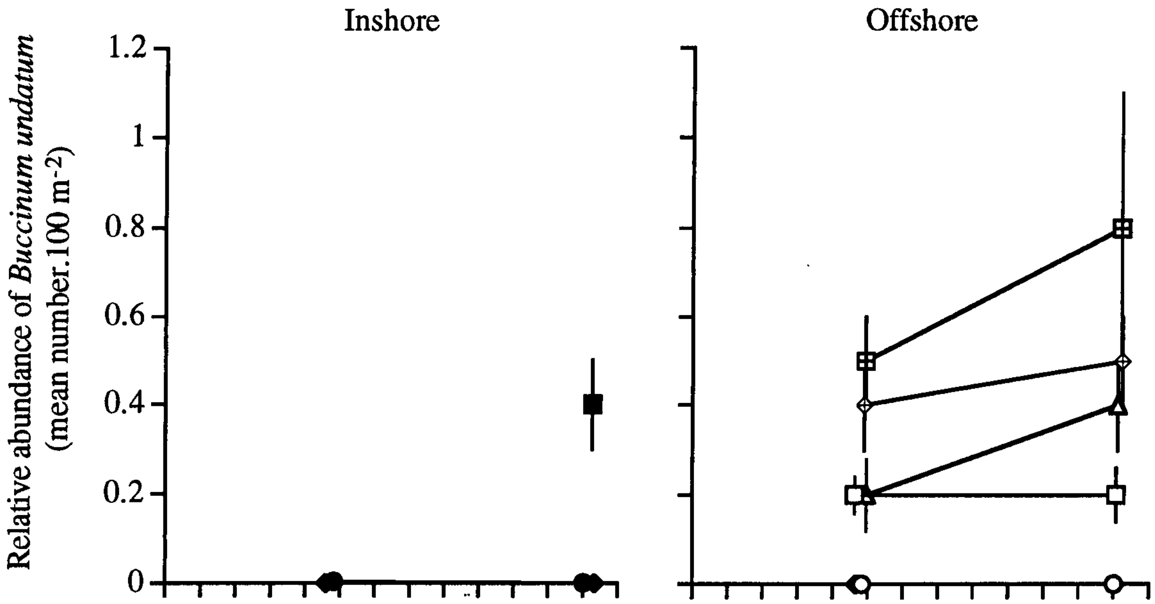
The octopus *Eledone cirrhosa* was taken at all sites in low numbers (Figure 2.8*a*). With the exception of 10' South Port St.Mary there was a common increase in abundance from October 1992 to June 1993 on all the grounds. The highest numbers were found on the offshore grounds, although the overall sample size was small and the variation between tows great.

Inshore, the queen scallop, *Aequipecten opercularis* was only found at the Targets, sampled on the June, post-season surveys (Figure 2.8*b*). The absence of a sample from October 1992 makes it impossible to observe any seasonal trend. There was a slight decline in abundance from June 1992 to June 1993. Offshore, the numbers of queens caught was greatest in October 1992 10' South of Port St.Mary, although the catch declined by June 1993. Queen abundance also fell at South-East Douglas from October to June but increased at East Douglas and 20' South Port St.Mary. There was often a high degree of variability in the numbers taken in different tows on the same ground, indicated by the large standard error bars.

2.3.5 Research vessel Catch Per Unit Effort (CPUE)

The calculated values of CPUE for the R.V. Roagan (10-30 scallops.$m^{-1}.h^{-1}$) were similar in magnitude to those presented by Allison (1993) for recent years for the portion of the Manx fleet that returned logbooks but the standard errors were much larger, as might be expected from such a limited sample size. There were marked seasonal fluctuations in research vessel CPUE on most of the inshore or nearshore fishing grounds. Values of CPUE were considerably higher in October

a. Buccinum undatum



b. Neptunea antiqua

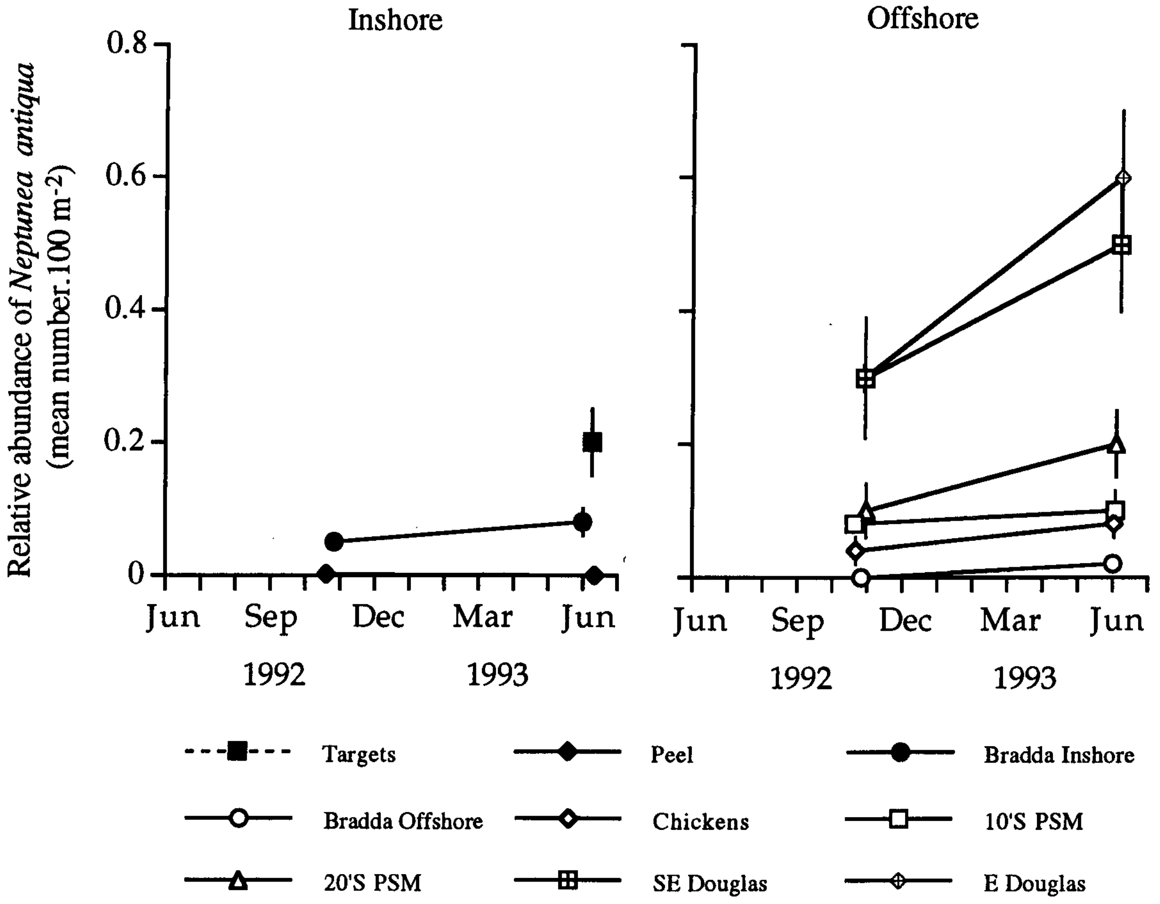
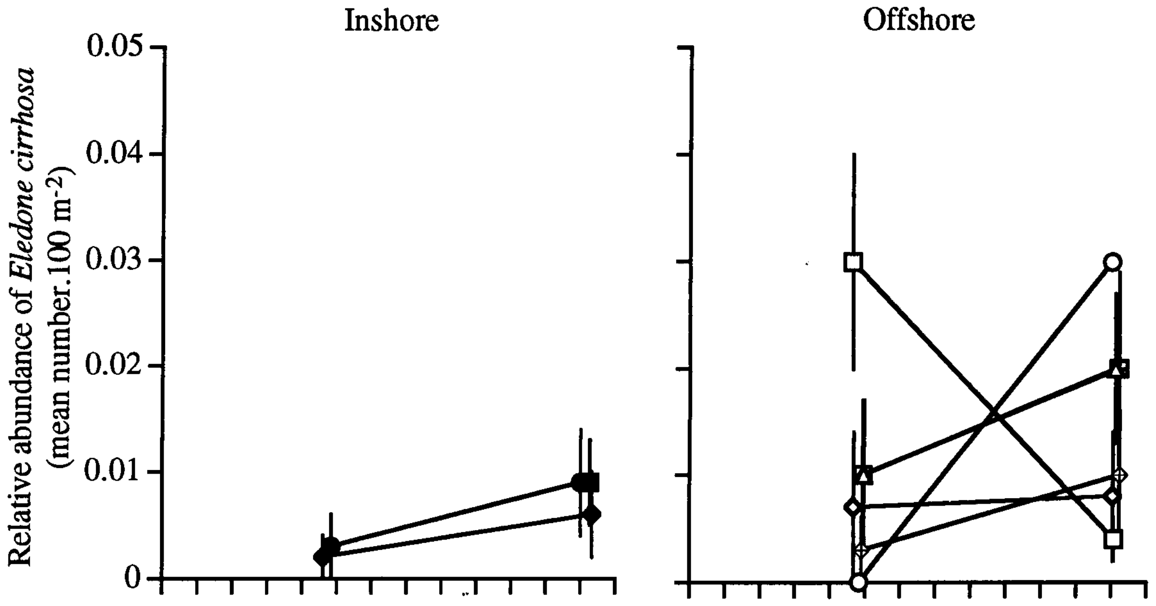


Figure 2.7. Relative abundance of by-catch species caught by queenie dredges on inshore and offshore grounds, mean number (±SE) per 100 m^2 of sea bed covered. ***a. Buccinum undatum. b. Neptunea antiqua.*** Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled.

a. Eledone cirrhosa



b. Aequipecten opercularis

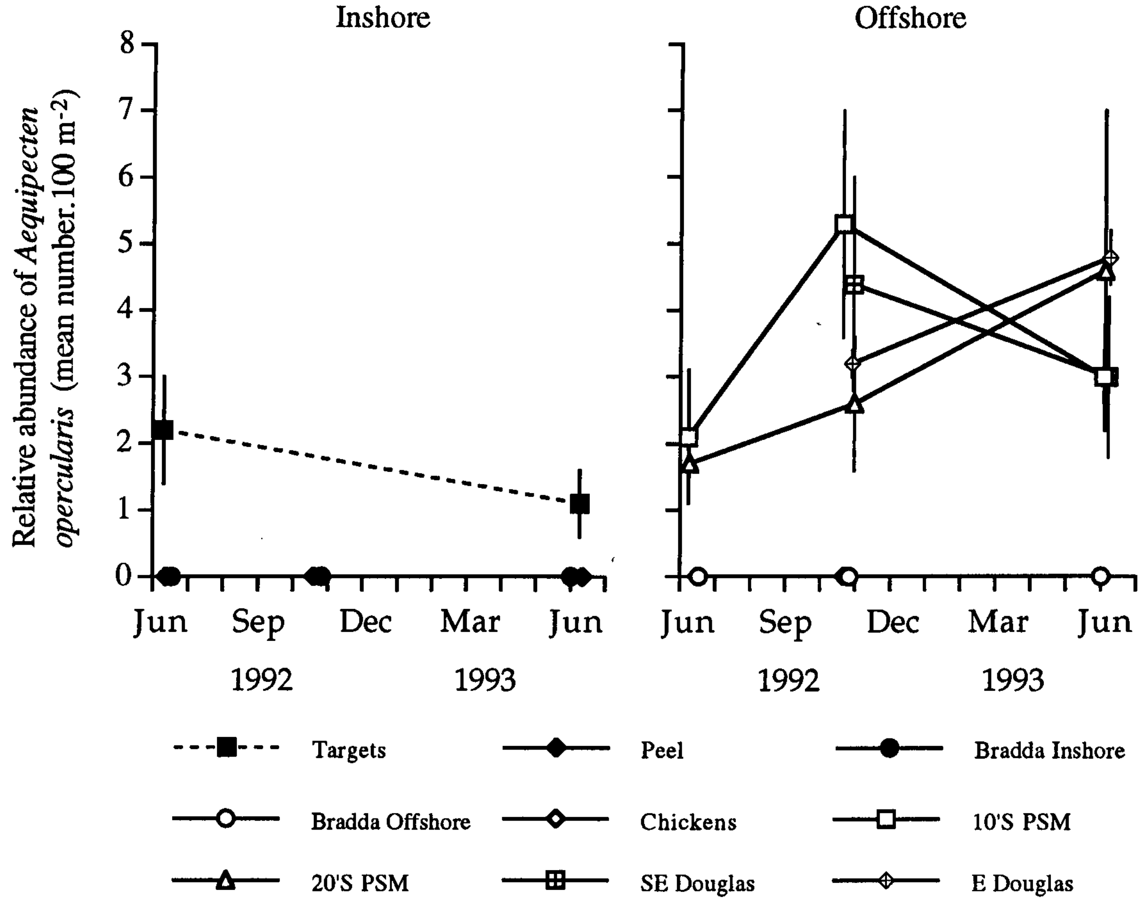


Figure 2.8. Relative abundance of by-catch species caught by queen dredges on inshore and offshore grounds, mean numbers (±SE) per 100 m^2 of sea bed covered. *a. Eledone cirrhosa. b. Aequipecten opercularis.* Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled.

1992 than in either of the June samples on all grounds, except 20' South Port St.Mary which showed a decline in CPUE across all surveys (see Table 2.6 below) and 10' South Port St.Mary which remained consistent. Post-season CPUE at the Targets and Peel was consistent from June 1992 to June 1993. Sharp increases in CPUE were found at Bradda Inshore and particularly at Bradda Offshore between June and October 1992, but the values for June 1993 were below those for the previous June.

2.3.6 Scallop density-at-age

Densities of post-recruit scallops per 100 m^2 caught in the scallop dredges are shown in Table 2.5. A dredge efficiency figure of 20 % was assumed, after Murphy (1986) and Allison (1993). The density of scallops of all age-classes was very low but there were extreme variations in the density of individual age-classes on the inshore, heavily exploited fishing grounds, reflecting the reliance of the success of the fishery on individual year-class recruitment.

Individual age-classes rarely occurred at densities of more than 1 per 100 m^2; the maximum observed density was 1.5 scallops per 100 m^2 for age 4 scallops at Peel in October 1992, consisting of those that had recruited over the summer and had not previously been exploited. Increases in density were apparent from June to October 1992 for individual age-classes but to follow the progress of individual cohorts one year must be added to the age by the time of the June 1993 survey. From October 1992 to June 1993 the densities of almost all year-classes decreased, suggesting high mortality over the winter. The seasonal variations in scallop density were clearest on the inshore/west grounds, Chickens and Bradda Offshore, but there was very little variation at the two Port St.Mary grounds. There were slight increases in scallop density over the period of the fishing season at 20' South Port St.Mary and South-East Douglas.

The overall density of all age-classes of post-recruit scallops (Figure 2.9) was highest at Peel and Bradda Offshore (3 scallops per 100 m^2, October 1992). The lowest total density was recorded at East Douglas in June 1993 where there were only 1.2 per 100 m^2. There were clear seasonal variations on the estimated density of post-recruit scallops on the inshore grounds at Bradda Inshore and Peel, and offshore at Chickens and Bradda Offshore.

Table 2.5. Estimates of the density of commercial size scallops (≥110 mm shell length, number.100 m^{-2}) on fishing grounds around the Isle of Man, calculated from the area swept by research vessel dredge surveys assuming a dredge efficiency of 20%.

	TARGETS			PEEL			BRADDA INSHORE		
Age	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993
2	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.133		0.074	0.220	0.098	0.011	0.014	0.418	0.000
4	1.308		0.653	0.742	1.530	0.206	0.850	1.024	0.190
5	0.166		0.727	0.178	0.426	1.129	0.652	0.981	0.600
6	0.022		0.160	0.178	0.175	0.293	0.099	0.101	0.424
7	0.011		0.000	0.627	0.273	0.130	0.028	0.029	0.059
8	0.011		0.012	0.188	0.361	0.217	0.071	0.072	0.029
9	0.011		0.025	0.115	0.098	0.119	0.000	0.000	0.044
10+	0.000		0.012	0.063	0.109	0.076	0.000	0.000	0.044
Total	1.663		1.663	2.311	3.071	2.182	1.714	2.626	1.390

Table 2.5. (continued).

	BRADDA OFFSHORE			CHICKENS			10' SOUTH PORT ST.MARY		
Age	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993
2	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.000	0.000
3	0.000	0.087	0.000	0.011	0.043	0.000	0.275	0.026	0.011
4	0.916	1.483	0.000	0.445	1.296	0.150	0.378	0.435	0.065
5	0.698	0.742	0.873	0.825	1.156	0.793	0.189	0.264	0.576
6	0.087	0.349	0.175	0.054	0.086	0.826	0.051	0.040	0.272
7	0.044	0.175	0.087	0.098	0.054	0.064	0.103	0.105	0.076
8	0.131	0.087	0.044	0.065	0.054	0.075	0.086	0.145	0.130
9	0.000	0.087	0.087	0.022	0.011	0.021	0.189	0.158	0.098
10+	0.000	0.000	0.087	0.011	0.000	0.000	0.395	0.382	0.304
Total	1.876	3.010	1.352	1.530	2.698	1.930	1.682	1.556	1.532

Table 2.5. (continued).

	20’ SOUTH PORT ST.MARY			SOUTH EAST DOUGLAS			EAST DOUGLAS		
Age	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993
2	0.000	0.000	0.000		0.000	0.000		0.000	0.000
3	0.101	0.000	0.000		0.011	0.000		0.677	0.000
4	0.476	0.424	0.046		0.306	0.022		0.648	0.428
5	0.274	0.381	0.599		0.273	0.427		0.074	0.353
6	0.259	0.424	0.307		0.372	0.262		0.162	0.107
7	0.245	0.198	0.200		0.273	0.416		0.044	0.064
8	0.274	0.127	0.200		0.306	0.317		0.015	0.054
9	0.317	0.184	0.169		0.164	0.284		0.044	0.064
10+	0.591	0.381	0.630		0.208	0.317		0.133	0.139
Total	2.537	2.118	2.151		1.914	2.045		1.797	1.209

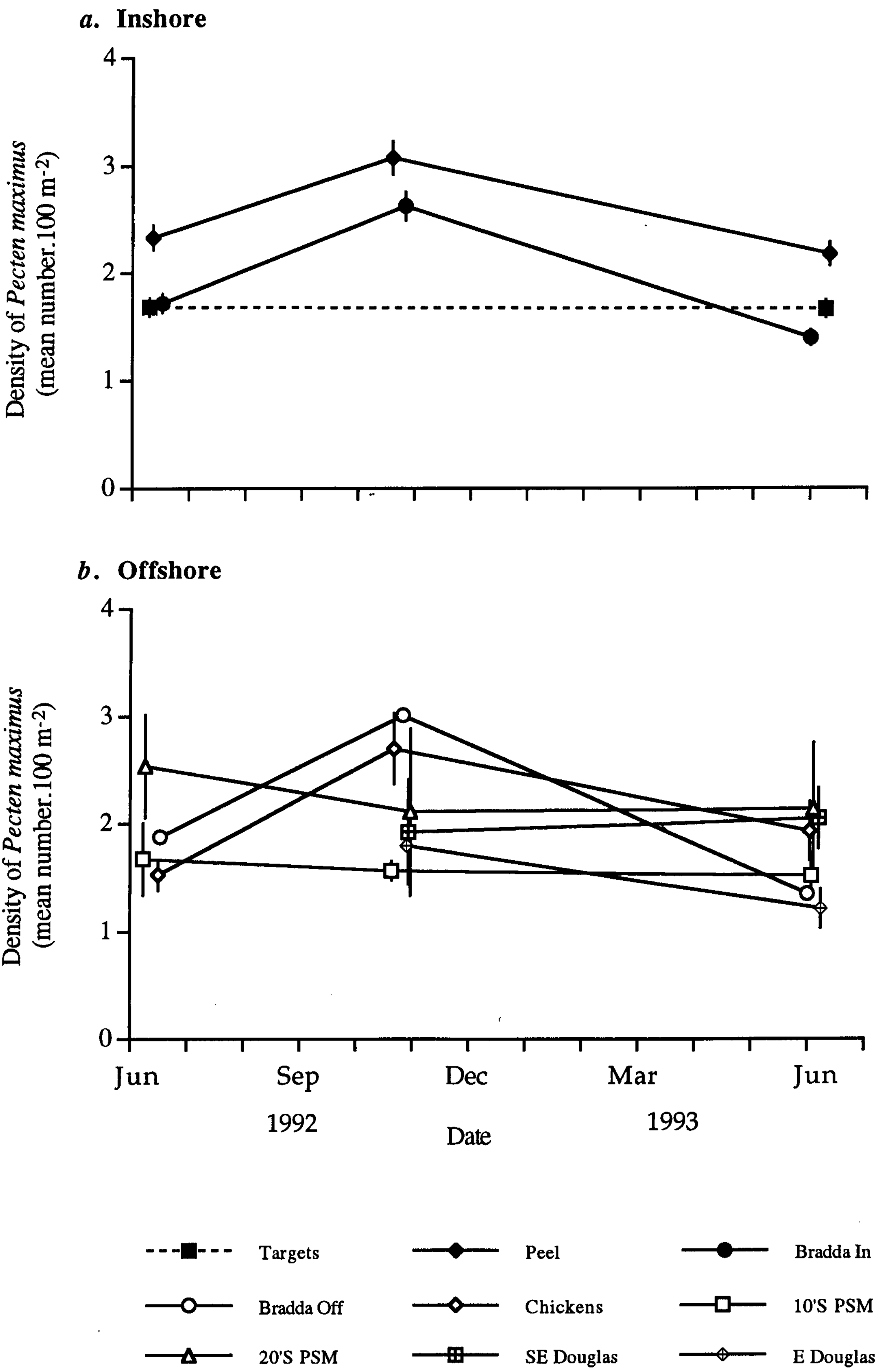


Figure 2.9. Density of commercial size scallops *Pecten maximus* (mean number (±SE) of scallops ≥110 mm shell length per 100 m^2 of sea bed covered by the dredges). ***a***. Inshore. ***b***. Offshore. Means are of 3-4 tows except Bradda Offshore (1 tow), individual dredges pooled. Assumed gear efficiency = 20%.

2.3.7 Implications of towing speed assumption

In order to test the sensitivity of density estimates made from CPUE data and research vessel age structures to variations in the assumption of towing speed, current scallop densities were re-calculated from research vessel CPUE and assumed towing speeds of 1.5, 2.0 and 2.5 knots (1 knot = 1 852 $m.h^{-1}$) using the methods of Murphy (1986) and Allison (1993) (Table 2.6).

The large influence of changes in assumed towing speed is clearly demonstrated: at a towing speed of 1.5 knots (the value taken by Murphy (1986) and Allison (1993)) the density of commercial size scallops calculated from CPUE values at Bradda Offshore in October 1992 was 5.56 scallops per 100 m^2, compared to a value of 3.33 at 2.5 knots and 3.01 scallops per 100 m^2 from the swept area calculations. The minimum CPUE-based density was 1.85 per 100 m^2 at a speed of 1.5 knots (Maughold Head, June 1992), 1.11 at 2.5 knots and 0.97 scallops per m^2 from the swept area estimates. The overall effect is an increase in the estimated density of commercial size scallops of 40% when the assumed speed is 1.5 knots compared to 2.5 knots. The CPUE-based method with an assumed towing speed of 1.5 knots produced density estimates that were 1.6-2.3 times greater than those calculated from the swept area of the research vessel surveys, whereas at a speed of 2.5 knots the estimates varied from 0.94-1.15 of the survey densities.

2.3.8 Recruitment ogives

Scallops enter the fishery when they reach the minimum legal landing size (MLLS) of 110 mm shell length. Due to differences in growth rate not all the members of a single cohort recruit to the fishery in the same year, either on the same ground or between grounds. A year-class is considered to have been recruited to the fishery if >50% of individuals within the cohort have reached this size. The proportion of each age-class which had recruited on each ground is presented in Table 2.7. The ogives show that recruitment of each cohort occurs over 2-3 years on most grounds. The age of recruitment was 4 years old on the majority of grounds in June 1992, with a higher proportion having recruited by October after the addition of growth over the summer. Recruitment occurred earliest at Targets, Bradda Inshore, East Douglas and the Point of Ayre.

The changes in age-class recruitment from one survey to the next, particularly from October 1992 to June 1993 when ageing was more reliable, indicates the high degree of exploitation of the recruiting year-class, especially on the inshore grounds (Table 2.7). 70% of age-3 scallops had recruited at Bradda

Table 2.6. Density of commercial size scallops, *Pecten maximus*, per 100 m^2 based on research vessel CPUE and assumed towing speeds of 1.5, 2.0 and 2.5 knots. Scallop density calculated directly from research vessel data is also shown.

	Survey CPUE (scallops.m^{-1}.h^{-1})	Assumed speed (knots) 1.5	 2.0	 2.5	Survey density (scallops.100^{-2})
June 1992					
Targets	15.46	2.78	2.09	1.67	1.663
Peel	22.20	4.00	3.00	2.40	2.311
Bradda Offshore	18.81	3.39	2.54	2.03	1.876
Bradda Inshore	15.08	2.71	2.04	1.63	1.714
Chickens	14.09	2.54	1.90	1.52	1.530
10'S Port St.Mary	15.86	2.85	2.14	1.71	1.682
20'S Port St.Mary	24.06	4.33	3.25	2.60	2.537
SE Douglas					
E Douglas					
Maughold Head	10.28	1.85	1.39	1.11	0.966
Ramsey Bay	14.92	2.69	2.01	1.61	1.169
October 1992					
Targets					
Peel	29.11	5.24	3.93	3.14	3.071
Bradda Offshore	30.87	5.56	4.17	3.33	3.010
Bradda Inshore	25.96	4.67	3.50	2.80	2.626
Chickens	25.05	4.51	3.38	2.71	2.698
10'S Port St.Mary	15.91	2.86	2.15	1.72	1.556
20'S Port St.Mary	20.65	3.72	2.79	2.23	2.118
SE Douglas	19.80	3.56	2.67	2.14	1.914
E Douglas	17.40	3.13	2.35	1.88	1.797
June 1993					
Targets	15.57	2.80	2.10	1.68	1.633
Peel	22.48	4.05	3.03	2.43	2.182
Bradda Offshore	11.97	2.15	1.62	1.29	1.352
Bradda Inshore	12.64	2.28	1.71	1.37	1.390
Chickens	17.45	3.14	2.36	1.88	1.930
10'S Port St.Mary	14.38	2.59	1.94	1.55	1.532
20'S Port St.Mary	18.79	3.38	2.54	2.03	2.151
SE Douglas	20.23	3.64	2.73	2.18	2.045
E Douglas	11.96	2.15	1.61	1.29	1.209

Table 2.7. Recruitment ogives for *Pecten maximus*. Values are percentage of each age class recruited to the fishery. Data from scallop and queenie dredges of pre- and post-season research vessel surveys. n = sample size. Year classes are considered to have recruited (shown in bold) when >50% are above the minimum legal landing size of 110 mm shell length.

Age-class	2	3	4	5	6	7	8+	n
June 1992								
Targets	0	7	**94**	100	100	100	100	454
Peel	0	20	**78**	100	100	100	100	657
Bradda Offshore	0	0	**61**	100	100	100	100	134
Bradda Inshore	0	1	**85**	98	100	100	100	384
Chickens	0	1	47	**95**	100	100	100	549
10'S Port St.Mary	3	26	**83**	100	100	100	100	276
20'S Port St.Mary	0	12	**91**	100	95	100	100	279
SE Douglas	-	-	-	-	-	-	-	-
E Douglas	-	-	-	-	-	-	-	-
Point of Ayre	0	19	**81**	100	100	100	100	110
Laxey	0	0	**56**	100	100	100	100	110
Maughold Head	0	4	**82**	100	100	100	100	186
Ramsey Bay	0	14	**94**	100	100	100	100	424
October 1992								
Targets	-	-	-	-	-	-	-	-
Peel	0	16	**95**	100	100	100	100	728
Bradda Offshore	0	7	**94**	100	90	100	100	147
Bradda Inshore	0	**70**	100	100	100	100	100	541
Chickens	0	2	**89**	99	100	100	100	853
10'S Port St.Mary	0	9	**88**	100	100	100	100	219
20'S Port St.Mary	0	0	**78**	98	100	100	100	360
SE Douglas	0	1	35	**100**	100	100	100	403
E Douglas	0	**64**	98	100	100	100	100	379
Point of Ayre	-	-	-	-	-	-	-	-
June 1993								
Targets	0	7	**74**	100	96	100	100	428
Peel	0	2	40	**94**	100	100	100	550
Bradda Offshore	0	0	0	**70**	85	100	100	124
Bradda Inshore	0	0	20	**86**	98	100	100	372
Chickens	0	0	8	**89**	97	90	100	943
10'S Port St.Mary	0	0	14	**94**	100	100	100	347
20'S Port St.Mary	0	0	11	**71**	100	100	100	261
SE Douglas	0	0	2	49	**100**	100	100	480
E Douglas	0	1	**72**	98	100	100	100	432
Point of Ayre	0	0	**77**	100	100	100	100	89

Inshore by October 1992. The same cohort (aged 4 years) at the end of the fishing season in June 1993 was only 20% recruited, reflecting the high rate of removal of commercial size scallops on this ground. The same phenomenon was observed at Bradda Offshore, although to a lesser extent and for older scallops: 94% of age-4 scallops were of commercial size in October 1992 but in June 1993 the same cohort, aged 5, were only 70% recruited.

2.3.9 Survival and mortality rate estimates

Age specific survival and mortality rates for post-recruit scallops on the major fishing grounds are presented in Table 2.8. Survival and mortality for each cohort can be followed horizontally from June to October 1992 as there was no growth ring formation during this period. Each cohort then added a ring between October 1992 and June 1993 and so survival was calculated diagonally from successive age-classes. In order to allow comparisons with published mortality rates (usually expressed as annual rates), the estimates of scallop mortality calculated in this study were 'annualised': the rates of mortality calculated from changes in age-class abundance over the closed and open phases of the fishing season were extrapolated to annual rates on the assumption that mortality continued at the closed or open season rate over a whole year. Thus calculated values of S_1 assumed that closed season mortality continued for a whole year and S_2 values assumed mortality continued all year at the rate experienced during the fishing season. An artefact of this technique was that, in some cases, the change in year-class abundance over the period of the fishing season was so great that when extrapolated over a year, a negative survival rate resulted. Such spurious figures are in themselves meaningless, but should be read as a zero survival for the year-class, emphasising the high rate of mortality incurred during the prosecution of the fishery. In such cases it was impossible to calculate instantaneous coefficients of mortality, Z.

There was a large variation in the calculated values, due substantially to the small sample sizes involved. The values from the scallop dredges might be considered more reliable as these dredges were optimised to fish for commercial size scallops and were very selective, never clogging up with by-catch as the queen dredges were observed to do. However, the results from the queen dredges did show consistently lower mortality rates over the summer closed season than during the winter. The results from the scallop dredges were clearer. The calculated values of survival rate S and total mortality Z, as well as Heincke's estimate of total mortality Z of all exploited age-classes, were reasonable for the highly exploited grounds of the inshore/west area, where changes in abundance between successive samples were high and adequately sampled by the limited survey programme. Calculated

Table 2.8. Survival (S) and total mortality (Z) rates-at-age calculated from density-at-age values (scallops.km^{-2}) from successive research vessel surveys, extrapolated to annual rates. S_1 and Z_1 refer to the period June 1992 - October 1992; S_2 and Z_2 to the period October 1992 - June 1993. Heincke estimates of total mortality over all fully exploited year-classes are also given, calculated with values of *a* (the age of full recruitment) of 4-6 years, to cover the period of recruitment for North Irish Sea scallops.

PEEL

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	0	0	0								
3	481	109	43	439	197	22	-1.19		4.19		-0.56		2.27	
4	1 506	3 650	369	1 485	3 060	413	5.03	4.69	-2.51	-1.89	4.00	2.70	-2.05	-1.15
5	690	590	1 867	355	852	2 258	0.59	0.24	0.44	1.04	4.96	0.59	-2.47	0.47
6	439	372	695	355	350	586	0.56	1.28	0.47	-0.25	0.95	0.51	0.05	0.58
7	627	393	239	1 255	546	261	-0.05	0.45	1.32	0.69	-0.60	0.60	2.35	0.46
8	251	393	434	376	721	434	2.61	1.16	-1.27	-0.15	3.59	0.68	-1.84	0.36
9	105	175	217	230	197	239	2.90	0.30	-1.46	0.92	0.59	-0.04	0.44	1.72
10+	209	131	109	125	219	152								
Heincke's Z (a=4)									-1.22	0.69			-0.98	0.59
Heincke's Z (a=5)									0.26	0.15			-0.10	0.75
Heincke's Z (a=6)									0.18	0.41			0.57	0.85

Table 2.8 (continued)

BRADDA INSHORE

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	0	0	0								
3	0	750	0	28	837	0					80.51		-9.43	
4	2 153	1 818	205	1 700	2 049	380	0.57	-0.22	0.47	2.17	1.57	0.09	-0.52	1.32
5	1 417	1 327	1 229	1 303	1 962	1 200	0.82	0.46	0.18	0.66	2.41	0.31	-1.14	0.90
6	113	87	1 815	198	202	849	0.34	1.61	0.75	-0.52	1.05	0.05	-0.05	1.40
7	113	87	293	57	58	117	0.34	4.99	0.75	-2.04	1.05	0.30	-0.05	0.91
8	0	58	29	142	144	59		-0.11		1.82	1.05	1.02	-0.05	-0.02
9	85	0	29	0	0	88	-1.79	0.17		1.14		0.34		0.83
10+	0	29	0	0	0	88								
Heincke's Z (a=4)									0.39	-0.01			-0.73	1.08
Heincke's Z (a=5)									0.29	-0.55			-0.92	1.26
Heincke's Z (a=6)									0.84	-0.70			-0.05	0.72

Table 2.8 (continued)

BRADDA OFFSHORE

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	0	0	0								
3	0	0	0	0	175	0								
4	2 007	2 269	2 269	1 832	2 967	1 745	1.36		-0.33		2.69	16.28	-1.31	-3.91
5	1 920	262	262	1 396	1 483	349	-1.35	-0.50	5.43	3.67	1.17	-0.50	-0.17	3.63
6	0	87	87	175	698	175		6.66		-2.49	9.17	-0.50	-3.78	3.63
7	0	0	0	87	349	87		4.40		-1.87	9.17	-0.49	-3.78	3.53
8	87	87	87	262	175	175	1.00		0.00		0.09	0.15	1.10	1.18
9	0	0	0	0	175	175		1.00		0.00		1.00		0.00
10+	87	175	175	0	0	0								
Heincke's Z (a=4)									1.07	0.58			-1.21	3.02
Heincke's Z (a=5)									4.16	-2.27			-1.10	2.53
Heincke's Z (a=6)									-1.89	-1.87			-2.67	1.75

Table 2.8 (continued)

CHICKENS

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	0	0	0								
3	0	21	0	22	86	0					9.47		-3.95	
4	1 107	642	214	890	2 591	300	-0.21		1.56		6.50	5.08	-3.07	-2.04
5	1 562	964	729	1 649	2 313	1 587	-0.10	1.22	1.39	-0.21	2.16	0.37	-0.97	0.80
6	108	128	665	108	171	1 651	1.53	0.49	-0.49	0.61	2.66	0.53	-1.31	0.55
7	65	21	64	195	107	129	-0.93	0.19	3.20	1.13	-0.30	0.59	1.73	0.47
8	43	64	64	130	107	150	2.38	4.27	-1.13	-1.79	0.49	1.65	0.56	-0.55
9	0	0	21	43	21	43		-0.09		1.79	-0.46	0.02	2.03	1.49
10+	0	0	0	22	0	0								
Heincke's Z (a=4)									1.32	0.27			-1.63	0.65
Heincke's Z (a=5)									1.19	0.60			-0.71	0.51
Heincke's Z (a=6)									0.04	0.58			0.46	0.29

Table 2.8 (continued)

10’ SOUTH PORT ST.MARY

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	34	0	0								
3	396	53	22	549	53	22	-1.36		5.49		-1.46		6.38	
4	792	870	109	755	870	130	1.27	2.71	-0.26	-1.17	1.42	3.38	-0.39	-1.46
5	311	422	1 130	378	527	1 152	1.97	1.48	-0.83	-0.42	2.08	1.52	-0.91	-0.45
6	226	185	435	103	53	543	0.50	1.05	0.55	-0.05	-0.33	1.05	1.82	-0.05
7	255	132	174	206	211	152	-0.31	0.91	1.79	0.10	1.07	4.04	-0.07	-1.71
8	283	211	130	172	290	261	0.31	0.98	0.80	0.02	2.88	1.38	-1.43	-0.34
9	339	237	152	378	316	196	0.18	0.55	0.97	0.53	0.56	0.47	0.48	0.64
10+	848	369	652	789	765	608								
Heincke’s Z (a=4)									0.19	-0.17			-0.36	-0.27
Heincke’s Z (a=5)									0.48	0.10			-0.34	-0.10
Heincke’s Z (a=6)									1.00	0.23			-0.04	-0.15

Table 2.8 (continued)

2O' SOUTH PORT ST.MARY

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2	0	0	0	0	0	0								
3	86	0	0	202	0	0	-1.55				-1.55			
4	778	1 199	56	951	1 158	92	2.38		-1.10		1.55		-0.50	
5	605	1 414	1 066	548	1 073	1 198	4.41	0.81	-2.17	0.20	3.45	1.06	-1.72	-0.06
6	29	615	674	519	932	615	52.89	0.12	-7.81	1.25	3.03	0.28	-1.49	0.94
7	375	246	421	490	536	399	0.12	0.47	1.07	0.64	1.24	0.04	-0.23	1.42
8	317	461	196	548	424	399	2.16	0.66	-0.96	0.38	0.42	0.57	0.66	0.50
9	346	369	196	634	395	338	1.17	0.03	-0.16	1.44	0.04	0.66	1.21	0.38
10+	980	1 107	1 319	1 182	1 101	1 260								
Heincke's Z (a=4)									-1.44	0.73			-0.52	0.56
Heincke's Z (a=5)									-1.58	1.03			-0.52	0.89
Heincke's Z (a=6)									-1.18	0.82			-0.11	0.86

Table 2.8 (continued)

SOUTH-EAST DOUGLAS

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2		0	0		0	0								
3		0	0		22	0								
4		612	22		612	44						2.65		-1.14
5		219	591		547	853		0.94		0.06		1.65		-0.55
6		525	416		744	525		2.49		-1.06		0.93		0.07
7		569	372		547	831		0.52		0.57		1.19		-0.18
8		284	416		612	634		0.56		0.52		1.26		-0.25
9		197	153		328	569		0.24		1.02		0.88		0.12
10+		306	416		416	634								
Heincke's Z (a=4)										0.21				-0.18
Heincke's Z (a=5)										0.27				-0.07
Heincke's Z (a=6)										0.63				-0.11

Table 2.8 (continued)

EAST DOUGLAS

	Density (scallops.km^{-2})													
	Queenie dredges			Scallop dredges			Queenie dredges				Scallop dredges			
Age	June 92	Oct 92	June 93	June 92	Oct 92	June 93	S_1	S_2	Z_1	Z_2	S_1	S_2	Z_1	Z_2
2		0	0		0	0								
3		1 031	21		1 355	0								
4		1 237	1 049		1 296	856		1.03		-0.03		0.40		0.75
5		324	235		147	706		-0.33		2.72		0.26		0.99
6		177	86		324	214		-0.20		2.18		1.74		-0.61
7		118	150		88	128		0.75		0.27		0.01		1.51
8		59	150		29	107		1.44		-0.39		1.35		-0.31
9		59	0		88	128		-0.64				6.50		-2.41
10+		29	43		265	278								
Heincke's Z (a=4)										1.84				0.63
Heincke's Z (a=5)										0.92				0.03
Heincke's Z (a=6)										0.27				0.32

survival rates greater than 1, giving rise to negative mortality rates, were common among the younger age-classes, reflecting the extended recruitment of cohorts of scallops (see Table 2.8).

Values of Z and Heincke's Z were consistently lower for the closed season (frequently negative). During this period when there was no scallop fishing, the only causes of mortality were the various components of natural mortality, rather than mortality induced directly or indirectly by fishing activity.

Heincke's Z, total mortality for all fully exploited age-classes increased from 0.59 to 0.85 at Peel with increasing age at first exploitation (a) over the period of the fishing season October 1992-June 1993. Values at Bradda Inshore varied from 1.08 to 0.72 for the same period. Closed season mortality rates were generally negative, due to the weight given to the most abundant year-classes in the calculation, which were also those that were still recruiting. Mortality rates at Bradda Offshore were unrealistic (giving rise to negative survival when extrapolated to annual rates) but were based on very low numbers of scallops with no replicate tows. To the south, at Chickens, total mortality rate varied from 0.65 - 0.51 for a=4 and a=5 respectively. At a=6 the value of 0.29 was unrealistically low, but it was again based on a very small sample size.

Negative values of Heincke's Z were found for both the open and closed seasons at 10' South Port St.Mary, reflecting the low exploitation rate at this ground. The scope of the sampling programme was too limited to measure anything but large changes in abundance, usually found on the more heavily fished grounds inshore. However, at 20' South Port St.Mary fishing season mortality rates of 0.56-0.89 were found, with negative values between June and October 1992 reflecting the large influence of increases in abundance of 4-6 year old scallops as they grew and entered the fishery during the summer closed season.

The grounds offshore to the east were only sampled in October 1992 and June 1993. At South-East Douglas, low numbers of scallops, spread over a wide range of year-classes, produced low negative values of Heincke's Z for the scallop dredges, but the queen dredge catches produced low but increasing mortality with increasing age at first exploitation, from 0.21 to 0.63 for a=4 to a=6. At East Douglas the changes in year-class abundance were greater and for a=4, Z=0.63. However, variations in the low numbers of older scallops influenced Z for a=5 and a=6 producing unrealistically low values (0.03 and 0.32).

2.3.10 Direct observations by SCUBA

The use of SCUBA equipment provided a useful opportunity to compare the density of scallops and other species observed directly, to those calculated from the more remote sampling method of dredging. The technique was limited by the physiological restrictions on diving imposed by the depth and limited air supply. In particular, the depths encountered in the Exclusion Zone (27-37 m) severely limited the time available and the area which could be successfully sampled.

The mean density of scallops within the Exclusion Zone showed a slight increasing trend over time, although the standard errors were large (Table 2.9, Figure 2.10*a*). These reflected the heterogeneous nature of scallop populations on a small spatial scale and variation in substratum type within the area covered by the Exclusion Zone (see Appendix 2 for substratum type). The Bradda Head ground was poorly sampled; limited resources were preferentially targeted on sampling the Exclusion Zone, but the density of scallops showed a consistent increase over the three surveys carried out off Bradda Head.

Aequipecten opercularis were rare at Bradda Head (Figure 2.10*b*) and did not support any fishing activity at this ground. This species was almost absent from the Exclusion Zone. The density of *A. opercularis* at Bradda Head fell over the three surveys from 2.8 per 100 m^2 to 0.5 per 100 m^2.

The densities of the major scallop predators *Asterias rubens* and *Cancer pagurus* were also estimated (Figures 2.10*c* & 2.10*d*). *C. pagurus* was extremely rare, but seen more often in the Exclusion Zone than off Bradda Head. Whenever they were seen they were either sheltering in a pit in the sand or under a rock. The density of *A. rubens* remained very consistent in the Exclusion Zone at 6-10 per 100 m^2, but off Bradda Head the density more than doubled from December 1990 to December 1992. However, because of the inconsistent sampling of this site the timing of the increase remained unknown. It is interesting to note, however, that the increase in density of *A. rubens* in the diver surveys at this site was also found in the dredge survey of Bradda Inshore in October 1992.

Table 2.9. Density (mean number.100 m^{-2}, and SE) of *Pecten maximus, Aequipecten opercularis, Asterias rubens* and *Cancer pagurus* within the Exclusion Zone and off Bradda Head. Data from replicate SCUBA diver line transects (each 200 m^{2}).

Location	Dates		*P. maximus*	*A. opercularis*	*A. rubens*	*C. pagurus*	n
Closed Area	30/3 - 12/4/1989	Mean	0.4	0.0	7.9	0.0	8
		SE	0.2	0.0	1.8	0.0	
Closed Area	6/9 - 13/9/1989	Mean	0.6	0.0	10.6	0.6	8
		SE	0.2	0.0	2.1	0.3	
Closed Area	8/12/1989	Mean	1.4	0.0	8.1	0.0	8
		SE	0.6	0.0	2.9	0.0	
Closed Area	28 - 29/11/1990	Mean	0.8	0.1	6.8	0.5	8
		SE	0.2	0.1	3.1	0.2	
Closed Area	8/12/1992	Mean	1.3	0.1	6.0	0.5	4
		SE	0.6	0.1	4.7	0.4	
Bradda Head	28/4 - 12/6/1989	Mean	0.8	2.8	9.3	0.1	8
		SE	0.3	1.2	1.0	0.1	
Bradda Head	5/12/1990	Mean	1.5	1.5	9.0	0.0	1
Bradda Head	10/12/1992	Mean	3.0	0.5	22.5	0.5	1

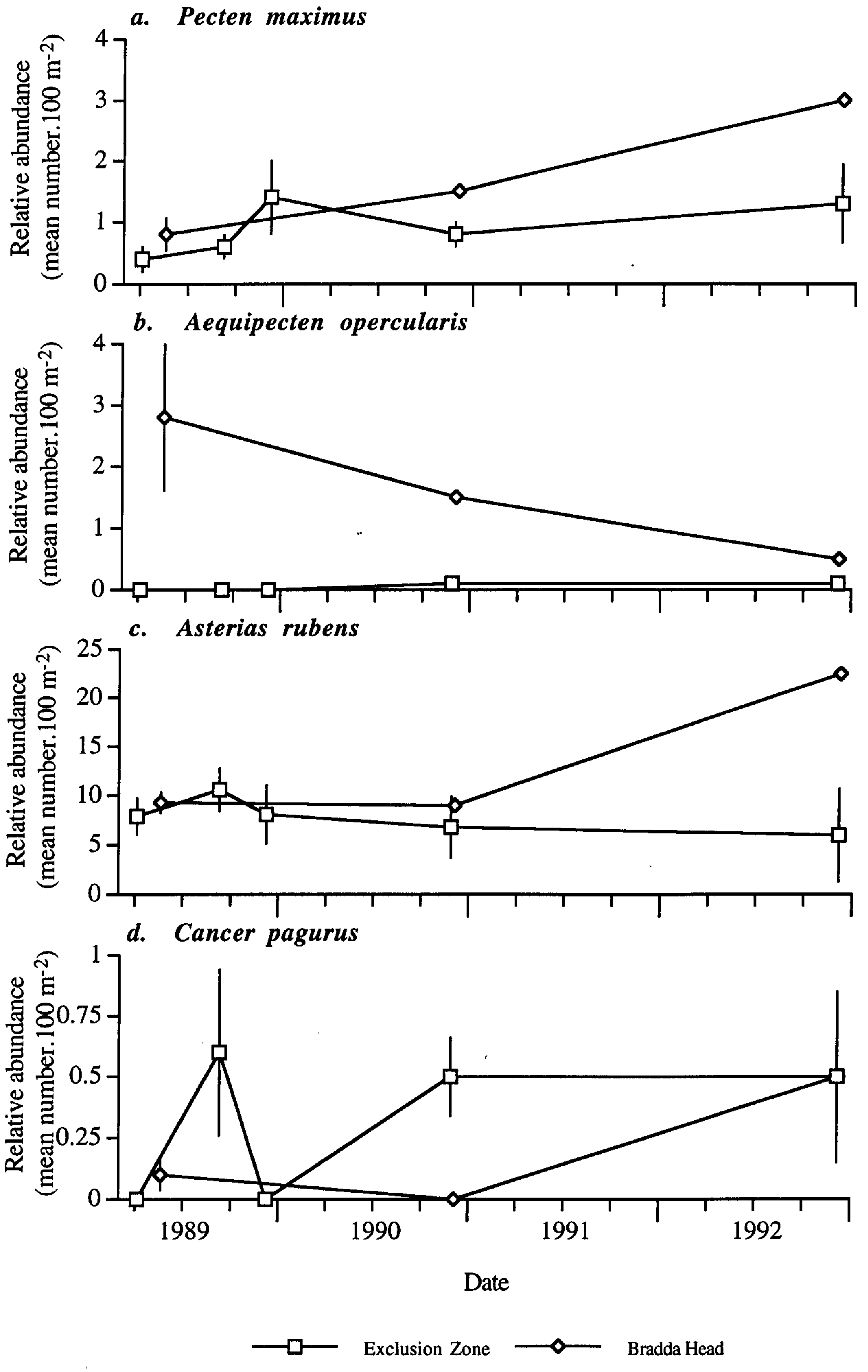


Figure 2.10. Relative abundance of pectinid species and major predators estimated from SCUBA diver surveys, mean number (± SE) per 100 m^2 of sea bed covered. ***a**. Pecten maximus.* ***b**. Aequipecten opercularis.* ***c**. Asterias rubens.* ***d**. Cancer pagurus.* Values are means of replicate 200 m^2 SCUBA diver line transects, n=1-8.

2.4 DISCUSSION

2.4.1 Methodological constraints

Scallop dredges can at best be described as semi-quantitative sampling devices as their efficiency is influenced by a host of variables that cannot be controlled. These include tides, weather, skipper's experience, tooth length, belly mesh size etc.. The work of Dare *et al.* (1993) highlights the large range of factors that influence dredge efficiency and estimates their relative importance, but most importantly points out that dredge efficiency varies continuously, even within a single tow, and so should be treated with caution. Extensive long-term sampling may compensate for several of these factors but was not practicable as part of this study, and so the results of the research vessel surveys must be viewed in the light of these considerations.

Twice yearly surveys, just prior to and just after the fishing season, have allowed recruitment to be studied in greater detail than in previous work (Murphy, 1986; Allison, 1993), sampling before the removal of new recruits and then after the fishery had been prosecuted. The current work covered the major fishing grounds around the Isle of Man, weather and resources permitting, although the scale of sampling was limited. Only four tows (and sometimes fewer) were carried out at each ground, providing relatively small numbers of scallops, hundreds rather than thousands. However, the area of sea bed from which the scallops were removed was large and known with reasonable accuracy (see Table 2.4).

Extremes of weather conditions were experienced between surveys: mirror calm sea conditions occurred in June 1992, large swells and strong winds in October 1992 and a return to relative calm in June 1993. However, any allowances for the probable reduction in dredge efficiency caused by the bad weather in October 1992 serve only to enhance the observed trends in scallop density, mortality and survival rates.

Allison (1993) found that research vessel scallop dredge samples resembled commercial catches in age structure, allowing their combination with commercial catch/effort statistics calculated from fishermen's logbooks. However, calculation of abundance- and density-at-age is dependent on assumptions of the dredge efficiency and towing speed of the commercial fleet. Research vessel surveys can overcome the latter by the use of electronic navigational aids but are still reliant on the accuracy of the former. The dredges were assumed to have a certain selection efficiency which was further assumed to be independent of scallops density and the same for all fishing grounds despite obvious differences in their bottom topography and substratum. This work has followed that of Murphy (1986) and Allison (1993) in assuming a constant value for gear efficiency of 20% based on the published literature (Rolfe, 1969; Gruffydd, 1974; Chapman *et al.*, 1977; Mason *et al.*, 1982; McLoughlin *et al.*, 1991 and see Iribarne *et al.*, (1991) for tabulated review). Recent work by Dare *et al.* (Dare *et al.*, 1993) has helped to quantify the variation in dredge performance on different grounds. Across all grounds they found an average efficiency of 22% but with extremes of as little as 6% on rough stony ground and up to 41% on muddy gravel. Detailed comparisons of the substrata fished in their work with that of the Manx scallops fishing grounds would be extremely useful in improving density and abundance estimates from the research vessel surveys and from catch/effort statistics.

Ageing of scallops for stock assessment purposes has traditionally been carried out by counting the number of growth rings visible on the shell valves. North Irish Sea scallops generally have clear rings and can be reliably aged by experienced workers. Possible errors can arise because of difficulties in determining the position of the first ring. This is small and often unclear and may in fact be absent, depending on the settlement time of the individual scallop. Such problems were overcome in this work by a practical approach: a thumb was held over the area close to the umbo where the first ring is located, and the first clearly visible ring assumed to be that laid down at the start of the scallop's second summer post settlement. A full discussion of the methods used to age scallops in the North Irish Sea, and potential sources of variation can be found in Allison (1993) and Allison *et al.* (1994).

Further difficulties can arise in distinguishing the later rings of older scallops as these are close together and indistinct. However, on most of the grounds sampled, particularly those inshore, the proportion of older scallops (with more than 8 growth rings) was small.

Similar difficulties were experienced when ageing the scallops from the June, post-season surveys. The growth ring in *Pecten maximus* is laid down during March/May in the North Irish Sea and at the time of the June survey was still very close to the shell margin. The amount of shell deposition on the outside of the growth ring varied between grounds, reflecting the spatial differences in growth rate between scallop fishing grounds around the Isle of Man (Allison, 1993). For the June surveys, when there was only an indistinct ring at the shell margin but a clear one significantly further in from the edge, then the outside ring was included in the ageing as being currently under formation. Ring identification was far easier in October after shell deposition over the summer growing season.

Calculation of mortality rates based on changes in year-class abundance can produce spurious results when sample sizes are small or where changes in abundance are slight. This was the case on the offshore grounds and more extensive sampling would be required to produce reliable age-specific mortality rates. In particular, on grounds where there were significant numbers of scallops in the older year-classes, changes in abundance between years were slight and sampling effort would have to be substantially increased to produce reliable results. On the inshore/west grounds, where exploitation by the fishery is high and dependence on newly recruited scallops produces large changes in the abundance of individual cohorts, then even the limited sampling undertaken produced acceptable results.

The use of divers to measure scallop densities is not uncommon where depth is shallow and densities are high (Brun, 1968; Butcher *et al.*, 1981; Fraser, 1983b; Howell & Fraser, 1984; Kalashnikov, 1985; Tettelbach, 1986; Coleman, 1988; Bull, 1988a), but where densities are very low it is difficult to sample a sufficient area to ensure a reliable density estimate. During the SCUBA surveys carried out as part of this work, each dive sampled an area of 200 m^2 using the ‘survey pole’. At the working depths (27-37 m) this was the practicable limit to the area which could be sampled accurately. However, scallops are now at such a low densities on the inshore grounds (Allison, 1993, this study) that a sampling unit of 200 m^2 was insufficient to provide accurate estimates of density. For comparison, the area sampled by the scallop dredges in the research vessel surveys was 35 000-45 000 m^2 at each site, with a minimum of 11 460 m^2 at Bradda Offshore.

The Exclusion Zone was nominally closed in March 1989 although fishing has continued illegally in the area, albeit at a reduced intensity. Buoying in May 1991 did not stop incursions into the area and each season a number of vessels have been observed fishing within its boundaries. Expectations of a large-scale recovery in scallop numbers following the closure of the area have been undermined by the failure of the closure to be enforced. The ability of SCUBA methods to detect anything but a dramatic increase in numbers is questionable, due to the limitations imposed by depth. Destructive dredge sampling was obviously not a viable option and trials using a Remotely Operated Vehicle (ROV) were unsuccessful because of the strength of the tidal currents in the Exclusion Zone and difficulties in quantifying the area sampled by the ROV. A heavy-duty sledge made to take the ROV and transform it into a towed camera proved unwieldy in use. Encouraging results have recently been seen from preliminary trials with a smaller sledge mounted with a low-light camera, which is capable of operating without the need for additional lighting.

2.4.2 Seasonal changes in scallop density and Catch Per Unit Effort (CPUE)

Stock assessments of scallop fisheries of the type recently completed by Allison (1993) have used pooled data from numerous samples to achieve large sample sizes. These data have been pooled over the period of the year when the scallops were not growing (November - March) to avoid inputs from recruitment. This provides an annual assessment of the population age-structure, and while the assumption of no recruitment is easily acceptable, the population is not static over the winter. The fishery is open over the time-span of the pooled samples and so progressive dredge samples become biased in favour of pre-recruits, due to the removal of commercial size scallops by the fishery. By sampling intensively at either end of the fishing season a more representative picture of recruitment was observed, as was the effect of the fishery on the recruited part (and indirectly on the pre-recruit part) of the population.

The density of commercial size scallops and CPUE have previously been used to demonstrate the effect of the fishery on scallop populations around the Isle of Man (Mason & Colman, 1955; Gruffydd, 1972; Murphy, 1986; Brand *et al.*, 1991a; Allison, 1993). These authors have generally considered inter-annual variations although Murphy (1986) estimated CPUE and scallop density within a fishing season. He demonstrated that CPUE varied on a weekly basis and that awareness of falling catch per unit effort was used by fishermen as one of the criteria for deciding where to fish. In my work, by calculating research vessel CPUE and post-recruit scallop density at the beginning and end of the fishing season, maxima and minima were established for each ground. Analysis of catch/effort data has shown that, within a season, individual grounds are actually fished for relatively short, and often well-defined periods (Murphy, 1986; Allison, 1993), suggesting that post-season CPUE values (particularly on the heavily exploited inshore grounds) might provide initial estimates for future economic analysis, of the thresholds beyond which fishing is deemed uneconomic by the inshore fleet.

Pre-season CPUE on the offshore grounds varied from 15-20 scallops.$m^{-1}.h^{-1}$ compared to 25-30 scallops.$m^{-1}.h^{-1}$ on the inshore grounds. After the prosecution of the fishery, CPUE levels inshore were similar to or below those offshore, in the range 10-20 scallops.$m^{-1}.h^{-1}$. The continued seasonal recovery of scallop density and CPUE on the inshore grounds despite heavy exploitation confirms their high productivity and unusually consistent recruitment (Brand *et al.*, 1991a). At a simplistic level, the relative profitability of scallop fishing on different grounds is a product of the CPUE (scallop density), the yield per recruit from that ground and the cost of catching the scallops (fuel spent steaming to and from the site as well as during fishing plus the costs of gear damage). Murphy (1986) found that the fleet concentrated on the inshore grounds at the start of the season until catches fell to some threshold, at which point they moved further offshore. The seasonal variation in CPUE revealed by the twice yearly sampling in my work, suggests that inshore CPUE may have to fall to below 15 scallops.$m^{-1}.h^{-1}$ before the offshore grounds become relatively more attractive, due to the greater costs of fishing there. Briggs (1991) estimated that a CPUE of 20-25 scallops.$m^{-1}.h^{-1}$ was the economic minimum for boats fishing off the Irish Sea coast of Northern Ireland. Spatial patterns of fishing are further modified by a large range of factors, not least among which are the weather (e.g. Bradda Inshore and Peel are sheltered by land from easterly winds) and legislation (boats longer than 50' (15.25m) can only fish outside the 3 mile limit).

The observed seasonal changes in post-recruit scallop density and CPUE reflect the balance of recruitment and the various components of total mortality (discussed later). The sharp increases over the summer closed season on the heavily exploited inshore grounds, as well as Chickens and Bradda Offshore, were due to net recruitment over the summer closed season of the in-coming year-classes into the ≥110 mm size group. Over the winter the density of post-recruit scallops (and hence CPUE) fell on nearly all grounds, and by half or more on Bradda Inshore and Bradda Offshore. This seasonal fall in density may be due to an increase in natural mortality (stress caused by falling temperatures and food supply). While the escape response of *P. maximus* may be adversely affected by low temperatures, the cold is likely to have similar physiological consequences for the predator community; increased natural mortality is an improbable explanation for the loss of half the population of scallops above 110 mm shell length off Bradda Head. A more credible hypothesis is that the primary source of scallop mortality is the fishery. There is some evidence for this suggestion. High levels of winter mortality were restricted principally to commercial size scallops (less liable to predation than smaller individuals Lake *et al.*, 1987; Lake, 1993), with the exception of the heaviest fished grounds such as Bradda Inshore where additional pre-recruit mortality may be due to indirect fishing damage. The spatial variations in mortality were consistent with the distribution of fishing effort (exploitation rates on the inshore west grounds are generally >20% and as high as 55% on Bradda Inshore (Allison, 1993)). Previous temporal variations in total mortality have been attributed to increased fishing effort and fishing mortality (Murphy, 1986; Allison, 1993). The fundamental impact of the fishery may also be seen in the shifts in the population age structures of scallops around the Isle of Man since its inception in the late 1930s (Brand *et al.*, 1991a); populations previously dominated by old scallops (50% >9 years old) are now dominated by pre-recruits.

Fishing intensity is historically lower on the offshore grounds (Murphy, 1986; Brand *et al.*, 1991a; Allison, 1993). This produced smaller seasonal changes in post-recruit scallop density and CPUE, and better representation of older age-classes in population age-structures. Only East Douglas showed signs of sustained fishing, with a truncated age distribution and obvious seasonal changes in density and CPUE.

Overall the densities of scallops recorded during the three surveys were extremely low on all grounds; densities of individual age-classes were rarely more than 1 scallop per 100 m^2, and that maximum was only recorded at the start of the season. These results were for commercial size scallops only and the dependence of the fishery on one or two year-classes on many grounds was confirmed; the greater part of the overall density was made up by the recent recruits, except on the offshore/south grounds where there remained significant numbers of scallops aged 8 and above.

Murphy (1986) and Allison (1993) calculated their post-recruit scallop densities by combining research vessel age structure data with CPUE from logbooks filled in by a 'sample fleet' of Manx fishing boats. Such density estimates are highly sensitive to the veracity of the assumptions of dredge efficiency and fishing boat towing speed used to calculate them. While this work followed Murphy (1986) and Allison (1993) in taking a dredge efficiency of 20%, Dare *et al.* (1993) demonstrated substrate-dependent variation in dredge efficiency from 6% on hard stony ground to 41% on muddy gravel, with a mean on 22%. Dare *et al.* (1993) also stressed that dredge efficiency changes constantly with variations in substratum, tooth wear, spring tension and numerous other variables. The sea bottom substratum is heterogeneous around the Isle of Man both within and between fishing grounds; the extremes being the hard sand and occasional rocks of Bradda Inshore (personal observations SCUBA diving) to the very stony grounds of South-East Douglas, Targets and Peel (research vessel observations). Although the springs on the dredges were adjusted to optimise their performance on each ground, further experimental work to quantify dredge efficiency on the various substrata would be of great value. In the light of the work of Dare *et al.* (1993) the current values of scallop density for the offshore grounds may be under estimates, due to over estimation of dredge efficiency. Conversely, dredge efficiency at Bradda Inshore may have been greater then the assumed 20%, with the result that the low calculated densities may in fact be over estimates.

The assumption of a 1.5 knot towing speed (over the ground) by Allison (1993) was based on that of Murphy (1986) who provided no justification for taking this value. Individual boats undoubtedly have preferred towing speeds based on the skipper's experience of gear performance at different depths and on different substrata, as well as the engine power available. The skipper of the R.V. Roagan considered a speed of 2.5 knots to be optimal and this was closely maintained; June 1992 mean towing speed over all tows (±SE) = 2.5 ±0.1 knot, October 1992 = 2.7 ±0.04 knot, June 1993 = 2.6 ±0.03 knot. Mason (1983) suggested that 2 knots was the common towing speed for scallop dredges in the UK.

Under-estimation of towing speed leads to spuriously high density estimates of commercial size scallops because the number of scallops caught is assumed to have come from a smaller swept area. The CPUE values of the survey cruises were broadly similar to those of the sample fleet logbook analyses of Allison (1993), and so the similarity of my scallop density estimates calculated from research vessel CPUE and an assumed speed of 1.5 knots (Table 2.6) to those of Allison (1993) (who estimated 3-6 post-recruit scallops per 100 m^2) supports the suggestion that his assumed towing speed of 1.5 knots was too slow. The current estimates of scallop density on Bradda Inshore are by far the lowest of all those that have been made from this ground (Table 2.10).

Table 2.10. Density estimates of commercial size scallops on the Bradda Inshore ground.

Year	Area per scallop (m^2)	Scallops per 100 m^2	Method	Reference
1954/55	8-11	9.1-12.5	Tagging	Mason & Colman (1955)
1965/66	5	20	Tagging	Gruffydd (1972)
81/82 start	23	4.4	CPUE	Murphy (1986)
season	27	3.7	"	
82/83 start	18	5.6	"	
season	24	4.2	"	
83/84 start	9	11.1	"	
season	15	6.7	"	
1986/87	30	3.4	CPUE	Allison (1993)
1987/88	32	3.1	"	
1988/89	30	3.3	"	
1989/90	26	3.9	"	
Off Bradda Head				
June 1989	125	0.8	Diving	This study
Dec. 1990	67	1.5	"	
Dec. 1992	33	3.0	"	
Exclusion Zone				
April 1989	250	0.4	Diving	This study
Sept. 1989	167	0.6	"	
Dec. 1989	71	1.4	"	
Nov. 1990	125	0.8	"	
Dec. 1992	77	1.3	"	
June 1992	58	1.7	Dredge	This study
Oct. 1992	38	2.6	"	
June 1993	72	1.4	"	

There is no doubt that the density of scallops on Bradda Inshore has fallen over the period of its exploitation, but past under estimation of towing speed suggests that the scallop densities of Murphy (1986) and Allison (1993) were over estimates despite their low values. As similar assumptions are used to calculate scallop abundance from catch/effort statistics, under estimation of towing speed may have serious consequences.

Temporal variation in scallop density within the fishing season was also found by Murphy (1986). He compared the density of scallops during the first week of fishing on each ground, with that for the season as a whole and found relative changes in density of a similar magnitude to those found here. However, the absolute densities he found were many times greater than those computed here, and actually increased between 1981 and 1984 due to good recruitment on many grounds.

The accuracy of CPUE-based estimates of scallop density is clearly highly sensitive to the accuracy of the assumptions used. While gear efficiency estimates, particularly with respect to the nature of the substratum, will only improve with careful experimentation (Dare *et al.*, 1993 is a good example of this), towing speed assumptions could easily be improved by surveying the skippers of vessels that return logbooks. Towing speed can have a dramatic impact on the way dredges fish (see Shepard 1991 for review) although it may be less important where the dredges are attached to a heavy steel pipe, as in the Manx scallop fishery, rather than directly to the wire warp.

The long-term decline in post-recruit scallop density on the Bradda ground is of obvious concern with respect to falling catches. Of even greater potential consequence is the danger that severely reduced scallop densities may diminish the ability of the stock to reproduce successfully. A stock-recruitment relationship for North Irish Sea scallop species has yet to be established but the available evidence of the persistent nature of the scallop fishing grounds in relatively precise geographical locations (Sinclair *et al.*, 1985), the limited potential for larval advection in the light of recent hydrodynamic modelling of short term residual circulation (discussed by Allison 1993), as well as the possible genetic isolation of queen scallop stocks around the Isle of Man (Lewis, 1992) suggest that the local fishing grounds may well be self-sustaining. Assuming this to be the case, then successful fertilisation may be threatened where scallop densities are reduced, by fishing, to very low levels. Sperm and ova become rapidly diluted by water movements (Pennington, 1985; Levitan, 1991; Levitan *et al.*, 1991; Levitan *et al.*, 1992) and see Denny (1988) and Ryland & Bishop (1993) for discussion of the hydrodynamical considerations. Thus, successful encounters between the gametes of individuals will be dependent on the scallops' spatial distribution . This has been demonstrated for echinoids by Levitan *et al.* (1992), Pennington (1985) and Babcock *et al.* (1992) and see also Stokesbury & Himmelman (1993b) for a discussion of the implications for pectinids. However, even at the low densities calculated here, the characteristic patchy distribution of scallop populations may provide pockets of sufficient density to ensure fertilisation, at a scale imperceptible to dredge sampling (Orensanz, 1986; Stokesbury & Himmelman, 1993a). MacDonald & Bajdik (1992) have suggested that scallops form aggregations when at low density, considered by Stokesbury & Himmelman (1993b) to be an adaptation to increased fertilisation success. The disturbance of these aggregations caused by dredging, will decrease reproductive success. The minimum legal landing size (MLLS) of 110 mm shell length within ICES area VIIa ensures that scallops spawn at least twice (once at the Targets) before becoming vulnerable to direct fishing mortality (Allison, 1993), preserving a minimum spawning-stock. However, this is a small fraction of their potential lifetime reproductive output and pre-recruits are still exposed to the effects of incidental damage from the dredges used by the scallop and queen fisheries. The effects of water movement and spatial distribution of spawning scallops on fertilisation success is a potentially important area of investigation which has yet to be undertaken, but the highly variable results found for echinoids (Pennington, 1985; Levitan, 1991; Levitan *et al.*, 1991; Babcock *et al.*, 1992; Levitan *et al.*, 1992) suggest that the production of zygotes may be far less than the production of eggs and hence population models based on egg production may be misleading.

Differential growth rates within and between fishing grounds mean that recruitment of each cohort occurs over several years in many locations and so the influx of new recruits (≥110 mm shell length) perceived by the fishery at the start of the season, may have come from up to four cohorts (Table 2.7). The fastest growing individuals of a cohort may recruit at age 3, the majority do so at age 4 and 5 and the slowest growing scallops may only recruit at age 6. This protracted recruitment was observed as the recovery of these age-classes over the closed season; recruitment in North Irish Sea scallops is not 'knife-edge' as defined by Ricker (1975).

The recruitment ogives for June 1992 may be unreliable because of inconsistencies in ageing. The difficulties in ageing scallops in June, soon after the formation of the annual growth ring, have been discussed above, but were not fully recognised in June 1992. Comparison with the more reliable results of June 1993 and with those from October 1992 confirm this.

Allison (1993) calculated recruitment ogives from samples of scallops taken over the winter (November - March) when there was little or no growth and so no further recruitment. However, those scallops from a cohort that have recruited represented a diminishing proportion of the age-class as they are removed by fishing over the period of the season. This gives the remaining slow-growing pre-recruits an increasing weighting in the calculation of recruitment ogives (Table 2.7) and ogives calculated in this manner are likely to result in under-estimates of percentage recruitment. The differences between the October 1992 and June 1993 ogives provide an extremely interesting example of the impact of the fishery. On the inshore grounds where the exploitation rate is known to be high (Allison, 1993), the proportion of the cohort that has recruited fell. At the end of the summer growing season, just prior to the start of fishing, 94% of age 4 scallops on Bradda Offshore were ≥110 mm shell length, but by the following June this proportion had fallen to 70% of that cohort (now age-class 5). At Bradda Inshore 70% of 3 year old scallops were post-recruits at the start of the season but by the end only 20% of that cohort that remained was over 110 mm. This severe depletion of post-recruit scallops is a reflection of fishing pressure and was not apparent on less heavily fished grounds. It also demonstrated the dangers inherent in using recruitment ogives from cumulative sampling over the fishing season in the calculation of abundance-at-age as done by Allison (1993).

If it is accepted that scallops grow little after the start of the fishing season on 1st November (Allison, 1993) then the degree of recruitment of each age-class of the population should be assessed just prior to the start of the season. This ‘snapshot’ of the population is far more useful than pooled samples taken over the season as it better represents the state of the fishery as it enters the period of exploitation. Similarly, population age structures should be assessed prior to the fishing season and this distribution used in age-specific density and abundance calculations in combination with CPUE data for the ensuing fishing season. Pooled samples taken over the period of the fishery are liable to lead to errors as the population changes in nature between sampling events, not through recruitment but through total mortality (natural, fishing and incidental fishing mortality combined).

2.4.3 Mortality rates and sources of mortality

It is apparent from the magnitude of the seasonal variations in total mortality rates revealed by the twice-yearly sampling in this work and from previous tagging studies (Murphy, 1986; Allison, 1993), that the scallop fishery is the major source of post-recruit mortality, at least on the more heavily exploited grounds (those inshore and on the west of the Island as well as the Chickens and East Douglas). The rate of Heincke’s total mortality for the fishing season on Bradda Inshore for ages of first full exploitation (a) of 4 and 5 (Z=1.08 and 1.26 respectively) were unrealistic and higher than those calculated by Allison (1993) from sample fleet CPUE and research vessel population age structures (Z=0.62-0.92, a=4). However, at age a=6 Heincke’s Z for the fishing season was 0.72, in the range recorded by Allison. Values for Peel (0.59, 0.75, 0.85, a=4-6) for the fishing season show increasing mortality with age but were also high compared to Allison (1993) (0.21, a=5). The extremely high estimates from my work were, however, inevitable in that they assume that fishing, and hence fishing season mortality rates continued all year. The estimates of Allison (1993) were a combination of high fishing season mortality and lower closed season mortality rates. It is clear from the extrapolated fishing season mortality rates that the scallop populations could not withstand year-round exploitation of the intensity experienced during the fishing season and that the closure of the fishery during the summer is important in preserving stocks.

Total mortality, Z, has three components: natural mortality M, fishing mortality F, and incidental or non-capture mortality F_i. Natural mortality operates all year round but may be liable to seasonal variations related to spawning stresses, food supply, temperature and temperature changes, and seasonal variation in the levels of natural predation. Assessment of M is extremely difficult in populations under exploitation as it cannot easily be separated from fishing mortality. Catch curve methods performed by Allison (1993) on the data of Gruffydd (1974) from a newly-discovered, previously unfished population produced estimates of M in the region of 0.3. This is high, biased as it is by the presence of large numbers of older scallops, which have higher mortality rates than younger age-classes (Gruffydd, 1974). Values of M calculated from tagging studies have yielded a value of M = 0.12 (Allison, 1993) which is similar to that conventionally assumed of 0.15 (Mason *et al.*, 1980; Bannister, 1986; Murphy, 1986; Murphy & Brand, 1987; Mason *et al.*, 1991) and the value of 0.164 for 7 year old scallops from an unfished population calculated by Gruffydd (1974).

Estimates of Heincke's Z for the closed season may potentially provide an additional estimate of M on grounds where there is no summer queen fishery (Bradda Inshore, Bradda Offshore, Peel and the Chickens), as natural mortality acts alone during this period. However, because of extended recruitment on many grounds, the influx of scallops into the exploited portion of the population tended to outweigh natural mortality to produce negative values in the majority of cases. Where Z was positive and the age-classes were fully recruited (Table 2.7), at Peel and the Chickens (Z=0.57 and Z=0.46 respectively, a=6), the estimates were well above the probable bounds of M of 0.1-0.3 suggested by Allison (1993). The population age structures of these grounds showed that scallops older than 6 years were scarce and that these estimates were based on small numbers of individuals. Larger scale sampling of the grounds not exploited by the queen fishery, yielding significant numbers of scallops from older fully-recruited age-classes, might produce better estimates of M, using this method.

Direct fishing mortality (F) results from the removal of post-recruit scallops by the fishing gear and has been estimated by tagging experiments (Gruffydd, 1972; Murphy, 1986; Allison, 1993) to vary greatly on the fishing grounds around the Isle of Man (e.g. from F=0.05 for South-East Douglas to F=0.64 for Bradda (Allison, 1993)). Fishing season mortalities are further increased by indirect, incidental or non-capture mortality (F_i), where damage is done to both pre-and post-recruits that come into contact with the gear and are not caught, and to pre-recruits that are damaged during capture and later discarded as undersized. Part of the damage sustained by undersize discards will be incurred as the dredge contents are emptied on to the deck of the vessel, particularly on the harder grounds where there is a high proportion of stones in the catch (e.g. South-East Douglas, Targets). Allison (1993) estimated indirect fishing mortality to range from 0.12-0.63 on grounds around the Isle of Man, the value being higher on more heavily fished areas, as expected. On grounds with lower fishing mortality rates, values of indirect fishing mortality exceeded those of direct fishing mortality. The indirect impact of the fishery may also be manifested in more subtle effects; altering rates of natural mortality by affecting the dynamics of the benthic community, such as changes in predator and competitor communities (Orensanz *et al.*, 1991), increased susceptibility to variations in environmental conditions due to stresses caused by intensive fishing (Dare, 1974) and increased susceptibility to diseases (McLoughlin *et al.*, 1991). Naidu (1988) estimated that indirect fishing mortality for *Chlamys islandica* off the east coast of Canada may be 4-8 times the rate of natural mortality depending on the type of dredge used. Allison's (1993) upper estimate of incidental fishing mortality (0.63) is approximately 5 times that of his natural mortality estimate of 0.12. These values suggest that a substantial proportion of scallops are wasted due to incidental fishing mortality. Modifications to the fishing gear or fishing methods to reduce the damage sustained by the scallops would reduce this source of non-yield mortality and should be pursued.

The causes and importance of indirect fishing damage have received considerable attention in recent years (reviewed by Caddy (1988), McLoughlin *et al.* (1991) and Orensanz *et al.* (1991)). An indication of the effect of substrate type on the mortality of undersize scallops discarded back to the sea after dredging can be gained from the tagging studies undertaken in the North Irish Sea. Murphy (1986) estimated a constant rate on all grounds of 10% tagging induced mortality, whereas Allison (1993) found spatial variation in this source of mortality, from analysis of the degree of repair by the scallop of the hole drilled in the auricle for the tagging wire. Tagging mortality was found to be much higher on the offshore/south grounds from both releases (9-28.5%), compared to the inshore/west grounds (0-5%). As only outwardly healthy scallops were tagged, and assuming that the process of tagging caused a similar level of mortality on all grounds, the differences in tagging mortality observed between the grounds must reflect differences in the degree of non-visible damage sustained during the fishing process. The offshore grounds are stony and damage to the shells retained in the dredges and then "dragged along a boulder-strewn sea bed in a stone-filled, heavy iron dredge for up to one hour" may well affect their condition in ways not immediately obvious (Allison, 1993). Estimates of incidental mortality from the Irish Sea and elsewhere are summarised in Table 2.11. Gruffydd (1972) suggested that burial and sand-packing may cause mortality due to damage of the mantle, such damage being hard to assess and leading to under-estimation of the rate of incidental mortality on sand.

Incidental mortality is difficult to separate from natural mortality experimentally, particularly as incidental mortality may act by facilitating the same processes as occur in natural mortality including predation and disease. Damaged scallops left in the wake of dredges, as well as undersized discards damaged in the dredges, are more likely to succumb to predators. Predators are readily attracted to high concentrations of prey and to those that are damaged (see also Chapter 5) and will aggregate in the tracks of dredges (Caddy, 1968; Medcof & Caddy, 1971; Chapman *et al.*, 1977; MacDonald, 1993). This aggregation will result in a higher frequency of encounter with predators for both damaged and undamaged scallops. Even slightly damaged scallops are more easily preyed upon by starfish (Medcof & Bourne, 1964), and crustacean predators, whose *modus operandi* is to chip at the shell margin of large scallops to gain entry, will benefit from damage caused by fishing gear (Elner & Jamieson, 1979; Lake *et al.*, 1987 and see also Chapter 5). Naidu (1988) suggested a method of estimating incidental mortality by calculating the ratio of dead but articulated scallop shells ("cluckers") to live scallops in dredge catches. This will, however, under-estimate incidental mortality by excluding those shells which are disarticulated by the dredges at the time of damage and not retained. Shepard & Auster (1991) found this to be among the most common forms of dredge damage. The complete loss of a fishery, due largely to incidental fishing mortality, has been detailed by McLoughlin *et al.* (1991) for *Pecten fumatus* (Reeve 1852) in Australia. Only 12-22% of a newly discovered stock was harvested; the remainder was damaged and the population was subsequently destroyed by a bacterial infection.

The rate of incidental mortality may vary between grounds due to differences in the substratum (Shepard & Auster, 1991) but it is intuitive that incidental damage should increase with increasing fishing effort on a particular ground. That such damage attracts predators has been demonstrated (Medcof & Caddy, 1971; Chapman *et al.*, 1977; Caddy, 1988; MacDonald, 1993) and heavily exploited grounds might be expected to support the greatest densities of predators. It is notable that the highest densities of *A. rubens* and *C. pagurus* observed in my work occurred on Bradda and Peel, which are among the most heavily fished grounds around the Isle of Man. Incidental mortality through increased predation was the likely cause of the

Table 2.11. Summary of data on incidental or "non-yield" fishing mortality from scallop dredge fisheries.

Species	Location	Method	Incidental mortality rate	Reference
Pecten maximus	Irish Sea	Tagging	Natural + incidental mortality = 56.5% (M estimated as 0.10)	Gruffydd (1972)
	"	Laboratory	25-75% of damaged undersized discards likely to die (in absence of predators)	"
"	West coast Scotland	Diver	3% left behind on sand fatally damaged	Chapman *et al.* (1977)
"	Irish Sea	Subtraction of M=0.12 from tagging based estimates of Z	0.12-0.63 Greater on more heavily fished grounds. On grounds with lower fishing mortality rates, indirect mortality exceeds fishing mortality	Allison (1993)
Placopecten magellanicus	Digby/Georges Bank, Canada	Analysis of commercial catches	Average 15% (range 11-42%)	Medcof & Bourne (1964)
"	Gulf St.Lawrence	Diver observations	30% of scallops left in tracks buried in sand	Caddy (1968)
"	Chaleur bay, Québec, Canada	Submersible	13-17% of scallops left in tracks were fatally damaged, greatest on hard ground	Caddy (1973)
"	Swans Island, Maine, USA	Diver	25.5% damaged on rock, 7.7% on sand. 35% mortality of damaged scallops after one encounter with dredges	Shepard & Auster (1991)
Chlamys islandica	Gulf St.Lawrence, Canada	Cluckers	17% Digby dredge, 31% New Bedford dredge	Naidu (1988)
Pecten fumatus	Jervis Bay, Australia	Diver	10% mortality of those missed, 20% damaged and discarded	Butcher *et al.* (1981)
"	Banks Strait, Australia	Diver, reseeding, logbooks, modelling.	High. 12-22% of new stock was harvested, rest wasted by incidental mortality and disease	McLoughlin *et al.* (1991)

decline in pre-recruit abundance observed in my work at Bradda Inshore over the period of the fishery, October 1992 - June 1993.

This decline cannot be due to removal directly by the fishery as the scallops were, by definition, under the legal landing size. Although undamaged scallops are considered to survive being discarded well (allowing the tagging studies of Franklin & Rolfe (1976), Howell & Fraser (1984), Dredge (1985), Murphy (1986) and Allison (1993)), they may be weakened and more liable to predation. Subsequent mortality of damaged discarded scallops was estimated by Gruffydd (1972) to be 25-75% in the absence of predators. Bradda Inshore had the highest predator densities (*Asterias rubens* and *Cancer pagurus*) of all the grounds sampled, and so the decline in pre-recruits may be a combination of high levels of 'natural' predation (predation on healthy, recessed scallops) and predation on scallops made more easily available or damaged incidentally by the fishery. It is difficult to establish a causal relationship between high predator densities, high natural mortality and the impact of the fishery; there was a high recruitment of *Asterias rubens* at Bradda Inshore over the summer of 1992, potentially leading to high predation rates, but high predator densities are more likely to be maintained where prey and carrion are easily available, as provided by incidental fishing mortality over the winter.

On grounds where scallops and queens co-exist (10' and 20' South Port St.Mary, South-East and East Douglas, Point of Ayre and the Targets) incidental fishing mortality may continue to be inflicted on scallops over the summer by the prosecution of the queen fishery, when scallops are nominally protected by a cessation of directed fishing. Some degree of incidental mortality of scallops from the queen fishery is inevitable, particularly as the dredges used for queen fishing (with extra, more closely spaced teeth and smaller belly rings, although not the only gear type) are likely to retain more and smaller scallops than the scallop dredges, which select at a larger size. This may account for the fall in CPUE at 20' South Port St.Mary over the summer. This year-round decline could not be sustained long-term, suggesting that the summer decline in CPUE was due in part to poor recruitment. Recruitment on the offshore grounds is more variable than inshore (Brand *et al.*, 1991a) but still more reliable than many other *Pecten maximus* fisheries (Franklin & Conner, 1980; Franklin *et al.*, 1980).

After providing an exhaustive summary of options available for the further management of the Manx scallop fishery, Allison (1993) recommended a restricted entry licence scheme as the most effective method of reducing total fishing effort. The consequent decline in wasteful incidental mortality from such a reduction in fishing effort adds further weight to this measure.

2.4.4 Predator abundance and impact

The major predators of *Pecten maximus* around the Isle of Man are thought to be *Asterias rubens* and *Cancer pagurus* (Paul, 1981; Brand *et al.*, 1991b), despite the assertion of Briggs (1983) that *A. rubens* played only a minor rôle in scallop and queen predation. Both of these species (and possibly many others) are likely to include scallops in their diet when they are easily available, and forego them in preference to other prey if it is energetically favourable to do so (see Chapter 5 for discussion of optimal foraging with respect to starfish and crabs). The study carried out by Briggs (1983) was on *A. rubens* from an area that was not dredged for scallops and this may explain the apparent contradiction of his work with other observations.

Predation on scallops is undoubtedly higher in fished areas, where incidental damage and stresses weaken individuals and facilitate predation. Opportunistic feeding by starfish and crabs on damaged scallops in dredge tracks has been frequently reported (Medcof & Bourne, 1964; Caddy, 1968; Medcof & Caddy, 1971; Chapman *et al.*, 1977; MacDonald, 1993) and appears common where scallops are exposed to other stresses such as storms (Kalashnikov, 1991) and on-bottom cultivation at high densities (see Chapter 5 for full discussion). It seems likely that a significant proportion of the diet of *A. rubens* and other predatory species may be a consequence of the damage and benthic disturbance caused by the dredge fishery, leading to high predator densities and further elevated predation on scallops. Any relationship might be expected to manifest itself on the heavily exploited inshore west grounds and this may explain the higher predator densities observed at Bradda Inshore and Peel.

The abundance of *A. rubens* appeared relatively constant across all the grounds sampled, both spatially and temporally, with the exception of Bradda Inshore (although Targets was not sampled in October 1992 and the Douglas grounds were missed in June 1992). The greatest abundances of *A. rubens* were recorded at this location and a three-fold increase in numbers was observed from June to October 1992, the majority of which were small individuals apparently recently settled. Future sampling will reveal whether this was a seasonal phenomenon or a stochastic event. The numbers caught fell back by June 1993, although they remained double that of any other ground, and above that at Bradda Inshore in June 1992. Periodic strong year-classes are likely to occur for *A. rubens* (as observed in *A. forbesi* by Loosanoff (1964)), as they do for scallops (Allison, 1993) and they may potentially be linked, as both are dependent on suitable environmental and hydrographic condition during their approximately simultaneous larval phases. The coincidence of successful asteroid recruitment to successful prey settlement has been demonstrated by Sloan (1980), Penney & Griffiths (1984) and Auster (1988). The 1987 year-class of scallops has been suggested by Allison (1993) to have been strong, and in the same year large numbers of *A. rubens* settled on scallop spat collectors placed off the north coast of the Calf of Man (Chapter 3).

The decline in numbers of *A. rubens* over the fishing season at Bradda Inshore may have been due to the dispersion of the large summer settlement or to their mortality. The intensity of dredging on this and the other inshore grounds, may influence the abundance of starfish as many are damaged by the fishing gear. However, the effect of such damage on a species which is capable of regeneration and repair of severe injuries is unclear.

The strong temporal variation in *Cancer pagurus* numbers on the inshore/west grounds was not due to recent settlement as the crabs caught were all mature rather than juvenile. Migration by *C. pagurus* offshore for the winter spawning is commonly perceived by fishermen but the greatest numbers of *C. pagurus* were found inshore in October 1992 with much lower numbers inshore in June. Pearson (1908) working at Port Erin, confirmed the spring/autumn inshore/offshore migration and suggested that the offshore migration was protracted, occurring from September to December. The depth to which the crabs migrated was dependent on location but was generally 20-30 fathoms (36-54 m) and the return inshore migration extended from February to May. This suggests that *C. pagurus* was present inshore at the time of the June survey but was not caught in the dredges, whereas in October (during the offshore migration) they were more vulnerable to dredging, possibly due to greater daytime activity. The definition of what is inshore and offshore with respect to *C. pagurus* is interesting; the same temporal variation in abundance occurred at Bradda Offshore as at Peel and Bradda Inshore, although the sampling site was 3 nautical miles farther offshore. Their migration may extend to the soft sediments to the west of the Isle of Man, as the females require the ability to recess into the substratum to ensure that the eggs adhere to the pleopods after spawning (Edwards, 1979). As only females are thought to migrate substantial distances, sex determination of those crabs recovered during future research vessel surveys may prove instructive.

Long distance migrations of female *C. pagurus* observed from tagging studies by Edwards (1979; 1988) were considered to be compensatory mechanisms for the advection of their larvae during the dispersive planktonic phase. By contrast, the offshore movements were thought to facilitate spawning and egg attachment.

The larvae of *C. pagurus* have a 23-30 day planktonic phase (Lebour, 1928) and are found in the waters of the Irish Sea over the summer months, with maxima occurring in May, September and October (Williamson, 1956). Thus hatching and release of larvae occur when the females are inshore, and juvenile *C. pagurus* have been commonly observed in inshore dredge and trawl catches (Pearson, 1908) and to have settled on scallop spat collectors (Whittington, 1993 and this work) suggesting that net larval advection is low. This may have implications for the degree of dispersal of scallop larvae originating in the inshore waters. The larvae of *Pecten maximus* and *Cancer pagurus* occur in the plankton simultaneously and will be subject to similar hydrographic influences (albeit modified by larval behaviour, diel vertical migrations etc.). The fact that *C. pagurus* release their larvae inshore off the west coast of the Isle of Man might be taken as supporting evidence that the inshore scallop grounds are self-sustaining. A tagging study similar to that carried out by Edwards (1979) on the Yorkshire coast, would be useful to investigate whether long distance migrations are undertaken by crabs living on the scallop fishing grounds around the Isle of Man, and might also provide some indication of the fate of scallop larvae spawned in Manx waters.

The impact of the other potential predator species is unknown but octopus in particular are major scallop predators in some regions, to the point of precluding on-bottom cultivation (Cochard *et al.*, 1991).

2.5 CONCLUSIONS

Twice yearly dredge sampling undertaken before and after the scallop fishing season provides a useful increase in temporal resolution for the analysis of the fishery, particularly as the processes acting on the populations are so different within and outside the fishing season.

The limited survey regime is adequate for the highly exploited grounds where changes in abundance of individual age-classes are significant. These changes are maximised by sampling at either end of the period of exploitation. On the grounds where changes in abundance are less pronounced, the extent of the sampling regime is insufficient for accurate assessments. Additional sampling on these grounds may not be justified because the small changes in age-class abundance and the broad age-class representation are in themselves evidence of low levels of fishing effort. While current levels of monitoring should be continued, these grounds do not appear to be under immediate threat.

Survey effort on the heavily exploited inshore grounds should be increased to provide a larger sample of scallops on which to base an annual 'snapshot' assessment of age structure and of age-class size distribution from which to construct recruitment ogives.

Bradda Offshore should be sampled as a separate site rather than as an adjunct to Bradda Inshore. There are obvious contrasts between these sites, particularly with respect to the abundance of predatory species. The Bradda ground straddles the 3-mile limit within which there are greater restrictions on fishing gear and vessel specifications, and so provides a convenient opportunity to examine the effects of these restrictions. However, commercial fishing effort on the inshore and offshore portions of this fishing ground cannot be resolved at the scale of the 5 × 5 nautical mile grid used in the fishermen's logbooks.

Age-% frequency distributions, research vessel CPUE and density estimates as well as total mortality rate estimates confirm that exploitation remains biased towards the inshore fishing grounds. Only East Douglas shows signs of heavy exploitation among the offshore grounds.

On grounds that are not fished for *Aequipecten opercularis*, Heincke's Z, total mortality rate for fully exploited age-classes based on changes in abundance, may be used to estimate natural mortality M, over the period of the closed season.

Incidental fishing mortality may cause considerable losses of scallops, even during the closed season on grounds where the queen fishery is prosecuted.

The decline in post-recruit scallop density on the Bradda Inshore ground appears to have continued since the work of Allison (1993), albeit subject to doubts over the assumptions used in past assessments.

SCUBA diver surveys in 30m+ depth are not suitable for scallop density assessment where densities are known to be very low. Further work on the use of towed cameras is likely to provide the best non-destructive sampling method.

CHAPTER 3

PECTINID SPAT COLLECTION AROUND THE ISLE OF MAN

3.1 INTRODUCTION

There is global interest in the cultivation of scallops, following the equally widespread decline in wild fisheries for many species (see chapter 14 of Shumway (1991) for review). A prerequisite for any successful scallop cultivation industry is a reliable supply of spat, a requirement that has lead to extensive research into both hatchery techniques for larval rearing (Comely, 1972; Gruffydd & Beaumont, 1972; Costello, 1973; Beaumont *et al.*, 1982; Beaumont, 1986; Bourne, 1991; Dabinett, 1991; Ballantyne & Williams, 1993; Millican, 1993) and collection of naturally occurring spat by the use of artificial collectors (Slater, 1977; Buestel *et al.*, 1979; Brand *et al.*, 1980; Ventilla, 1981; Fegan, 1983; Goodwin *et al.*, 1985; Ruzzante & Zaixso, 1985; Paul, 1985a; Fraser, 1987; Hortle & Cropp, 1987; Roman & Cano, 1987; Aoyama, 1988; Bonardelli, 1988; Coleman, 1988; Ito & Byakuno, 1988; Miller, 1988; Bull, 1988a; Ambrose Jr & Peterson, 1989; Sumpton *et al.*, 1990; Burnell *et al.*, 1991; Ruiz-Verdugo & Caceres-Martinez, 1991; Brand *et al.*, 1991b; Young *et al.*, 1992). Some species have proven more amenable to larval rearing than others; the American bay scallop now supports a culture industry in China producing some 50 000 tonnes live weight annually, all from hatchery produced seed (Chew, 1990; Zhang, 1991; Jian-Guang, 1993). However, for many pectinid species the collection of naturally occurring spat remains the only successful or economical source of spat for cultivation (Ventilla, 1982; Cropp & Frankish, 1988; Bull, 1988b).

Scallop spat collection techniques developed in Japan, starting in the 1930s with cedar twigs as the settlement surface (Kinoshita (1935) cited in Ventilla 1982)). Synthetic materials later replaced the natural ones and in the 1960s the fundamental step of enclosing the settlement substratum in a mesh bag increased yields from the collectors to commercial levels (Ventilla, 1982). Spat collection now operates on massive scale (1.8×10^9 spat in 1984 (Ito, 1991)), supplying a culture industry that produced 341 618 t fresh weight of scallops in 1988 (Ito, 1992).

The rationale behind the use of artificial substrata for the collection of scallop spat and the factors affecting collector efficiency are reviewed in Chapter 1.

The first scallop spat collection at Port Erin was carried out in 1975 as part of a study into the biological feasibility of pectinid cultivation (Brand, 1976). Further experimental collection continued intermittently until 1984, with modifications to collector design, at various locations around the south of the Isle of Man (Paul, 1978; Brand *et al.*, 1980; Duggan, 1987; Brand *et al.*, 1991b). All of these collections have been experimental and carried out on a relatively small scale.

The mean numbers of scallop and queen spat recorded on collector bags by previous workers have been highly variable both between years and between sites. The highest settlement of *A. opercularis* was recorded at the North Calf in1983, with a mean number of spat per onion bag of 411 (Duggan, 1987). The following year, the maximum settlement recorded for *P. maximus* occurred at the same location, 80 spat per onion bag. The North Calf has been the most productive site for the collection of both pectinid species and on that basis was chosen as the site at which bulk collection was attempted.

Prior to this study there had only been one attempt to collect pectinid spat on the east coast of the Isle of Man (Coles, unpublished data summarised in Brand *et al.*, 1991b). The mean settlement of spat on these onion bag collectors was <1 individual, for both species. This remarkably low settlement appeared inconsistent with the known presence of *P. maximus* close by the Derbyhaven site used.

3.1.2 Aims of the work

This work aims to continue and expand the data series of spat collection carried out around the Isle of Man since 1975, using comparable methods at some of the same locations that have previously been used, in order to examine inter-annual variations in spatfall. Further, previous work (Coles, unpublished) indicated that spatfall on the east coast may be substantially lower than the levels observed at the better studied west coast sites (Brand, 1976; Paul, 1978; Brand *et al.*, 1980; Duggan, 1987). This spatial variation has been studied by setting experimental collectors at several locations on the east and west coasts.

Previous spat collection carried out around the Isle of Man has been restricted to experimental, small-scale arrays of collectors suspended from individually anchored vertical lines. This study has attempted larger scale bulk collection of pectinid spat using modified Japanese longline techniques to assess the potential for commercial scale spat collection as a precursor to a local scallop cultivation industry.

The optimum design of spat collector is likely to be location and species specific and thus trials have been carried out with various types of collector in addition to the traditional onion bag collector; the 'humbug' design of collector used in Scotland for spat monitoring (Fraser, 1983a; Fraser, 1991) has been tested as has an alternative onion bag more akin to that used in Japan.

The importance of correct timing of spat collector placement is well known and the times of peak settlement for *P. maximus* and *A. opercularis* have been studied using pairs of collector strings deployed for short periods over the summer months (Paul, 1978; Duggan, 1987). The effect on spat yield of collector timing has been further studied by setting collectors at different times, but retrieving them simultaneously in the autumn as would be the case under commercial conditions.

3.2 METHODS

The design of spat collection equipment varied between years and so the methods used each year are treated separately. In particular the design of the longlines evolved as experience was gained in their use, as did the sorting methods. A standardised design of onion bag collector was used throughout this work, with some additional designs used in 1989.

The 'standard onion bag' collectors were made by loosely stuffing an onion bag[1] (500 mm × 600 mm, 10 mm × 3 mm mesh size) with 1.5 m^2 of 6 mm × 6 mm plastic mesh[2] (total surface area available for settlement approximately 1.90 m^2, based on $\pi \times$ diameter of monofilament × total length of monofilament). The drawstring on the top of each bag was tied and the string passed through the lay of the rope and tied. To increase security the bag and a portion of the filling was also attached to the rope by a plastic cable tie[3]. Care was taken to ensure a part of the mesh filling was caught by the cable tie in order to stop the filling from compacting at the bottom of the bag when in the sea.

3.2.1 1987 spat collection

Two longline systems (Figure 3.1) were placed just off Kione Beg, north Calf of Man on 23rd June 1987 (Figure 3.2). The longlines were placed perpendicular to the shoreline, and the prevailing currents. 40 strings of 10 standard onion bag collectors were attached to each line the following day, with a small concrete weight at the bottom to help maintain the correct position in the water.

The North Calf collectors were checked by divers on 14th July. One of the longlines had partially collapsed and some of the collectors had been dragging on the sea bed. The collectors appeared heavily fouled. *P. maximus* and *A. opercularis* spat were visible in the collectors but there was also a very heavy settlement of the starfish *Asterias rubens.*

The spat collectors were brought in to the Laboratory from 28th September to 29th March 1989, and stored in tanks of running aerated sea water, or in sea water storage ponds, until sorting. Each collector bag was opened and the filling removed. The filling and the bag were each rinsed and shaken in a 600 l tank of sea water to remove the settled spat. A 5 mm mesh screen was then lifted from the bottom of the tank to recover the contents of each collector. This screen was 'panned' to float off the majority of unwanted organisms and the pectinid spat were separated by hand.

---

[1] Superscripts refer to key of materials and suppliers, Appendix 3.

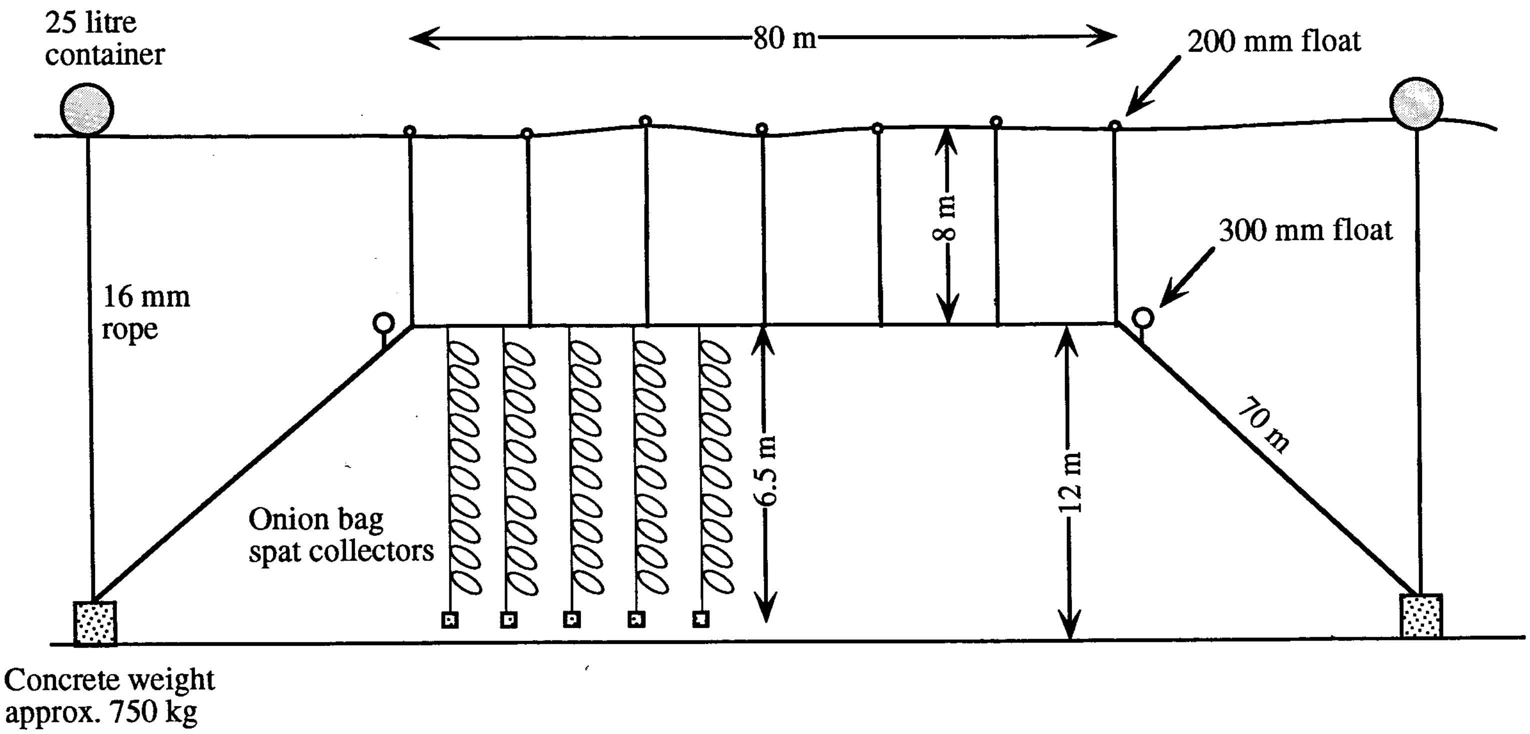


Figure 3.1 Spat collection longline North Calf, 1987.

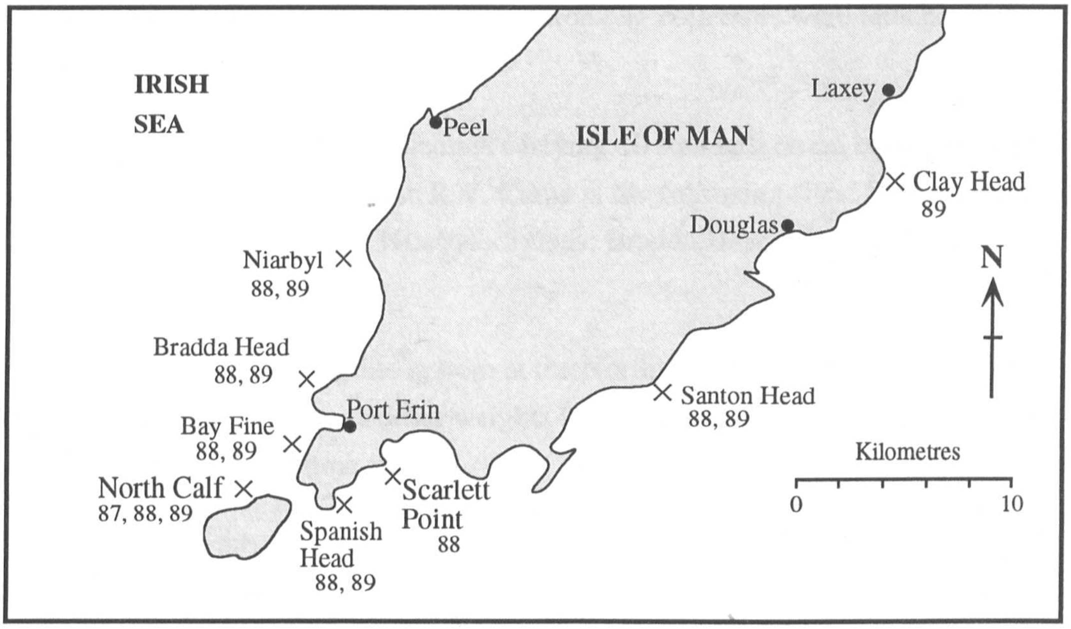


Figure 3.2 Sites at which spat collection trials were carried out, 1987-89. Crosses mark locations and figures indicate years when collectors were placed at each site. All collectors used were experimental single line collectors, except North Calf where collectors were suspended from subsurface longlines.

The sorted spat were maintained in stacks of wooden framed trays with a 5 mm mesh bottom to allow water circulation. 12 strings of 10 collectors were sorted in detail to provide data on the number of spat per bag. Shell heights (from hinge to ventral margin) of spat were measured to 0.1 mm with dial callipers.

3.2.2 1988 spat collection

Two longlines were put out at Kione Beg, North Calf, on 23th June, 1988. These were modified from the previous year, with double warps and anchor blocks to improve stability (Figure 3.3). They were placed perpendicular to the shore and prevailing currents. Forty 6 m strings of 10 onion bag collectors were attached to the longlines on 28th and 29th June.

On 30th June single line collectors carrying 10 standard onion bag collectors (Figure 3.4) were deployed from the R.V. Cuma at the following sites: Scarlett Point - 2 lines; Spanish Head - 5 lines; Niarbyl - 5 lines; Bradda Head - 8 lines (Figure 3.2).

The most westerly longline system at the North Calf became tangled on 5th July and by 18th July all four mooring weights had been drawn inward, allowing the system enough slack to become tangled.

On 6th September the remaining easterly system at North Calf appeared collapsed at the landward end, and diving revealed that a string of lobster pots had been shot over the system. The bags were very heavily fouled.

Two sorting methods were used in 1988: a large tank (800 l) was set up in which to rinse the spat collectors, fitted with a 5 mm mesh frame over the base of the tank which could be raised to recover the sorted spat. The second method used plastic household dustbins, half full of sea water in which to do the sorting. After 10 collectors had been sorted the bin was tipped up and its contents poured through a 5 mm mesh to retain the spat. Where collectors were sorted and analysed in detail then the spat were recovered from individual collectors. Three collectors from a single line from each site (bags 2, 5, and 9 from Niarbyl, Bradda Head and Scarlett Point) were sorted in detail and all the settled organisms identified to genus or species where possible. The pectinid spat from all of the single line collectors were counted and measured to 0.1 mm with dial callipers.

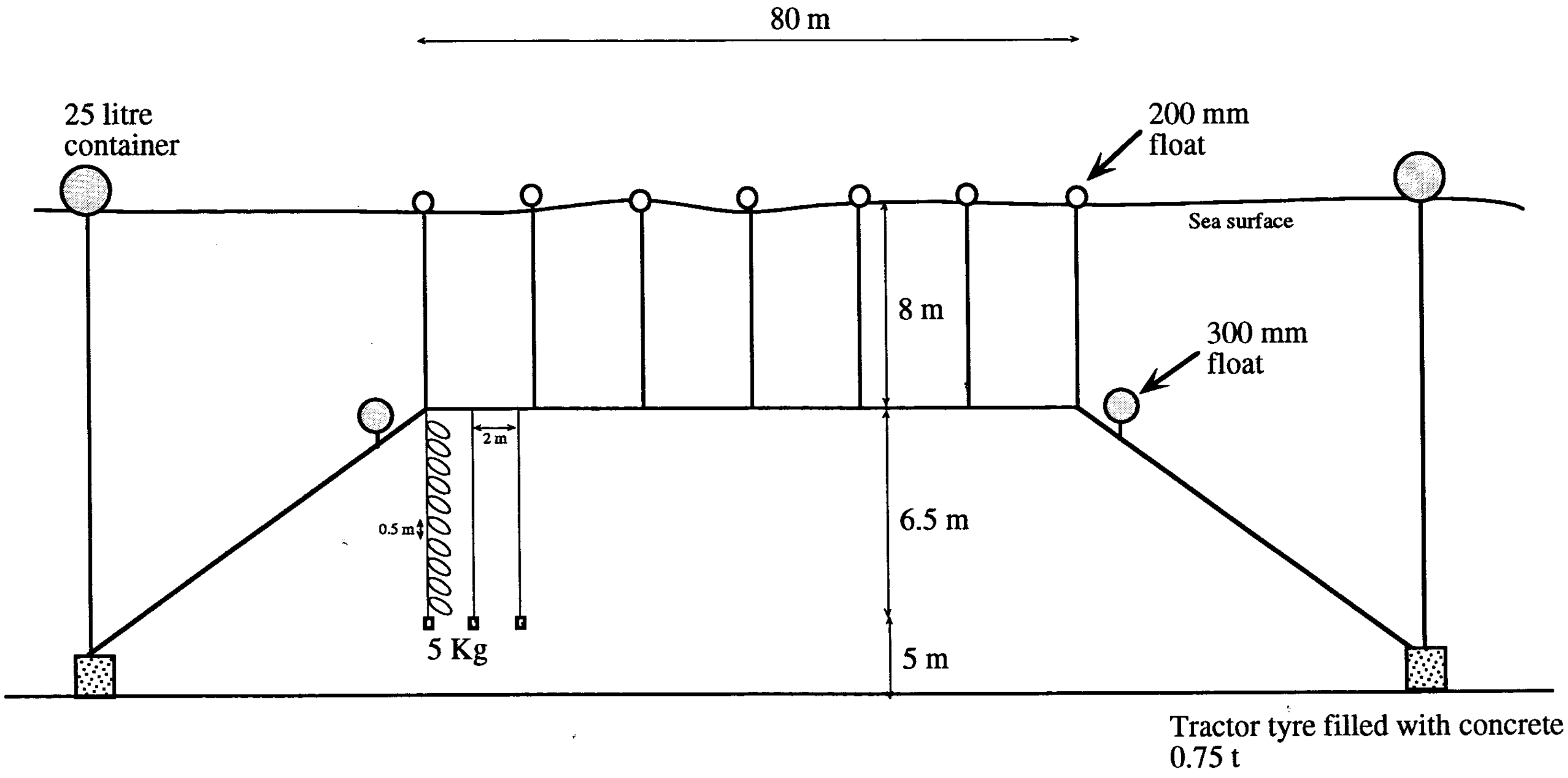


Figure 3.3 Spat collector longline, North Calf, 1988.

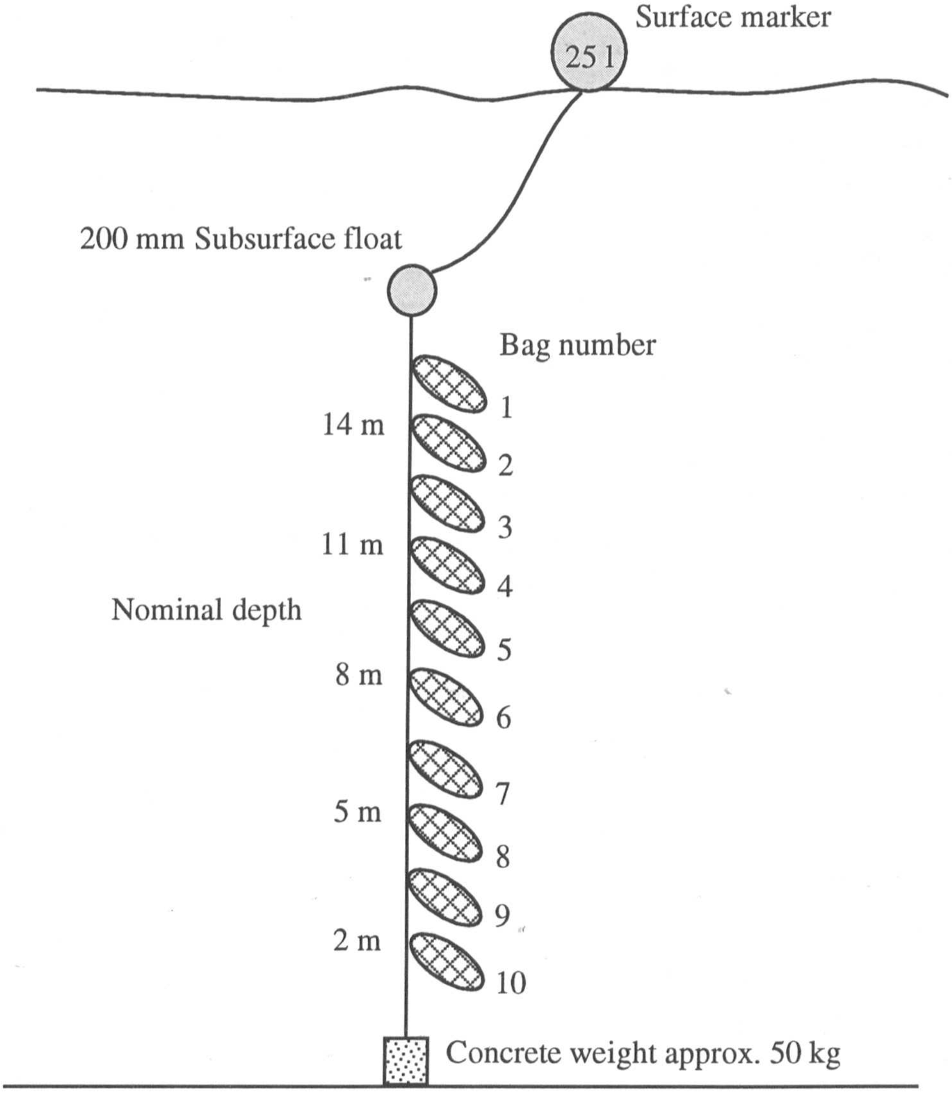


Figure 3.4 Experimental single line collector design, 1988. All collectors placed at approximately 20 m depth below CD.

3.2.3 1989 spat collection

Two longlines were again put out at Kione Beg, North Calf, on 26th June 1989. The design of the systems was further modified with weighted downlines in the middle and at either end of the headrope (Figure 3.5). The systems were also set parallel to the shore and direction of the prevailing current. Forty 6 m long weighted droppers, each carrying 10 onion bag collectors, were attached to the inshore system on the 6th July, 1989. Strings of collectors were attached to the offshore system on the 7th and 10th July. Half of the spat collectors attached to the offshore system were of the Japanese design; woven from pink round section plastic, 360 × 500 mm, mesh size 7 × 2 mm, filling 0.75 m^2 of the same 6 × 6 mm Netlon mesh as the standard collectors, total available surface area for settlement approximately 0.95 m^2.

Three single line collectors were placed in Strangford Lough, Northern Ireland on 22th June (55° 23.20' - 55° 23.28'N, 05° 36.65' - 05° 36.85' W). These lines were never recovered as they disappeared during September (Alistair Davidson, Northern Ireland Aquarium, personal communication).

Groups of three single line collectors, each carrying 6 onion bags (Figure 3.6), were placed at three sites on the east and three sites on the west coast of the Isle of Man (Figure 3.2). Collectors were set on 27th June at Clay Head, Santon Head and Black Head, and on 30th June identical groups of collectors were placed at three sites on the west coast of the Island: Niarbyl, Bradda Head, Bay Fine. At North Calf three strings of 5 'humbug' style collectors (1 m × 0.5 m with the ends closed perpendicular to each other to create a 'humbug' shaped tetrahedron, filled with 8 m^2 of 19 mm green diamond mesh netting, total available surface area approximately 3.31 m^2) were placed on 30th June to test them in comparison with onion bags. However, due to the density of lobster pots along the coast at North Calf it was not deemed safe to place further single lines of onion bags at the site and so comparisons between the humbugs and onion bags were restricted to the onion bags on the longline systems.

A further three single lines of onion bag collectors were placed off Bradda Head on 19th July (20 days after the first wave of collectors were set) to investigate temporal variations in spat settlement.

Retrieval of spat collectors began on 6th September. Each collector was individually bagged, labelled and frozen. All three lines were recovered from Clay Head and Santon Head. Single lines from Bradda Head, Niarbyl and Bay Fine were recovered on 21st September: all of the first group of collectors from Bradda Head

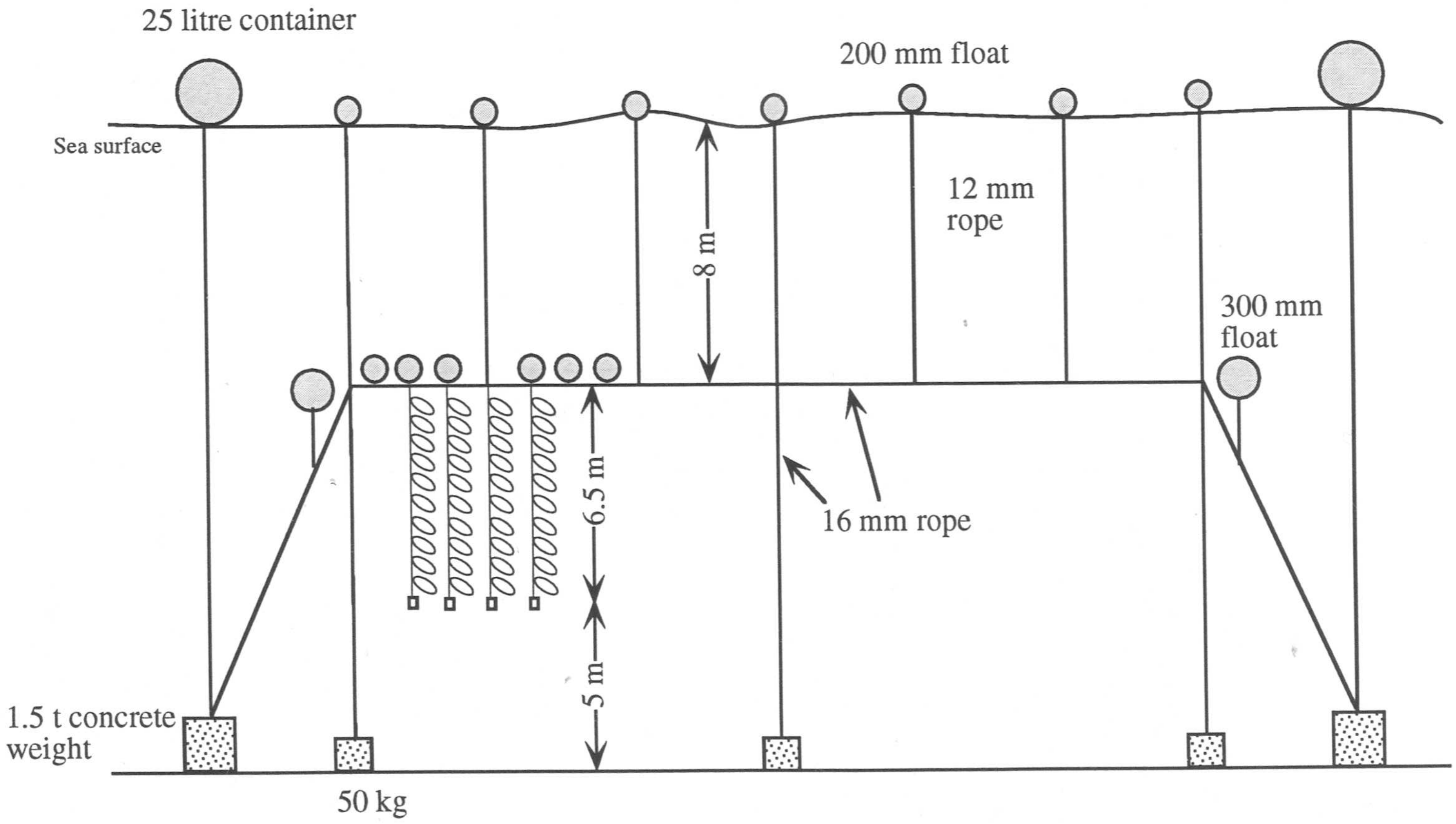


Figure 3.5 Spat collection longline North Calf, 1989. Additional weighted downlines to seabed added stability.

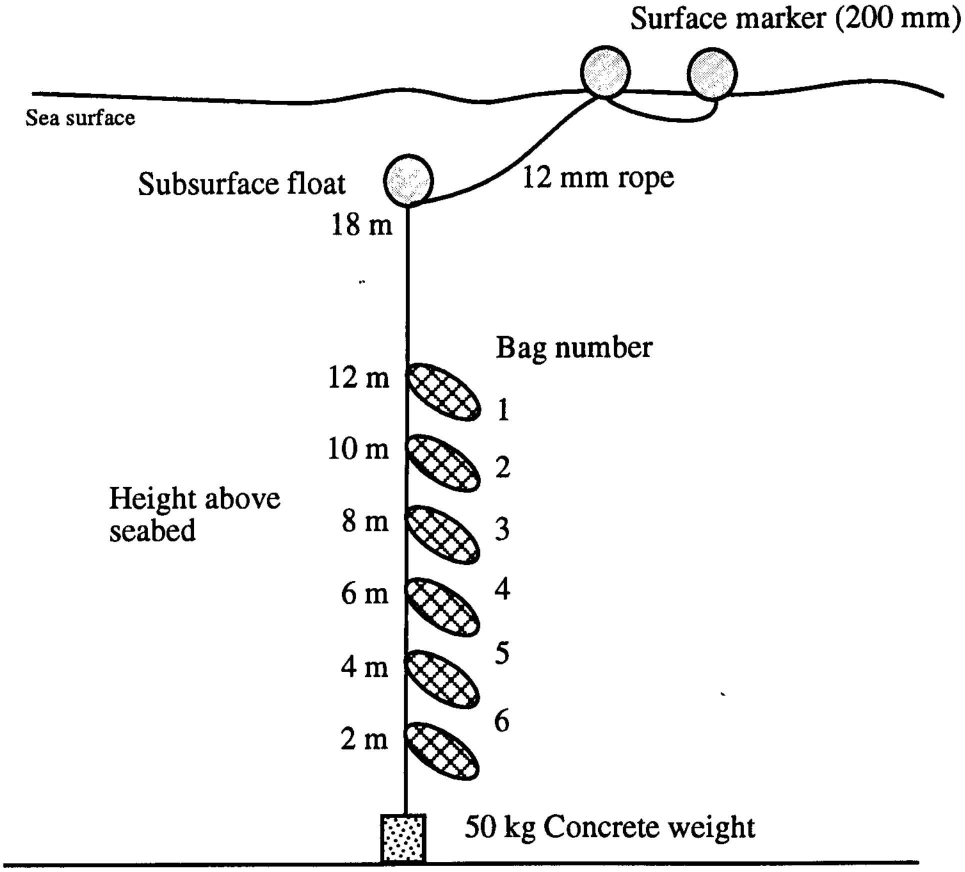


Figure 3.6 Experimental single line collector design, 1989. All lines placed at approx 20m below CD.

were recovered but only one of the later set could be found, two out of the three lines from Bay Fine and all of the lines from Niarbyl were recovered. Two of the three single lines of humbug collectors placed at North Calf were found on 22nd September, one of which had lost three collectors.

Three lines of collectors from one of the North Calf longlines (30 onion bags) were bagged and frozen on 14th November, and the rest brought in for immediate sorting. The resulting spat were placed in pearl nets and returned to sea for intermediate culture (Chapter 4).

The collectors from 1989 were sorted in dustbins half filled with sea water, using the same technique as 1988. Collectors sorted in detail were individually sorted in shallow dishes or in a dustbin, with the bin emptied through a 500 µm mesh to retain all size classes of scallops. All the pectinid spat were counted and those from selected bags were measured to 0.1 mm using dial callipers. The organisms from one line of six collectors from each location were identified to genus or species where possible for use in community analysis.

3.2.4 Multivariate community analysis

Species data from the collector bags examined in close detail from 1988 and 1989 were compared using cluster analyses and multi-dimensional scaling. Data matrices of species presence-absence were compared by hierarchical clustering (using group average linkage) of Bray-Curtis similarities and non-metric multi-dimensional scaling of Bray-Curtis similarities. Analyses were carried out using Primer v3.1a (Plymouth Routines in Multivariate Ecological Research, Plymouth Marine Laboratory).

3.3 RESULTS

3.3.1 1987 spat collection

The spatfall of *A. opercularis* was considerable greater than that of *P. maximus* (Table 3.1); the mean number of spat collected per bag was over six times higher (145 ± 3.3 SE *A. opercularis* c.f. 23 ± 0.8 *P. maximus*). There was an increase in the mean number of spat per collector bag with increasing depth for both *P. maximus* and *A. opercularis*, although this trend was more obvious for *P. maximus* where there was an increase of >50% in settlement between the top and bottom collectors (Figure 3.7*a, b*). The highest number of both species settled in the lowest collectors at a nominal depth of 10 m below the surface, which was approximately in midwater.

Size frequency distributions of live pectinid spat from one string of ten collectors revealed a single mode for each species, suggesting that there was a single pulse of larval settlement in each case (Figure 3.7*c, d*). The modal shell height for *P. maximus* was between 12-14 mm but that for *A. opercularis* was lower at 10-11 mm. There were notable differences in the shapes of the distributions of the two species; that of *P. maximus* was skewed to the right while that for *A. opercularis* was much more symmetrical.

3.3.2 1988 spat collection

A large proportion of the single line collectors were lost over the summer, before retrieval. Only three lines from eight were recovered from Bradda Head, one out of two from Scarlett Point and two out of five from Niarbyl. All five single lines from Spanish Head were lost; the only data available from the east coast of the Isle of Man was from the one line remaining at Scarlett Point.

The mean number of *A. opercularis* spat settling on the longline collectors at the North Calf in 1988 was approximately 9 times greater than the settlement of *P. maximus* (182 ± 25.5 SE c.f. 20 ± 4.2). The mean number of *P. maximus* spat per collector was slightly lower in 1988 than 1987 while for *A. opercularis* there was an increase in numbers (Table 3.1).

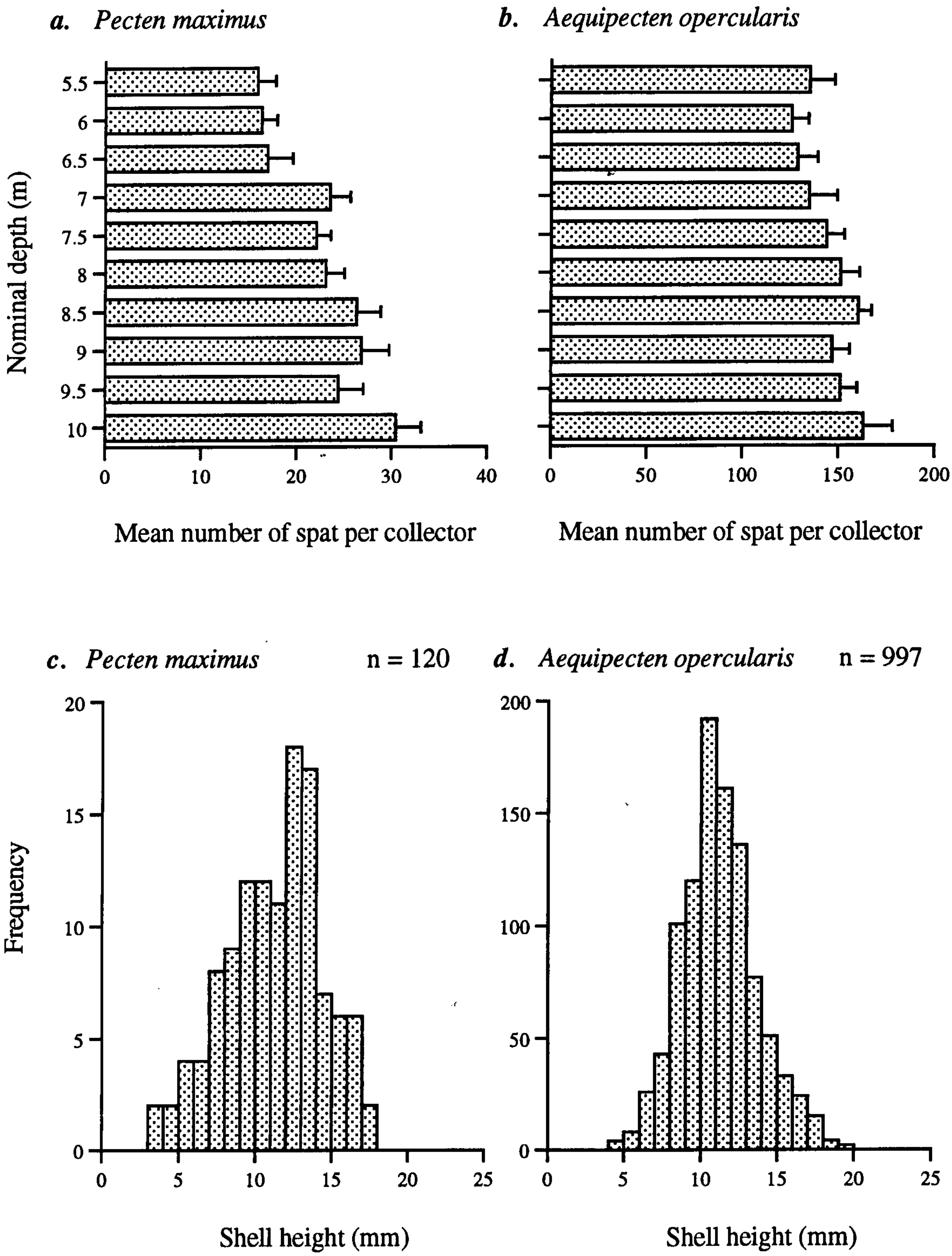


Figure 3.7. Settlement of pectinid spat on longline onion bag collectors placed at North Calf in 1987. Depth distribution of settlement (mean number of spat per collector + SE) for ***a*. *Pecten maximus*, *b*. *Aequipecten opercularis*.** n =11 or 12 replicates at each depth. Size frequency distributions of ***c*. *Pecten maximus*, *d*. *Aequipecten opercularis*** from spat collectors. Note variation in scale of the axes.

Table 3.1. Summary of pectinid settlement (number of individuals ± SE) on spat collectors placed around the Isle of Man, 1987-89. Collectors were standard onion bag collectors suspended from bottom anchored single lines except North Calf (longline).

	P. maximus			*A. opercularis*			*C. varia*
Site	1987	1988	1989	1987	1988	1989	1989
West Coast							
Niarbyl		13 (1.7)	**122** (12.6)		134 (12.7)	**439** (57.9)	**442** (65.7)
Bradda Head		**30** (4.6)	54 (3.9)		166 (13.2)	273 (15.8)	153 (18.7)
Bay Fine			27 (3.1)			176 (29.1)	75 (12.7)
North Calf							
Onion bag	23 (0.8)	20 (4.2)	12 (1.3)	145 (3.3)	**182** (25.5)	226 (12.2)	47 (5.8)
Pink bag (longline)			6 (0.9)			109 (8.7)	36 (7.1)
Humbug			39 (9.0)			412 (37.1)	73 (16.5)
East coast							
Spanish Head			2 (0.3)			25 (2.3)	0.7 (0.4)
Scarlett Point		1.8 (0.6)			7 (0.9)		
Santon Head			0.3 (0.2)			4 (0.8)	0.1 (0.1)
Clay Head			0.7 (0.2)			9 (2)	0

The mean number of *P. maximus* and *A. opercularis* spat that settled on the single line collectors in 1988 was much greater on the west coast sites (Bradda Head and Niarbyl) than on the east coast (Scarlett Point, Table 3.1). The intensity of spat settlement at the North Calf was closer to the levels observed at the other west coast locations rather than to the sites on the east coast. The maximum mean number of *P. maximus* spat per collector was 30 (± 4.6 SE) at Bradda Head; for *A. opercularis* the highest mean settlement was at the North Calf (182 ± 25.5 SE).

The mean number of *A. opercularis* that settled per bag was far in excess of the settlement of *P. maximus* but the pattern of greatest settlement on the west coast was repeated: Bradda Head 166 ± 13.2, Niarbyl 134 ± 12.7, Scarlett Point 7 ± 0.9.

The depth profile of *P. maximus* settlement exhibited a bias towards the deeper placed collectors at all locations, on both the longline and the single lines. The distribution of *A. opercularis* spat was generally less variable over the depth range covered by the collectors with peak settlement usually occurring higher in the water column than for *P. maximus.*

Information about the depth distribution of pectinid settlement from the North Calf was only available from a single line of collectors. However, the distribution of settlement showed an obvious bias towards a greater settlement with increasing depth for both species, with the relative variation in numbers collected per onion bag being greater for *P. maximus* than for *A. opercularis* (Figure 3.8*a, b*). The poor settlement at the 9 m depth for both species was probably due to a fault with the individual collector bag (a failure to attach the mesh filling firmly to the rope occasionally resulted in the mesh becoming compacted at the bottom of the bag, leading to a poor collection because of the reduction in available settlement area). A low settlement was also observed in the bottom collector bag at 10 m depth.

The depth distribution of *P. maximus* spat at Bradda Head (Figure 3.8*c*) revealed an increase in settlement with increasing depth, to a maximum spatfall of over 50 per collector 13.5-16.5 m below CD. There was then a decline in settlement in the lowest collectors to just over 30 spat per collector bag. *P. maximus* settlement at Niarbyl (Figure 3.8*e*) was very poor in the upper collectors (≤ 5 per bag between 4.5-7.5 m), but increased rapidly to a peak settlement at 12 m (25 per collector bag) before steadily declining towards the seabed, where there were only 13 spat per collector. However, the decline in settlement with depth towards the seabed commenced higher in the water column at Niarbyl than at Bradda Head. Settlement of *P. maximus* at Scarlett Point (Figure 3.8*g*) was very low, with a maximum at 12 m depth of only 5 spat per bag. There was no *P. maximus* settlement in the bags at 16.5 and 18 m.

The depth distributions of *A. opercularis* at Bradda Head and Niarbyl were similar to those for *P. maximus* but a greater proportion of the settlement occurred lower in the water column (Figure 3.8*d, f*). At Niarbyl the heaviest spatfall was at 12 m as observed for *P. maximus* but settlement was more uniform over the depth of the water column covered by the spat collectors. At Bradda Head the shape of the depth distribution was very similar to that for *P. maximus* at the same site although there was a very distinct peak of settlement at 10.5 m depth, 3 m shallower than for *P. maximus*. The settlement of *A. opercularis* on the east coast at Scarlett Point was extremely low in comparison to the west coast sites with a maximum of 13 spat per bag at a depth of 15 m (Figure 3.8*h*). There was, however, spat settlement in all of the bags including those closest to the seabed.

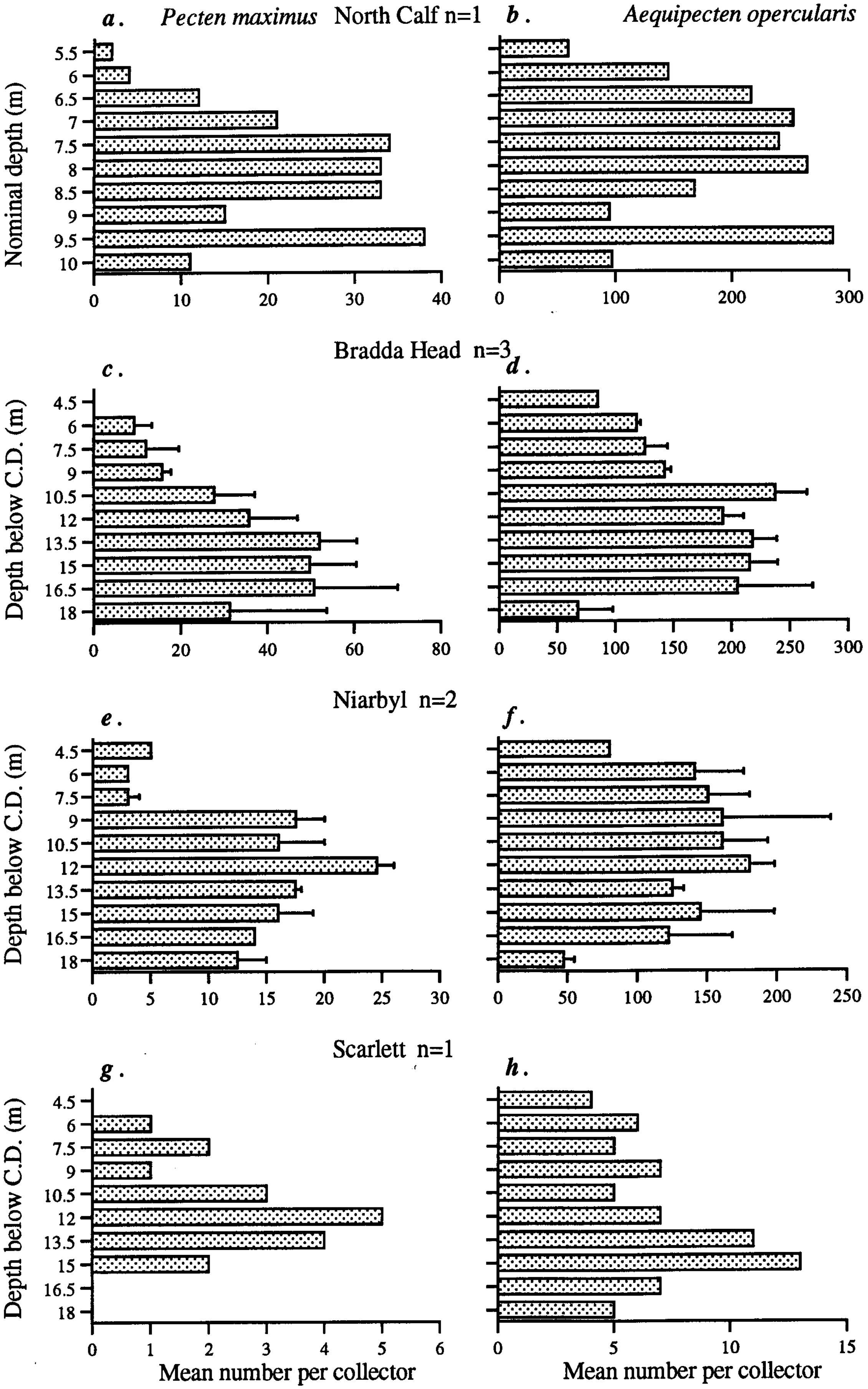


Figure 3.8. Depth distribution of *Pecten maximus* and *Aequipecten opercularis* spat on onion bag collectors around the Isle of Man in 1988 (mean number of spat +SE, water depth 20 m below CD). ***a.*** North Calf (longline) ***b*** . Bradda Head ***c.*** Niarbyl ***d*** . Scarlett Point. n = number of replicates lines. Note variation in scale of the axes.

The size frequency distribution of *P. maximus* spat from the North Calf, although based on a relatively low number of spat (n = 132) showed a broad range of shell heights with a single poorly defined modal peak between 14-17 mm shell height (Figure 3.9*a*).

The Bradda Head distribution was unimodal, with a large spread of data (shell heights 3-20 mm) and a mode of 14-15 mm (Figure 3.9*b*). The size frequency distribution of *P. maximus* from Niarbyl was bimodal although the separation of the modes was not distinct enough to suggest that there had been two settlements (Figure 3.9*c*). The total settlement of *P. maximus* at Scarlett Point was very low (n = 18) and so the size frequency distribution was not reliable, although the modal shell height was smaller (10-11 mm) than at Niarbyl or Bradda Head, which were sampled at the same time (Figure 3.9*d*). This may suggest that the settlement of *P. maximus* was later on the east coast or that the rate of growth was greater on the west coast.

There was evidence of two modes in the size frequency distribution of *A. opercularis* where the number of spat measured was large (North Calf n = 1 287, Niarbyl n = 1 736, Bradda Head n = 3 603), suggesting two peaks in spat settlement at all of these sites (Figure 3.10*a-c*).

At the North Calf there were modal peaks at 16-17 mm and at 9-10 mm shell height. This latter mode may include some *Chlamys varia* which were not separated from the smaller queens in 1988. The wide range of shell sizes covered by the distribution may also suggest that spawning was protracted or that there was more than one settlement of larvae.

At Niarbyl and Bradda Head there were common modes at 15-16 mm and 5-7 mm shell height (Figure 3.10*b, c*). This suggests that there were at least two waves of *A. opercularis* settlement at these sites.

Interpretation of the size frequency distribution of *A. opercularis* from Scarlett Point was complicated by the small number of spat recorded (n = 69) and hence many of the size classes had very low frequencies (Figure 3.10*d*). There was a mode at 9-11 mm shell height and a further peak at 5-6 mm, similar to the secondary modes at Bradda Head and Niarbyl. This may suggest that on the east coast the first settlement occurred later or that there were fewer settlements than on the west coast.

The modal peaks for *P. maximus* and *A. opercularis* from the North Calf longline were of a larger shell height than those from the single line collectors, reflecting the further month that the North Calf collectors spent at sea. The single lines were sorted on 4th and 5th October whereas the North Calf bags were sorted

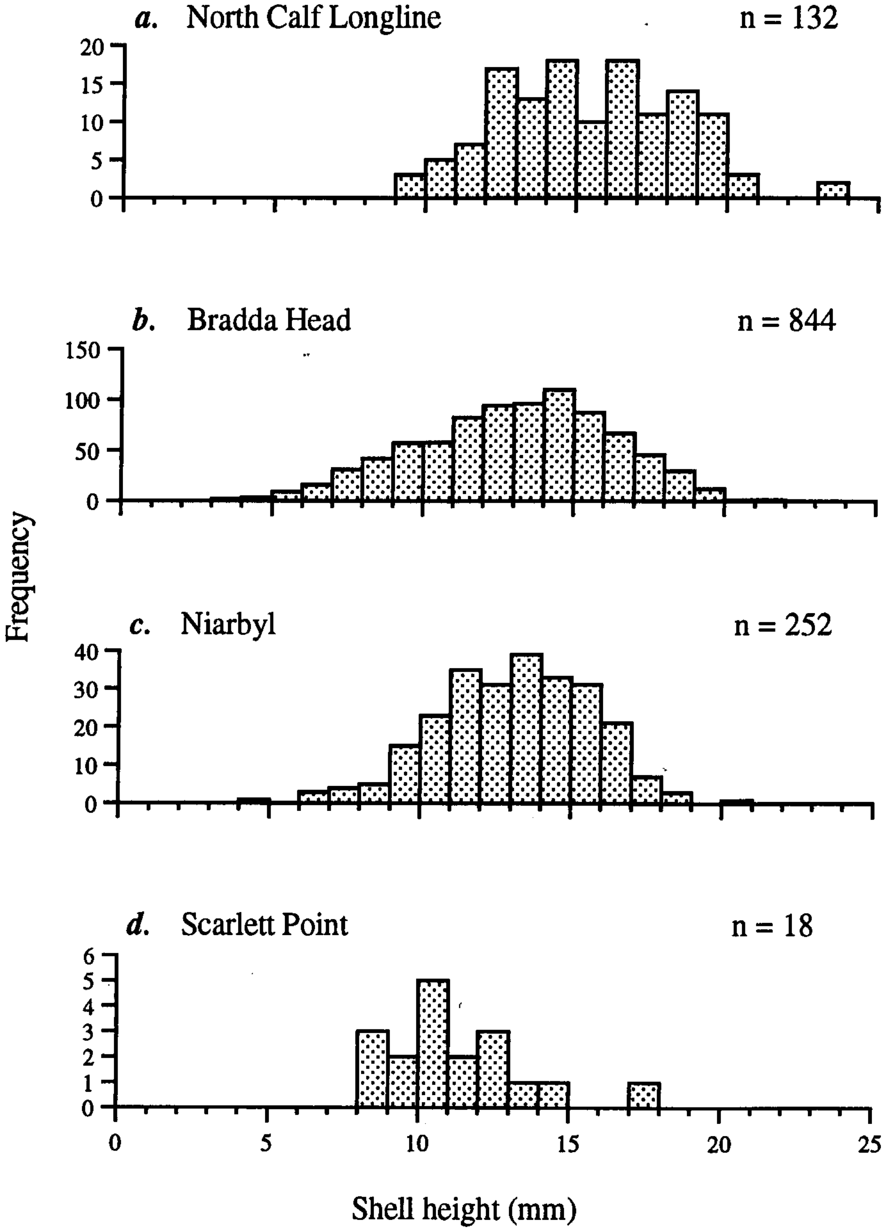


Figure 3.9. Size frequency distributions of *Pecten maximus* spat found on onion bag collectors placed around the Isle of Man in 1988. ***a***. North Calf, ***b***. Bradda Head, ***c***. Niarbyl, ***d***. Scarlett Point. n = number of individuals measured. Note the variation in scale of the ordinates.

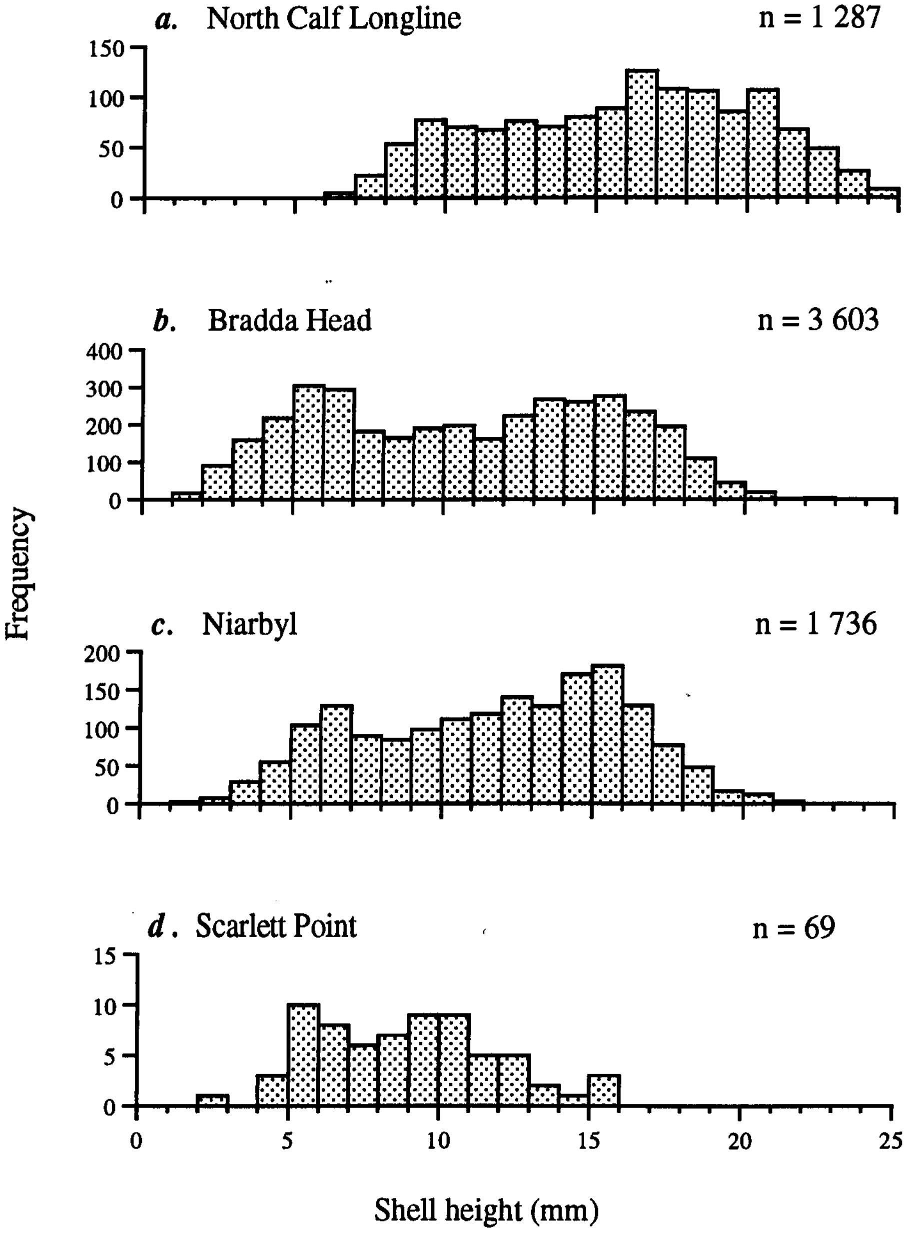


Figure 3.10. Size frequency distributions of *Aequipecten opercularis* spat found on onion bag collectors placed around the Isle of Man in 1988. ***a***. North Calf, ***b***. Bradda Head, ***c***. Niarbyl, ***d***. Scarlett Point. n = number of individuals measured. Note the variation in scale of the ordinates.

and measured on the 3rd November, 1988. Assuming that the spat present at the various sites settled at approximately the same time then the differences in shell height were due to the extra month of growth while at sea.

3.3.3 1989 spat collection

The modified longline systems used at the North Calf in 1989 were successful and did not become tangled. Three strings of ten collectors were removed and frozen for later detailed analysis; the remainder were sorted to provide animals for other experimental work. Information regarding the depth positions of the pink bags was lost and it was not therefore possible to examine the depth distribution of spat settlement on these collectors. One of the single lines of humbug design collectors deployed at North Calf was lost, as were three of the five collectors form a second of these lines.

All of the single lines of onion bag collectors were recovered from Clay Head, Santon Head, Niarbyl and Spanish Head. Only two single lines were retrieved from Bay Fine and at Bradda Head only seven of the nine single lines that were set there were retrieved. The two lines that were lost from Bradda Head were both from the second wave of collectors placed to examine the effects of timing of collector setting on the settlement of spat, leaving this part of the study unreplicated.

The spat collectors examined in detail in 1989 were sorted over a 500 µm mesh so a higher proportion of the small spat were retained, and in particular *C. varia* was included in the analysis. In previous years any *C. varia* that were retained on the 5 mm mesh were not separated from the *A. opercularis* as they were not considered to occur in significant numbers above this shell height.

The mean number of *P. maximus* spat per collector bag from the North Calf longline was only 12 (± 1.3 SE), lower than in previous years whereas the settlement of *A. opercularis* increased over the period of study; in 1989 the mean settlement of *A. opercularis* was 226 ± 12.2 SE (Table 3.1). The intensity of *P. maximus* settlement at Bradda Head and Niarbyl was greater in 1989 than in the previous year, and the settlement recorded at Niarbyl (122 ± 12.6 SE *P. maximus* spat per onion bag collector) was the highest that has been recorded around the Isle of Man (Table 3.1).

The number of *P. maximus* spat that were collected on the east coast was extremely low, with a maximum mean number per bag at Spanish Head of only 2 (0.3 SE) and numbers of less than one at the other two sites (Table 3.1). The maximum settlement of *P. maximus* in any one collector was 4 at Spanish Head; many bags at Clay Head and Santon Head contained no *P. maximus* spat at all.

The overall intensity of *A. opercularis* spatfall appeared to be greater in 1989 than in previous years where collections were made in the same areas (Table 3.1). At the North Calf location the mean number of spat per collector increased between 1987-89 from 145 (±3.3 SE) to 182 (±25.5 SE) in 1988 to 226 (±12.2 SE) in 1989, whereas over the same period the settlement of *P. maximus* fell from 23 to 12 spat per bag. However, there was a very low settlement on the east coast collectors as was observed for *P. maximus*. The mean settlement on the east coast ranged from 4 to 25 spat per collector bag, whereas that on the west was 176 to 439 per collector.

The highest mean settlement of *A. opercularis* was recorded on the west coast at Niarbyl (439 ± 57.9 SE per bag) where the greatest number of spat in a single onion bag was 710.

The intensity of *Chlamys varia* settlement was also greatest on the west coast at Niarbyl (442 ± 65.7 SE per collector bag), almost three times greater than the next best location, Bradda Head (Table 3.1). At the North Calf the mean number of *Chlamys varia* spat per bag was 47 ± 5.8 SE but *C. varia* was almost absent from the collectors placed on the east coast; the greatest number were found at Spanish Head (n = 12), a single specimen was identified from Santon Head, and none were found at Clay head.

There was a high level of agreement between the rank abundances of the three pectinid species recorded on the spat collectors from the various locations (Table 3.2). The consistency of this pattern suggests that the factors influencing spat settlement for *P. maximus*, *A. opercularis* and *C. varia* may have been the same. Minimum recorded levels of settlement consistently occurred at the east coast locations.

Table 3.2. Rank abundances (mean number of spat per bag) of pectinid spat from onion bag collectors placed around the Isle of Man, 1988 and 1989. West coast sites ordered north to south, east coast sites ordered south to north to emphasise distribution of spat settlement.

Site	1988		1989		
	P. maximus	*A. opercularis*	*P. maximus*	*A. opercularis*	*C. varia*
West coast					
Niarbyl	3	3	1	1	1
Bradda Head	1	2	2	2	2
Bay Fine			3	4	3
South					
North Calf	2	1	4	3	4
East coast					
Spanish Head			5	5	5
Scarlett Point	4	4			
Santon Head			7	7	6
Clay Head			6	6	absent

The settlement of *P. maximus* on the onion bag collectors suspended from the subsurface longline at the North Calf was strongly skewed towards the deeper bags, with a maximum settlement of >20 spat per bag at a depth of 9.5 m as in 1988 with a similar number at 8 m depth (Figure 3.11*a*). The trend of increasing settlement with increasing depth was consistent with that observed for *P. maximus* at this site in previous years, and the characteristic decline in settlement in the bottom bag of the string of collectors was also observed in the single lines of this year and the previous years.

The 1989 single line spat collectors covered a smaller range of depth than in 1988. However, taking this into account the settlement of spat remained less variable with depth than previously observed at Bradda Head and Niarbyl (Figure 3.11*b, d*). Settlement was also consistent with depth at Bay Fine (Figure 3.11*f*). The settlement of *P. maximus* on the east coast was extremely low but there was more settlement closer to the seabed at Spanish Head and Santon Head than at the top of the array of collectors (Figure 3.11*c, e, g*).

The settlement of *A. opercularis* on the longline onion bag collectors at North Calf in 1989 was similar to that of previous years but there was a stronger skew towards the deeper collectors (Figure 3.12*a*). A stronger than usual bias towards the deeper collectors was also noted for *P. maximus* in 1989 at the North Calf. There was a decline in settlement in the lowermost bag as was previously observed on the bottom-anchored single lines. The relative variation in settlement with depth was not as great as for *A. opercularis*, consistent with the results of previous years. The

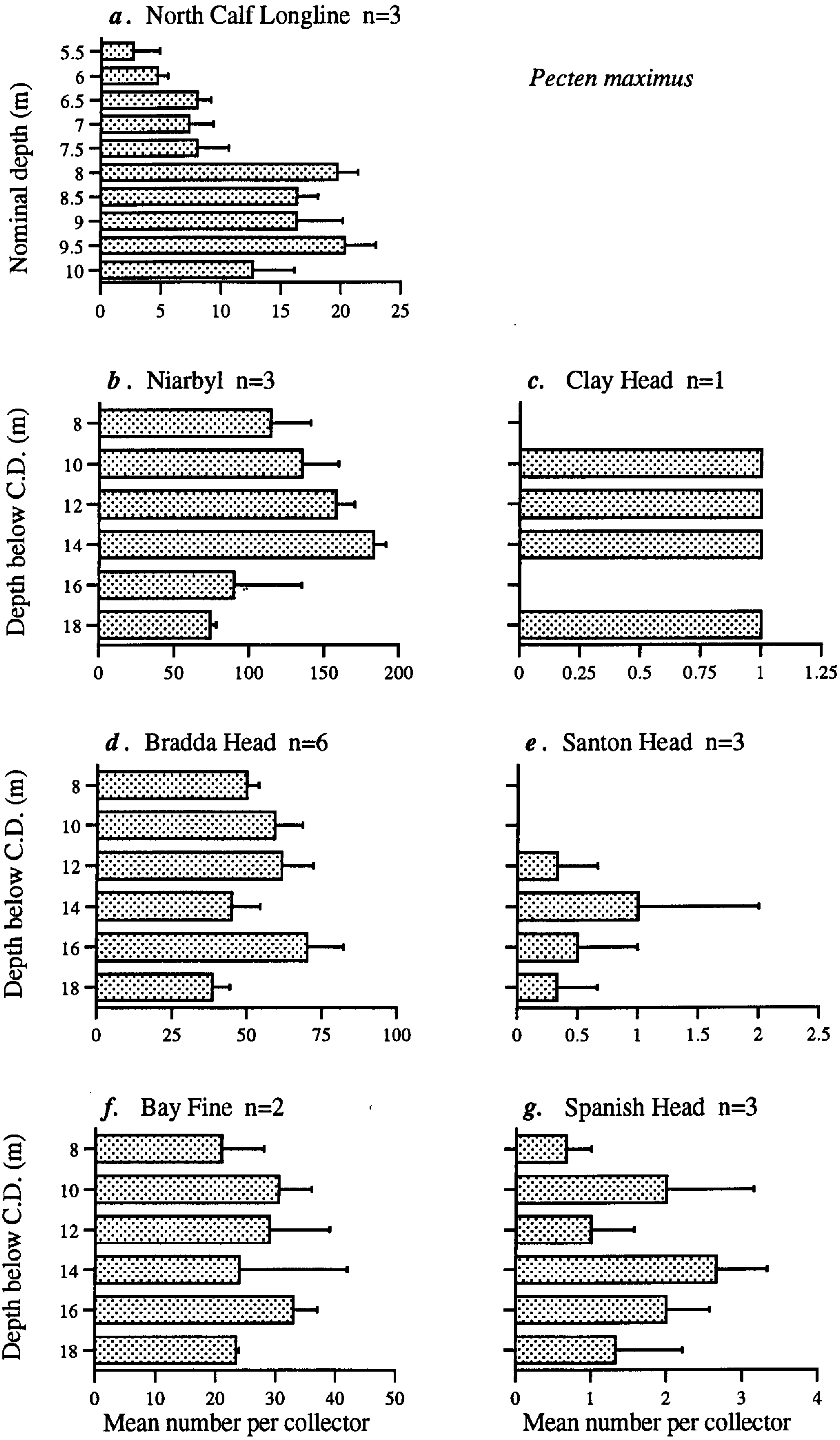


Figure 3.11. Depth distribution of *Pecten maximus* spat on onion bag collectors placed around the coast of the Isle of Man in 1989 (mean number of spat per collector +SE, water depth 20 m below CD). All collectors bottom anchored single lines except North Calf (longline). n=number of replicate lines. Note variation in scale of axes.

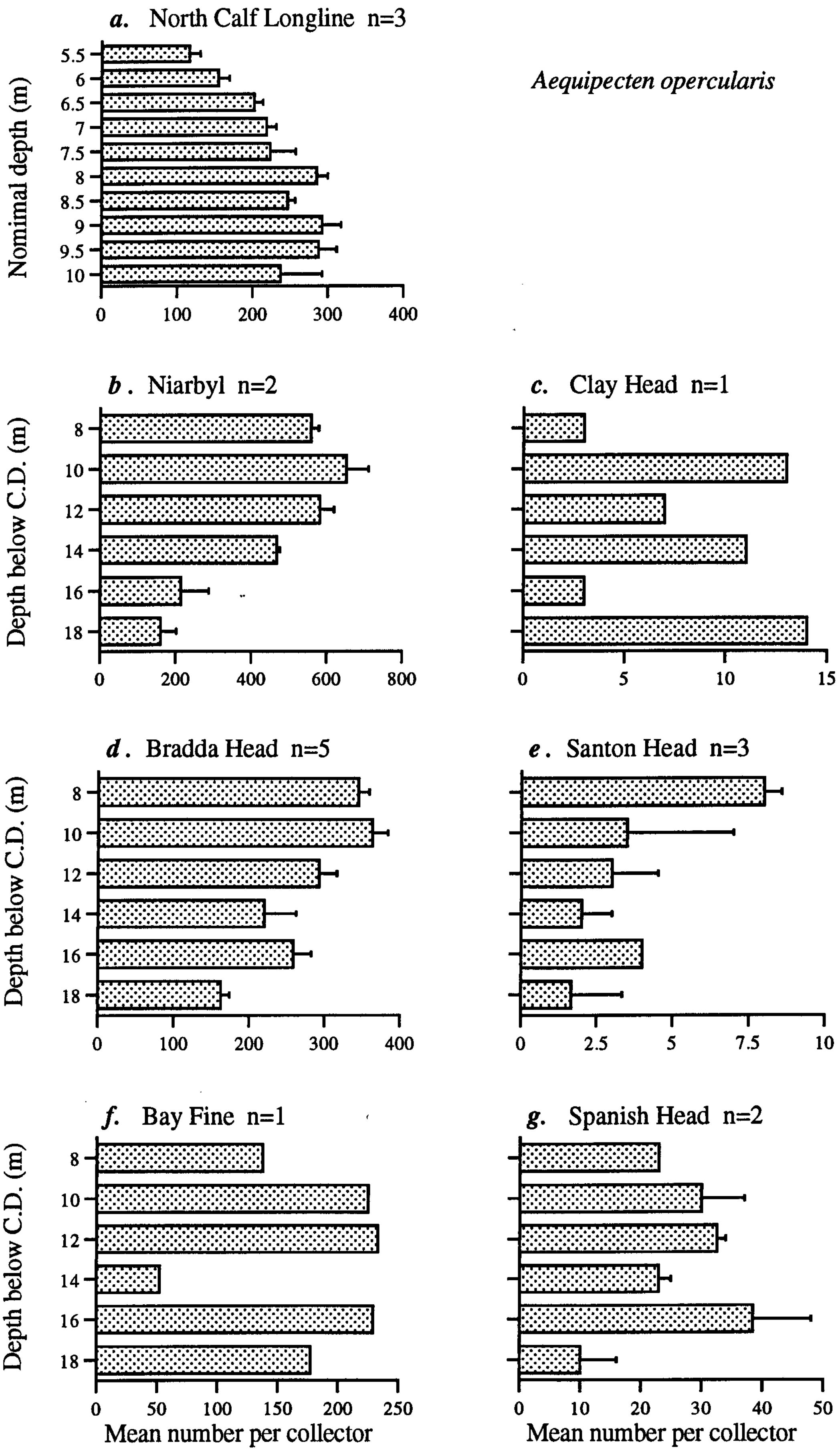


Figure 3.12. Depth distribution of *Aequipecten opercularis* spat on onion bag collectors placed around the coast of the Isle of Man in 1989 (mean number of spat per collector +SE, water depth 20 m below CD).
All collectors bottom anchored single lines except North Calf (longline).
n = number of replicate lines. Note variation in scale of axes.

maximum settlement occurred at 9 m depth with similar values at 8 m and 9.5 m depth.

The depth profiles of *A. opercularis* settlement at Niarbyl and Bradda Head indicated that peak settlement occurred at a depth of 10 m (midwater depth) at both sites with a subsequent decrease in the numbers of spat closer to the seabed (Figure 3.12*b, d*). Minimum settlement at both sites was recorded in the bottom collector, 2 m off the seabed. At Bay Fine the peak spatfall was at 12 m, but similar numbers were also recorded at 10 m and 16 m with a minimum settlement at 14 m (Figure 3.12*f*). However, as only one if the collectors strings was recovered from Bay Fine the results were unreplicated and again liable to great influence from variations in individual collector performance.

The largest spatfall of *A. opercularis* on the east coast was at Spanish Head (mean number per collector 25 ± 2.3 SE) where the maximum settlement was at 16 m (39 spat) and minimum settlement in the next collector down (10 spat in the lowermost spat bag). This relatively deep maximum is unusual for this species (Figure 3.12*g*). At Santon Head peak settlement was at 8 m depth with a decline towards the seabed, with the minimum spatfall in the bottom collector bag (Figure 3.12*e*). The distribution of settlement at Clay Head was highly variable over the depth range studied with the maximum settlement in the lowermost collector bag (Figure 3.12*c*). However, only one of the three lines was recovered from this location and so the data were unreplicated and liable to be affected unduly by the performance of individual collector bags.

Chlamys varia were separated from the other species in 1989 and the depth distribution of their settlement on the onion bag collectors at North Calf was similar to that for *P. maximus*; settlement increased dramatically with increasing depth to a maximum of >75 spat per bag at 9 and 9.5 m depth, but fell in the lowermost collector to less than 40 spat per bag (Figure 3.13).

The number of *P. maximus* that settled on the three lines of spat collectors analysed from the North Calf was relatively low (n = 108) and so interpretation of the size frequency distribution remained tentative (Figure 3.14*a*). There was an obvious mode at 11-12 mm shell height but the rest of the distribution was unclear.

There was a mode in the size frequency distribution of *P. maximus* at both Niarbyl and Bradda Head on the west coast (Figure 3.14*b,c*), although the modal shell height was larger at Niarbyl (11-12 mm) than at Bradda Head (9-10 mm). The size frequency distribution for *P. maximus* at Bay Fine was bimodal with the lower

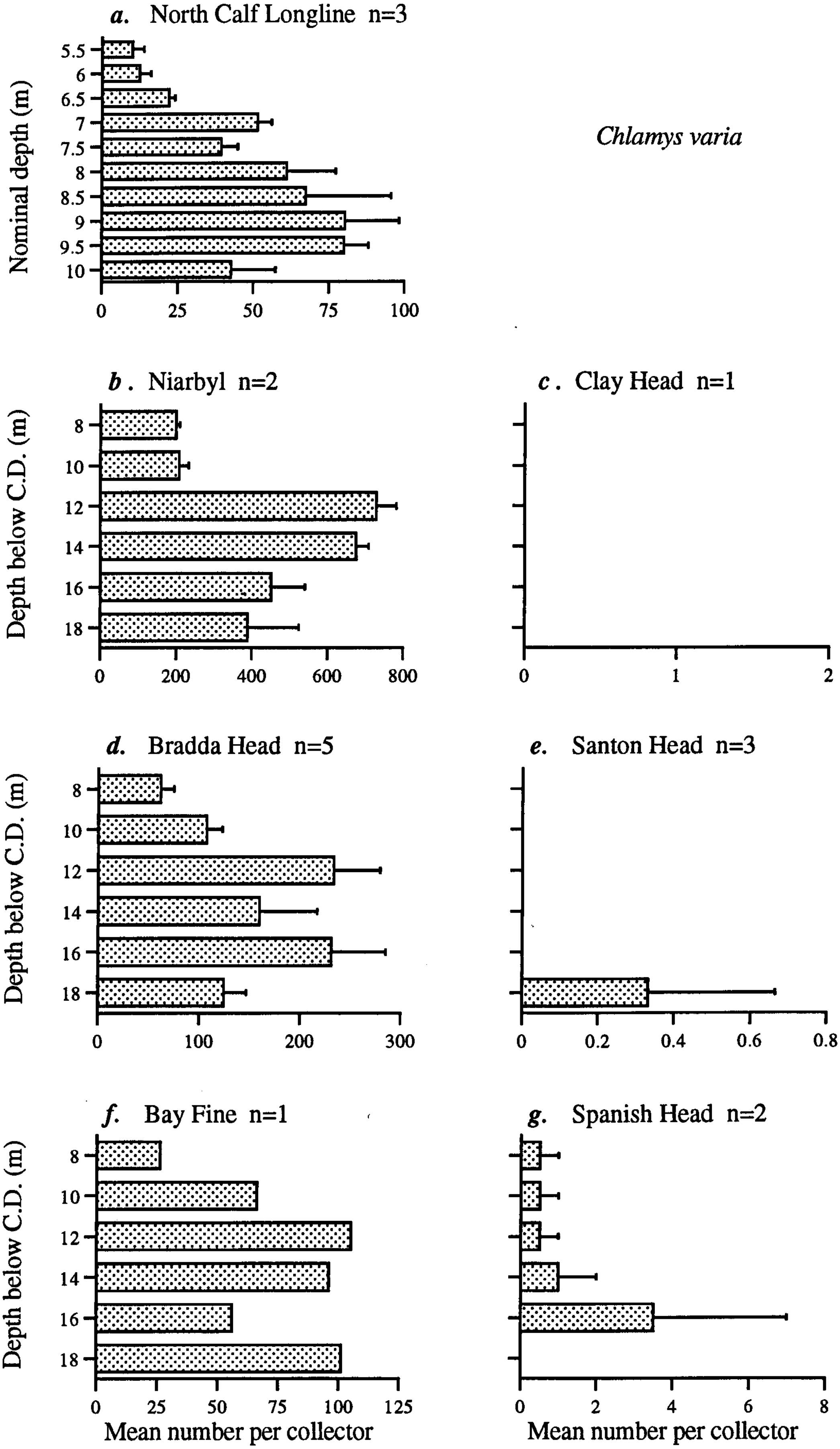


Figure 3.13. Depth distribution of *Chlamys varia* on onion bag collectors placed around the coast of the Isle of Man in 1989 (mean number of spat per collector +SE, water depth 20 m below CD). All collectors bottom anchored single lines except North Calf (longline). n = number of replicate lines. Note variation in scale of axes.

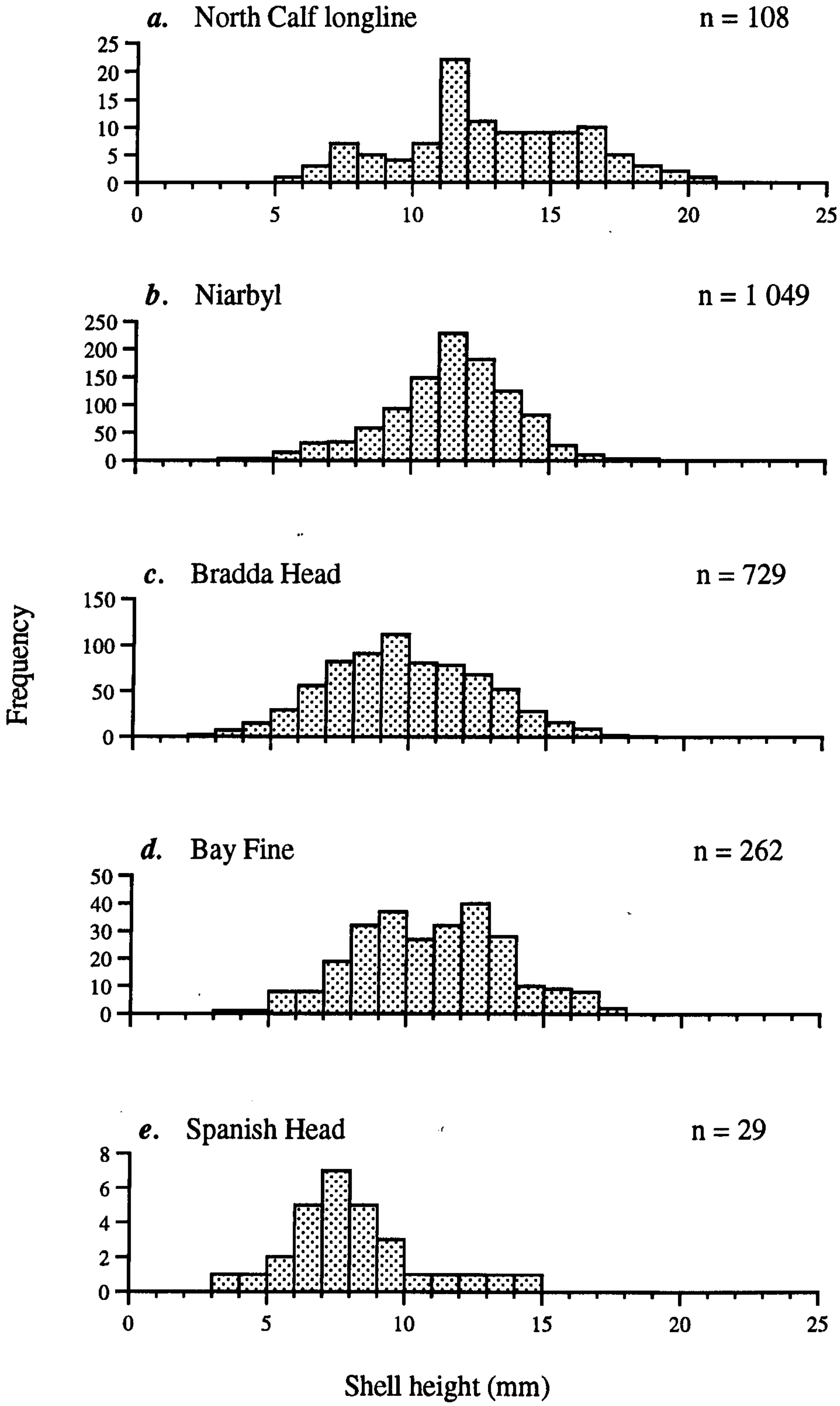


Figure 3.14. Size frequency distributions of *Pecten maximus* spat settled on onion bag collectors placed around the Isle of Man in 1989. ***a.*** North Calf longline, ***b*** . Niarbyl ***c*** . Bradda Head, ***d*** . Bay Fine ***e.*** Spanish Head. n = number of individuals measured. Note variation in scale of the ordinates.

peak at 9-10 mm and the greater one at 12-13 mm shell height, suggesting two peaks of spat settlement (Figure 3.14*d*). There were insufficient numbers of spat to construct meaningful size frequency distributions for Clay Head or Santon Head but at Spanish Head there was a single mode at a shell height of 7-8 mm (Figure 3.14*e*).

The size frequency distribution of *A. opercularis* at North Calf in 1989 was bimodal, with one peak at 19-21 mm much stronger than the other at 7-8 mm (Figure 3.15*a*). The form of the distribution suggests that there may have been two discrete and widely temporally separated settlements of *A. opercularis* at North Calf. The greater mode was at a larger size than that for *P. maximus* whereas that the smaller peak was at a smaller shell height than the mode of *P. maximus* settlement.

The size frequency distributions of *A. opercularis* from the west coast collector locations were based on large numbers of spat (547-2 457 individuals) and each showed a single peak of settlement, as reflected by the unimodal distributions. The largest mode of these sites was at Niarbyl (12-14 mm shell height, Figure 3.15*b*), whereas at Bradda Head there was a clear mode at 11-12 mm (Figure 3.15*c*). At Bay Fine the modal shell height was 10-11 mm but there were similar frequencies between 11-13 mm shell heights (Figure 3.15*d*).

On the east coast there also appeared to be a single settlement of *A. opercularis* spat, although the distributions for Santon Head and Clay Head were based on low numbers of measurements. The modal shell height at Spanish Head was 9-10 mm (Figure 3.15*e*) but at the two more northerly sites, Santon Head and Clay Head, the mode occurred at a shell height of 6-7 mm (Figure 3.15*f, g*).

There appeared to have been only a single settlement of *C. varia* on the North Calf longlines on the basis of the unimodal size frequency distribution (Figure 3.16*a*). This contrasted with the two settlements observed for *A. opercularis* on the same collectors, although there was probably only a single settlement of *P. maximus*. The modal shell height of *C. varia* was 4-5 mm, smaller than those for *A. opercularis* (7-8 mm and 20-21 mm) or *P. maximus* (11-12 mm).

The size frequency distributions of *C. varia* from the west coast sites and from Spanish Head were all unimodal, again suggesting a single settlement of larvae (Figure 3.16*b-e*). The modal shell heights at Niarbyl, Bradda Head and Bay Fine were 3-4 mm and the shapes of the distribution were almost identical; settlement may have been simultaneous at all three sites.

Only one of the strings of spat collectors placed at Bradda Head 20 days after the initial wave of collector placement was recovered. The settlement of all three

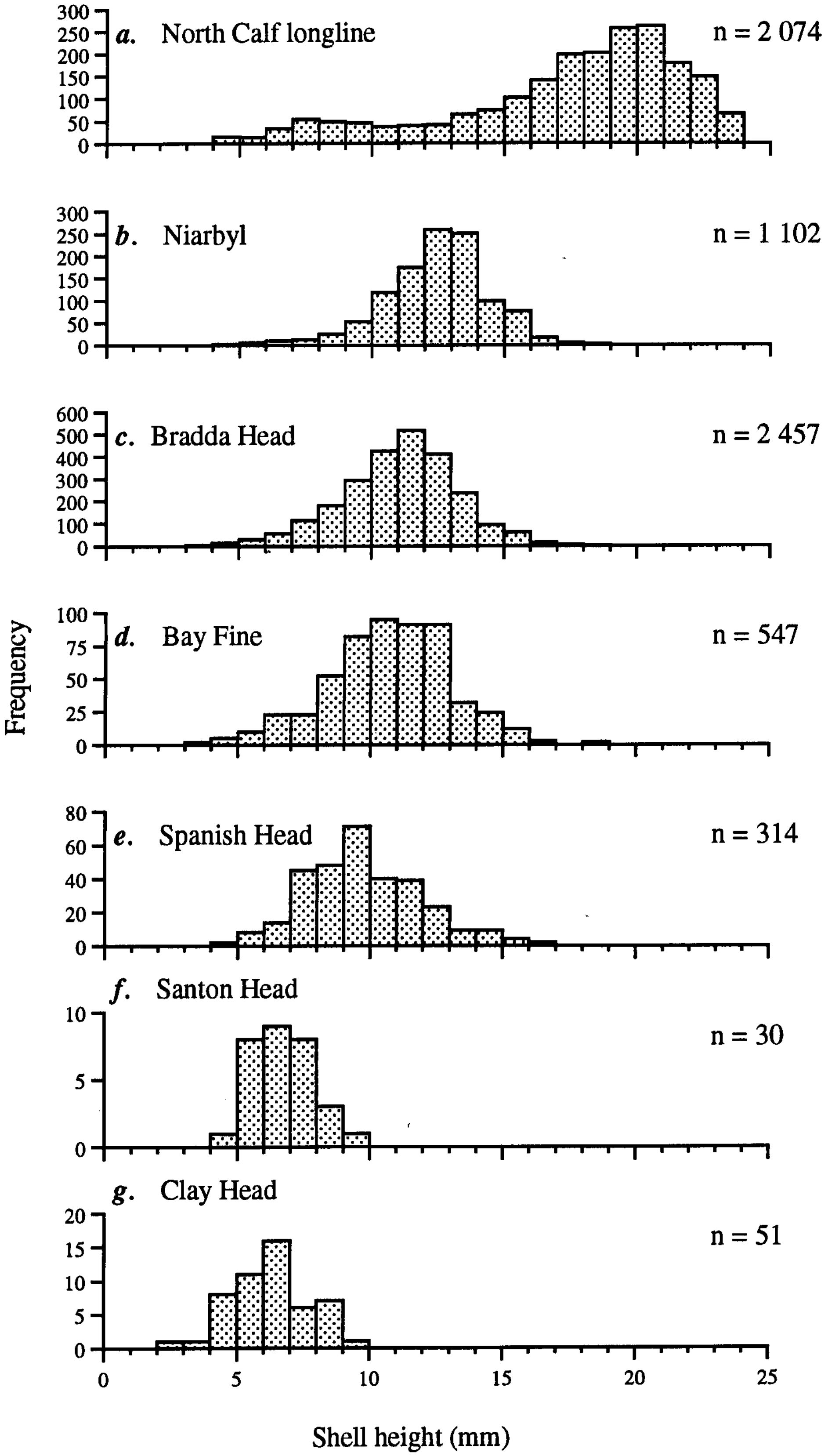


Figure 3.15. Size frequency distributions of *Aequipecten opercularis* spat settled on onion bag collectors placed around the Isle of Man in 1989. ***a***. North Calf longline, ***b***. Niarbyl, ***c***. Bradda Head, ***d***. Bay Fine, ***e***. Spanish Head, ***f***. Santon Head, ***g***. Clay Head. n = number of individuals measured. Note variation in scale of the ordinates.

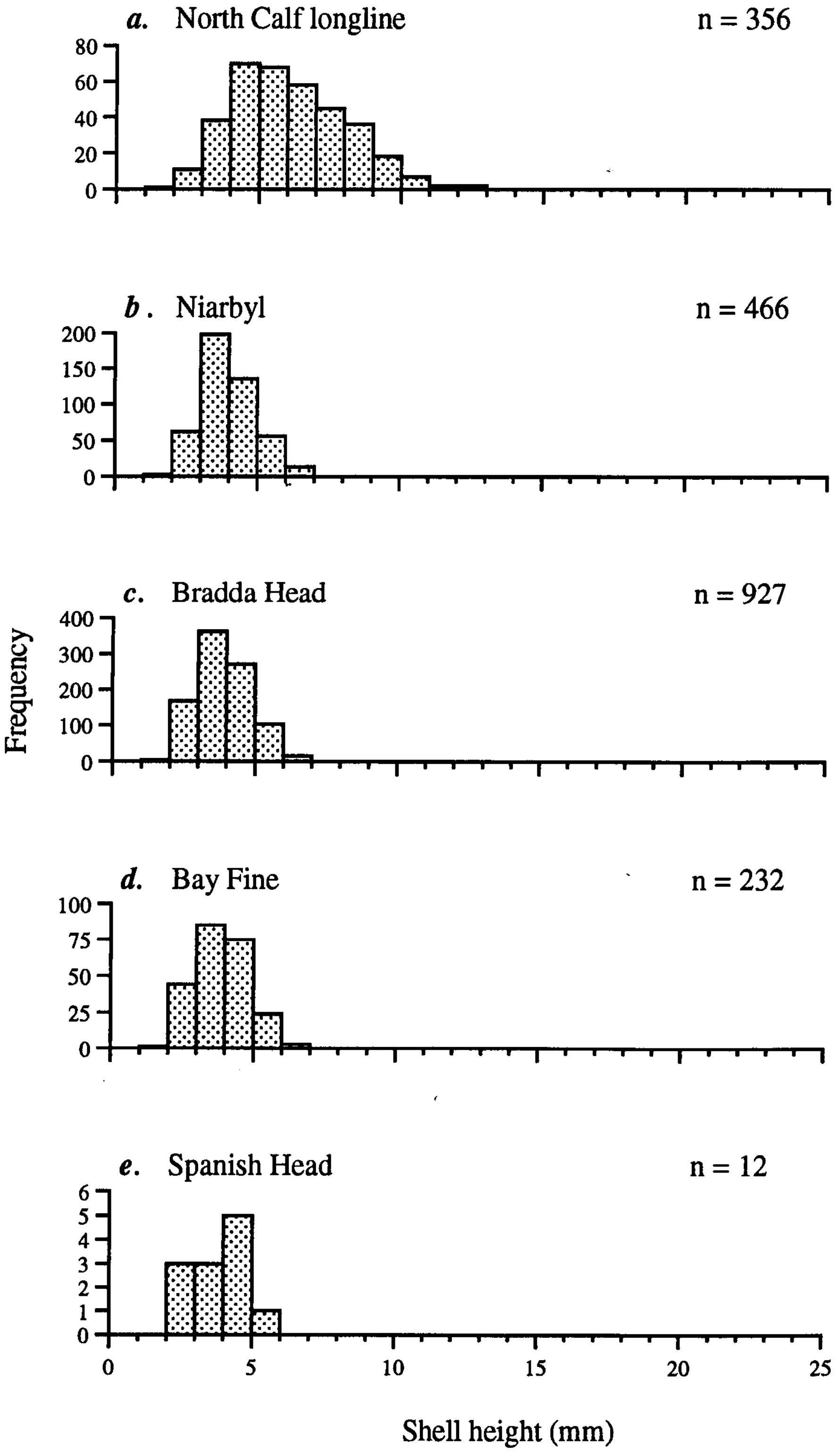


Figure 3.16. Size frequency distributions of *Chlamys varia* spat settled on onion bag collectors placed around the Isle of Man in 1989. ***a.*** North Calf longline, ***b***. Niarbyl, ***c***. Bradda Head, ***d***. Bay Fine, ***e.*** Spanish Head. n = number of individuals measured. Note variation in scale of the ordinates.

pectinid species was substantially lower on the late-placed collectors than on those set on 30th June, 1989 (Table 3.3). The relative difference in settlement was greater for *A. opercularis* than for *P. maximus* or *C. varia.*

Table 3.3. The settlement of three pectinid species (mean number of spat ± SE per onion bag collector) at Bradda Head, on collectors placed 20 days apart. Collectors were all retrieved on 21st September, 1989.

Date set	*P. maximus*	*A. opercularis*	*C. varia*
30th June, 1989	54 (3.9)	273 (15.8)	153 (18.7)
19th July, 1989	14 (3.3)	29 (2.9)	36 (8.8)

The peak settlement of all three species occurred at the same depth on the late collectors (16 m) which may reflect the variation in performance of the individual collectors on the single unreplicated line that was recovered (Figure 3.17*a-c*). However, this was also the depth of peak settlement for *P. maximus* on the first wave of collectors as well as that of the close second best depth for *C. varia.* Only for *A. opercularis* was the depth distribution significantly different between the two sets of collectors. On the early-set collectors peak settlement occurred at 10 m and declined towards the seabed, whereas on the later collectors the number of spat per bag increased with depth form the shallowest collector at 8 m to the peak settlement at 16 m and only then decreased in the lowermost bag; the shape of the distribution was effectively reversed.

The size frequency distribution for *P. maximus* on the later collectors was based on a relatively small number of spat (n = 81) but was apparently unimodal, similar to that of the earlier bags. However, the modal shell height was 1 mm smaller, at 8-9 mm (Figure 3.17*d*). The modal shell height of *A. opercularis* was also at a shell height 1 mm smaller than that from the initial collectors (10-11 mm c.f. 11-12 mm), but displayed a second mode at 4-5 mm not observed on the earlier distribution (Figure 3.17*e*). The modal shell height of *C. varia* was the same (3-4 mm) in both cases (Figure 3.17*f*).

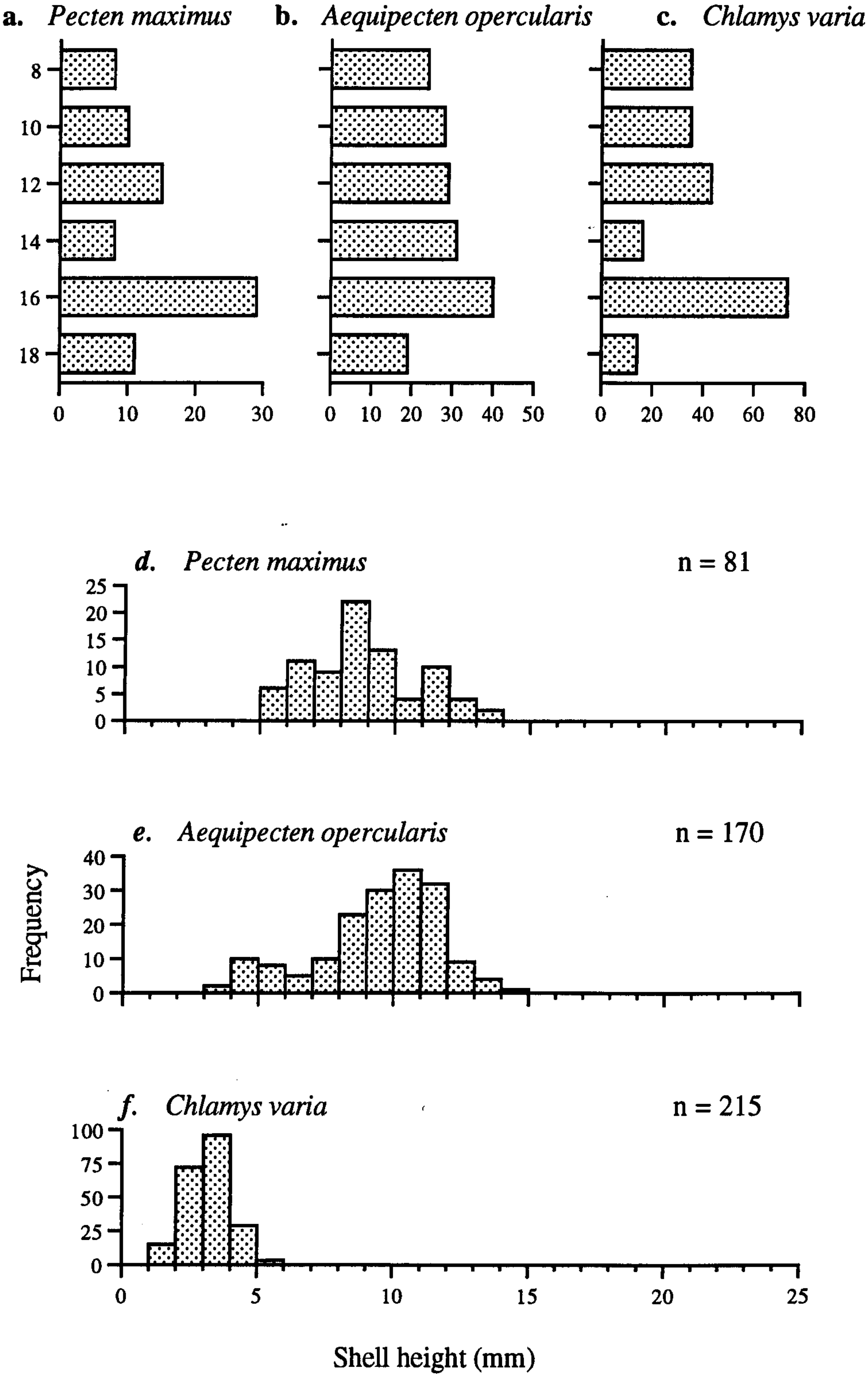


Figure 3.17. Pectinid settlement on the second wave of single line spat collectors placed at Bradda Head, 19th July 1989, 20 days after bulk spat collection, raised 21st Sept. 1989 with bulk collectors. Depth profiles of settled spat and size frequency distributions of *Pecten maximus, Aequipecten opercularis* and *Chlamys varia.* No replication of lines, n = number of indiviuals measured. Note variation in scale of axes.

3.3.4 Humbug and Japanese style collectors

The available surface area of the internal mesh filling of the humbug collectors was greater than that of the standard onion bags (approximately 3.3 m^2 c.f. 1.9 m^2) and of a different material; a soft plastic 19 mm mesh rather than the 6 mm mesh Netlon. The rigid plastic outer casing of the humbug (oyster bag) provided a much larger three-dimensional form in the water column. Of the three strings of humbug collectors that were deployed only two were recovered, one of which had only the lower two bags remaining. Therefore there was little or no replication of this part of the work. The pink Japanese style collector bags were smaller than the standard onion bags used in the rest of this study and contained half the amount of mesh filling (0.75 m^2 equivalent to 0.95 m^2 of available surface area).

The pink Japanese style collectors yielded only half the number of *P. maximus* spat found in the standard onion bags, commensurate with their smaller size and filling content, suggesting that they were no more efficient at collecting spat than the standard onion bag (Table 3.4). There was no significant difference between the number of *P. maximus* spat collected by the standard onion bags and the number collected by the pink bags per square metre surface area of internal mesh but significantly more *P. maximus* settled on the humbug collectors (ANOVA, $F_{0.05, 2, 53} = 7.02$, $P < 0.01$, Table 3.5). However there were no significant differences between the performance of the different collector types for *A. opercularis* (ANOVA, $F_{0.05, 2, 53} = 0.69$, $P = 0.507$) or *C. varia* (ANOVA, $F_{0.05, 2, 53} = 2.11$, $P = 0.131$).

Table 3.4 The settlement of three pectinid species (mean number of spat ± SE per onion bag collector and mean number per square metre surface area of mesh filling ± SE) at North Calf, on three designs of spat collector in 1989. Period spent at sea for each collector type: standard onion bag on longline 6/7/89 - 14/11/89, pink Japanese style bags on longline 7/7/89 - 24/11/89, humbug collectors on single line 30/6/89 - 22/9/89.

Collector type	Surface area (m^2)	*P. maximus* per bag	*P. maximus* per m^2	*A. opercularis* per bag	*A. opercularis* per m^2	*C. varia* per bag	*C. varia* per m^2
Onion bag	1.90	12 (1.3)	6 (0.7)	226 (12.2)	119 (6.4)	47 (5.8)	25 (3.0)
Pink bag	0.95	6 (0.9)	6 (0.9)	109 (8.7)	108 (10.3)	36 (7.1)	37 (7.5)
Humbug	3.31	39 (9.0)	13 (3.0)	412 (37.1)	125 (11.2)	73 (16.5)	22 (5.0)

Table 3.5. Analysis of Variance of mean number of *P. maximus* collected per metre squared surface area of spat collector bag filling in three collector types; standard onion bag, Japanese style pink onion bag and humbug collector. Levels of significance indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$). Comparisons of individual levels were made with the Tukey test adopting an experimentwise error rate (EER) of 0.05.

Source	DF	SS	Adj. MS	$F_{0.05}$	P	Significance
Collector type	2	281.2	140.6	7.02	0.002	**
Error	53	1060.9	20.0			
Total	55	1342.1				
Conclusion						
	Standard onion bag		Pink onion bag		Humbug	

Affinities of groups compared are indicated by underlining

Despite the limitations of the experiment there was a clear bias towards a greater settlement of *P. maximus* at increasing depths on the humbug collectors (Figure 3.18*a*). The heaviest settlement was at 15.25 m nominal depth (> 60 *P. maximus* per collector) with a decrease in the lowermost humbug at 17.75 m (> 50 per collector), attached to the rope 2-2.5 m above the seabed. The variation in settlement with depth was extreme, with a 12 -fold increase in spatfall the shallowest collector (7.75 m) and the peak settlement. This was greater than that found for onion bag collectors on single lines placed at other locations around the Isle of Man or for those on the subsurface longlines at the North Calf site.

A. opercularis settlement on the humbug collectors was much higher than for *P. maximus* (mean number per bag 412 ± 37.1 SE c.f. 39 ± 9.0, Table 3.4) and the variation of settlement with depth was much less; the difference between the greatest and least settlement being less than a factor of two. However, the pattern of settlement with increasing depth was identical for the two species; lowest settlement occurred at the shallowest collector (268 spat per humbug) with the greatest spatfall found at 15.25 m (497 spat per humbug) and a subsequent decrease in the bottom collector at 17.75 m (414 spat per humbug, Figure 3.18*b*).

The depth distribution of *C. varia* spat from the humbug collectors followed exactly the same pattern as those of *P. maximus* and *A. opercularis*; increasing settlement with depth to a maximum at 15.25 m (>100 spat per collector), with a subsequent decline in the bottom collector (Figure 3.18*c*).

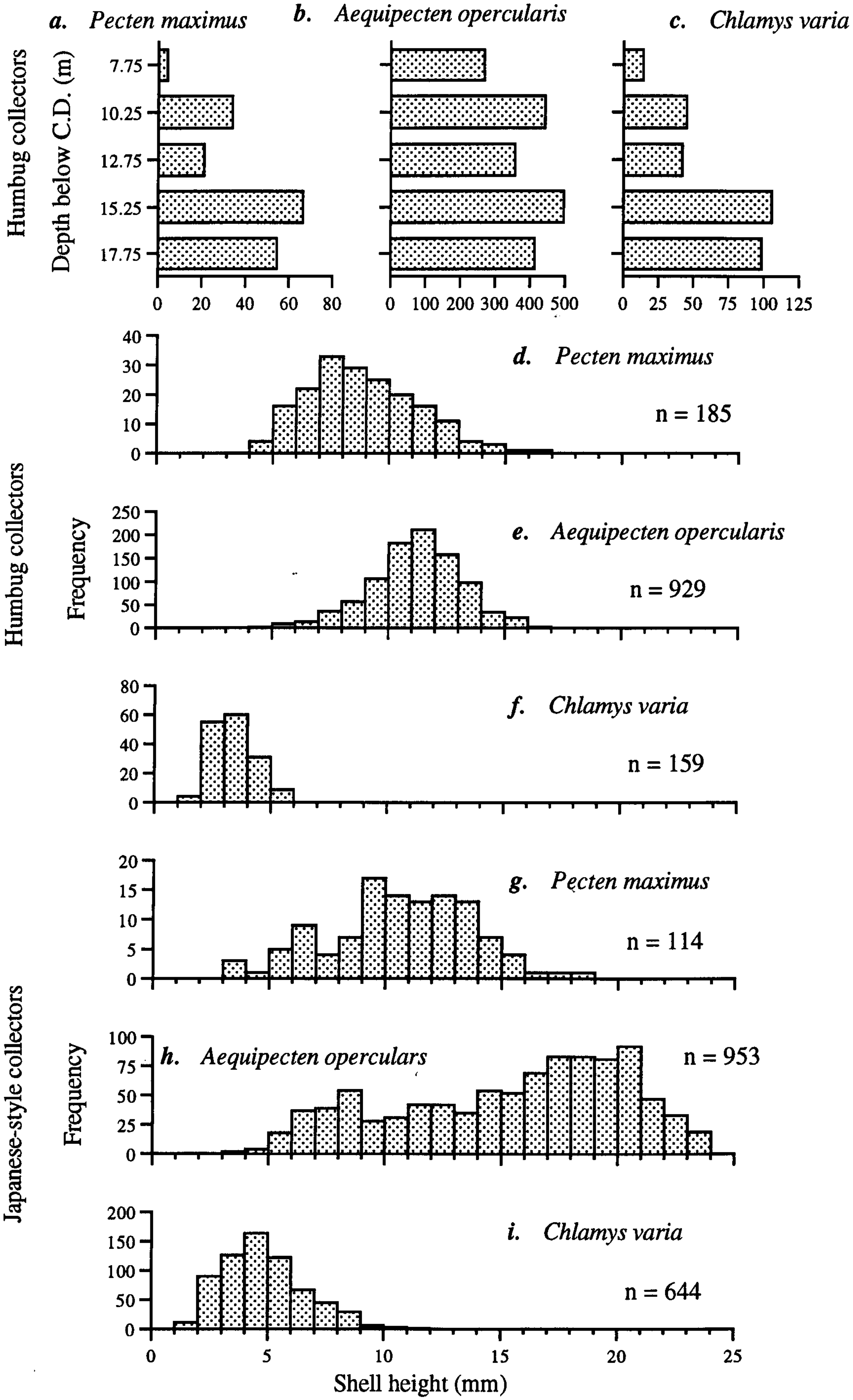


Figure 3.18. Pectinid settlement on alternative spat collector designs at North Calf. ***a-c.*** Depth distribution of pectinids on humbug collectors (single lines). ***d-f.*** Size frequency distributions of pectinids from humbug collectors. ***g-i.*** Size frequency distributions of pectinids from Japanese style pink onion bag collectors. n = number of individuals measured. Note variation in scale of axes.

The size frequency distributions of spat from the humbug collectors were all unimodal (Figure 3.18*d-f*); modal shell heights *P. maximus* were 7-8 mm, *A. opercularis* 11-12 mm, *C. varia* 3-4 mm. This suggests that there were single settlements of all of these species on to the collector bags, despite the evidence for two peaks of *A. opercularis* settlement on the standard onion bags that were in the water at the same time.

The distributions of spat from the pink bags were very similar to those of the standard onion bags, although the modal shell height was smaller for *P. maximus* from the pink bags; 9-10 mm c.f. 11-12 mm (Figure 3.18*g-i*). The distribution of *A. opercularis* was almost identical for the two collector types; both were bi-modal with the greater mode at 20-21 mm shell height and the lesser one between 7-9 mm.

3.3.5 Multivariate analysis of spat collector communities

A total of 60 species were identified from the single line spat collectors in 1988 and 53 in 1989, despite the number of collector bags analysed in detail being higher in 1989 (9 vs 36). The total number of species found was 83 over the two years; there were substantial differences in species composition between the seasons' collectors. The dominant species used for the multivariate analysis varied between the two years and are presented in Table 3.6.

The spat collector communities from each location were compared for 1988 and 1989 on the basis of the most common species using hierarchical clustering and multi-dimensional scaling of Bray-Curtis similarities. This technique calculates a similarity matrix from the station/species data matrix, and produces an ordination dependent only on the ranks of similarities (Warwick & Clarke, 1991; Rees, 1993). The MDS plot gives the positions of samples relative to each other and attempts to preserve the rank order of dissimilarities as accurately as possible. The 'stress' value quantifies the distortion between the ranked dissimilarities and corresponding distances in the two-dimensional plot (Rees, 1993). The use of presence-absence data is less powerful than numerical or biomass data, however, significant differences were found between the communities in both years: ANOSIM (Clarke & Green, 1988), 1988 three replicates at Niarbyl, Bradda Head and Scarlett Point, $R = 0.864$, significance level = 0.4%: 1989 six replicates at Niarbyl, Bradda Head, Bay Fine, Spanish Head, Santon Head and Clay Head, $R = 0.388$, significance level < 0.1%.

The dendrogram for the 1988 results was divided into three groups, the first of which was made up solely of the replicate collectors from the east coast at Scarlett

Table 3.6 Species used in multivariate analysis of spat collector communities. Analysis based on presence/absence of most abundant species found on the collectors from each site within each year: 1988 - Niarbyl, Bradda Head, Scarlett Point; 1989 - Niarbyl, Bradda Head, Bay Fine , Spanish Head, Santon Head and Clay Head.

Phylum	Sub-phylum	Class	Order	Family	Species	1988	1989
Arthropoda	Crustacea	Malacostraca	Amphipoda	Ischyroceridae	*Jassa falcata*		x
				Caprellidae	*Phtisica marina*	x	
					Caprella spp.	x	
			Decapoda	Galatheidae	*Galathea* spp.	x	x
				Porcellanidae	*Porcellana* spp.		x
				Portunidae	*Liocarcinus depurator*		x
					Necora puber		x
				Xanthidae	*Pilumnus hirtellus*	x	
				Majidae	*Macropodia* spp.		x
Mollusca		Lamellibranchia	Dysodonta	Mytilidae	*Modiolus/Mytilus*	x	x
			Pseudolamellibranchia	Anomiidae	*Anomia ephippium*	x	x
				Pectinidae	*Aequipecten opercularis*	x	x
					Chlamys varia	x	x
					Pecten maximus	x	x
Echinodermata		Crinoidea		Antedonidae	*Antedon bifida*	x	
		Asteroidea	Forcipulata	Asteriidae	*Asterias rubens*	x	x
		Ophiuroidea	Ophiurae	Ophiotrichidae	*Ophiothrix fragilis*	x	
		Echinoidea	Diadematoidea	Echinidae	*Echinus/Psammechinus*	x	
Chordata	Tunicata	Ascidiacea	Enterogona	Cionidae	*Ciona intestinalis*		x
			Pleurogona	Styelidae	*Botryllus schlosseri*	x	
					Botrylloides leachi	x	

Point (Figure 3.19*a*). The second and third groupings divided the west coast samples but included one of the Bradda Head communities with the replicates from Niarbyl. The same groupings are reflected in the MDS plot (Figure 3.19*b*), but further emphasises the similarity of one of the Bradda Head collectors to those at Niarbyl and the difference between one of the Scarlett Point communities. The low stress value of the plot (0.009) indicated that the two dimensional plot was an excellent representation of the relationships between the collector communities.

The dendrogram from 1989 was extremely complex but generally showed good replicate grouping (Figure 3.20*a*). The complete dissimilarity of three of the collectors from Santon Head and one from Bay Fine from the other collectors resulted in two distinct clusters in the MDS plot masking other potential clusters (Figure 3.20*b*). The second dichotomy of the dendrogram separates five of the six replicates from the most northerly east coast site (Clay Head) from the remaining sites. The east/west separation was not as distinct as that in 1988 but occurred at the same level of similarity, approximately 70%.

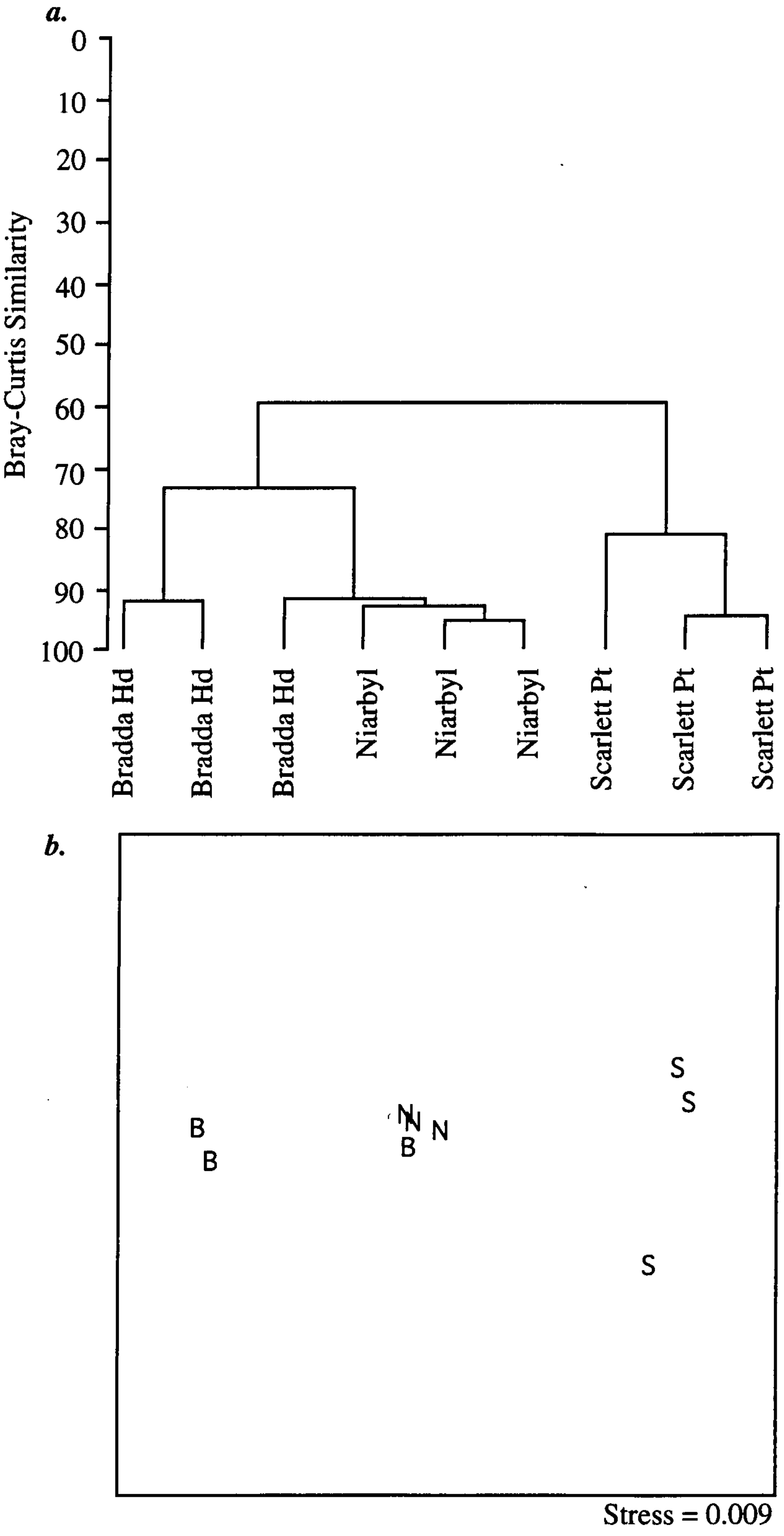


Figure 3.19 Multivariate analysis of commonest species found on spat collectors in 1988. ***a.*** Dendrogram (group-average link) from Bray-Curtis (presence-absence data) similarities of 3 replicate collectors from 3 sites. ***b.*** MDS using Bray-Curtis sililarities of same data.

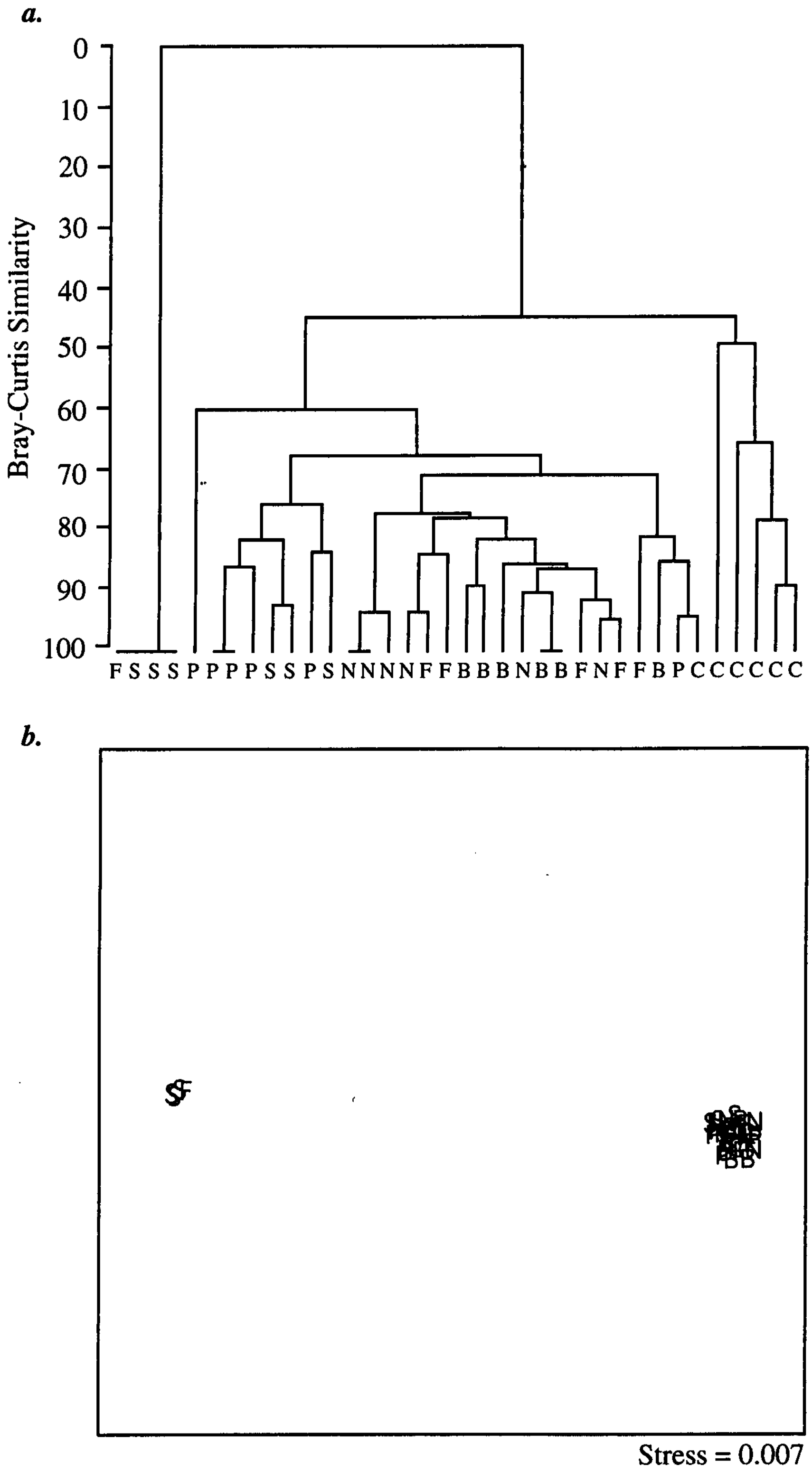


Figure 3.20 Multivariate analysis of commonest species found on spat collectors in 1988. ***a.*** Dendrogram (group-average link) from Bray-Curtis (presence-absence data) similarities of 6 replicate collectors from 6 sites. ***b.*** MDS using Bray-Curtis sililarities of same data. Codes used: N=Niarbyl, B=Bradda Head, F=Bay Fine, P=Spanish Head, S=Santon Head, C=Clay Head.

3.4 DISCUSSION

3.4.1 Methodological constraints

Problems were encountered with the longline systems, caused by interference from local crab and lobster fishermen whose gear became fouled in the systems and from movement of the anchors which affected the tension on the headropes. The initial longline design was of a kind that needed frequent buoyancy adjustments to compensate for the increasing weight of the organisms that settled on the collectors. Delays in providing additional flotation caused some of the lower collectors to drag on the seabed, damaging the bags and causing siltation. These strings of collectors were excluded from the analysis.

The design of the longline systems used for the bulk collection of spat at the North Calf evolved over the period of this study; they became more stable and less liable to damage from the effects of tides and adverse weather. The system used in 1989 (with weighted downlines) maintained the collector bags at a more consistent depth than the modified seaweed cultivation longline used in 1987 and 1988. The longline tangling experienced in 1987 and 1988 may have reduced the effectiveness of the spat collectors by adversely affecting the water flow through the bags and their position in the water column. However, the damage was only incurred after the collectors had been in the water for some time and were likely to have already been settled by the pectinid spat.

The exposed nature of the Manx coast hampered the single lines as well as the longline systems; several of the single lines were never recovered, reducing the degree of replication in parts of this work (in some cases only one line was retrieved). All of the single lines placed in Strangford Lough, Northern Ireland, were lost.

A potential source of variation in the results was lack of uniformity between individual onion bags. Collectors of the same design contained the same amount of mesh filling but the orientation of this within the bag was liable to variation. In particular, the proportion of the filling that was caught up with the cable tie and held to the rope inevitably varied between collector bags, altering the effective area available for settlement. This inter-collector variation in design may have been significant in the cases where there was little or no replication due to collector losses.

Table 3.7. Summary of pectinid spat collection around the Isle of Man (1975-1989), with some comparative data from the west coast of Scotland. Spat numbers have been approximately standardised to the 'onion bag' collector design (except *) using regression equations obtained in a comparative study: number of *P. maximus* per onion bag = 0.1 + 0.9 × number per Netlon envelope. Number of *A. opercularis* per onion bag = 1.7 + 1.1 × number per Netlon envelope. Table modified and updated (†) from Brand *et al.* (1991b).

			Mean (max.) number per collector (standardised)		
Year	Collector type	Site	*A. opercularis*	*P. maximus*	Worker
1975	Netlon	Bay Fine	60	<1	Brand *et al.* (1980)
1976	Netlon	Bay Fine	37	7	Brand *et al.* (1980)
1977	Netlon	Bay Fine	32	5	Paul (1978)
1978	Netlon/ onion bag	Bay Fine	45	2	Coles (unpub.)
		Sker	50	2	
		North Calf	196	10	
		Fleshwick	53	4	
		Cronk ny Arree Laa	64	3	
		Derbyhaven (east)	<1	<1	
1979	Onion Bag	Bay Fine	59 (77)	<1 (4)	Coles (unpub.)
		Sker	60 (94)	<1 (3)	
1983	Onion Bag	North Calf	411 (607)	11 (22)	Duggan (1987)
		Sker	197 (264)	13 (33)	
1984	Onion Bag	North Calf	250	80	Duggan (1987)
		Sker	140	60	
1987	Onion Bag	North Calf	147 (263)	23 (50)	This study/Brand *et al.* (1991b)
1988	Onion Bag	Niarbyl	134 (238)†	13 (26)	This study/Brand *et al.* (1991b)
		Bradda Head	166 (333)†	30 (89)†	
		North Calf	182 (286)†	20 (38)†	
		Scarlett Point (east)	7 (13)	2 (5)	
1989	Onion Bag	Niarbyl	439 (710)	122 (191)	This study
		Bradda Head	273 (408)	54 (104)	
		Bay Fine	176 (233)	27 (42)	
		North Calf	226 (328)	12 (25)	
		Spanish Head (east)	25 (48)	2 (4)	
		Santon Head (east)	4 (9)	<1 (2)	
		Clay Head (east)	9 (14)	<1 (1)	
1976	Humbug	West coast Scotland	590*	483*	Ventilla (1977d)
1975-1980	Humbug	West coast Scotland	500-2000*	250-550*	Ventilla (1981)
1984	Onion Bag	West coast Scotland	400 (600)	70 (85)	Paul (1985a)

3.4.2 Variation in spat settlement

The numbers of pectinid spat settling on artificial collectors around the Isle of Man has historically been low (Paul, 1978; Brand *et al.*, 1980; Duggan, 1987; Brand *et al.*, 1991b) compared to elsewhere in the British Isles (Ventilla, 1977c, 1977d; Paul, 1985a; Fraser, 1991), and a fraction of those recorded for *Mizuhopecten yessoensis* in Japan (Ventilla, 1982). The levels of settlement recorded in my work were comparable to or higher than those previously reported (Table 3.7). In 1987 there was a good settlement of *P. maximus* at the North Calf compared to previous years, only being matched in 1983 and 1984 (Duggan, 1987), although the settlement of *A. opercularis* was relatively low. The subsequent reduction in *P. maximus* settlement at the same site in 1988 and 1989 was accompanied by a rise in

A. opercularis numbers. Conversely, the settlement of *P. maximus* at the other west coast sites increased between 1988 and 1989 and the spatfall of both species at Niarbyl in 1989 established new records for the Isle of Man. However, the intensity of pectinid settlement observed in my work remained low in comparison to that observed elsewhere for the same species (Ventilla, 1977b; Gillespie, 1983; Paul, 1985a; Wilson, 1987; Fraser, 1991) or for other pectinids (Ventilla, 1982; Body & Murai, 1986; Dadswell *et al.*, 1987; Bull, 1988a; Sumpton *et al.*, 1990; Ito, 1991; Robinson *et al.*, 1991; Young *et al.*, 1992).

The reasons for the relatively low spat settlement on artificial collectors around the Isle of Man remain unclear. The design of the collectors may not have been appropriate for the local conditions, although different designs were tried that have been successful elsewhere; the humbug collectors used in Scotland proved significantly better at collecting *P. maximus* spat than the two onion bag designs at North Calf, for the surface area of internal mesh available, but still yielded only low numbers of spat. However, the humbugs were unwieldy to use and more expensive than the onion bag collectors and could not be recommended as an alternative design, despite their greater efficiency. This design has been used successfully for a number of years for monitoring of spat settlement in Scotland (Fraser, 1991). Improvements in settlement may be achievable by increasing the amount of filler used in the onion bag collectors although ultimately this would adversely affect the flow of water through the bag and the space available for shell growth; Motoda (1977) considered the ideal water movement to be ‘moderately stagnant’ but not still. The quantities currently used (1.5 m^2) may be close to the optimum as a small proportion of the spat collected showed shell deformations from growth when confined against the mesh, the most extreme examples had taken on the shape of a clover leaf.

Poor timing of spat collection may have accounted for the low spat settlement although the collectors in my work were generally set at the end of June in order to maximise settlement, based on the findings of Paul (1978) and Duggan (1987). Both authors deployed collectors for short periods throughout the summer and autumn to ensure that the time of peak settlement was not missed, and neither recorded commercial levels of spat settlement at any time. Setting collectors at the end of June/beginning of July ensured they were in place before the period of peak settlement but relied on the collectors remaining attractive until this time. The attractiveness of artificial spat collectors as a settlement substratum for mature scallop larvae varies over time as the virgin surface becomes colonised by a biofilm and subsequent fouling. However, the relative attraction of a completely clean surface and one which has been ‘conditioned’ is uncertain and may be species specific. Minchin (1992) considered the development of fouling a hindrance to *P. maximus* settlement and recommended collector deployment just prior to the peak settlement whereas, for several other pectinids, the presence of a biofilm or light fouling can produce significantly higher settlement (Bonardelli, 1988; Hodgson & Bourne, 1988; Parsons *et al.*, 1989; O'Foighil *et al.*, 1990; Xu *et al.*, 1991; Parsons *et al.*, 1993). Bull (1988a) found experimental collectors remained effective at collecting *P. novaezelandiae* spat for a month after placement and recommended that collectors be placed on a pre-set date in preference to reliance on time-consuming forecasting techniques and Xu *et al.* (1991) found *P. maximus* equally competent at settlement on fouled or clean substrata, showing a preference for neither. Therefore, the low spatfall was unlikely to be a product of poor collector timing, particularly as levels of settlement recorded in my work were comparable to or surpassed those previously recorded in this area (Table 3.6).

The size frequency distributions of the spat from the two waves of collectors set at Bradda Head suggest that although the majority of settlement occurred soon after the collectors were placed in the sea (although from this work it cannot be deduced whether this occurs before or after the formation of a biofilm) they may have remained capable of further collection for sometime; the left-hand tails of the distributions were extended suggesting larval settlement continued after the initial settlement. However, the late-set collectors at Bradda Head picked up a second settlement of *A. opercularis* that was not present on the earlier collectors. As all the collectors from Bradda Head were retrieved on the same day, the absence of a second *A. opercularis* settlement on the early-set collectors might imply they had ceased to be an attractive substratum by the time of the second *A. opercularis* settlement; the finite limit of the collectors' effectiveness was between 64 and 83 days. The low settlement on the second wave collectors was by the remaining larvae from the 'pulse' that colonised the earlier collectors. It is not possible to discern when the peak settlement period was, although it was clearly closer to the time the first wave of collectors was placed in the water; approximately at the end of June or early July.

Inappropriate choice of collection site seems an unlikely cause of the low spat numbers as the collectors, particularly on the west coast, were on the margins of consistently productive commercial scallop fishing grounds (Allison, 1993). However, taking into account the strong coastal currents around the Isle of Man and the 2-5 week larval life of *P. maximus* (Cragg & Crisp, 1991), there is considerable potential for dispersal of larvae from the point of spawning and the degree to which Manx scallop beds are self-recruiting or reliant on external larval supply is unknown. Further investigation of this question is urgently required but the weight of current evidence suggests that they may be self-sustaining (Allison, 1993). The presence or absence of spat on collectors when they are retrieved in the autumn does not necessarily preclude substantial initial settlement; it is not possible from my work to distinguish between low settlements and high post-settlement mortality as causes for poor spat collection. Low post-settlement survival may be caused by predators (crabs and starfish were present in some collectors) or by disturbance and agitation of the collectors in the exposed waters around the Isle of Man.

In the light of this study and the research on spat collection in Manx waters that preceded it (Brand, 1976; Paul, 1978; Brand *et al.*, 1980; Duggan, 1987; Brand *et al.*, 1991b) the most likely cause of the consistently low spat collection remains a poor supply of larvae to the collectors. Locations where scallop spat collection is highly successful are commonly semi-enclosed water bodies or are in areas where local hydrographic conditions retain and concentrate larvae; examples include Mutsu Bay, Japan (Ventilla, 1982; Ito & Byakuno, 1988; Ito, 1991), Golden Bay, New Zealand (Bull, 1987; Bull, 1991), Mulroy Bay and Lough Ine, Ireland (Minchin, 1976; Minchin, 1980; Minchin & Ni Donnachada, 1991), and certain sea lochs on the west coast of Scotland (Fraser, 1983a; Fraser, 1991). The topography of the Manx coast does not conform to this ideal and the hydrography of the waters around the Island are complex and characterised by strong inshore tidal currents which may not retain high concentrations of larvae. It is possible that areas like the west coast of the Isle of Man, where there are historically productive fishing grounds, may have very consistent low density settlement but good early survival, leading to regular 'trickle' recruitment to the natural populations. This may occur without the high planktonic larval densities required for good spat collection. Other benthic species such as barnacles have lower settling densities of spat on the Isle of Man compared to elsewhere (Hawkins & Hartnoll, 1982), which may indicate the dispersive characteristics of the water masses in this area.

In both 1988 and 1989 when single line collectors were placed on either coastline of the Isle of Man, there was a remarkable dichotomy in the spatial pattern of spat settlement. East coast settlement was a small proportion of that on identical collectors placed on the west coast. As all three species of pectinid studied showed a similar east-west split in distribution of settlement and similar rank abundances between sites, this suggests there may have been common causative factors. East-west differences were also emphasised by the multivariate analysis of the spat collector communities, further suggesting that the influences that produced the observed variation in pectinid settlement also affect other species that have a pelagic larval phase coincident with that of the scallops. Greater abundances of microflagellates, dinoflagellates, ciliates, zooplankton and nauplii have been reported from the western Irish Sea when compared to the waters to the east (Graziano, 1988). Hydrographic conditions around the Isle of Man are likely to be one of the fundamental causes of these differences between the east and west coasts.

Despite many years of study the hydrography of the Irish Sea as a whole is still poorly understood and controversy remains over whether the bulk of water moving through the Irish Sea passes to the east or west of the Isle of Man. A consensus in the literature is that the annual residual flow averaged across the whole basin is northward from the Celtic Sea and out through St. George's Channel. Several workers have used estimates of this residual flow in their considerations of the potential transport of pectinid larvae, with respect to their source and genetic heterogeneity (Brand *et al.*, 1980; Macleod *et al.*, 1985; Duggan, 1987). However, this approach must be considered simplistic as the hydrography of the Irish Sea varies radically on a seasonal basis and the annual residual flow is unlikely to accurately represent conditions during the spring and summer months when scallop larvae are to be found in the plankton and caught on artificial collectors. In particular, seasonal fronts form to the south and north of the Irish Sea (the Celtic Sea front and the Islay front respectively) and a remarkably stable front extends from the south of the Isle of Man to the coast of Ireland, to the north of Dublin (Ramster & Hill, 1969). The water to the west of the Isle of Man becomes thermally stratified and this may affect larval transport. Lewis (1992) attributed the genetic heterogeneity of *A. opercularis* between the east and west of the Isle of Man to partial isolation caused by fronts and other hydrographic features. He pointed out the necessity of considering the hydrographic conditions prevailing at the time the larvae were in the water rather than averaging them out over the whole year and cited output from various numerical models which suggested that net water flow during June and July may in fact be both limited and southward in nature rather than northward, as suggested by the annual residual flow. Further evidence for the apparent isolation of the two sides of the island has been reported by Allison (1993) and Murphy (1986)who hypothesised that there were two separate recruitment regions for scallops in the North Irish Sea from visual analysis of year-class frequency distributions; they have suggested the grounds to the east and offshore to the south constituted one region and the grounds to the west formed the other.

It is clear that knowledge about the temporal variation of hydrographic influences in the Irish Sea must be improved if the dispersal of pectinid larvae is to be understood and definitive conclusions reached as to the sources of scallop and queen recruitment. In addition, the behaviour of the larvae and post-larvae will affect their settlement distribution; vertical migration though the water column and its timing relative to tidal currents may result in net advection (Hill, 1991a; Hill, 1991b), sampling of the substratum and secondary dispersal by renewed swimming after initial settlement and byssal drifting will all combine to determine dispersal (Lane *et al.*, 1985; Beaumont & Barnes, 1992). Subsequent post-settlement survival will then modify this distribution.

Larval advection has been modelled for *Pecten fumatus* in Australia, and the strength and direction of the wind during the larval period and the timing of the onset of thermal stratification had significant influence on the predicted distance of advection (Young *et al.*, 1992). They suggested that in years of calm weather during the larval period scallop beds were likely to be self-recruiting and that in windy summers larvae may be imported from great distances. Variations in wind effects, and the presence of fronts and thermal stratification to the west of the Isle of Man during the summer months, may have considerable influence on the distribution of spat settlement and be partially responsible for the observed dichotomy around the Island.

3.4.3 Depth distribution

The depth distributions of the scallop and queen spat were relatively consistent on the single line collectors across differences in collector design, timing of collection and the density of overall settlement; the depth of maximum settlement was deeper for *P. maximus* than for *A. opercularis* with a greater variation in settlement over depth for scallops, and was skewed strongly downward. The distribution of *C. varia* was similar to that for *P. maximus*, with a strong bias to increased settlement with depth, contrary to the more mid-water distribution observed by Paul (1978).

Poor settlement in the top collectors and in those nearest the seabed was evident from the bottom anchored single line collectors, a pattern of settlement that has been frequently observed for these species (Ventilla, 1977c; 1977d; Paul, 1978; Brand *et al.*, 1980; Pickett, 1980; Fraser, 1983a; Duggan, 1987); and has been attributed to algal fouling and disturbance close to the surface and to siltation of the collectors near the seabed. Similar depth distributions of spat settlement have been found for *Placopecten magellanicus* (Dadswell *et al.*, 1987; Bonardelli, 1988), *Chlamys islandica* (Bonardelli, 1988), *Pecten fumatus* (Hortle & Cropp, 1987; Sause *et al.*, 1987; Young *et al.*, 1992) and for *Decatopecten decatopecten strangei* and *Mimichlamys gloriosa* (Sumpton *et al.*, 1990). It appears likely that all newly metamorphosed spat are vulnerable to these same factors.

3.4.4 Potential for commercial spat collection

The numbers of *P. maximus* and *A. opercularis* spat caught at Niarbyl in 1989 were the highest yet recorded around the Isle of Man, yet the mean number of *P. maximus* per bag was still only half the 250 per collector considered economically viable for commercial spat collection (Wieland & Paul, 1983). Further refinements to spat collection techniques are unlikely to produce a fundamental and reliable increase in the yield of spat; there is apparently little potential for the development of commercial scale spat collection around the Isle of Man. If economic levels of settlement could be achieved, there would remain technical and logistical obstacles because of the exposed nature of the Manx coastline and the potential danger to shipping of extensive longline systems. Any attempt at large scale scallop cultivation would be reliant upon the production of spat from a hatchery or on the importation of spat from locations where there is substantial spatfall such as Scotland or Ireland. Pectinid spat are commercially available but would be subject to an import licence and concerns over the potential effects of imported disease and genetic contamination of indigenous stocks.

The use of single line collectors in this study has revealed the extent of spatial variation in pectinid settlement, but the intensity of settlement may also be related to future recruitment to the fishery. Good settlements of *P. maximus* in 1984 (Duggan, 1987) and 1987 (this work and Brand *et al.* 1991b) have been translated into good recruitment to the fishery, observed as strong year classes in age-% frequency distributions (Allison, 1993). Further, there is preliminary evidence that the good *P. maximus* settlement on the west coast single line collectors in 1989 may have appeared as a strong year class at the start of the 1993/4 scallop fishing season (unpublished research vessel survey data from June1994 and impressions from fishermen, K. Prudden, personal communication). However, these remain tentative relationships because although intense settlement of spat on artificial collectors may indicate good natural settlement (Ambrose Jr *et al.*, 1992)(Ambrose Jr *et al.*, 1992 but see Young *et al.*, 1989) high rates of natural mortality may prevent heavy spatfall being translated into good recruitment: Minchin (1983a) suggested that an intense settlement of *P. maximus* in Mulroy Bay, Ireland in 1979 was only poorly represented a year later, because of predation from a large cohort of *Asterias rubens* that settled simultaneously. The disruptive effects of natural mortality (and if it is assumed that the spat settle and develop on the commercial fishing grounds then incidental fishing mortality should also be included, Chapter 2) on the relationship between settlement and recruitment to the fishery will be exacerbated by the relatively long period taken by *P. maximus* to recruit (3-6 years, Chapter 2). It is notable that in cases where such a relationship has been established, it has usually been for fast growing species, often in semi-enclosed areas e.g. *A. opercularis* (Fraser, 1991), *Pecten alba (fumatus)* (Sause *et al.*, 1987; Coleman, 1988), and *Argopecten irradians* (Ambrose Jr *et al.*, 1992).

Although Allison (1993) recognised two possible regions of recruitment, the settlement of pectinid spat on single lines collectors in my work, while exhibiting a similar east-west dichotomy, also demonstrated considerable variation in spat numbers between sites separated by only a few kilometres on the west coast: in 1988 the settlement of *P. maximus* at North Calf was double that at Niarbyl whereas in 1989 the number of this species was ten times higher at Niarbyl that at the North Calf (Table 3.7).

If a relationship could be established to link settlement on spat collectors to subsequent recruitment to the fishery, then in combination with research vessel surveys for pre-recruits it may be possible to provide some degree of pre-emptive stock management strategy. Further, spat collection on or closer to the individual scallop fishing grounds may permit a spatial element to be included in such a strategy.

3.4 CONCLUSIONS

The potential for economic large scale pectinid spat collection around the Isle of Man seems low. Poor larval supply to the collectors is the most likely reason for the observed poor settlements, due to extended low level spawning or unfavourable hydrographic conditions, or a combination of these two factors. There appears to be no justification for continued attempts at bulk collection, although experimental collection at sites around the island should continue and expand.

Spatial variation in pectinid settlement on artificial collectors are extreme; differences in spatfall on the west coast may be two orders of magnitude greater than on the east coast. Large scale differences may also occur over kilometre distances on the west coast.

Tentative links are suggested between high levels of *P. maximus* settlement on collectors and subsequent strong recruitment to the fishery four years later.

The 'standard' onion bag collector design was the most successful and practicable type of collector used in this study. The number of spat collected on the standard and Japanese style onion bags appeared to be directly related to the amount of filling (and hence surface area) provided inside the collectors.

CHAPTER 4

THE GROWTH OF *PECTEN MAXIMUS* AND *AEQUIPECTEN OPERCULARIS* IN SUSPENDED CULTURE

4.1. INTRODUCTION

Scallop cultivation has generated a great deal of interest globally as a means of supplementing or replacing wild fisheries that have been over-exploited (see Shumway, 1991 for review) . The Japanese were the first to successfully cultivate scallops (*Mizuhopecten yessoensis*) and the technology and methodology they developed has been adopted world-wide. The history and development of Japanese scallop culture has been well documented (Ventilla, 1982; Body & Murai, 1986; Aoyama, 1988; Ito & Byakuno, 1988; Ito, 1991; Ito, 1992).

The first UK experiments on the growth of *P. maximus* in artificial containers appear to have been conducted by Mason (1969) in Loch Torridon, Scotland, although he was primarily concerned with the formation of the first growth ring rather than the potential for aquaculture. Pickett & Franklin (1975) published the first cultivation trial involving *Aequipecten* (cited as *Chlamys) opercularis* in cages off Plymouth, SW England.

Scallop cultivation in the waters around the Isle of Man was initiated by Brand (1976) and co-workers (Paul, 1978; Brand *et al.*, 1980; Paul, 1981; Paul *et al.*, 1981). They were able to demonstrate that cultivation of *A. opercularis* was feasible in Manx waters, using mesh covered wooden trays held in metal frames above the seabed. However, *P. maximus* did not appear to respond well to this method of culture and they suggested that this species may require an alternative methodology. Scallop spat collection was continued by Duggan (1987), although there was no further research on pectinid cultivation as such.

Ventilla (1977a; 1977b; 1981) appears to have been the first to utilise Japanese scallop cultivation techniques in the UK after successful spat collection trials (Ventilla, 1977c; Ventilla, 1977d) off the west coast of Scotland by the White Fish Authority (later the Sea Fish Industry Authority, SFIA). Ventilla's frequently cited report on the scallop industry in Japan (Ventilla, 1982) did much to bring their techniques to the attention of aquaculturists in the West, although it also highlighted some of the problems that had been encountered, such as mass mortalities.

The biological feasibility of *P. maximus* and *A. opercularis* culture has now been proven in UK waters (Ventilla, 1981; Wieland & Paul, 1983; Paul, 1987; Hardy, 1991) but no further scallop cultivation work has been carried out in the Isle of Man since that of Paul (1978). The decline of the Manx fishery for scallops and the success of scallop cultivation in a growing number of countries led to renewed interest in the potential for pectinid culture in the sea around the Isle of Man. This work is the first response to that interest.

The time taken for *P. maximus* to reach harvestable size (3-5 years to reach 110 mm shell length, Wieland & Paul, 1983) is significantly longer than for *Mizuhopecten yessoensis* in Japan (2-3 years, Ventilla, 1982) and this has cast some doubt over the economic potential of scallop culture in the British Isles (Wieland & Paul, 1983). Frequent net changes are required as well as thinning to prevent overcrowding and maintain optimum growth. This maintenance imposes a high cost on production and the length of the culture period means that there is a long delay before there is any return on investment.

The focus of much contemporary research has been on improving the economics of scallop cultivation. To this end trials have been conducted using techniques of ear-hanging (Paul, 1988) and bottom culture (Paul *et al.*, 1986; Lake & MacMillan, 1991) as alternatives to suspended cultivation to harvest size. However, both of these methods of final grow-out require at least some measure of intermediate culture to raise the animals to a minimum size prior to drilling or reseeding. Drilling and ear-hanging too early can lead to high losses (Paul, 1988), and reseeding at too small a size risks a high degree of predation, particularly from crabs (Lake *et al.*, 1987; Lake & MacMillan, 1991; Lake, 1993). The minimum size requirement for both methods is 30-40 mm, approximately equivalent to one year in intermediate culture.

The long 'lead-in time' before any money is recouped from the cultivation of *P. maximus* has lead to the suggestion that queens should be cultivated in parallel (Wieland & Paul, 1983; Hardy, 1991); they require less than 2 years to reach a commercially acceptable size and could provide a valuable interim cash flow prior to the realisation of a scallop harvest. *A. opercularis*, however, is a much lower value species than *P. maximus* and this has provided the impetus for research into cheaper methods of queen cultivation. Further, the promotion by the SFIA of 'princess scallops', juvenile *A. opercularis* between 35 and 50 mm queens marketed whole rather than processed, may provide an opportunity to start harvesting *A. opercularis* only 12-15 months after spat collection and with no requirement for net changing (Paul, 1987).

Pocket nets made from cheap mussel stocking crimped on to a central polypropylene rope have been suggested as a low cost alternative to pearl nets (Paul, 1987), at least for the culture of *A. opercularis*, the shells of which are more robust than *P. maximus*. These pocket nets bear no resemblance to those used in Japan for the on-growing of *Mizuhopecten yessoensis* (Ventilla, 1982; Ito, 1991).

There has been substantial research into the effects of stocking density on the growth and survival of pectinid species in pearl nets and lantern nets (Duggan, 1973; Ventilla, 1981; Ventilla, 1982; Ito & Byakuno, 1988; Cropp, 1988b; Widman & Rhodes, 1991; Dadswell & Parsons, 1991a; Dadswell & Parsons, 1991b; Parsons & Dadswell, 1992; Côté *et al.*, 1993). Therefore, no attempt was made to investigate this further.

Handling scallops in order to change fouled nets and reduce stocking density, while providing ideal conditions for growth, has been shown by some workers to interrupt growth and increase mortality (Ventilla, 1977e; Wildish *et al.*, 1988; Dadswell & Parsons, 1991b; Parsons & Dadswell, 1992). Problems have also been encountered with the settlement of predators into culture nets during the summer growing season, facilitated by the clean mesh of recently changed nets. Experience at the SFIA Marine Farming Unit at Ardtoe has suggested that longterm economic benefits may be gained by stocking scallops at low density in the autumn after settlement and leaving them for a full year, foregoing the usual spring net change (J.T. MacMillan, SFIA, personal communication). The reduction in growth rate over the summer due to external fouling on the nets is considered to be offset by the benefits of uninterrupted growth during the spring. In addition, predator settlement into the nets may be reduced due to the layer of fouling on the outside of the nets.

4.1.1 Aims of this work

This chapter aimed to examine some of the alternative regimes for scallop and queen cultivation, designed to reduce costs of production. Results are presented of the growth and survival of both *P. maximus* spat and intermediate size individuals cultivated at low density in pearl nets left undisturbed for extended periods, in order to examine the effects of prolonged cultivation in nets with well developed fouling.

There is no published information on the performance of *A. opercularis* in pocket nets and so this work sought to examine the growth and survival of queen spat stocked at three densities compared to the more commonly used pearl nets.

The use of plastic trays, deployed in stacks on the seabed, for the cultivation of scallop and queen spat was also investigated as a low maintenance alternative to methods of suspended culture.

Finally, this study compares the different gear types in terms of growth, survival and frequency of shell deformities, as well as ease of handling and cost.

4.2 METHODS

The *Pecten maximus* and *Aequipecten opercularis* spat used in this work were collected locally on onion bag spat collectors (see Chapter 3). Prior to cultivation at sea they were maintained in tanks of running aerated sea water at ambient temperature, held in stacks of wooden or plastic trays. All experiments were performed after the separation of the two species as scallop growth suffers and mortality is increased when they are grown together (Wieland & Paul, 1983).

The growth of scallops and queens was considered with respect to shell height (the greatest distance perpendicular to the hinge, from the umbo to the ventral margin) as this was the easiest measurement to make, particularly when the spat were very small. However, regulations on the landing and processing of *P. maximus* consider shell length from anterior to posterior (the greatest dimension of the shell parallel to the hinge), and so the height and length of the final incoming scallops were measured to provide a comparison. All measurements of shell parameters were made to the nearest 0.1 mm using dial callipers.

4.2.1 Longline cultivation

Two subsurface longlines were installed in Bay Fine on 13th November 1989 (Figure 4.1). These were used for growth trials of scallops and queens in both pearl nets and pocket nets. Experienced gained in the use of longlines for spat collection proved valuable when designing the on-growing longlines. The basic design was similar to that used in some regions of Japan (Ventilla, 1982; Hardy, 1991) with weighted vertical ropes extending down to the sea bed from the headrope. This allowed the headrope and its load of pearl/pocket nets to be set slightly over-buoyant (held down by the concrete weight on the verticals). As the animals grew and fouling developed on the culture equipment it did not immediately become negatively buoyant and collapse onto the sea bed but instead the excess buoyancy provided valuable compensation. This was particularly important as it was not always possible to service the systems as often as necessary due to the restrictions of the weather and boat availability.

The rope systems were designed to withstand the relatively exposed aspect of Bay Fine. The Bay provided some shelter from the prevailing south-westerly winds but was open to storms from the north and north-west, and so to make the systems as robust as possible the headrope was nominally set at 8 m depth to reduce the amount of wave action transmitted to the culture nets. To provide additional security, the systems were stretched taught especially during the winter months to try and reduce

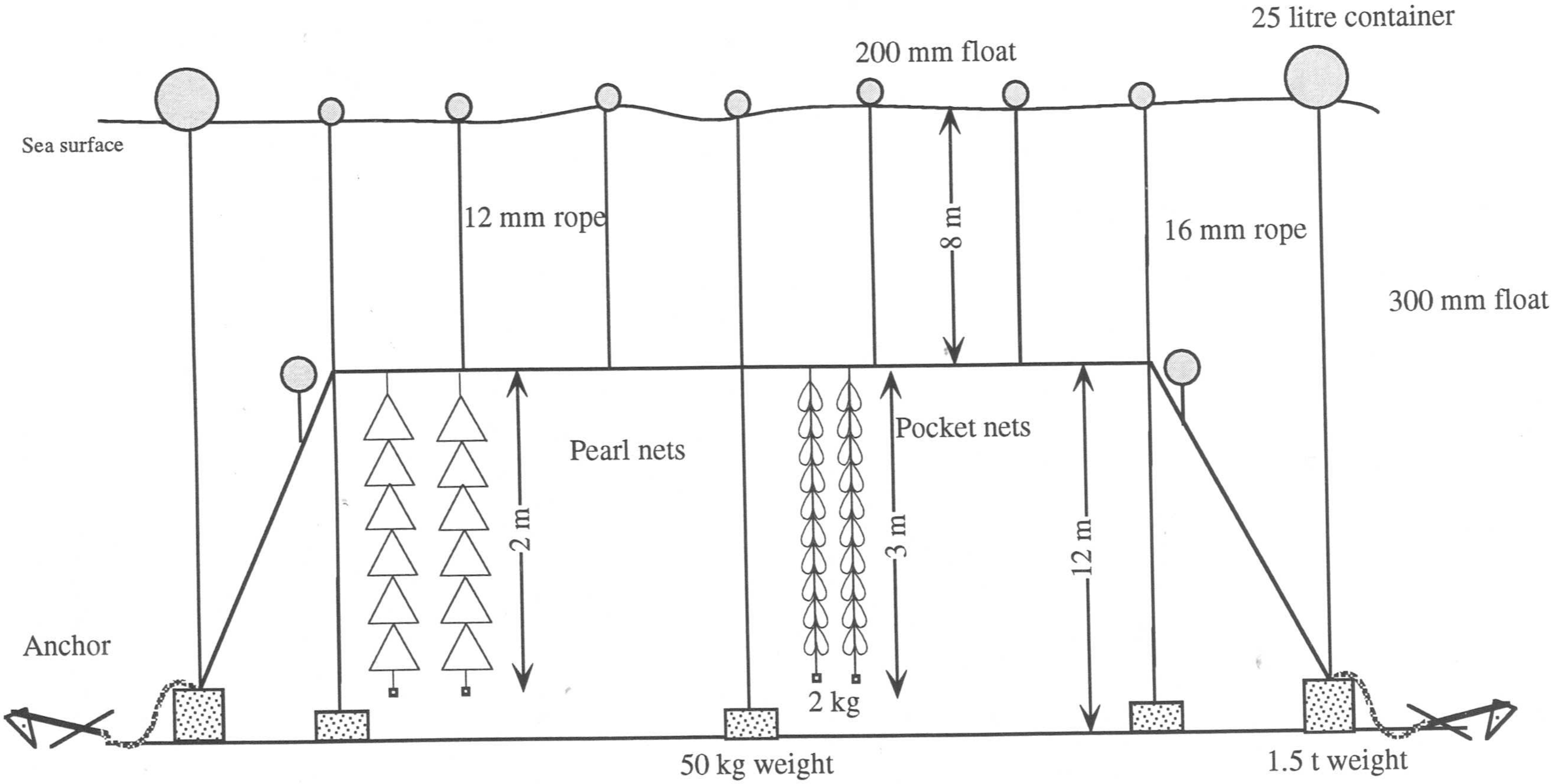


Figure 4.1 Cultivation longline design, Bay Fine 1989. Steel anchors used to augment concrete weights.

movement as much as possible. At each end the longlines were held in place by concrete filled tractor tyres (weight approximately 750 kg in water) augmented with steel anchors[4].

4.2.2 North-West Plastics trays (NWP)

These trays were 0.51 m square × 54 mm deep, with a 5 mm square mesh commonly used in the cultivation of oysters[5]. They stack readily, each one providing the lid for the one below. They were used in stacks of 10 trays; the bottom tray held a concrete paving slab as ballast to provide stability and the top tray was effectively a lid, providing 8 trays to hold animals. The lowermost animals were approximately 5 cm above the sea bed and the topmost ones approximately 45 cm.

One stack containing scallops (mean shell height 17.0 mm ± 0.10 S.E.) and one of queens (19.0 ± 0.13) were deployed in Bay Fine using a weighted ground line similar to that used with lines of crab pots (Figure 4.2). 200 animals were placed in each tray (sub-samples of 50 were measured); approximately 20% coverage (density 770 shells.m^{-2}). The spat used were from the 1988 settlement and had been held in tanks since sorting in November 1988. The stacks of trays were place in Bay Fine on 15th April 1989 and recovered on 29th November 1989, a period of 228 days.

4.2.3 Pearl nets

Scallop and queen spat were cultivated in Japanese pearl nets[6]. These were pyramidal wire-framed bags with a rope running through from top to bottom so they could be tied together to form strings (Figure 4.3). The outer mesh was 4.5 mm square and the floor area 0.123 m^2. Strings of 6 pearl nets with a small concrete weight at the bottom were suspended from longline systems in Bay Fine, with the top-most bag at 8 m depth and the lowest at 10 m below CD. These depths were approximate and varied with tidal height and the relative buoyancy of the head rope as the animals grew, fouling communities developed and additional flotation was added.

4.2.3*a* *Pecten maximus* spat

Two trials were carried out with *P. maximus* spat held in pearl nets at a stocking density of 50 per net (equivalent to 408 shells.m^{-2}); the 'short' experiment ran from 20th November 1989 until 26th September 1990 (310 days), the 'long' experiment from 6th December 1989 until 12th March 1991 (461 days). Four lines of six pearl nets were used in the short experiment and two lines in the longer one.

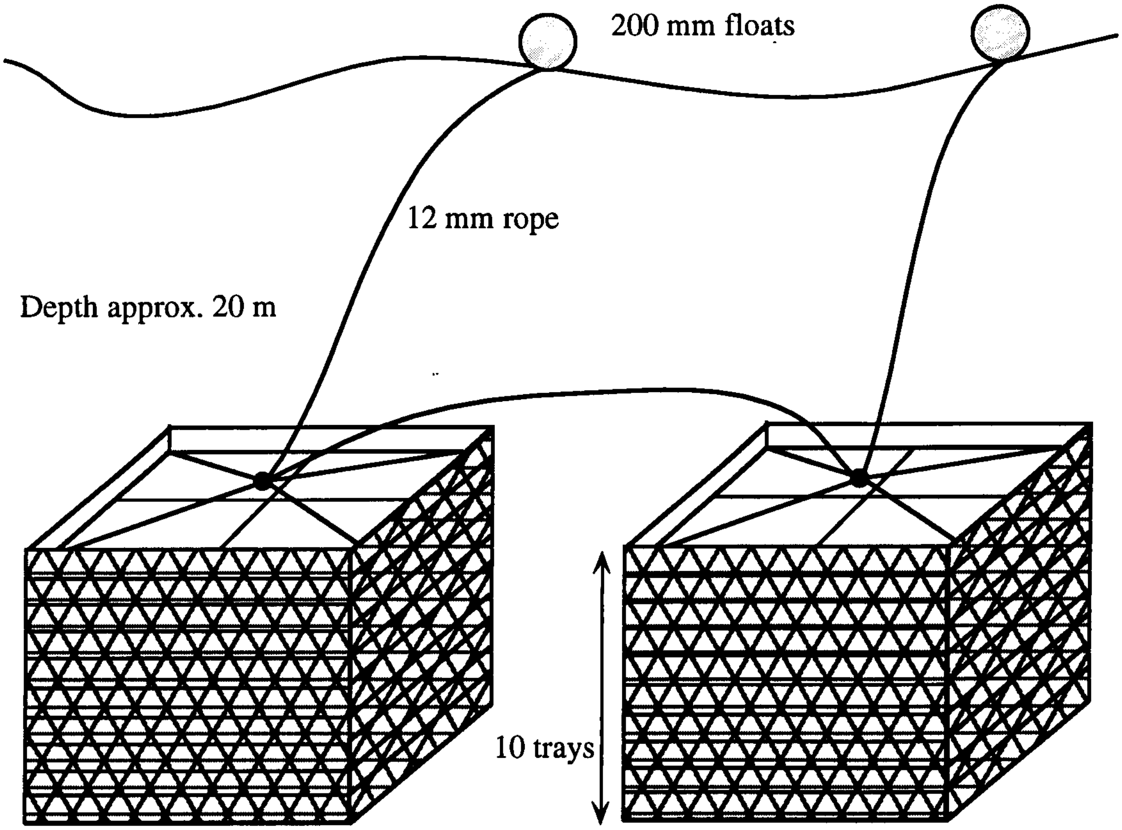


Figure 4.2 Deployment of North West Plastics Trays in Bay Fine. Each stack consisted of 10 trays, the bottom tray held a concrete paving slab as ballast and top tray acted as a lid, providing 8 trays to hold scallops or queens.

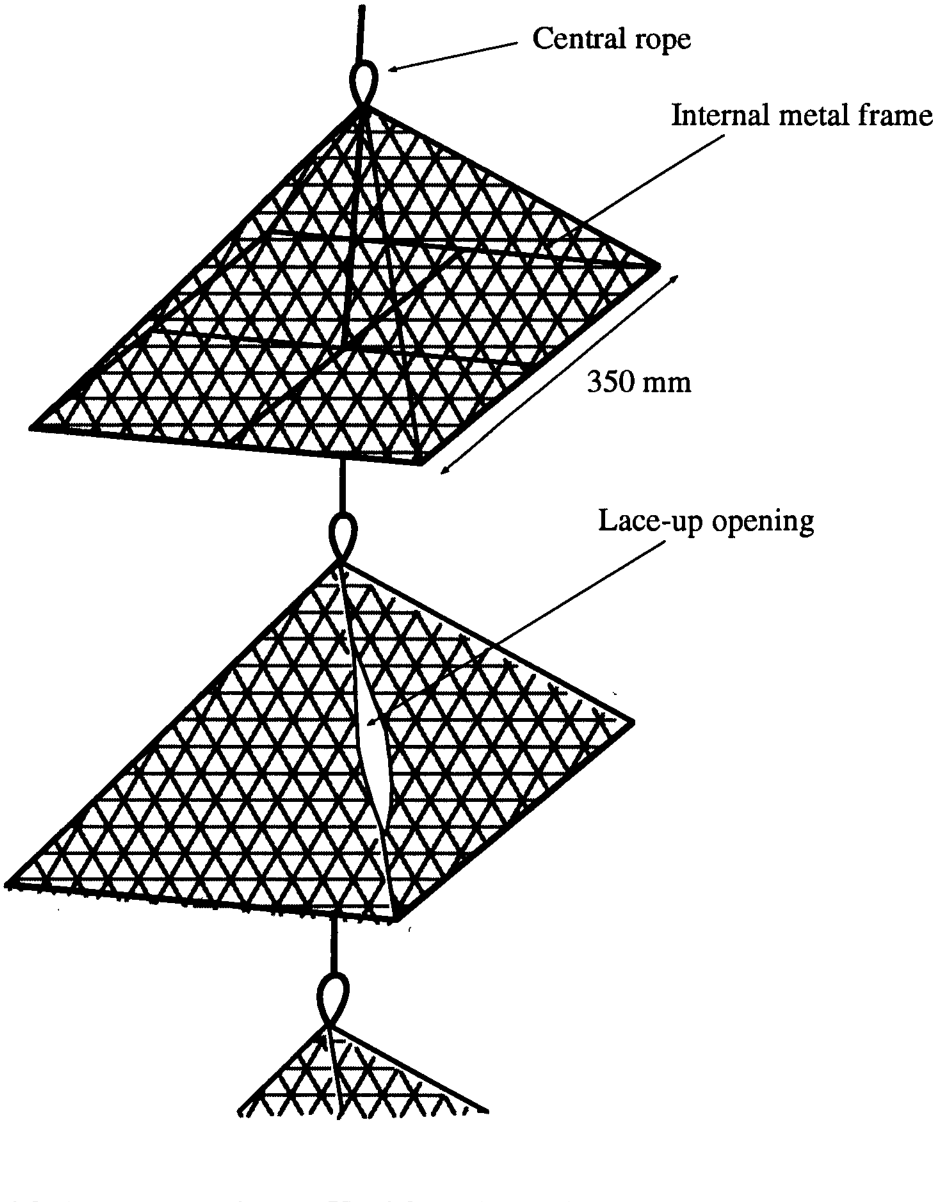


Figure 4.3 Japanese pearl nets. Used for culture of scallops and queens.

The spat for these trials were taken from a common pool of animals sorted from the spat collectors; mean shell height 12.5 mm ± 0.11 (S.E.).

4.2.3*b* Intermediate size *Pecten maximus*

The scallops from the short trial were thinned to a density of 10 per pearl net (82 shells.m^{-2}) and grown on for further periods in identical 4.5 mm pearl nets (mean shell height 50.2 mm ± 0.19). Thirteen lines of six pearl nets were placed on the longlines on 1st October 1990. One line was recovered on 21st May 1991 (232 days) and a further eight lines on 15th January 1992 (471 days). The remaining lines had lost their identification markings and as such were lost from the experiment.

4.2.3*c* *Aequipecten opercularis* spat

Three lines of six pearl nets (4.5 mm mesh) of *A. opercularis* were measured and placed on the longlines in Bay Fine at a stocking density of 150 per net (1225 shells.m^{-2}) . Mean shell height was 19.8 mm ± 0.09 (S.E.). These spat were on-grown for the same period as the *P. maximus* spat (6th December 1989 to 12th March 1991, 461 days). *Aequipecten opercularis* spat have a more robust shell than *P. maximus* of a similar size and can cope with stocking at higher densities. They actively climb up the inside of the nets and byssally attach. This 3-dimensional use of space increases the area available to them, effectively reducing density. Queens also seem less liable to shell interlocking, possibly due to the bi-convex nature of the shell.

4.2.3*d* Intermediate size *Aequipecten opercularis*

Intermediate size *A. opercularis* (that had previously been grown in the NWP trays) were cultured in pearl nets (4.5 mm mesh) at a stocking density of 25 per net (204 shells.m^{-2}) for a further 461 days (6th December 1989 to 12th March 1991). Three lines of six pearl nets were used.

4.2.4 Pocket Nets

The pocket nets were self-made from lengths of 6 mm mussel stocking[7] crimped onto a central core of 6 mm polypropylene rope. 4 m lengths of rope were used and the queen spat loaded into the pockets as they were made; 30 cm lengths of stocking were crimped to the rope at 15 cm intervals, to produce pear-shaped bags or pockets (Figure 4.4). 20 pockets were made on each length of rope. The crimping was done with a 'hog-ring' gun[8] powered by compressed air from a SCUBA diving cylinder.

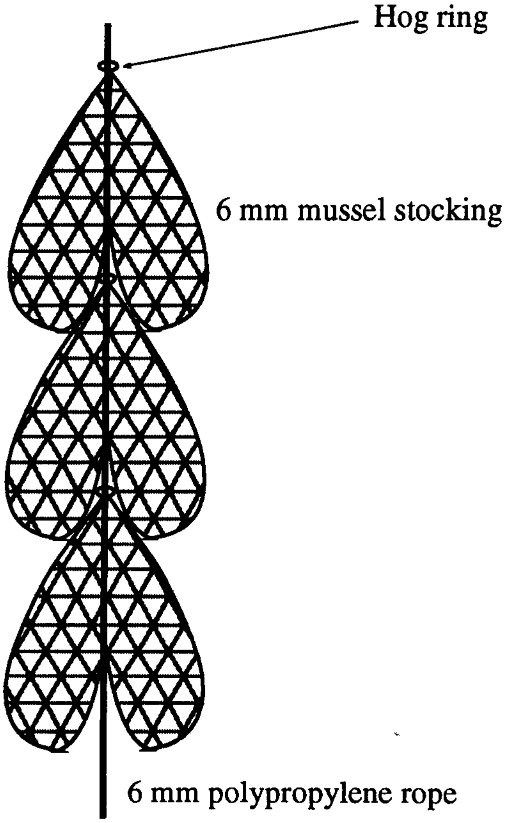


Figure 4.4 Design of self-made pocket nets for use with *Aequipecten opercularis*. 20 pockets per 3 m length or rope, loaded with 5, 10 or 15 queenies.

Eleven strings of pocket nets were made and tied to the headrope of a longline in Bay Fine on 11th December 1989. Queen shell heights were measured to 0.1 mm with callipers and loaded at three densities: 5, 10 and 15 per pocket, four strings each of 5 and 10 per pocket and 3 strings of 15 per pocket. The pocket nets were retrieved the following 14th November, after 338 days at sea and the queens re-measured. One string of 5 queens per pocket was lost during the course of the experiment. The initial shell heights of the queens in those strings that were recovered were: 5 shells.pocket^{-1} - 22.9 mm ± 0.10, 10 shells.pocket^{-1} - 22.8 mm ± 0.06, 15 shells.pocket^{-1} - 23.0 ± 0.05. Statistical comparison of these mean shell heights revealed that the shells at 15 shells.pocket^{-1} were significantly larger at the start of the experiment than those stocked at 10 shells.pocket^{-1}, although this was the only significant difference between the groups (ANOVA followed by Tukey test, $F_{0.05, 2, 1998} = 3.25$, $P = 0.039$).

4.2.5 Growth analysis

Growth was calculated on the basis of the increase in the mean shell height of the animals within a particular net or pocket. However, to remove the influence of variation in initial size on final size when making comparisons, an Instantaneous Growth Rate (G) was calculated (Ricker, 1968):

$$G = \frac{\ln H_2 - \ln H_1}{t}$$

$\ln H_2$ = Natural logarithm of final shell height
$\ln H_1$ = Natural logarithm of initial shell height
t = Growth period in days

4.2.6 Statistical analysis

The data were checked for normality of distribution using the Minitab ‘Nscores’ command (approximately equivalent to the Shapiro-Wilk test (Shapiro & Wilk, 1965)) and for homogeneity of variance (homoscedasticity) using the F_{max} test (Sokal & Rohlf, 1981) or by visual examination of the distribution of the fitted values versus the residuals following preliminary analysis of variance.

Where analysis of variance indicated significant results, the location of significant levels within a factor were revealed using the Tukey test or the Bonferroni Least Significant Difference (L.S.D.) test (Morrison, 1976). The latter is an *a priori* test which takes account of the total number of comparisons being made in calculating the least significant difference between means and so maintains the "experimentwise error rate" or probability of committing a Type I error (incorrectly rejecting the null hypothesis, H_0) at 0.05 overall (Morrison, 1976; Zar, 1984).

If the data were seriously heteroscedastistic or non-normal, Kruskal-Wallis tests were performed as nonparametric substitutes for ANOVA. The locations of significant levels of a factor were revealed using Tukey-type nonparametric multiple comparisons employing mean ranks, for equal and unequal sample sizes as appropriate (Zar, 1984). All proportional data (e.g. percentage survival) was subject to an arcsine transformation (Zar, 1984, his equation14.5) to normalise the distributions prior to statistical analysis.

4.3 RESULTS

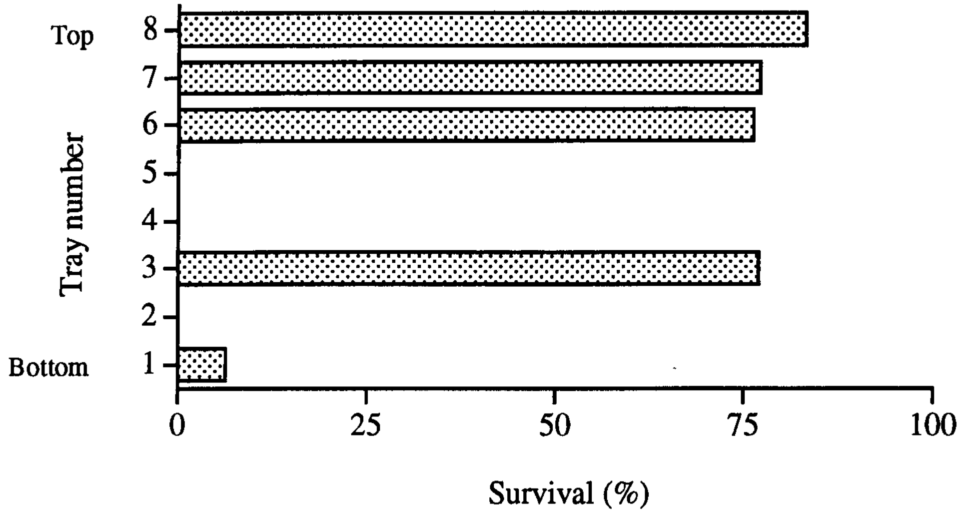
4.3.1 North West Plastics Trays

The stack of North-West Plastics trays containing *Aequipecten opercularis* was the only one recovered (29th November, 1989). There was evidence that the equipment had been recently lifted as many of the fouling organisms on the surface line and trays were damaged or had been stripped from the rope. The *Pecten maximus* were lost completely (although many of the trays were later recovered from Port Erin beach after a storm) and the trays holding the queens had been poorly re-tied, allowing the stack of trays to shear horizontally, providing access for predators. Several *Asterias rubens* were found among the trays (Table 4.1) as well as a well-developed fauna similar to that found on scallop spat collectors, including large numbers of ascidians (*Ciona intestinalis*), brittlestars (*Ophiothrix fragilis*), urchins (*Psammechinus miliaris*), feather stars (*Antedon bifida*) and squat lobsters (*Galathea* spp.).

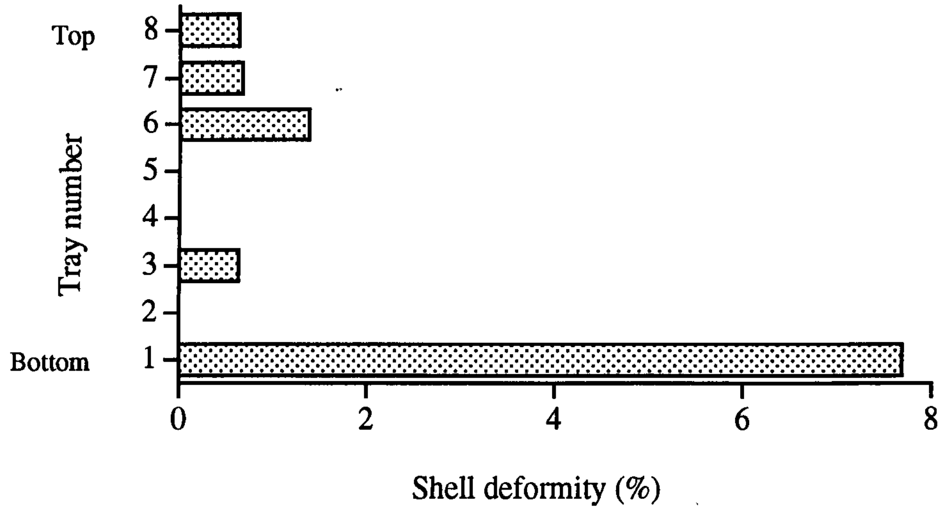
The survival of *A. opercularis* spat in the NWP trays was highly variable (0-83.2% and see Figure 4.5*a*, Table 4.1). All trays had a proportion of small dead shells reflecting early mortalities, probably due to damage and stress incurred during measuring and handling, but trays 2, 4 and 5 suffered 100% mortality, apparently from starfish predation. The lowest survival occurred in the trays containing *A. rubens* larger than 70 mm from the centre of the oral disc to the tip of the longest arm (distance R). These trays also contained large empty queen shells which suggested that this mortality was recent and that the starfish had not been present in the trays over the duration of the experiment but had gained entry to the stack of trays a short time before they were retrieved. Survival in the other trays varied from 77.0 - 83.2% despite the presence of smaller starfish (R ≤ 25 mm). Starfish of this size were likely to have settled from the plankton over the course of the culture period, and did not appear to have caused any queen mortality.

Less than 1% of the recovered queen spat from the NWP trays suffered any shell deformities (most frequently a deflection of both valves where they had been in contact with the side of the tray). The relatively high frequency of deformed shells observed in the bottom tray (Figure 4.5*b*) was exaggerated by low survival (Figure 4.5*a*) and did not represent a substantial increase in the number of deformed shells.

a. **Survival**



b. **Shell deformities**



c. **Growth rate**

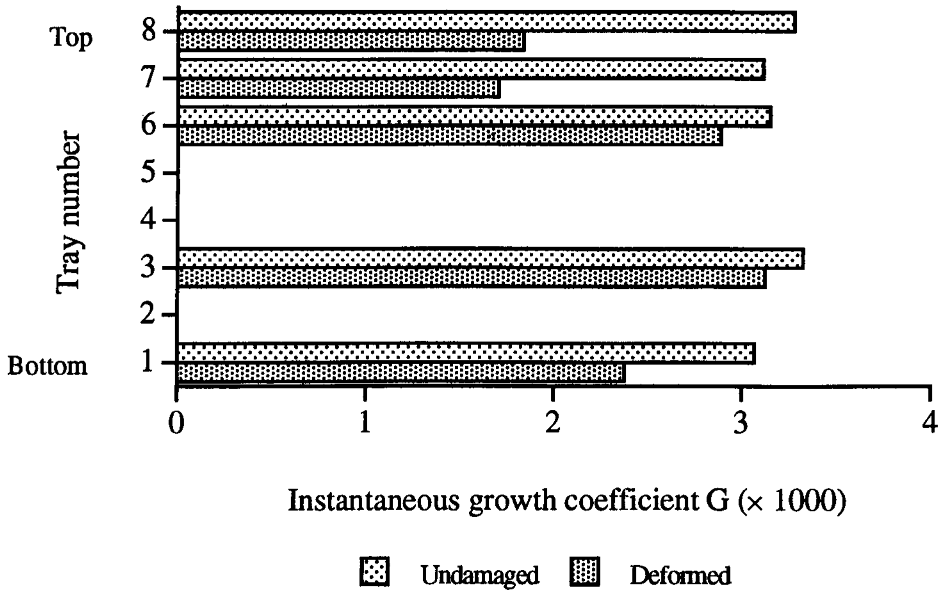


Figure 4.5. Performance of *Aequipecten opercularis* spat grown in North West Plastics trays for 228 days (15th April - 29th November). ***a***. Survival rate, ***b***. Percentage of shell deformities, ***c***. Growth (instantaneous growth coefficient, G × 1000) of undamaged and deformed shells.

Table 4.1. Survival of *Aequipecten opercularis* spat in North-West Plastics trays and the presence of predators after 228 days in Bay Fine. R = distance from centre of oral disc to the tip of the longest leg of *Asterias rubens*.

Tray	Queen survival (%)	Predators	Notes
8 - top	83.2	none	mortalities all small
7	77.2	none	
6	76.3	2 *Asterias* R<25 mm	
5	0	none	
4	0	4 *Asterias* R = 25, 70, 80, 85 mm	
3	77.0	1 *Asterias* R = 10 mm	all mortalities (except one) small shells
2	0	1 *Asterias* R = 115 mm	mortalities almost all large
1 - bottom	6.3	1 *Asterias* R = 90 mm	mortalities almost all large

The mean shell height (± SE) of the deformed queens was 33.2 mm (±1.95) compared to 38.6 mm (±0.13) for undeformed shells. The growth rate of the undamaged shells appeared consistent within the stack of trays (Figure 4.5*c*, reflecting the small difference in height above the seabed between the top and bottom trays (40 cm). The growth of the deformed shells was significantly lower than that of the undamaged shells when the data for all trays were pooled (Kruskal-Wallis, H = 4.81, 1, P = 0.029).

4.3.2 Pearl nets

The pearl nets suffered from mechanical damage due to adjacent strings becoming tangled with each other and with the vertical downlines of the rope systems. In some cases this resulted in the wire frame of the nets being severely bent, forcing the scallops into a corner of the bag. This kind of damage was most frequently observed on the upper bags of the strings of pearl nets. Some damage was also caused by bags touching the seabed and by predation.

4.3.2*a* *Pecten maximus* spat

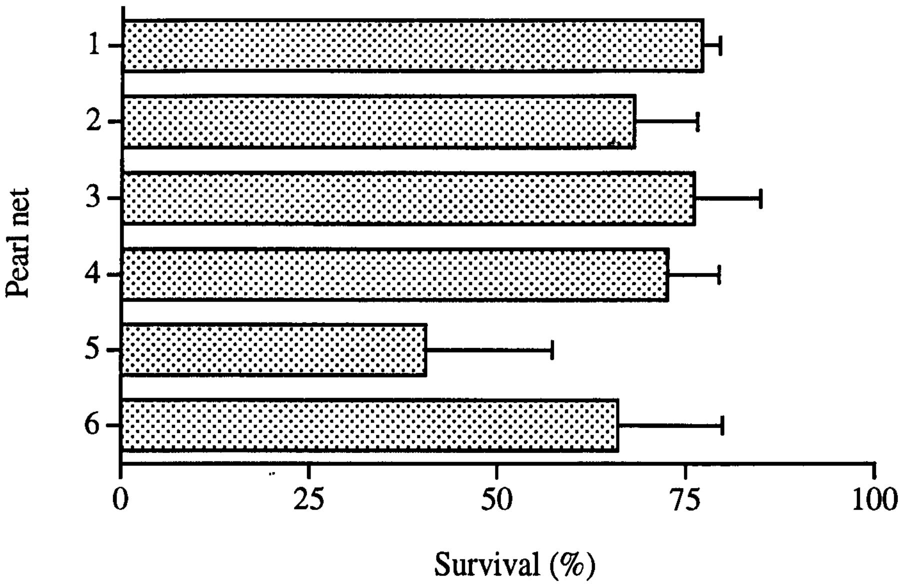
The pearl nets that remained on the longline for the longest period developed substantial fouling communities. The most serious effect of which was the settlement of mussels (*Mytilus edulis*) and ascidians (*Ciona intestinalis*) on the outsides of the bags, whose attachments (byssus threads and tunic respectively) entangled scallops on the inside. Scallops were frequently held in deleterious positions leading to shell deformities. However, not all scallops with deformed shells were tangled by mussels and ascidians, and not all tangled scallops were deformed, indeed some were clearly held in advantageous positions on the sides of the pearl nets and grew successfully. The proportion of scallops that were entangled varied form 5-74%, with the highest values in the uppermost pearl nets, although the variation with depth was not significant (Kruskal-Wallis test, $H = 6.02, 5, P = 0.305$).

The survival of *P. maximus* spat in the short experiment ranged from 20-96%. Analysis of the dead shell found in the pearl nets revealed that the majority was similar in size to the initial shell height when the nets were stocked; most mortality occurred as the spat were sorted from the spat collectors and transferred to pearl nets. This sorting and measuring was an extended process, as there were not the facilities available to do the sorting/transfer at sea as is generally practised commercially. Instead the collectors were transported to the laboratory for sorting, loaded into strings of pearl nets and then returned to the culture site. This extensive handling, involving aerial exposure and other stresses, was the likely cause of much of the observed mortality.

An additional source of mortality were the large edible crabs (*Cancer pagurus*) observed on the outside of the bags, during diving maintenance of the longline systems. Insufficient buoyage of the longlines resulted in some of the bags (or just the small concrete weight tied below) touching the seabed. This caused damage to the pearl nets and losses of scallops through the resulting holes, and also allowed crabs to climb up the strings of pearl nets. Crabs were observed crushing shells through the nets and apparently successfully feeding on them through the 4.5 mm square mesh. The dead shells found in the nets that were larger than the initial size at stocking and showed evidence of shell chipping and crushing consistent with crab predation. Such damage was only observed in the lower two bags of two of the strings of pearl nets. However, overall survival of *P. maximus* in this trial was unrelated to depth (ANOVA (arcsine transformed) $F_{0.05, 5, 15} = 0.2, P = 0.958$, Figure 4.6*a*). Across all nets the survival rate was 66.7% ±5.52 SE.

The survival of *P. maximus* spat in the long experiment was also affected by damage to the pearl nets; most damage occurred to the upper nets from tangling with other nets and the weighted verticals of the longline. There appeared to be a trend for increasing survival with depth (Figure 4.6*b*) although it was not quite of statistical significance (ANOVA (arcsine transformed) $F_{0.05, 5, 6} = 3.51, P = 0.079$). There was no overall variation in survival rate between the long and the short experiments (70.6% vs 66.7%), data pooled over depth (ANOVA (arcsine transformed) $F_{0.05, 1, 31} = 0.57, P = 0.456$).

***a.* Short experiment**



***b.* Long experiment**

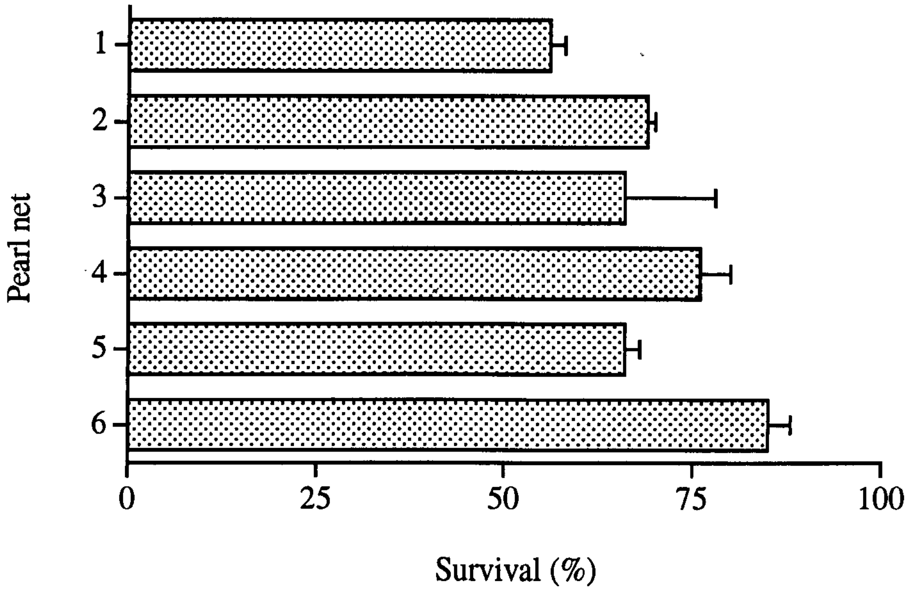


Figure 4.6. Survival of *Pecten maximus* spat grown in pearl nets at a density of 50 per net. ***a*****.** Short experiment (310 days), ***b*** **.** Long experiment (461 days). Values are mean percentage survival + standard error.

There were very few deformed *P. maximus* shells in the short experiment; deformities occurred in only five pearl nets and the numbers of scallops involved in each instance was small (1-7 deformed shells out of 50, Figure 4.7*a*). None of these scallops had become entangled with any of the fouling organisms on the outsides of the pearl nets and so were classified as deformed. The proportion of deformed shell was unrelated to depth (ANOVA (arcsine transformed) $F_{0.05,5,18} = 0.26$, $P = 0.931$).

At the end of the long experiment, substantial numbers of scallops were found to be deformed and/or tangled in mussel byssus threads and ascidian tunics. These scallops were categorised as undamaged, deformed, undamaged/tangled and deformed/tangled (Figure 4.7*b*). The fouling communities were well-developed and had become a serious impediment to water flow through the nets. There was no significant relationship between the proportion of scallops that were deformed (whether tangled or not) and depth (ANOVA (arcsine transformed) $F_{0.05,5,6} = 1.34$, $P = 0.363$).

There was a significantly higher proportion of deformed shells found in the long experiment than in the short experiment (ANOVA (arcsine transformed) $F_{0.05,1,34} = 33.51$, $P < 0.001$). This suggests that the majority of shell deformities occurred between the termination of the short experiment and that of the long trial, 26th September 1990 and 12th March 1991.

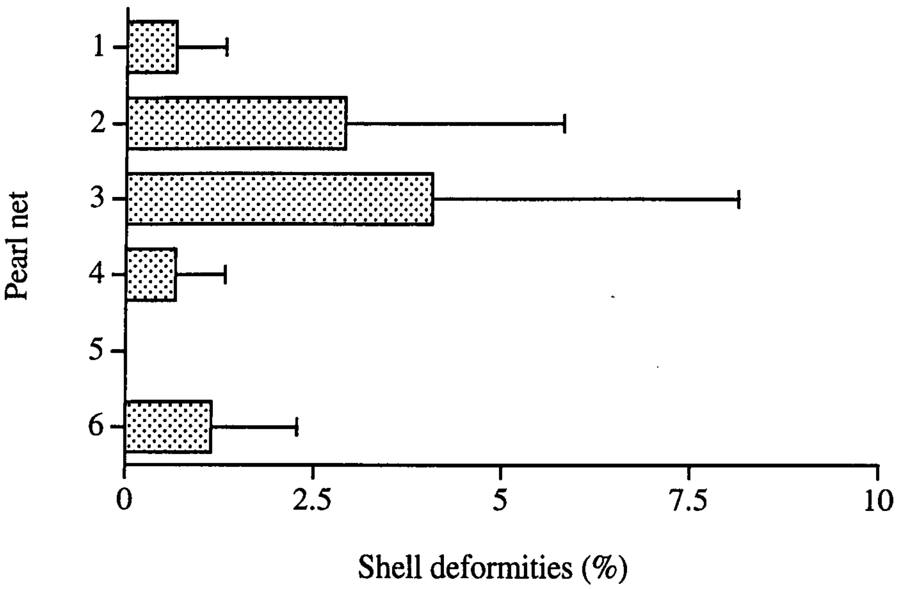
The growth of *P. maximus* spat from the short experiment varied significantly with depth over the range covered by the string of pearl nets (approx. 2.5 m, Kruskal-Wallis, H = 15.10, 5, P = 0.01, Figure 4.8*a*, Table 4.2).

Table 4.2 Kruskal-Wallis test of Instantaneous Growth Coefficient of undamaged shells (× 1000) with depth (pearls net number) for *Pecten maximus* cultures for 310 days.

Pearl net	n	Median	Mean rank	Z value
1	4	4.55	19.0	2.01
2	4	4.529	16.7	1.32
3	4	4.533	17.7	1.63
4	4	4.451	9.2	-1.01
5	4	4.476	8.3	-1.32
6	4	4.173	4.0	-2.63
Overall	24		12.5	

H = 15.10 d.f. =5 p =0.01

a. **Short experiment**



b. **Long experiment**

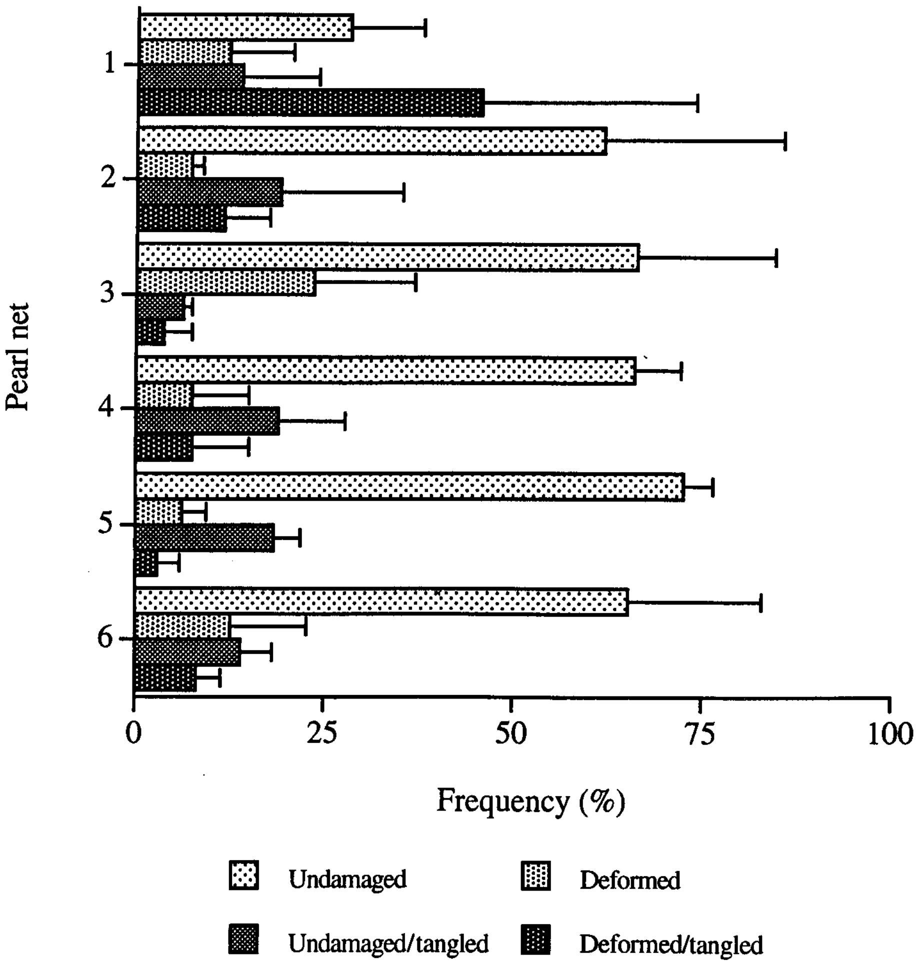


Figure 4.7. Frequency of shell deformities among *Pecten maximus* grown in pearl nets at a density of 50 per net. ***a*.** Short experiment (310 days), ***b*.** Long experiment (461 days). Values are mean percentage occurrence + SE. Note different axis scales.

Tukey-type nonparametric multiple comparison test (for equal sample sizes) to locate significant differences between medians, experimentwise error rate = 0.05.

Comparison	Difference	S.E.	q	$q_{0.05,\infty,6}$	Significance
1 vs 6	15	3.536	4.243	4.03	Significant
1 vs 5	10.7	3.536	3.027	4.03	n.s.
3 vs 6	13.7	3.536	3.875	4.03	n.s.

Conclusion

6 5 4 2 3 1

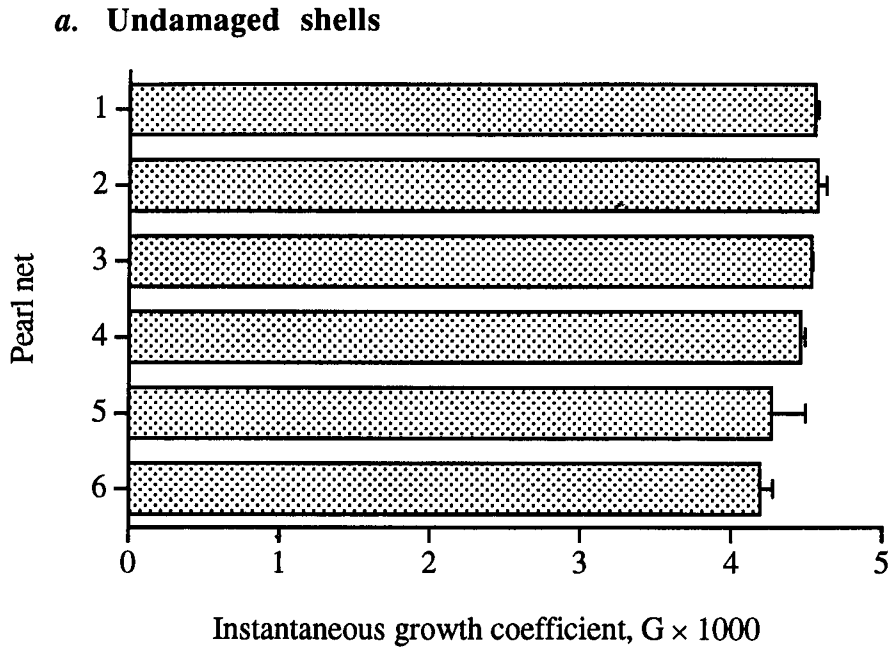
Affinities of pearl nets are indicated by underlining

A posteriori multiple comparison testing revealed that scallops in the top pearl net grew significantly faster than those in the bottom net, while differences between other heights were not statistically significant. The trend of reduced growth rate with depth is clear from Figure 4.8*a*.

The growth rate of the deformed shells was lower than that of undamaged ones (pooled over all depths); mean IGC (× 1000 ± S.E.) of deformed shells = 3.409 ± 0.301, undamaged shells = 4.428 ± 0.48. However, the low numbers of deformed shells and their concentration in only a few pearl nets made statistical comparison unreliable. There was no apparent trend in the growth rate of the deformed scallops with depth (Figure 4.8*b*).

The growth rate of all the scallops from the long experiment combined was not related to depth (ANOVA, $F_{0.05,5,8} = 0.32$, $P = 0.892$). Any effect on growth rate due to depth or some function of pearl net position in the string might be expected to be most apparent in those scallops that were healthy and undamaged. However, the growth rate of the undamaged scallops was also not significantly related to depth although the probability was markedly different to that for all the scallops combined (ANOVA, $F_{0.05,5,6} = 2.65$, $P = 0.134$).

The growth of *P. maximus* spat in the long experiment was significantly lower among the deformed and deformed/tangled groups than the undamaged and undamaged/tangled shells ($F_{0.05,3,40} = 32.26$, $P < 0.001$, Table 4.3, Figure 4.9).



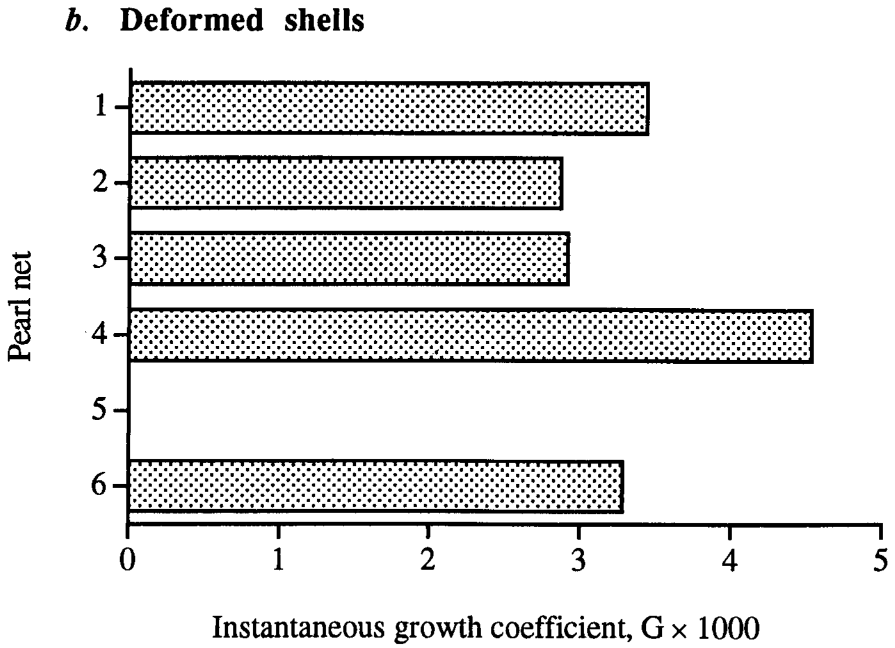


Figure 4.8. Growth of *Pecten maximus* spat grown in pearl nets at a density of 50 per net for 310 days (short experiment). ***a***. Undamaged shells, ***b***. Deformed shells. Values are mean instantaneous growth coefficient, G x 1000 + standard error.

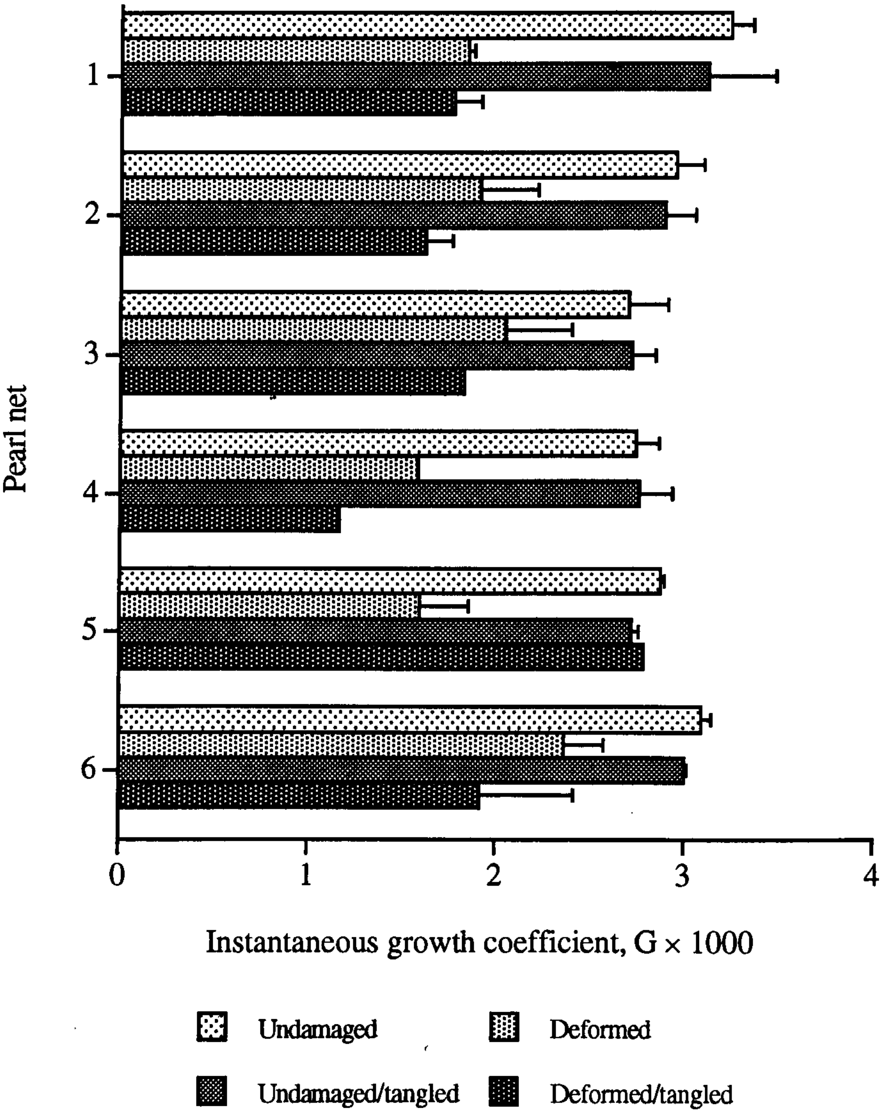


Figure 4.9. Growth rate of *Pecten maximus* spat grown in pearl nets at a density of 50 per net for 461 days (long experiment). Values are mean instantaneous growth coefficient, G x 1000 + standard error for shells classified by deformity and presence of entangling mussel byssus threads or ascidian attachment.

Table 4.3. Analysis of Variance of instantaneous growth coefficient G (× 1000) with shell deformity, all depths pooled. Levels of significance indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$). Comparisons of individual levels were made with the Tukey test adopting an experimentwise error rate (EER) of 0.05.

Source	DF	SS	Adj. MS	$F_{0.05}$	P	Significance
Deformity	3	11.526	3.842	32.26	< 0.001	***
Error	40	4.763	0.119			
Total	43	16.289				

Conclusion

Deformed tangled	Deformed	Undamaged tangled	Undamaged

Deformed tangled — Deformed (underlined together); Undamaged tangled — Undamaged (underlined together)

Affinities of groups compared are indicated by underlining

There was no difference in growth rate between the two undamaged classes or between the two deformed classes; entanglement with fouling organisms did not significantly reduce growth rate *per se* unless the scallops were held in such a position that they also became deformed.

The initial shell heights of the *P. maximus* spat from the long and short experiments were assumed to be equal as they were divided randomly for the two trials (mean shell ± SE = 12.5 mm ±0.11). At the end of their respective periods of growth, the undamaged scallops from the long and short experiments remained indistinguishable (50.1 mm ±0.16 vs 48.9 mm ±0.39 respectively) despite the difference in the lengths of time they spent at sea (151 days), as did the deformed shells from each trial (32.7 mm ± 2.22 vs 29.5 mm ±1.07, Table 4.4). However, the scallops from each experiment that escaped damage had significantly larger shell heights than those with deformed shells (Kruskal-Wallis adjusted for rank ties, H = 158.92, 3, P < 0.001).

Table 4.4. Kruskal-Wallis test of *Pecten maximus* final shell height from the long and short trials in pearl nets at 50 per net. Comparison are between undamaged and deformed shells in each trial (excluding all tangled shells in the long experiment) pooled over depth.

Factor/level	n	Median	Mean rank	Z value
Short/undamaged	778	50.4	591.8	6.89
Short/deformed	15	33.6	87.9	-5.68
Long/undamaged	258	49.6	538.5	-0.64
Long/deformed	47	29.8	57.8	-10.87
Overall	1098	549.5		

$H = 158.91$ d.f. = 3 $p < 0.001$

$H = 158.92$ d.f. = 3 $p < 0.001$ (adj. for ties)

Tukey-type nonparametric multiple comparison test of mean rank (for unequal sample sizes) to locate significant differences between categories, experimentwise error rate = 0.05.
Sh = short experiment, Lg = long experiment, un = undamaged shells, def = deformed shells.

Comparison	Difference	S.E.	Q	$Q_{0.05,4}$	Significance
Sh/un vs Lg/def	534.0	47.63	11.21	2.639	significant
Sh/un vs Sh/def	503.9	82.66	6.09	2.639	significant
Sh/un vs Lg/un	53.3	22.78	2.34	2.639	n.s.
Lg/un vs Lg/def	480.7	50.29	9.56	2.639	significant
Lg/un vs Sh/def	450.6	84.22	5.35	2.639	significant
Sh/def vs Lg/def	30.1	94.04	0.32	2.639	n.s.

Conclusion

Long deformed	Short deformed	Long undamaged	Short undamaged

Affinities of categories compared are indicated by shared underlining

The rate of growth of *P. maximus* spat in pearl nets was compared between the long and short experiments, pooling data over all depths and comparing only the undamaged shells and those that were deformed but not tangled (Table 4.5).

Table 4.5. Kruskal-Wallis test comparing instantaneous growth coefficients (G ×1000) for undamaged and deformed *Pecten maximus* spat grown in pearl nets in the long and short experiments.

Factor/level	n	Median	Mean rank	Z value
Long/undamaged	12	2.901	18.5	-2.08
Long/deformed	11	1.856	6.1	-5.03
Short/undamaged	24	4.504	39.7	5.82
Short/deformed	5	3.284	27.2	0.11
Overall	52		26.5	
$H = 41.54$	d.f. = 3	$p < 0.001$		

Tukey-type nonparametric multiple-comparison test of mean rank (for unequal sample sizes) to locate significant differences between categories, experimentwise error rate = 0.05.
Sh = short experiment, Lg = long experiment, un = undamaged shells, def = deformed shells.

Comparison	Difference	S.E.	Q	$Q_{0.05,4}$	Significance
Sh/un vs Lg/def	33.6	5.518	6.09	2.639	Significant
Sh/un vs Lg/un	21.2	5.358	3.96	2.639	Significant
Sh/un vs Sh/def	12.5	7.450	1.68	2.639	n.s.
Sh/def vs Lg/def	21.1	2.581	2.581	2.639	n.s.

Conclusion	Long deformed	Long undamaged	Short deformed	Short undamaged

Affinities of categories compared are indicated by shared underlining

The growth rate of undamaged *P. maximus* from the short experiment was significantly greater than that of the undamaged and deformed shells of the long experiment, although not significantly higher than that of the deformed scallops from the same trial. The growth of the deformed *P. maximus* from the short experiment was not significantly different from that of the undamaged or deformed shells from the long experiment. The extra time spent under culture by the scallops in the long experiment was a period of low growth, even for the undamaged shells.

4.3.2*b* Intermediate size *Pecten maximus*

The performance of intermediate size *P. maximus* (shell height 50.2 mm ± 0.19 S.E.) in 4.5 mm pearl nets was assessed over a period of 471 days at a stocking density of 10 shells per pearl net, although one string was recovered after a shorter period of 232 days. Nine of the original thirteen lines of pearl nets were recovered; the remaining lines had lost their identification and could not be separated from each other or the other lines on the culture longlines.

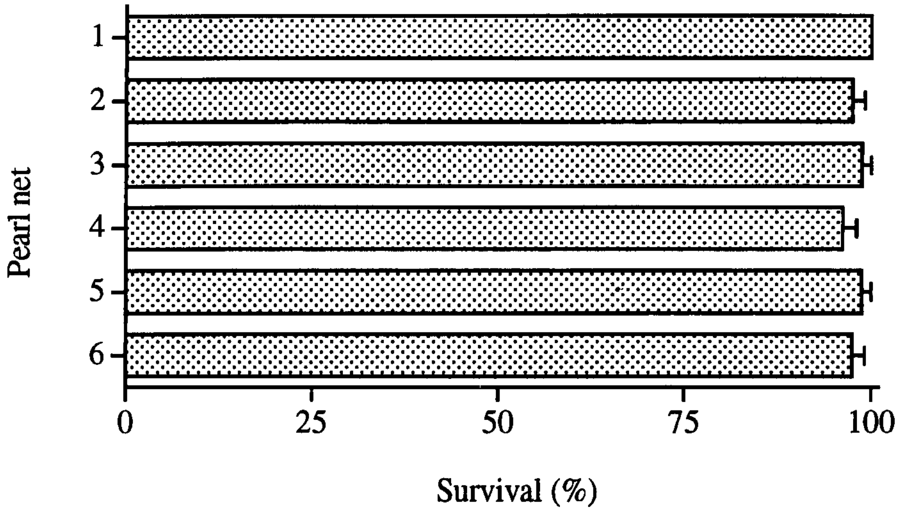
Extensive fouling communities had developed on the outsides of the pearl nets, including large numbers of ascidians and tube worms. However, the fouling organisms did not appear to have the same deleterious effects on the intermediate size *P. maximus*. The density of scallops in two of the lines recovered was accidentally reduced in the latter stages of the experiment as individuals were removed by divers for experimental use by another researcher. As these reductions occurred towards the end of the trial, the effects of the reduced stocking density on growth and survival were considered to be negligible and the data from these lines included in the analysis.

The survival of the intermediate size *P. maximus* was extremely high (Figure 4.10*a*). The line recovered after 232 days showed 100% survival and after 471 days mean survival (± S.E.) over all depths was 98.5% ±0.57. Survival was not related to depth (Kruskal-Wallis test adjusted for rank ties, H = 5.98, 5, P = 0.309).

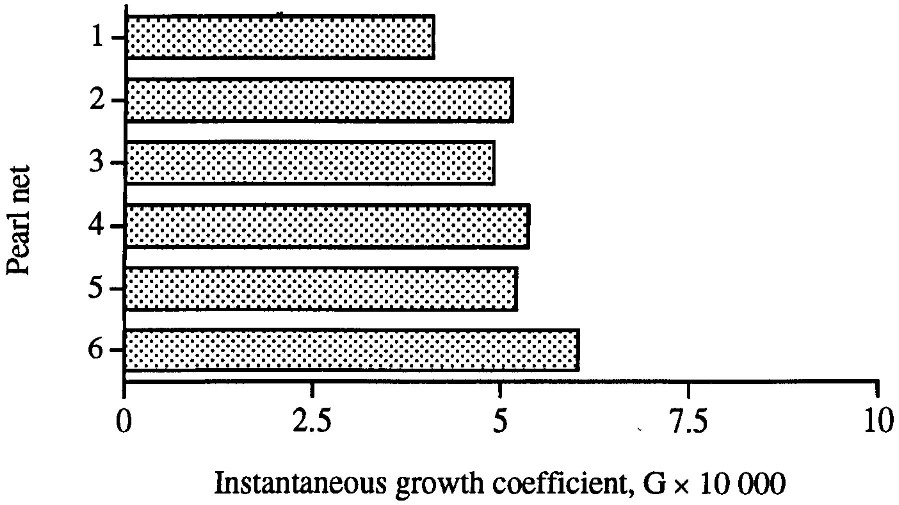
No scallops with shell deformities were found in this trial, either after 232 days or after 471 days. Intermediate size *P. maximus* were substantially more robust than the spat and the shell less liable to damage due to contact with the sides of the pearl net. In addition, the intermediate size scallops did not suffer from entanglement with mussel byssus threads or ascidians as did the *P. maximus* spat, despite the presence of similar fouling organisms on the pearl nets.

The observed growth rate (G) of intermediate size *P. maximus* in this experiment was considerably slower than that of the spat (Figure 4.10*b, c*). This lower rate was partly attributable to the nature of the growth coefficient employed; it relied on the increase in a linear shell height, known to decrease with increasing size and the onset of sexual maturity. After 232 days the growth rate appeared to show an increasing trend with depth (Figure 4.10*b*) although there was no indication of this after the full period of 471 days (ANOVA $F_{0.05,5,42} = 0.13$, P = 0.984, Figure 4.10*c*).

a. **Survival after 471 days**



b. **Growth after 232 days (survival 100%)**



c. **Growth after 471 days** (n = 9)

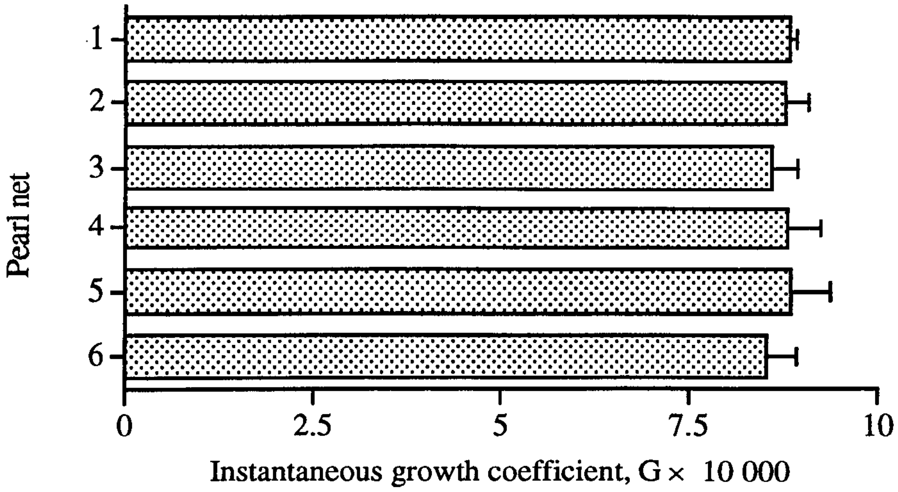


Figure 4.10. Performance of intermediate size *Pecten maximus* grown in pearl nets at a stocking density of 10 per net. ***a*****.** Percentage survival after 471 days (100% after 232 days). Instantaneous growth coefficient, G × 10 000 ***b*****.** after 232 days, ***c*****.** after 471 days. Error bars indicate standard error.

4.3.2*c* *Aequipecten opercularis* spat

Three lines of pearl nets containing *A. opercularis* spat were grown on the longline system for 461 days at a density of 150 per net. Two of these lines lost their identifying labels and only a single line was recovered intact. The pearl nets were severely overcrowded by the end of the trial but were most noticeable for their lack of fouling organisms. The mesh of the nets was coated in fine particulate material but their were almost no hydroids, mussels, ascidians or tube worms growing on the exterior of the nets. The gross overcrowding and consequent contact with the sides of the nets appeared to have prevented external settlement and development of a fouling community, of the kind found on the pearl nets containing *P. maximus* spat. The only parts of the pearl net strings that had been successfully colonised were the ropes tying the nets together, to the headrope and the concrete weight.

The survival of *A. opercularis* spat in the pearl nets was very high overall, 95.2% (±0.86 S.E.) despite the overcrowding. The dead shells that were found in the nets were of a broad range of sizes suggesting that mortality had occurred over the duration of the trial and had not been concentrated during any one period. There was no apparent trend in survival with depth (Figure 4.11*a*).

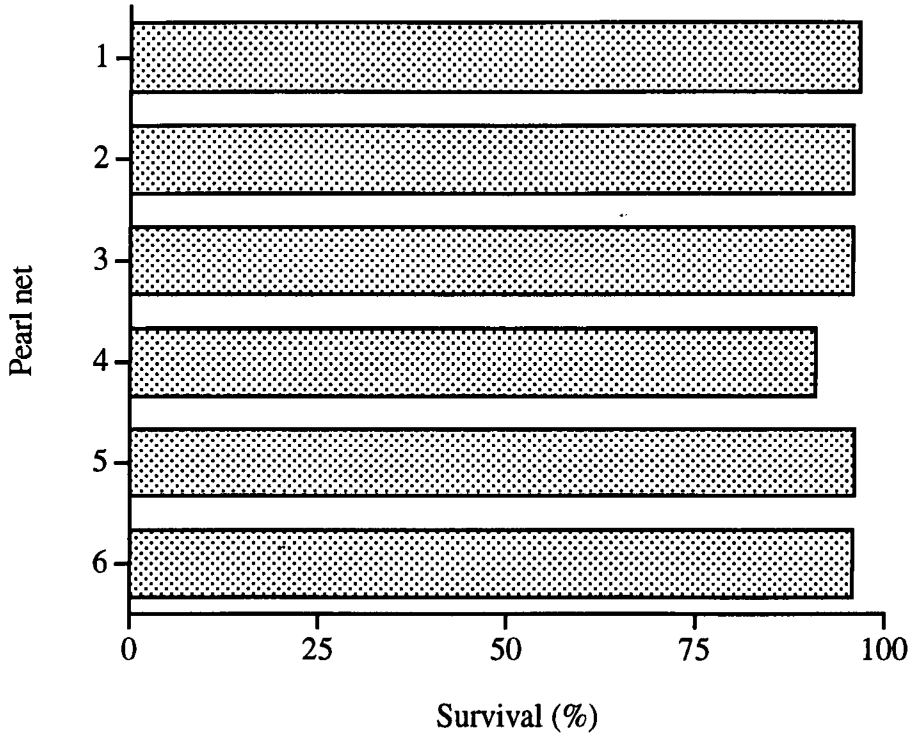
There were no *A. opercularis* spat with deformed shells in the line of pearl nets, despite the high stocking density and overcrowding; the queens shells were robust enough to resist damage when in contact with the mesh. The absence of fouling species capable of entangling the queens and holding them in restricted positions may also have reduced the chances of shell deformities developing.

The growth of *A. opercularis* spat in the pearl net trials was approximately half that of the *P. maximus* spat over the same period. The queens would have benefited from a lower stocking density or thinning out once they had grown to levels were the pearl nets became overcrowded. The growth rate of *A. opercularis* did not demonstrate any trend with depth (Figure 4.11*b*).

4.3.2*d* Intermediate size *Aequipecten opercularis*

This experiment continued the culture of the *A. opercularis* that survived the NWP trays (mean shell height 38.0 mm ± 0.16 S.E.). These queens were also grown in the 4.5 mm mesh pearl nets, at a density of 25 per net. The pearl nets developed a substantial fouling community, similar to that found on the nets containing *P. maximus* spat but absent from the nets holding *A. opercularis* spat. There had also been a settlement of pectinid spat into the pearl nets during the summer and all pearl nets contained newly settled *A. opercularis*, up to 23 individuals in one net.

***a.* Survival**



***b.* Growth rate**

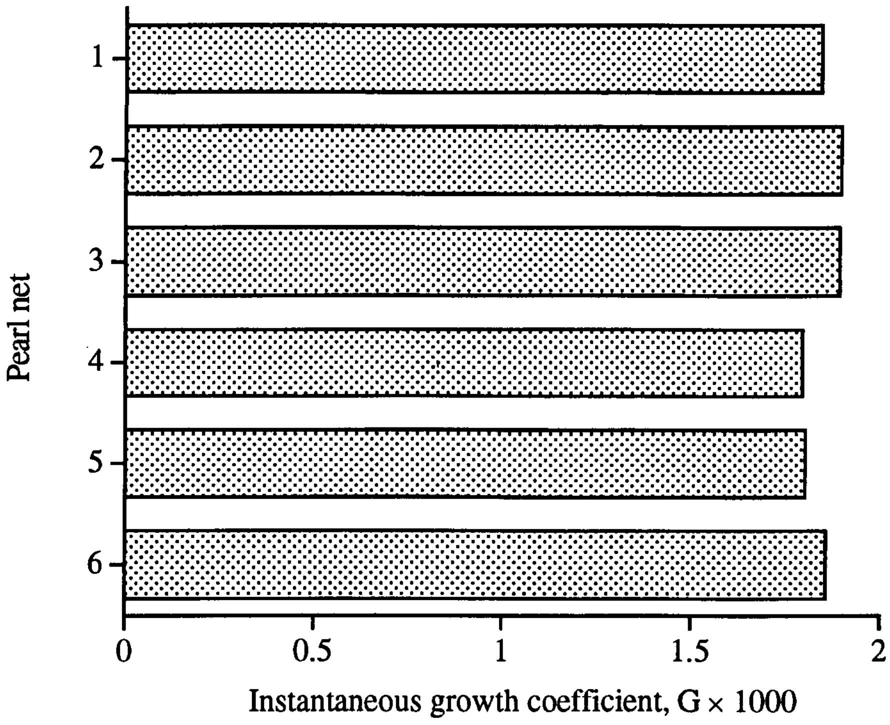


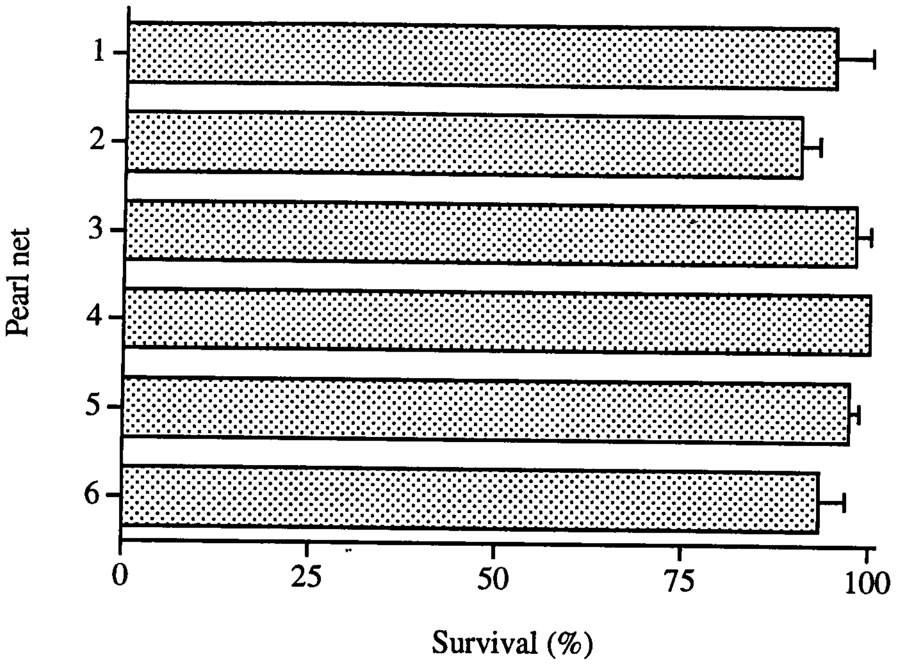
Figure 4.11. Performance of *Aequipecten opercularis* spat grown in pearl nets for 461 days at a density of 150 per net. ***a*****.** Percentage survival, ***b*** . Instantaneous growth coefficient, G × 1000.

The survival of the intermediate size *A. opercularis* was high; 95.7% ±1.4 S.E.. The was no trend in survival rate with depth (ANOVA (arcsine transformed) $F_{0.05, 5, 10} = 1.18$, $P = 0.383$, Figure 4.12*a*).

No shell deformities were found in any of the three lines of pearl nets when they were recovered. The intermediate size *A. opercularis* did not appear liable to entanglement with byssus threads or ascidian tunics despite their presence on the pearl nets.

In common with the larger *P. maximus*, the growth rate of the intermediate size *A. opercularis* was approximately half that of the spat over the same period, in the same type of culture equipment. There was no relationship between the position in the string of pearl nets (depth) and growth rate (ANOVA $F_{0.05, 5, 11} = 1.91$, $P = 0.173$, Figure 4.12*b*).

***a.* Survival**



***b.* Growth rate**

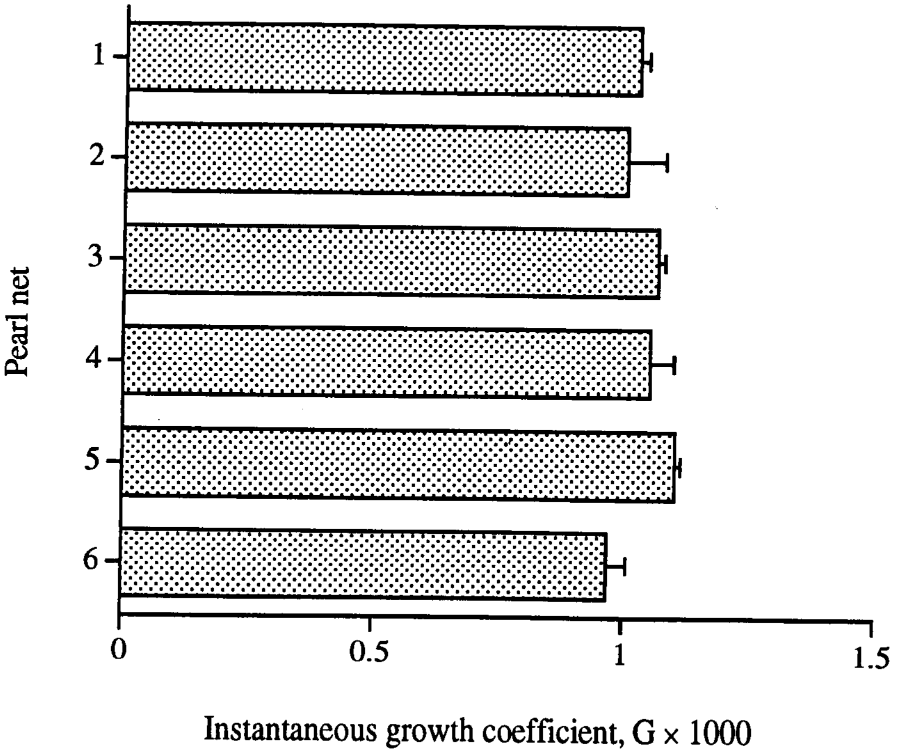


Figure 4.12. Performance of intermediate size *Aequipecten opercularis* grown in pearl nets at a density of 150 per net for 461 days. ***a*****.** Survival rate (%) ***b*** . Mean instantaneous growth coefficient, G x 1000. Values are means + standard error.

4.3.3 Pocket nets

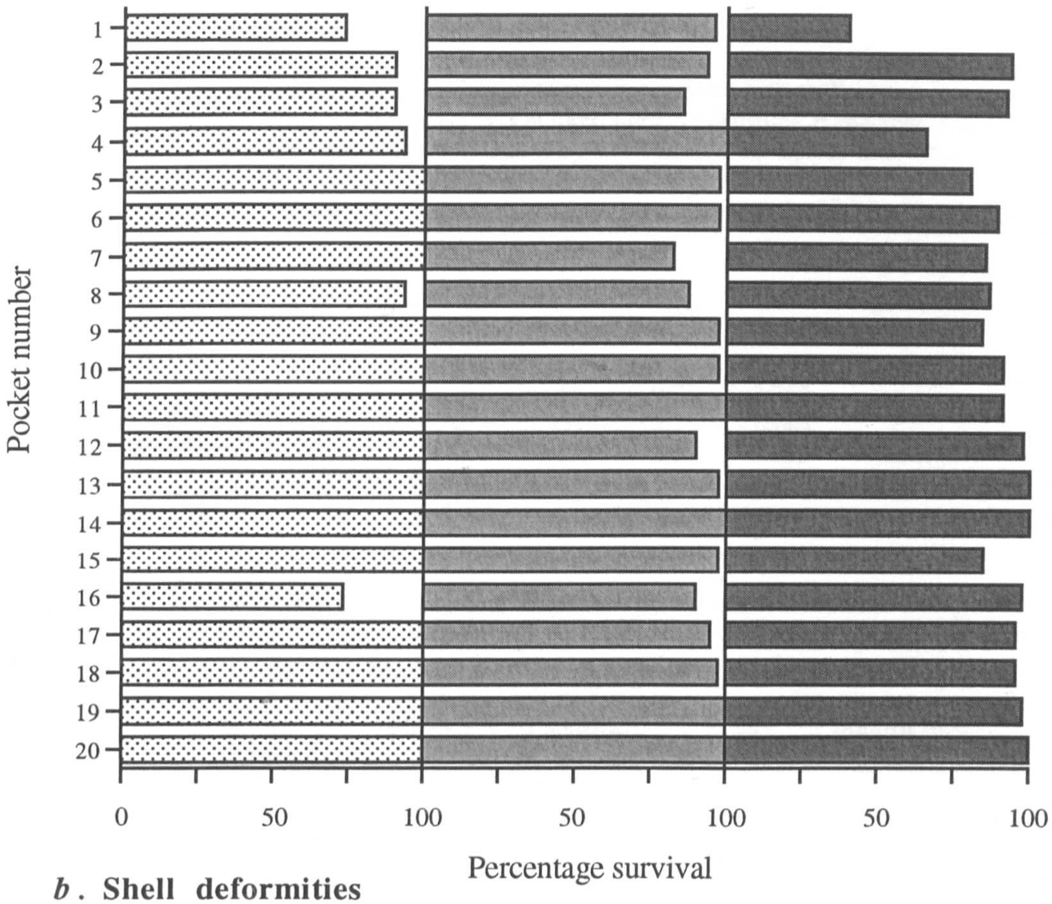
In some cases, the hog-rings separating the pockets corroded and were lost, effectively joining pockets together into larger nets with a greater number of shells. Diving observations during the growth period indicated that the pockets only merged toward the end of the experiment and so were included in the analysis. Some pockets were lost completely due to damage to the culture equipment. In calculating Instantaneous Growth Coefficients for individual pocket nets where they had become joined, the final shell height of the combined pocket was used in combination with the initial shell heights of the individual pockets.

There was very little fouling on the outsides of the pocket nets, with the exception of some mussel spat which settled onto the central rope at the core of the pockets. Many shells exhibited a clear growth check or shock ring from the process of loading the pockets and those from one of the lines carrying 15 shells per pocket had a second shock ring at approximately 30 mm shell height, from where the line had become tangled with one of the longline verticals. The queen shells grown in pocket nets appeared to have more deeply convex shells than those grown in pearl nets.

Survival rates for combined pockets were averaged over those pockets. The survival rate for *A. opercularis* was highest at the lowest density and fell with increasing stocking density and also increased with depth (Figure 4.13*a*). Two-way analysis of variance revealed that survival of *A. opercularis* in pocket nets was very close to statistical significance with both factors: ANOVA (arcsine transformed) density, $F_{0.05, 2, 131} = 2.93$, $P = 0.057$; depth, $F_{0.05, 19, 131} = 1.66$, $P = 0.052$.

The shell deformities exhibited by the *A. opercularis* grown in pocket nets appeared close to the shell margins, suggesting that they were relatively recent; there was clear evidence of successful shell growth since the start of the experiment prior to the onset of the damage. The proportion of *A. opercularis* that became deformed during the period of culture in pocket nets was analysed with respect to depth and stocking density, after arcsine transformation to normalise the data (Table 4.6). Shell deformity was not related to depth but occurred significantly more often at an initial stocking density of 5 shells per pocket than at 10 or 15 shell per pocket.

a. **Survival**



b. **Shell deformities**

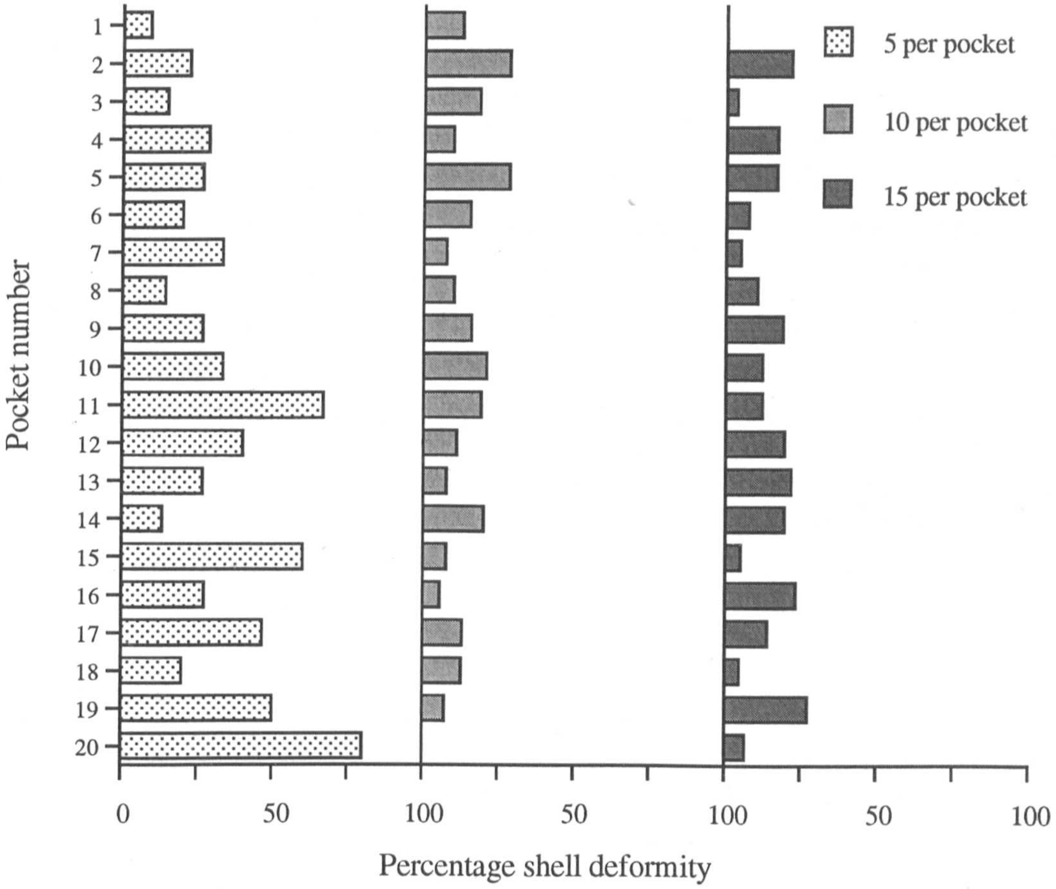


Figure 4.13. Performance of *Aequipecten opercularis* spat grown in pocket nets at three densities for a period of 338 days. ***a***. Percentage survival, ***b***. Percentage of shells showing shell deformities.

Table 4.6. Analysis of Variance of the proportion of *Aequipecten opercularis* with shell deformations after 338 growth in strings of 20 pocket nets at three stocking densities. Data analysed after arcsine transformation. Levels of significance indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$). Comparisons of individual levels within significant factors were made using Bonferroni's Least Significant Difference using an experimentwise error rate (EER) of 0.05.

Source	DF	Seq. SS	Adj. SS	Adj. MS	$F_{0.05}$	P	Significance
Depth	19	0.794	0.885	0.047	0.76	0.752	n.s.
Density	2	1.670	1.931	0.965	15.71	<0.001	***
Depth × Density	38	2.104	2.104	0.055	0.90	0.635	n.s.
Error	131	8.048	8.048	0.061			
Total	190	12.616					

Bonferroni Least Significant Difference. Density comparisons made between levels of initial stocking density (shells per pocket).

Comparison	n_1	n_2	MS_{error}	$F_{Bonferroni}$	L.S.D.	Significance
Density						
5 vs 10	57	79	0.061	5.885	0.104	significant
5 vs 15	57	55	0.061	5.885	0.114	significant
10 vs 15	79	55	0.061	5.885	0.106	n.s.

The relative frequency of shell deformities followed a different distribution than the trend observed for shell growth. The higher proportion of deformities at the lowest density was surprising because of the less crowded conditions experienced by the queens in these pockets (Figure 4.13*b*). However, the proportional nature of the data exaggerated the results because of the increased weighting given to individual deformed shells from the lower densities. Two-way analysis of variance of the absolute number of deformed shells with density and depth was insignificant for both factors and the interaction term, suggesting that the number of deformities arising was independent of density and may in fact be a product of the culture equipment (Table 4.7).

Table 4.7. Analysis of Variance of absolute numbers of deformed *Aequipecten opercularis* occurring in pocket nets stocked at three densities (5, 10 and 15 per packet) at 20 depths covered by the range of the culture equipment. Levels of significance indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$).

Source	DF	Seq. SS	Adj. SS	Adj. MS	$F_{0.05}$	P	Significance
Depth	19	40.703	42.917	2.259	0.74	0.769	n.s.
Density	2	9.927	8.840	4.420	1.45	0.238	n.s.
Depth × Density	38	98.570	98.570	2.594	0.85	0.710	n.s.
Error	131	398.684	398.684	3.043			
Total	190	547.885					

The growth of *A. opercularis* in pocket nets was significantly greater at stocking densities of 5 and 10 per pocket, than at 15 per pocket ($F_{0.05, 2, 128} = 19.62$, $P \leq 0.001$), but there was no significant difference in growth between the two lower densities (Table 4.8). Analysis of variance suggested that depth (as pocket number) was also a significant factor but the Bonferroni L.S.D. test failed to detect any significant difference from an *a priori* selection of pockets over the depth range covered by the culture equipment (3m). This may have been a reflection of the lower power of the Bonferroni test in individual pairwise comparisons when controlling experimentwise error rate (EER) over a large number of such comparisons (see Day & Quinn (1989) for a discussion of this).

Table 4.8. Analysis of Variance of Instantaneous Growth Coefficient (of undamaged shells) with stocking density and depth (Pocket number). Levels of significance indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$). Comparisons of individual levels within significant factors were made using Bonferroni's Least Significant Difference using an experimentwise error rate (EER) of 0.05.

Source	DF	Seq. SS	Adj. SS	Adj. MS	$F_{0.05}$	P	Significance
Density	2	1.947	2.043	1.021	19.62	<0.001	***
Depth	19	1.658	1.785	0.094	1.80	0.029	*
Density × Depth	38	0.882	0.882	0.0234	0.45	0.997	
Error	128	6.663	6.663	0.052			
Total	187	11.149					

Bonferroni Least Significant Difference. Depth comparisons made with selected levels equally spaced over the depth range employed. Densities are initial stocking densities (shells per pocket).

Comparison	n_1	n_2	MS_{error}	$F_{Bonferroni}$	L.S.D.	Significance
Density						
5 vs 10	55	80	0.052	5.885	0.097	n.s.
5 vs 15	55	54	0.052	5.885	0.106	significant
10 vs 15	80	54	0.052	5.885	0.098	significant
Depth						
2 vs 6	8	10	0.052	8.16	0.309	n.s.
2 vs 10	8	9	0.052	8.16	0.317	n.s.
2 vs 14	8	10	0.052	8.16	0.309	n.s.
2 vs 18	8	10	0.052	8.16	0.309	n.s.
6 vs 10	10	9	0.052	8.16	0.300	n.s.
6 vs 14	10	10	0.052	8.16	0.292	n.s.
6 vs 18	10	10	0.052	8.16	0.292	n.s.
10 vs 14	9	10	0.052	8.16	0.300	n.s.
10 vs 18	9	10	0.052	8.16	0.300	n.s.
14 vs 18	10	10	0.052	8.16	0.292	n.s.

Examination of Figure 4.14*a* suggested a slight increase in growth with depth, but considering the small depth range covered and the location of the longline and pocket nets in mid-water (well mixed) the differences were more likely to be due to the behaviour of the culture equipment.

The relatively small numbers of deformed shells precluded their inclusion in a multi-way analysis of variance with depth, however, when the data were pooled over depth and re-analysed with respect to density and shell deformation, both were significant factors (Table 4.9). The effect of stocking density was confirmed as significantly reducing growth rate at 15 per pocket relative to 5 and 10 shells per pocket, although there was again no difference in queen growth between the two

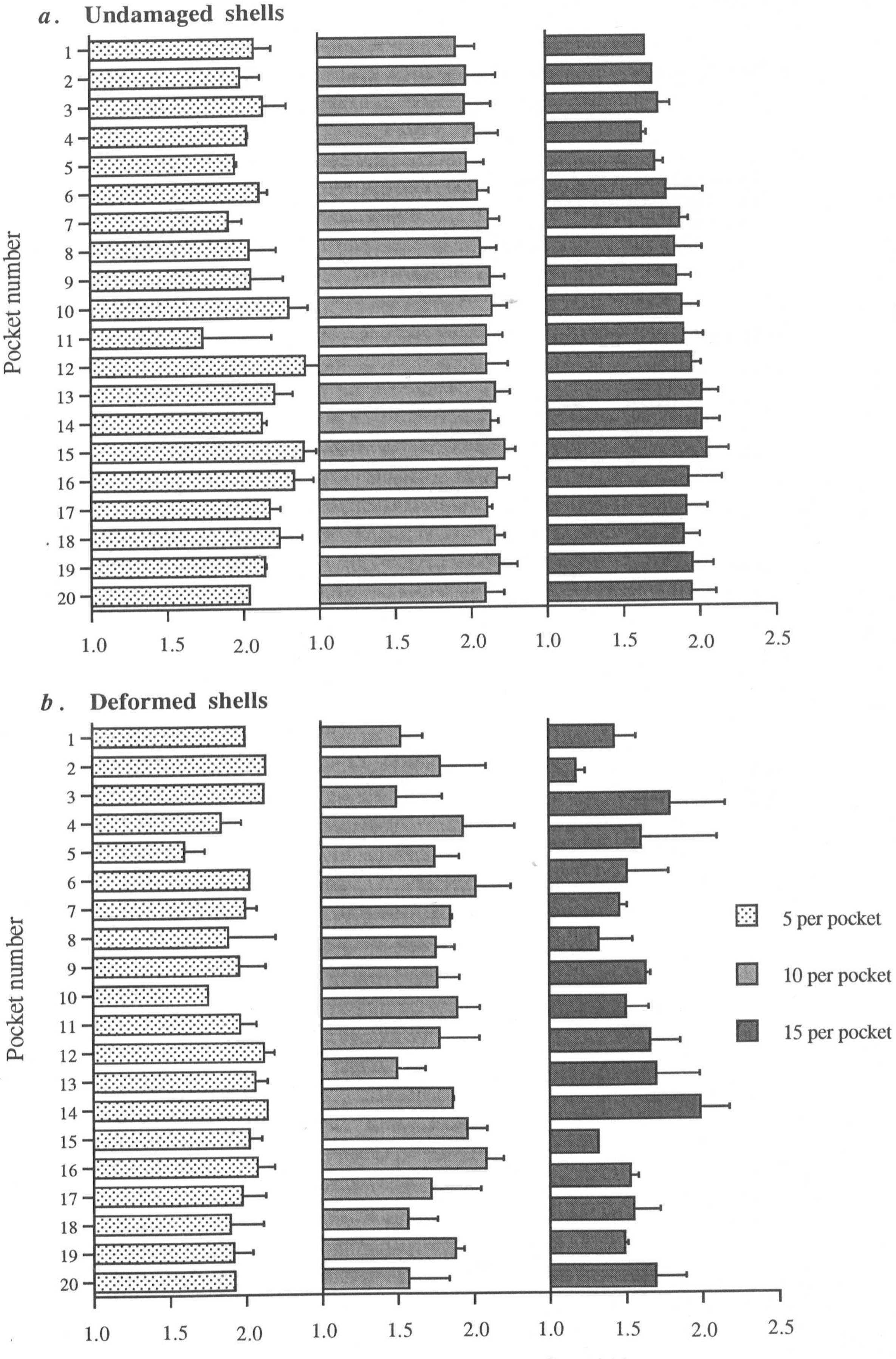


Figure 4.14. Instantaneous growth coefficients of *Aequipecten opercularis* spat grown in pocket nets at three densities for a period of 338 days. ***a***. Undamaged shells, ***b***. Deformed shells.

lower densities. The growth rate of the deformed shells was significantly lower than the undamaged shells (ANOVA, $F_{0.05,1,304} = 75.10$, $P < 0.001$).

Table 4.9. Analysis of Variance of Instantaneous Growth Coefficient of *Aequipecten opercularis* spat grown in pocket nets at 5, 10 and 15 per pocket, analysed for deformed and undamaged shells. Levels of significance indicated by * (P≤0.05), ** (P≤0.01) and *** (P≤0.001). Comparisons of individual levels within significant factors were made using Bonferroni's Least Significant Difference using an experimentwise error rate (EER) of 0.05.

Source	DF	Seq. SS	Adj. SS	Adj. MS	$F_{0.05}$	P	Significance
Density	2	4.681	4.780	2.390	39.85	<0.001	***
Shell	1	4.687	4.503	4.503	75.10	<0.001	***
Density × Shell	2	0.301	0.301	0.151	2.51	0.083	n.s.
Error	304	18.230	18.230	0.060			
Total	309	27.898					

Bonferroni Least Significant Difference. Comparisons are between differences in initial stocking densities.

Comparison	n_1	n_2	MS_{error}	$F_{Bonferroni}$	L.S.D.	Significance
5 vs 10	93	126	0.060	5.73	0.080	n.s.
5 vs 15	93	91	0.060	5.73	0.086	significant
10 vs 15	126	91	0.060	5.73	0.081	significant

4.3.4 Shell height/length relationship

Shell height was used throughout this chapter to characterise the size of both *P. maximus* and *A. opercularis* as it was the easiest dimension to measure, particularly on pectinid spat. However, legislation restricting the minimum legal landing size (MLLS) of *P. maximus* to 110 mm utilises shell length (see Chapter 2). There is no MLLS for *A. opercularis,* but a practical minimum of 55 mm is set by the reluctance of the processing factories to accept queens below this size Allison (1993).

Log-log Regression analysis of shell length and height of the intermediate size *P. maximus* grown in pearl nets (final shell height 72.8 mm ± 0.38 S.E.) produced the relationship: Log_{10} length = 0.188 × height + 0.923 ($r^2 = 88.7\%$). Thus if the same MLLS was applied to cultured scallops then the shell height would have to reach a minimum of approximately 102 mm at the time of harvest. This may, however, be an over-estimate due to the allometric nature of scallop growth; the relationship of shell length and height would be different for commercial size shells with a greater disparity between them.

The *A. opercularis* grown in NWP trays and then pearl nets exceeded the minimum acceptable size of 55 mm; their mean shell height was 61.2 mm ±0.19 S.E. equivalent to a shell length of approximately 64 mm (length = 1.126 × height - 4.492 from Soemodihardjo (1974)).

4.4 DISCUSSION

4.4.1 Methodological constraints

The poor settlement of pectinid spat on collectors during this study (see Chapter 3), while consistent with previous work (Paul, 1978; Brand *et al.*, 1980; Paul *et al.*, 1981; Duggan, 1987; Brand *et al.*, 1991b), provided a very limited number of animals with which to experiment. An attempt to import spat from Scotland proved unsuccessful due to extremely high mortalities incurred after poor conditions during transit. The lack of spat contributed to the low replication in some experiments and consequent difficulties with some statistical analyses.

The pearl nets used in this research were of a small mesh (4.5 mm) obtained prior to the start of this work. This mesh size was unnecessarily small and was likely to have reduced water supply and hence food availability to the scallops and queens and to have provided a large area for the settlement of fouling organisms. This size of net is not commonly used; 6 mm square mesh is more frequently used as the first pearl net size (Hardy, 1991). Intermediate size *P. maximus* are usually grown on in lantern nets, with an increasing large outer mesh as the scallops get older. Initial trials with lantern nets proved unsuccessful as the particular design of net was very difficult to work with and was abandoned in favour of continued use of pearl nets.

The index of growth used in these experiments (Instantaneous Growth Coefficient) was preferred to other measures of growth in order to remove the influence of the initial shell height on estimates of growth. Practical constraints meant that scallops were frequently measured and loaded directly into new pearl nets as they came out of old ones, rather than being pooled and then randomly re-assigned to new nets and re-measured. The use of an instantaneous growth rate took account of small variations in initial size introduced by these methods. However, statistical comparisons of growth rate could not be made between groups of scallops of substantially different sizes (e.g. spat and intermediate size scallops) because of the reduction in the rate of linear increase in shell height with increasing scallop size and the onset of sexual maturity.

4.4.2 Impact of handling

The survival of both pectinid species in this work was high (>95%) with the exception of the trials of *P. maximus* spat in pearl nets and *A. opercularis* spat in the NWP trays. A large proportion of the dead shells that were found in these experiments were small and had clearly died soon after the start of the period in culture. Similar early mortalities were not observed during the experiments with *A. opercularis* spat in pearl nets or intermediate sized animals of either species.

The causes of this early mortality were likely to have been the stresses of handling encountered during the sorting of the spat collectors and the transfer to the on-growing equipment. This stage of the culture process has been recognised as critical to survival of *P. maximus* (Ventilla, 1977e; Hardy, 1991) as well as other species, with rigorous guidelines developed to minimise mortalities (Body & Murai, 1986; Townsend & Bourne, 1989; Hardy, 1991; Dadswell & Parsons, 1991a). The sorting process became extended in my work by limitations on resources and manpower; there was no potential for sorting the collectors at sea and the transfer to the laboratory and maintenance of the collectors in tanks and ponds prior to sorting were an added stress on the spat. Further handling was involved in the measurement of the spat for experimental purposes as they were loaded into the pearl nets and trays. In particular the shells of *P. maximus* were extremely delicate and were frequently chipped when the collectors were sorted.

A. opercularis spat were not as susceptible to damage as *P. maximus* as their shells were generally thicker and larger at the time of spat sorting. The early mortality of *A. opercularis* spat observed in the NWP trays was similar to that for *P. maximus* in the pearl nets, but did not occur among the queens grown on pearl nets. This unexpected result may be due to the long period of maintenance in the laboratory of the *A. opercularis* spat used in the NWP trays. These spat were from the 1988 settlement and were held in tanks from October 1988 until the following April before they were put out to sea in the NWP trays; they were likely to have been in relatively poor condition.

The importance of separating *A. opercularis* from *P. maximus* spat prior to on-growing was stressed by Paul (1985b) who suggested a method which exploited the climbing and attachment behaviour of *A. opercularis*. This method was not practicable in my work because of the amount of tank space required. I separated the two species manually, but this process did involve further aerial exposure.

The larger intermediate size shells experienced similar aerial exposure during transport to and from the longline site, and during measuring and net changes, but proved far more robust. They were also not exposed to the stresses of the spat collector sorting process. Richardson *et al.* (1982) found no significant difference in the growth of *Aequipecten opercularis* from the Clyde Sea measured monthly or every three months, suggesting that this species was not easily affected by handling. However, investigations into the performance of *Placopecten magellanicus* in suspended culture have reported elevated mortalities and reduced growth attributed to repeated handling (Wildish *et al.*, 1988; Dadswell & Parsons, 1991a; Dadswell & Parsons, 1991b; Parsons & Dadswell, 1992) and it is now acknowledged that all handling of scallops, of whatever age, should be kept to a minimum (Côté *et al.*, 1993).

4.4.3 Gear types

The performance of the different types of culture equipment was characterised by several factors in addition to the rate of growth of the scallops and queens held inside. The usefulness of any particular system for scallop on-growing depends not only on the growth rate but on the ease of use, the degree of fouling incurred, how space efficient they were in terms of shells held per station on the longline headrope, as well as cost.

4.4.4 Fouling

The settlement of fouling organisms on any clean surface placed in the sea is inevitable without specialist anti-fouling treatments. The ability of fouling organisms to settle and develop on culture equipment and on the scallops themselves is important in both the choice of culture method and location.

The NWP trays became heavily fouled with ascidians, tube-dwelling worms and other filter feeders, potential competitors for the supply of particulate food. The impact of these was difficult to assess because of the lack of replication in the experiment and the damage inflicted by the late ingress of *Asterias rubens*. Deployment in April resulted in the trays becoming heavily fouled soon after entering the water; their use from the October or November after spat collection would have allowed a longer period of maximum water flow due to low larval settlement over the winter. Wildish *et al.* (1988) found less fouling on benthic trays than other types of culture equipment and attributed this to sediment and grazing, but also experienced up to 75.2% mortality of 3 year old *Placopecten magellanicus* due to attacks from *A. rubens*.

The pocket nets suffered least from fouling because of the small surface area presented by the monofilament mesh of the outer stocking, although there was a substantial settlement of mussels onto the core rope of some of the nets. The mytilid settlement had no obvious deleterious effect; their byssus threads were directed onto the central rope and impinged on only a few of the queens. In contrast, mussel byssus threads and ascidian tunics (not found on the pocket nets) caused significant problems to *Pecten maximus* in pearl net culture in the long experiment, entangling a large proportion in some nets (5-74%). However, such entrapment did not always result in shell deformity or a significant reduction in growth rate. The fouling communities that developed on the pearl nets in the short experiment did not entangle the scallops inside, this apparently only occurred later on and so could have been avoided in the long experiment by a net change.

Entanglement was only observed with the *P. maximus* spat and not among the *A. opercularis* spat or the intermediate size individuals of either species despite heavy fouling in some cases; the larger, heavier and more robust shells may have been able to break any fouling attachments that developed. Indeed, the virtual absence of fouling organisms on the pearl nets containing queen spat at high density (150 shells.net^{-1}) was apparently due to the friction of the over-stocked shells against the mesh.

The woven construction of the pearl net mesh provided a relatively large settlement surface for fouling organisms in comparison to the monofilament of the pocket nets, making them vulnerable to heavy fouling. The re-design of this widely used style of net to incorporate a low surface area monofilament mesh might reduce the degree of fouling and potentially increase growth rates. There has recently been a trend to avoid the use of pearl nets altogether by using lantern nets with an outer mesh made from tubular monofilament stocking with a mesh size of 6 mm as a replacement (J. Walford, Highland Aquaculture Ltd, personal communication, and see Hardy (1991) for details and photograph of the system used).

In addition to the physical impact of the fouling organisms on the scallops in terms of entanglement and the reduction of water flow, many of the species involved were filter feeders and as such were potential competitors for the supply of particulate food. The importance of net fouling on pectinid cultivation in UK waters was recognised by Wieland & Paul (1983) and is an important limiting factor in the suspended culture of many bivalves (Bull, 1987; Heffernan *et al.*, 1988; Wildish *et al.*, 1988; Mallet & Carver, 1991; Cropp & Hortle, 1992; Claereboudt *et al.*, 1994). The effects of fouling may be limited by the selection of appropriate culture equipment (such as the pocket nets used in my work, lantern nets with a monofilament outer mesh, or some form of ear-hanging (Paul, 1988), tape (Cropp, 1988b) or “bondo” culture (Ventilla, 1982) where there is no mesh surrounding the scallops whatsoever). The nature and degree of fouling varies spatially and so careful location of the culture site may reduce this problem. Wildish *et al.* (1988) noted “considerable fouling on nets” in Passamaquoddy Bay, North America, whereas Parsons & Dadswell (1992) remarked on the low fouling of their pearl nets over the period of a year, at another location in the same bay.

The development of fouling communities also varies temporally, depending as it does on the settlement of planktonic larvae and propagules. Ventilla (1982) mentioned the practice in Japan of lowering culture nets deeper in the water column to avoid mytilid and barnacle settlements which were heaviest nearer the surface and between 5-12 m respectively. Net changes soon after periods of peak settlement may also be used to minimise fouling, although there remains a danger of interrupting growth by the disturbance of this process (Ventilla, 1982). Monthly net cleaning has been suggested (Heffernan *et al.*, 1988), but such repeated handling of the pearl nets would be certain to impair growth (and be unacceptably labour intensive), although high pressure water jets have been used successfully in Japan (Ventilla, 1982). Optimal strategies for dealing with net fouling will ultimately vary between locations and culture species, dictated by economic considerations. For *P. maximus* in the U.K., the pragmatic approach of the S.F.I.A. (reflected in my short experiment) would appear to have potential; stock at low density, with no net change until the following autumn (approximately 12 months in suspended culture) to minimise handling and permitting the accumulated fouling to act as a barrier to predator settlement over the summer (but see Chapter 6).

4.4.5 Capacity of gear types

The ease of use and growth characteristics of different cultivation equipment are of prime importance in their assessment, but so too is the capacity of the equipment. For gear used in suspended culture, the number of shells per metre of longline is a useful measure of its utility although obviously dependent on the number of nets used in each string. The length of the suspended nets below the longline is clearly limited by the water depth, but also by the ability to handle the gear when it is heavy with fouling. In my work pearl nets were used in strings of six with an approximate drop of 2 m, whereas the pocket nets were approximately 3 m in length. The capacity of the equipment used in my work is summarised in Table 4.10.

Table 4.10. The holding capacity of culture equipment used in this work for pectinid spat, in terms of the numbers held per metre of longline headrope, assuming strings of nets attached at one metre intervals. NWP trays are included for comparison although these were operated from a groundline.

Gear type	Species	Stocking density per net	Stocking density per m^2	No. of nets	Capacity (shells.m^{-1})
Pearl net	*P. maximus*	50	408	6	300
	A. opercularis	150	1225	6	900
Pocket nets	*A. opercularis*	5	-	20	100
		10	-	20	200
		15	-	20	300
NWP tray	Both	200	270	8	1 600 per stack

It is clear that the pearl nets were compact in that they held a larger number of spat per station on the longline, compared to the pocket nets. The vertical length occupied by the pearl net was only two thirds of that taken by the pocket nets and so for the same space occupation the use of pearl nets would allow 1 350 shells to be cultivated for each metre of longline headrope, at a stocking density of 150 shells.net^{-1}. The low cost and fouling of the pocket nets made them attractive, although they were inefficient in terms of space utilisation. Further work on the effects of pocket size and stocking density is necessary before they can be recommended as an alternative to pearl nets.

4.4.6 Density

The effects of stocking density on the performance of *A. opercularis* in pocket nets indicated that growth was significantly reduced at 15 shells.$pocket^{-1}$ compared to the lower densities used. Survival rate fell with increasing density but not significantly over the range of densities tested. Similar results have been obtained for *Placopecten magellanicus* in pearl nets (Parsons & Dadswell, 1992; Côté *et al.*, 1993), although significant increases in mortality with density have also been reported for *Placopecten magellanicus* (Dadswell & Parsons, 1991b) and *Argopecten irradians* (Duggan, 1973; Widman & Rhodes, 1991).

The mechanism by which stocking density operated to influence growth in the pocket nets was unclear but there has been considerable research into the effects of density on the growth of scallops in pearl nets (Duggan, 1973; Ventilla, 1981; Ventilla, 1982; Dadswell & Parsons, 1991b; Parsons & Dadswell, 1991b; Côté *et al.*, 1993) and such effects are likely to be independent of gear design. The frequency of physical contact with other scallops and with the mesh of the net has been suggested as a possible density-dependent mechanism. Both Widman & Rhodes (1991) and Côté *et al.* (1993) found an increased frequency of shell biting (interdigitation) and thickening of the shell margins at high stocking density. Valve closure and mantle retraction resulting from contact may affect growth by reducing the time spent feeding and shell repair may be necessary, diverting resources from shell growth and possibly leading to shell deformities. However, in my work the number of deformed queen shells was statistically independent of stocking density, although greatest at the highest density.

Another possible effect of high stocking density was competition for food particles. The supply of seston to the animals within the nets was dependent on replenishment by water flow from outside. This incoming flow was independent of scallop density and so at higher stocking densities the potential food available per individual was lower (Parsons & Dadswell, 1992). At high scallop density particle removal by filtration may have outstripped replacement from the water column outside, producing a microcosm of the "seston depletion effect" (Wildish & Kristmanson, 1984; Wildish & Kristmanson, 1985) and see also the work of Kirby-Smith (1972) and Kirby-Smith & Barber (1974). This may well have occurred inside the pocket nets (and inside the pearl nets although this was not investigated). The build up of fouling on the exterior of the nets would have further reduced flow and hence replenishment of seston. Although the mesh of the pocket nets was not heavily fouled the settlement of *M. edulis* on to the core rope may have exacerbated the effect, adding interspecific competition for limited particulate food to the intraspecific competition caused by the high stocking density.

4.4.7 Growth

Comparisons of growth rate between my work and that of others is complicated by the manner in which the data were gathered; initial and final mean shell heights are available but no intermediate values and hence it has not been possible to construct a growth curve for either species. Mann & Taylor (1981) present instantaneous growth coefficients calculated using length data from Gutsell (1930) for field populations of the bay scallop *Argopecten irradians*; values (× 1000) range from 7 to 24 at temperatures of 12 - 21°C. Although not strictly comparable, these values are much higher than those recorded in my work for *P. maximus* and *A. opercularis*. However, the bay scallop is a fast-growing, short-lived species (Rhodes, 1991) from an inshore, shallow water environment that is very different from the Irish Sea. For species such as *P. maximus* and *A. opercularis* with strongly seasonal growth, comparisons of instantaneous growth coefficients should be made over comparable time intervals. Paul (1978) plotted growth curves for *A. opercularis* held in cages in Port Erin bay, Isle of Man, as well as for a wild population using the data of Aravindakshan (1955). The same author later produced a seasonal growth curve for *A. opercularis* (1987) as a guide to prospective aquaculturists. Data from these curves can be used to calculate approximate instantaneous growth coefficients for similar time intervals and sizes of queens as used in my work. These comparisons are summarised in Table 4.11.

Table 4.11. Comparisons of instantaneous growth coefficients, G (x 1000) for *Pecten maximus*, *Aequipecten opercularis* and *Argopecten irradians*. Shell heights and culture durations estimated from the growth curves in Paul (1978) and Paul (1987). Values of growth coefficients from this work are those of undamaged shells

Species	Dates	Initial size (mm)	Final size (mm)	Instantaneous Growth Coefficient	Reference
Argopecten irradians					
Wild population				7.0 @ 12°C	Mann & Taylor (1981)
Aequipecten opercularis					
Wild population from Isle of Man	approx. 6th Dec. year 0 to 12th Mar. year 2	15.0	30.0	1.50	Data from Aravindakshan (1955) plotted in Paul (1978)
Spat in cages and lanterns	approx. 6th Dec. year 0 to 12th Mar. year 2	21.0	53.5	2.03	Paul (1978)
Spat in NWP trays	15th April 1989 to 29th Nov. 1989	19.0	38.6	3.17	This work
Spat in pearl net	approx. 6th Dec. year 0 to 12th Mar. year 2	18.0	50.0	2.22	Estimated from Paul (1987)
Spat in pearl net	6th Dec. 1989 to 12th Mar. 1991	19.8	46.4	1.85	This work
Spat in pearl net	approx. 11th Dec. year 0 to 14th Nov. year 1	18.5	48.0	2.82	Estimated from Paul (1987)
Spat in pocket nets					
5 per pocket	11th Dec. 1989 to 14th Nov. 1990	22.9	47.0	2.12	This work
10 per pocket	"	22.8	46.1	2.09	"
15 per pocket	"	23.0	43.5	1.88	"
Intermediate size in lantern nets	appox. 6th Dec. year 1 to 12th Mar. year 3	48.5	67.0	0.71	Estimated from Paul (1987)
Intermediate size in pearl nets	6th Dec. 1989 to 12th Mar. 1991	38.0	61.2	1.04	This work
Pecten maximus					
Spat in pearl nets, short trial	20th Nov. 1989 to 26th Sep. 1990	12.5	50.1	4.43	This work
Spat in pearl nets, long trial	6th Dec. 1989 to 12th Mar. 1991	12.5	49.6	2.95	"
Intermediate size in pearl nets	1st Oct. 1990 to 15th Jan. 1992	50.2	72.8	0.87	"

The growth of *A. opercularis* in my work was below that projected by Paul (1987) for the same periods, both in the Isle of Man and in Scotland. The relatively poor growth recorded in my work was probably a result of overcrowding. Paul

(1978) used low densities (444 or 888 shells.m^{-2}) and although the 150 shells.net^{-1} (1225 shells. m^{-2}) used in my work is standard for initial intermediate culture Paul (1987), this would normally be reduced after 6-8-months. The queens in my work were left for 15 months without thinning. However, despite the long period of culture in overcrowded pearl nets, the growth rate was still higher than that of the wild population studied by Aravindakshan (1955), emphasising the benefits of suspended culture over that on the seabed (Ventilla, 1982; Wieland & Paul, 1983; Wallace & Reinsnes, 1984; Wallace & Reinsnes, 1985; Wildish *et al.*, 1988; Dadswell & Parsons, 1991b; Parsons & Dadswell, 1992).

The growth rates of *A. opercularis* recorded by Paul (1978) for growth in cages and lantern nets over the same period as the pocket net culture, were identical to those I recorded in the lowest density pocket nets, although at the higher densities growth rate was reduced. The growth rate reported by Paul (1987) for *A. opercularis* in pearl nets and lanterns in Scotland was substantially greater than that recorded in any of the pocket nets. Intermediate size *A. opercularis* grew faster in my work than projected by Paul (1987), although from a smaller initial shell height. Some of the height differential was made up over this time, suggesting that the growth of queens in suspended culture in Manx waters may be sufficiently fast to be of commercial potential.

The data for *P. maximus* from my work are included in Table 4.11 for comparative purposes; a high growth rate was achieved by the spat at a density of 50 shells.net^{-1}. I have been unable to find a growth curve in the literature for *P. maximus* in suspended culture, which takes into account the seasonal variation in the rate of shell growth. However, the high growth rate recorded over the 10 month short experiment implies that this species may also be commercially attractive for suspended culture, either right through to harvest or as a precursor to seabed cultivation.

The overall performances of the different culture equipment used in this study are summarised in Table 4.12. The plastic trays and pearl nets were the easiest types of gear to handle but both are relatively expensive in comparison to the pocket nets. However, the pocket nets were essentially disposable, whereas the pearl nets should stand several seasons use if cleaned and the plastic trays should last for many years. All of these systems are more suited to the cultivation of spat, as the space requirements of larger scallops would make them expensive for adult culture; multi-level lantern nets may prove more economical because of their greater capacity per station on the longline headrope. The economic benefits of different scallop cultivation schemes are discussed in Chapter 6.

Table 4.12. Summary table of the performance of the different types of equipment used during the course of this work for the cultivation of *Pecten maximus* and *Aequipecten opercularis*.

Gear type	Survival	Shell deformity	Fouling	Growth	Ease of use	Capacity.m^{-1} longline	Equipment cost	Cost per 100 shells
North West Plastics trays								
P. maximus	Lost							
A. opercularis	77-83% in absence of large starfish (R=25mm)	< 1%	Heavily fouled, impact unknown	Good growth from poor condition spat	Easy to handle, zero maintenance when used on sea bed, long lasting	200.tray^{-1}	£6.00 each	£3.00
Pearl nets								
P. maximus spat	67% (short expt.) 71% (long expt.)	< 2% (short expt.) 25% (long expt.)	Heavily fouled, 28% of scallops in long experiment entangled in fouling organisms	Good growth, in short expt., very little growth over second winter.	Easy although tying into strings and lacing up entrance was time consuming	300.m^{-1} for six nets @ 50.net^{-1}	£1.54 each	£3.08
Intermediate size	100% (232 days) 98.5% (471 days)	None	Heavy but no entanglement of shells	Good	"	60.m^{-1} for six nets @ 10.net^{-1}	"	£15.40
A. opercularis spat	95%	None	None, possibly due to over-stocking	Moderate growth at high density	"	900.m^{-1} for six nets @ 150.net^{-1}	"	£1.03
Intermediate size	96%	< 1%	Heavy but no entanglement of shells	Good	"	150.m^{-1} for six nets @ 25.net^{-1}	"	£6.16
Pocket nets								
A. opercularis spat	**5**†-95% **10**-95% **15**-90%	**5**-33% **10**-14% **15**-13%	Low fouling on mesh, mussel fouling on core rope	Moderate	Time consuming to make, low maintenance	**5**-100.m^{-1} **10**-200.m^{-1} **15**-300.m^{-1} for 20 pockets	Approximately £1.00 per 3 m length with 20 pockets	£1.00 £0.50 £0.33

† Stocking density shown in bold type

The results presented here confirm that juvenile *A. opercularis* grow well in suspended culture in Manx waters (Paul *et al.*, 1981). These authors had disappointing results with *P. maximus* but I have demonstrated that this species is also amenable to suspended culture in Manx waters. The widespread and continued use of pearl nets in scallop cultivation around the world is testament to the quality of this design, but their high cost will continue the search for cheaper alternatives. The NWP trays and pocket nets each have potential but require further work. In particular the effect of pocket size and stocking density on queen growth deserves investigation to provide a low coat alternative to the pearl net for a species attractive for its fast growth to commercial size and robustness in culture, but of relatively low value.

CHAPTER 5

EXPERIMENTAL RESEEDING OF THE GREAT SCALLOP, *PECTEN MAXIMUS* (L.)

5.1. INTRODUCTION

Extensive aquaculture provides one approach to counter the declining profitability of inshore fisheries, including scallops. This is an intermediate stage between fishing and intensive aquaculture. Extensive aquaculture enhances natural recruitment, often combined with a reduction in adverse biological interactions: predators can be removed and, in the case of sessile or sedentary animals like scallops the density of competitors can be manipulated. This chapter explores the problems likely to be encountered when re-seeding scallops in the waters around the Isle of Man.

Reseeding has been identified as having the most economic potential for development in several studies (Wieland & Paul, 1983; Paul *et al.*, 1986; Lake *et al.*, 1987; Slater, 1987; Wildish *et al.*, 1988; Hardy, 1991; Ito, 1991; Lake, 1993), and in Japan makes up approximately half of total scallop production (Ventilla, 1982; Body & Murai, 1986; Ito, 1988; Dao, 1991; Hardy, 1991). It is particularly attractive as a on-growing method in western countries where capital and labour costs are higher and may preclude economical suspended culture.

The three major problems associated with reseeding (ownership, dispersal and predation) were identified in Chapter 1 and this chapter presents the results of a study into the dispersal and rates of predation experienced by *Pecten maximus* reseeded onto the seabed.

The Japanese scallop *Mizuhopecten yessoensis*, which has a similar lifespan and growth rate to *P. maximus*, has been cultivated commercially on the seabed since the 1960s (Ventilla, 1982; Ito & Byakuno, 1988; Ito, 1991). Areas of the seabed are leased to co-operatives and reseeded with scallops after predators and competitors have been removed by repetitive dredging (Ventilla, 1982; Ito, 1991). The central region of the leased area is then seeded from the surface with the aim of achieving a final density of 5-6 scallops.m^{-2} after allowing for dispersal over the area of the lease (Quéllerou, 1975).

Predation of reseeded scallops is minimised by continued removal of crabs and starfish using traps and tangle mops. As predators can never be eradicated from the reseeding site, scallops are generally seeded at a stage when they are too large to be vulnerable to most predators; after they have achieved a size-refuge (Paine, 1976). For *Mizuhopecten yessoensis* this minimum size is considered to be 30-40 mm (Ito & Byakuno, 1988). Similar minimum sizes have been suggested for *Argopecten irradians* (Tettelbach & Feng, 1986) and *Pecten maximus* (Dao, 1979; Minchin, 1984). However, Lake *et al.* (1987) considered 7 cm to be the minimum size at which *P. maximus* would be relatively immune to predation, and *Cancer pagurus* has been shown to take scallops up to 9 cm (Lake, 1993).

Reseeding at an appropriate minimum size is clearly essential in order to avoid large scale losses of stock but must be balanced against the costs incurred in keeping the scallops in suspended culture until large enough. It requires 18-20 months of hanging culture for *P. maximus* to reach the 6-7 cm size recommended by Lake *et al.* (1987).

5.1.1 Aims of this work

On-bottom cultivation of scallops is attractive as a grow out method because of the reduced capital and labour cost when compared to maintaining scallops in suspended culture. However, this laissez-faire approach carries with it increased risks of catastrophic losses from dispersal and predation. These losses are the crucial obstacles to successful seeding in almost all regions where scallops are cultivated. The aim of this work was to investigate the behaviour of, and interactions between scallops, and their major predators under seeding conditions around the Isle of Man. Replicate areas were reseeded at high density with large, near commercial size scallops to reflect the later stages of *P. maximus* seabed cultivation.

Predator aggregation on reseeded scallops has important implications for scallop survival rate and hence the potential returns from seabed cultivation. This work monitored the speed and extent of aggregation and subsequent disaggregation of the starfish *Asterias rubens*, on high density patches of reseeded scallops, in an area of commercial scallop ground closed to fishing. The possible cues for aggregation and measures which might reduce this behaviour in the context of scallop reseeding are discussed.

Dispersal of scallops away from the area reseeded is a further source of losses from on-bottom cultivation; the rate and direction of scallop dispersal was assessed by divers and the impetus behind the movements considered.

The minimum level of survival required for economical seabed cultivation of scallops has been estimated at 30% (Slater, 1987). Levels of *P. maximus* survival in this study are expressed as a proportion of the number of scallops whose fate was known, and the potential survival of those scallops unaccounted for is discussed.

The major predators of *P. maximus* around the Isle of Man are thought to be the edible crab, *Cancer pagurus*, and the starfish, *Asterias rubens*. The impact of these predators has been investigated by analysis of shell remains recovered from the reseeding areas, and their relative importance is discussed.

5.2 METHODS

5.2.1 Collection and holding

The scallops (*Pecten maximus*) used for the reseeding work were collected by the R.V. Cuma from inshore fishing grounds off Port St.Mary using 2'6" (0.762 m) spring toothed dredges (two per side). Three year old scallops were selected from the catch as the best represented year class. It proved impossible to obtain sufficient numbers of 1+ or 2+ scallops because of the inefficiency of the scallop dredges when fishing for such small pre-recruits. The 3 year old scallops were returned to the Laboratory and maintained in running aerated sea water at ambient temperature (15.3-13.3 °C) in a 3.66 m × 1.22 m fibreglass tank.

5.2.2 Marking

Scallops were marked on the upper (left, flat) valve close to the umbo, where the shell is smooth. Groups of approximately 20 scallops at a time were selected and marked with a 4mm diameter (Ø) coloured vinyl dot[9] of red, silver or green and a number[10]. Although both markers were self-adhesive, earlier trials had shown occasional loss of adhesion after several weeks in sea water, so the markers were embedded in a drop of rapid setting glue[11]. One hundred animals (numbered 0-99) were marked with each colour. Scallops were only selected if the shell was undamaged and there was no sign of mantle retraction from the shell margin. During marking the scallops were emersed for a maximum of 30 minutes.

5.2.3 Site

The seeding experiments were carried out in the "Scallop Fishing Exclusion Zone" off Port Erin (Figure 5.1). The site for the Zone was chosen because it is an area where scallops occur naturally and has been fished since 1937, making experiments here particularly relevant. In March 1989 the area was closed to all dredging and trawling by the Isle of Man Government, although lobster and crab potting were allowed to continue. The closure to fishing has been violated numerous times, even since the area was buoyed in May 1991. Nonetheless it still represented an area of reduced fishing effort compared with other areas nearby.

Three sets of three grids were placed in two depths of water, approximately 25 m and 35 m below C.D. However, due to a shortage of suitable scallops, divers and boat time, experiments were restricted to one set of grids at the shallower depth. The actual depths recorded whilst diving at the site were between 27-33 m. The

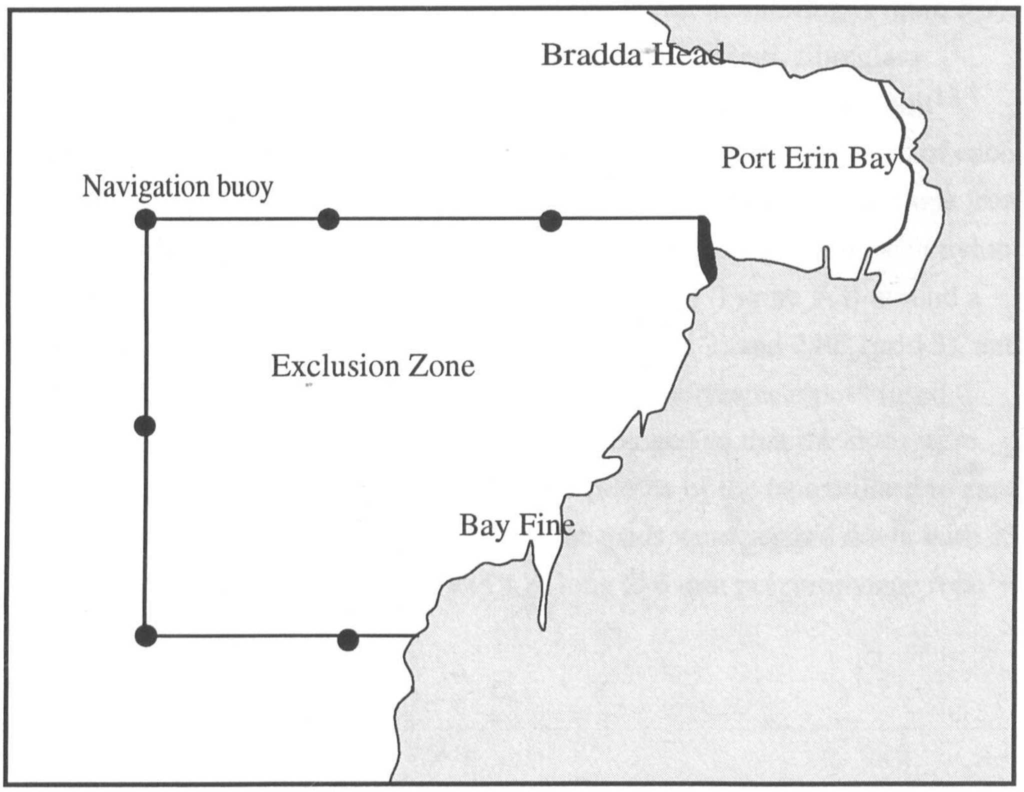


Figure 5.1 Diagram of scallop fishing exclusion zone of Port Erin, closed March 1989.

substratum was sandy with broken shell debris, pebbles, cobbles and occasional boulders (Wentworth scale in Buchanan, 1984).

5.2.4 Grids

The grids used as seeding areas measured 3 m × 3 m, sub-divided into 1 m × 1 m squares to allow accurate seeding densities and initial monitoring (Figure 5.2). The grids were made from 3 m strips of 23 mm wide fluorescent, fibreglass reinforced "Duoglo"tape[12], joined at each junction with a nylon nut and bolt[13] through Ø 6 mm holes strengthened with brass eyelets[14]. The four corners of each grid were reinforced with 0.5 m × 0.5 m right angles of 25 mm × 25 mm angle iron, with a ring welded onto the outside corner[15]. These were also attached with nylon nuts and bolts. The grids were arranged in groups of three (Figure 5.3) around a central concrete weight at angles of 0° (grid 1), 120° (grid 2) and 240° (grid 3), and attached to it by 10 m lengths of Ø 4 mm pre-stretched polyester rope[16] (used because it is negatively buoyant). Each grid was arranged so that the sides were orientated north-south and east-west and the two colours of the tape utilised to ease orientation relative to the grid. At each corner the grids were pegged down with 230 mm galvanised steel angle tent pegs[17] and 1 m long Ø 6 mm polypropylene rope[18] guy-lines.

5.2.5 Deploying grids

The grids were laid by SCUBA divers working from the R.V. Sula. The central weight[19] was dropped into position with a Ø 12 mm polypropylene rope[18] attached, marked at the surface with an 8" (200 mm) buoy[20]. This 'shot-line' was long enough to allow for tidal depth variation, wave action and tidal currents. Generally 8 m of rope beyond the approximate depth below C.D. was allowed, although at times of severe current the buoy was pulled underwater by the drag of the rope. Excess slack rope was kept off the surface by a small concrete weight[21] tied approximately 10 m below the buoy.

The grids were carried down to the sea bed pre-constructed and meticulously folded and secured. The 10 m 'guide line' was tied to the weight and laid by a diver navigating along the appropriate bearing from the weight and the grid tied to the other end. The ties binding the grid were cut in stages and the grid pegged out. Good diver communication was required and all the divers practised laying out grids on land before attempting to do so underwater.

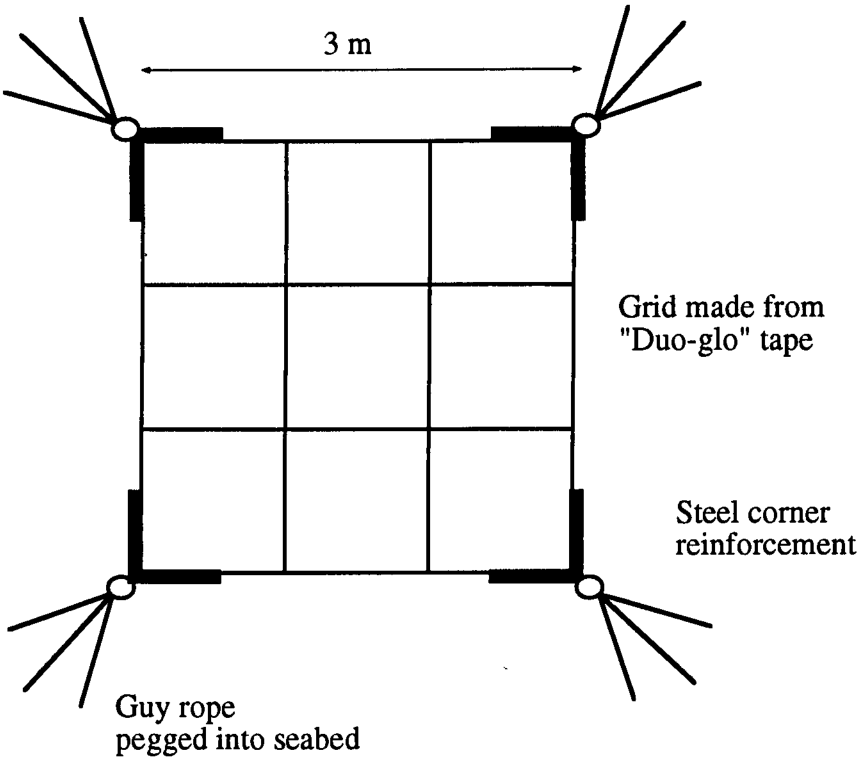


Figure 5.2 Tape grid used for reseeding. Corners were reinforces with angle-iron and pegged to the seabed.

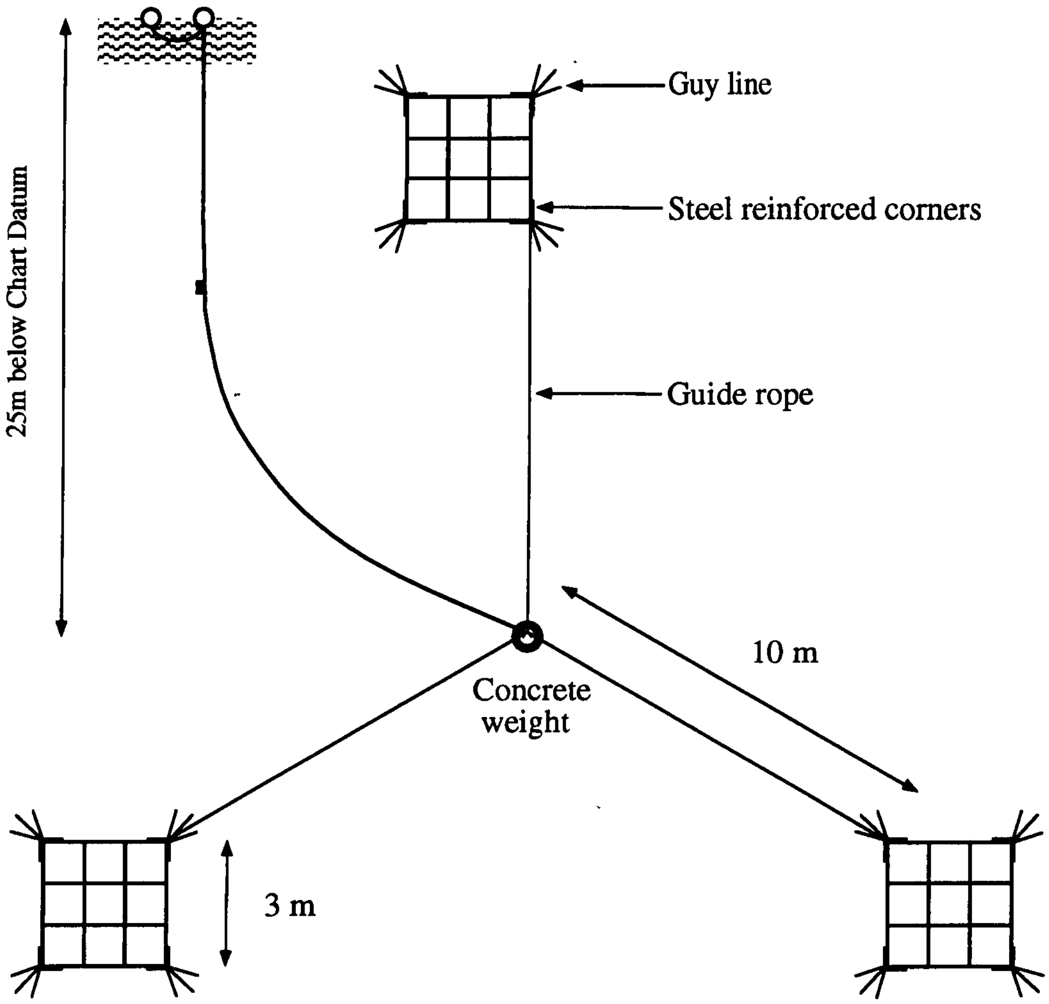


Figure 5.3 Layout of experimental reseeding grids on the sea bed.

5.2.6 Reseeding

The reseeding was carried out on 25th September, 1990 by SCUBA diving. Just prior to diving, 81 (or 83 for grid 2) numbered scallops of each colour were selected from those previously marked, and their numbers noted. Only scallops in good condition were selected as before. Scallops marked with each colour were put into separate net bags and carried out to the site in sea water-filled fishboxes on board R.V. Sula. The selection of scallops in good condition introduced some size bias: red mean shell length = 93.4 (S.D. 4.8) mm; silver mean shell length = 92.1 (S.D. 5.8) mm; green mean shell length = 91.5 (S.D. 5.2) mm. However, these size distributions were not significantly different (Analysis of Variance, $P = 0.07$).

Scallops were seeded into the grids at a density of 9 m^{-2}. The scallops were placed in their natural orientation on the surface of the substratum and no attempt was made to recess them. The red marked scallops were seeded into grid 1, silver into grid 2 and green into grid 3.

No predators (*Asterias rubens, Marthasterias glacialis, Cancer pagurus, Homarus gammarus, Eledone cirrhosa*) were found in the grids prior to reseeding.

5.2.7 Monitoring

The grids were monitored by divers after 1, 2, 16, 31, 43 and 63 days. The experiment was concluded on the 8th and 10th July, 1991 by a large scale search after 286-8 days. When monitoring, the position relative to the grid and the identity (number and colour) of all scallops was mapped on a foamex slate[22]. All dead shell was removed after its position had been noted, and shell damage analysed in the laboratory. The presence and position of any predators was also recorded, but no attempt was made to remove them.

Density and positions of scallops were easily assessed within the grids, but beyond their boundaries only a direction relative to the grid and approximate distance was noted, distance being very difficult to estimate underwater and liable to great variation between divers. More detailed monitoring of the experiment was not possible due to limitations on dive-time with compressed air SCUBA equipment at the working depths, without incurring excessive decompression.

Diver surveys of the Exclusion Zone carried out on the 28th and 29th November 1990 provided background data of starfish abundance (Chapter 2). In addition, extra survey dives were carried out in the vicinity of the seeded grids on 5th

November (day 41) and 27th November 1990 (day 63). Starfish densities were sampled on different scales using alternative survey methods:

i) Unseeded grids located ≈ 100 m NE of the seeded scallops were monitored for starfish. Area = 9 m^2.

ii) Circular searches, initially 6 m radius (area = 113.1 m^2) but later of 4 m radius (area = 50.3 m^2) so that more replicate samples could be taken per dive.

iii) The linear transects of the Exclusion Zone surveys each covered 200 m^2.

On days 286-8 the experiment was terminated by a large scale search of the area and the recovery of all the remaining scallops. The search followed a circular pattern, centred on the concrete weight, with a radius of 30 m (Figure 5.4). Due to the extent of the search and the depth involved, it was split up into three sections, each of 120°. One part was carried out on the morning of 8th July 1991 and another that afternoon. The third and final section was completed on 10th July after a delay due to poor weather. Six divers were involved in each part of the search - one at the perimeter of the circle who controlled the line and five carrying out the search/collection proper. Each of the five searchers had an arc of equal area to cover (189 m^2), delimited by coloured tape tied into the search line (diver's surface marker buoy reel) and by the distance covered by the line as it travelled around the arc. The divers collected all shells, dead or alive, marked or unmarked, from their track. The time taken for each third of the search was standardised at 10 minutes; this was the responsibility of the swimmer at the end of the line who travelled around the perimeter of the circle, keeping the line taut, at a speed of approximately 6 $m.min^{-1}$. The contents of the collection bags were analysed at the Laboratory and the density and identity of the scallops noted for each track. All of the live marked scallops were re-measured to assess growth over the period of the experiment.

5.2.8 Analysis of dead shells

The dead shells retrieved from each monitoring and from the final search were identified by the coloured dot and number attached to the flat valve. Each shell was examined for signs of damage due to predator activity. Those with clear signs of predator attack were assumed to have been damaged by crabs. Other predators, such as lobsters and octopus, may produce similar shell damage but the relative impact of these is unknown. Those exhibiting no shell damage were assumed to have died from starfish predation. However, because of the length of the experiment, it is necessary to take natural mortality into account. The primary source of natural mortality for an unexploited population of three year old scallops (such as the experimental population) is predation, but also includes other natural

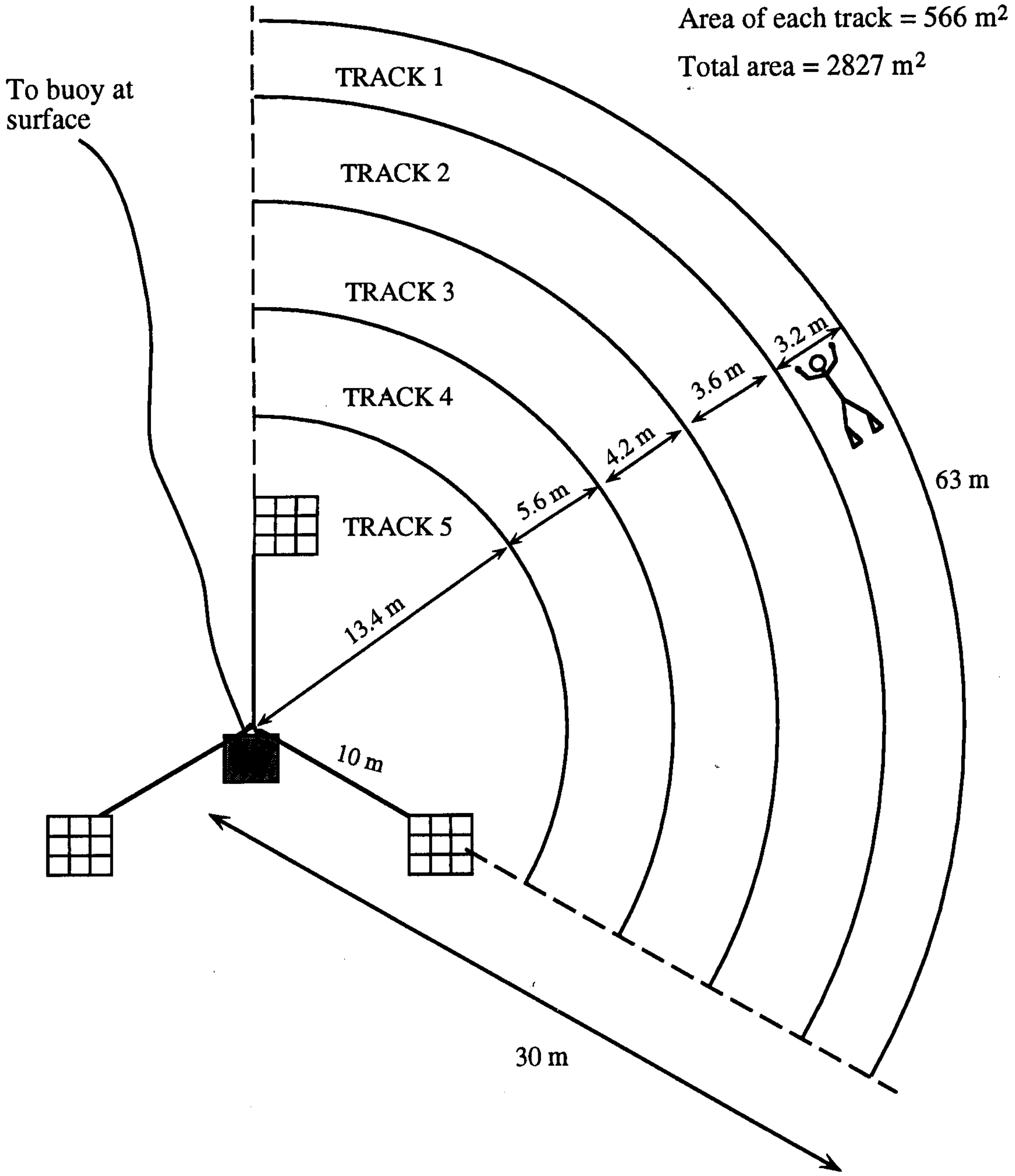


Figure 5.4 Plan of 3-part circular search used to terminate reseeding experiment.

premature senescence, starvation, burial etc. The separation and enumeration of these factors is one of the greatest challenges for population dynamicists, but for young mature scallops predators are the principal threat. Therefore, a part of the predation on those scallops accounted for is 'natural' and the remainder is a product of experimental conditions. The two have been separated by subtracting an estimate of natural mortality (Equation 5.2) from the observed total mortality, to give an estimate of excess mortality generated by the experiment. Annual mortality (Equation 5.1) was based on an Instantaneous Coefficient of Natural Mortality (M) for 3-year old *P. maximus* of 0.15 (Allison, 1993). As the reseeded scallops were in effect an unfished population then Total Mortality Z is equal to Natural Mortality M.

$$A = 1 - e^{-M} \qquad \text{Equation 5.1}$$

$$\text{Natural mortality} = \frac{\text{day no.} \times A}{365.25} \qquad \text{Equation 5.2}$$

where: A = Annual rate of mortality
M = Instantaneous rate of natural mortality
day no. = days after seeding

Shells with clear damage were scored as to the nature and location of the damage. Each valve was treated separately as in some cases only the left (flat) valve was retrieved. Damage was scored as present or absent on any part of the shell (Figure 5.5); no attempt was made to quantify the degree of damage. The categories used were: hinge, anterior ear (auricle), anterior siphon (siphonal aperture), anterior margin (from siphonal aperture to centre of ventral margin), posterior margin, siphon and ear, shell hole (crushed shell or punctures from crab chelae).

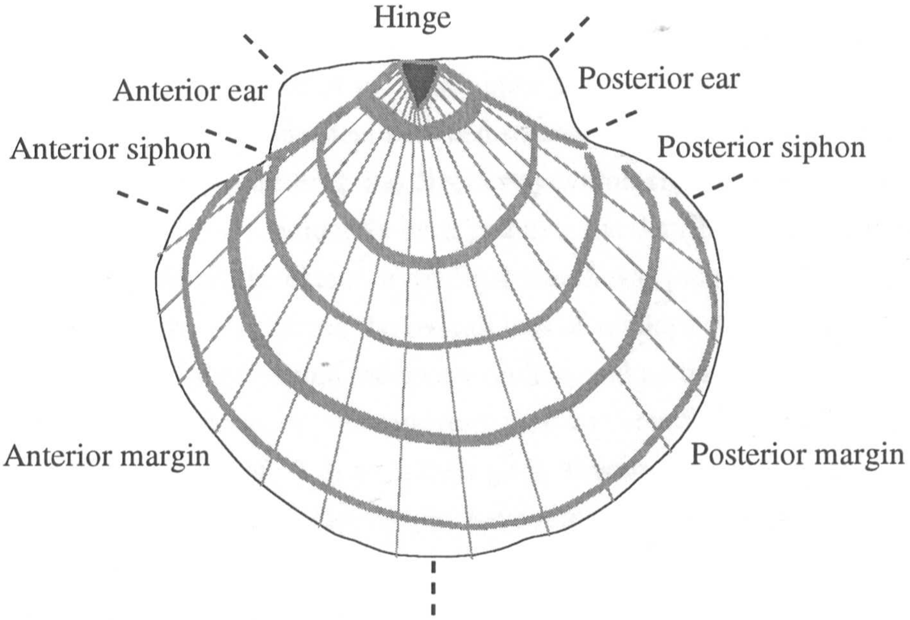


Figure 5.5 Key to areas of *Pecten maximus* shell scored for damage from crab predation.

5.3 RESULTS

5.3.1 Scallops accounted for

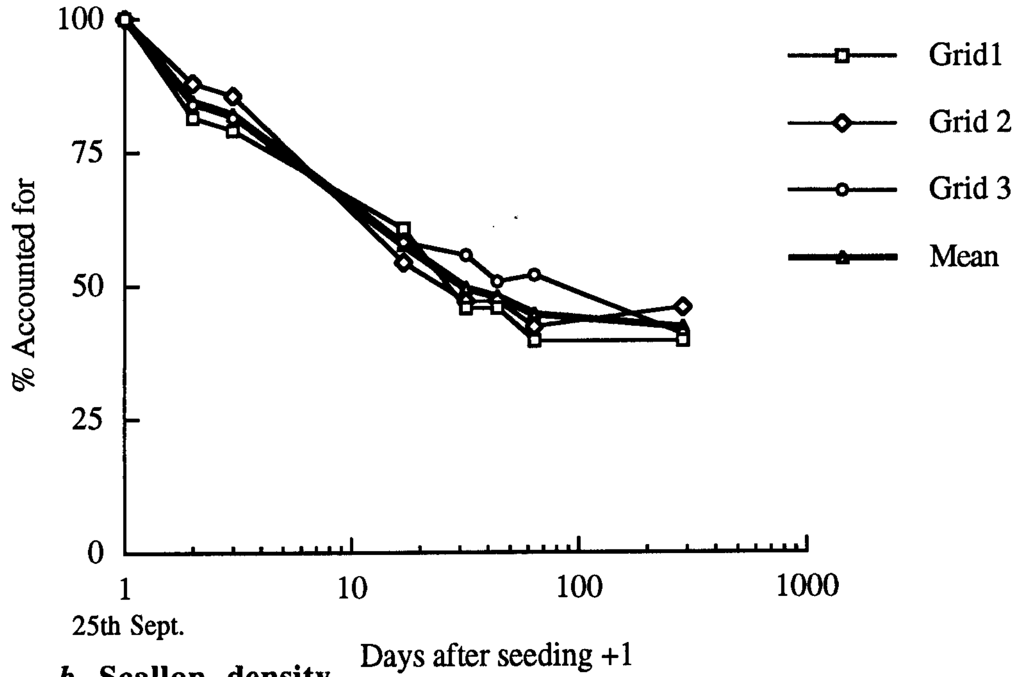
The proportion of scallops accounted for fell rapidly as a result of their movement out of the area of seabed that was monitored by the divers (Figure 5.6*a*). The number of scallops accounted for consisted of the total number of scallops found alive at a monitoring, those found dead at that and any previous monitoring and those subsequently found alive and so clearly alive at all previous times. The area sampled by the divers was not consistent between sampling events because of variations in visibility and the requirement that divers stay within sight of the grids, or were at least able to navigate confidently back and map the distribution of scallops relative to the grids. However, the extent of the final search was precise and revealed that at the termination of the experiment the overall loss of scallops was 58%. Assuming 100% recovery of dead shell within the area searched, and no transport of dead scallops out of the area by predators or water movement, then these 58% travelled a minimum straight line distance of 17 m from their grids directly out of the final search area. It is possible that crabs and octopus may have removed scallops from the area and eaten them elsewhere, particularly as both animals utilise refuges from which to forage.

The number of scallops accounted for initially fell rapidly; after 31 days the fate of only 49% was known, although the rate of this loss from the experimental area decreased over time. The fall in the percentage of scallops accounted for was consistent between all three grids.

5.3.2 Scallop density

The seeding of scallops into the grids at 9 m^{-2} represented a 1125-fold increase in scallops density from the background density recorded by contemporaneous diver surveys (0.008 $scallops.m^{-2}$, equivalent to one scallop every 125 m^2, Chapter 2). The initial density of 9 $scallops.m^{-2}$ fell precipitously in all three grids; mean density after only one day was 4 m^{-2} (Figure 5.6*b*). After 16 days scallop density was below one per square metre in all the grids. At the termination of the experiment, the circular search revealed a final density of marked scallops of 0.005 m^{-2} but a density of resident scallops of 0.013 m^{-2}. This is higher than the value found by divers at the start of the experiment. This difference may represent a real increase in the density of the resident population or may be an artefact of the different sampling methods (linear transect vs circular search) and their ability to sample contagiously distributed populations.

***a*. Scallops accounted for**



***b*. Scallop density**

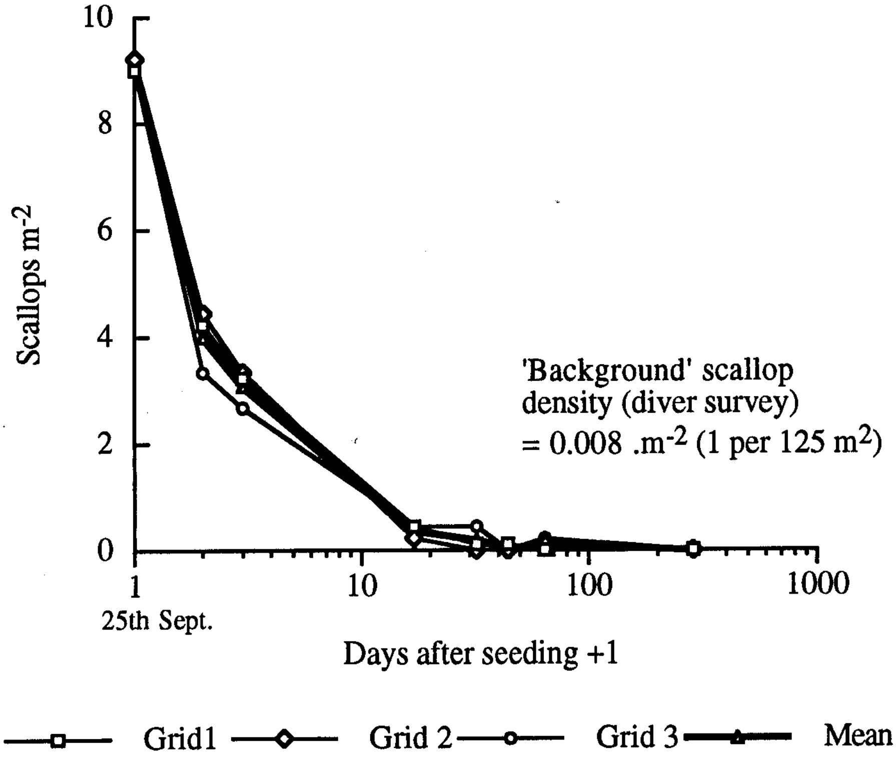


Figure 5.6 ***a*.** Percentage of scallops (*Pecten maximus*) accounted for at each monitoring after seeding. ***b*.** Density of live scallops within replicate 3m x 3m grids after seeding at an initial density of 9 scallops.m^{-2}.
Note logarithmic time scale

The position fixing of scallops relative to the grids was liable to error, but over the first 16 days the dispersal was primarily along the tidal axis (Figure 5.7). At the later monitoring occasions the area sampled was not sufficient to include the more mobile scallops and a random residual distribution remained.

5.3.3 Scallop survival

Survival and mortality, expressed as a proportion of those scallops accounted for at each monitoring, was very consistent over the three replicate grids (Figure 5.8*a*). The fate of the other scallops was unknown. Initial mortality was high (4% of those scallops accounted for per day) but the rate decreased throughout the experiment. The time for 50% mortality of those accounted for (LT_{50}) was 37 days. At the end of the experiment less than 14% remained alive.

5.3.4 Mortality rate

At each monitoring event all the dead shell was collected and removed so that a daily mortality rate could be calculated (Figure 5.8*b*). Although the accuracy of these figures was liable to bias from the variable search area at each monitoring, there was an obvious trend: the daily mortality rate peaked during the first day after seeding, and then fell steeply. After initial variation, the mortality rates were very consistent between the grids. The mortality rate remained above the calculated rate of natural mortality until after day 63 post-seeding.

5.3.5 Starfish density

The number of starfish (*Asterias rubens*) within each grid was noted at each monitoring and a background level established by the diver transect surveys and circular searches in the vicinity of the reseeding grids (Table 5.1). The mean density of starfish was 0.15 m^{-2} but variable between samples (S.D. = 0.09).

At the time of the scallop seeding there were no *Asterias* within any of the grids. After one day the mean density was 1.43 starfish.m^{-2} and this peaked after two days at a mean density of 1.63 m^{-2} (range 0.9-2.9 m^{-2}); equivalent to more than 10 times background density (Figure 5.8*c*). This marked influx of starfish into the grids and the surrounding areas (aggregation) was rapid and was followed by a much slower disaggregation, although even after 63 days the mean starfish density was double the previous background level.

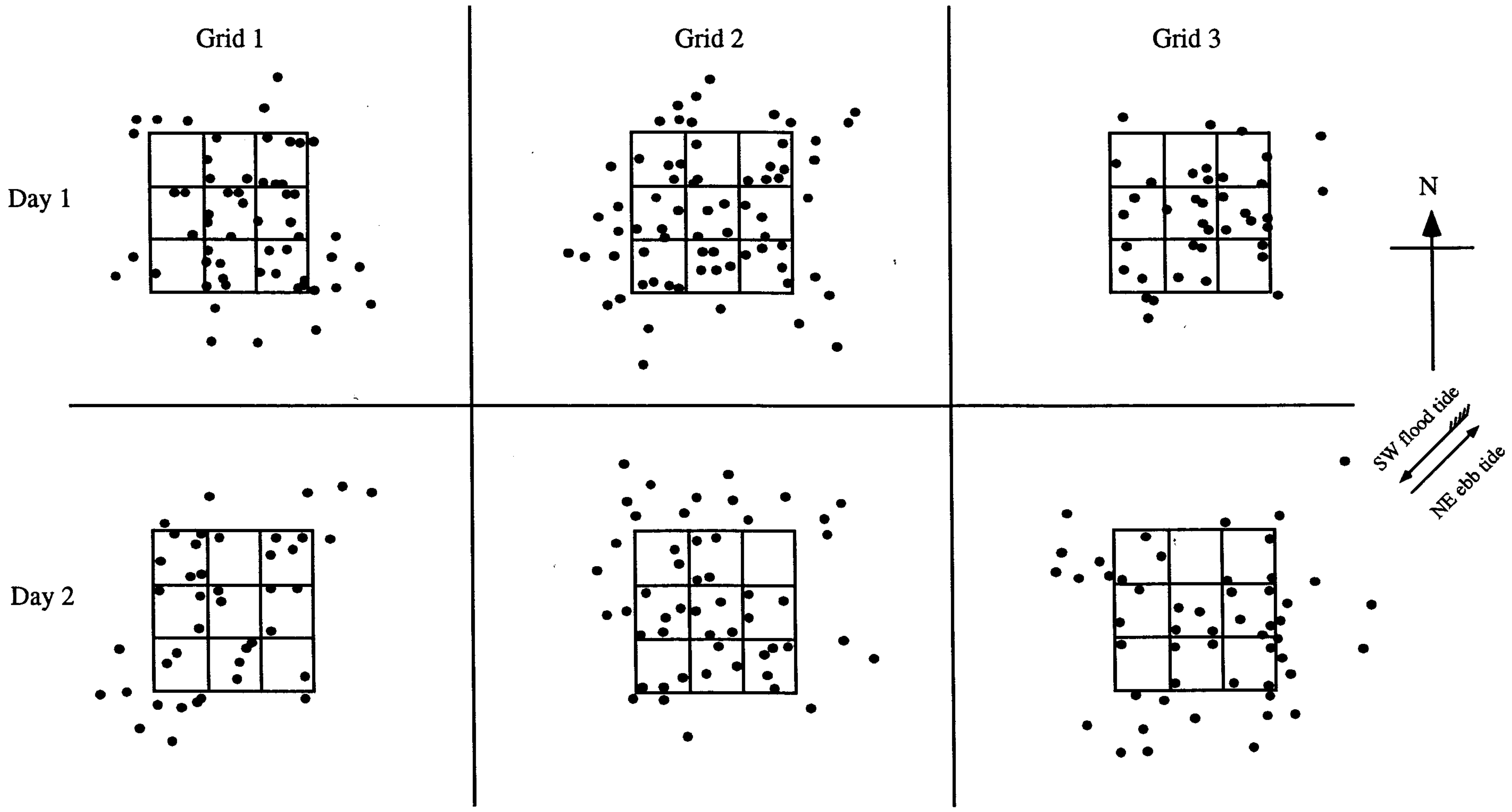


Figure 5.7 Post-seeding dispersal of *Pecten maximus*. Initial density was 9 scallops.m^{-2} evenly spaced throughout each 3 m × 3 m grid.

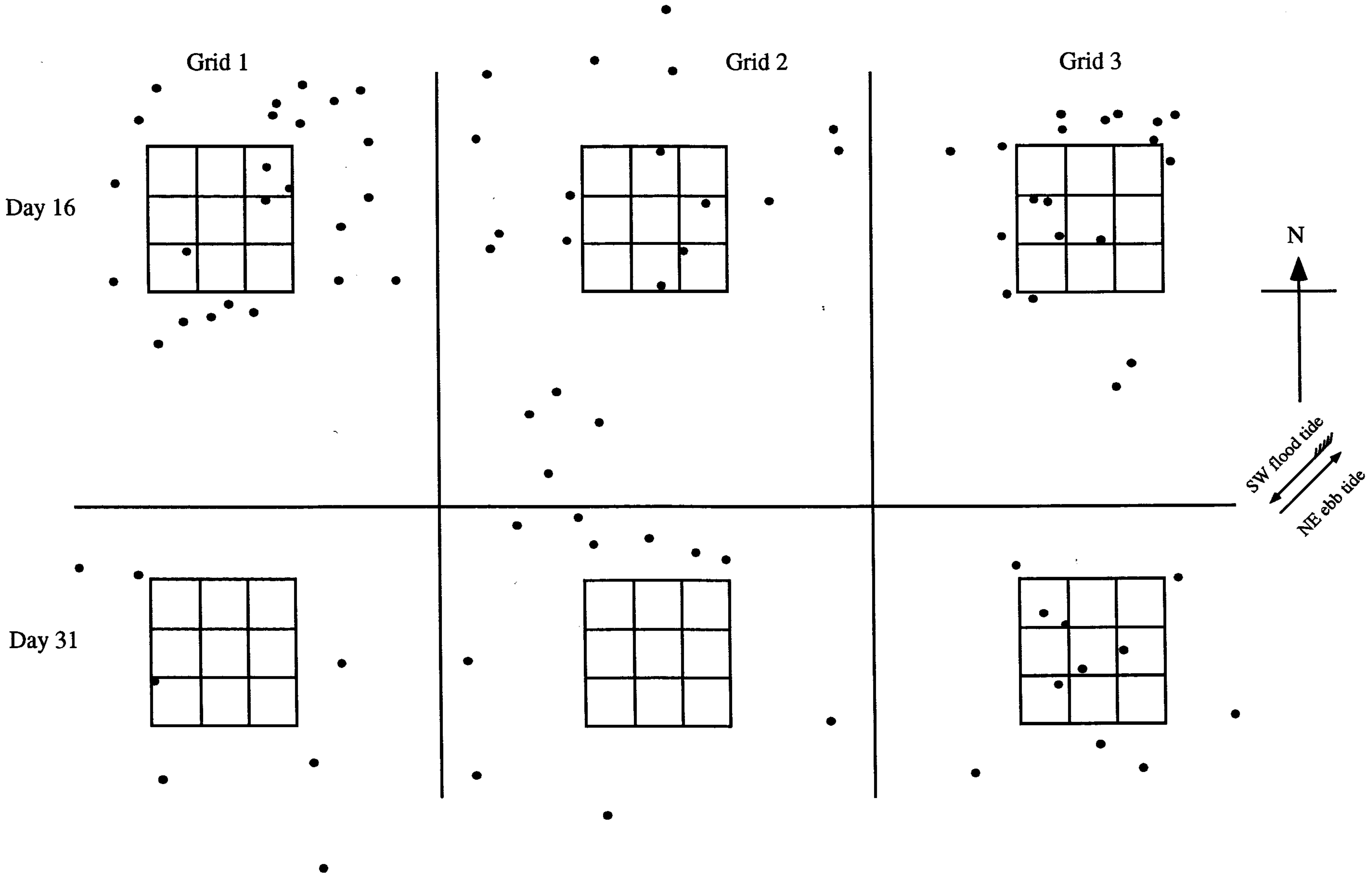


Figure 5.7 (continued). Post-seeding dispersion of *Pecten maximus*. Initial density was 9 scallops.m^{-2} evenly spaced throughout each 3 m × 3 m grid.

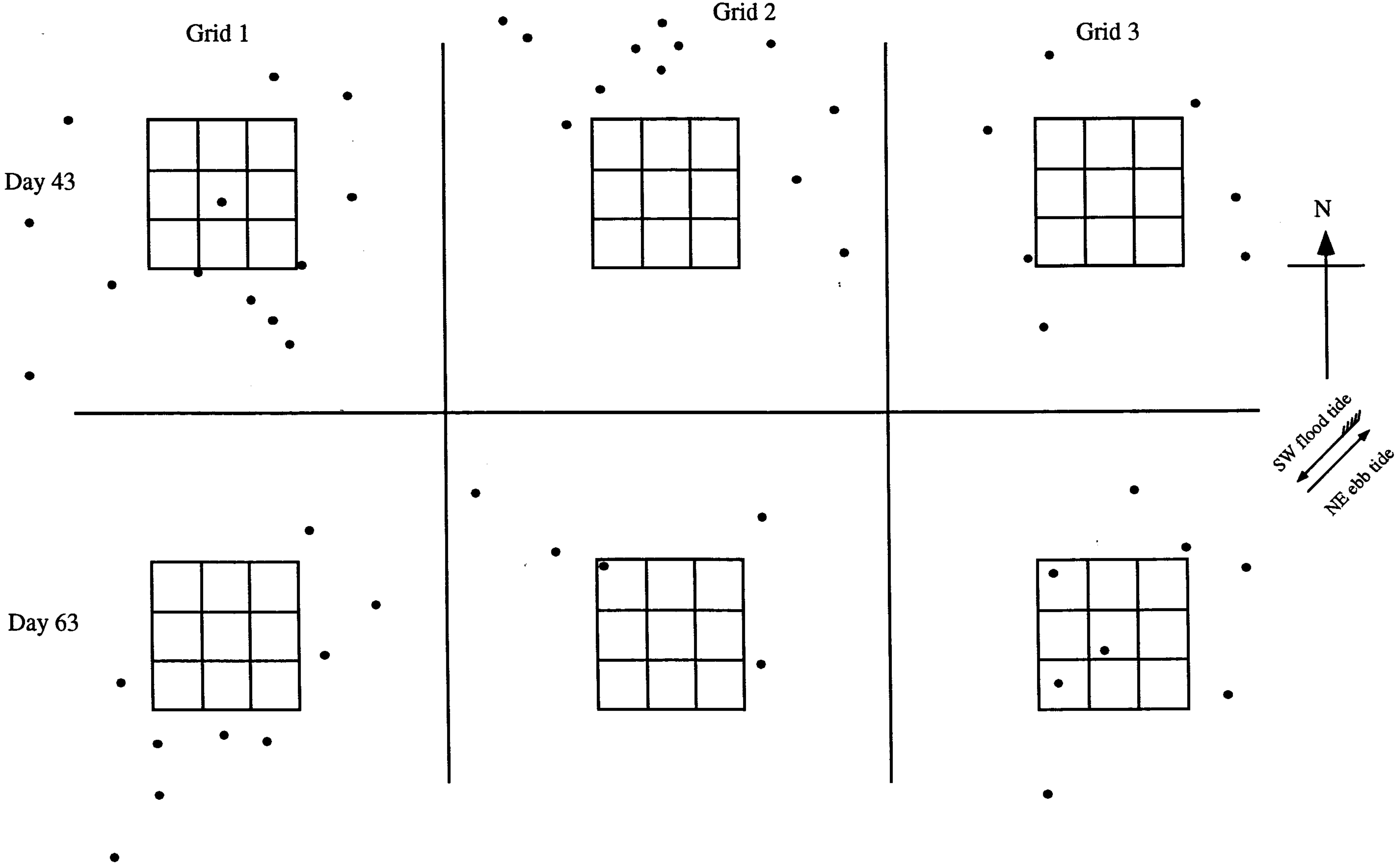


Figure 5.7 (continued). Post-seeding dispersion of *Pecten maximus*. Initial density was 9 scallops.m^{-2} evenly spaced throughout each 3 m × 3 m grid.

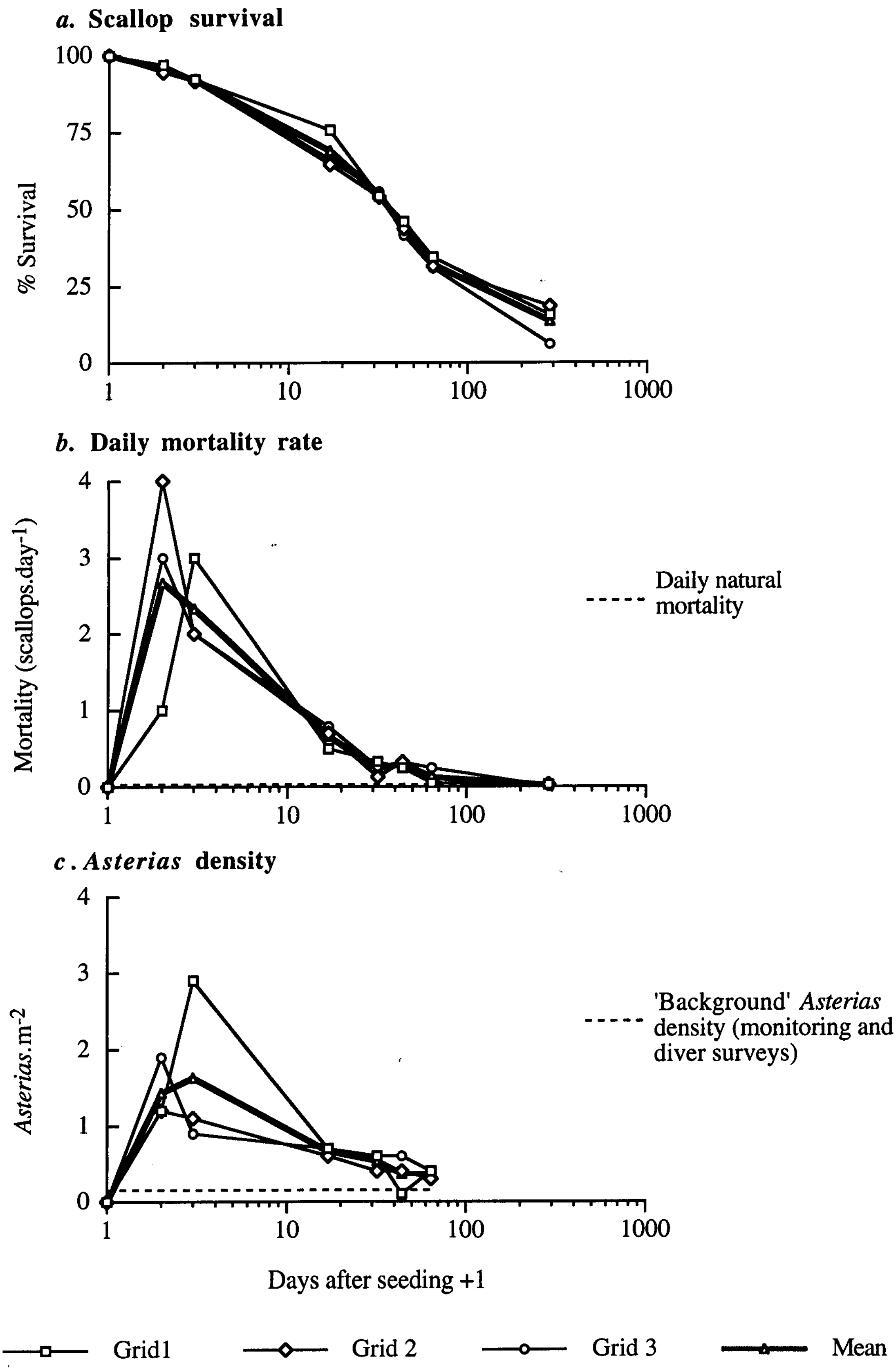


Figure 5.8 ***a*****.** Scallop (*Pecten maximus*) survival expressed as a percentage of those scallops accounted for. ***b*****.** Daily mortality rate of scallops after reseeding at 9 scallops.m-2, based on the collection of dead shell at each monitoring. ***c*****.** Starfish (*Asterias rubens*) density within 3m x 3m scallop reseeding grids. Note logarithmic time scale.

Table 5.1. Density of *Asterias rubens* (numbers.m^{-2}) estimated by diver surveys using different sampling methods.

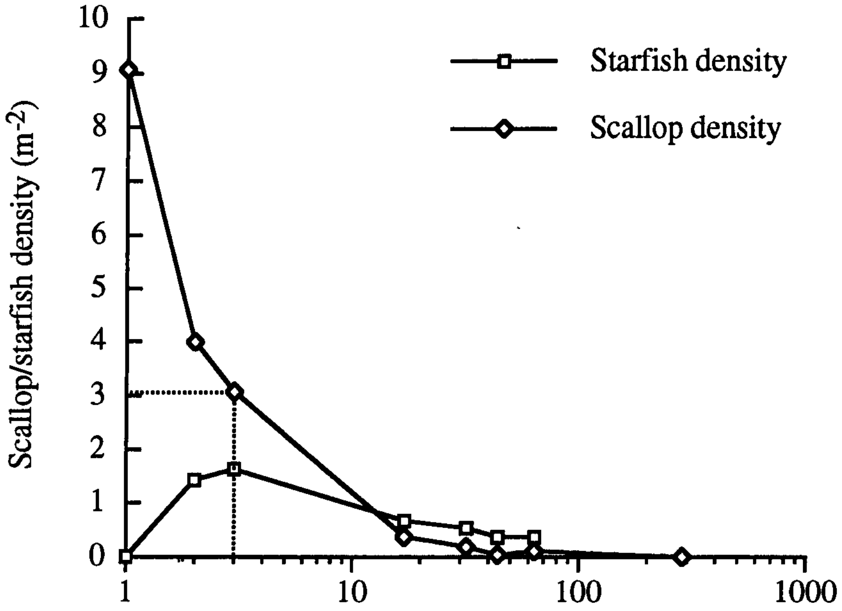
Date	Method	No. *Asterias*	Area sampled (m^2)	Density
5th Nov. 1990	Grid	3	9.0	0.33
	Circular	16	113.1	0.14
27th Nov. 1990	Grid	2	9.0	0.22
	Circular	12	50.3	0.24
	Circular	6	50.3	0.12
	Circular	10	50.3	0.20
28th Nov. 1990	Transect	11	200	0.06
	Transect	15	200	0.08
	Transect	15	200	0.08
29th Nov. 1990	Transect	10	200	0.05
			Mean density of *Asterias* =	0.15

5.3.6 Scallop density and starfish aggregation

The stimulus for the aggregation of *Asterias* was the sudden appearance of high density patches of scallops created by reseeding. Figure 5.9*a* shows the densities of both scallops and starfish over the duration of the experiment. The aggregation of starfish continued while the density of scallops remained above 3 m^{-2} after which disaggregation began.

5.3.7 Sources of scallop mortality

Mortality due to the tagging and reseeding procedure itself was considered to be negligible. Scallops which were tagged but remained in the laboratory showed zero mortality, and the transport and seeding itself were carried out with great care. Figure 5.9*b* shows the proportions of the total mean daily mortality attributed to each predator species. Crab predation was maximal during the first 24 hours after seeding, then fell rapidly as the density of starfish increased. Starfish predation peaked during the second day as their density reached a maximum, and then fell as the density of scallops declined. Between days 31 and 43 starfish predation fell below the rate of crab predation and after this time crab predation remained the more important source of mortality for the rest of the experiment. The initial rates of mortality from predators were far in excess of the estimated natural mortality of 0.03 scallops.day^{-1}, but fell to comparable levels by the monitoring on the 63 day as the predator density *a*. **Scallop density and starfish aggregation**



b. **Sources of scallop mortality**

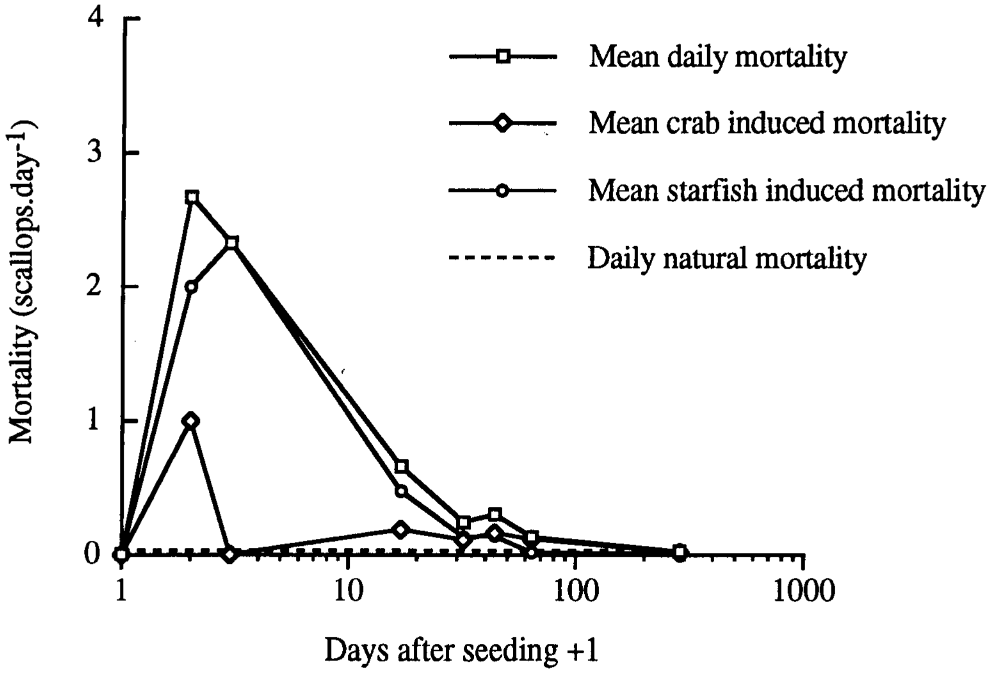


Figure 5.9 *a*. Effect of scallop (*Pecten maximus*) density on starfish (*Asterias rubens*) aggregation. *b*. Proportion of scallop mortality attributed to *Asterias rubens* and *Cancer pagurus*. Note logarithmic time scale.

and activity declined as a consequence of the falling prey availability. At a high density of scallops, predators were attracted and there was a consequent high mortality rate. As scallop density declined, through predation and dispersal, the predators began to disaggregate and the mortality rate declined.

5.3.8 Potential scallop survival

The logistical restrictions on monitoring of the experiment and the natural inclination of *Pecten maximus* to swim when disturbed, resulted in an increasing proportion of the scallops initially released being lost from the experiment. The fate of these animals was unknown but a maximum and minimum survival of scallops can be calculated by assuming that all the unaccounted scallops were either alive or dead respectively.

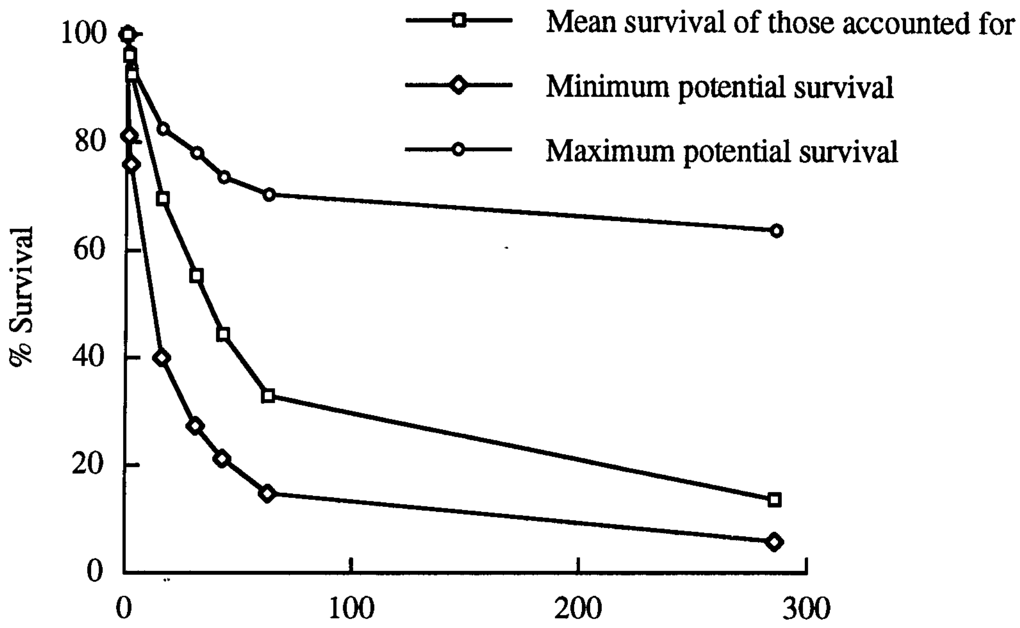
Figure 5.10*a* shows the range within which the true survival lies, and the calculated survival as a proportion of those accounted for. The proportional survival is clearly pessimistic and the potential range of survival extreme: after 286 days the maximum survival was 64%, the minimum was 6% and the rate as a proportion of those accounted for was 14%.

5.3.9 Predation rates

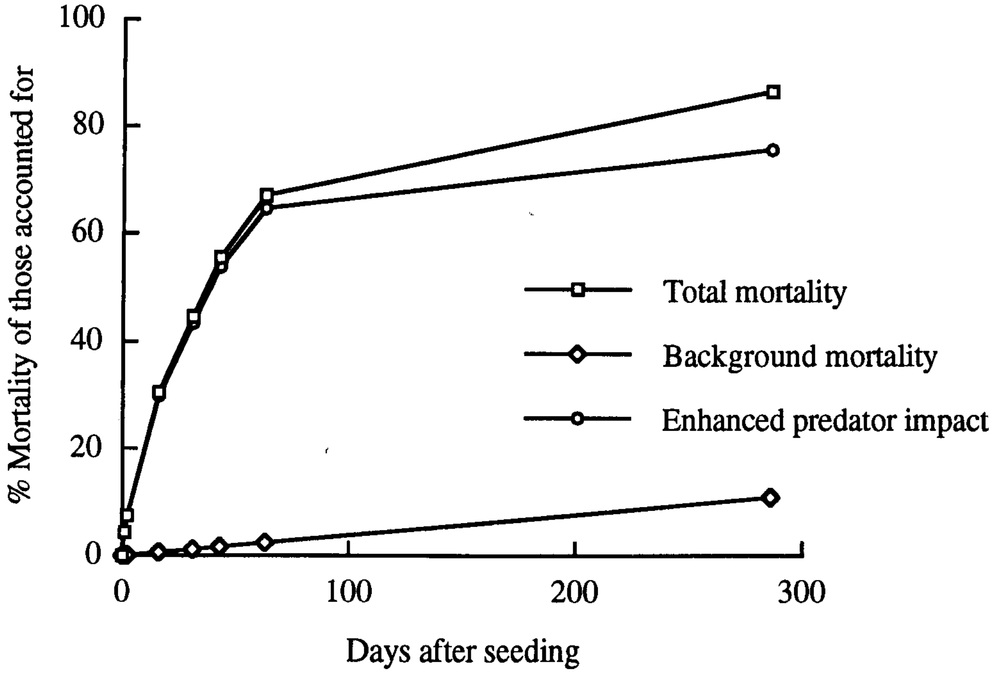
Assuming an Instantaneous Coefficient of Natural Mortality, $M = 0.15$, the annual natural mortality rate (A) for the scallops used was 0.14 or 14% (Equation 5.1). Therefore, over the 288 day duration of this experiment, 10% of the scallops seeded could be expected to have died of natural mortality (Equation 5.2). If this natural mortality is subtracted from the total mortality of those accounted for then the impact of the predators over and above their contribution to background natural mortality can be seen (Figure 5.10*b*). The elevated rate of predator-induced mortality is represented by the steep gradient. This gradient decreased with time as the rate of 'excess' predation declined. Between days 63 and 286 the rate of mortality fell back to a level comparable to that calculated for natural mortality, indicated by the near parallel nature of the lines of natural mortality and predator impact.

5.3.10 Shell damage

A total of 89 dead scallops were recovered (from the 245 reseeded) over the course of the experiment. Of these, 40 showed signs of shell damage indicating crab predation. All shell damage was attributed to *Cancer pagurus*. No other predatory crab species were observed during any of the monitoring. The octopus, *Eledone cirrhosa* (Lamarck) and the lobster, *Homarus gammarus* (L.), are potential scallop



a. **Potential scallop survival**



b. **Impact of predator aggregation**

Figure 5.10 *a*. Potential survival of *Pecten maximus* seeded in replicate 3 m x 3 m grids. Maxima and minima assume complete survival or complete mortality, respectively, for those scallops not otherwise accounted for. *b*. Estimated elevation of scallop mortality due to pradator aggregation on reseeded scallops, assuming constant natural mortality at an assumed instantaneous coefficient of M = 0.15.

predators which may cause similar shell damage, but their abundance and importance is unknown, and none were observed at any of the monitorings. All of these species are primarily active at night and return to refuges during daylight. Evidence of their impact is provided by the shell damage they produce but it is impossible to separate the individual species.

The distribution of shell damage was very similar around the two valves (Figure 5.11). Most damage occurred around the margins with more frequent damage to the anterior margin of both the left and right valves. No shells were recovered with holes or signs of crushing. The shell damage consisted of chipping, with only small pieces removed to allow entry to the mantle cavity. There was no statistical difference in the distribution of shell damage between the left and right valves (χ^2 tests, v=1, P>0.05).

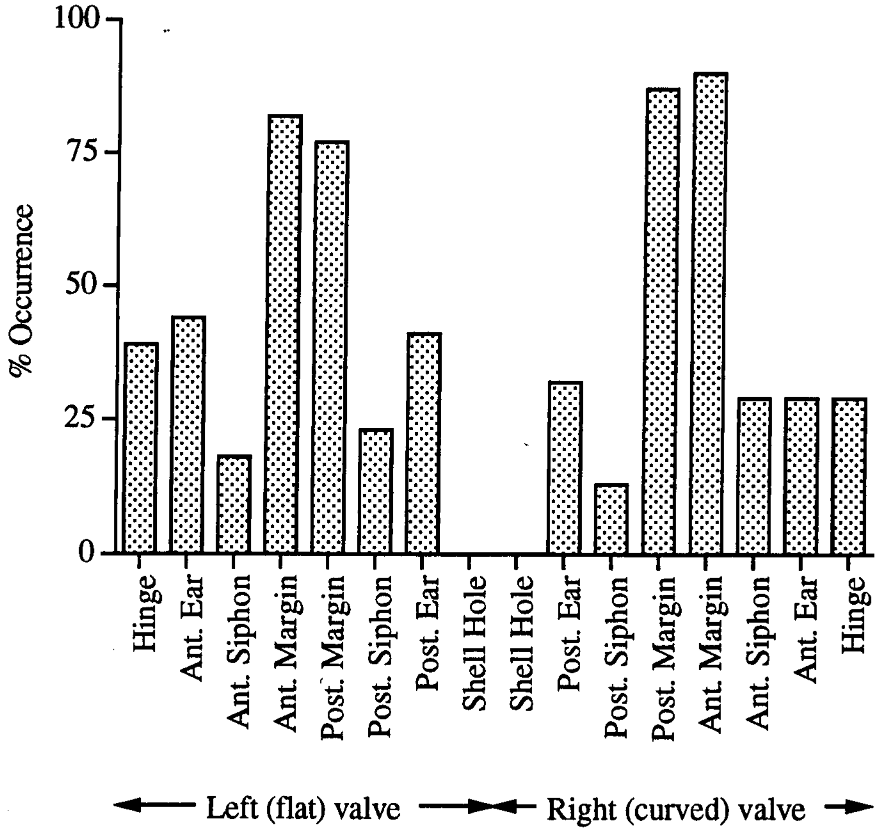


Figure 5.11. Distribution of shell damage to left (n = 40) and right (n = 31) valves of *Pecten maximus*.

5.4. DISCUSSION

5.4.1 Methodological constraints

Observing the grids by SCUBA diving was the only practicable method available, but imposed severe restrictions on the scale of monitoring that could be undertaken. The area sampled at each monitoring was limited and variable between monitoring events because of variations in underwater visibility and diver experience. The resources required to carry out even this limited work at depths of 27-35 m precluded any greater degree of replication or control of the experimental conditions. The techniques employed, however, allowed detailed examination of the reseeding trial under conditions relevant to any commercial scale operation that may be carried out in the future.

Scallops distributions are usually contagious (Caddy, 1970; Orensanz *et al.*, 1991; Thouzeau *et al.*, 1991; Stokesbury & Himmelman, 1993b) and notoriously difficult to sample accurately; the scale of the sampling unit relative to patch size being fundamentally important (Briggs, 1983; Holme & McIntyre, 1984; Andrew & Mapstone, 1987; Orensanz *et al.*, 1991). The linear transect (4 m × 50 m) provided a convenient sampling method at the working depths but may not be as suitable as the much larger circular search for the scale and distribution of scallops in the area. The diver transect surveys estimated the density of the local scallop population to be much lower than that found by the circular search that terminated the trial. It is not possible to determine whether this reflected variation in spatial distribution or was a function of the different sampling methods.

5.4.2 Aggregation

Asterias rubens aggregated on the grids and the area surrounding them within 24 hours of reseeding. The cue for this concentration of individuals was likely to be the chemical signature given off by the scallops, enhanced by their high density at reseeding and possibly by stress-related secretions (Minchin, 1991). The tidal currents of the Exclusion Zone provided directionality to the chemical stimulus. This made it possible for the predators to locate the reseeded scallops, as suggested by Carthy (1958), and demonstrated emphatically by Lapointe & Sainte-Marie (1992) for *Buccinum undatum*. The importance of water currents and their directional stability for successful prey detection and the problems involved in static systems (such as experimental aquaria) as demonstrated by Valentincic (1973; 1985), Doering (1982) and Lapointe & Sainte-Marie (1992), can help to explain some of the contradictory results presented in the review of Sloan & Campbell (1982) for the presence of distance chemoreception in asteroids. Prey location by *A. rubens* along the chemical gradient may also have been supported by their rheotactic behaviour (Castilla, 1972).

The sensitivity of asteroid predators to prey extracts was demonstrated by Valentincic (1985), and minute quantities shown to invoke feeding behaviour (Sloan & Campbell, 1982). Volkov *et al.* (1982) observed similarly rapid aggregation of starfish to that found in this work, following a large high density reseeding of *Mizuhopecten yessoensis*, and furthermore, found that the temporal and spatial distribution of the starfish mirrored that of the scallops.

Crab antennules are also highly sensitive to chemical cues from prey, with concentrations of nanogrammes.l^{-1} able to release feeding behaviour in *Cancer magister* and a rapid reaction to dense aggregations of prey (Pearson *et al.*, 1979). Minchin (1991) observed the aggregation of portunid crabs within minutes of reseeding *P. maximus* onto the seabed, but crabs were seldom seen during the daytime monitoring of the grids in my work. There was, however, ample indirect evidence of crab predation from the dead shell retrieved, reflecting the nocturnal foraging of *C. pagurus* (Edwards, 1979; Minchin, 1983b; Whittington, 1993). Crab damaged shells were recovered over the duration of the experiment, suggesting that the patches of reseeded scallops were visited repeatedly, even as the density of scallops fell. Learning of predatory skills has been demonstrated in *Carcinus maenas*, resulting in reduced handling times and improved feeding efficiency (Cunningham & Hughes, 1984).

The aggregative behaviour of *A. rubens* was very rapid, as was the first exploitation of the scallops by *C. pagurus*. The subsequent disaggregation of starfish occurred much more slowly. The grids remained a positive incentive to further starfish aggregation until the second day after seeding when the density of scallops had fallen to 3 scallops.m^{-2}. After the rapid aggregation the number of starfish in the grids decreased slowly, despite the swift decline in scallop density, and even after 63 days the density of *A. rubens* remained double the background level. The aggregation was a positive response to a sensory cue; movement up a chemical concentration gradient. Conversely, the disaggregation occurred not as a stimulus mediated behaviour but as a reversion to a basal pattern of random prey searching (Campbell, 1984). This rapid taxic aggregation to a resource followed by a slow random dispersal as the attractiveness or extent of the resource declines, in the absence of any alternative stimulus, is an interesting phenomenon which may be common to many predator-prey or animal-resource systems (Hawkins & Hartnoll, 1983; Hartnoll & Hawkins, 1985). Rapid starfish aggregation to patches of experimentally enhanced prey density have also been observed by Jost (1980) and Volkov *et al.* (1982).

The commencement of starfish disaggregation when the density of scallops fell below 3.m^{-2} suggests that this may represent an approximate threshold above which aggregation is provoked, and below which starfish and scallops may co-exist without exaggerated density dependent predator aggregation. Further, if starfish aggregation is not provoked at this level then reseeding might be successfully continued at this density with the expectation of lower starfish-induced mortality. The potential effect of reseeding at a lower density on the degree of crab predation is unclear as they are much more mobile; cancrid crabs forage over large areas and preferentially in patches of high prey density (Boulding & Hay, 1984). Whether 3 scallops.m^{-2} is sufficiently dense to retain the predatory interest of *C. pagurus* is unknown. Whittington (1993) observed aggregation of *A. rubens* on 48 mm shell height *P. maximus* reseeded at 2 and 5 scallops.m^{-2} into plots within Port Erin Bay, and although the time scale for aggregation was similar, the increase in starfish density was far less than that experienced in the current work (75% and 146% compared to ≈1000% here). He also found that starfish density declined to control levels within 72 hours despite the density of scallops in the grids being above that of the surrounding area.

5.4.3 Dispersal

Pecten maximus is generally a reluctant swimmer unless provoked, and tagged scallops have been shown to move relatively little (Baird & Gibson, 1956; Baird, 1958; Hartnoll, 1967; Thomas, 1969; Thomas & Gruffydd, 1971; Franklin & Rolfe, 1976). However, on the scale of the present work the distances reported by these authors are far in excess of anything that could be monitored and would therefore be significant. On a more relevant scale, Howell & Fraser (1984) recovered 60% of their commercial size tagged scallops within 30m of the release point after a period of 18 months. This result is particularly interesting as their initial reseeding density was very similar to that in the current work (9.6 scallops.m^{-2} compared to 9 scallops.m^{-2} here). The large proportion of unaccounted scallops encountered here due to dispersal out of the monitored experimental area may be attributed to the presence of aggregating predators and strong tidal currents, factors which were absent from the work of Howell & Fraser (1984).

Many stimuli are considered able to induce swimming in scallops (see Chapter 1 and Orensanz *et al.* 1991) but those most likely to be responsible for the rapid dispersal observed here are density and escape reactions in response to predator attacks. Seston depletion may have been significant immediately after reseeding when the density was 9 scallops.m^{-2} (c.f. density dependent growth limitation above 6 scallops.m^{-2} found for *Mizuhopecten yessoensis* (Aoyama, 1988), and for *Chlamys tehuelcha* (Orensanz, 1986; Iribarne *et al.*, 1991)), but density fell rapidly within 24 hours to the extent that seston depletion seemed unlikely.

The high initial scallop density after the reseeding contributed to the early dispersal, exacerbated by the fact that the scallops were placed on the surface of the substratum and not recessed (Baird, 1958; Hartnoll, 1967). Kalashnikov (1991) found that high density was responsible for increased swimming in *Mizuhopecten yessoensis* and the dispersal from the grids in my trial was similar to that commonly experienced by other workers after high density reseeding of scallops (Quéllerou, 1975; Morgan *et al.*, 1980; Volkov *et al.*, 1982; Tettelbach, 1986; Bull, 1988a). Chain reaction behaviour, where the swimming of one scallop provokes the same behaviour in others, is common in high density patches (Chapman *et al.*, 1979; Vahl & Clausen, 1980; Minchin & Mathers, 1982; Howell & Fraser, 1984), and may have accelerated dispersal in the first few days. As each reseeded grid represented a small, extremely high density patch relative to the local scallop density, swimming in any direction would lead to a reduction in density within the grids.

Density may be indirectly related to the dispersal of scallops, owing to the aggregation of predators on areas of high scallop density (Caddy, 1988). Increased predator density in the grids and surrounding area would have led to a high incidence of predator attacks on scallops and subsequent escape responses.

The observed influence of tidal currents on the dispersal of the scallops as they spread along the tidal axis (NE ebb tide, SW flood) confirms similar reports of Moore & Marshall (1967), Morgan *et al.* (1980), Caddy (1988)and Orensanz *et al.* (1991). Tidal currents in the Exclusion Zone have been estimated by divers to reach 3-4 kt (1 kt = 52 cm.s^{-1}) at spring tides. Under such conditions, the height attained and the duration spent in the water column will have a greater influence on distance travelled than the swimming speed of individual scallops.

5.4.4 Mortality

The primary predator of *Pecten maximus* in this work, *Asterias rubens*, was seen actively feeding at every monitoring of the grids after seeding. Crab predation, assessed on the basis of shell damage, accounted for 45% of scallop mortality and was attributed to the edible crab *Cancer pagurus*, on the grounds that it was the only predatory crab found during the monitoring of the grids or the diver surveys of the

Exclusion Zone, and the only crab species likely to be able to attack such large scallops successfully (Lake *et al.*, 1987).

The peak mortality rate during the first 24 hours after reseeding coincided with the rapid aggregation of predators into the area of the grids. Crabs had the greater impact initially, despite their apparent absence from the grids at the times of monitoring, reflecting their high mobility and nocturnal habit (Edwards, 1979; Minchin, 1983b). Minchin (1991) found almost immediate predatory activity after reseeding *P. maximus*. Starfish induced mortality peaked during the second 24 hour period as they reached their maximal density. *A. rubens* can move at up to 5-8 cm.min^{-1} having detected food (Feder & Christensen, 1966) but cannot sustain such speeds for long periods. The frequency of monitoring was insufficient to provide information on the arrival rate of *A. rubens* at the grids, but it is hypothesised that as the cue for aggregation is a chemical signal released by the scallops then starfish arrivals may be correlated to the tidal cycle. Starfish would travel up the chemical plume towards the scallops during times of directionally stable tidal flow. Personal observations while monitoring the grids suggested that the local tides were essentially bi-directional and so the expectation would be that the majority of starfish would have arrived from arcs either side of the tidal axis. Furthermore, movement towards the grids is likely only to have occurred when the starfish were downstream of the scallops; when the tide turned and the predators became upstream of the grids then random foraging would be expected (Campbell, 1984).

Lapointe & Sainte-Marie (1992) provide a useful model and discussion of chemotaxic attraction to prey for slow moving predators/scavengers, based on their study of the whelk *Buccinum undatum*. Although this model was conceived to describe the fishing ability of baited pots, its application to predator responses to high density reseeding is clear.

It is interesting to consider the effects of scale of reseeding on its attractiveness to predators in the light of the work of Lapointe & Sainte-Marie (1992). Directional behaviour of *Buccinum undatum* was most marked among remote (up to 20 m) individuals because of the distant perception of the bait as a point source. Close to the bait orientation was much more varied, and several directions of travel could lead to the diffuse bait. Small scale scallop reseeding trials such as the present one may be perceived by starfish as a point source, providing a highly directional chemical cue to downstream predators. When carried out on a much larger scale, predators within or close to the area seeded will receive olfactory stimuli but the directionality will be confused. Within the seeded area the chemical cue may be perceived as omnidirectional with changes in current direction. The lack of directionality would reduce the potential for aggregative behaviour. This may in part account for the greater degree of success often experienced with large scale reseeding in comparison with pilot scale trials (Morgan *et al.*, 1980; McHugh, 1981; Ito, 1988; Ito & Byakuno, 1988; Bull, 1988a). The exception is the experience in Ireland presented by Burnell & Slater (1989) where better results were obtained from small scale reseeding.

Towards the end of this experiment, starfish induced mortality was less important than that of crabs. The remaining scallops were dispersed and the *A. rubens* had effectively disaggregated and apparently switched to alternative prey, while *C. pagurus* remained a threat. Briggs (1983) found little evidence of predation by sublittoral communities of *A. rubens* on *P. maximus* and *Aequipecten (*cited as *Chlamys) opercularis* and considered them only minor predators of these commercial pectinids. However, in these reseeding trials and the work of many others (Galtsoff & Loosanoff, 1939; Brun, 1968; Morgan *et al.*, 1980; Ventilla, 1982; Volkov *et al.*, 1982; Tettelbach, 1986; Ito, 1991; Kalashnikov, 1991; Lake & MacMillan, 1991; Minchin & Ni Donnachada, 1991; Barbeau & Scheibling, 1993; Lake, 1993), starfish have been considered to be major scallop predators, and has lead to the perception of them as a principal threat to on-bottom cultivation.

Kalashnikov (1991) reported a case of predatory starfish co-existing with scallops at high density for several years until storm disturbance provoked a change in behaviour after which the scallops were heavily predated. Disturbance of some form to scallops would also appear to change the feeding behaviour of *A. rubens.* Minchin (1991) suggested that stress-related secretions encouraged predation in crabs and it may be that such chemicals also provoke aggregation and feeding by *A. rubens* on prey it might not normally include in its diet. Storms caused the onset of predation observed by Kalashnikov (1991), but similar facilitation of starfish predation has been seen after incidental damage to scallops after dredging (Bourne, 1964; Medcof & Bourne, 1964; Caddy, 1968; Medcof & Caddy, 1971; Shepard & Auster, 1991). Reseeding may be sufficiently stressful to the scallops involved that it too stimulates starfish predation.

Successful reseeding without provocation of predator aggregation may depend on reducing this stress at reseeding and so reducing the attractiveness of the scallops to their predators. This may be done by refinements to the reseeding process or removal of the predators until the scallops have had time to recover from reseeding. This concept may underlie the effectiveness of predator clearance prior to reseeding as practised in Japan (Ventilla, 1982; Body & Murai, 1986; Ito & Byakuno, 1988; Ito, 1991); when predators re-colonise the seeded area, the scallops have recessed and recovered from having been reseeded and represent a resident population. In Japan it is recommended that only healthy scallops are reseeded and that if more than 5% are damaged then all of them are likely to be lost to predators aggregating on the area (Dr. A.R. Brand, pers. comm.).

The scallops used in this work were at the limit of the size range of prey that *C. pagurus* can handle (Lake *et al.*, 1987); further evidence for this was provided by the chipping of the shell margins as the means of entry to the shell, characteristic of *C. pagurus* and other crab species feeding close to their upper prey size limit (Elner, 1978; Tettelbach & Feng, 1986; Ameyaw-Akumfi & Hughes, 1987; Lake *et al.*, 1987). Smaller scallops or other prey items may be energetically preferable, but in cases where the density of prey is high and hence searching time reduced, otherwise poor prey may become acceptable. Such optimal foraging or optimisation of diet has been found in both crabs (Hughes & Seed, 1981; Dare *et al.*, 1983; Jubb *et al.*, 1983; Boulding & Hay, 1984; Davidson, 1986; Ameyaw-Akumfi & Hughes, 1987; Lake *et al.*, 1987; Auster & Malatesta, 1991), and starfish (Hancock, 1974; Anger *et al.*, 1977; Scheibling, 1981; Campbell, 1984; Penney & Griffiths, 1984; McClintock & Robnett, 1986). Size selection and optimal foraging experiments have not been carried out for *Cancer pagurus*. To date work has shown that *C. pagurus* of all sizes eat more smaller scallops than larger scallops, but that the maximum size of scallop that can be eaten increases with increasing crab carapace width (Lake *et al.*, 1987). However, these crabs were only presented with one size class of scallop at a time and so were unable to actively select prey on the basis of size.

The large (mean shell length 92.3 mm) reseeded scallops were close to the minimum legal landing size of 110 mm shell length, and at this size *P. maximus* are generally accepted to have achieved a size refuge and be relatively invulnerable to predation (Lake *et al.*, 1987). The overall degree of mortality and in particular the high initial mortality rate suggest that a size refuge had not been reached or that the normal behaviour of the prey and/or the predators had been altered.

Commercial reseeding would require scallops to be placed on the seabed at a smaller size than in this trial, providing easier prey for *C. pagurus* and so initial predator clearance and continued crab potting may be necessary to reduce scallop mortality.

Within the grids the very high density of scallops altered the behaviour of the starfish and crabs, such that they took prey beyond their normal size preference range. At the density of 9 m^{-2} the reseeded scallops swamped the indigenous population and there was little other epifauna present to provide alternative prey.

This dense patch of uniformly large prey altered the foraging behaviour of the predators and resulted in a higher rate of predation than might be expected from the results of work done on the size selection of crabs and starfish (Hancock, 1974; Elner & Hughes, 1978; Hughes & Seed, 1981; Jubb *et al.*, 1983; Penney & Griffiths, 1984; Davidson, 1986; McClintock & Robnett, 1986; Tettelbach, 1986; Ameyaw-Akumfi & Hughes, 1987; Lake *et al.*, 1987). This density dependent scallop mortality is perhaps the most important obstacle to on-bottom cultivation of scallops, where at least initial scallop densities will necessarily be higher than those that occur naturally.

5.4.5 Potential survival

The high proportion of scallops that remained unaccounted for complicates the discussion of survival; at the end of the experiment survival rate was anywhere in the range 6-64% depending on the proportion of those unaccounted for that are assumed to be alive. The estimate based on the proportion accounted for was liable to be pessimistic because of the increased likelihood of detecting initial mortalities close to the grids where the predators aggregated, in comparison with the living mobile scallops that dispersed rapidly.

The maximum survival of 64% after 286 days would be encouraging considering the lack of predator clearance and the degree of predator aggregation. This survival rate compares favourably with those summarised in Table 5.2 and even the worst case scenario of 6% survival is not unusual, although unlikely to be commercially attractive. Slater (1987) considered that reseeding may be economical at a minimum survival at harvest of 30%.

In regions of Japan where on-bottom cultivation is carried out, the areas to be seeded are first cleared of predators by intense dredging, and use of tangle mops (Ventilla, 1982; Cropp, 1988a; Ito, 1991). Not only does this remove the predators but the starfish can be sold to the fishery co-operatives or used as fertiliser on the land (Ventilla, 1982; Cropp, 1988a). Yields of starfish can be very high in places, 5-8 $t.ha^{-1}$ (Ventilla, 1982). No predator clearance was carried out in this work, and although there were no predators in the grids at the beginning of the experiment, starfish were present at every subsequent visit to the site. Predator removal, if carried out, may have reduced the degree of scallop dispersal as there would have been fewer attacks to provoke swimming, and increased survival.

This work has further confirmed the importance of predation as a potentially limiting factor in scallop reseeding and on-bottom cultivation. Examination of the

Table 5.2. Summary of scallop reseeding around the world. Table includes experimental and commercial scale trials.

Country	Species	Size at seeding	Density at seeding	Survival	Reference
Japan	*Mizuhopecten yessoensis*	30-40 mm	1.3 m^{-2}	88% after 18 months	Kanno (1970)
	"	30 mm	5-6 m^{-2}	25-30% after 2.5-3.5 years	Ventilla (1982)
	"	30 mm	5-6 m^{-2}	30-40%	Ito & Byakuno (1988)
	"	one year old	5-6 m^{-2}	54.7-98.0% after one year	Ito (1991)
	"		5-6 m^{-2}	5.5-28.9% after two years	"
Other Pacific countries					
Russia	*Mizuhopecten yessoensis*	juvenile	1000 m^{-2}		Volkov *et al.* (1982)
	"	yearling	3.5-9.6 m^{-2}		Kalashnikov (1985)
	"	25-30 mm shell length	10-40 m^{-2}	5-50% after 2-4 years	Kalashnikov (1991)
China	*Chlamys farreri*				Lou (1991)
New Zealand	*Pecten novaezelandiae*	10-15 mm	9.7 m^{-2}	22% at harvest	Bull (1988b)
	"	after 3-6 months intermediate culture	3 m^{-2}	44-75% after 14 months	"
Mexico	*Argopecten circularis*		30 m^{-2}		Felix-Pico (1991)
Atlantic					
USA	*Argopecten irradians*	15-45 mm shell height	35-2000 m^{-2}	5% after one week to several months	Morgan *et al.* (1980)
France	*Pecten maximus*	30-40 mm	4.3 m^{-2}	50% after 14 months	Dao (1979)
Ireland	*Pecten maximus*			0-87% high survival of experimental seedings but poor survival of large scale seedings.	Burnell & Slater (1989)
United Kingdom	*Pecten maximus*	49 mm		31% after two weeks	Lake *et al.* (1987)

results presented here and those reviewed from the literature suggests that the fundamental problem is not the presence of predators *per se* but modifications of their behaviour brought about by scallop reseeding.

Kalashnikov (1991) noted that scallops and starfish were able to co-exist until the behaviour of the starfish was modified by the effects of storm disturbance on the scallops. This disturbance weakened the scallops and the starfish appeared able to sense this (probably by detecting stress-related products released by the scallops) and exploited the increased vulnerability to predation of the scallops. In the waters around the Isle of Man Briggs (1983) considered *A. rubens* of little significance to the scallop and queen fisheries as they were so rarely found feeding on these species naturally. However, after disturbance from scallop dredging *A. rubens* were observed by MacDonald (1993) to aggregate on dredge damaged scallops, as has frequently been observed elsewhere (Bourne, 1964; Medcof & Bourne, 1964; Caddy, 1973; Shepard & Auster, 1991).

Predator aggregation following scallop reseeding was clearly observed in this work and by many others (Volkov *et al.*, 1982; Caddy, 1988; Minchin, 1991; Whittington, 1993), suggesting that the process of reseeding is a sufficiently severe disturbance for the scallops to be stressed and weakened to the point that they become attractive prey items. Healthy scallops may be resistant enough to predation to make them energetically unattractive for predators unless weakened, or at such a high density as to alter foraging behaviour, as noted for starfish by (Hancock, 1974) and Kalashnikov (1991), and for crabs (Elner & Hughes, 1978; Ameyaw-Akumfi & Hughes, 1987).

The requirement for successful reseeding would appear, then, to be that the scallops should be as healthy as possible, handled as little as is necessary and allowed to recover from reseeding for a period prior to exposure to predators. This emphasises the necessity of effective predator clearance from the reseeding area and a buffer zone beyond in order to allow the scallops the opportunity to recover and recess into the sediment. Minchin (1991) recognised this in respect of crab predators and suggested that reseeding be carried out in daylight in the morning to allow the scallops some recovery time before the crustacean predators became active at dusk. Predators returning to an area where scallops are present at high density but healthy and recessed may not exhibit the aggregative feeding behaviour observed in this work, where high density patches of unrecessed scallops were created within an existing and unmodified predator field. The commencement of *A. rubens* disaggregation while scallop density in the region of 3 scallops.m^{-2} suggests that reseeding might be possible at this density without provoking starfish aggregation. Higher densities of scallops may be practicable if combined with predator clearance.

CHAPTER 6

GENERAL DISCUSSION

The decline in capture fisheries for pectinid species has fuelled interest in the potential for cultivation in many countries (see Shumway, 1991 for reviews). The model example of aquaculture enhancing scallop production is that of Japan where the total weight of scallops produced rose from 5 000 t to 100 000 t over a six year period from 1969 (Ventilla, 1982). In 1988, the production of scallops from reseeding and the wild fishery amounted to 159 689 tonnes and hanging culture accounted for 181 929 tonnes, a total of 341 618 t (Ito, 1992).

The Isle of Man fishery for the scallop *Pecten maximus* has been under increasing pressure and there has been a general decline in catch per unit effort on many of the fishing grounds since the early 1980s (Murphy, 1986; Allison *et al.*, 1989). This thesis has further considered some aspects of the fishery and in particular, has shown that the density of commercial size scallops on the fishing grounds is low (<3 scallops.100 m^{-2}) at the start of the fishing season and yet may be halved by the close of fishing on 31st May. The biological feasibility of scallop cultivation has been demonstrated by this work, and this general discussion will attempt a simple economic assessment of different methods of cultivation followed by a consideration of the factors affecting the success of scallop reseeding.

There has been no attempt at commercial scallop cultivation in the waters around the Isle of Man, on which to base a consideration of its economic viability. This study represents the largest scale experimental trial of scallop cultivation techniques to date and the economic assessment presented in this chapter is based largely on extrapolation from the experience gained during this work. Additional information has come from a variety of other studies which have considered the economics of scallop cultivation (Ventilla & al, 1980; Berry & Burnell, 1981; Ventilla, 1981; Wieland & Paul, 1983; Wildish *et al.*, 1988). The models generated are simplistic and not presented as alternative business plans but rather as a comparison of the different cultivation methods.

6.1 General model design

The four models were created as a series of linked Microsoft Excel spreadsheets. All capital equipment was assumed to have been purchased as and when required using an overdraft facility, with interest applied to the balance outstanding at the end of each year. Initial costs include the purchase of a boat

(£30 000, minimum lifespan of 10 years) and a vehicle (£15 000, lifespan 5 years). Each model was then run over a period of 10 cycles of cultivation, in order to spread the cost of the large capital items. The cultivation equipment (longlines, buoys, nets) was assumed to last for five years before requiring replacement, and facilities released by the completion of one culture cycle were made available for re-use.

As additional culture cycles began, the amount of culture equipment in use increased until after 4 cycles there was no net increase in the number of longlines or culture nets required for the operation as a whole. This decline in the need for additional equipment purchases was reflected in falling costs; at the start of the fifth cycle of cultivation no additional capital investment in longlines and nets was necessary (Appendix 4). Subsequent equipment costs were based on a constant rate of 20% replacement of the total quantity of equipment in use.

The re-use of spaces on the longline and of pearl nets incurred no costs apart for the labour costs required to make the net changes. The lantern nets, however, were of the type that use a disposable outer mesh stocking over reusable plastic partitions, and so each re-use incurred a cost from the replacement of the outer mesh.

No allowance was made for carriage costs of materials as these are highly variable, however, transport to the Isle of Man can be expensive and may be a significant factor when considering the detailed economics of any business.

6.2 Assumptions

It is inevitable that any economic assessment of scallop cultivation will rely on numerous assumptions, as many of the parameters for such a model cannot be calculated accurately. The major variables are scallop survival during the different stages of the culture process and the market value of the scallops when they are of harvestable size. These variables were adjusted to investigate the profitability of scallop cultivation under different scenarios. There are, however, many other factors where cost must be estimated for input into the model. These are detailed below.

6.3 Longline systems

The design of subsurface longline used for this analysis was the same throughout all stages of cultivation, and consists of a 200 m headrope, with weighted lines to the seabed and buoyed lines to the surface at 25 m intervals (a scaled up version of that used in Chapter 4). This provides 192 locations at which culture equipment can be hung (net spaces) at 1 m intervals. Steel anchors are used to secure the system (Hardy, 1991) rather than the combination of concrete weights and anchors used on the systems in Bay Fine. The labour and boat time used in assembling and deploying the longline are included in the capital cost of each line and incorporated as a cost per net space on the longline. Details of the cost assumptions are presented in Appendix 4.

6.4 Spat collection

Scallop spat may be acquired by spat collection (where the intensity of spatfall is sufficient) or by purchased commercially from areas where spat settlement is greater (Hardy, 1991). The approximate costs of large scale scallop spat collection are estimated below.

It is assumed in this case that spat collection is carried out at the same location as subsequent cultivation and hence the same longlines may be used throughout the rest of the year when not in use for spat collection. For 1 000 onion bag spat collectors attached 10 to a dropper, 100 net spaces are required, so the longline costs incurred for spat collection = 100 × £12.42 (the capital costs per longline net space, Appendix 4), depreciated over 5 years = £284.40 per 1 000 collectors. The collectors are only at sea for approximately 4 months and the longline is otherwise fully utilised for the remainder of the year so the longline costs fall to £284.40 × 4/12 = £82.80 per 1 000 collectors.

The materials required for spat collection cost £331.61 per 1 000 collectors (Appendix 4). If it takes approximately 2 minutes to prepare and assemble one onion bag collector and attach it to a dropper, then 33 hours labour is required for 1 000 collector bags. Labour cost are assumed to be £4 per hour, so the manufacture of the collectors costs 33 × 4 = £132 per 1 000 collectors. Two people can attach 100 lines of 10 collectors to a longline in one day. The running costs of the boat are assumed to be £5 per hour, hence the costs of hanging the collectors are 2× 8 hours labour @ £4 per hour plus 8 hours boat time = £104 per 1 000 collectors. If spat collector sorting was carried out at sea with the spat immediately loaded into culture nets, then if one person can sort 150 collectors in one day, two people could sort 1 000 collectors in 3.5 days. The costs would be 2 × 3.5 × 8 @ £4 per hour = £224 for labour and 8 × 3.5 @ £5 per hour for boat time = £140 per 1 000 collectors for sorting. The total cost of spat collection is thus £1 014 per 1 000 collectors.

P. maximus spat may be bought commercially at a cost of approximately £1 per 1 000 per mm shell height (this cost has remained static for some time, Berry & Burnell, 1981; Hardy, 1991). In order to achieve a comparable price, the collectors costed above must produce a mean yield of 84 spat per collector at a shell height of

12 mm. This level of spatfall has only been achieved once around the Isle of Man (122 ± 12.6 SE *P. maximus* per collector at Niarbyl, 1989, see Chapter 3) and it thus appears unlikely that commercial spat collection could be economically undertaken in Manx waters. The models assume spat are purchased at the above price at a size of 12 mm shell height (£12 per 1000).

6.5 Outline of the models

Four different models for scallops cultivation were considered: suspended culture in Japanese pearl nets and then lantern nets through to commercial size with twice yearly net changes; ear-hanging after one year of intermediate culture in pearl and lantern nets; reseeding or bottom culture after one year of intermediate culture in pearl and lantern nets; and finally suspended culture through to commercial size but with low stocking densities and only a single net change per year.

6.5.1. Model 1. Suspended culture

This model used suspended culture in lantern nets through to harvest size, based closely on the recommendations of the S.F.I.A. (Ventilla, 1981) which were in turn adapted from that used in Mutsu Bay, Japan (Ventilla, 1982). The stocking densities were adjusted to compensate for the smaller lantern ring size used in the model (400 mm diameter lanterns from Highland Aquaculture Ltd c.f. 500 mm), to maintain the final percentage cover of scallops in the nets at comparable levels. Nets changes were carried out twice per year, in April/May before the start of the annual growth period, and again afterwards in October/November. Intermediate culture was carried out in 6 mm pearl nets (350 × 350 mm base, £1.54 each) used in strings of 10 nets, followed by a change to 15 level 12 mm mesh lantern nets (£14.39 each) in the first April after settlement. All subsequent net changes were to 15 level 21 mm mesh lantern nets (£14.10 each) with a decrease in stocking density to compensate for increasing shell size.

It was assumed that one person could sort and re-hang 12 lantern nets in a day, and two people working from the same boat double this. The cost of harvesting the scallops was based on the labour required for the final net change, without the accompanying capital costs.

6.5.2. Model 2. Ear-hanging

The second model employed ear-hanging as an alternative to suspended culture in lantern nets, after an initial period of one year of intermediate culture in 6 mm pearl nets and 12 mm lantern nets. In October/November of the first year, a

2 mm hole is drilled through both valves at the posterior auricle and the scallops attached to lengths of braided line using plastic 'Securitie' fasteners (Paul, 1988). Pairs of scallops (approximately 50 mm shell height) are attached at 10 cm intervals on 7.5 m droppers; 150 scallops per net space on the longline. Each dropper costs £1.00 in materials and one person can complete 10 in one day (Hardy, 1991). It is assumed that one person can harvest 40 droppers of ear-hung scallops in one day, two people working from the same boat double this amount.

6.5.3. Model 3. Reseeding

The third model was based on reseeding the scallops on to the seabed at approximately 50 mm shell height, after one year in suspended culture. The cost of reseeding per 1 000 scallops was calculated from the assumed costs of reseeding a 200 m × 200 m area at a mean density of $6.m^{-2}$ (240 000 scallops). In practice the central portion of this area would be sown at a higher density to allow for subsequent dispersal of the scallops (Quéllerou, 1975). It is assumed that a commercial scallop fishing boat would be hired (£500 per day) to clear predators prior to reseeding and to harvest the scallops at the end of the culture period. The hired vessel tows the maximum permissible spread of gear for an inshore scallop fishing boat (5 × 2'6'' dredges per side, total width of gear 25' (7.62 m)).

Using 7.62 m of gear, a total of 26 parallel adjacent passes would cover the area once. Each pass would take 2.6 minutes at a towing speed on 2.5 knots and hence the time required to cover the area once would be 68.4 minutes. Allowing an equal time for vessel turning at the end of each pass and assuming that the dredges are lifted and emptied 5 times during this period (time required, 20 minutes per emptying), then the total time needed to cover the reseeded area once would be 236.8 minutes, approximately 4 hours. The area could thus be covered twice in one day. Dredge efficiency is assumed to be 20% on each pass, unrelated to scallop density. A diminishing number of scallops would be caught each time the area was covered by the dredges, but the point beyond which it would no longer be viable to keep fishing would depend on the density of surviving scallops at the start of harvesting. The reseeding model assumes that the area is covered 8 times over a period of 4 days, each time removing 20% of the remaining scallops. Therefore, the final yield of scallops was approximately 80% of the live scallops present at the start of harvesting.

Predator clearance is assumed to cover the reseeding area and a 100 m strip around the perimeter; four passes with commercial scallop fishing gear being deemed sufficient to remove the majority of predators. Thus the area cleared of predators is 4 times that actually used for reseeding.

6.5.4. Model 4. Low density suspended culture

The fourth model was based on suspended culture through to harvest size (using lantern nets throughout), with the scallops stocked at a low density and only one net change per year. The rationale behind this is that although growth rates may be reduced by the presence of fouling on the outside of the nets, the scallops are not disturbed at the start of the summer growing season by the handling involved in a net change. Excessive handling can cause growth checks and, with fewer net changes, labour costs may be reduced.

6.6 Maintenance

As the scallops grow and as communities of fouling organisms develop on the culture equipment, additional buoyancy must be added to the systems to compensate for the increased weight. The models assume that buoyancy is added to each system 18 times per year and that one person can add extra flotation to eight 200 m longlines per day (Hardy, 1991). Initial buoyancy per line is one buoy per 3 net spaces, increasing by one buoy per addition to a maximum of 18 buoys per 3 nets spaces. Less additional buoyancy is required for longlines of ear-hung scallops as they present less available space for the development of fouling; each ear-hanging system receives 12 additions of buoyancy. When net changes are frequent (as in model 1) then the overall amount of flotation required is lower, as buoys can be removed and later added again as the fouled nets are replaced with clean ones.

6.7 Yield of scallops

The yield of edible flesh from scallops (adductor muscle plus gonad) is assumed to be 10 per pound, approximately $22.kg^{-1}$ (local processors still pay fishermen per pound of meat weight for their catch). Scallop meat weights vary considerably from different locations and at different times of the year, primarily due to the seasonal reproductive cycles, and may cover a broad range of 4-15 meats per pound (Tim Croft, Island Seafare Ltd., personal communication).

The models assume that the scallops produced are sold direct to a processing factory and that the price received is calculated on the same basis as for wild caught scallops. The price is influenced by fluctuations in the supply and demand for scallops in European and global markets and may vary on a weekly basis. The financial returns from each of the models has been calculated for a price of £4 per pound of meat, an approximately median value for the past eight years (Figure 6.1).

6.8 Model parameters

Two inputs to the models were varied: survival rate and scale of production. Survival rates were applied in stages, reflecting the different stages of the cultivation cycle. During intermediate culture (over-winter growth after sorting from the spat collectors) the spat are small and vulnerable and liable to higher mortality than during the later stages of suspended culture and so this stage was treated separately. Survival at subsequent stages of suspended culture was assumed to be constant. A third survival rate was employed for the ear-hanging and reseeding stages, in models 2 and 3 respectively. Two levels of overall mortality were considered: a high survival of 90% overall and a low survival of 50%. For each of these scenarios, the yield from the reseeding model (model 3) was only 80% of the number of scallops surviving to the time of harvest, reflecting the losses due to the inefficiency of the dredge harvesting. The combinations of survival rate input to the model are summarised in Table 6.1.

Table 6.1 Summary of survival rate inputs to scallop cultivation models and resulting overall survival rate. The overall survival of scallops in the reseeding model is only 80% of the true survival, reflecting the inefficiency of harvest in this scheme. S_1 = survival during intermediate growth over the first winter after settlement, S_2 = survival rate during subsequent suspended net culture stages, S_3 = survival during ear-hanging or reseeding (models 2 & 3 only).

Survival rate (S)	Model 1 Suspended culture	Model 2 Ear-hanging	Model 3 Reseeding	Model 4 Low density suspended culture
High survival				
S_1	0.95	0.95	0.95	0.95
S_2	0.991	0.99	0.99	0.981
S_3		0.96	0.96	
Overall survival	90%	90%	72%	90%
Low survival				
S_1	0.9	0.9	0.9	0.9
S_2	0.907	0.907	0.907	0.82
S_3		0.61	0.61	
Overall survival	50%	50%	40%	50%

For each combination of survival rate parameters, three scales of spat input were used: 100 000, 250 000 and 1 000 000. The profitability of scallop cultivation estimated using these models is summarised in Table 6.2.

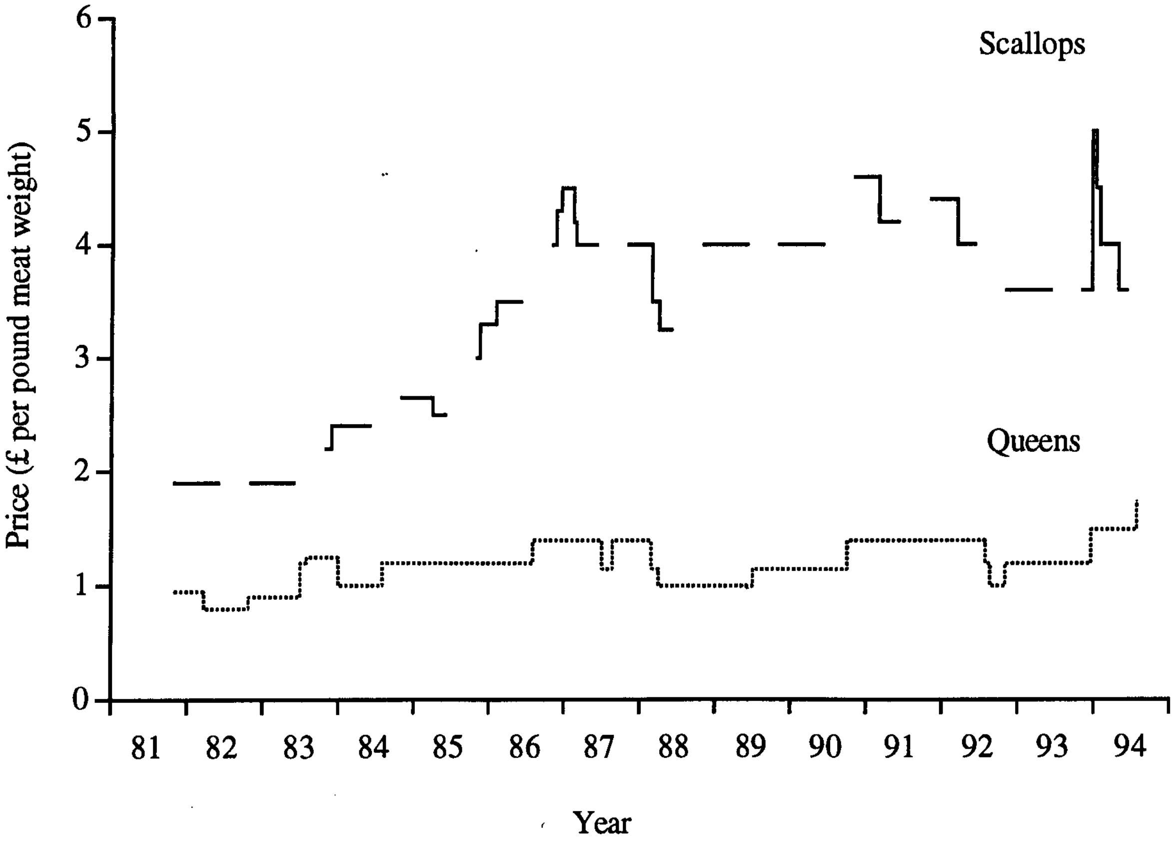


Figure 6.1 First sale prices of scallops *(Pecten maximus)* and queens *(Aequipecten opercularis)* on the Isle of Man, 1981-94. Data for scallops is intermittent, reflecting the closed season from 1st June - 31st October. Prices are still currently paid in £/pound (lb) fresh shucked weight of adductor muscle and gonad, 1lb = 0.454 kg.

Table 6.2 Summary table of profit/loss predictions from four scallop cultivation models, at three scales of production, run over a period of 10 culture cycles. The number of scallop meats per pound is assumed to be 10, and the price of scallops at first sale, £4 per pound. Levels of survival are as Table 6.1. Instances of profit are indicated in bold.

Survival	Model 1 Suspended culture	Model 2 Ear-hanging	Model 3 Reseeding	Model 4 Low density suspended culture
Spat input = 100 000				
High survival	-£ 680 625	-£ 553 671	-£ 488 560	-£ 603 790
Low survival	-£ 766 351	-£ 690 533	-£ 612 640	-£ 707 812
Spat input = 250 000				
High survival	-£ 553 305	-£ 359 339	-£ 187 590	-£ 484 642
Low survival	-£ 767 608	-£ 701 496	-£ 497 795	-£ 744 698
Spat input = 1 000 000				
High survival	**£ 83 316**	**£ 612 321**	**£ 1 317 245**	**£ 111 108**
Low survival	-£ 773 908	-£ 756 309	**£ 76 433**	-£ 929 116

6.9 Profitability of scallop cultivation

It is clear from Table 6.2 that all the methods of scallop cultivation are potentially profitable over a period of 10 cycles of cultivation, if survival rates of ≥90% can be achieved at the largest scale of production. However, a net return of £83 316 over 10 years with suspended culture (model 1) compared to a loss of £773 908 if survival is only 50% suggests that this method and the low density suspended culture (model 4) are only marginally profitable under favourable conditions of survival. These methods are capital intensive in that they each require large numbers of nets and longline spaces, as well as being highly labour intensive for net changes. Although, each of the net culture models showed a modest profit at the highest level of survival and production, the use of a single boat for an operation of this size (requiring up to 40 longlines for the final stage of culture of a single cycle) is unlikely to be practicable and further vessels would be required. It is likely that these additional capital investments would more than offset the low levels of estimated profitability.

The use of ear-hanging techniques for final cultivation of scallops appears to have considerable potential, returning a profit of £612 321 at the highest scale of operation and highest survival. This method is initially highly labour intensive when scallops must be drilled and attached to the droppers, but subsequently there are no net changes and less additional buoyancy is required than for lantern net culture. Ear hanging requires an earlier investment in large numbers of longlines than the other methods of suspended cultivation; at the start of ear-hanging after one year of suspended net culture, each location on the longlines can accommodate 150 scallops. At the same stage of lantern net culture 450 scallops can be housed in the same space at a standard density (model 1) or 300 at low density (model 4).

Reseeding of scallops on to the seabed after a period of intermediate culture (model 3) produced the most favourable predictions, with profits of £1 317 245 at 90% overall survival (72% harvested) and even marginal profits of £76 433 at the low survival rate of 50%. This method requires relatively little input in terms of capital and labour, required primarily during the initial period of suspended culture. If reseeding of the scallops from one cycle is carried out prior to the purchase/spat collection of the next, then a single set of longlines can be used for each cycle of cultivation. The relatively low labour demands of this method of cultivation make it amenable to the scale of production necessary for profitability; at the 90% level of overall survival after an input of 1 000 000 spat the maximum requirement is for 9 longline systems during the later stages of intermediate culture in 12 mm lantern nets. This scale of operation should be well within the scope of the facilities included in the model. The scale of production is crucial to success, in order to overcome the fixed costs of the essential capital items e.g. boat and vehicle. None of the cultivation methods modelled produced a profit over 10 cycles at the small (100 000) or medium (250 000) scales.

The two values of overall survival incorporated into the economic analysis cover a wide range and might be considered extremes for suspended cultivation methods (Hardy, 1991). Mortality rates are likely to be lower, and are certainly more controllable in a suspended culture system than when scallops are reseeded onto the seabed. In suspended culture predators are excluded from the nets (although settlement of predators into the nets from the plankton during the summer months may lead to mortalities if net changes are not undertaken regularly) and other than stochastic natural phenomena, such as toxic algal blooms the remaining causes of mortality (overcrowding, physical disturbance) are largely under the control of the scallop farmer. Conversely, after scallops have been reseeded on to the seabed there is relatively little that can be done to influence subsequent losses.

These models make no allowance for the faster growth often exhibited by scallops in suspended culture relative to those living on the seabed, or the better yield of meat per shell. The meat yield from ear hung scallops may be 84% higher than that from scallops of the same age cultured in lantern nets (Paul, 1988).

6.10 Potential for pectinid cultivation in Manx waters

The continuing high demand for scallop meats and the problems facing the Manx scallop industry in terms of declining catches and profitability (Brand *et al.*, 1991a, and Chapter 2; Allison, 1993), provide potentially ideal conditions for the development of pectinid mariculture (Wildish *et al.*, 1988). The basic methodology for the cultivation of both *P. maximus* and *A. opercularis* is well established (Paul *et al.*, 1981; Ventilla, 1981; Wieland & Paul, 1983; Paul, 1987; Paul, 1988; Hardy, 1991), and improvements in culture equipment to adapt it to conditions in the British Isles and to increase cost-effectiveness continue (Hardy, 1991). What then are the prospects for a scallop cultivation industry in the Isle of Man?

6.11 Spat collection

As the starting point for scallop cultivation, a reliable and economical supply of spat is a pre-requisite. Spat collection techniques have become almost standardised on the Japanese style onion bag collectors, and in many countries these produce high yields of spat (see Chapter 1). These same methods have not been highly successful around the Isle of Man, where spatfall on artificial collectors has historically been low compared to elsewhere in the British Isles (Brand *et al.*, 1991b, and see Chapter 3) and never attained the minimum estimated commercial settlement of 250-550 *P. maximus* spat per collector (Wieland & Paul, 1983).

There are two alternatives to the collection of wild scallop spat: larval culture in a hatchery or the importation of spat from another location. Larval rearing techniques for *P. maximus* have been described in detail (Comely, 1972; Gruffydd & Beaumont, 1972) and there has been a considerable amount of work under taken to refine these techniques (reviewed by Ansell *et al.*, 1991). In France there has been large scale hatchery production of *P. maximus* as part of a government funded programme to restock the Rade de Brest (Cochard & Gerard, 1987) but the economics of this operation are doubtful. However, research into commercial larval rearing continues and may prove viable in the future (Ballantyne & Williams, 1993).

It is possible to transport spat considerable distances, from a site where spat collection is successful to another location for on-growing (Hardy, 1991). The spat should ideally be packed loosely in insulated boxes to keep them cool, but also in conditions of high humidity. *P. maximus* from Scotland and Ireland have been used to help re-instate populations in France (Dao *et al.*, 1985). The importation of spat would require a government licence and there may be arguments against importation on the basis of potential disease introductions from elsewhere and genetic contamination of local stocks, depending on the source of spat.

6.12 Growth

The biological feasibility of *A. opercularis* culture in the waters around the Isle of Man was demonstrated by (Paul *et al.*, 1981), although they were less successful with *P. maximus*. Chapter 4 of this thesis confirmed the potential for queen cultivation and also showed that scallops could be grown effectively in suspended culture, using Japanese pearl nets. The shell heights of scallops grown in this work appeared comparable to those expected at similar times in the cultivation cycle in Scotland (Ventilla, 1981; Wieland & Paul, 1983), despite less than ideal conditions. Thus the biological feasibility of pectinid culture in Manx waters has been established, although the economic assessment presented above suggests that suspended culture would be uneconomical. Reseeding, however, may be economically viable if practised on a large enough scale.

6.13 Reseeding

The cultivation of scallops on the seabed by reseeding appears to be the only method of cultivation considered in my work, that has economic potential. Similar conclusions have been drawn for *Placopecten magellanicus* off the eastern seaboard of North America (Frishman *et al.*, 1980; Wildish *et al.*, 1988). Extensive cultivation of this sort is, however, vulnerable to heavy losses from dispersal of reseeded scallops and predation (reviewed in Chapter 1). These problems occurred during my work (Chapter 5) despite the large size of the scallops employed; 58% of the reseeded scallops dispersed beyond the 30 m radius search area after 286 days, and of those that were accounted for, survival was only 14%. This high level of mortality was apparently due to the aggregation of predators on the newly reseeded scallops. The influx of predators may also have contributed to the speed of dispersal as the scallops responded to attacks from predators. Commercial seeding with one year old scallops might be expected to result in severe losses to both dispersal and predation as they would be more vulnerable to both crabs and starfish (Lake *et al.*, 1987; Lake, 1993), and smaller scallops tend to be more frequent swimmers (however, the relationship between scallop size and swimming frequency, endurance and distance covered is a complex one, see Brand, 1991 for review) .

Measures can be taken to reduce predation during reseeding: active predator clearance by intensive dredging is common practice in Japan prior to reseeding, as well as the use of rope mops to tangle starfish and baited traps to remove them (Ito, 1991). The area cleared may be several times larger than the area to be initially seeded to allow a buffer zone around the scallops (Quéllerou, 1975; Neville, 1988). The removal of predators from the immediate locality reduces predator aggregation as the chemical scent reaching the edge of the buffer zone is diluted over the distance travelled, by dispersal and turbulent mixing (Doering, 1982). Predators will gradually move back into the area cleared, by which time the density of scallops has fallen to less provocative levels at which aggregation is less significant. Predator control, continued in the form of crab potting may keep down the number of crab predators in the area.

The size of scallops at reseeding influences their vulnerability to predation (see Chapter 1) and the optimal size may be dependent on the suite of predators resident at a particular site (Minchin, 1991). In addition, as decapod predators are most active at night, reseeding could be carried out in the morning to maximise the length of time available for stress induced chemical attractants to disperse and respiration to normalise.

The economic model of reseeding presented above suggests that if reseeding is to be profitable, it must be undertaken on a large scale. This would require a large financial investment as well as commitment from the Isle of Man Government; there is currently no provision in legislation for the granting of an equivalent to a Several Order, to provide protection and ownership to scallops reseeded onto the seabed. Further, the prospects for seabed cultivation would benefit from a change in the minimum legal landing size, as applied to cultivated scallops. Currently the same MLS would be applied to farmed scallops as to wild caught ones (≥110 mm), whereas scallop farmers in Scotland are governed by European Community legislation limiting the landing size to 100 mm shell length (David MacKay, SOAFD, personal communication). This change would, however, be open to abuse from undersize scallops being sold as cultured stock. The requirement of extensive cultivation for areas of the seabed to be converted from common access to restricted access would inevitably raise a great deal of objections, not least from the fishing industry. As such, any proposal for scallop cultivation on the seabed should ideally incorporate fishermen or fishermen's representatives in order to reduce opposition.

6.14 Suggestions for further work

Urgent work is required to improve or justify the assumptions behind density/abundance calculations based on CPUE (dredge efficiency and towing speed) in this and previous studies. An investigation into the efficiency of Manx spring-loaded dredges on different substrata, similar to that carried out by Dare *et al.* (1993), is highly desirable. A questionnaire/survey of local fishermen should be undertaken forthwith to determine an accurate figure for scallop dredge towing speed.

Quantification of the efficiency of queen dredges at catching different size classes of pre-recruit scallops, would provide an insight into the strength of as yet unexploited cohorts and may facilitate investigation of incidental mortality rates of pre-recruit scallops based on changes in abundance.

Calibration of queen dredge efficiency with respect to different size classes of predators caught as by-catch during assessment surveys (again *A. rubens* would be of particular interest) would help in quantifying their abundance on the scallop fishing grounds and hence their relative importance to the fishery. Further, all the crabs caught during stock assessment surveys should be sexed to confirm or refute the impression that the individuals caught are almost exclusively females, possibly migrating offshore in order to lay their eggs.

Investigation of incidental damage obtained from examination of repairs to previous shell damage, visible in the rings of scallops caught on the research vessel surveys and/or recovered from processing factories, may provide information on the frequency of damage sustained on different grounds.

As scallop densities are now extremely low, an investigation into the effects of spatial distribution and water movements on the dilution of gametes, their longevity and fertilisation rates would be extremely pertinent.

There is little existing work on the feeding behaviour of *Cancer pagurus*, largely because it is often intractable in the laboratory. The work of Lake *et al.* (1987) on the size relations between *C. pagurus* and their *P. maximus* prey suggested that a partial size refuge for scallops was attained at a shell height of 6-7 cm. However, the crabs were never presented with a choice of prey sizes and so there was no indication of active size selection. An opportunity exists for research into size selective behaviour and diet optimisation, where *C. pagurus* is presented with a choice of prey sizes simultaneously under as natural conditions as possible. This should be extended to investigate whether any size selective behaviour can be overwhelmed by repeated encounters with large, sub-optimal scallops and re-instated by the presence of optimal prey, as per *Carcinus maenas* feeding on *Mytilus edulis* (Elner & Hughes, 1978; Ameyaw-Akumfi & Hughes, 1987).

Research is also required on the influence of scallop size and density at reseeding on predator behaviour, particularly with comparisons of areas cleared of predators to those uncleared. The response of predators to field manipulations of scallop density, may provide information on the threshold densities at which predator aggregation is stimulated. The use of time-lapse video equipment would facilitate this study and other field experiments.

CONCLUSIONS

Pecten maximus and *Aequipecten opercularis* have both been shown to be amenable to cultivation in the waters around the Isle of Man. However, the costs involved in suspended culture would appear to preclude these techniques on economic grounds. Extensive cultivation of *P. maximus* on the seabed appears to be an economically attractive prospect, although there are ecological and political obstacles that need to be addressed: mortality rates due to predation have been shown to be high in the absence of predator clearance, and changes are necessary to Manx legislation to allow the granting of licences for aquaculture on the seabed. Furthermore, wide-ranging objections to the awarding of exclusive rights to individuals or companies can be foreseen, unless it is done with the co-operation of the fishing industry.

LITERATURE CITED

Allen, E. J. (1899). On the fauna and bottom-deposits near the thirty-fathom line from the Eddystone grounds to Start Point. Journal of the Marine Biological Association of the United Kingdom **5**: 365-542.

Allen, P. L. (1983). Feeding behaviour of *Asterias rubens* (L.) on soft bottom bivalves: a study in selective predation. Journal of Experimental Marine Biology and Ecology **70**: 79-90.

Allison, E. H. (1993). The dynamics of exploited populations of scallops (*Pecten maximus* L.) and queens (*Chlamys opercularis* L.) in the North Irish Sea. Ph.D. thesis, University of Liverpool. 254pp.

Allison, E. H., A. R. Brand and E. J. Murphy (1989). Mortality rates in North Irish Sea *Pecten maximus,* from tagging experiments. 7th International Pectinid Workshop. Portland, Maine, 7.

Allison, E. H., U. A. W. Wilson and A. R. Brand (1994). Age determination and the first growth ring in North Irish Sea populations of the scallop, *Pecten maximus* (L.). Journal of Molluscan Studies **60**: 91-95.

Ambrose Jr, W. G. and C. H. Peterson (1989). Effects of location and type of substratum, and adult stock on bay scallop, *Argopecten irradians,* recruitment. 1990 Annu. Meet. of the National Shellfisheries Association; Williamsburg, VA (USA); 1-5 Apr 1990 **8**: 454-455.

Ambrose Jr, W. G., C. H. Peterson, H. C. Summerson and J. Lin (1992). Experimental tests of factors affecting recruitment of bay scallops (*Argopecten irradians*) to spat collectors. Aquaculture **108**: 67-86.

Ameyaw-Akumfi, C. and R. N. Hughes (1987). Behaviour of *Carcinus maenas* feeding on large *Mytilus edulis.* How do they assess the optimal diet? Marine Ecology Progress Series **38**: 213-216.

Andersson, M. (1981). On optimal predator search. Theoretical Population Biology **19**: 58-86.

Andrew, N. L. and B. D. Mapstone (1987). Sampling and the description of spatial pattern in marine ecology. Oceanography and Marine Biology Annual Review **25**: 39-90.

Anger, K., U. Rogal, G. Schriever and C. Valentin (1977). In situ investigation on the echinoderm *Asterias rubens* as a predator of soft bottom communities in the western Baltic Sea. Helgoländer wissenschaftliche Meeresuntersuchungen **29**: 439-459.

Ansell, A. D., J.-C. Dao and J. Mason (1991). Three European scallops: *Pecten maximus, Chlamys (Aequipecten) opercularis* and *C. (Chlamys) varia. In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 715-751.

Aoyama, S. (1988). The Mutsu Bay scallop fisheries: scallop culture, stock enhancement, and resource management. *In*: Marine invertebrate fisheries: their assessment and management. J. F. Caddy (ed.). John Wiley and Sons Inc., 525-539.

Aravindakshan, I. (1955). Studies on the biology of the Queen scallop, *Chlamys opercularis* (L.). Ph.D. thesis, Liverpool.

Auster, P. J. (1988). Response of megafaunal predators to synchronous settlement of sessile prey. Journal of Shellfish Research **7**: 108-109.

Auster, P. J. and R. J. Malatesta (1991). Effects of scale on predation patterns. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 198-203.

Babcock, R. C., C. N. Mundy and D. Whitehead (1992). *In situ* fertilization rates for *Acanthaster planci* during induced and natural spawnings. 6th International Congress on Invertebrate Reproduction, Dublin, Abstract only.

Baird, R. H. (1958). On the swimming behaviour of escallops (*Pecten maximus* L.). Proceedings of the Malacological Society of London **33**: 67-71.

Baird, R. H. and F. A. Gibson (1956). Underwater observations on escallop (*Pecten maximus* L.) beds. Journal of the Marine Biological Association of the United Kingdom **35**: 555-562.

Ballantyne, I. and P. Williams (1993). An investigation of techniques for the hatchery and nursery rearing of the king scallop (*Pecten maximus* (L.)). 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Bannister, R. C. A. (1986). Assessment and population dynamics of commercially exploited shellfish in England and Wales. North Pacific Workshop on stock assessment and management of invertebrates, 182-194.

Barbeau, M. A. and R. E. Scheibling (1993). Effect of water temperature on predation of juvenile sea scallops (*Placopecten magellanicus*) by sea stars and crabs. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Beaumont, A. R. (1986). Genetic aspects of hatchery rearing of the scallop, *Pecten maximus* (L.). 2. Int. Symp. on Genetics in Aquaculture; Davis, CA (USA); 1985 **57**: 99-110.

Beaumont, A. R. and D. A. Barnes (1992). Aspects of veliger larval growth and byssus drifting of the spat of *Pecten maximus* and *Aequipecten* (*Chlamys*) *opercularis*. ICES Journal of Marine Science **49**: 417-423.

Beaumont, A. R., M. D. Budd and L. D. Gruffydd (1982). The culture of scallop larvae. Fish Farming International **9**: 10-11.

Beaumont, A. R., G. Tserpes and M. D. Budd (1987). Some effects of copper on the veliger larvae of the mussel *Mytilus edulis* and the scallop *Pecten maximus* (Mollusca, Bivalvia). Marine Environment Research **21**: 299-309.

Berry, T. and G. M. Burnell (1981). The potential of scallop culture in Ireland. Aquaculture Technical Bulletin, Ireland 3, 1-33.

Blankley, W. O. and G. M. Branch (1984). Co-operative prey capture and unusual brooding habits of *Anasterias rupicola* (Verril) (Asteroidea) at sub-antartic Marion Island. Marine Ecology Progress Series **20**: 171-176.

Body, A. G. and T. Murai (1986). Scallop culture in Japan. Australian Fisheries **45**: 30-33.

Bonardelli, J. (1988). Optimizing collection of pectinid spat on collectors. 1987 Annu. Meet. of the Natl. Shellfisheries Assoc.; Halifax, N.S. (Canada); 9 Aug 1987 **7**: 50.

Boulding, E. G. and T. K. Hay (1984). Crab response to prey density can result in density-dependent mortality of clams. Canadian Journal of Fisheries and Aquatic Sciences **41**: 521-525.

Bourne, N. (1964). Scallops and the offshore fishery of the Maritimes. Bulletin of the Fisheries Research Board of Canada **14**: 2-7.

Bourne, N. F. (1991). The potential for scallop culture in British Columbia, Canada. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

Brand, A. R. (1976). Pectinid settlement on artificial collectors: initial results of the Wolfson Foundation Scallop Cultivation Project at Port Erin, Isle of Man. 1st International Pectinid Workshop, Baltimore, Ireland, 11th-16th May, 1976. (mimeo).

Brand, A. R. (1991). Scallop ecology: distributions and behaviour. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 517-584.

Brand, A. R., E. H. Allison and E. J. Murphy (1991a). North Irish Sea scallop fisheries: a review of changes. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 204-218.

Brand, A. R., J. D. Paul and J. N. Hoogesteger (1980). Spat settlement of the scallops *Chlamys opercularis* (L.) and *Pecten maximus* (L.) on artificial collectors. Journal of the Marine Biological Association of the United Kingdom **60**: 379-390.

Brand, A. R., U. A. W. Wilson, S. J. Hawkins, E. H. Allison and N. A. Duggan (1991b). Pectinid fisheries, spat collection, and the potential for stock enhancement in the Isle of Man. ICES Marine Science Symposia **192**: 79-86.

Briggs, C. F. (1983). A study of some sublittoral populations of *Asterias rubens* and their prey. Ph.D. Thesis thesis, University of Liverpool.

Briggs, R. P. (1991). A study of the Northern Ireland fishery for the escallop *Pecten maximus* (Linnaeus 1758). *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p .

Bruce, J. R., J. S. Colman and N. S. Jones, Ed. (1963). Marine fauna of the Isle of Man and its surrounding seas. Liverpool Marine Biology Committee Memoirs No.36. Liverpool, Liverpool University Press. 307pp.

Brun, E. (1968). Extreme population density of the starfish *Asterias rubens* L. on a bed of Iceland scallop *Chlamys islandica* (O.F. Müller). Astarte **32**: 1-4.

Buchanan, J. B. (1984). Sediment analysis. *In*: Methods for study of marine benthos. N. A. Holme and A. D. McIntyre (ed.). Blackwell Scientific Publications, Oxford. p 41-65.

Buestel, D. and J.-C. Dao (1979). Extensive aquaculture of the scalllop *Pecten maximus:* experimental stocking results. Peche Maritime **1215**: 361-365.

Buestel, D., J.-C. Dao and G. Lemarie (1979). Collection of pectinid spat in Brittany. Rapport et Procès-Verbaux des Réunions. Conseil International pour l'Exploration de la mer **175**: 80-84.

Bull, M. F. (1987). Scallop seeding trials in New Zealand. 6th International Pectinid Workshop, Menai Bridge, Wales, 9th-14th April, 1987. (mimeo).

Bull, M. F. (1988a). Lessons and mistakes from recent trials of methods for spat catching and grow out of scallops in New Zealand. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 253-263.

Bull, M. F. (1988b). New Zealand scallop enhancement project - cost and benefits. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 154-165.

Bull, M. F. (1988c). The New Zealand scallop fishery: A brief review of the fishery and its management. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 42-50.

Bull, M. F. (1991). New Zealand. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 853-859.

Burnell, G. M., M. Barnett, T. O'Carroll and V. Rowntree (1991). Scallop collection and on-growing trials in south-west Ireland. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (mimeo).

Burnell, G. M. and J. Slater (1989). Scallop culture in Ireland: fact or fantasy? 7th International Pectinid Workshop, Portland, Maine, 20th-25th April, 1989. (mimeo).

Buss, L. W. and J. B. C. Jackson (1981). Planktonic food availability and suspension feeder abundances: evidence of *in situ* depletion. Journal of Experimental Marine Biology and Ecology **49**: 151-162.

Butcher, T., J. Matthews, J. Glaister and G. Hamer (1981). Study suggests scallop dredges causing few problems in Jervis Bay. Australian Fisheries **40**: 9-12.

Caddy, J. F. (1968). Underwater observations on scallop (*Placopecten magellanicus*) behaviour and drag efficiency. Journal of the Fisheries Research Board of Canada **25**: 2123-2141.

Caddy, J. F. (1970). A method of surveying scallop populations from a submersible. Journal of the Fisheries Research Board of Canada **27**: 533-549.

Caddy, J. F. (1973). Underwater observations on the tracks of dredges and trawls and some effects of dredging on a scallop ground. Journal of the Fisheries Research Board of Canada **30**: 173-180.

Caddy, J. F. (1988). A perspective on the population dynamics and assessment of scallop fisheries, with special reference to the sea scallop *Placopecten magellanicus* Gmelin. *In*: Marine Invertebrate Fisheries: their assessment and management. J. F. Caddy (ed.). Wiley, 559-589.

Campbell, D. B. (1984). Foraging movements of the sea star *Asterias forbesi* (Desor) (Echinodermata, Asteroidea) in Narragansett Bay, Rhode Island, U.S.A. Marine Bahaviour and Physiology **11**: 185-198.

Carsen, A. E., B. G. Hatcher and R. E. Scheibling (1993). Swimming of sea scallops (*Placopecten magellanicus*) under different current regimes: comarison of flume and field measurements. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Carthy, J. D. (1958). An introduction to the behaviour of invertebrates. George Allen & Unwin Ltd, London. 380pp.

Castagna, M. and W. D. Duggan (1971). Rearing of the Bay Scallop, *Aequipecten irradians*. **61**: 80-85.

Castilla, J. C. (1972). Responses of *Asterias rubens* to a bivalve prey in a Y-maze. Marine Biology **12**: 222-228.

Chapman, C. J., J. Main, T. Howell and G. I. Sangster (1979). The swimming speed and endurance of the queen scallop *Chalmys opercularis* in relation to trawling. *In*: Progress in Underwater Science. J. C. Gamble (ed.). Pentech Press, London. p 57-72.

Chapman, C. J., J. Mason and J. A. M. Kinnear (1977). Diving observations on the efficiency of dredges used in the Scottish fishery for the scallop, *Pecten maximus* (L.). Scottish Fisheries Research Report 10. 16pp.

Charnov, E. L. (1974). Optimal foraging, the marginal value theorem. Theoretical Population Biology **9**: 129-136.

Chew, K. K. (1990). Global bivalve shellfish introductions. World Aquaculture **21**: 9-22.

Claereboudt, M. R., D. Bureau, J. Côté and J. H. Himmelman (1994). Fouling development and its effect on the growth of juvenile giant scallops (*Placopecten magellanicus*) in suspended culture. Aquaculture **121**: 327-342.

Clarke, K. R. and R. H. Green (1988). Statistical design and analysis for a 'biological effects' study. Marine Ecology Progress Series **46**: 213-226.

Cochard, J. C., M. Comps, D. Buestel and P. Paquotte (1991). Introduction of the Japanese scallop *Patinopecten yessoensis* (Jay) into France and the hatchery production of the F1 generation. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 281-286.

Cochard, J. C. and A. Gerard (1987). Production artificielle de naissain de coquille Saint-Jacques *Pecten maximus* (L.) en rade de Brest: Analyse des facteurs affectant la croissance larvaire. 6th International Pectinid Workshop, Menai Bridge, Wales, UK, 9th-14th April, 1987. 13pp. (mimeo).

Coleman, N. (1988). Spat catches as an indication of recruitment to scallop populations in Victorian waters. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 51-60.

Comely, C. A. (1972). Larval culture of the scallop *Pecten maximus* (L.). Journal du Conseil International pour l'Exploration de la Mer **34**: 365-378.

Costello, T. J. (1973). Larval culture of the Calico scallop, *Argopecten gibbus*. Proceedings of the National Shellfisheries Association **63**: 72-76.

Côté, J., J. H. Himmelman, M. Claereboudt and J. C. Bonardelli (1993). Influence of density and depth on the growth of juvenile sea scallops (*Placopecten magellanicus*) in suspended culture. Canadian Journal of Fisheries and Aquatic Sciences **50**: 1857-1869.

Cragg, S. M. and D. J. Crisp (1991). The biology of scallop larvae. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 75-132.

Cropp, D. A. (1985). Scallops thrive in TFDA culture program. Australian Fisheries. **44**: 16-18.

Cropp, D. A. (1988a). Scallop culture in the Pacific region. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 134-153.

Cropp, D. A. (1988b). Ongrowing scallop culture in Tasmania. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 182-195.

Cropp, D. A. and K. R. Frankish (1988). Cost comparison of hatchery and naturally produced spat for the scallop *Pecten fumatus* Reeve. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 196-225.

Cropp, D. A. and M. E. Hortle (1992). Midwater cage culture of the commercial scallop *Pecten fumatus* Reeve1852 in Tasmania. Aquaculture **102**: 55-64.

Cunningham, P. N. and R. N. Hughes (1984). Learning of predatory skills by shorecrabs *Carcinus maenas* feeding on mussels and dogwhelks. Marine Ecology Progress Series **16**: 1-2.

Dabinett, P. E. (1991). Experimental hatchery production and grow-out of the giant scallop *Placopecten magellanicus* in Newfoundland, Canada. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

Dadswell, M. J., R. A. Chandler and G. J. Parsons (1988). Spat settlement and early growth of *Placopecten magellanicus* in Passamaquoddy Bay, Canada. Journal of Shellfish Research **7**: 153-154.

Dadswell, M. J., R. A. Chandler and J. Parsons (1987). Spat settlement and early growth of *Placopecten magellanicus* in Passamaquoddy Bay, Canada. 6th International Pectinid Workshop, Menai Bridge, Wales, UK, (mimeo).

Dadswell, M. J. and G. J. Parsons (1991a). Accelerated growth, increased meat yield and enhanced survival of giant scallop (*Placopecten magellanicus*) grown in suspended culture: implications for large-scale aquaculture in Atantic Canada. 8th International Pectinid Workshop, Cherbourg, France, (Abstract).

Dadswell, M. J. and G. J. Parsons (1991b). Potential for aquaculture of the sea scallop, *Placopecten magellanicus* (Gmelin, 1791) in the Canadian Maritimes using naturally produced spat. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p .

Dao, J.-C. (1979). The latest results on scallop restocking in Brittany. 10th Annual Shellfish Conference, Fishmongers Hall, London, .

Dao, J. C. (1991). World distribution of exploited Pectinids. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

Dao, J. C., D. Buestel and C. Halary (1985). Note sur l'evolution comparee des coquilles Saint-Jacques d'origine differente en Bretagne Nord. 5th International Pectinid Workshop, La Coruña, Spain, 6th-10th May, 1985. 12pp. (mimeo).

Darbishire, R. D. (1886). The testaceous Mollusca. *In*: Fauna of Liverpool Bay and the neighboring seas. W. A. Herdman (ed.). Longmans, Green and Co., London. p 232-266.

Dare, P. J. (1974). Damage caused to mussels (*Mytilus edulis* L.) by dredging and mechanised sorting. Journal du Conseil International pour l'Exploration de la Mer **35**: 296-299.

Dare, P. J. and R. C. A. Bannister (1987). Settlement of scallop, *Pecten maximus*, spat on natural substrates off south west England: the hydroid connection. 6th International Pectinid Workshop, Menai Bridge, Wales, ICES. pp .

Dare, P. J., G. Davies and D. B. Edwards (1983). Predation on juvenile pacific oyster (*Crassostrea gigas* Thunberg) and mussels (*Mytilus edulis* L.) by shore crabs (*Carcinus maenas* L.). MAFF Directorate of Fisheries Research, Lowestoft. Fish. Res. Tech. Rep. 73.

Dare, P. J. and M. R. Deith (1991). Age determination of scallops, *Pecten maximus* (Linnaeus, 1758), using stable oxygen isotope analysis, with some implications for fisheries management in British waters. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 118-133.

Dare, P. J., D. Key and P. M. Connor (1993). The efficiency of spring-loaded dredges used in the western English Channel fishery for scallops, *Pecten maximus* (L.). International Council for the Exploration of the Sea, Fish Capture Committee CM 1993/B:15 (Ref.K). 8pp.

Davidson, R. J. (1986). Mussel selection by the paddle crab *Ovalipes catharus* (White): evidence of flexible foraging behaviour. Journal of Experimental Marine Biology and Ecology **102**: 281-299.

Day, R. W. and G. P. Quinn (1989). Comparisons of treatments after an analysis of variance in ecology. Ecological Monographs **59**: 433-463.

Denny, M. W. (1988). Biology and the mechanics of the wave-swept environment. Princeton University Press, Princeton (N.J.). 304pp.

Dickie, L. M. and J. C. Medcof (1963). Causes of mass mortalities of scallops (*Placopecten magellanicus*) in the Southwestern Gulf of St. Lawrence. Journal of the Fisheries Research Board of Canada **20**: 451-480.

Dix, T. G. (1981). Preliminary experiments in commercial scallop (*Pecten meridionalis*) culture in Tasmania. Tasmanian Fisheries Research. **23:** 18-24.

Doering, P. H. (1982). Reduction of attractiveness to the sea star Asterias forbesi (Desor) by the clam Mercenaria mercenaria (Linnaeus). Journal of Experimental Marine Biology and Ecology **60**: 47-61.

Dredge, M. C. L. (1985). Estimates of natural mortality and yield-per-recruit for *Amusium japonicum* balloti Bernardi (Pectinidae) based on tag recoveries. Journal of Shellfish Research **5**: 103-109.

Duggan, N. A. (1987). Recruitment in North Irish Sea scallop stocks. Ph.D. thesis, Liverpool. 142pp.

Duggan, W. P. (1973). Growth and survival of the bay scallop, *Argopecten irradians*, at various locations in the water column and at various densities. Proceedings of the National Shellfisheries Association **63**: 68-71.

Edwards, E. (1979). The edible crab and its fishery in British waters. Buckland Foundation/Fishing News Books, Farnham. 142pp.

Edwards, E. (1988). Crab fisheries and their management in the British Isles. *In*: Marine Invertebrate Fisheries: their assessment and management. J. F. Caddy (ed.). Wiley, 241-259.

Elner, R. W. (1978). The mechanics of predation by the shore crab, *Carcinus maenas* (L.), on the edible mussel, *Mytilus edulis* (L.). Oecologia (Berl) **36**: 333-344.

Elner, R. W. and R. N. Hughes (1978). Energy maximization in the diet of the shore crab, *Carcinus maenas*. Journal of Animal Ecology **47**: 103-116.

Elner, R. W. and G. S. Jamieson (1979). Predation of sea scallops *Placopecten magellanicus*, by the rock crab *Cancer irroratus* and the American lobster *Hommarus americanus*. Journal of the Fisheries Research Board of Canada **36**: 537-543.

Evans, J. W., R. Scaplen and D. R. Idler (1973). Scallop aquaculture report for 1972-73. Newfoundland Fisheries Development Authority

Feder, H. M. and A. M. Christensen (1966). Aspects of asteroid biology. *In*: Physiology of echinodermata. R. A. Boolootian (ed.). Interscience Publishers, New York. p 87-129.

Fegan, D. F. (1983). Scallop spat collection in the Oban area, 1982. 4th International Pectinid Workshop, Aberdeen, Scotland, 19pp. (mimeo).

Felix-Pico, E. F. (1991). Mexico. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 943-979.

Flores-Briceño, A., B. L. Garcia, B. A. Trench, J. C. Véliz and R. Gonzales-Piaza (1993). Developments in the industrial production of scallop seeds (*Argopecten purpuratus*, Lamarck1891) in semi controlled environments in the north of Chile. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Forbes, E. (1838). Malacologia monensis. A catalogue of the Mollusca inhabiting the Isle of Man and the neighbouring sea. John Carfrae and Son, Edinburgh.

Franklin, A. and P. M. Conner (1980). Cardigan Bay scallop survey. M.A.F.F. Directorate of Fisheries Research Fisheries Notices 66. 8pp.

Franklin, A., G. D. Pickett and P. M. Conner (1980). The escallop (*Pecten maximus*) and its fishery in England and Wales. M.A.F.F. Laboratory Leaflet 51. 19pp.

Franklin, A. and M. S. Rolfe (1976). Scallop tagging experiments off Plymouth. Min. Agric. Fish. & Food (UK) Fish. Notice 45. 4pp.

Fraser, D. I. (1983a). Observations on the settlement of pectinid spat off the west coast of Scotland in 1982. International Council for the Exploration of the Sea CM 1983/K:40.

Fraser, D. I. (1983b). Survival of dredge and diver caught scallops returned to the sea. 4th International Pectinid Workshop, Aberdeen, Scotland, (mimeo).

Fraser, D. I. (1987). Pectinid spat studies in selected areas of the west coast of Scotland, 1982-86. 6th International Pectinid Workshop, Menai Bridge, Wales, 9th-14th April, 1987. (Abstract).

Fraser, D. I. (1991). Settlement and recruitment in *Pecten maximus* (Linnaeus 1758) and *Chlamys (Aequipecten) opercularis* (Linnaeus 1758). *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 28-36.

Fréchette, M. and E. Bourget (1985). Energy flow between the pelagic and benthic zones: Factors controlling particulate organic matter available to an intertidal mussel bed. Canadian Journal of Fisheries and Aquatic Science **42**: 1158-1165.

Fréchette, M., C. A. Butman and W. R. Geyer (1989). The importance of boundary-layer flows in supplying phytoplankton to the benthic suspension feeder, *Mytilus edulis* L. Limnology and Oceanography **34**: 19-36.

Frishman, Z., A. Nooman, K. S. Naidu and F. M. Cahill (1980). Farming scallops in Newfoundland Canada. Third International Scallop Workshop, Port Erin, Isle of Man, 13th-16th May, 1980. 28pp. (mimeo).

Fullarton, J. H. (1888). On the habits of *Pecten* and on the clam beds of the Firth of Forth. Fishery Board of Scotland Annual Report 8.

Galtsoff, P. A. and V. L. Loosanoff (1939). Natural history and method of controlling the starfish (*Asterias forbesi*, Desor). U.S. Bur. Fish. Fish. Bull. 49.

Gibson, F. A. (1956). Escallops (*Pecten maximus* L.) in Irish waters. Scientific Proceedings of the Royal Dublin Society **27**: 253-271.

Gillespie, M. J. S. (1983). Results of recent pectinid R & D carried out at MFU, Ardtoe. 4th International Pectinid Workshop, Aberdeen, Scotland, (mimeo).

Goodwin, C. L., J. Bronson and T. E. Bettinger (1985). Investigations of spat collection on artificial substrates for the scallops *Patinopecten caurinus* (Gould) and *Hinnites multirugosus* (Gale) in Washington State. Journal of Shellfish Research **5**: 52-53.

Graziano, C. (1988). Some observations on the plankton of the North Irish Sea. Ph.D. thesis, University of Liverpool.

Gruffydd, L. D. (1972). Mortality of scallops on a Manx bed due to fishing. Journal of the Marine Biological Association of the United Kingdom **52**: 449-455.

Gruffydd, L. D. (1974). An estimate of natural mortality in an unfished population of the scallop *Pecten maximus* (L.). Journal du Conseil International pour l'Exploration de la Mer **35**: 209-210.

Gruffydd, L. D. (1976). Swimming in *Chlamys islandica* in relation to current speed and an investigation of hydrodynamic lift in this and other scallops. Norwegian Journal of Zoology **24**: 365-378.

Gruffydd, L. D. and A. R. Beaumont (1972). A method of rearing *Pecten maximus* larvae in the laboratory. Marine Biology **15**: 350-355.

Gulland (1983). Fish stock assessment. A manual of basic methods. John Wiley & Sons, Chichester, UK. 223pp.

Gutsell, J. S. (1930). Natural history of the bay scallop. United States Bureau of Fisheries Bulletin **46**: 569-632.

Gwyther, D., D. A. Cropp, L. M. Joll and M. C. L. Dredge (1991). Australia. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 835-851.

Hancock, D. A. (1974). Some aspects of the biology of the sunstar *Crossaster papposus* (L.). Ophelia **13**: 1-30.

Hardy, D. (1991). Scallop Farming. Fishing News Books, Oxford. 237pp.

Hartnoll, R. G. (1967). An investigation of the movement of the scallop *Pecten maximus*. Heligoländer Wissenschaftliche Merresuntersuchungen **15**: 523-533.

Hartnoll, R. G. and S. J. Hawkins (1985). Patchiness and fluctuations on a moderately exposed rocky shore. Ophelia **24**: 53-63.

Harvey, M., E. Bourget and G. Miron (1993). Settlement of Iceland scallop *Chlamys islandica* spat in response to hydroids and filamentous red algae: Field observations and laboratory experiments. Marine Ecology Progress Series **99**: 283-292.

Hawkins, S. J. and R. G. Hartnoll (1982). Settlement patterns of *Semibalanus balanoides* (L.) on the Isle of Man (1977-1981). Journal of Experimental Marine Biology and Ecology **62**: 271-283.

Hawkins, S. J. and R. G. Hartnoll (1983). Grazing of intertidal algae by marine invertebrates. Oceanography and Marine Biology Annual Review **21**: 195-282.

Heffernan, P. B., R. L. Walker and D. M. Gillespie (1988). Biological feasibility of growing the northen bay scallop, *Argopecten irradians irradians* (Lamarck, 1819), in coastal waters of Georgia. Journal of Shellfish Research **7**: 83-88.

Heincke, F. (1913). Investigations on the Plaice. I. Plaice fishing and protection measures. Rapport et Procès-Verbaux des Rèunions. Conseil International pour l'Exploration de la mer **16**: 1-67.

Herdman, W. A. (1886). The fauna of the south end of the Isle of Man. *In*: The fauna of Liverpool Bay and the neighbouring seas. W. A. Herdman (ed.). Longmans, Green & Co., London. p 318-341.

Herdman, W. A. (1895). 7th annual report of the Liverpool Marine Biological Station, Port Erin. Liverpool Marine Biology Committee Reports **4**: 162-215.

Hill, A. E. (1991a). A mechanism for horizontal zooplankton transport by vertical migration in tidal currents. Marine Biology **111**: 485-492.

Hill, A. E. (1991b). Vertical migration in tidal currents. Marine Ecology Progress Series **75**: 39-54.

Hodgson, C. A. and N. Bourne (1988). Effect of temperature on larval development of the spiny scallop, Chlamys hastata Sowerby, with a note on metamorphosis. Journal of Shellfish Research **7**: 349-357.

Holme, N. A. and A. D. McIntyre, Ed. (1984). Methods for the study of marine benthos. IBP Handbook 16. Oxford, Blackwell Scientific Publications. 387pp.

Hortle, M. (1983). TFDA scallop project opens up alternatives. Australian Fisheries **42**: 34-37.

Hortle, M. E. and D. A. Cropp (1987). Settlement of commercial scallops, *Pecten fumatus* (Reeve) 1855, on artificial collectors in eastern Tasmania. Aquaculture **66**: 79-95.

Howell, T. R. W. (1983). A comparison of the efficiency of two types of Scottish commercial scallop dredge. International Council for the Exploration of the Sea CM-1983/K:38. 3pp.

Howell, T. R. W. and D. I. Fraser (1984). Observations on the dispersal and mortality of the scallop, *Pecten maximus* (L.). ICES ICES CM1984/K:35.

Hughes, R. N. (1980). Optimal foraging in the marine environment. Oceanography and Marine Biology Annual Review **18**: 423-481.

Hughes, R. N. and R. Seed (1981). Size selection of mussels by the blue crab *Callinectes sapidus* : energy maximizer or time minimizer? Marine Ecology Progress Series **6**: 83-89.

Imai, T. (1980). Aquaculture in shallow seas. A. A. Balkena, Rotterdam. 615pp.

Iribarne, O. O., M. I. Lasta, H. C. Vacas, A. M. Parma and M. S. Pascual (1991). Assessment of abundance, gear efficiency and disturbance in a scallop dredge fishery: results of a depletion experiment. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 242-248.

Ito, H. (1988). Sowing culture of scallop in Japan. NOAA NMFS 70: 63-69.

Ito, H. (1991). Japan. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 1017-1055.

Ito, H. (1992). Mass production methods for industrializing scallop culture. Journal of Shellfish Research **11**: 198.

Ito, S. and A. Byakuno (1988). The history of scallop culture techniques in Japan. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 166-181.

Jangoux, M. (1982). Food and feeding mechanisms: asteroidea. *In*: Echinoderm nutrition. M. Jangoux and J. M. Lawrence (ed.). A.A. Balkena, Rotterdam. p 117-158.

Jian-Guang, F. (1993). Artificial seed production and culture of scallops in Sungo Bay. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Jost, P. (1980). Reaction of two seastar species to an artificial prey patch. *In*: Echinoderms: present and past. M. Jangoux (ed.). A.A. Balkena, Rotterdam. p 197.

Jubb, C. A., R. N. Hughes and T. Ap Rheinault (1983). Behavioural mechanisms of size-selection by crabs, *Carcinus maenas* (L.), feeding on mussels, *Mytilus edulis* (L.). Journal of Experimental Marine Biology and Ecology **66**: 81-87.

Kalashnikov, V. Z. (1985). Dynamics of population density of the Japanese scallop culture on the bottom of Posiet Bay, Sea of Japan. Marine Biology, Vladivostok **5**: 58-63.

Kalashnikov, V. Z. (1991). Soviet Union. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 1057-1082.

Kassner, J. and R. E. Malouf (1982). An evaluation of "Spawner transplants" as a management tool in Long Island's hard clam fishery. Journal Shellfish Research **2**: 165-172.

Kirby-Smith, W. W. (1972). Growth of the bay scallop: the influence of experimental water currents. Journal of Experimental Marine Biology and Ecology **8**: 7-18.

Kirby-Smith, W. W. and R. T. Barber (1974). Suspension-feeding aquculture systems: effects of phytoplankton concentration and temperature on growth of the bay scallop. Aquaculture **3**: 135-145.

Krebs, J. R. (1978). Optimal foraging. *In*: Behavioural ecology. J. R. Krebs and N. B. Davies (ed.). Blackwell Scientific, London. p 23-63.

Lake, N. C. H. (1993). Crab and starfish predation of the scallop *Pecten maximus* (L.) during seabed cultivation. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Lake, N. C. H., M. B. Jones and J. D. Paul (1987). Crab predation on scallop (*Pecten maximus*) and its implications for scallop cultivation. Journal of the Marine Biological Association of the United Kingdom **67**: 55-64.

Lake, N. C. H. and J. T. MacMillan (1991). Potential for seabed cultivation of the King scallop *Pecten maximus* in the United Kingdom. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

Lane, D. J. W., A. R. Beaumont and J. R. Hunter (1985). Byssus drifting and the drifting threads of young post-larval mussel *Mytilus edulis* (L.). Marine Biology **84**: 302-308.

Lapointe, V. and B. Sainte-Marie (1992). Currents, predators, and the aggregation of the gastropod *Buccinum undatum* around bait. Marine Ecology Progress Series **85**: 245-257.

Lebour, M. V. (1928). Larval stages of the Plymouth Brachyura. Proceedings of the Zoological Society of London 473-560.

Legault, C., M. Harvey and E. Bourget (1993). Potential use of the hydroid, *Tubularia larynx*, for collecting larvae of the giant scallop, *Placopecten magellanicus*. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Levitan, D. R. (1991). Influence of body size and population density on fertilization success and reproductive output in a free-spawning invertebrate. Biological Bulletin **181**: 261-268.

Levitan, D. R., M. A. Sewell and F.-S. Chia (1991). Kinetics of fertilization in the sea urchin *Strongylocentrotus franciscanus*: interaction of gamete dilution, age, and contact time. Biological Bulletin **181**: 371-378.

Levitan, D. R., M. A. Sewell and F. S. Chia (1992). How distribution and abundance influence fertilization success in the sea urchin Strongylocentrotus franciscanus. Ecology **73**: 248-254.

Lewis, R. I. (1992). Population genetics of the Queen scallop, *Chlamys opercularis* (L.). Ph.D. thesis, Liverpool. 245pp.

Loosanoff, V. L. (1964). Variations in time and intensity of setting of the starish, *Asterias forbesi*, in Long Island Sound during a twenty-five-year period. Biological Bulletin **126**: 423-439.

Loosanoff, V. L. and H. C. Davis (1963). Rearing of bivalve molluscs. Advances in Marine Biology **1**: 1-136.

Lou, Y. (1991). China. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 809-824.

Lyon-Dean, W. J., L. i. Bø, A. B. Bowers, J. H. Goodlad, R. H. Milne and M. J. Ball (1983). Report of the commission of enquiry into the fishing industry. Isle of Man Government 128pp.

MacDonald, B. A. and C. D. Bajdik (1992). Orientation and distribution of individual *Placopecten magellanicus* (Gmelin) in two natural populations with differing production. Canadian Journal of Fisheries and Aquatic Sciences **49**: 2086-2092.

MacDonald, D. S. (1993). Ecological studies on the effects of scallop dredging on the benthos of the North Irish Sea. Ph.D. thesis, Liverpool. 224pp.

Mackie, A. M. (1975). Chemoeception. *In*: Biochemical and biophysical perspectives in marine biology. D. C. Malins and J. R. Sargent (ed.). Academic Press, New York. p 69-105.

Macleod, J. A. A., J. P. Thorpe and N. A. Duggan (1985). A biochemical study of population structure in queen scallop (*Chlamys opercularis*) stocks in the North Irish Sea. Marine Biology **87**: 77-82.

Mallet, A. L. and C. E. A. Carver (1991). An assessment of strategies for growing mussels in suspended culture. Journal of Shellfish Research **10**: 471-477.

Mann, R. and R. E. J. Taylor (1981). Growth of the bay scallop *Argopecten irradians*, in a waste recycling aquaculture system. Aquaculture **24**: 45-52.

Manuel, J. L. and M. J. Dadswell (1991). Swimming bahaviour of juvenile giant scallop. *Placopecten magellanicus*, in relation to size and temperature. Canadian Journal of Zoology **69**: 2250-2254.

Mason, J. (1953). Investigations on the scallop, *Pecten maximus* (L.), in Manx waters. Ph.D. thesis, University of Liverpool.

Mason, J. (1957). The age and growth of the scallop, *Pecten maximus* (L.), in Manx waters. Journal of the Marine Biological Association of the United Kingdom **36**: 473-492.

Mason, J. (1969). The growth of spat of *Pecten maximus* (L.). International Council for the Exploration of the Sea C M CM 1969/K:.32.

Mason, J. (1970). A comparison of various gears used in catching queens and scallops in Scottish waters. International Council for the Exploration of the Sea CM1970/K:19. 3pp.

Mason, J. (1983). Scallop and Queen fisheries in the British Isles. Fishing News Books, Farnham. 144pp.

Mason, J., C. J. Chapman and J. A. M. Kinnear (1979). Population abundance and dredge efficiency studies on the scallop, *Pecten maximus* (L.). Rapport et Procès-Verbaux des Réunions. Conseil International pour l'Exploration de la mer **175**: 91-96.

Mason, J. and J. S. Colman (1955). Note on a short-term marking experiment on the scallop *Pecten maximus* (L.) in the Isle of Man. Annual Report of the Marine Biological Station, Port Erin **67**: 34-35.

Mason, J., R. M. Cook, N. Bailey and D. I. Fraser (1991). An assessment of scallops, *Pecten maximus* (Linnaeus 1758), in Scotland west of Kintyre. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 231-241.

Mason, J., J. Drinkwater, T. R. W. Howell and D. I. Fraser (1982). A comparison of methods for determining the distribution of the scallop, *Pecten maximus* (L.). International Council for the Exploration of the Sea 1982/K:24:5.

Mason, J., A. M. Shanks and D. I. Fraser (1980). An assessment of scallop, *Pecten maximus* (L.), stocks off south-west Scotland. International Council for the Exploration of the Sea ICES CM 1980/K:27. 4pp.

McClintock, J. B. and T. J. Robnett (1986). Size selective predation by the asteroid *Pisaster ochraceus* on the bivalve *Mytilus californianus* - a cost benefit analysis. Marine Ecology - Publicazioni della Stazione Zoologica di Napoli I **7**: 321-322.

McHugh, J. L. (1981). Recent advances in hard clam mariculture. Journal of Shellfish Research **1**: 51-55.

McLoughlin, R. J., P. C. Young, R. B. Martin and J. Parslow (1991). The Australian scallop dredge: estimates of catching efficiency and associated indirect mortality. Fisheries Research **11**: 1-24.

Medcof, J. C. and N. Bourne (1964). Causes of mortality of the sea scallop, *Placopecten magellanicus*. Proceedings of the National Shellfisheries Association **53**: 33-50.

Medcof, J. C. and J. F. Caddy (1971). Underwater observations on performance of clam dredges of three types. International Council for the Exploration of the Sea, Gear and behaviour committee ICES CM 1971/B. 10pp.

Miller, H. J. (1988). Settlement of scallop spat on artificial collectors in Desolation Sound, British Columbia. Aquaculture International Congress and Exposition, Vancouver, B.C. (Canada), 6-9 Sep 1988. pp 65.

Millican, P. F. (1993). Initial studies in the hatchery culture of king scallop (*Pecten maximus*). 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Minchin, D. (1976). Spawning and rearing of *Pecten maximus* at Lough Hyne (Ine). Proceedings of the 1st Scallop Workshop, Baltimore, Ireland, (mimeo).

Minchin, D. (1980). Room for the Scallop. Fish Farmer. **3**: 18-21.

Minchin, D. (1983a). The escallop, *Pecten maximus* in Mulroy Bay - Part 2. 4th International Pectinid Workshop, Aberdeen, Scotland, (mimeo).

Minchin, D. (1983b). Predation on young *Pecten maximus* (L.) (Bivalvia), by the anemone *Anthopleura ballii* (Cocks). Journal of Molluscan Studies **49**: 228-321.

Minchin, D. (1984). Aspects of the biology of young escallops *Pecten maximus* (Linnaeus) (Pectinidae: Bivalvia) about the Irish coast. Ph D thesis thesis, Trinity College, University of Dublin.

Minchin, D. (1991). Decapod predation and the sowing of the scallop *Pecten maximus* (Linnaeus 1758). *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 191-197.

Minchin, D. (1992). Biological observations on young scallops, *Pecten maximus.* Journal of the Marine Biological Association of the U.K. **72**: 807-819.

Minchin, D. and N. F. Mathers (1982). The escallop, *Pecten maximus* (L.), in Killary Harbour. Irish Fishery Investigations Series B 25: 13pp.

Minchin, D. and C. Ni Donnachada (1991). Optimising scallop sowings for the restocking of an adult population in Mulroy Bay, Ireland. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (mimeo).

Moore, J. D. and E. R. Trueman (1971). Swimming of the scallop, *Chlamys opercularis*,(L.). Journal of Experimental Marine Biology and Ecology **6**: 179-185.

Moore, J. K. and N. Marshall (1967). An analysis of the movements of the bay scallop *Argopecten irradians* in a shallow estuary. Proceedings of the National Shellfisheries Association **57**: 77-82.

Morgan, D. E., J. Goodsell, G. C. Mathiessen, J. Garey and P. Jacobson (1980). Release of hatchery reared bay scallops (*Argopecten irradians*) onto a shallow coastal bottom in Waterford, Connecticut. Proceedings of the World Mariculture Society **11**: 247-261.

Morrison, D. F. (1976). Multivariate analysis. McGraw-Hill Book Company, New York.

Morton, B. (1980). Swimming in *Amusium pleuronectes* (Bivalvia: Pectinidae). **190**: 375-404.

Motoda, S. (1977). Biology and artificial propagation of Japanese scallop (General review). 2nd Soviet-Japan Joint Symp. Aquaculture November 1973, Moscow,.

Murphy, E. J. (1986). An investigation of the population dynamics of the exploited scallop, *Pecten maximus* (L.), in the North Irish Sea. Ph.D. thesis, University of Liverpool. 155pp.

Murphy, E. J. and A. R. Brand (1987). Yield per recruit analysis for North Irish Sea scallop (*Pecten maximus* (L.)) populations. 6th International Pectinid Workshop, Menai Bridge, Wales, 9th-14th April, 1987. 12pp. (mimeo).

Naidu, K. S. (1988). Estimating mortality rates in the Iceland scallop *Chlamys islandica* (O.F. Müller). Journal of Shellfish Research **7**: 61-71.

Naidu, K. S. (1991). Sea scallop, *Placopecten magellanicus. In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 861-897.

Naidu, K. S. and R. Scaplen (1976). Settlement and survival of the giant scallop, *Placopecten magellanicus*, larvae on enclosed polythene film collectors. F.A.O. Technical Conference on Aquaculture1976.

Neville, P. (1988). Forum - Costs and benefits of hatchery reared and wild caught spat for grow out and fisheries enhancement. Proceedings of the Australasian Scallop Workshop, Hobart, Australia, M.C. Reed. pp 272-290.

O'Foighil, D., B. Kingzett, G. O'Foighil and N. Bourne (1990). Growth and survival of juvenile Japanese scallops, *Patinopecten yessoensis* , in nursery culture. Journal of Shellfish Research **9**: 135-144.

Ordzie, C. J. and G. C. Garofalo (1980a). Behavioural recognition of molluscan and echinoderm predators by the bay scallop, *Argopecten irradians* (Lamark), at two temperatures. Journal of Experimental Marine Biology and Ecology **43**: 29-37.

Ordzie, C. J. and G. C. Garofalo (1980b). Predation, attack success and attraction to the bay scallop, *Argopecten irradians* (Lamark), by the oyster drill, *Urosalpinx cinerea* (Say). Journal of Experimental Marine Biology and Ecology **47**: 95-100.

Orensanz, J. M. (1986). Size, environment and density: the regulation of a scallops stock and its management implications. Canadian Special Publication Fisheries and Aquatic Sciences **92**: 192-227.

Orensanz, J. M., A. M. Parma and O. O. Iribarne (1991). Population dynamics and management of natural stocks. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 625-713.

Ormond, R. F. G., A. C. Campbell, S. M. Head, R. J. Moore, P. R. Rainbow and A. P. Saunders (1973). The formation and breakdown of aggregations of the crown-of-thorns starfish, *Acanthaster planci.* Nature **246**: 167-169.

Paine, R. T. (1976). Size limited predation: an observational and experimental approach with the *Mytilus-Pisaster* interaction. Ecology **57**: 858-873.

Parsons, G. J. and M. J. Dadswell (1991a). Swimming bahaviour of the giant scallop, *Placopecten magellanicus.* 8th International Pectinid Workshop, Cherbourg, France, (Abstract).

Parsons, G. J. and M. J. Dadswell (1991b). Effect of stocking density of growth, production and survival of the giant scallop, *Placopecten magellanicus*, held in intermediate suspension culture in Passamaquoddy Bay, New Brunswick, Canada. 8th International Pectinid Workshop, Cherbourg, France, (Abstract).

Parsons, G. J. and M. J. Dadswell (1992). Effect of stocking density on growth, production, and survival of the giant scallop, *Placopecten magellanicus*, held in intermediate suspension culture in Passamaquoddy Bay, New Brunswick. Aquaculture **103**: 291-309.

Parsons, G. J., J. C. Roff and M. J. Dadswell (1989). Influence of environmental factors on the maximization of spat settlement in the giant scallop, *Placopecten magellanicus*. Journal of Shellfish Research **8**: 458.

Parsons, J., M. J. Dadswell and J. C. Roff (1993). Influence of biofilm on settlement of sea scallop, *Placopecten magellanicus* (Gmelin, 1791) in Passamaquoddy Bay, New Brunswick, Canada. Journal of Shellfish Research **12**: 279-283.

Paul, J. D. (1978). The biology of the Queen scallop, *Chlamys opercularis* (L.) in relation to its prospective cultivation. Ph.D. thesis, University of Liverpool.

Paul, J. D. (1981). Natural settlement and early growth of spat of the Queen scallop *Chlamys opercularis* (L.) with reference to the formation of the first growth ring. Journal of Molluscan Studies **47**: 53-58.

Paul, J. D. (1985a). Scallop spat collection 1984, with comparisons of methods of spat sorting. S.F.I.A. Technical Report 277.

Paul, J. D. (1985b). Scallop cultivation: a simple method of separating spat of *Pecten maximus* (L.) and *Chlamys opercularis* (L.) by means of behavioural differences. Aquaculture **50**: 161-167.

Paul, J. D. (1987). An introductory guide to cultivation of the Queen scallop (*Chlamys opercularis*). S.F.I.A. Technical Report 297.

Paul, J. D. (1988). Cultivation of the scallop, *Pecten maximus*, using the technique of ear hanging. S.F.I.A. M.A.F.F. Commission Technical Report 326.

Paul, J. D., A. R. Brand and J. N. Hoogesteger (1981). Experimental cultivation of the scallops *Chlamys opercularis* (L.) and *Pecten maximus* (L.) using naturally produced spat. Aquaculture **24**: 31-44.

Paul, J. D., N. C. H. Lake and M. B. Jones (1986). Scallop predation by crabs, in relation to the development of on-bottom cultivation. Sea Fish Industry Authority Technical Report 289.

Pearson, J. (1908). *Cancer* (the edible crab). Memoirs of the Liverpool Marine Biological Committee, 263pp.

Pearson, W. H., P. C. Sugarman, D. L. Woodruff and B. L. Woodruff (1979). Thresholds for detection of feeding behaviour in the Dungeness crab, *Cancer magister*. Journal of Experimental Marine Biology and Ecology **39**: 65-78.

Penney, A. J. and C. L. Griffiths (1984). Prey selection and the impact of the starfish *Marthasterias glacialis* (L.) and other predators on the mussel *Choromytilus meridionalis* (Krauss). Journal of Experimental Marine Biology and Ecology **75**: 19-36.

Pennington, J. T. (1985). The ecology of fertilization of echinoid eggs: the consequences of sperm dilution, adult aggregation, and synchronous spawning. Biological Bulletin **169**: 417-430.

Peterson, C. H., J. Ambrose, W.G. and J. H. Hunt (1982). A field test of the swimming response of the bay scallop (*Argopecten irradians*) to changing biological factors. Bulletin of Marine Science **32**: 939-944.

Phleger, C. F. and S. C. Cary (1983). Settlement of spat of the purple-hinge rock scallop *Hinnites multirugosus* (Gale) on artificial collectors. Journal of Shellfish Research **3**: 71-73.

Pickett, G. A. and A. Franklin (1975). The growth of Queen scallops (*Chlamys opercularis*) in cages off Plymouth, South-West England. International Council for the Exploration of the Sea Papers and reports K:25. 4pp.

Pickett, G. D. (1980). The settlement of young scallops *Pecten maximus* and queens, *Chlamys opercularis*, on artificial substrates and their subsequent growth and mortality in captivity. 3rd International Pectinid Workshop, Port Erin, Isle of Man, 16pp. (mimeo).

Pitcher, C. R. and A. J. Butler (1987). Predation by asteroids, escape response and morphometrics of scallops with epizoic sponges. Journal of Experimental Marine Biology and Ecology **112**: 233-249.

Posgay, J. A. (1981). Movements of tagged scallops on St.Georges Bank. Marine Fisheries Review **43**: 19-25.

Pyke, G. H., H. R. Pulliam and E. L. Charnov (1977). Optimal foraging theory: a selective review of theory and tests. Quarterly Review of Biology **52**: 137-154.

Quéllerou, J. (1975). Exploitation des coquilles Saint-Jacques, *Patinopecten yessoensis* Jay, au Japon. Milieux, méthodes, résultats, organisation de la production. Publ. Assoc. Dev. Aquicult. 75. 82pp.

Ramster, J. W. and H. W. Hill (1969). Current systems in the northern Irish Sea. Nature **224**: 59-61.

Rees, H. L. (1993). Analysis and interpretation of benthic community data at sewage sludge disposal sites. MAFF Benthos Task Team 37.

Rhodes, E. W. (1991). Fisheries and aquaculture of the Bay Scallop, *Argopecten irradians*, in the eastern United States. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 913-923.

Richardson, C. A., A. C. Taylor and T. J. Venn (1982). Growth of the queen scallop *Chlamys opercularis* in suspended cages in the Firth of Clyde. Journal of the Marine Biological Association of the United Kingdom **62**: 157-169.

Ricker, W. E. (1968). Methods for assessment of fish production in fresh waters. I.B.P. Handbook No. 3. Blackwell Scientific Publiations, Oxford. 348pp.

Ricker, W. E. (1975). Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada **191**: 382 pp.

Robinson, S. M. C., J. D. Martin, R. A. Chandler and G. J. Parsons (1991). Spatial patterns of spat settlement in the sea scallop, Placopecten magellanicus , compared to hydrographic conditions in Passamaquoddy Bay, New Brunswick, Canada. Journal of Shellfish Research **10**: 272-273.

Robinson, S. M. C., J. D. Martin, R. A. Chandler, G. J. Parsons and C. Y. Couturier (1993). Larval settlement patterns of the giant scallop (*Placopecten magellanicus*) in Passamaquoddy Bay, New Brunswick. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Rolfe, M. S. (1969). The determination of the abundance of scallops and of the efficiency of the Baird escallop dredge. ICES CM 1969/K:22. 5pp.

Roman, G. and J. Cano (1987). Pectinid settlement on collectors in Malaga, S.E. Spain, in 1985. 6th International Pectinid Workshop, Menai Bridge, Wales, UK, (Abstract).

Ruiz-Verdugo, C. A. and C. Caceres-Martinez (1991). Experimental spat collection of scallops, *Argopecten circularis* (Sowerby, 1835) auct. and *Argopecten vogdesi* (Arnold 1906) on a filament substrate in Falsa Bay, B.C.S. Mexico. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 21-27.

Ruzzante, D. E. and H. E. Zaixso (1985). Settlement of *Chlamys tehuelchus* (D'Orb.) on artifical collectors. Seasonal changes in spat settlement. MAR. ECOL. (PROG. SER.). **26**: 195-197.

Ryland, J. S. and J. D. D. Bishop (1993). Internal fertilisation in hermaphroditic colonial invertebrates. Oceanography and Marine Biology Annual Review **31**: 455-477.

Sause, B. L., D. Gwyther and D. Burgess (1987). Larval settlement, juvenile growth and the potential use of spatfall indices to predict recruitment of the scallop *Pecten alba* Tate in Port Phillip Bay, Victoria, Australia. Fisheries Research **6**: 81-92.

Scheibling, R. E. (1980). Dynamics and feeding activity of high density aggregations of *Oreaster reticulatus* (L.) (Echinodermata: Asteroidea) in a sand patch habitat. Marine Ecology Progress Series **2**: 321-327.

Scheibling, R. E. (1981). Optimal foraging movementsof *Oreaster reticulatus* (L.) (Echinodermata: Asteroidea). **51**: 173-185.

Scheibling, R. E. (1993). Movement and mortality of juvenile scallops released in bottom culture trials. 9th International Pectinid Workshop, Naniamo, Canada, 22nd-27th April, 1993. (Abstract).

Scheibling, R. E., M. A. Barbeau, B. G. Hatcher and L. Taylor (1991). Mortality and dispersion of juvenile sea scallops *Placopecten magellanicus*) in a tidal channel. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

Shapiro, S. S. and M. B. Wilk (1965). An analysis of variance test for normality (complete samples). Biometrika **52**: 591.

Shepard, A. N. and P. J. Auster (1991). Incidental (non-capture) damage to scallops caused by dragging on rock and sand substrates. *In*: An international compendium of scallop biology and culture. S. E. Shumway and P. A. Sandifer (ed.). World Aquaculture Society, Baton Rouge. p 219-230.

Shumway, S. E., Ed. (1991). Scallops: biology, ecology and aquaculture. Developments in Aquaculture and Fisheries Science. Amsterdam, Elsevier. 1095pp.

Sih, A. (1984). Optimal behaviour and density-dependent predation. American Naturalist **123**: 314-326.

Sinclair, M., R. K. Mohn, G. Robert and D. L. Roddick (1985). Considerations for the effective management of Atlantic scallops. Canadian Technical Report in Fisheries and Aquatic Sciences 1382. 113pp.

Slater, J. (1977). Collection of naturally released scallop spat 1977. White Fish Authority Field Report 536.

Slater, J. (1987). Is there money in scallops? Aquaculture Ireland **March/April**: 16-19.

Sloan, N. A. (1980). Aspects of the feeding biology of Asteroids. Oceanography and Marine Biology Annual Review **18**: 57-124.

Sloan, N. A. (1984). Interference and aggregation - close encounters of the starfish kind. Ophelia **23**: 23-31.

Sloan, N. A. and T. M. Aldridge (1981). Observations on an aggregation of the starfish *Asterias rubens* L. in Morecambe Bay, Lancashire, England. Journal of Natural History **15**: 407-418.

Sloan, N. A. and A. C. Campbell (1982). Perception of food. *In*: Echinoderm nutrition. M. Jangoux and J. M. Lawrence (ed.). A.A. Balkena, Rotterdam. p 3-23.

Smith, G. F. M. (1940). Factors limiting distribution and size in the starfish. Journal of the Fisheries Research Board of Canada **5**: 84-103.

Smith, W. C. (1938). Report on the Manx sea fisheries 1935-37. 23pp.

Soemodihardjo, S. (1974). Aspects of the biolgy of *Chlamys opercularis* (L.) (Bivalvia) with comparative notes on four allied species. Ph.D. thesis, Liverpool.

Sokal, R. R. and F. J. Rohlf (1981). Biometry. W.H. Freeman and Company, San Francisco. 859pp.

Stokesbury, K. D. E. and J. H. Himmelman (1993a). Spatial distribution of the giant scallop *Placopecten magellanicus* in unharvested beds in the Baie des Chaleurs, Québec. Marine Ecology Progress Series **96**: 159-168.

Stokesbury, K. D. E. and J. H. Himmelman (1993b). Spatial distribution of the giant scallop *Placopecten magellanicus* in unfished beds in the Baie des Chaleurs, Québec. 9th International Pectinid Workshop, Naniamo, Canada, (Abstract).

Sumpton, W. D., I. W. Brown and M. C. L. Dredge (1990). Settlement of bivalve spat on artificial collectors in a subtropical embayment in Queensland, Australia. Journal of Shellfish Research **9**: 227-231.

Tettelbach, S. T. (1986). Dynamics of crustacean predation on the northern Bay Scallop, *Argopecten iradians irradians*. Ph.D. thesis, University of Conecticut.

Tettelbach, S. T. and S. Y. Feng (1986). Intensity of predation on northern Bay Scallops *Argopecten irradians irradians*: effects of prey size and predator assemblages on seasonal patterns. Journal of Shellfish Research

Thomas, G. E. (1969). The responses of *Pecten maximus* (L.) to various starfish species. M.Sc. thesis, University of Wales.

Thomas, G. E. and L. D. Gruffydd (1971). The types of escape reactions elicited in the scallop *Pecten maximus* by selected sea star species. Marine Biology **10**: 87-93.

Thouzeau, G., G. Robert and S. J. Smith (1991). Spatial variability in distribution and growth of juvenile and adult sea scallops *Placopecten magellanicus* (Gmelin) on eastern Georges Bank (Northwest Atlantic). Marine Ecology Progress Series **74**: 205-218.

Townsend, L. and N. Bourne (1989). Improved methods of handling juvenile scallops in an intensive culture operation. Journal of Shellfish Research **8**: 16.

Tritar, S., D. Prieur and R. Weiner (1992). Effects of bacterial films on the settlement of the oysters, *Crassostrea gigas* (Thunberg, 1793) and *Ostrea edulis* (Linnaeus, 1750) and the scallop *Pecten maximus* (Linnaeus, 1758). Journal of Shellfish Research **11**: 325-330.

Vahl, O. and B. Clausen (1980). Frequency of swimming and energy cost of byssus production in *Chlamys islandica* (O.F. Müller). **39**: 101-103.

Valentincic, T. (1973). Food finding and stimuli to feeding in the sea star *Marthasterias glacialis*. Netherlands Journal of Sea Research **7**: 191-199.

Valentincic, T. (1985). Behavioral study of chemoreception in the sea star *Marthasterias glacialis*: Structure-activity relationships of lactic acid, amino acids, and acetylcholine. Journal of Comparative Physiology A **157**: 537-545.

Ventilla, R. F. (1977a). A preliminary investigation of the growth of potential of the collected scallop spat. White Fish Authority Field Report 502.

Ventilla, R. F. (1977b). Preliminary investigations into the spat collection, nursery maintenance and on-growing of the scallops *Pecten maximus* and *Chlamys opercularis.* 8th conference of the Shellfish Association of Great Britain, Fishmongers' Hall, London, 12-16.

Ventilla, R. F. (1977c). A scallop spat collector trial off the Northern Ardnamurchan coast. White Fish Authority Field Report 485.

Ventilla, R. F. (1977d). Further investigations into the collection of natural scallop spat off the Ardnamuchan coast. White Fish Authority Field Report 536.

Ventilla, R. F. (1977e). Overwinter growth of Pecten maximus in a nursery. White Fish Authority Technical Report 152.

Ventilla, R. F. (1981). An outline of the application of Japanese scallop culture techniques in Scotland and a review of recent W.F.A. scallop culture research. White Fish Authority Field Report 937.

Ventilla, R. F. (1982). The scallop industry in Japan. Advances in Marine Biology **20**: 309-382.

Ventilla, R. F. and e. al (1980). A study to forecast the costs of farming scallops (*Pecten maximus*) and queens (*Chlamys opercularis*) (1980 prices). White Fish Authority Technical report 181.

Volkov, Y. P., A. A. Dadaev, V. S. Levin and A. M. Murakhveri (1982). Changes in the distribution of Yezo scallops and starfishes after mass plantings of scallops at the bottom of Vityaz Bay (Sea of Japan). Soviet Journal of Marine Biology **8**: 216-223.

Wallace, J. C. and T. G. Reinsnes (1984). Growth variation with age and water depth in the Iceland scallop (*Chlamys islandica*, Pectinidae). Aquaculture **41**: 141-146.

Wallace, J. C. and T. G. Reinsnes (1985). The significance of various environmental parameters for growth of the Iceland scallop, *Chlamys islandica* (Pectinidae), in hanging culture. Aquaculture **44**: 229-242.

Warner, G. F. (1979). Aggregation in echinoderms. *In*: Biology and systematics of colonial organisms. G. Larwood and B. R. Rosen (ed.). Academic Press, London. p 375-396.

Warwick, R. M. and K. R. Clarke (1991). A comparison of some methods for analysing changes in benthic community structure. Journal of the Marine Biological Association of the U.K. **71**: 225-244.

Whittington, M. W. (1993). Scallop aquaculture in Manx waters: spat collection and the role of predation in seabed cultivation. Ph.D. thesis, University of Liverpool. 203pp.

Widman, J. C. and E. W. Rhodes (1991). Nursery culture of the bay scallop, *Argopecten irradians irradians*, in suspended mesh nets. Aquaculture **99**: 257-267.

Wieland, T. and J. D. Paul (1983). Potential for scallop culture in the U.K. Sea Fish Industry Authority Technical Report 224.

Wildish, D. J. and D. D. Kristmanson (1979). Tidal energy and sublittoral macrobenthic animals in estuaries. Journal of the Fisheries Research Board of Canada **36**: 1197-1206.

Wildish, D. J. and D. D. Kristmanson (1984). Importance to mussels of the benthic boundary layer. Canadian Journal of Fisheries and Aquatic Sciences **41**: 1618-1625.

Wildish, D. J. and D. D. Kristmanson (1985). Control of suspension feeding bivalve production by current speed. Heligoländer Wissenschaftliche Merresuntersuchungen **39**: 237-243.

Wildish, D. J. and D. D. Kristmanson (1988). Estimating bivalve carrying capacity and potential production. Journal Shellfish Research **7**: 181.

Wildish, D. J., D. D. Kristmanson, R. L. Hoar, A. M. DeCoste, G. D. McCormick and A. W. White (1987). Giant scallop feeding and responses to flow. Journal of Experimental Marine Biology and Ecology **113**: 207-220.

Wildish, D. J., A. J. Wilson, W. Young Lai, A. M. DeCoste, D. E. Aiken and J. D. Martin (1988). Biological and economic feasibility of four grow-out methods for the culture of giant scallops in the Bay of Fundy. Biological Station, St.Andrews, New Brunswick Canadian Technical Report of Fisheries and Aquatic Sciences 1658.

Wilkens, L. A. (1991). Neurobiology and behaviour of the scallop. *In*: Scallops: biology, ecology and aquaculture. S. E. Shumway (ed.). Elsevier, Amsterdam. p 429-469.

Williamson, D. I. (1956). The plankton of the Irish Sea 1951 and 1952. Bulletin of Marine Ecology **4**: 87-144.

Wilson, J. H. (1987). Spawning of *Pecten maximus* (Pectinidae) and the artificial collection of juveniles in two bays in the West of Ireland. Aquaculture **61**: 99-111.

Winter, M. A. and P. V. Hamilton (1985). Factors influencing swimming in bay scallops, *Argopecten irradians* (Lamark, 1819). Journal of Experimental Marine Biology and Ecology **88**: 227-242.

Xu, H., B. Xu and W. Ji (1991). Component of bacteria and their effects on settlement of larvae of scallop. Journal of Fisheries China **15**: 117-123.

Young, P. C., R. B. Martin, R. J. McLoughlin and G. West (1989). Variability in spatfall and recruitment of commercial scallops (*Pecten fumatus*) in Bass Strait. Australasian Scallop Workshop; Taroona (Australia); Jul 1988, 80-91.

Young, P. C., R. J. McLoughlin and R. B. Martin (1992). Scallop (*Pecten fumatus*) settlement in Bass Strait, Australia. Journal of Shellfish Research **11**: 315-323.

Zar, J. H. (1984). Biostatistical analysis. Prentice-Hall International, New Jersey. 718pp.

Zhang, F. (1991). The rise of the Bay Scallop culture in China. 8th International Pectinid Workshop, Cherbourg, France, 22nd-29th May, 1991. (Abstract).

APPENDIX 1

SUMMARY OF RESEARCH VESSEL SURVEYS

8th - 17th June 1992
19th - 30th October 1992
1st - 11th June 1993

Research vessel survey, June 1992.

Site	Date	Tow	Poor Tows (T.d)	Start posn.	Finish posn.	Distanc	nm	Start	Finish	Duratio	Av.speed kt	Depth	Tides	Notes
Bradda	17/6/92	1	Offshore	E10.61/E42.5	E10.5/E47.5	3760	2.03	10:52	11:37	0:45	2.71	41	HW 1404/8.5m	3 miles W of other tows. Q:1/4 full D.Sh. Stones. S: clean.
		2		E6.2/E32.6	E2.5/E46.8	4100	2.21	12:05	13:00	0:55	2.42	34		As above, clean.
		3		E2.57/E46.4	E5.79/G33.2	3840	2.07	13:18	14:10	0:52	2.39			Few more stones
		4		E5.5/E32.0	E2.59/E45.9	3640	1.97	14:28	15:19	0:51	2.31			V. clean.
Chickens	16/6/92	1		E14.0/F47.0	E19.0/F45.6	3760	2.03	10:25	11:14	0:49	2.49		HW 1253/8.7m	Q: 3/4 full St. D.Sh. etc. S: 1/2 full stones and scallops.
		2		E18.3/F44.8	E15.0/F47.3	3730	2.01	11:40	12:27	0:47	2.57			Very clean.
		3		E15.7/F47.0	E14.36/F47.1	3920	2.12	12:52	13:47	0:55	2.31			Slack water. Q:1/3 full D.Sh. S: clean.
		4		E15.28/F45.9	E20.6/F44.9	3710	2.00	14:10	14:56	0:46	2.61			Clean. 3 kts at times.
Peel	12/6/92	1		D18.37/E32.1	D16.73/E33.7	3580	1.93	9:14	10:01	0:47	2.47	30	HW 0949/8.3m	Q: 1/2 full St+Sc. (slack springs) S:1/4 full stones.
		2		D19.2/E32.5	D19.3/E33.3	3860	2.08	10:23	11:12	0:49	2.55			Q: 1/2full stones and scallops. S:clean few stones.
		3		D18.8/E32.5	D18.2/E32.6	4120	2.22	11:33	12:24	0:51	2.62			As above.
		4		D18.3/E32.3	D18.6/E34.4	4130	2.23	12:42	13:31	0:49	2.73			Further S than 1,2 or 3. Similar bags.
SE Douglas		1												
		2												
		3												
		4												
E Douglas		1												
		2												
		3												
		4												
10'S PSM	8/6/92	1	D6 loose teeth	E2.45/H35.65	E4.0/H39.9	4080	2.20	11:05	11:51	0:46	2.87	53-70	HW 1706/8.1m	Q: D.Sh. few stones. Stars. V.few mussels. S: Clean.
		2	D6 loose teeth	E4.5/H39.7	E1.9/H35.8	4080	2.20	12:14	13:06	0:52	2.54	53-70		Q: 1/2 full. more stones. S: 1/4 full, stones and scallops.
		3		E1.6/H35.75	E3.4/H39.9	3440	1.86	13:31	14:19	0:48	2.32	62		Slowed at start. Q: 3/4 full, fine D.Sh. soft. S: St. & Scallops.
		4	short tow	E2.6/H39.04	E1.44/H35.5	2800	1.51	14:38	15:17	0:39	2.33	64		Short tow, dredges stuck fast. Came fasr, short tow, 1.5 miles. Stones and scallops, few que
20'S PSM	9/6/92	1		E0.9/I34.95	E3.67/I38.5	3800	2.05	10:34	11:25	0:51	2.41	61-62	HW 0632/8.3m	Very stoney.Bags 3/4 full, stones and scallops, large scallops.
		2	Tow void	E5.5/I38.6	E8.0/I39.0			11:47	12:24	0:37	0.00	56		Short tow, stuck fast on Modiolus bank. 1.25 miles, mussels and heart urchins.
		3		E8.26/I31.03	E4.09/I31.3	3700	2.00	13:00	13:45	0:45	2.66	57-62		1/2 bags D.Sh. Q.S. starfish.
		4		E3.68/I31.0	E3.4/I31.17	3880	2.10	14:09	14:57	0:48	2.62	67		2 mile circle east end. 1/2 bags D.Sh. Q+stars.
Targets	10/6/92	1		D0.6/D34.6	C18.5/D30.9	3840	2.07	10:42	11:28	0:46	2.70	30-31	HW 0741/8.2m	2.7 kts. 1/2full stones.
		2		C16.9/D30.3	C13.12/D31.2	3460	1.87	11:47	12:32	0:45	2.49	30-19		Loop. Full stones both sides.
		3		C14.79/D32.2	C21.1/D34.0	3800	2.05	12:53	13:44	0:51	2.41	16-26		Full D.Sh. + small stones.
		4		C13.6/D30.1	C19.8/D33.0	3700	2.00	14:26	15:15	0:49	2.45	28-30		Full D.Sh. + stones.
Pt of Ayre	11/6/92	1		A14.87/C30.1	A18.6/B46.2							44-60	HW 0848/8.2m	NE 3-4. Towing down tide, 3.5 kts. Q: 3/4 full D.Sh. small St. S:1/2 full st.+stars. (2 B Q.).
		2		A15.5/B46.8	A16.1/B44.3							35-50		Down tide 3 kts. Stones. Q: as above, more stones, less D.Sh. more Q.
		3												
		4												
Ramsey	15/6/92	1		B15.3/D43.87	B14.5/D38.5	3770	2.04	12:29	13:19	0:50	2.44		HW 1218/8.7m	Weed at N.end. Q:3/4 full D.Sh. St.Q. S:1/4 full, good mixture, stars etc.
		2		B14.3/D39.8	B16.7/D44.7	3560	1.92	13:42	14:27	0:45	2.56			As above. Start tow 1/2 way down box. Sign of limbs.
		3												
		4												
Maughold	15/6/92	1		B21.8/E35.5	B16.8/E3.0	3920	2.12	10:16	10:58	0:42	3.02		HW 1218/8.7m	Clean, few stones stars D.Sh.
		2		B16.0/E31.0	B16.0/E32.9	3840	2.07	11:15	12:03	0:48	2.59			Clean, more bulk than above. Few spider crabs. Circle, top of tow. (Scallops mostly smalls
		3												
		4												
Laxey	15/6/92	1		B22.5/E36.8	C6.22/E43.0								HW 1218/8.7m	1/2 full some limbs. travel down outside edge. Teeth off Q dredges.
		2												
		3												
		4												

Research vessel survey, October 1992.

Site	Date	Tow	Poor Tows (T.d)	Start posn.	Finish posn.	Distanc	nm	Start	Finish	Duratio	Av.speed kt	Depth	Tides	Notes
Bradda	26/10/92	1		E5.25/F32.4	E1.3/F46.4	3810	2.06	11:04	11:50	0:46	2.68	33	HW 1104/9.8m	Both sides 1/2 full, stones D.Sh. etc.
		2		E2.1/F46.4	E5.37/F32.8	3760	2.03	12:13	12:59	0:46	2.65	33		*Q:full St.. D.Sh. gravel. S: 1/2 full.*
		3		E4.9/F32.1	E1.2/F45.9	3800	2.05	13:20	14:06	0:46	2.68	33		1/2 full both sides.
		4	Offshore	E11.9/F46.5	E10.4/F41.6	3760	2.03	14:52	15:36	0:44	2.77	33		3'W of previous tows. 1/2 full both sides.
Chickens	21/10/92	1		E18.4/F45.6		3760	2.03	10:25	11:12	0:47	2.59	60	HW 0734/7.8m	Q: teeth bent back, 1/4 full stones etc. S:clean.
		2		E20.9/F44.4	E17.1/F45.4	3850	2.08	11:36	12:29	0:53	2.35	60		Q:1/2 *full. S:1/2 full, better bulk.*
		3		E20.5/F44.5	E15.5/F45.7	3710	2.00	13:11	13:57	0:46	2.61	60		Q:1/2 full, more D.Sh. S:1/2 full.
		4		E15.6/F45.7	E21.0/F44.5	4000	2.16	14:21	15:13	0:52	2.49	60		both sides 1/2 full, best tow, 220m wire, slack water.
Peel	19/10/92	1		D19.6/E33.8	D18.3/E32.7	3690	1.99	10:52	11:37	0:45	2.66	33	HW1617/7.8m	Q:short teeth, 3/4 full stones. S:1/4 full stones.
		2		D20.8/E33.2	D20.4/E32.5	3750	2.02	11:58	12:45	0:47	2.58	33		Q:full shell+stones. S:1/2 full.
		3		D21.0/E32.7	D21.0/E33.0	3760	2.03	13:05	13:53	0:48	2.54	33		Q:Full S:1/4 full.
		4		D21.3/E32.6	D20.9/E33.7	3810	2.06	14:17	15:07	0:50	2.47	33		Q:Full. S:1/4 full.
SE Douglas	29/10/92	1		D2.8/G45.5	C22.7/G46.8	3760	2.03	11:43	12:24	0:41	2.97	50-55	HW 1303/9.3m	med.springs. Both sides full stones, slacken springs.
		2		C22.0/G45.8	D2.25/G46.6	3680	1.99	13:01	13:44	0:43	2.77	50-55		both sides full stones.
		3		D1.5/G47.6	C21.4/G30.2	3800	2.05	14:10	14:59	0:49	2.51	42		both sides full stones, more Q than 2.
		4		C22.4/G46.5	D3.3/G30.2	3760	2.03	15:22	16:03	0:41	2.97	50-56		Less *stones more* D.Sh. + *stars. More Q less Sc. Level tow, Good*
E Douglas	28/10/92	1		C8.9/G30.67	C4.64/F47.5	3760	2.03	12:01	12:46	0:45	2.71	30	HW 1224/9.6m	medium springs. Q:1/2 full D.Sh. stars. bag of Q. S:clean, stars.
		2		C4.25/F46.9	C8.5/G30.2	3700	2.00	13:05	13:52	0:47	2.55	30		similar to 1.
		3		C8.9/G30.2	C4.6/G47.4	3680	1.99	14:09	14:55	0:46	2.59	30		similar tow.
		4												
10'S PSM	20/10/92	1		E1.55/H36.7	E3.9/H40.6	3860	2.08	10:57	11:45	0:48	2.61	57-72	HW 0608/7.6m	Q: 1/2 full D.Sh. Q. stones (box Q.). S:clean.
		2		E4.1/H40.0	E2.0/H36.0	3780	2.04	12:14	13:03	0:49	2.50	46-73		Q:1/2 full stones, less Queens. S: clean.
		3		E2.2/H36.3	E3.2/H41.1	4800	2.59	13:25	14:14	0:49	3.17	60-70		Similar to 1, 1.5 bags Q.
		4	poor tow	E2.95/H40.8	E1.5/H35.8	3900	2.11					60-70		clean, poor tow, 1/2 bag Q.
20'S PSM	30/10/92	1		*E3.0/I31.0*	E2.4/I30.5				12:14			60-68	HW *1425/8.4m*	*Q:1/3 full D.Sh. St. 1.5 bags Q. S: clean.*
		2		E2.0/I30.5	E6.0/31.0	3760	2.03	12:36	13:21	0:45	2.71	65-60		Q: v.clean, 2 blades bent, poor scallops. S:1/3 full.
		3		E4.15/I30.4	E4.5/I31.8	4060	2.19	13:44	14:36	0:52	2.53	67-65		springs tightened, better bags.
		4	D8 void	E3.6/I37.4	E0.83/I34.0	3800	2.05	15:06	15:52	0:46	2.68	71-62		2' SE of previous tows. Q: 3/4 full. S:full stones.
Targets		1												
		2												
		3												
		4												
Pt of Ayre		1												
		2												
		3												
		4												
Ramsey		1												
		2												
		3												
		4												
Maughold		1												
		2												
		3												
		4												
Laxey		1												
		2												
		3												
		4												

Research vessel survey. June 1993.

Site	Date	Tow	Poor Tows (T.d)	Start posn.	Finish posn.	Distanc	nm	Start	Finish	Duratio	Av.speed ki	Depth	Tides	Notes
Bradda	1/6/93	1		E5.0/F31.5	E1.76/F45.2	3680	1.99	10:35	11:23	0:48	2.48	33	HW 0902/8.6m	Both clean, stars + stones, tighten springs.
		2		E1.81/F45.3	E4.8/F31.81	3730	2.01	11:46	12:34	0:48	2.52	33		*Q:1/2 full stones etc.*
		3		E4.4/F31.03	E1.78/F44.5	3800	2.05	12:50	13:42	0:52	2.37	33		Q:1/2 full stones. S:clean.
		4	Offshore	E9.5/E42.1	E11.16/E46.9	3760	2.03	14:15	15:06	0:51	2.39	36		3'W of previous tows. Q:3/4 full stones D.Sh.. S:1/4 full stones.
Chickens	2/6/93	1		E15.78/F45.7	E20.78/F44.6	3960	2.14	10:12	11:00	0:48	2.67		HW 1001/8.8m	Q: 1/4 stones. S:clean
		2		E21.2/F44.77	E16.0/F45.64	3860	2.08	11:19	12:10	0:51	2.45			As No.1
		3		E16.3/F45.55	E21.3/F43.8	3760	2.03	12:23	13:21	0:58	2.10			Strong tide, 2 kts. Q: full dead Gly. S:OK few stones.
		4		E16.6/F46.2	E21.6/F44.8	3720	2.01	13:59	14:45	0:46	2.62			Q: 1/3 full stones + shell. S:clean.
Peel	11/6/93	1				3920	2.12	9:25	10:10	0:45	2.82			Q. 3/4/full clean, stones. S. <1/4 full.
		2				3590	1.94	10:28	11:10	0:42	2.77			Q. 3/4 full stones. S. <1/4 full, springs too slack.
		3				3840	2.07	11:29	12:14	0:45	2.76			Q. 1/2 full clean stones. S. 1/4 full despite tighter springs, teeth too long?
		4				3760	2.03	12:31	13:15	0:44	2.77			Q. 1/3 - 1/2 full stones. S. 1/4 full.
SE Douglas	7/6/93	1		D2.81/G45.5	C22.71/G46.2	3720	2.01	10:41	11:24	0:43	2.80	42-55	HW 1400/8.9m	New S. teeth. Q. teeth worn. Down tide, 2.5 kts. Q:full stones+shell. S:clean.
		2		D1.6/G46.46	C21.2/G46.38	3800	2.05	11:59	12:44	0:45	2.74	47-62		*Q:full St.+Gly, Buccies. S:clean, few st.+stars.*
		3		D0.88/H30.1	C20.16/H30.2	3760	2.03	13:22	14:08	0:46	2.65	44		On bank. Q:full small st., D.Sh. some limbs. S:few st.
		4		C23.7/G46.5	D3.8/G45.8	3720	2.01	14:37	15:25	0:48	2.51	44-62		Slack water. Q:full stones, less D.Sh. S:clean.
E Douglas	8/6/93	1		C8.9/G30.0	C4.5/F47.54	3720	2.01	10:15	11:01	0:46	2.62	30-33	HW 1441/8.6m	Q.teeth v.short, S.med. springs. Q:full D.Sh. stars+buzzers (3/4 B Q.). S:clean.
		2		C5.0/F47.57	C9.2/F30.07	3920	2.12	11:23	12:10	0:47	2.70	30-36		Q:full, more stones than 1. Same tow reversed.
		3		C7.8/F47.7	C6.3/F30.6	3930	2.12	12:30	13:17	0:47	2.71	35		Cleaner tow inside box. Q:3/4 full 1.25 box Q.. S:clean.
		4		C7.19/F30.29	C5.4/F30.18	3760	2.03	13:33	14:19	0:46	2.65	36		As 3, one blade off. Box Q.
10'S PSM	3/6/93	1		E1.91/H38.88	E2.62/H38.9	3980	2.15	10:52	11:42	0:50	2.58		HW 1056/9.1m	slackened springs. Q:3/4 full St. + D.Sh. S:empty.
		2		E2.26/H38.4	E2.8/H38.8	3660	1.98	12:05	12:50	0:45	2.63			Q: 1/2 full, more Q.. S:empty.
		3		E2.1/H37.6	E4.8/H38.6	3760	2.03	13:13	14:02	0:49	2.49			Strong ebb tide. D. Sh. heart urchins. box Q.. Q:3/4 full D.Sh.
		4		E3.14/H39.6	E1.51/H34.9	3700	2.00	14:23	15:12	0:49	2.45			Both clean, some stones and stars, best tow, into tide.
20'S PSM	4/6/93	1		E3.34/I38.1	E0.5/I34.5	3840	2.07	10:46	11:38	0:52	2.39	68-66	HW 1147/9.2m	Q:slack springs, 1/2 full stones. Good tow 1/4B Q.
		2	dredge 7	E3.6/I31.9	E1.9/I31.0	4050	2.19	12:07	13:05	0:58	2.26	74-67		*Dredge 7 no measurements of scallops. Q:1/2 full Q.+D.Sh.+stars. 3/4B Q. per dredge. springs medium, slack wat*
		3		E2.36/I30.8	E3.41/I31.5	3800	2.05	13:25	14:15	0:50	2.46	65-75		Tide strong. Few stones D.Sh. similar to 2.
		4	poor tow	E3.23/I30.62	E5.4/I30.17			14:39	15:10	0:31				*Port dredges stuck fast, none fished well, short tow. Bent blades on S.dredges. Came fast after 30 mins.*
Targets	9/6/93	1		D8.17/D38.6	D2.03/D35.5	3740	2.02	11:04	11:51	0:47	2.58	27	HW 1420/8.3m	Q>teeth too short! Q: 1/2 full D.Sh buzzers. S:clean.
		2	dredge 7	D0.55/D34.67	C18.16/D31.0	3820	2.06	12:05	12:54	0:49	2.53	30		dredge 7 not measured? Q:3/4 full st. Q: clean.
		3	dredge 7	C15.2/D30.2	C14.8/D31.8	3940	2.13	13:15	14:09	0:54	2.36			dredge 7 wire hauser caught early in tow, void. Q:full St.+junk. S:1/4 full.
		4		C13.95/D30.2	C20.13/D33.1	3760	2.03	14:39	15:24	0:45	2.71			Q:full St. D.Sh.. S:1/4 full stars sh. etc.
Pt of Ayre	10/6/93	1		A17.68/B46.8	A14.28/C30.2	3760	2.03	11:15	11:59	0:44	2.77	52	HW 0336/8.6m	Q:full small St. D.Sh. 3/4 Bx Q/drdge. S:clean, plenty stars.
		2	poor tow	A17.5/B46.8	A14.35/C30.7	3780	2.04	12:41	13:23	0:42	2.92	52		Queen dredges rapidly filled with trash, affected whole tow, void.
		3												
		4												
Ramsey		1												
		2												
		3												
		4												
Maughold		1												
		2												
		3												
		4												
Laxey		1												
		2												
		3												
		4												

APPENDIX 2

SUMMARY OF DIVER SURVEYS

			Survey			Latitude			Longitude								
DD	MM	YY	Number	Locatio	Deg	Min	Hun	Deg	Min	Hun	Depth	Headin	Dive no	Side	Diver	Substrate	Notes
30	3	89	1	E. Zone	54	4	62	4	47	39	33	180	1	L	MB	SHELL/GRAVEL	
30	3	89	1	E. Zone	54	4	62	4	47	39	33	180	1	R	UW	SHELL/GRAVEL	
31	3	89	1	E. Zone	54	5	42	4	47	46	33.5	0	2	R	UW	SAND/GRAVEL	
31	3	89	1	E. Zone	54	5	42	4	47	46	33.5	0	2	L	MB	SAND/GRAVEL	
31	3	89	1	E. Zone	54	5	17	4	47	44	33.8	180	3	L	MB	SAND/GRAVEL/SHELL	
31	3	89	1	E. Zone	54	5	17	4	47	44	33.8	180	3	R	UW	SAND/GRAVEL/SHELL	
4	4	89	1	E. Zone	54	4	70	4	47	14	32	90	4	R	DM	SAND/GRAVEL/SHELL	
4	4	89	1	E. Zone	54	4	70	4	47	14	32	90	4	L	MB	SAND/GRAVEL/SHELL	
4	4	89	1	E. Zone	54	4	65	4	47	5	29.1	35	5	R	UW	SAND/STONES	
4	4	89	1	E. Zone	54	4	65	4	47	5	29.1	35	5	L	MB	SAND/STONES	
12	4	89	1	E. Zone	54	4	86	4	46	94	29.8	330	6	L	UW	SAND/SHELL/GRAVEL	
12	4	89	1	E. Zone	54	4	86	4	46	94	29.8	330	6	R	BH	SAND/SHELL/GRAVEL	
12	4	89	1	E. Zone	54	4	97	4	46	97			7	R	DM	FINE GRAVEL/SAND/SHELL	
12	4	89	1	E. Zone	54	4	97	4	46	97			7	L	MW	FINE GRAVEL/SAND/SHELL	
12	4	89	1	E. Zone	54	4	74	4	47	70	35		8	L	MB		
12	4	89	1	E. Zone	54	4	74	4	47	70	35		8	R	AR		
28	4	89	1	Bradda								180	9	L	LC	SAND	
28	4	89	1	Bradda								180	9	R	DM	SAND	
28	4	89	1	Bradda								180	10	R	BM	FINE SAND	
28	4	89	1	Bradda								180	10	L	RL	FINE SAND	
10	5	89	1	Bradda	E2.75	F47.85						310	11	L	AB	FINE SAND/SHELL	
10	5	89	1	Bradda	E2.76	F47.86						310	11	R	DM	FINE SAND/SHELL	
7	6	89	1	Bradda	F30	E1.5						330	12		AB	GRAVEL/SHELL	
7	6	89	1	Bradda	F31	E1.6						330	12		BH	GRAVEL/SHELL	
7	6	89	1	Bradda	E2	F30.5						60	13	L	LC	GRAVEL/SHELL	
7	6	89	1	Bradda	E3	F30.6						60	13	R	DM	GRAVEL/SHELL	
12	6	89	1	Bradda								120	14	R	MB		
12	6	89	1	Bradda								120	14	L	PF		
12	6	89	1	Bradda								270	15		AB		
12	6	89	1	Bradda								270	15				
12	6	89	1	Bradda									16	L	LC		
12	6	89	1	Bradda									16	R	DM		
12	6	89	1	Bradda									17	L	RL		
12	6	89	1	Bradda									17	R	BM		
7	9	89	2	E. Zone									18		BM	FINE SHELL	
7	9	89	2	E. Zone									18			FINE SHELL	
7	9	89	2	E. Zone									19		DM	FINE SAND/SHELL	
7	9	89	2	E. Zone									19		UW	FINE SAND/SHELL	
13	9	89	2	E. Zone									20		MB	SAND	
13	9	89	2	E. Zone									20		UW	SAND	
7	9	89	2	E. Zone									21	R	DM	GRAVEL	
7	9	89	2	E. Zone									21	L	UW	GRAVEL	
			2	E. Zone									22	L	ADB	SHELL	
			2	E. Zone									22	R	MB	SHELL	
6	9	89	2	E. Zone	54	4	91	4	46	83		0	23		MB	SAND/GRAVEL	
6	9	89	2	E. Zone	54	4	91	4	46	83		0	23		PF	SAND/GRAVEL	
	9	89	2	E. Zone									24		MB	SAND/GRAVEL	
	9	89	2	E. Zone									24		JA	SAND/GRAVEL	
	9	89	2	E. Zone								35	25				
	9	89	2	E. Zone								35	25		AB		
8	12	89	3	E. Zone	54	4	92	4	47	2		75	26		BM	SAND/SHELL	Many dredge tracks
8	12	89	3	E. Zone	54	4	92	4	47	2		75	26		UW	SAND/SHELL	starfish feeding-carrio
8	12	89	3	E. Zone	54	4	94	4	47	50		60	27		MB	SAND/SHELL	2 dredge tracks
8	12	89	3	E. Zone	54	4	94	4	47	50		60	27		TH	SAND/SHELL	2 dredge tracks
8	12	89	3	E. Zone	54	4	79	4	47	47		90	28		JA	SHELL SAND	
8	12	89	3	E. Zone	54	4	79	4	47	47		90	28		BH	SHELL SAND	
8	12	89	3	E. Zone	54	4	85	4	47	52		230	29		BM	SAND/SHELL	
8	12	89	3	E. Zone	54	4	85	4	47	52		230	29		UW	SAND/SHELL	
8	12	89	3	E. Zone	54	4	94	4	47	38		80	30		DM	SAND/SHELL	
8	12	89	3	E. Zone	54	4	94	4	47	38		80	30		MW	SAND/SHELL	
8	12	89	3	E. Zone	54	4	73	4	47	9		205	31		TH	SHELL/SAND	
8	12	89	3	E. Zone	54	4	73	4	47	9		205	31		MB	SHELL/SAND	
8	12	89	3	E. Zone	54	4	64	4	47	5		240	32		DM	BOULDERS/STONES	
8	12	89	3	E. Zone	54	4	64	4	47	5		240	32		MW	BOULDERS/STONES	
8	12	89	3	E. Zone									33		JM		
8	12	89	3	E. Zone									33		BH		
28	11	90	4	E. Zone	54	4	96	4	47	84	35	30	34	R	DM	FINE GRAVEL/SAND	
28	11	90	4	E. Zone	54	4	96	4	47	84	35	30	34	L	TH	FINE GRAVEL/SAND	
28	11	90	4	E. Zone	54	4	90	4	47	73	25	30	35	L	SW	FINE SAND/GRAVEL	
28	11	90	4	E. Zone	54	4	90	4	47	73	25	30	35	R	MB	FINE SAND/GRAVEL	
28	11	90	4	E. Zone	54	4	62	4	47	84	36		36	L	MW	FINE GRAVEL/SAND	
28	11	90	4	E. Zone	54	4	62	4	47	84	36		36	R	UW	FINE GRAVEL/SAND	
28	11	90	4	E. Zone	54	4	62	4	47	25			37	R	D	GRAVEL	
28	11	90	4	E. Zone	54	4	62	4	47	25			37	L	TH	GRAVEL	
28	11	90	4	E. Zone	54	4	88	4	47	19		15	38	L		MIXED	Dredge track at
28	11	90	4	E. Zone	54	4	88	4	47	19		15	38	R	MB	MIXED	end of transect
28	11	90	4	E. Zone	54	4	70	4	47	31	29.7		39	L	UW	SHELL	
28	11	90	4	E. Zone	54	4	70	4	47	31	29.7		39	R	MW	SHELL	
29	11	90	4	E. Zone	54	4	99	4	46	98	28		40	R	MB	FINE SAND/STONES	
29	11	90	4	E. Zone	54	4	99	4	46	98	28		40	L	RL	FINE SAND/STONES	
29	11	90	4	E. Zone	54	4	70	4	47	65	27.5	180	41	L	MW	SAND/GRAVEL	
29	11	90	4	E. Zone	54	4	70	4	47	65	27.5	180	41	R	UW	SAND/GRAVEL	
5	12	90	4	Bradda	54	6	14	4	47	85	37	330	42	R	BM	FINE SAND/STONES	
5	12	90	4	Bradda	54	6	14	4	47	85	37	330	42	L	D	FINE SAND/STONES	
8	12	92	5	E. Zone	54	4	90	4	47	73		315	43	R	UW	FINE SAND/SHELL	
8	12	92	5	E. Zone	54	4	90	4	47	73		315	43	L	DP	FINE SAND/SHELL	
8	12	92	5	E. Zone	54	4	62	4	47	63		0	44	L	MB	SHELL/GRAVEL	
8	12	92	5	E. Zone	54	4	62	4	47	63		0	44	R	DH	SHELL/GRAVEL	
8	12	92	5	E. Zone	54	4	62	4	47	25		100	45	L	DP	MIXED	
8	12	92	5	E. Zone	54	4	62	4	47	25		100	45	R	UW	MIXED	
8	12	92	5	E. Zone	54	4	90	4	47	25		270	46	R	DH	SHELL/SAND	
8	12	92	5	E. Zone	54	4	90	4	47	25		270	46	L	MB	SHELL/SAND	
10	12	92	5	Bradda	54	6	2	4	47	1		270	47	R	UW	HARD SAND/SH	Old dredge tracks
10	12	92	5	Bradda	54	6	2	4	47	1		270	47	L	DP	HARD SAND/SHELL	

APPENDIX 3

LIST OF MATERIALS USED AND SUPPLIERS

MATERIALS AND SUPPLIERS

1.	Onion bags	Kerrypak Ltd, Longbrook House, Ashton Vale Road, Bristol, BS3 2HA. Tel: 0272 669684/662455 Fax: 0272 231251
2.	Onion bag mesh filler - Netlon Type 1005	Netlon, Kelly Street, Balckburn, Lancashire, BB2 4PJ. Tel: 0254 62431 Fax: 0254 680008
3.	Cable ties (no. 543-349)	RS Components Ltd. PO Box 99, Corby, Northants, NN17 9RS, Tel: 0536 201201
4.	Longline anchors	SFIA design, made locally by Metalco Engineering, Metals House, Port St. Mary.
5.	North West Plastics Trays	North West Plastics (Hyware), Mosley Common Road, Worsley, Manchester, M28 4AJ. Tel: 061 790 4433/9, Fax: 061 790 2026.
6.	Pearl Nets	Iron Strand, 16 South Crescent, The Headland, Hartlepool, Cleveland, TS24 0QD. Fax: 0429 267663.
7.	Mussel stocking	Salen Shellfish, Salen, Acharacle, Argyll. Tel: 0397 4030.
8.	Hog ring gun	Young Black Industrial Stapling Ltd. 25b Techno Trading Estate, Bramble Road, Swindon, Wilts. SN2 6EZ
9.	Vinyl dots (vinyl used for vehicle signs and displays, cut into Ø 4mm dots)	Whittington Sign Services (no longer trading).
10.	Scallop taging numbers, Brady Micro-markers	Barnes & Steel Ltd, 14 Carr Lane Industrial Estate, Hoylake, Wirral, L47 4AX. Tel: 051 632 4655.
11.	Cyanoacylate glue, Loctite Superglue Extra Gel.	Bought locally
12.	Duo-glo tape, as used as a barrier around roadworks.	Colas (I.o.M.) Ltd., Balthane Industrial Estate, Ballasalla.
13.	Nylon nuts and bolts as used for attaching vehicle registration plates.	Industrial Equipment, Tynwald Street, Douglas.
14.	Hole punch and eyelet tool.	DTP Supplies, Fieldhouse Industrial Estate, Fieldhouse Road, Rochdale, OL12 0AA. Tel: 0706 522113
15.	Metal corner reinforcements	Own design made up my Metalco Engineering Ltd.
16.	4 mm diameter prestretched polyester rope	H. & T. Marow Ltd (Marlow Ropes) , Hailsham, East Sussex, BN27 3JS. Tel: 0323 847234. Fax: 0323 440093.

17.	Galvanised tent pegs	Newson Trading, North Quay, Douglas
18.	6, 12 & 16 mm polypropylene split-film rope	W. & R. Lewis, 286 Broomloan Road, Glasgow, Glasgow, G51 2DP. Tel: 041 445 2217. Fax: 041 445 4534.
19.	Concrete weights, car, lorry or tractor tyres as required. Filled with concrete with Ø 10 mm metal shape inserted to provide tying loops (Metalco Engineering).	Douglas Tyre & Battery Co., 5-7 South Quay, Douglas. Tel: 676532. Concrete: 45Nm mix from Island Aggregates Ltd, Treger House, Circular Road, Douglas Used car tyres free from ATS, North Quay, Douglas
20.	200 mm floats	Highland Aquaculture Limited, Scalpay House, Broadford, Isle of Skye, IV49 9BS. Tel & Fax: 0471 822539
21.	Small concrete weights - plastic freezer bag filled with concrete and wire loop inserted.	
22.	Foamex slate	Whittington Sign Services (no longer trading).

APPENDIX 4

COST ASSUMPTIONS FOR ECONOMIC ASSESSMENT

Longline costs (200m) = 192 hanging spaces

	no.per line	unit cost	total cost
16 mm rope	2	52.88	105.76
12 mm rope	1	20.56	20.56
6 mm rope	3	4.70	14.10
Anchors etc	2	**100.00**	200.00
car tyre weights	9	5.00	45.00
small weights	192	0.10	19.20
Large buoys	9	**30.00**	270.00
small buoys	10	**1.47**	14.70
metalwork	1	50.00	50.00
Total materials cost per longline			739.32
Total materials cost per net space			3.85

Labour

	hours	unit cost	cost
To rig & moor longline per net space	1.83	**4.00**	7.32

Boat time

To rig & moor longline per net space	0.25	**5.00**	1.25
Total labour/boat cost per net space (After Berry & Burnell, 1981)			8.57

Spat collection

Standard longline capital and labour costs for setting up.
100 net spaces = 100 × £12.42 = £1242.00 depreciated over 5 years = £284.40
But collectors only out for appox 4 months so cost = 4/12 ×284.40 = **£82.80/1000** bags

per 1000 bags

10 collectors to a dropper, therefore require 100 net spaces = about half a longline/1000 bags.
Bags: 1000 ×£0.14 = £140 = £164.50 inc. VAT
Filler: 1000 ×(1.5/1000) ×£60 = £90 = £105.75 inc. VAT

Cable ties: 1000 @ £3.28/100 = = £38.54 inc. VAT
Small concrete weights: 100 × £0.10 = =£ 10.00
6 mm rope: 100 × 6 m lengths/£4.70 = = £12.82

Total materials for spat collection per 1000 bags = £331.61 inc. VAT

Labour/1000 bags

Time to cut/stuff/tie knot/tie onto dropper/ and add cable tie ≈ 2 min
therefore ≈ 33 hours/1000 bags
33 hours @ £4 per hour = £132/1000 bags

Hanging collectors

Two people on boat can hang 100 lines in one day
so 2 × 8 hours @ £4 per hour = £64
plus 8 hours boat time @ £5 per hour = £40
Total hanging costs = £104/1000 bags

Sorting

If one person can sort 150 bags in one day then 2 people could sort 1000 bags in 3.5 days, at sea.
7 × 8 hours labour @ £4 per hour = £224
3.5 days boat time × 8 hours @ £5 per hour = £140
Total sorting costs = £364

CULTURE

Assumes intermediate culture in 6mm pearl nets
followed by 12mm lanterns over first summer.
Autumn year 1 when approx. 50 mm go into 21mm lanterns and remain in these with twice yearly net changes to adult size in summer of 4th year.

Table 2.5. Estimates of the density of commercial size scallops ($\geq$110 mm shell length, number.100 m^{-2}) on fishing grounds around the Isle of Man, calculated from the area swept by research vessel dredge surveys assuming a dredge efficiency of 20%.

	TARGETS			PEEL			BRADDA INSHORE		
Age	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993	June 1992	Oct. 1992	June 1993
2	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.133		0.074	0.220	0.098	0.011	0.014	0.418	0.000
4	1.308		0.653	0.742	1.530	0.206	0.850	1.024	0.190
5	0.166		0.727	0.178	0.426	1.129	0.652	0.981	0.600
6	0.022		0.160	0.178	0.175	0.293	0.099	0.101	0.424
7	0.011		0.000	0.627	0.273	0.130	0.028	0.029	0.059
8	0.011		0.012	0.188	0.361	0.217	0.071	0.072	0.029
9	0.011		0.025	0.115	0.098	0.119	0.000	0.000	0.044
10+	0.000		0.012	0.063	0.109	0.076	0.000	0.000	0.044
Total	1.663		1.663	2.311	3.071	2.182	1.714	2.626	1.390