Studies of aspects of predation on the Manx scallop, *Pecten maximus* (L.), populations.

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by

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Dedication

This thesis is dedicated to mum and dad and Nic for all their support.

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Abstract.

Studies of aspects of predation on the Manx scallop, *Pecten maximus* (L.), populations.

Intensive dredging leading to declining scallop stocks has prompted investigation of methods of enhancing scallop populations in Manx waters. One potential method of stock enhancement is seabed re-stocking and on-growing after an initial culture period. The timing of re-stocking and the size of scallops used are both important factors in determining the success, and economic viability of re-stocking operations. Re-stocking trials suggest that predation is one of the main problems associated with this method. This study uses field tethering of two sizes of scallop, *Pecten maximus*, to investigate the timing and intensity of predation on this species off the south west coast of the Isle of Man from October 1993 to November 1995. Time lapse video surveys suggested that the common starfish *Asterias rubens* and the edible crab *Cancer pagurus* posed the main threat to scallops in the area studied. The 1993 tethering experiments showed crab predation reaching a peak in autumn coinciding with high water temperatures and the offshore migration of females as part of the reproductive cycle. The 1995 experiments showed significantly lower overall crab predation and no autumn peak despite warmer sea temperature. It was felt that this could be a result of an 8-fold increase in crab landings for the local fishery. The smaller size class of scallop (65mm shell length) was significantly more susceptible to crab predation than the larger scallops (75mm shell length) suggesting that a size refuge is achieved between these sizes. Starfish showed no identifiable year to year variation in overall predation but did show bimodal feeding peaks in both 1993/4 and 1995. This bimodal pattern results from the breeding cycle. The relationship of starfish feeding to temperature was not as simple as that for crabs but an observed shift in both feeding peaks to later in the year during 1995 may have resulted from significantly lower water temperature in that year. The 1993/4 tethering experiments indicated that scallop size did not affect starfish predation while in 1995 significant differences were identified with more small scallops being consumed by starfish. Laboratory experiments indicate that scallops achieve a size refuge from starfish at

around 75mm shell length. This was determined under high predator and prey densities in enclosed areas so the true size refuge may be lower. Choosing the smallest size scallop that is likely to avoid predation will minimise the expense of culture prior to re-stocking. Literature suggests that, under similar experimental conditions of high predator and prey densities in an enclosed space, a similar scallop size refuge is achieved from crabs. Again this could be artificially high. The tethering method used did not affect the likelihood of predation in the laboratory but this was felt to be an effect of the relatively small tanks used in these experiments. Predator surveys carried out indicate that the seabed to the south west of the Isle of Man may be the most suitable of the sites surveyed for re-seeding trials in terms of predator densities and mean sizes. The increase in crab landings and decrease in crab predation during the course of this study indicate that predator removal could be a successful means of enhancing survival of re-seeded, juvenile scallops. Evidence of this was also observed during time lapse video monitoring of tethered scallops. Analyses of the growth rates of scallops at different sites around the Isle of Man show that significant differences occur. However, the site showing the fastest growth rate for scallops also had high densities of large predators. Growth rate of scallops may help re-seeded scallops achieve a size refuge from predation more quickly but may be less important than predator size and density locally because it is no good having a fast growing population of scallops if it is more likely to be eaten than to survive. If the differences in growth rate are due to genetic rather than hydrodynamic factors at each site then differences in growth rates will not be relevant unless the scallops used for re-seeding are known to be predisposed high growth rates.

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Chapter 1 - General Introduction.

Since the late 1930s a fishery for the scallop *Pecten maximus* has existed in the waters around the Isle of Man, situated in the Irish Sea between mainland Britain and Ireland. However, the first signs of over fishing in Manx waters were documented as early as 1940 (Smith, 1940). In recent years the over-exploitation of commercial shellfish stocks, including those in Manx waters (see Shumway, 1991 for a review of world pectinid fisheries) has led to increased interest in cultivation techniques (Minchin, 1991) and there are now many small scale projects using cultivated scallops to attempt to restock areas where fisheries once existed (Brand et al., 1991). Most of the culture methods used for *Pecten maximus* have been developed from those in Japan for *Patinopecten yessoensis* (Ventilla, 1982). In the past these methods involved wild spat collection and on-growing in hanging culture using pearl nets and lantern nets. These methods of on-growing are, however, labour intensive and were proving too costly for the traditionally low paid, collectively organised Japanese work force even during the 1980's (Bolton, 1982; Ventilla, 1982; Minchin, 1991).

Consequently, attention has been turning more and more to on-growing on the seabed and rotational closed area management (Lake et al., 1987; Brand et al., 1991; Minchin 1991; Minchin, 1995; Strand et al., 1995; Bricelj et al., 1995), where initial on-growing after spat collection takes place in hanging culture and then, once a predetermined size is reached, the scallops are relaid onto the seabed until they reach commercial size. Ventilla (1982) suggests that compared with hanging culture this method can reduce costs by up to a third. Wilson (1994) identified seabed on-growing as potentially economically viable in Manx waters. Use of this method introduces a different set of problems from those associated with hanging culture, mainly related to predation, but also encompassing legal considerations such as ownership of a seeded stock and fishing rights (Wilson, 1994). Norman & Ludgate (1995) reported variable survival of re-seeded, juvenile scallops (1 - 137%) after 30-60 days on the seabed. The figure of 137% arose because of movement of naturally occurring scallops into the area used for re-seeding. Encouraging results regarding longer term survival of *Pecten maximus* were obtained by Mikolajunas (1995), where survival rates of 78% were achieved over 32 month period for two and four year old scallops. Thomson et al. (1995) reported survival rates of between 11 and 60% three years after re-seeding. This indicates that re-seeding could, potentially, be a viable means by which scallop stocks could be enhanced.

Predation becomes a major problem when shellfish are seeded onto the seabed for on-growing (Arnold, 1984; Jory et al., 1984; Bull, 1987; Auster & Malatesta, 1991). The main predators of *Pecten maximus* in Manx waters are similar to those of scallops worldwide (Paul, 1981; Brand et al., 1991), namely starfish, particularly *Asterias rubens* and

Marthasterias glacialis, and crabs (*Cancer pagurus*) with the possibility that the lesser octopus (*Eledone cirrhosa*) may also be a threat. It is very difficult to estimate levels of predation in the deeper, subtidal environment given the logistical constraints involved with diver monitoring and through losses of mobile prey and removal of prey by predators that leave no evidence of predation. The methods of assessing predation or relative predation levels used in this study addresses these problems. When re-seeding shellfish onto the seabed it is important to ensure that the shellfish are of such a size as to minimise the effects of predation. Conversely, they should not be so large as to induce uneconomically large culture costs. Another factor which must be considered during re-seeding is the growth rate of the shellfish concerned. If shellfish grow more quickly in one area, compared with another, then they will more quickly achieve a size refuge from predation (Olson, 1996).

Aims of the project.

The aims of this work are to investigate the predator prey interactions between *Pecten maximus* and its two main predators, *Cancer pagurus* and *Asterias rubens*. The work aims to investigate predation in the natural environment off the south west coast of the Isle of Man, to survey local predator populations and determine size distributions of those predators. Predator aggregation and any correlation between predator species and their prey will also be investigated to gain a clear picture of predator prey interactions in this area. These results could then be used to plan a trial reseeding programme to determine the feasibility or otherwise of this method of stock enhancement. Laboratory work is used to determine potential prey size refuges and differences between predation for different experimental treatments.

Environmental factors known to significantly affect the foraging efficiency of epifaunal predators are sediment composition and water temperature. Sediment type has been shown to be an important factor in determining the efficiency of foraging of crustacean predators (Kraeuter & Castagna, 1977; Arnold, 1984; Gibbons & Castagna, 1985). Consequently the experimental sites employed for the field tethering experiments were chosen to be of very similar sediment composition. Temperature is also known to have an effect on the activity of the two main predators cited in terms of feeding behaviour. Water temperature, monitored throughout the year, will be correlated with the results of the prey tethering experiments to attempt to explain observed differences.

Surveys of the predator populations in the areas of the tethering work were carried out using dredges, divers and a sled mounted video camera. The dredge surveys have covered inshore and offshore sites off Bradda Head in detail, including size frequency analysis of *Pecten maximus* and its two main predators, and analyses of the numbers of animals caught in different dredge gear types. These data provide estimates of relative predator densities at inshore and offshore sites at different times of the year which can then be used to explain observed differences in relative predation rates identified by the tethering experiments. The size frequency analyses of the predator populations provide information on when potential prey size refuges might be attained and, consequently, the optimum reseeding size for scallops.

Video surveys of the local predator populations have also been made and, more recently, these have been made concurrently with dredge surveys over the same areas. The video survey work provides a more accurate estimate of predator densities and the combined video and dredge work should provide data on the efficiencies of the different dredge gear types in catching the predator species. A correction factor (effectively a measure of dredge efficiency in catching predator species) was then calculated for the dredges so that estimated densities could be converted into more accurate estimates of actual densities. Video survey data were also used directly to highlight variations in predator densities which, in turn, helped to explain the results of the tethering experiments.

Diver surveys were carried out on a limited scale, given the logistical constraints imposed upon diving operations. Where possible the results of these diver surveys were compared with the video and dredge surveys. Diver surveys were also used to assess predator aggregation on tethering experiments.

The logistics of monitoring, usually involving divers, become complicated and if free ranging prey are used results can be lost through migration of prey animals out of the survey area (Whittington, 1993; Wilson, 1994). For these reasons it was considered best to use a seabed tethering method which could be deployed and retrieved from the surface, and which would help to retain as many prey animals and/or shell fragments as possible. This methodology should maximise the chance of obtaining meaningful results.

Tethering experiments in the first year of study were carried out to the west of Bradda Head and in the Exclusion Zone which has been closed to commercial scallop dredging since 1989 (Brand & Prudden, 1997). This was designed to investigate possible differences in predation rate upon scallops in areas subjected to different levels of commercial fishing effort. These site to site differences were found not to be significant, so the tethering experiments in the second year concentrated on the Exclusion Zone, with a higher degree of replication. The tethering experiments provided data on seasonal differences in relative predation rate, year to year differences, and differences in predation rate upon different sizes of scallops. Relative levels of predation at different times of the year, and upon different sizes of scallops, are important factors to consider when carrying out seabed re-seeding.

Allied with the main tethering experiment were a series of identical tethering experiments run in the shallower waters of Port Erin Bay. These experiments were monitored using divers in an attempt to assess whether the tethered scallop experiments could attract predators from a wide area, thus yielding artificially high predation mortality rates compared with areas with natural densities of scallops.

Laboratory work included experiments to investigate the interactions between scallops (*Pecten maximus*) and their main predators (*Cancer pagurus* and *Asterias rubens*). These were carried out in aquaria in the hatchery area of Port Erin Marine Laboratory (PEML) and aimed to determine potential prey size refuges and any other potential interactions that may take place between predators and their prey. The results could help to explain any differences observed in losses of different size classes of prey used in the tethering experiments. Laboratory experiments to determine differences in predator success rates between tethered and untethered scallops were also carried out for both predators. These experiments showed the effects of tethering on the ability of scallops to evade predators. They also provided data on the types of shell damage inflicted upon the scallops, which can in turn be used to help with the interpretation of the field tethering experiments where shell damage was assessed upon retrieval.

A brief investigation of scallop growth rates at different sites around the Isle of Man was also carried out during this study. Scallops lay down annual growth rings which lend themselves to relatively simple growth analysis both for current and previous year-classes. These analyses aimed to determine whether there are areas of high scallop growth rates that would be particularly suitable for re-seeding.

The lesser octopus *Eledone cirrhosa* has also been cited as a predator of bivalve molluscs (Ambrose, 1986) and could present a threat to seabed re-seeded, juvenile scallop stocks. Although difficult to work with under laboratory conditions some feeding trials with this predator were carried out, primarily to determine the type of shell damage inflicted and to determine possible size ranges of prey which could be consumed by this species.

Chapter 2 - Tethering Experiments.

2.1 Introduction.

One of the main aspects which needs to be considered when investigating seabed on-growing or seabed restocking programmes for shellfish is predation upon the re-seeded, juvenile stocks. Large losses can be incurred if stocks are re-seeded at the wrong size, density or time of year (Auster & Malatesta, 1991). Arnold (1984) observed that artificially seeded *Mercenaria* beds were devastated by crustacean predators. Similar results were obtained in a tag release study carried out by Auster & Malatesta (1991) where 70% of pre-adult mortality in bay scallops was caused by predation. Predation is considered to be a critical factor in the culture of many marine molluscs: hard shell clam (Kraeuter & Castagna, 1977); soft shell clam (Glude, 1955); mussels (Dare & Edwards, 1976); oysters (Gunter, 1979) and scallops (Bull, 1987; Lake et al, 1987). Potential ways around this problem include seeding at lower densities and making the correct choice of substrate on which to seed (Fouke & Lawton, 1990). Use of enclosures, chemical poisons and predator removal by various means have also been suggested (Jory et al., 1984). Relative levels of predation at different times of the year will also be an important factor. This has been investigated in the past using prey tethering in the field (Heck & Thoman, 1981; Heck & Wilson, 1987; Pitcher & Butler, 1987; Pohle et al., 1991; Good, 1992; Kuhlmann, 1992). Molluscan survival during seabed on-growing is mainly affected by the degree of predation experienced, which in turn depends on many factors: size at time of release (balanced against cost of hanging culture); the area of release; season; time of day; density at release point; local density of predators/competitors; degree or types of protection employed and interactions of the above (Pyke et al., 1977; Hughes, 1980; Jory et al., 1984; Ito, 1991). Auster & Haskell (1988) also stress the importance of factors such as predator density, distribution and behaviour.

Tethering prey species in the marine environment as a means of assessing degrees of predation, and other factors, has been used successfully in previuos studies (Pohle et al., 1991; Heck & Thoman, 1981; Heck & Wilson, 1987; Pitcher & Butler, 1987; Wilson, 1989; Wilson et al., 1990; Kuhlmann, 1992; Fernandez et al., 1993; Arsenault & Himmelman, 1995; Barbeau et al., 1995). Most of the tethering studies carried out employ monofilament fishing line and either knotting, super gluing or both as a means of tethering prey species (Wilson, 1989; Kuhlmann, 1992; Whittington, 1993). Other factors investigated using tethering techniques include habitat selection by moulting crabs (Shirley et al., 1990); sensitivity to near UV light in pelagic Crustacea (Frank & Widder, 1994) and aggregation of scallops into areas where predators could not efficiently forage (Stokesbury & Himmelman, 1995). Arsenault & Himmelman (1996) used tethering methods to show that the vulnerability of scallops to predators decreased with increasing scallop size.

When applied to predation studies, tethering methods have been used to assess relative levels of predation on a variety of marine invertebrates and for several predator species: spiny lobster (Herrnkind & Butler, 1986; Eggleston et al., 1990); bay scallops (Peterson et al., 1989); blue crabs (Wilson et al., 1990); mangrove crabs (Wilson, 1989); bay scallops (Barbeau et al., 1995) and ascidians (Davies, 1988). Tethering is a means by which natural conditions under which predation occurs can be most closely simulated without losing data as a result of migration of mobile prey from an experimental area (Whittington, 1993; Wilson, 1994; Zimmer-Faust et al., 1994) or removal by predators. Tethering has been successfully used to assess differences in predation between different habitats (Heck & Thoman, 1981; Herrnkind & Butler, 1986; Heck & Wilson, 1987; Eggleston et al., 1990; Fernandez et al., 1993 and Minello, 1993) and between different latitudes (Heck & Wilson, 1987). The potential for investigating seasonal variations in predation using tethering techniques is evident but there appears to be an absence of published data in this field. One of the aims of the present study is to address this issue by investigating predation levels on scallops in the field over a two year period. It would be very difficult to gather such data in the field by any other means.

Barbeau & Scheibling (1994b) mention that, in their study, the different sizes of prey preferred by two different predators meant that direct comparisons between predator types were not possible if tethering affected the probability of capture by different predators in different ways. Kuhlmann (1992) states that field studies with as near to natural conditions as possible are required for a more complete understanding of the effects of predation. Laboratory experiments can be highly artificial and potentially misleading unless combined with field studies.

Without exception, the authors of these tethering studies state that their results do not represent absolute or totally natural rates of predation. Rather they show relative rates of predation between different sites under the experimental regime imposed (Wilson, 1989; Wilson et al., 1990; Eggleston et al., 1990). As such, it is possible to compare sites which are treated in the same manner experimentally (Peterson & Black, 1994).

Several studies have attempted to quantify the effect of their tethering methods on the health or viability of the species being tethered. This has normally been carried out using control animals tethered in the same way, and placed in the same environment, as experimental animals but with the risk of predation removed (Heck & Thoman, 1981; Pohle et al., 1991; Aronson, 1992). Zimmer-Faust et al. (1994) state that several investigators including Heck & Thoman (1981) and Aronson (1992) found no adverse effects of tethering upon the health of prey species in the absence of predators.

Initial data analysis of information generated by tethering experiments has been by standard analysis of variance techniques (Pohle et al., 1991). Factors to consider include experimental site, animal size and season or month. For three factors, three way ANOVA can be employed as detailed in Sokal & Rohlf (1969). These authors also detail methods of multiway ANOVA, if more factors need to be considered, although interpretation then becomes much more difficult.

For the purposes of this study, which aims to compare scallop predation at two sites off the west coast of the Isle of Man, tethering scallops on the seabed would appear to be a very useful method of assessing relative predation rates through the year. Consequently, it was decided to investigate the effects of scallop size and time of year upon predation in the field using subtidal tethering systems. These experiments were deployed on the seabed of two areas with potential for scallop restocking or on-growing. *Pecten maximus* was chosen as the prey species since this constitutes an important part of the catch of the Manx fishing fleet in local waters.

Two different sizes of scallop were used in an attempt to estimate the optimum restocking size which would minimise predation, at the same time as minimising culture and associated labour costs. The smaller size class was chosen to be vulnerable to attack by the edible crab *Cancer pagurus* and the larger size class to be at or just above the size vulnerable to such attack, as determined by Lake et al. (1987). By deploying these tethered animals throughout the year it was also possible to determine the best times for restocking to take place in terms of predator activity and to obtain an estimate for the optimum size of scallop to use for reseeding. Laboratory experiments were also carried out to assess the possible effects of tethering on the prey species.

2.2 Materials and Methods.

2.2.1 Maintenance of experimental animals.

The scallops used in these experiments were obtained from Highland Aquaculture, Scalpay, N.W. Scotland. The mean shell length of the larger scallops used during the 1993/4 experiments was 77.6mm±0.34 (mean±s.e.) and that of the smaller scallops 60.5mm±0.36 (mean±s.e.). The corresponding mean shell lengths for the 1995 experiments were 65.5mm±0.17 and 74.7mm±0.16 respectively. Scallops were measured at the time of deployment. These scallops were stored in lantern nets on a 220m sub-surface long line in Bay Fine (54° 04.31'N, 04° 46.52'W) until needed for experimental use. Once required, the scallops were retrieved from the long line and brought to the laboratory where they were tethered using the method detailed in Whittington (1993). First the anterior ear was drilled with a 1.5mm drill and a short length of nichrome wire passed through the hole and twisted to form a secure, wide loop to allow shell articulation. The animals were then held in 1.5m x 1.5m x 3m hatchery tanks and supplied with unfiltered sea water at an approximate flow rate of 4-5 litres min^{-1} until the tethering experiments could be deployed.

2.2.2 Locations and dates of tethering experiments.

Tethering experiments were deployed on a monthly basis from September 1993 to December 1994. Two sites were investigated with this technique, each with two replicate lines of tethered animals. The local scallop fishing season lasts from 1 November to 31 May inclusive. The Bradda Head site was open to dredging during the scallop fishing season and the Exclusion Zone was closed to mobile fishing gear all year round. The position of the Bradda Head experimental deployments lay in the box: 54° 05.80' - 54° 06.05'N and 04° 46.62' - 04° 46.92'W and the positions of the Exclusion Zone experimental deployments lay in the box: 54° 04.99' - 54° 05.21'N and 04° 46.55' - 05° 46.78'W (see Fig. 2.1). The north east quarter of the Exclusion Zone was used. These sites were chosen to be approximately the same distance from nearby land, in the same depth of water and with similar substrate types.

Identical experiments were carried out throughout 1995 employing four replicate lines deployed only at the Exclusion Zone site as described above. This concentrated limited experimental resources and replicates in one place to enable more accurate statistical analysis to be performed on the seasonal and prey size data.

2.2.3 Preparation of experiments.

Tethering experiments were deployed each month, weather permitting, with a planned duration of 5 to 10 days. Prior to deployment the 34m long ground lines were wound on to bars lashed across each end of a fish box specially adapted for deploying tethering lines, without tangling problems, as used by Whittington (1993) and shown in Fig. 2.2. Two such fish boxes held the four ground lines used. The lines were marked at 2m intervals using an indelible marker pen. As each mark was reached, when the ground line was wound on to the bars, a fishing swivel was attached to the line through the weave of the rope. To each swivel was attached a one metre length of nylon fishing line (6lb breaking strain, later increased to 15lb to help reduce total losses due to snapping) with a spring clip at the other end. As each monofilament tether was put on the line they were fed over into the fish box and the spring clips were placed over pins nailed into wooden battens cut to length so they wedged securely in the bottom of the fish box (Fig. 2.2). Each monofilament tether line was taped in position on battens running along the top edges of the fish box, perpendicular to the end bars, and numbered (1-14). Large scallops were allocated to odd numbers and small ones to even numbers, but the order of the numbers along the line was determined randomly using the

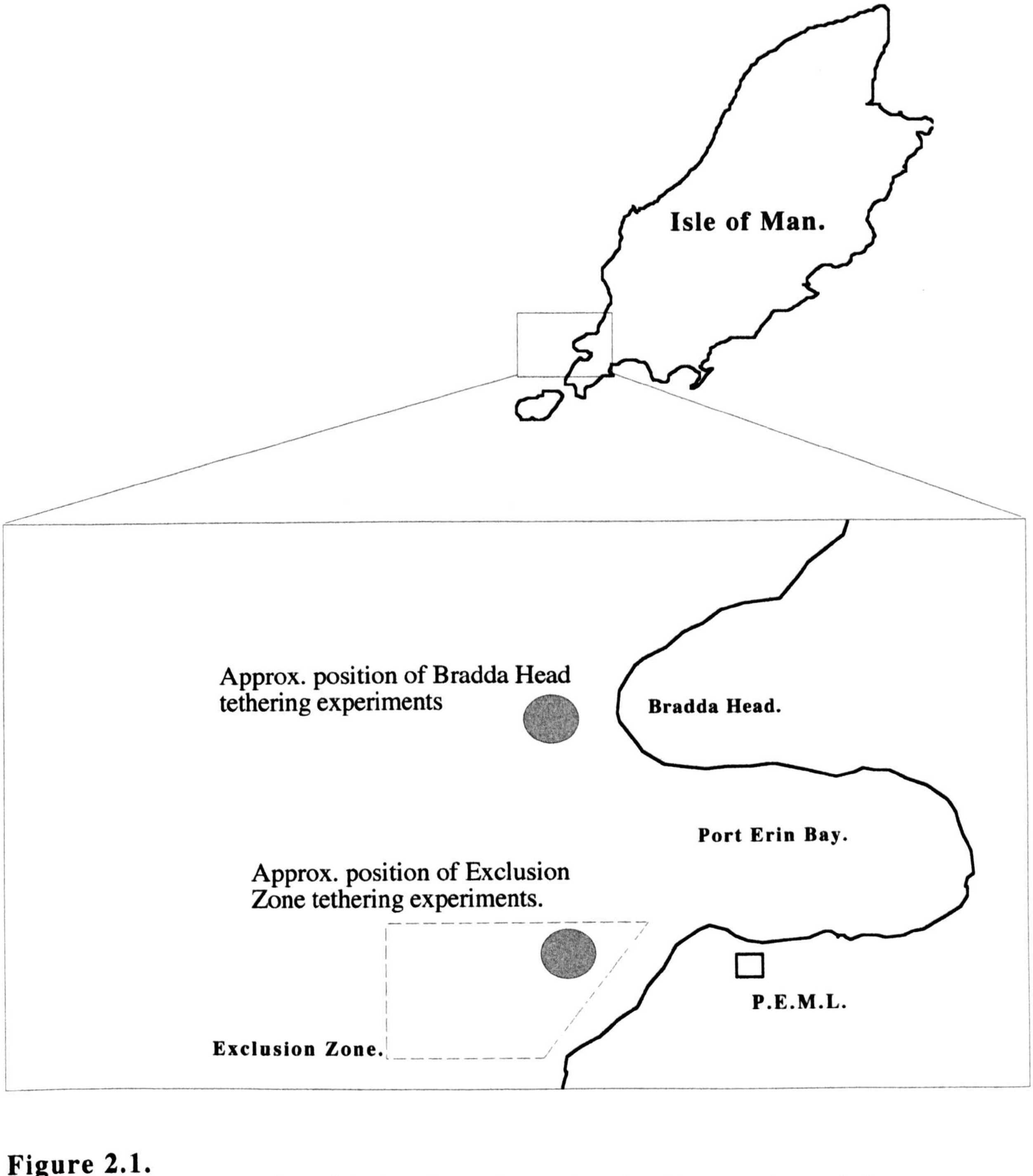


Figure 2.1.
Diagrammatic representation of the locations of the tethered scallop experimental sites.

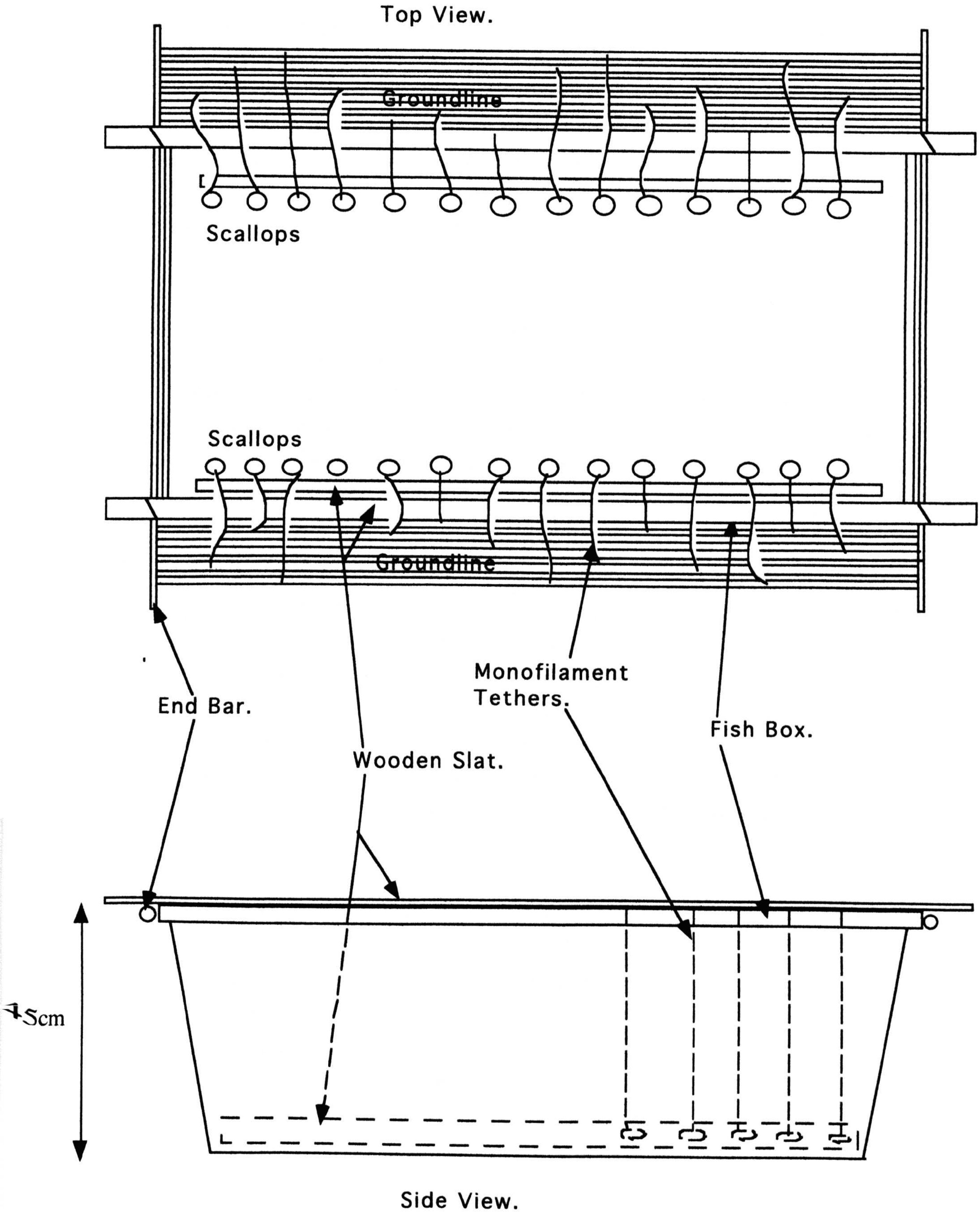


Figure 2.2.
Specially adapted fishbox used for deployment of tethering experiments.

randomisation function of Minitab 8.1, this ensuring that the size classes were distributed randomly and did not simply alternate between large and small animals.

This technique avoided tangling problems, allowed accurate referencing of each scallop for size and ensured a random pattern of large and small scallops along the ground line. The method of tethering each individual scallop is detailed in Fig. 2.3. There was 4m of ground line between each of the end scallops and the two end weights (Fig. 2.4). Once a set of ground lines (4) was deployed, the next set was prepared.

Immediately prior to deployment, scallops were measured and attached to the spring clips along the ground line using *Pecten maximus* of two different size classes. A note was made of the size of each scallop and its position on each line. The bottom of the fish box was then filled with water to just cover the animals and prevent desiccation in transit. The lines were then deployed using the Port Erin Marine Laboratory research vessel *Sula* (Fig. 2.5).

2.2.4 Deployment and retrieval of experiments.

For each line the small weight (6-8kg) was lowered slowly to the seabed while the tethered scallops were paid out one at a time. Each fish box held two ground lines i.e. one site. Once a ground line was fully paid out the end was shackled to a concrete sinker using a 0.5cm galvanised steel shackle. A pearl net containing 4 scallops tethered identically to those on the ground line was attached to the shotline, 1-2m above this concrete sinker, using a plastic cable tie. This acted as a control to check for adverse effects of the tethering method without predation being a mortality factor (Pohle et al., 1992) (Fig. 2.4). All control animals were tethered in exactly the same manner as the scallops on the ground line, with the tethers being attached to the walls of the pearl net.

The main sinker was then lowered to the seabed using the shot line which was shackled to the sinker using larger 1.5cm galvanised shackle. These shackles were replaced every 3-4 months to avoid loss of experiments since the shotline anchored a pair of 20 cm orange, plastic surface marker buoys which allowed location and retrieval of the systems (Fig. 2.4). The final lowering of the concrete sinker was performed carefully but as rapidly as possible so that the drift of the boat maintained tension in the ground line in order to lay it straight, while at the same time minimising losses resulting from the system dragging along the seabed (Fig. 2.5). This experimental set up allowed every scallop on each line to be fully referenced for size and assessed for damage category. This allows conclusions to be drawn regarding the assumed predator type causing the observed damage. With data on size and assumed predator type for each date it was possible to test whether each assumed predator

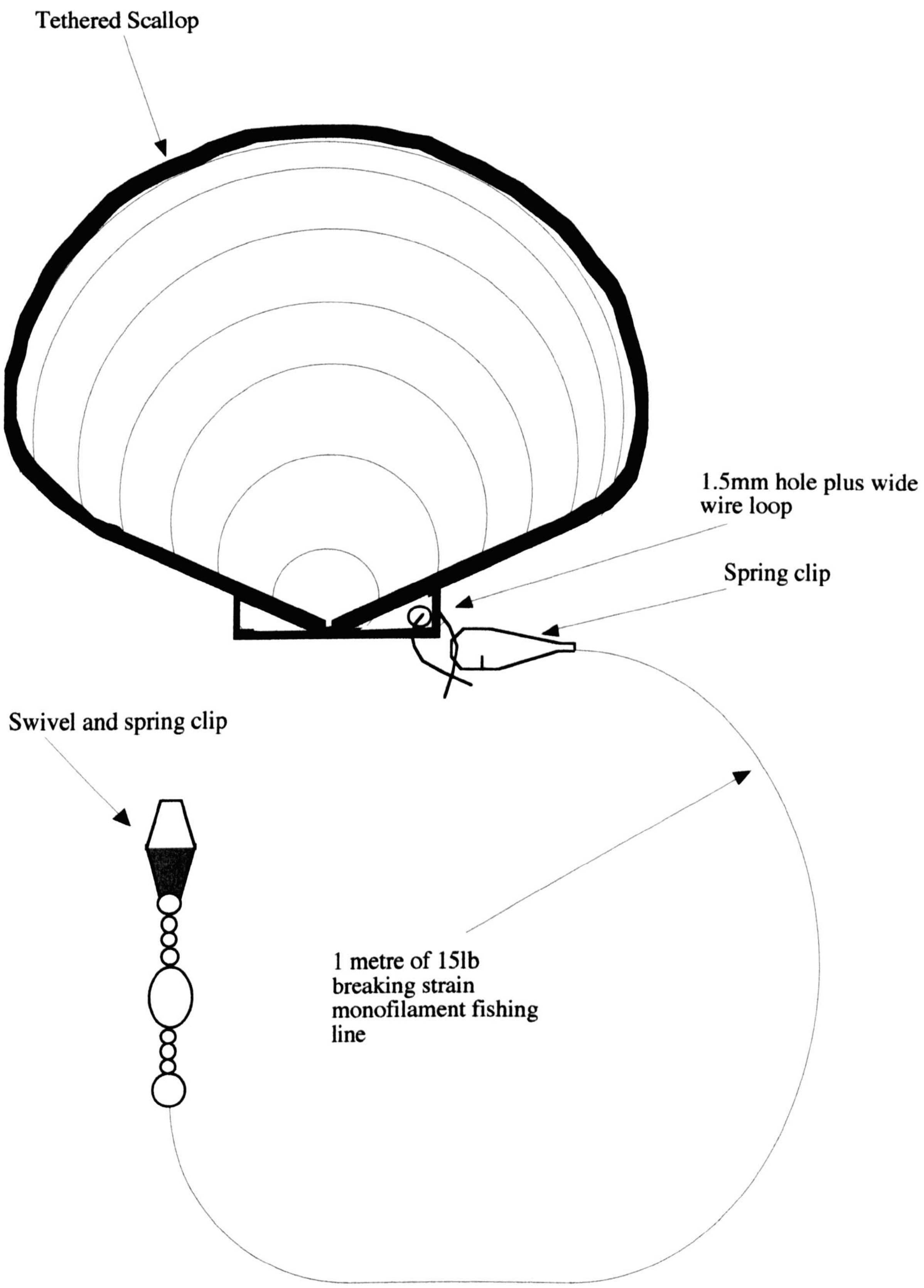


Figure 2.3.
Details of the tethering method used during field and laboratory experiments.

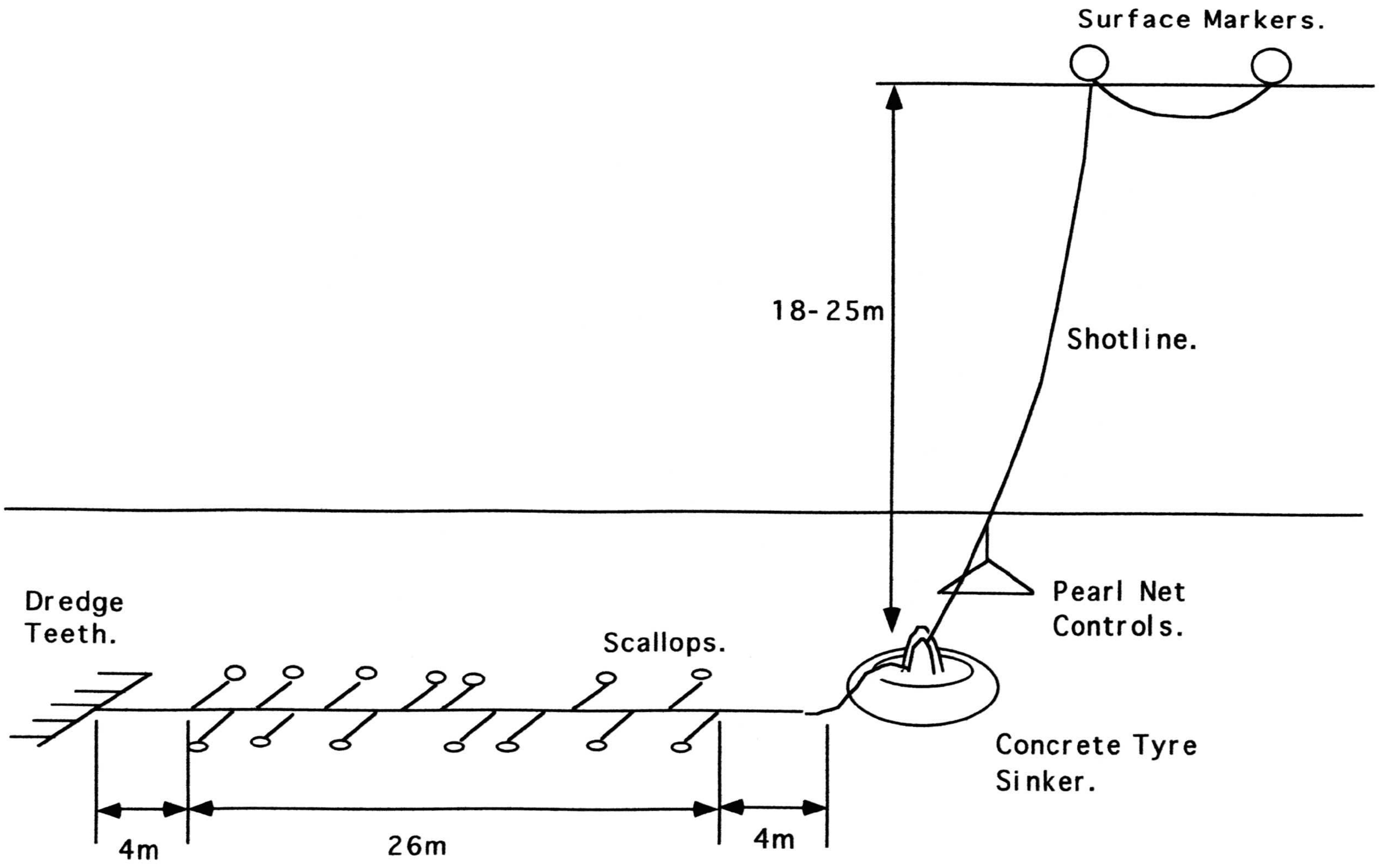
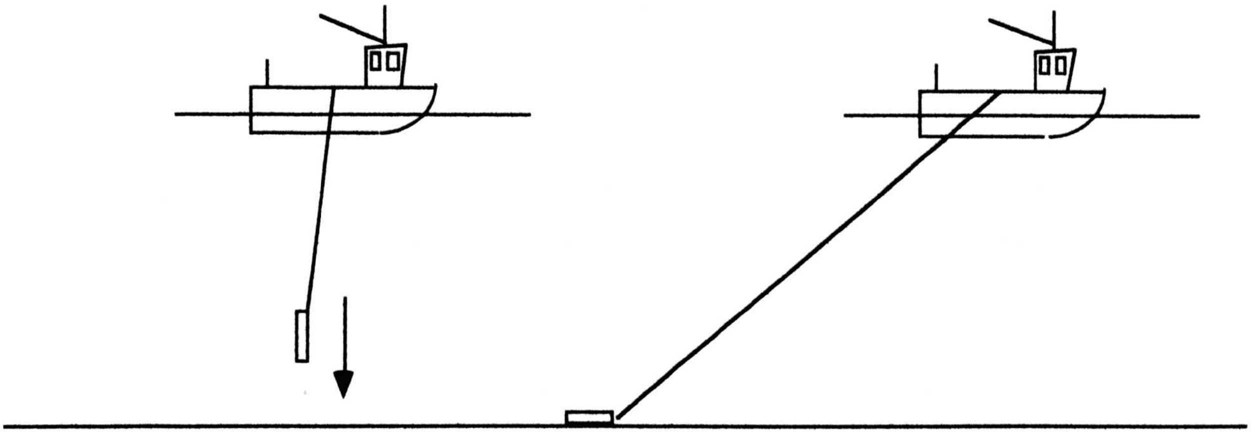
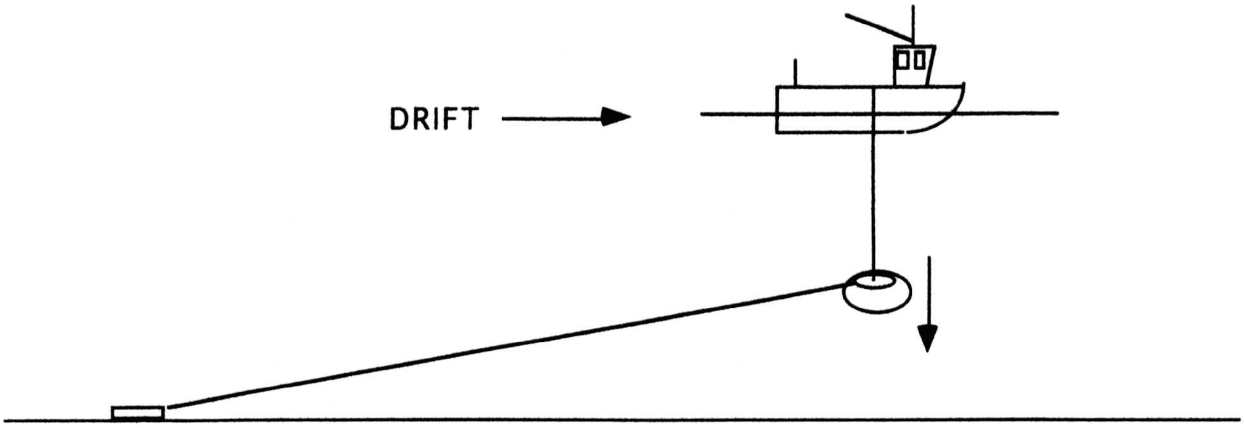


Figure 2.4.
Tethering experiment set up (one replicate) as it appears when deployed on the seabed.

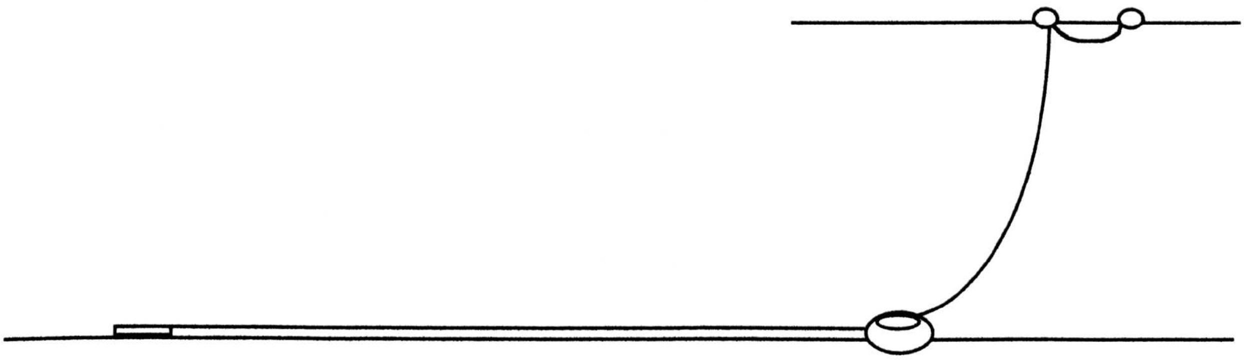


1. Lowering first end weight.

2. Paying out groundline from modified fish box.



3. Lowering concrete end sinker when groundline is fully paid out. Tidal/wind drift maintains groundline tension. Deployment made as rapid as possible to avoid undue dragging of tethered animals along the sea bed.



4. System fully deployed with surface marker buoys.

Figure 2.5.
Method used for deployment of scallop tethering experiments.

type (separately) showed selectivity towards either of the two size class of prey offered. Testing for seasonal variations in relative predation rates was also made possible.

Whenever possible, the experiments were retrieved after a period of between 5-10 days. This period had to be varied according to the time of year since, at certain times, predation of all the tethered animals could occur very quickly. At other times inclement weather greatly delayed retrieval.

Recovering each experimental line entailed picking up the surface marker buoys, hauling in the shotline using the hydraulic pot hauler aboard R.V. *Sula* and then hand hauling the tethering ground line. This was coiled into a bucket and the scallops were removed and checked for predator damage back at PEML. The pearl net control was cut free and placed with its associated ground line. Concrete sinkers and shotlines, when not in use, were left at sea in the Exclusion Zone to minimise handling problems.

2.2.5 Scoring damage inflicted on scallop shells.

Back at PEML the scallops were assessed for survival and shell damage. Predation was divided into categories, according to the damage inflicted on retrieved shells, listed below. A modified version of the five point damage scale used by Whittington (1993) was used to assess the assumed type of predation on tethered animals. In this study the fate of totally lost scallops, where the spring clip and or wire were retrieved, was not initially attributed to crabs whereas Whittington (1993) had attributed this damage category to crabs. This hypothesis was tested using correlation analysis. It must be stressed that the damage categories can only be attributed to assumed predators since other, unknown predators may be present and acting upon the tethered systems. Laboratory work was, however, carried out to try to back up these assumptions.

1) Monofilament snapped - fate of scallop unknown, no predator assigned. (**Total Loss**).

2) Monofilament plus wire loop and snap shackle remaining - no predator assigned initially. (**Scallop lost but clip and/or wire retained**).

3) As 2) but with part of a broken scallop shell or single valve still attached - crab predation most likely. (**Crustacean predation**).

4) As 2) but with a whole complete articulated shell still attached - starfish predation most likely. (**Echinoderm predation**).

5) Scallop recovered alive with no signs of damage. (**Alive**).

The number of scallops suffering each type of damage during each experiment, divided by the number of days deployed, were used to provide mean values of scallops eaten per day for each site and for each damage (predator) type.

Local sea water temperature readings from PEML monitoring records were also employed to be related to the predation level figures. The time consuming and complex nature of the method, coupled with the confined deck area aboard R.V. *Sula*, meant that replicates were severely limited in number.

2.2.6 Scallop sizes - large and small.

The sizes of all scallops deployed during the 1993-4 and 1995 experiments were measured. In total, 11 experiments were deployed using 56 scallops per experiment giving a total of 616 scallops used during 1993-1994. Nine dates were sampled using the same methodology during 1995 giving a total of 504 scallops deployed in this year.

Half of all the scallops deployed were categorised as small and half categorised as large. The scallop size data were tested to ensure that the means of the two size categories were significantly different during both the 1993/4 and 1995 experiments. This was done using the paired sample t test function of the Minitab 8.1 package, using the null hypothesis that $\mu_1 = \mu_2$. This tests whether the mean of sample one can be considered to be equal to the mean of sample two. Minitab was also employed to calculate the means of the two size classes.

2.2.7 Correlating the damage categories (assumed predator types).

Correlation coefficients and significance levels were calculated between each damage type using mean values of damage inflicted per day calculated from the four observations made per damage type on each date i.e. two replicates at each of two sites with no significant differences identified between the two sites. t tests were performed to assess the significance of any relationships identified by the correlation analysis using the method described in Zar (1984).

2.2.8 Plotting predation against date.

Mean values of scallops lost per day for each damage category at each site were plotted against date using the site replicates to calculate mean values and error bars (± 1s.e.). The 1993/4 data and the 1995 data were plotted separately so that year to year comparisons could be made. Independent lines for large and small scallops were plotted on the same axes in each plot.

The ratio of crab to starfish predation and total relative predation (crabs+starfish) was also calculated for each month at each site. These figures were used to plot monthly relative predation levels for each assumed predator and total predation (starfish + crabs) for each month to show any seasonal variations in relative predation levels throughout the year. Plots of assumed crab predation, both including and excluding the occurrences of losses with deformation to spring clips and/or wires, were made for comparative purposes.

2.2.9 Differences in predation rates between sites and dates: 1993/4 data.

Initial analysis of tethering data involved dividing results by scallop size and assumed predator type. For each size class (large and small) and assumed predator type a 2 factor Kruskal-Wallis test (Zar, 1984) was performed. The 2 factors used were site and date, with the response variable being scallops eaten per day. The null hypotheses employed for each analysis were:

H_o = Mean number of scallops lost is the same at both sites sampled.
H_a = Mean number of scallops lost is not the same at both sites sampled.

H_o = Mean number of scallops lost is the same on each date sampled.
H_a = Mean number of scallops lost is not the same on each date sampled.

H_o = There is no significant interaction between these two factors.
H_a = There is a significant interaction between these two factors.

Results are presented in the form of plots of mean numbers of scallops lost to each assumed predator type and ANOVA summary tables indicating the significance or otherwise of the results.

2.2.10 Differences in predation rates on different sizes of scallop.

Subsequent analysis of tethering data involved dividing results by assumed predator type. During 1995 only one site (Exclusion Zone) was sampled and the sites used during 1993-4 were integrated for comparative purposes. For each assumed predator type a 2 factor Kruskal-Wallis test was performed. The 2 factors used were scallop size and date, with the response variable being scallops eaten per day. The null hypotheses employed for each analysis were:

H_o = Mean number of scallops lost is the same for both large and small scallop sizes.
H_a = Mean number of scallops lost is not the same for both large and small scallop sizes.

H_0 = Mean number of scallops lost is the same on each date sampled.
H_a = Mean number of scallops lost is not the same on each date sampled.

H_0 = There is no significant interaction between these two factors.
H_a = There is a significant interaction between these two factors.

Results are presented in the form of plots of mean numbers of scallops lost to each assumed predator type, plus ANOVA summary tables indicating the significance or otherwise of the results. Any significant results arising from these analyses were further investigated using non-parametric multiple comparison tests detailed in Zar (1984). Results of these tests are also presented in summary form.

2.2.11 Comparison of the 1993/4 and 1995 data - year to year variation.

Where the same months were sampled using tethering experiments in different years the data were compared. This should determine whether any observed patterns in predator activity occur at the same times of year or whether the pattern can shift within the year. Table 2.1 shows which months were sampled, using tethering experiments, during which years

Table 2.1 Showing the months sampled during all tethering experiments.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1993									x	x	x	
1994	x	x		x	x	x	x	x	x			
1995		x	x	x	x	x	x	x	x			x

February, April, May, June, July, August and September were all sampled during the 1994 and 1995 tethering experiments. These months were compared on an individual basis using t-tests since month to month variability in relative predation rates was assessed elsewhere and only September was sampled in more than two years.

2.2.12 Assessment of the effect of temperature on predation levels.

Records of mean seawater temperatures are kept by staff at PEML. These data were used in a regression analysis with the level of relative predation observed each month for each predator type and prey size. The results should determine whether the activity of each predator was determined by environmental temperature or whether some other behavioural or environmental factor is acting.

2.3 Results.

2.3.1 Correlating the damage categories (assumed predator types).

Table 2.2a shows that the only potentially significant correlation is between crab predation and loss of scallops where clips or wires were retained. A t test was then performed to assess the significance level of the correlations, in turn, as described by Zar (1984). The null hypothesis employed for the comparison of each correlation coefficient was:-

H_0: rho = 0 with the alternative hypothesis being:-
H_A: rho $\neq$ 0.

Where rho = the population correlation coefficient.

When t observed $\geq$ t tabulated, H_0 is rejected. Therefore, the only significant correlation coefficient identified is that between GCW and CA damage categories - scallop gone with clip and/or wire remaining and crab (assumed) respectively. If the assumption that crushed or chipped shells are attributable to crab predation is correct then the significance level of this correlation ($P < 0.001$) between GCW and CA damage categories suggests that the GCW category may also be attributable to crab predation.

2.3.2 Plotting predation against date for both sampling sites for 1993/4.

Figs. 2.6 and 2.7 show mean numbers of scallops which were assumed to have been consumed by starfish at the Exclusion Zone and Bradda Head sites respectively during the 1993/4 tethering experiments. Both show bimodal feeding patterns through the year with peaks in November 1993 and in April/May 1994, with a minimum during January at the Exclusion Zone site and during February at the Bradda Head site. These plots show that there are times during the year when starfish predation is greatly reduced suggesting that any re-seeding trials could be timed to coincide with periods of low predator activity. This would maximise the chances of survival of re-seeded scallops. There was very little difference between the consumption of large and small scallops at the Bradda Head site (Fig. 2.7). However, there was a greater differential between the size classes at the Exclusion Zone site with more small scallops being consumed consistently throughout the year apart from November 1993 and July to September 1994 (Fig. 2.6). During this latter period consumption of large scallops actually overtook that of small scallops.

Figs. 2.8 and 2.9 show mean numbers of scallops which were assumed to have been consumed by crabs at the Exclusion Zone and Bradda Head sites respectively during the 1993/4 tethering experiments. Both sites show crab predation falling dramatically from September to January with some fluctuations at the Exclusion Zone site. Crab predation then

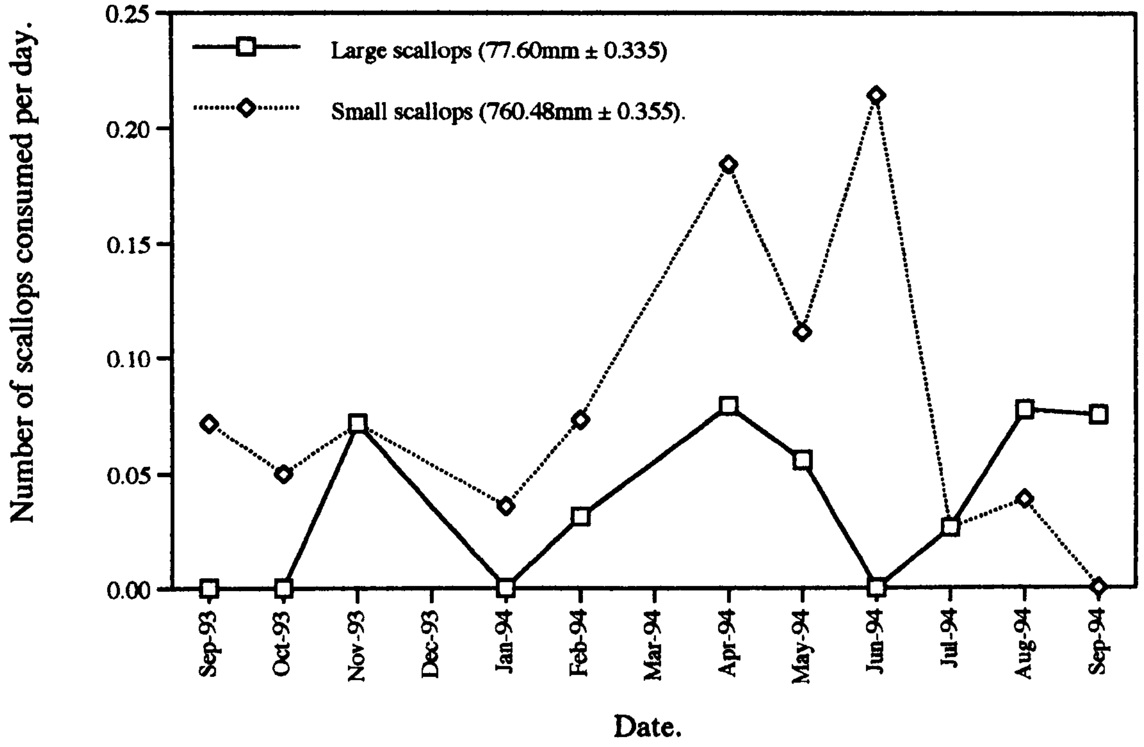


Figure 2.6
Numbers of large and small scallops consumed per day by starfish at the Exclusion Zone site plotted against date for the 1993/4 tethering experiments. Error bars not shown for clarity.

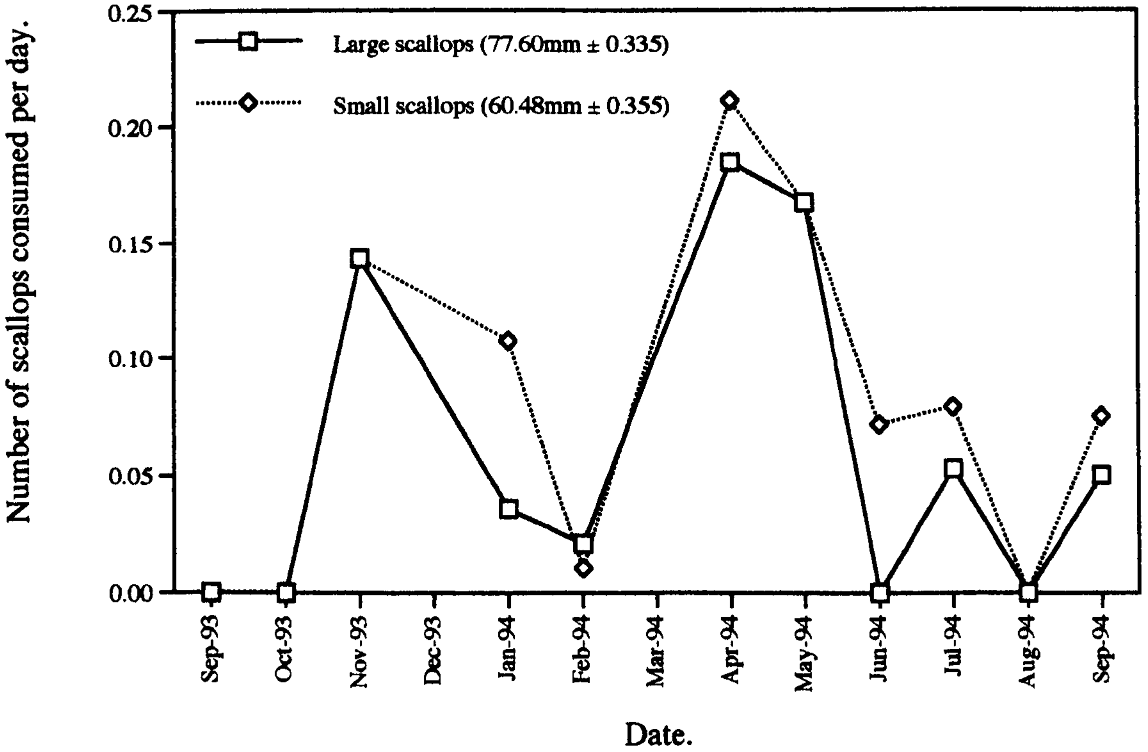


Figure 2.7
Numbers of large and small scallops consumed per day by starfish at the Bradda Head site plotted against date for the 1993/4 tethering experiments. Error bars not shown for clarity.

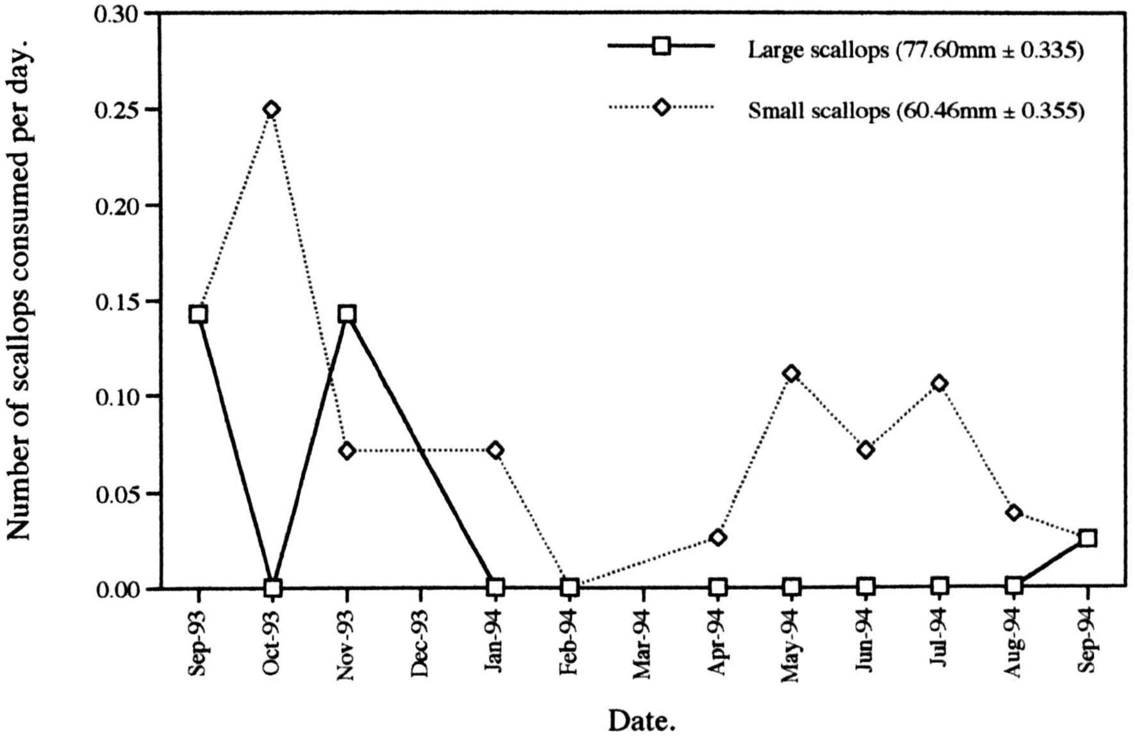


Figure 2.8
Numbers of large and small scallops consumed per day by crabs at the Exclusion Zone site plotted against date for the 1993/4 tethering experiments. Error bars not shown for clarity.

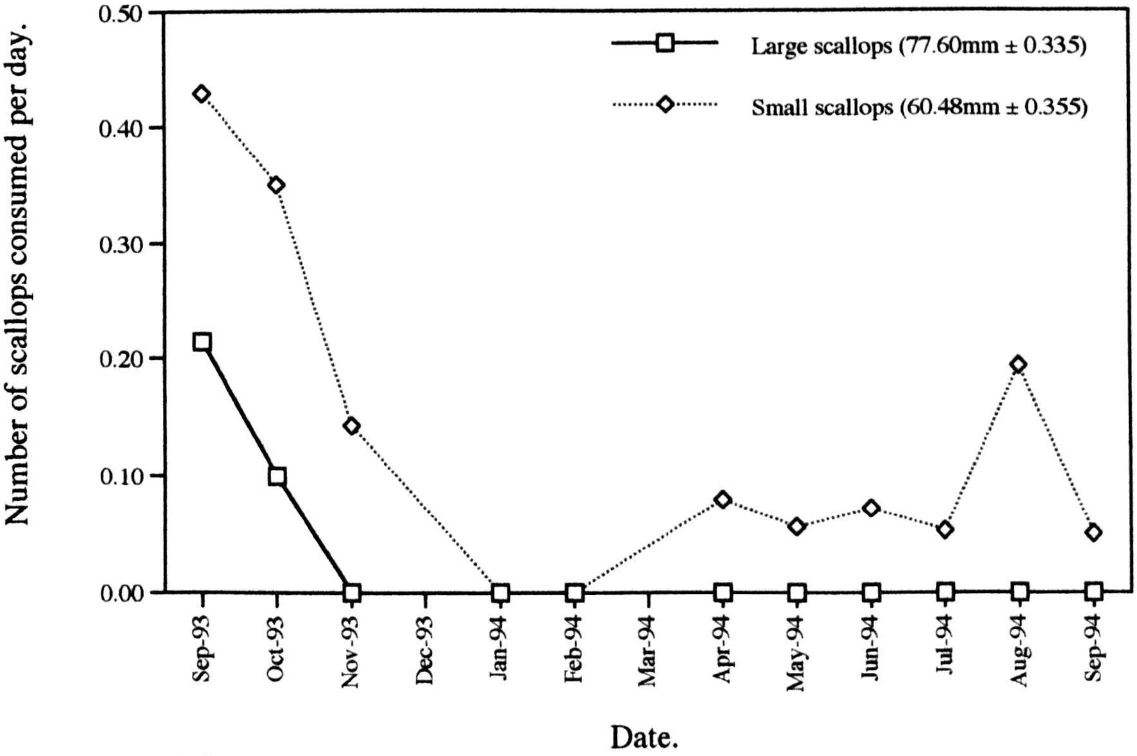


Figure 2.9
Numbers of large and small scallops consumed per day by crabs at the Bradda Head site plotted against date for the during 1993/4 tethering experiments. Error bars not shown for clarity.

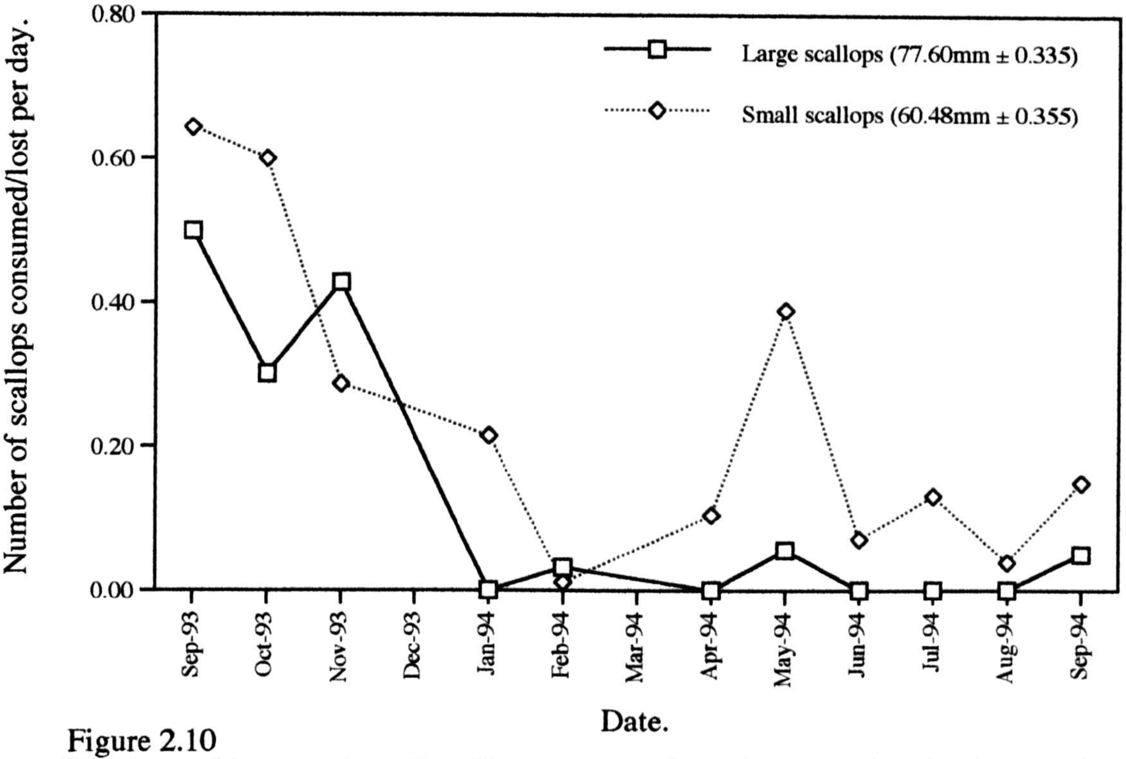


Figure 2.10
Numbers of large and small scallops consumed per day by crabs, plus losses where clips/wires were retained, at the Exclusion Zone site, plotted against date for the 1993/4 tethering experiments. Error bars not shown for clarity.

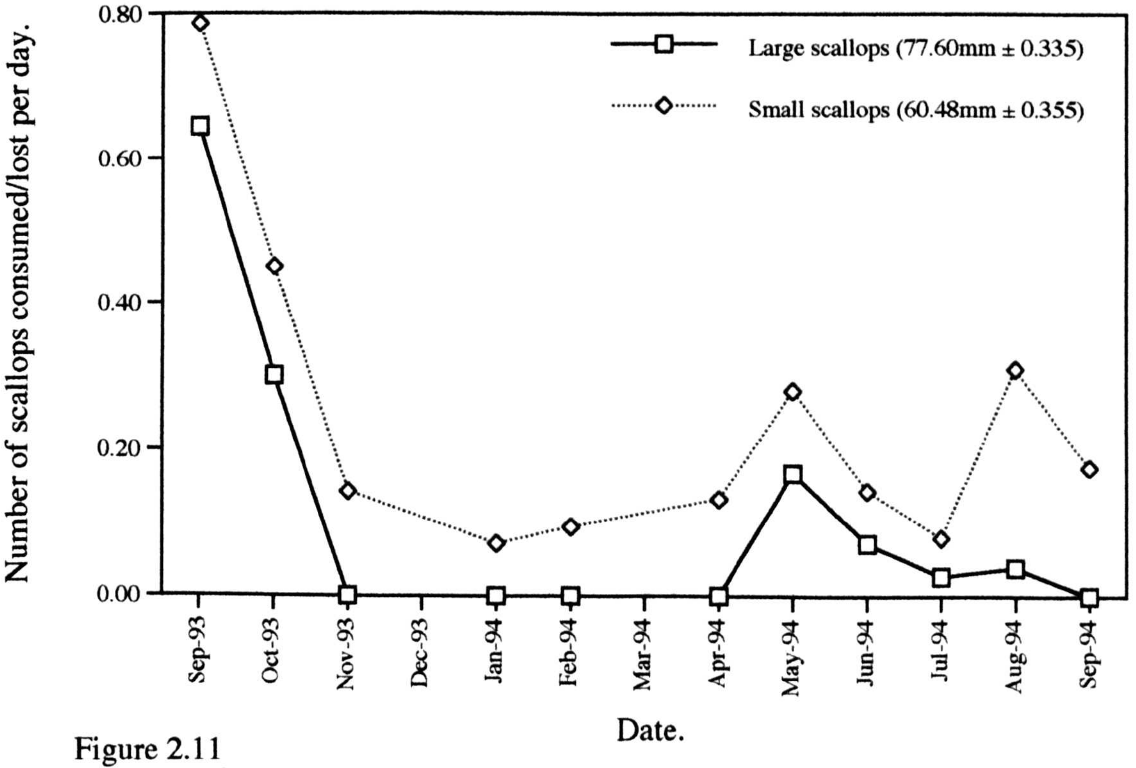


Figure 2.11
Numbers of large and small scallops consumed per day by crabs, plus losses where clips/wires were retained, at the Bradda Head site, plotted against date for the 1993/4 tethering experiments. Error bars not shown for clarity.

Table 2.2

Results of correlation analysis between damage categories during all tethering experiments.

Damage.	**GCW**	**GT**	**CA**
GT	0.383	-	-
CA	0.935	0.113	-
AS	-0.273	0.171	-0.401

GCW - Scallop gone with clip and/or wire remaining.

GT - Scallop gone totally.

CA - Crab predation assumed as indicated by shell remains.

AS - Starfish predation assumed as indicated by shell remains.

Table 2.3

Comparison of correlation coefficients between damage categories using damage inflicted per day for each category. Significant correlations are indicated in bold.

Comparison	**Correlation coefficient (r)**	**S.E. (r)**	**t observed**	**$t_{0.05(2),9}$**	**Result**	**P.**
GCW vs GT	0.383	0.3079	1.2438	2.262	Accept	0.2<P<0.5
GCW vs CA	0.935	0.1182	7.9093	2.262	Reject	**P<0.001**
GCW vs AS	-0.273	0.3207	0.8513	2.262	Accept	0.2<P<0.5
GT vs CA	0.113	0.3312	0.3412	2.262	Accept	P>0.5
GT vs AS	0.171	0.3284	0.5207	2.262	Accept	P>0.5
Ca vs AS	-0.401	0.3054	1.3132	2.262	Accept	0.1<P<0.2

GCW - Scallop gone with clip and/or wire remaining.

GT - Scallop gone totally.

CA - Crab predation assumed as indicated by shell remains.

AS - Starfish predation assumed as indicated by shell remains.

remains low through to March at both sites where it begins to pick up again. Fig. 2.8 suggests that crab predation increased during April and May and then remained fairly constant till July. Crab predation then fell at the Exclusion Zone site while it rose at the Bradda Head site in August 1994 (Fig. 2.9). Both sites then showed a fall to low levels of crab predation in September. These figures show crab predation following an expected pattern for crustacean predators throughout the 1993/4 tethering experiments. It is also evident that small scallops were consumed in much greater numbers at both sites, with large scallops often experiencing zero predation by crabs. Crabs are known to exhibit temperature dependent activity patterns and to engage in annual migrations to offshore grounds in winter as part of their reproductive cycle. The manner in which crabs feed on scallops, by physically breaking open the shell, means that crabs are more likely to be affected by scallop size during feeding experiments. These factors probably explain the observed results.

Figs. 2.10 and 2.11 show mean crab predation combined with scallops which were lost but where tethering clips or wires were retrieved. This combination of results was felt to be justified given the strong correlation observed between these two types of loss i.e. losses where clips or wires were retrieved may well be attributable to crustacean predation. Both sites show increased levels of crab predation in May and both sites show small increases in crab predation on larger scallops. Otherwise the patterns observed are the same as those of Figs. 2.8 and 2.9.

2.3.3 Differences in predation between sites and dates - 1993/4.

The statistical analyses presented here refer to the data presented in graphical format in Figs. 2.6 - 2.11. Results are split by scallop size and analysed for the influence of date and site on scallops consumed.

2.3.3.1 Analysis of results for small scallops.

For these ANOVAs:

Correction factor C = 22275; Total observations N = 44; Total MS = (N(N+1))/12 = 165
Critical value for chi square$_{0.05,1}$ = 3.841; Critical value for chi square$_{005,10}$ = 18.307

Significant results appear in bold.

Table 2.4 shows that significant differences occurred in the numbers of small scallops which were assumed to be lost to crustacean predators between dates sampled during the 1993/4 tethering experiments. No differences were detectable between the two sites sampled. This shows that, for small scallops, date was a significant factor in affecting the level of assumed crustacean predation, while the location of tethering experiments was not significant.

Table 2.4

Testing the significance of sampling site and date where crab predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	79.11	1	0.48	0.25<P<0.5
Date	3482.5	10	21.11	**0.01<P<0.025**
Interaction	737.89	10	4.47	0.9<P0.95
Cells (Error)	4299.5	21		

Table 2.5

Testing the significance of sampling site and date where starfish predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	2.27	1	0.014	0.9<P<0.95
Date	2430.75	10	14.73	0.1<P<0.25
Interaction	1319.23	10	7.80	0.5<P<0.75
Cells (Error)	3752.25	21		

Table 2.6

Testing the significance of sampling site and date where retaining clips/wires were retrieved.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	84.57	1	0.51	0.25<P<0.5
Date	3653.63	10	22.14	**0.01<P<0.025**
Interaction	1379.81	10	8.36	0.5<P<0.75
Cells (Error)	5118	21		

Table 2.7

Testing the significance of sampling site and date where assumed crab predation and losses where clips/wires were retrieved were combined.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	0.091	1	0.0006	P>0.975
Date	4378.88	10	26.54	**0.001<P<0.005**
Interaction	1050.28	10	6.37	0.75<P<0.9
Cells (Error)	5429.25			

Table 2.5 shows that no significant differences occurred in numbers of small scallops which were assumed to be lost to echinoderm predators between dates sampled during the 1993/4 tethering experiments. This shows that, for small scallops, neither date nor location of tethering experiments was a significant factor in affecting the level of assumed echinoderm predation during the 1993/4 tethering experiments.

Table 2.6 shows that significant differences occurred in numbers of small scallops which were lost where tethering clips or wires were retrieved between dates sampled during the 1993/4 tethering experiments. No differences were detectable between the two sites sampled. This indicates that, for small scallops, date was a significant factor in affecting this type of loss, while the location of tethering experiments was not significant.

Table 2.7 shows that significant differences occurred in numbers of small scallops which were assumed to be lost to crustacean predators, including losses where tethering clips/wires were retained, between dates sampled during the1993/4 tethering experiments. No differences were detectable between the two sites sampled. The combination of assumed crustacean predation and losses where clips/wires were retained appears to be justified, given the results of the correlation analysis above.

2.3.3.2 Analysis of results for large scallops.

For these ANOVAs:

Correction factor $C = 22275$; Total observations $N = 44$; Total MS = $(N(N+1))/12 = 165$

Critical value for chi square$_{0.05,1}$ = 3.841; Critical value for chi square$_{005,10}$ = 18.307

Significant results are highlighted in bold.

This analysis shows that no significant differences occurred in the numbers of large scallops which were assumed to be lost to echinoderm predators between dates sampled during the 1993/4 tethering experiments. No differences were detectable between the two sites sampled. Thus, for large scallops, neither date nor location of tethering experiments were significant factors in affecting the level of assumed echinoderm predation during the 1993/4 tethering experiments.

Table 2.9 shows that no significant differences occurred in numbers of large scallops which were assumed to be consumed by crabs between the dates or sites sampled during the1993/4 tethering experiments. For large scallops, neither date nor site was a significant factor in affecting the level of assumed crab predation.

Table 2.8

Testing the significance of sampling site and date where starfish predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	61.46	1	0.37	0.5<P<0.75
Date	914.38	10	5.54	0.75<P<0.9
Interaction	2062.92	10	12.50	0.25<P<0.5
Cells (Error)	3038.75	21		

Table 2.9

Testing the significance of sampling site and date where crab predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	0.023	1	0.00014	P>0.975
Date	1091.75	10	6.62	0.75<P<0.9
Interaction	453.73	10	2.75	0.975<P<0.99
Cells (Error)	1545.5			

Table 2.10

Testing the significance of sampling site and date where only retaining clips/wires were retrieved.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	13.09	1	0.079	0.75<P<0.9
Date	3172.63	10	19.23	**0.025<P<0.05**
Interaction	955.53	10	5.79	0.75<P<0.9
Cells (Error)	4141.25	21		

Table 2.11

Testing the significance of sampling site and date where assumed crab predation and losses where clips/wires were retrieved were combined.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Site	16.57	1	0.10	0.75<P<0.9
Date	3333.5	10	20.20	**0.025<P<0.05**
Interaction	1001.68	10	6.07	0.75<P<0.9
Cells (Error)	4351.75	21		

Significant differences occurred in the numbers of large scallops which were lost where tethering clips or wires were retrieved between dates sampled during the1993/4 tethering experiments (Table 2.10). No differences were detectable between the two sites sampled. This shows that, for large scallops, date was a significant factor in affecting this type of loss while the location of tethering experiments was not significant.

Significant differences occurred in the numbers of large scallops which were assumed to be lost to crustacean predators, including losses where tethering clips/wires were retained, between dates sampled during the1993/4 tethering experiments (Table 2.11). No differences were detectable between the two sites sampled. The combination of assumed crustacean predation and losses where clips/wires were retained appears to be justified given the results of the correlation analysis above.

The plots of relative predation throughout the year assumed to be by starfish at the Bradda Head and Exclusion Zone sites (Figs. 2.6 and 2.7) both show good agreement in terms of peaks and troughs in relative predation rates. No statistical difference could be identified between the two sites. The Exclusion Zone plot showed relative predation level rising from zero in September 1993 to a small peak in November 1993, with a subsequent fall to January 1994 followed by a rise to a second peak in April 1994 (Fig. 2.6). Slight fluctuations occurred in a generally falling trend thereafter to September 1994.

The Bradda Head site showed peaks at the same times as those observed in the Exclusion Zone plots (Fig. 2.7). The peaks appear to be similar in magnitude but were more clearly defined. The Bradda Head plot also shows a steeper drop after the April 1994 peak falling steeply to a low level in June 1994 with a further, smaller, drop in August 1994, followed by a rise in September 1994. This indicates that starfish behaviour was consistent across a large area.

The graphs of relative predation assumed to be by crabs both show good agreement in terms of peaks and troughs in relative predation rates (Figs. 2.8 and 2.9) and there was no statistical difference between the two sites. The Exclusion Zone plot (Fig. 2.8) shows a very large peak in crab predation rate during October 1993, falling to a minimum between February and April before rising to a well defined but much smaller peak in May. June to August figures show similar, low levels of relative predation rate while there was a rise in September which, unfortunately, could not be monitored further due to adverse weather conditions. It is assumed that the observed peaks and troughs in the levels of assumed crab predation result from biological and environmental constraints on the predator. During the autumn female *Cancer pagurus* migrate offshore as part of their breeding cycle (Edwards, 1979). The large peaks in feeding activity observed in the graphs at both sites may result from migrating crabs passing through the experimental site. After this large peak the relative predation rate falls rapidly with the onset of winter. The associated temperature drop will also lead to a reduction in activity of the remaining inshore males (Edwards, 1979; Bennett & Brown, 1983). This would tend to suppress observed crab predation.

A very similar pattern emerged from the Bradda Head data (Fig. 2.9) with the autumn peak occurring slightly earlier in September. Relative predation rate then fell to a minimum in January and rose to a smaller peak, again in May, although this peak lacked the definition of that identified at the Exclusion Zone site. A second small peak in assumed crab predation occurred in August but the whole period from April through to September showed a fairly even level of crab predation with the small, poorly defined peaks mentioned and there was no rise in September. Relative predation rates during the autumn peaks were very similar (0.80 mean at the Exclusion Zone and 0.85 mean at Bradda Head) while the May peak at the Exclusion Zone was slightly higher than that at Bradda Head. At the Bradda Head site from April to September there appeared to be a higher level of relative predation, except during May when the relative rate at the Exclusion Zone was higher. This may compensate for the lower level overall at this site which might help to explain why no statistical difference could be identified between the sites. The fall in relative predation rate after the autumn peak appeared to be more rapid at the Bradda Head site. The inability to identify statistical differences will not have been aided by the low level of replication employed (n=2 at each site). Figs. 2.10 and 2.11 show effectively the same patterns as the results for crabs at the two sites sampled (Figs. 2.8 and 2.9).

At each sampling date crabs generally consumed the smaller scallops in greater numbers than the larger scallops. The larger size class of scallop did not appear to be consumed at all between January and August at the Exclusion Zone site and between January and September at the Bradda Head site. In general, the smaller scallops were consumed during these periods at both sites. Prey size selectivity among crustacean predators has been demonstrated in the field (Elner & Lavoie, 1983) and in the laboratory (Lake et al., 1987) so this result is not entirely unexpected. One theory put forward to explain this selectivity is that crustacean predators will not attempt to attack a prey item if the risk of sustaining claw damage in doing so is significant (Juanes, 1992).

2.3.4 Plotting predation against date - combining sampling sites 1993/4.

Fig. 2.12 shows mean starfish predation, where the results from both the Bradda Head and Exclusion Zone experiments were combined for the 1993/4 tethering experiments. The graph fairly clearly shows a bimodal feeding pattern with peaks in November of 1993 and April of 1994. After the second peak, the level of starfish predation remains low from June/July

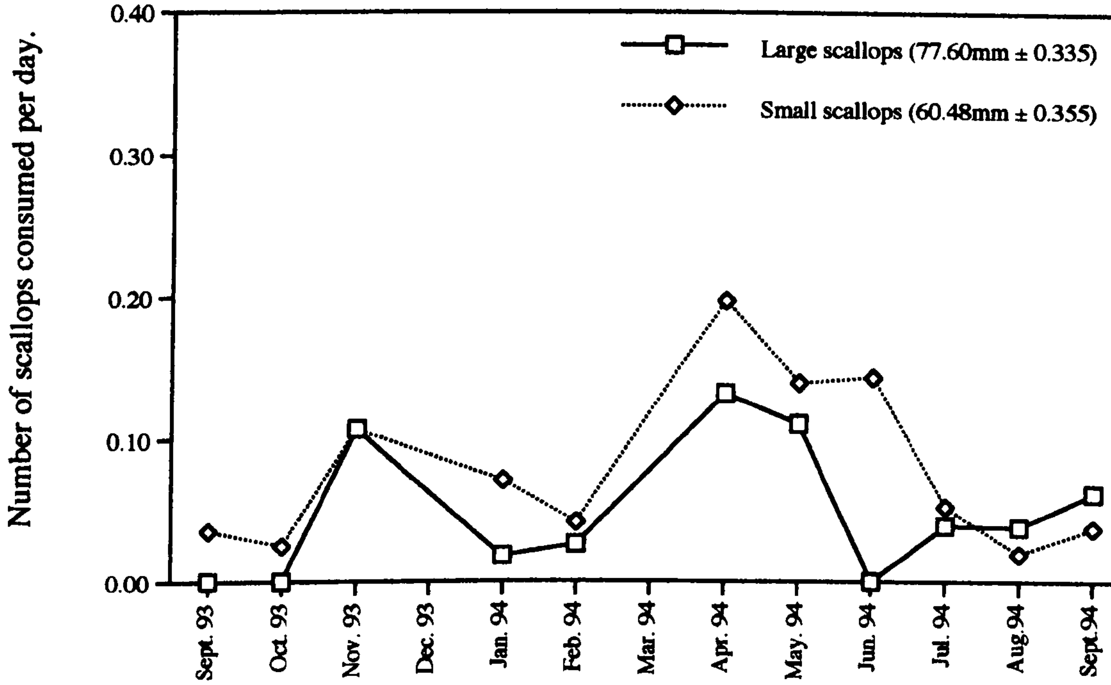


Figure 2.12
Numbers of large and small scallops consumed per day by starfish plotted against date. Combined Exclusion Zone and Bradda Head results (4 replicates) for the 1993/4 tethering experiments. Error bars not shown for clarity.

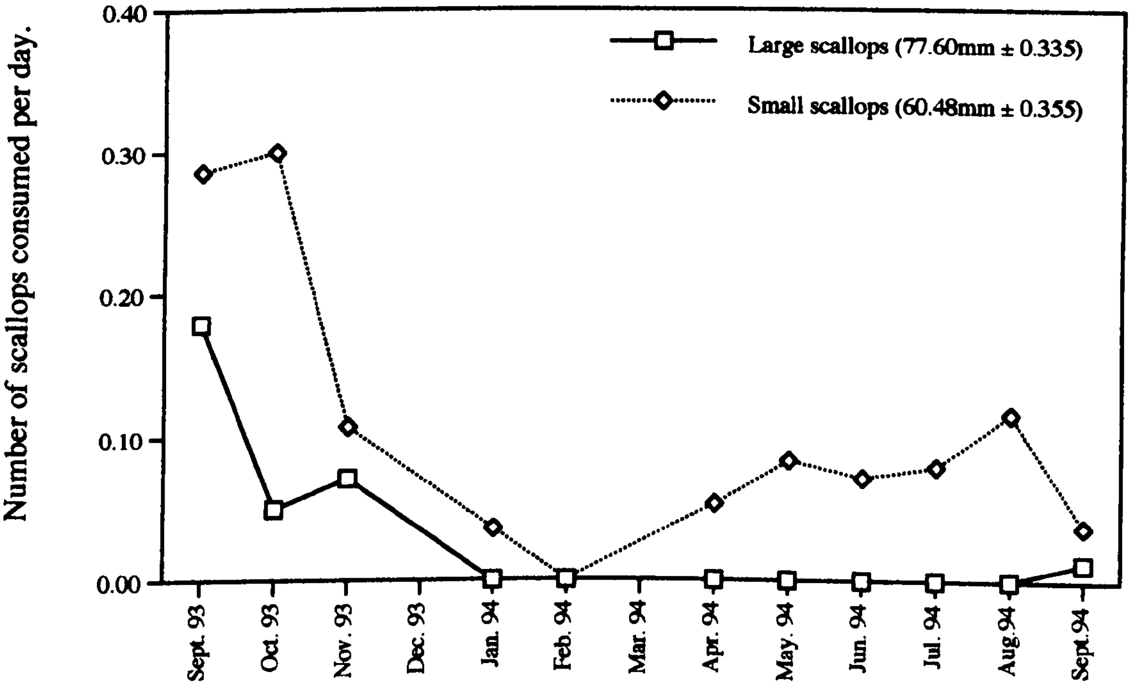


Figure 2.13
Numbers of large and small scallops consumed per day by crabs plotted against date. Combined Exclusion Zone and Bradda Head results (4 replicates) for the 1993/4 tethering experiments. Error bars not shown for clarity.

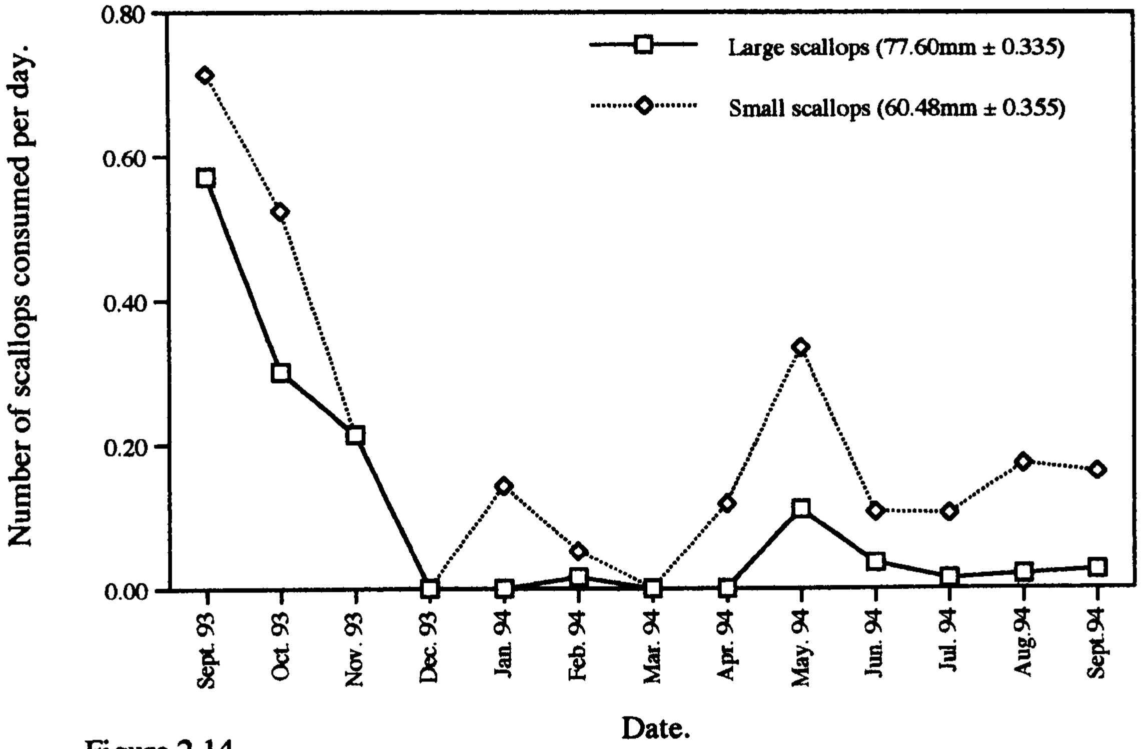


Figure 2.14
Numbers of large and small scallops consumed per day by crabs plus losses where clips/wires were retrieved plotted against date. Combined Exclusion Zone and Bradda Head results (4 replicates) for the 1993/4 tethering experiments. Error bars not shown for clarity.

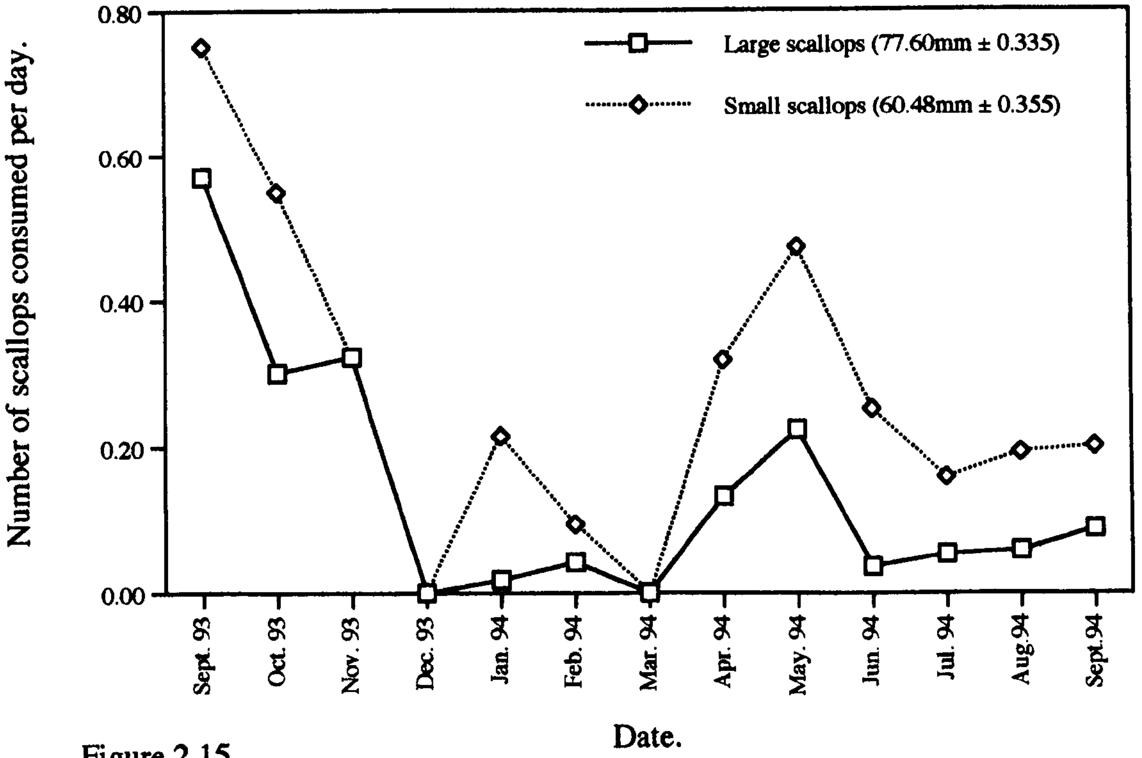


Figure 2.15
Numbers of large and small scallops combining losses due to crabs and starfish plus losses where clips/wires were retrieved plotted against date. Combined Exclusion Zone and Bradda Head results (4 replicates) for the 1993/4 tethering experiments. Error bars not shown for clarity.

through to September. Small scallops were taken in slightly higher numbers but overall there appears to be little difference in predation levels on large and small scallops during these experiments. These results indicate that June or July would be the best time of year for re-seeding as far as echinoderm predation is concerned. If this pattern were consistent from year to year then re-seeded scallops would experience lower levels of threat from starfish during the initial period after re-seeding.

Fig 2.13 shows mean crab predation, where the results from both the Bradda Head and Exclusion Zone experiments were combined for the 1993/4 tethering experiments. Crab predation dropped from a high point in September/October 1993 to a minimum in January/February 1994 before rising again to plateau during May to July. A slight rise occurred during August, prior to a fall in September 1994, which mirrored the fall in 1993 but from a much lower initial starting point. Crab predation is almost exclusively directed at the smaller size class of scallop presented in these experiments. High levels of crab predation during September and October probably result from increased levels of activity with higher temperature, and from increased encounters of scallops with crabs as the crabs migrate to offshore areas at this time of year. The requirement for crabs to break scallop shells in order to consume them will explain the difference in predation levels on large and small scallops. Fig. 2.13 indicates that the best time for re-seeding juvenile scallops, as far as crab predation is concerned, would be in December, after the autumn feeding peak and before the increase in activity in early summer.

Fig. 2.14 shows mean crab predation combined with scallops which were lost but where tethering clips/wires were retrieved. This combination was felt to be justified for the reasons detailed above. Essentially this graph shows the same pattern of activity as the graph detailing crab activity (Fig. 2.13). However, Fig. 2.14 does indicate slightly higher levels of predation on the large size class of scallops compared to Fig. 2.13. There is also evidence of a small peak in crab predation on smaller scallops during January and the rise in crab predation in May appears to be magnified compared to Fig. 2.13. These results may indicate that crabs are more active during the winter months than was first assumed.

Fig. 2.15 shows mean total predation for the 1993/4 tethering experiments. This graph shows the combined effects of all predators on the tethered scallops throughout the year. The graph indicates that scallops are potentially vulnerable to predation throughout the year with only December 1993 and March 1994 giving no losses due to predation. Again the larger size class of scallop fares better than the small size class. The only sustained period of lower predation appears to extend from June to September 1994. Low levels of predation are also experienced between December 1993 and March 1994 but the peak in predation on small scallops during January 1994 shows that predators are still active at this time of year.

2.3.5 The effects of prey size and sampling date - 1993/4 data.

For these ANOVAs:

Correction factor C = 174262; Total observations N = 88; Total MS = (N(N+1))/12 = 652.67
Critical value for chi square$_{0.05,1}$ = 3.841; Critical value for chi square$_{005,10}$ = 18.307

Significant results are highlighted in bold.

This analysis shows that significant differences occurred in the numbers of scallops which were lost where echinoderm predation was assumed only between dates and not between size class of scallops used during the 1993/4 tethering experiments. Scallop size was therefore not a significant factor in affecting the number of scallops lost to starfish during the 1993/4 tethering experiments, while sampling date was a significant factor.

Significant differences occurred in the numbers of scallops which were lost where crustacean predation was assumed (Table 2.13) both between dates and between size class of scallops used during the 1993/4 tethering experiments. This shows that both scallop size and sampling date were significant factors in affecting the number of scallops lost to crustacean predators during the 1993/4 tethering experiments.

Table 2.14 shows that significant differences occurred in numbers of scallops which were lost where tethering clips or wires were retrieved both between dates and between size class of scallops used during the 1993/4 tethering experiments. Both scallop size and sampling date were significant factors in affecting the number of scallops lost by this means during the 1993/4 tethering experiments.

Table 2.15 shows that significant differences occurred in the numbers of scallops which were assumed to be consumed by crabs, including losses where tethering clips/wires were retained. Both sampling date and prey size were identified as significant factors during the 1993/4 tethering experiments. This shows that both scallop size and sampling date were significant factors in affecting the number of scallops lost to crustacean predators, including losses where clips/wires were retained, during the 1993/4 tethering experiments.

Where significant results were identified in Tables 2.12 - 2.15, Tukey multiple comparison tests were carried out in order to identify where the differences lay. The results of the Tukey multiple comparison tests are summarised in Tables 2.16 - 2.22.

Table 2.12

Testing the significance of size and date where starfish predation was assumed.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**H**	**P**
Size	1764.05	1	2.70	0.1<P<0.25
Date	14094.19	10	21.59	**0.01<P<0.025**
Interaction	3973.64	10	6.09	0.75<P<0.90
Cells (Error)	19831.88	21		

Table 2.13

Testing the significance of prey size and sampling date where crab predation was assumed.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**H**	**P**
Size	9786.18	1	14.99	**P<0.001**
Date	12396.69	10	18.99	**0.025<P<0.005**
Interaction	3487.51	10	5.34	0.75<P<0.90
Cells (Error)	25670.38	21		

Table 2.14

Testing the significance of prey size and sampling date where only retaining clips/wires were retrieved.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**H**	**P**
Size	2806.92	1	4.30	**0.025<P<0.05**
Date	23175.63	10	35.51	**P<0.001**
Interaction	3707.46	10	5.68	0.75<P<0.90
Cells (Error)	29690	21		

Table 2.15

Testing for significance of site and date where assumed crustacean predation and losses where clips/wires were retrieved were combined.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**H**	**P**
Size	8700.28	1	13.33	**P<0.001**
Date	26397.75	10	40.45	**P<0.001**
Interaction	2366.22	10	3.63	0.95<P<0.975
Cells (Error)	37464.25	21		

Table 2.16

Multiple Comparison Test Results Using Date as the Factor - Assumed Starfish Predation for the 1993/4 Tethering Experiments.

SE = $\sqrt{(s^2/an)} = \sqrt{((19831.9/21)/8)} = 10.865$; Critical value of $q_{0.05,\infty,11} = 4.552$. Summary includes the sampling date and rank sum for that date.

Oct 93	**Sept 93**	**Aug 94**	**Feb 94**	**Jan 94**	**Jun 94**	**Jul 94**	**Sept 94**	**Nov 93**	**May 94**	**Apr 94**
218.5	230	270	323.5	333.5	343.5	356.5	365	407	498	570.5

Table 2.17

Multiple Comparison Test Results Using Date as the Factor - Assumed Crab Predation for the 1993/4 Tethering Experiments.

SE = $\sqrt{(s^2/an)} = \sqrt{((25670.38/21)/8)} = 12.36$; Critical value of $q_{0.05,\infty,11} = 4.552$. Summary includes the sampling date and rank sum for that date.

Feb 94	**Jan 94**	**Jun 94**	**May 94**	**Apr 94**	**Sept 94**	**Aug 94**	**Jul 94**	**Nov 93**	**Oct 93**	**Sept 93**
220	262.5	305	309	324.5	336	354.5	368	371.5	493.5	571.5

Table 2.18

Multiple Comparison Test Results Using Prey Size as the Factor - Assumed Crab Predation for the 1993/4 Tethering Experiments.

Large	**Small**
1494	2422

Table 2.19

Multiple Comparison Test Results Using Date as the Factor - Losses where Clips/Wires were Retrieved for the 1993/4 Tethering Experiments.

SE = $\sqrt{(s^2/an)} = \sqrt{((29690/21)/8)} = 13.29$; Critical value of $q_{0.05,\infty,11} = 4.552$. Summary includes the sampling date and rank sum for that date.

Jul 94	**Apr 94**	**Jan 94**	**Aug 94**	**Feb 94**	**Jun 94**	**Sept 94**	**Nov 93**	**May 94**	**Oct 93**	**Sept 93**
245.5	249	249	252	283	285.5	341.5	365	468	525.5	652

Table 2.20

Multiple Comparison Test Results Using Prey Size as the Factor - Losses where Clips/Wires were retrieved for the 1993/4 Tethering Experiments.

Large	**Small**
1709.5	2206.5

Table 2.21

Multiple Comparison Test Results Using Date as the Factor - Assumed Crab Predation Combined with Losses where Clips/Wire were retrieved for the 1993/4 Tethering Experiments.

SE = $\sqrt{(s^2/an)} = \sqrt{((37464.25/21)/8)}$ = 14.933; Critical value of $q_{0.05,\infty,11}$ = 4.552. Summary includes the sampling date and the rank sum date.

Feb 94	**Jun 94**	**Apr 94**	**Jan 94**	**Jul 94**	**Aug 94**	**Sept 94**	**Nov 93**	**May 94**	**Oct 93**	**Sept 93**
228	248.5	257.5	257.5	269.5	284	311.5	388.5	430	583.5	657.5

Table 2.22

Multiple Comparison Test Results Using Prey Size as the Factor - Assumed Crab Predation Combined with Losses where Clips/Wires were Retrieved for the 1993/4 Tethering Experiments.

Large	**Small**
1520.5	2395.5

Table 2.16 shows that the two peaks of the observed bimodal feeding pattern of the starfish (Fig. 2.12) are both statistically significantly different from the results for the other months sampled, and that the two peaks are statistically different from one another. This shows that the feeding peaks are significant and that the peak in April/May 1994 is significantly higher than the peak in November 1993. For the 1993/4 experiments there was no statistical difference between the numbers of large and small scallops consumed by starfish.

Table 2.17 shows that, where crab predation was positively identified, the highest levels of crab predation occurred during the later months of the years sampled. The results also suggest that crab predation was significantly higher during the 1993/4 tethering experiments than during the 1995 tethering experiments. Only two sizes of scallops were used in these experiments - Table 2.18 therefore shows that a significant difference exists between the number of large and small scallops assumed to have been consumed by crabs. The rank sums indicate that a larger number of small scallops were consumed compared to large scallops.

Assuming that losses where tethering clips/wires were retrieved are attributable to crab predation then Table 2.19 shows that crab predation was highest during the latter part of 1993, with a further high peak in May 1994. These results appear to agree generally with the results presented for crab predation in Table 2.17. Generally the earlier months of the years sampled have lower levels of crab predation, while months later in the years sampled have higher levels of crab predation. The agreement between this type of loss and losses where crab predation was positively identified, combined with the significant correlation between these two types of loss, strongly suggest that losses where clips/wires were retrieved are attributable to crab predation. Combining these two types of loss for further analysis would therefore appear to be justified. Only two sizes of scallops were used in these experiments - Table 2.20 therefore shows that a significant difference exists between the number of large and small scallops have been lost where retaining clips/wires were retrieved. The rank sums indicate that a larger number of small scallops were consumed compared to large scallops.

Table 2.21 shows that the highest levels of crab predation on tethered scallops tended to occur quite late in 1993 and in May 1994. The highest values of crab predation were observed in September and October 1993. November 1993 was also identified as a month where many scallops were consumed by crabs, or were lost but where clips/wires were retrieved. The earlier months of 1994 are identified as having lower levels of crab predation. May 1994 is identified as a high crab predation month. Fig. 2.14 shows this peak quite clearly. Whether the losses where clips/wire were retrieved can actually be attributed to crabs will determine how accurate this analysis is compared to Table 2.17 which analyses only those results where crab predation was positively identified. Only two sizes of scallops were used in these experiments - Table 2.22 therefore shows that a significant difference exists between the number of large and small scallops lost where the two categories of assumed crab predation were combined. The rank sums indicate that a larger number of small scallops were consumed compared to large scallops.

When the site data were combined for the 1993/4 experiments, statistical analysis demonstrated that the two observed feeding peaks for echinoderm predators were significant, compared to the remainder of the year (Fig. 2.12). The analysis also showed that the spring feeding peak (April/May) was significantly higher than the winter peak (November). The size of scallops presented during these experiments did not have a significant effect on the number of scallops consumed by echinoderm predators (Tables 2.12). January, February, June, July and September were grouped by the analysis as periods of lower predator activity (Table 2.16).

During the 1993/4 tethering experiments no statistically significant differences in crab predation could be identified between the Bradda Head and Exclusion Zone sites. Subsequent analysis where the data from the two sites were combined (Figs 2.12 - 2.16) showed the highest levels of crustacean predator activity to be in September/October 1993 (Fig. 2.13). The level of crustacean predation on both size classes of scallop presented then fell to a minimum in February 1994. Crab predation on the small scallops rose again during the spring/summer, while crab predation on the larger scallops ceased until September. This follows the expected pattern of crustacean activity with temperature. The higher sea temperatures later in the year tend to be associated with higher levels of crustacean predator activity. The 1993/4 tethering experiments also showed that size of scallop prey was a significant factor in determining the number of scallops consumed by crustacean predators (Tables 2.13 and 2.18). Significantly more small scallops were consumed by crabs than large scallops during these experiments. A very similar pattern in predator activity was observed when the losses due to crustacean predators were combined with losses where tethering clips/wires were retained. The final results of the multiple comparison test after the Kruskal-Wallis analysis were better defined with less ambiguity. Possibly the only difference arose where May 1994 was placed higher in the order of rank sums (Table 2.19). Prey size was also found to be a significant factor for this combination (Table 2.20), with more small scallops than large consumed in this way.

2.3.6 Plotting damage inflicted per day against date - 1995.

Fig. 2.16 shows mean starfish predation plotted against time. The graph shows the same bimodal feeding pattern identified in the 1993/4 data but this time the first peak in starfish predation occurs in March/April rather than in November. The minimum between the two peaks occurs in May/June and the second peak arrives in July. The whole plot of mean

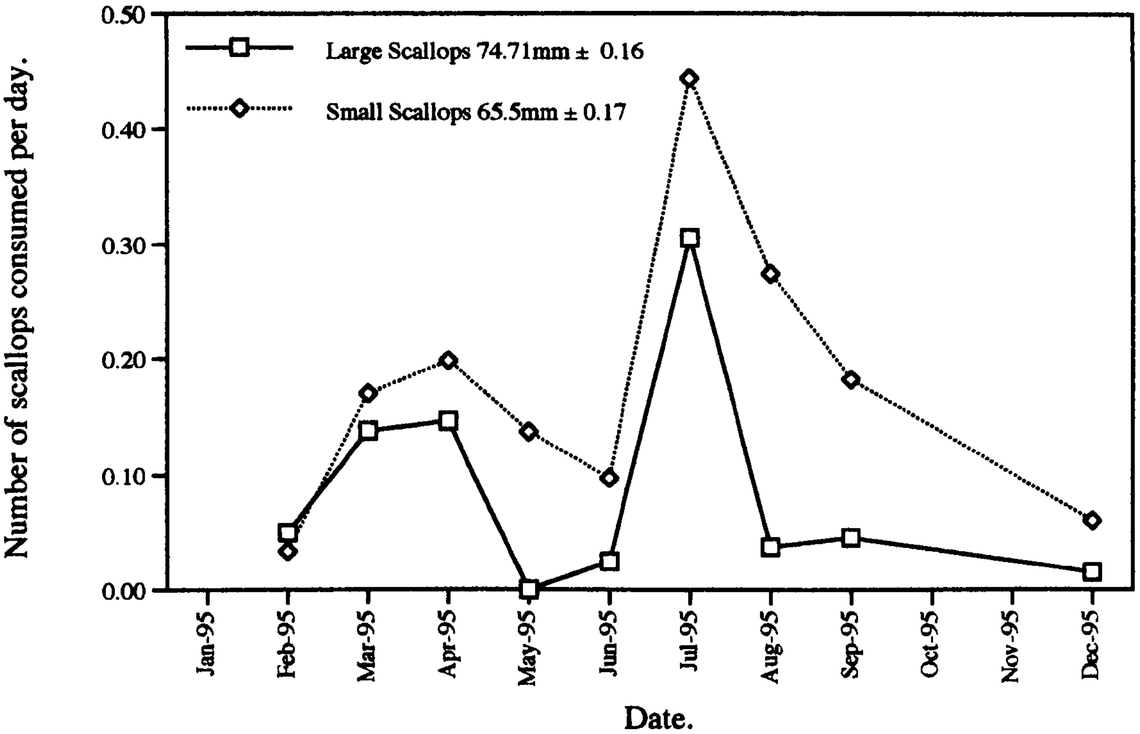


Figure 2.16
Numbers of large and small scallops consumed per day by starfish plotted against date for the 1995 tethering experiments. Error bars not shown for clarity.

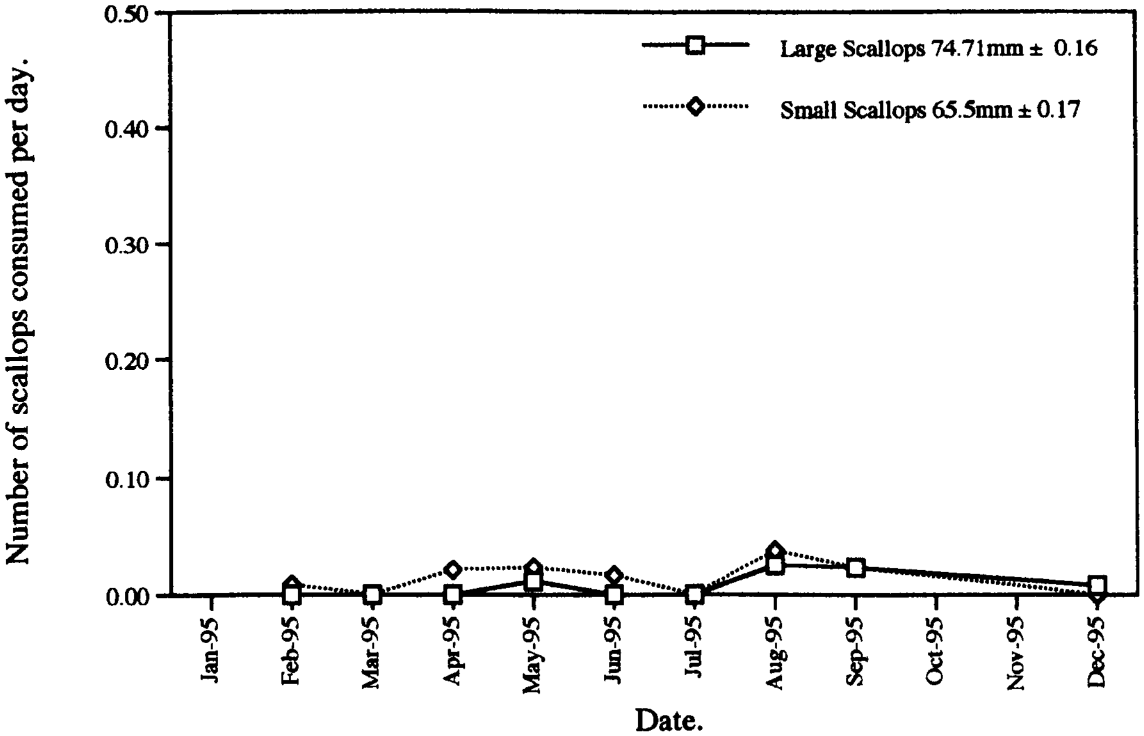


Figure 2.17
Numbers of large and small scallops consumed per day by crabs plotted against date for the 1995 tethering experiments. Error bars not shown for clarity.

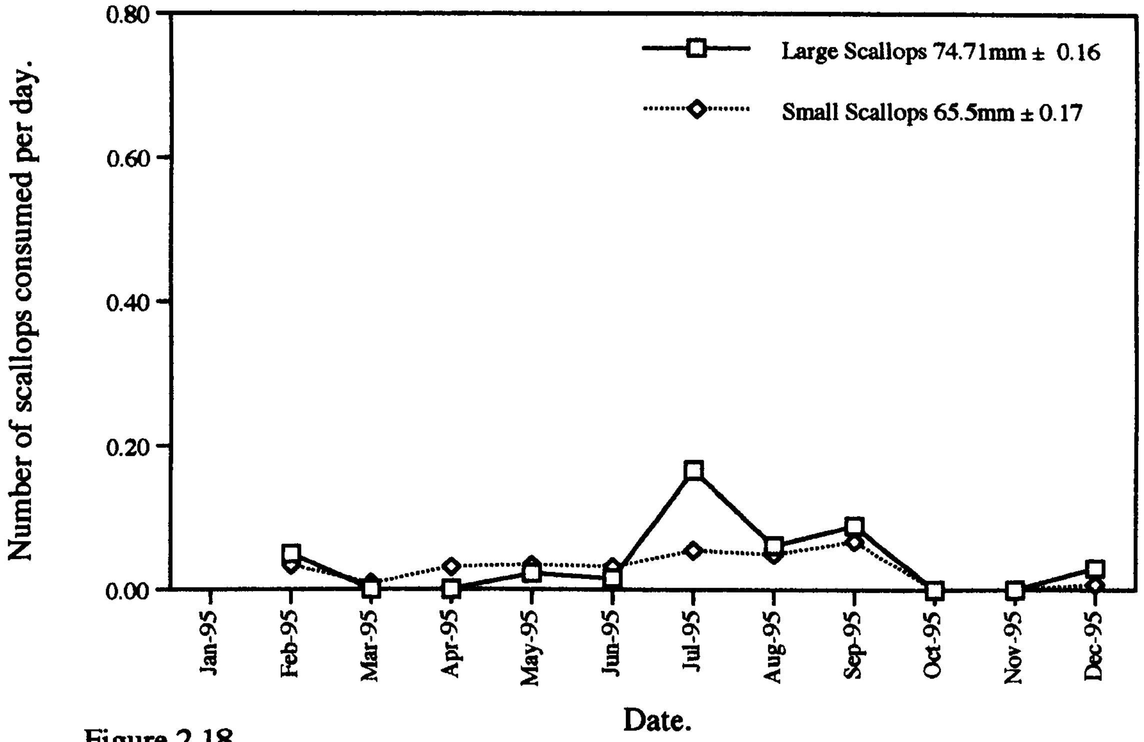


Figure 2.18
Numbers of large and small scallops consumed by crabs combined with losses where clips/wires were retained plotted against date for 1995 tethering experiments. Error bars not shown for clarity.

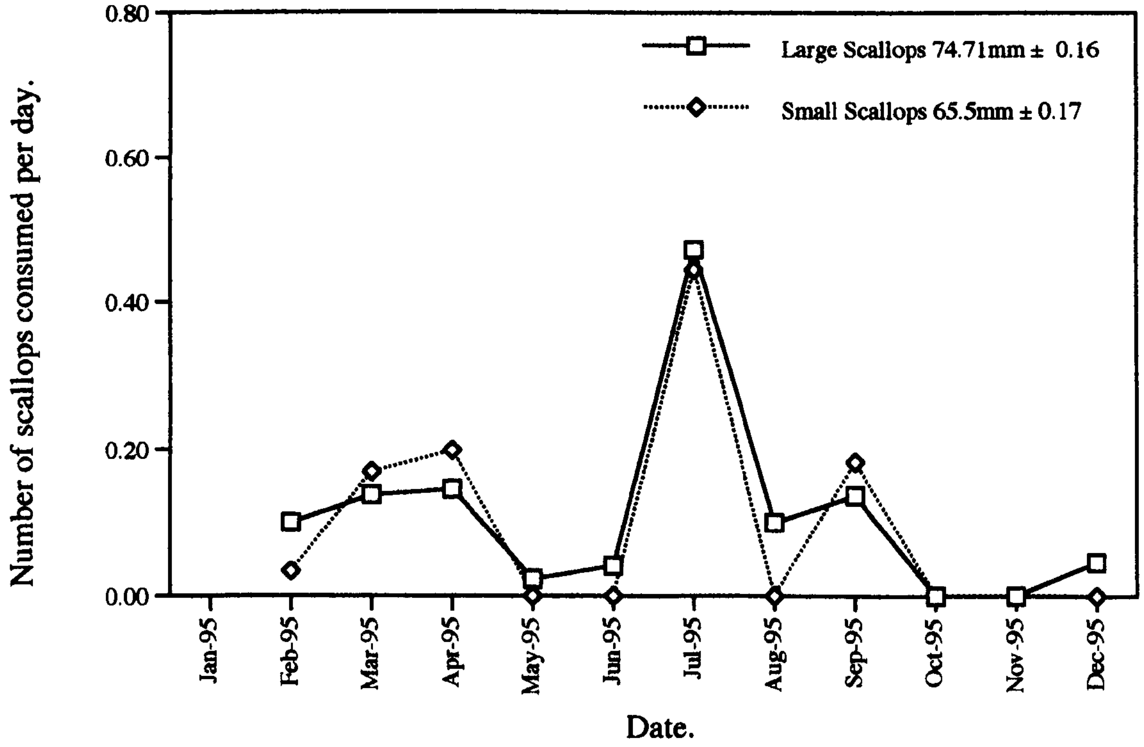


Figure 2.19
Numbers of large and small scallops consumed per day by crabs and starfish plus losses where clips/wireswere retained plotted against date for the 1995 tethering experiments. Error bars not shown for clarity.

relative starfish predation appears to have been shifted to the right compared to the 1993/4 results. Both peaks and trough occurred later in the year in 1995 compared to 1993/4. This suggests that some factor delayed the feeding or reproductive cycle of the starfish during 1995.

Fig. 2.17 shows mean crab predation plotted against time. The graph shows very little crab predation occurred during the 1995 tethering experiments. Very low levels of crab predation are evident from April to June and in August and September. Otherwise very few scallops were consumed by crabs during 1995, compared to the 1993/4 experiments. The 1995 experiments coincided with a marked increase in the scale of the Port Erin crab fishery which may explain the lower levels of crab predation. There simply may not have been enough crabs in the area to generate the same levels of predation on tethered scallops. Temperature records also indicate that seawater temperature near Port Erin was lower during 1995 than 1994.

Fig. 2.18 shows mean crab predation combined with losses where clips/wires were retrieved. Again this shows a marked decrease in predation compared to the 1993/4 experiments. Low levels of crab predation in the first 6 months of the year were followed by a peak in crab activity during July which fell towards October and thereafter remained low. The observed peak in July was actually greater in magnitude than the corresponding summer levels observed during 1993/4 but was much shorter lived. The 1993/4 results also show a much earlier rise in crab predation during the spring, rather than in the summer. This suggests that crab as well as starfish predation was later in 1995, compared to 1993/4.

Fig. 2.19 shows combined total predation on tethered scallops plotted against time during 1995. This shows a low magnitude, long lasting (2 month) peak in predation during March and April, followed by a minimum in May and June. This in turn was followed by a second, much larger but shorter lived (1 month) peak in predation in July. Predation then fell away with some variation to October, after which it remained low.

2.3.7 Analysis of the effects of prey size and sampling date - 1995 data.

For these ANOVAs:

Correction factor C = 174262; Total observations N = 72; Total MS = (N(N+1))/12 = 438
Critical value for chi square$_{0.05,1}$ = 3.841; Critical value for chi square$_{005,8}$ = 15.507

Significant results are highlighted in bold.

Table 2.23

Testing the significance of prey size and sampling date where starfish predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Size	4720.68	1	10.78	**0.001<P<0.005**
Date	14659.75	8	33.47	**P<0.001**
Interaction	3203.57	8	7.31	0.5<P<0.75
Cells (Error)	22584	18		

Table 2.24

Testing the significance of prey size and sampling date where crab predation was assumed.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Size	406.13	1	0.93	0.25<P<0.5
Date	2728.5	8	6.23	0.5<P<0.75
Interaction	1017.25	8	2.32	0.95<P<0.975
Cells (Error)	4151.88	18		

Table 2.25

Testing the significance of prey size and sampling date where only retaining clips/wires were retrieved.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Size	355.56	1	0.81	0.25<P<0.5
Date	4488.5	8	10.25	0.1<P<0.25
Interaction	999.19	8	2.28	0.95<P<0.975
Cells (Error)	5843.25	18		

Table 2.26

Testing the significance of prey size and sampling date where assumed crab predation and losses where clips/wires were retrieved were combined.

Source of Variation	Sum of Squares	Degrees of Freedom	H	P
Size	74.01	1	0.17	0.5<P<0.75
Date	5953.69	8	13.59	**0.05<P<0.1**
Interaction	1909.55	8	4.36	0.75<P<0.90
Cells (Error)	7937.25	18		

Table 2.23 shows that both sampling date and prey size class were significant factors affecting assumed starfish predation during the 1995 tethering experiments. This contrasts with the analysis of the 1993/4 data where only sampling date was identified as a significant factor.

However, neither sampling date nor prey size were significant factors in affecting assumed predation by crabs during the 1995 tethering experiments (Table 2.24). This contrasts with the 1993/4 results where both factors were found to be significant. This difference may well stem from the increase in activity of the local crab fishery and consequent reduction in crab numbers in the experimental areas. Far fewer scallops were consumed by crabs during the tethering experiments in 1995 compared with 1993/4.

Neither sampling date nor prey size were significant factors in affecting losses where clips/wires were retrieved during the 1995 tethering experiments (Table 2.25). This contrasts with the 1993/4 results, where both factors were found to be significant. Given that this type of loss correlates strongly with assumed crab predation, these results provide further evidence that the two types of loss are indeed linked and that losses where clips/wires were retrieved are attributable to crab predation. Again the observed differences between the 1993/4 and 1995 experiments probably stems from the increase in activity of the local crab fishery and consequent reduction in crab numbers in the experimental areas. Far fewer scallops were consumed by crabs during the 1995 tethering experiments than during the 1993/4 experiments.

Only sampling date was identified as a significant factor affecting assumed crab predation combined with losses where clip/wires were retrieved (Table 2.26). The combination of these two types of loss gives a significant result where individually neither type of loss gave significant results for the two factors analysed. The significance of the sampling date probably results from the higher number of large scallops lost with retained clips/wires during July.

Where significant results were identified in Tables 2.23 - 2.26 Tukey multiple comparison tests were carried out in order to identify where the differences lay. The results of the Tukey multiple comparison tests are summarised in Tables 2.27 - 2.29.

Table 2.27 shows that the two peaks in the bimodal feeding pattern of starfish are statistically distinct both from one another and from the other months in the year. The second peak in starfish predation is higher than the first, as was the case for the 1993/4 tethering experiments. The two peaks occurred in March/April 1995 and July 1995. This second peak in July was not observed in the 1993/4 experiments. The months of May, June, December

Table 2.27

Multiple Comparison Test Results Using Date as the Factor - Assumed Starfish Predation for the 1995 Tethering Experiments.

$SE = \sqrt{(s^2/an)} = \sqrt{((22584/17)/8)} = 12.89$; Critical value of $q_{0.05,\infty,9} = 4.387$. Summary includes sampling date and rank sum for that date.

December	**May**	**February**	**June**	**September**	**August**	**March**	**April**	**July**
160	171.5	186.5	216	276.5	334.5	374	396	513
———	———	———	———	———		———	———	———
					———	———		

Table 2.28

Multiple Comparison Test Results Using Prey Size as the Factor - Assumed Starfish Predation for the 1995 Tethering Experiments.

Large	**Small**
1022.5	1605.5
———	———

Table 2.29

Multiple Comparison Test Results Using Date as the Factor - Crab Predation Combined with Losses where Clips/Wires were Retained for the 1995 Tethering Experiments.

$SE = \sqrt{(s^2/an)} = \sqrt{((5843.25/17)/8)} = 6.555$; Critical value of $q_{0.05,\infty,9} = 4.387$. Summary includes sampling date and rank sum for that date.

Mar	**Apr**	**May**	**Jun**	**Dec**	**Aug**	**Sept**	**Feb**	**Jul**
218	220	251.5	261.5	275	297	323	370	416
———	———				———	———	———	———
				———	———			
		———	———	———				

and February gave the lowest observed levels of starfish predation for the 1995 tethering experiments. Only two sizes of scallops were used in these experiments - Table 2.28 therefore shows that a significant difference exists between the number of large and small scallops assumed to have been consumed by echinoderm predators. The rank sums indicate that a larger number of small scallops were consumed compared to large scallops. This contrasts with the 1993/4 results where no difference was identified between numbers of large and small scallops consumed by starfish.

Crab predation during the 1995 tethering experiments was generally highest during the months of July, August, September and February and lowest during the months of March and April (Table 2.29). The combined results for crab predation, plus losses where clips/wires were retrieved, were significant between dates but no prey size effect was detected. This could result from the very low overall levels of crab predation during the 1995 tethering experiments. This may have been a consequence of increased crab fishing activity in the area which was observed during the course of running the experiments. When viewed independently, neither the crab results alone nor the losses with clip/wire retention alone showed significant differences between dates or prey sizes. This was likely to be for the same reason given above.

The results of the analysis of the 1995 tethering experiments demonstrated certain similarities to the 1993/4 experiments but also showed some differences in starfish activity (Fig. 2.16). Unlike the 1993/4 results, scallop size was found to be a significant factor in determining the level of predation with significantly more small scallops being consumed than large scallops (Table 2.28). Analysis revealed two statistically significant peaks in echinoderm predation during the year in March/April and in July/August (Table 2.27). Again, the earlier peak was significantly smaller than the later peak. The 1995 peaks both arose later in the year than those identified during the 1993/4 experiments. The fact that the 1993/4 experiments showed a peak in November 1993 suggests a third peak during the year. Unfortunately, bad weather precluded sampling during the later months of 1994 and 1995 so this could not be substantiated.

The 1995 tethering experiments indicated that, for crustacean predators, neither size of scallop prey nor date significantly affected the number of scallops consumed (Table 2.24). The graphs of damage inflicted by crabs against time, for the two size classes of scallop, appear to show much lower overall levels of crab predation through the year (Fig. 2.17). The most marked differences occurring in the period April to August for small scallops. Very little crab predation occurred during 1995 on the tethering experiments. This coincided with a significant increase in crab fishing from Port Erin where hundreds of crabs were observed being landed from the surrounding waters which had not previously been fished so intensively.

Evidence of a bimodal feeding pattern in *Asterias* has been previously presented by Doering (1982) and of a winter (February) feeding minimum by Castle (1972). The reason put forward for this winter minimum was temperature dependent feeding activity with low temperatures causing low feeding rates. The subsequent peak is thought to be a necessary precursor to spawning which occurs in spring and which would require energy for gonad development (Gangue & Van Impe, 1977). The data presented in the graphs of assumed starfish predation (Figs. 2.6, 2.12 and 2.16) all show this bimodal feeding phenomenon. Comparing the graphs obtained for assumed starfish predation to those obtained for assumed crab predation (Figs. 2.8, 2.13 and 2.17) it can be seen that starfish appeared to feed throughout a greater proportion of the experimental periods, although they did not quite achieve the same peak levels as the crabs. Throughout the year the overall percentages of scallops assumed to have been taken by starfish and crabs seem to bear this out, with starfish achieving a slightly higher overall assumed consumption rate (13.3%) compared to crabs (9.6%).

The 1993/4 results showed that 65.9% of the large scallops used in the tethering experiments survived intact. This figure does not take into account any total losses (8.4%) which may or may not have survived. This compares with 52.2% which survived intact during the 1995 experiments (12.3% totally lost). Assumed crab predation accounted for only 3.25% of the large size class during 1993/4 and 2% during 1995 which suggests that this size of scallop might successfully avoid or minimise predation by crustacean predators in the field. However, the results of the correlation analysis between crab damage and losses with clips or wires retained suggest that the latter category was also attributable to crab predation. Combining these figures gives an overall crab predation rate of 14.9% during 1993/4 and 11.8% during 1995.

The smaller size class of scallop proved to be far more susceptible to predation with only 39% overall survival during 1993/4 and 37.5% during 1995. These figures do not include total losses which may or may not have survived - 6.5% during 1993/4 and 9% during 1995. Assumed crab predation on small scallops accounted for 15.9% of losses during 1993/4 and 4.5% of losses during 1995. This suggests a reduction in crab predation on small scallops during 1995 by a factor of more than 3. Combining these figures with losses where clips/wires were retrieved gives losses to crustacean predators of 38.7% during 1993/4 and 10.2% during 1995. This indicates nearly a fourfold reduction in crustacean predation on small tethered scallops during 1995. Comparing crab predation on small and large scallops indicates that a higher percentage of small scallops were consumed than large scallops during both 1993/4 and 1995 tethering experiments. The data also show that far fewer scallops overall were consumed by crabs during the 1995 experiments than during the 1993/4 experiments. This suggests that crabs were either less active or that fewer were present in the experimental area during 1995.

Overall predation appeared to be high during autumn, falling off over winter to a minimum in December, reaching a smaller peak in January, followed by a minimum in March before rising again through April and May. A drop to sustained, lower levels of relative predation then begins and continues till September. The winter and spring peaks appear to be largely due to starfish, while the autumn peak appeared to be largely due to crabs. The plots for assumed crab predation on the larger size class of scallop suggest that the level of relative predation was low or zero from January 1994 to August 1994. The second starfish feeding peak fell to a minimum and remained low from July 1994 to September 1994. This period appeared to be the longest sustained period of low relative predation during the course of the 1993 - 1994 tethering experiments. Consequently, it is tentatively suggested that July would be the best month to seed scallops in a re-seeding trial as this would, on the strength of the data collected so far, provide the re-seeded animals with approximately 2-3 months of lower predation pressure.

2.3.8 Comparing the 1993/4 tethering data with the 1995 tethering data.

Figs. 2.20 - 2.26 show scallops consumed per day plotted against sampling date for starfish and crabs. Each graph compares data from the 1993/4 and the 1995 tethering experiments. Graphs are presented for each assumed predation category for both size class of scallop used during these experiments. Only months which were sampled during both sets of experiments were compared.

Fig. 2.20 compares starfish predation on the small size class of scallops between the 1993/4 and the 1995 tethering experiments. The plots for each year look very similar from February to June but diverge significantly from July to September. For the1993/4 plot the April peak is the second of the two feeding peaks observed while for the 1995 plot the April peak is the first feeding peak of that year and the July peak, where the plots diverge, is the second. The results obtained show that starfish probably do have two peaks of feeding activity within any year but that these feeding peaks can occur at different times within that period. Environmental parameters may affect this behaviour which would mean that identification and monitoring of these parameters would be necessary prior to re-seeding trials.

Fig. 2.21 compares crab predation on the small size class of scallop between the 1993/4 and 1995 tethering experiments. Both plots show crab predation increasing from winter into

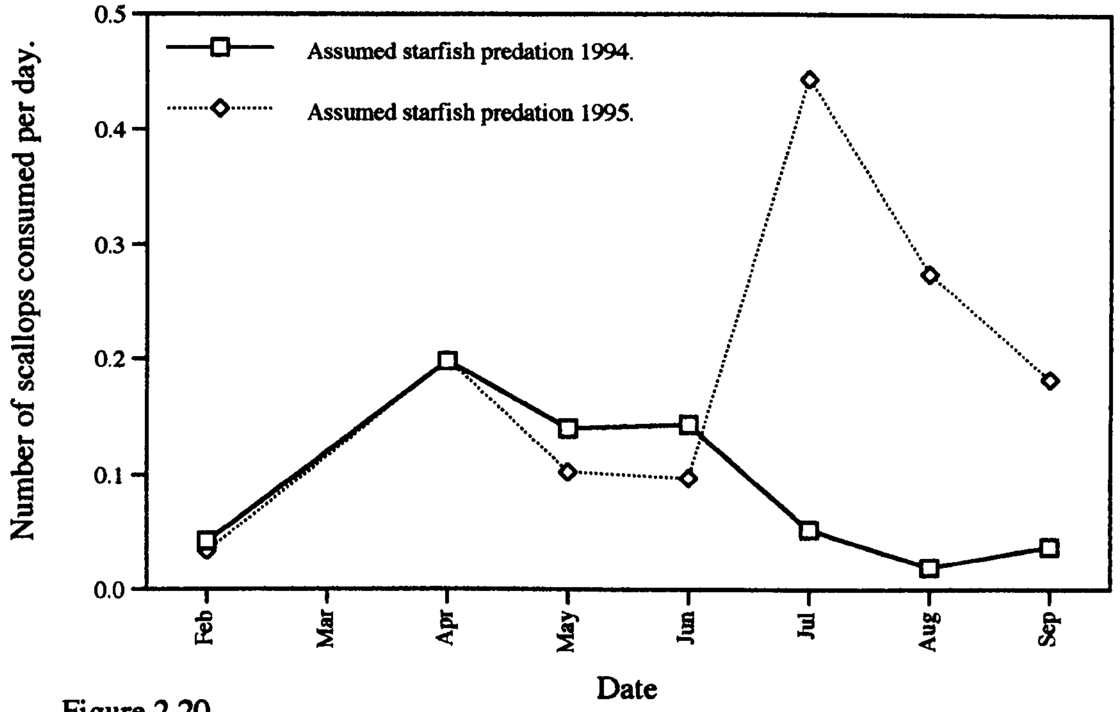


Figure 2.20
Numbers of small scallops consumed per day by starfish plotted against date comparing results from the 1994 and 1995 tethering experiments.

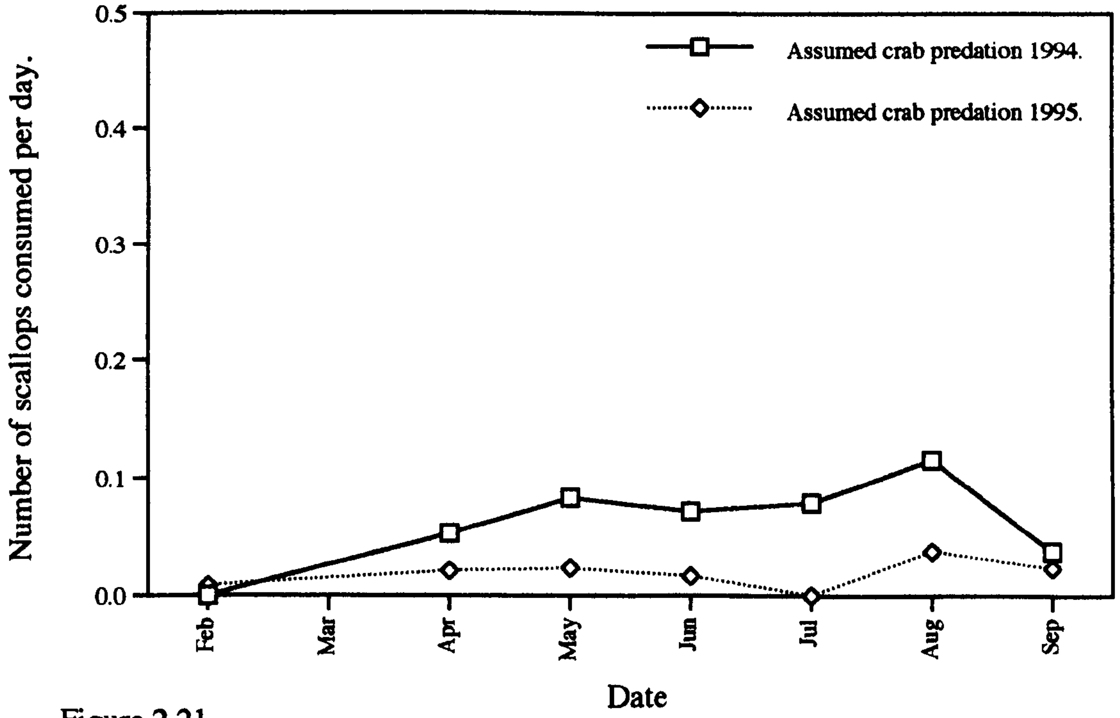


Figure 2.21
Numbers of small scallops consumed per day by crabs plotted against date comparing results from the 1994 and 1995 tethering experiments.

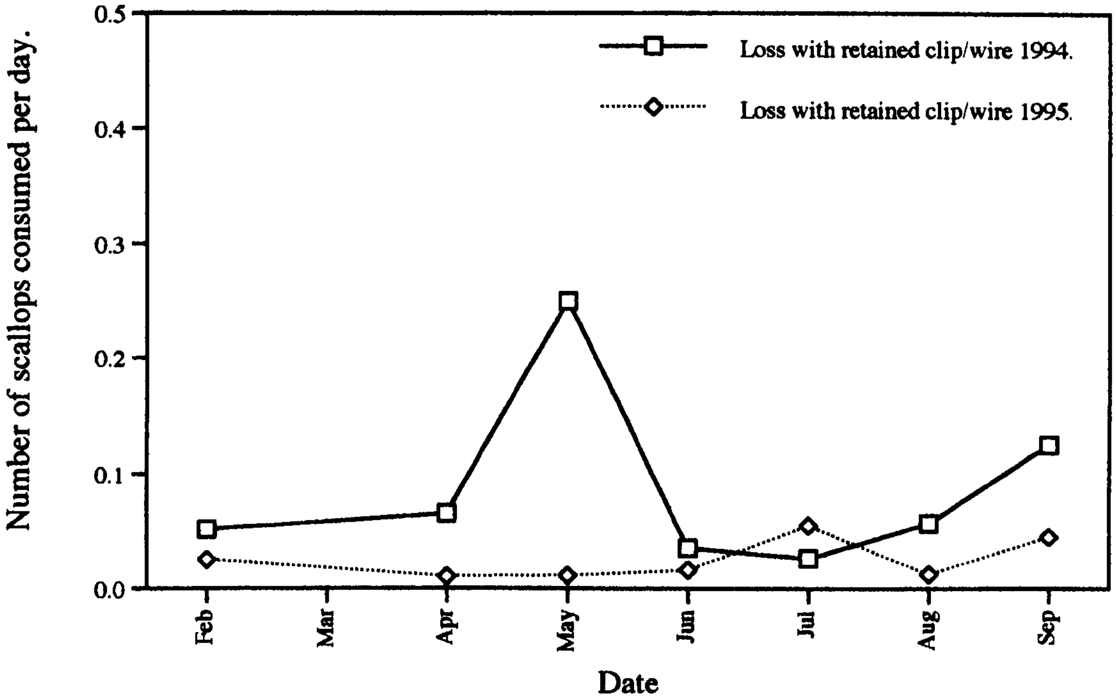


Figure 2.22
Numbers of small scallops lost per day where clips/wires retained plotted against date comparing results from the 1994 and 1995 tethering experiments.

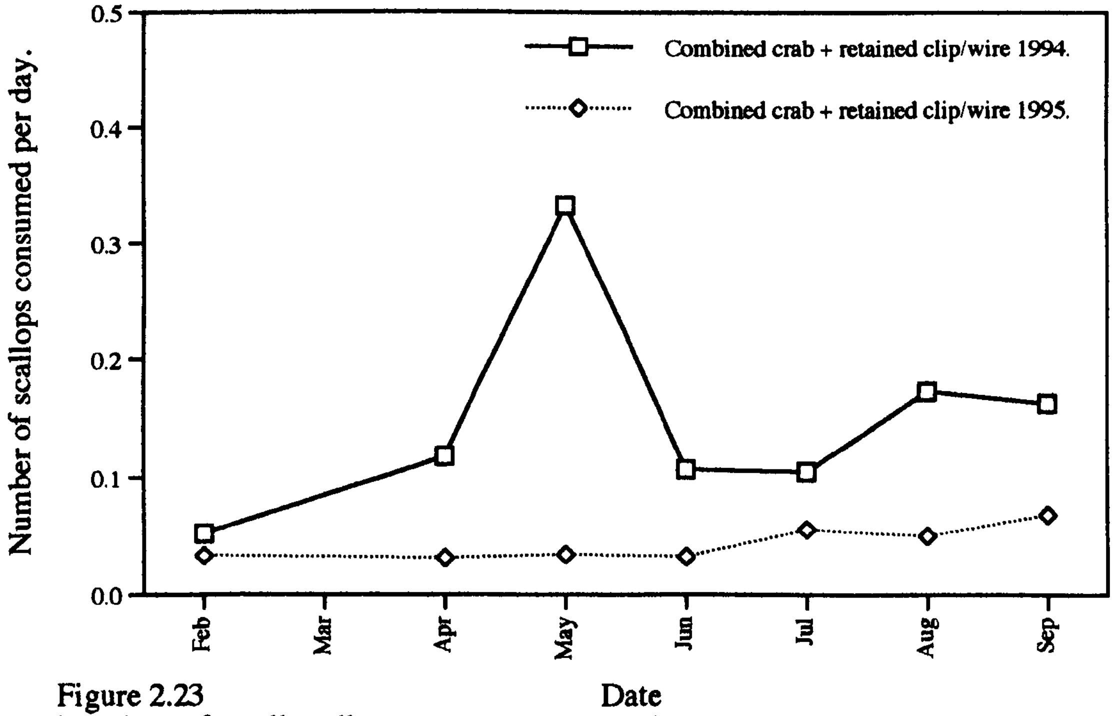


Figure 2.23
Numbers of small scallops consumed per day by crabs plus scallops lost where clips/wires retained plotted against date comparing results from the 1994 and 1995 tethering experiments.

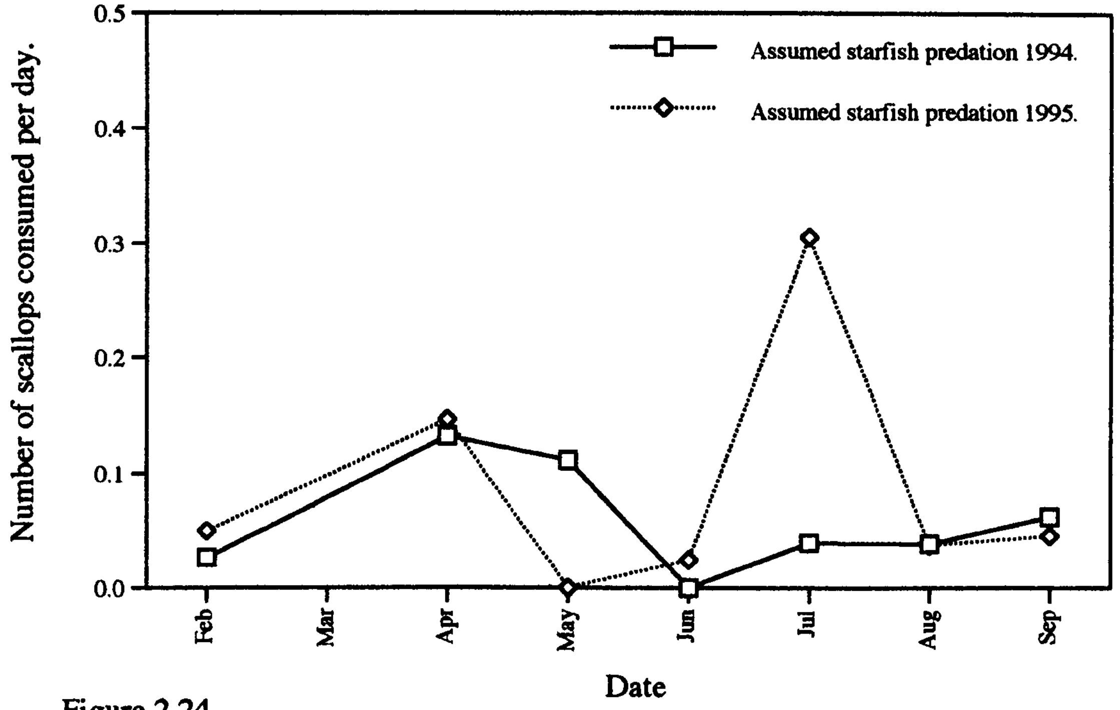


Figure 2.24
Number of large scallops consumed per day by starfish plotted against date comparing results from the1994 and 1995 tethering experiments.

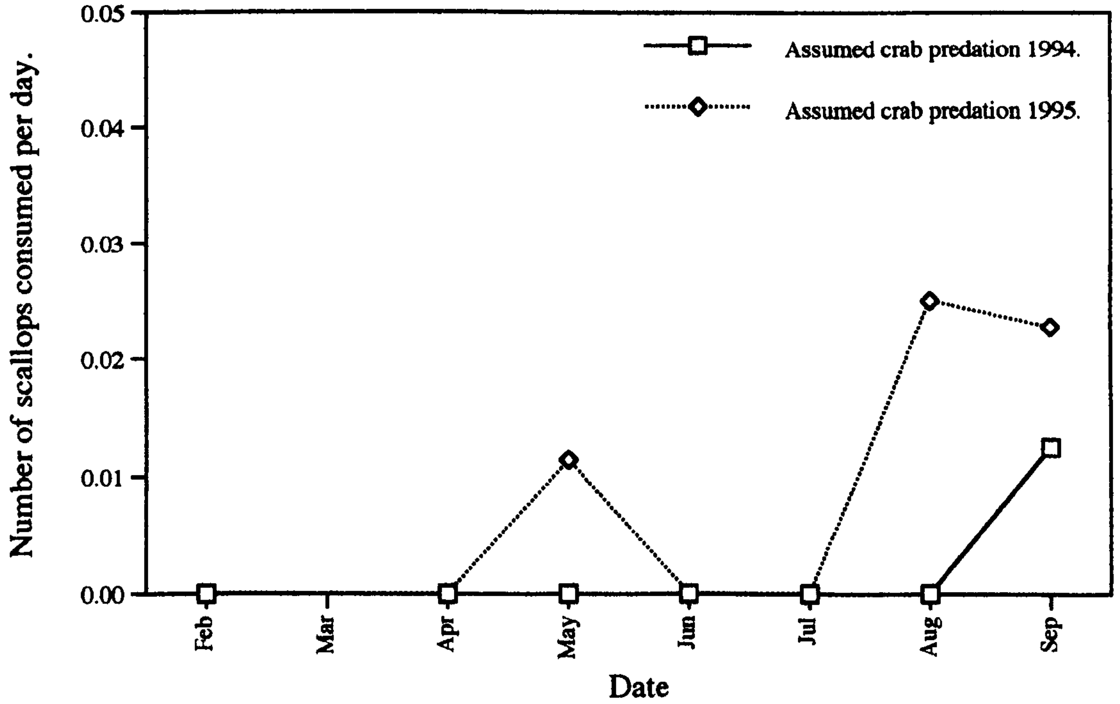


Figure 2.25
Number of large scallops consumed per day by crabs plotted against date comparing results from the 1994 and 1995 tethering experiments.

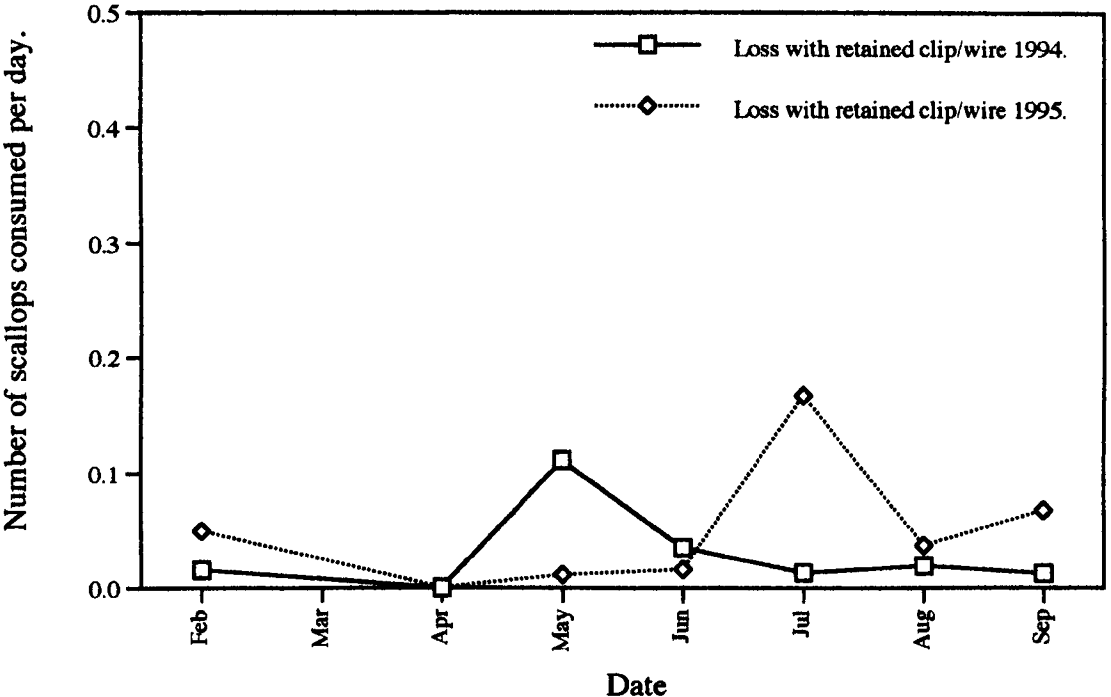


Figure 2.26
Numbers of large scallops scallops lost per day where clips/wires retained plotted against date comparing results from the 1994 and 1995 tethering experiments.

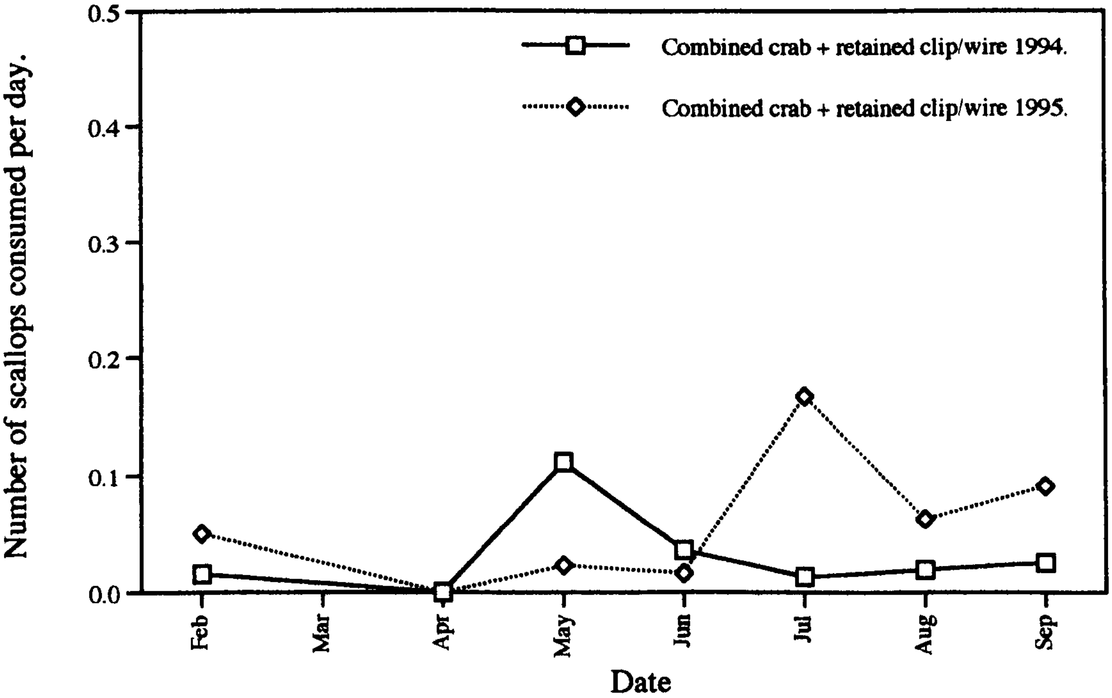


Figure 2.27
Numbers of large scallops consumed per day by crabs plus losses where clips/wires were retained plotted against date comparing results from the 1994 and 1995 tethering experiments.

summer and then falling away again in the autumn. The 1995 results indicate much lower levels of crab predation in all months compared apart from February. These results reflect the behavioural responses of crustacean predators to temperature and fit the annual pattern of migration of female crabs to offshore grounds in winter. The results also show that the increase in crab fishing activity may have significantly affected the local population of crabs to the degree that crab predation on tethered scallops was decreased.

Fig. 2.22 compares the mean losses where tethering clips/wires were retrieved for the small size class of scallop for the 1993/4 and 1995 tethering experiments. This type of loss, as discussed previously, is considered to be attributable to crab predation. This graph shows very similar trends to those observed in Fig. 2.21 (crab predation) apart from a peak in May of the 1993/4 experiments. The 1993/4 experiments generally have higher losses than the 1995 experiments in each month apart from July. Fig. 2.23 compares the mean losses where crab predation was assumed combined with losses where tethering clips/wires were retained for the small size class of scallop the 1993/4 and 1995 tethering experiments. This shows that crab predation was greater during the 1993/4 experiments than during the 1995 experiments.

Fig. 2.24 compares starfish predation on the large size class of scallop between the 1993/4 and 1995 tethering experiments. The plots look very similar to those for small scallops (Fig. 2.22) with both years showing a peak around April. The 1994 plot falls away to July and remains low, while the 1995 plot peaks again in July before falling away. The graph for 1995 indicates that the two peaks of starfish predation occurred within the calendar year, whereas the 1993/4 plot shows only one peak in 1994, the first peak having occurred late in 1993.

Crab predation on the large size class of scallop between the 1993/4 and 1995 experiments is compared in Fig. 2.25. The plots both show no activity prior to May when some crab predation occurred during 1995. This fell to zero during June and July, before rising in August and September. During 1993/4 a rise was observed during September. Overall this shows very little crab predation on large scallops during both years, with most losses occurring during August and September.

Losses where tethering clips/wires were retained for the large size class of scallop between the 1993/4 and 1995 tethering experiments are compared in Fig. 2.26. This graph shows that this type of loss peaked in May 1994 and during July in 1995. This suggests a shift in crab predation between these two years, assuming that this type of loss can be attributed to crab predation. Fig. 2.27 compares crab predation including losses where tethering clips/wires were retained for the large size class of scallops between the 1994 and 1995 tethering experiments. This graph does not differ greatly from the graph in Fig. 2.26 because of the very low levels of crab predation on this size class of scallop.

2.3.9a Year to year differences in predation on large scallops.

Results of the t-tests for year to year variability for predation on large scallops are summarised in Table 2.30. P values are included. In each test the null hypothesis used was:

$H_0 : \mu_{1994} = \mu_{1995}$

Where a significant difference between years was detected the result is indicated in bold.

Table 2.30 shows that, for large scallops, a majority of months are identified as having the same mean predation levels during 1994 and 1995. The only exceptions were May and July for starfish predation. May 1994 was identified as having a significantly higher mean starfish predation level than May 1995, and July 1994 was identified as having a significantly lower mean starfish predation level. Half of the months sampled showed no crab predation at all during either year on the large scallops. These results show that differences in relative levels of predation from year to year would appear to be very small. The main differences occurred in starfish predation during May and July for large scallops. The July difference probably arises from the shift in feeding peaks observed between the two years sampled. The 1993/4 tethering experiments gave a single peak in starfish predation during 1994, whereas the 1995 experiments identified a second peak during the summer, reaching a maximum in July.

The lack of significant difference between years may be a result of the relatively low level of replication involved ($n = 4$) for each set of experiments. A comparison of the year as a whole, using paired sample t-tests for starfish predation revealed that year to year differences in predation were not statistically significant for small or large scallops ($p = 0.09$ and 0.277 respectively, $a = 0.05$).

2.3.9b Year to year differences in predation on small scallops

Results of the t-tests for year to year variability for predation on large scallops are summarised in Table 2.31. P values are included. In each test the null hypothesis used was:

$H_0 : \mu_{1994} = \mu_{1995}$

Where a significant difference between years was detected the result is indicated in bold.

For small scallops a majority of months are identified as having the same mean predation levels during 1994 and 1995 (Table 2.31). The only exceptions were July and August for

Table 2.30

Summary of the comparisons made between monthly tethering experiments where sampling was carried out for these months in both years. Results are for the large size class of scallop and for both crab and starfish predation. Crab + Loss indicates results where crab predation was combined with losses where clips/wires were retrieved.

Month	Starfish Predation	Crab Predation	Crab + Loss
February	n.s. p=0.24	n.s. (all values=zero)	n.s p=0.183
April	n.s. p=0.82	n.s. (all values=zero)	n.s (all values zero)
May	**sig. p=0.0498 94>95**	n.s. p=0.356	n.s p=0.309
June	n.s. p=0.168	n.s. (all values=zero)	n.s p=0.635
July	**sig. p=0.035 95>94**	n.s. (all values=zero)	n.s p=0.079
August	n.s. p=0.984	n.s. p=0.134	n.s p=0.208
September	n.s. p=0.579	n.s. p=0.707	n.s p=0.191

Table 2.31

Summary of the comparisons made between monthly tethering experiments where sampling was carried out for these months in both years. Results are for the small size class of scallop and for both starfish and crab predation. Crab + Loss indicates results where crab predation was combined with losses where clips/wires were retrieved.

Month	Starfish Predation	Crab Predation	Crab + Loss
February	n.s. p=0.807	n.s. p=0.356	n.s p=0.624
April	n.s. p=0.991	n.s. p=0.244	n.s p=0.096
May	n.s. p=0.635	n.s. p=0.311	**sig. p=0.007 94>95**
June	n.s. p=0.47	n.s. p=0.239	n.s p=0.378
July	**sig. p=0.013 95>94**	**sig. p=0.024 94>95**	n.s p=0.245
August	**sig. p=0.0005 95>94**	n.s. p=0.207	n.s p=0.286
September	n.s. p=0.08	n.s. p=0.590	n.s p=0.082

starfish predation, July for crab predation and May for combined crab predation and unattributed loss. July and August 1995 were identified as having significantly higher mean starfish predation levels than July and August 1994. Mean crab predation during July was significantly higher in 1994 compared to 1995. Combined crab predation and unattributed loss during May was also significantly higher in 1994 compared to 1995. All months sampled during both years showed some level of predator activity on small scallops.

The increase in starfish predation during the summer of 1995 is probably accounted for by the shift in feeding activity observed between the two years. The only significant difference between 1994 and 1995 for crab predation occurred in July where the 1994 level was significantly higher than the 1995 level for small scallops. This month by month comparison relies on a fairly low level of replication which probably explains why few differences were identified.

The lack of significant difference between years may be a result of the relatively low level of replication involved ($n = 4$) for each set of experiments. A comparison of the year as a whole, using paired sample t-tests for crab predation revealed that significantly more small scallops were consumed by crabs during 1994 than 1995 ($p = 0.006$, $a = 0.05$). No statistically significant difference in the numbers of large scallops consumed by crabs was identified ($P = 0.058$, $a = 0.05$). The lack of difference in crab predation on large scallops probably results from the scallops being large enough to avoid predation in both sets of tethering experiments. The drop in crab predation on small scallops during 1995 was unexpected because the records revealed that seawater temperature was significantly higher in 1995 which could potentially lead to higher levels of crab activity. The observed drop in crab predation may have resulted from increased crab fishing activity, during 1995, in the area around the tethering experiments. This may have lead to a reduction in the local crab population with a resultant drop in crab predation. Figures obtained from the Department of Agriculture, Fisheries and Forestry appear to back this up. Crab landings for the DAFF statistical grid square K12 (5km x 5km), which covers the experimental area, show an increase from 3340kg in 1994 to 26564kg in 1995 and to 33077.45kg in 1996. So, from 1994 to 1995, there was almost an eight fold increase in crab landings by weight. The DAFF figures do not allow detailed analysis of where these crabs were actually caught but the data suggest that this may have had a significant effect upon the crab population in the area surrounding the tethering experiments. Brand & Prudden (1997) also present evidence that annual catches of crabs, on the Isle of Man as a whole, rose sharply from 1994 to 1995.

2.3.10 The effect of temperature on predation.

The numbers of scallops consumed per day by each assumed predator type against sampling date are plotted in Figs. 2.28a - 2.39a. The graphs also include a plot of seawater temperature (degrees centigrade) taken from records kept at PEML for the appropriate periods. Beneath each graph of predation against time there is a regression plot of the number of scallops consumed per day against temperature (Figs. 2.28b - 2.39b). Each graph includes the regression equation and a p value representing the significance of the relationship between the two variables at the 0.05 level. Fig. 2.40 compares the monthly measurements of seabed temperature for the years in which tethering experiments took place. A paired sample t-test performed using the 1994 and 1995 temperature data showed that the overall mean seawater temperature was significantly greater during 1995 than 1994 ($p = 0.004$, $a= 0.05$). This indicates that, if crab activity were related to temperature, crabs would be more active during 1995 than 1994. The results of the tethering experiments indicate that the opposite is true which suggests that other factors are affecting crab predation during 1995.

The analysis of the regression lines presented in figs 2.28b - 2.39b are summarised in Table 2.32. Analysis involved testing the slopes for significant difference from zero. The null hypothesis used in each test was H_o: Slope $ß = 0$. Significant results where the null hypothesis was rejected are highlighted in bold.

Table 2.32 shows that, during the 1993/4 tethering experiments, the crab predation and crab predation combined with unattributed loss showed a consistently positive relationship with temperature, although no value of ß was found to be significantly different from zero. Starfish predation levels showed a consistently negative relationship with temperature but with only the small scallops giving a slope significantly different from zero.

During the 1995 experiments all predation results showed a positive relationship with temperature but with only combined crab and loss predation having a slope significantly different from zero. The consistently positive slopes obtained for crab predation plotted against temperature suggest, but do not prove, that crab predation is to a large extent temperature mediated with higher predation rates in warmer temperatures. The lack of significance of the results indicates that more replicates would need to be made for this method to be able to demonstrate this relationship consistently.

Analyses of temperature dependency for predation rates did not show any statistically significant trends for either predation type. Predation by starfish on small scallops gave a

Table 2.32

Results of the regression analysis of predation rates with temperature.

Predator/Prey Interaction	**1993/4 Data**	**1995 Data**
Large scallops - Crabs	n.s. (+ve slope) $0.1<p<0.25$	n.s. (+ve slope) $0.05<p<0.1$
Large scallops - Crabs+Loss	n.s. (+ve slope) $p>0.25$	n.s. (+ve slope) $p>0.25$
Large scallops - Starfish	n.s. (-ve slope) $p>0.25$	n.s. (+ve slope) $p>0.25$
Small scallops - Crabs	n.s. (+ve slope) $0.1<p<0.25$	n.s. (+ve slope) $p>0.25$
Small scallops - Crabs+Loss	n.s. (+ve slope) $p>0.25$	**sig. (+ve slope) $0.01<p<0.005$**
Small scallops - Starfish	**sig. (-ve slope) $0.0025<p<0.005$**	n.s. (+ve slope)$0.1<p<0.25$

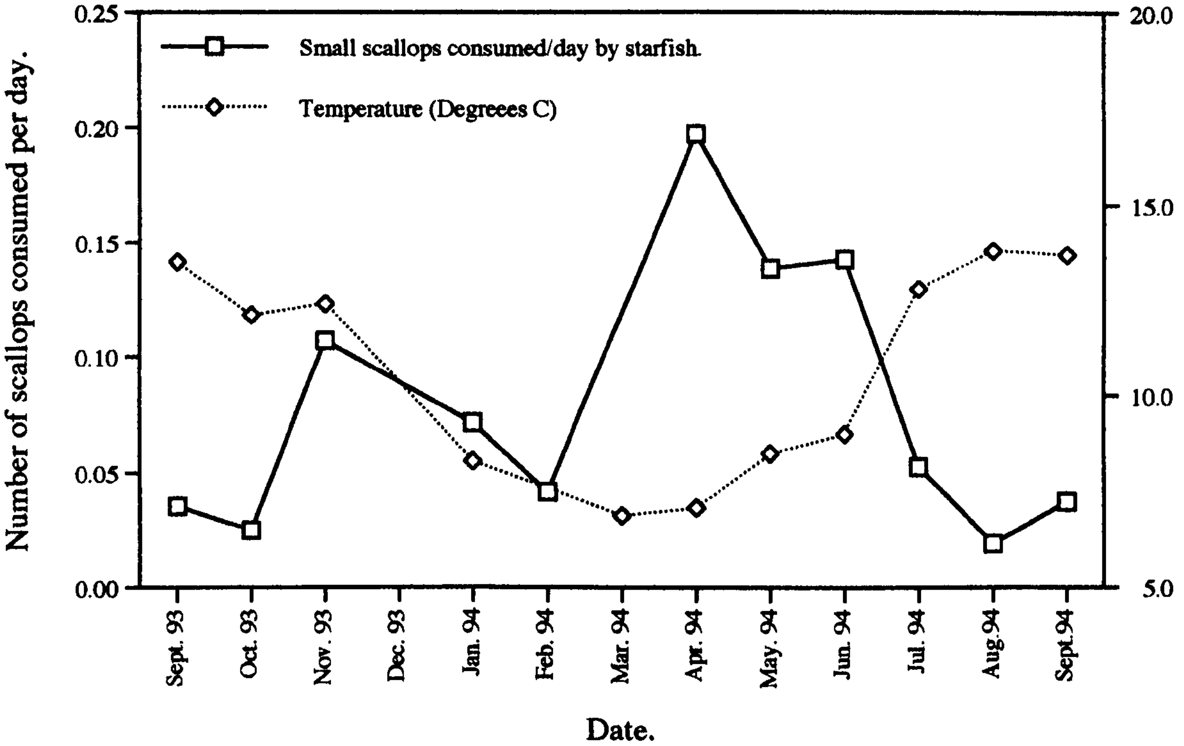


Figure 2.28a
Small scallops consumed per day by starfish plotted against date for the 1993/4 tethering experiemnts.Seabed temperature is also plotted.

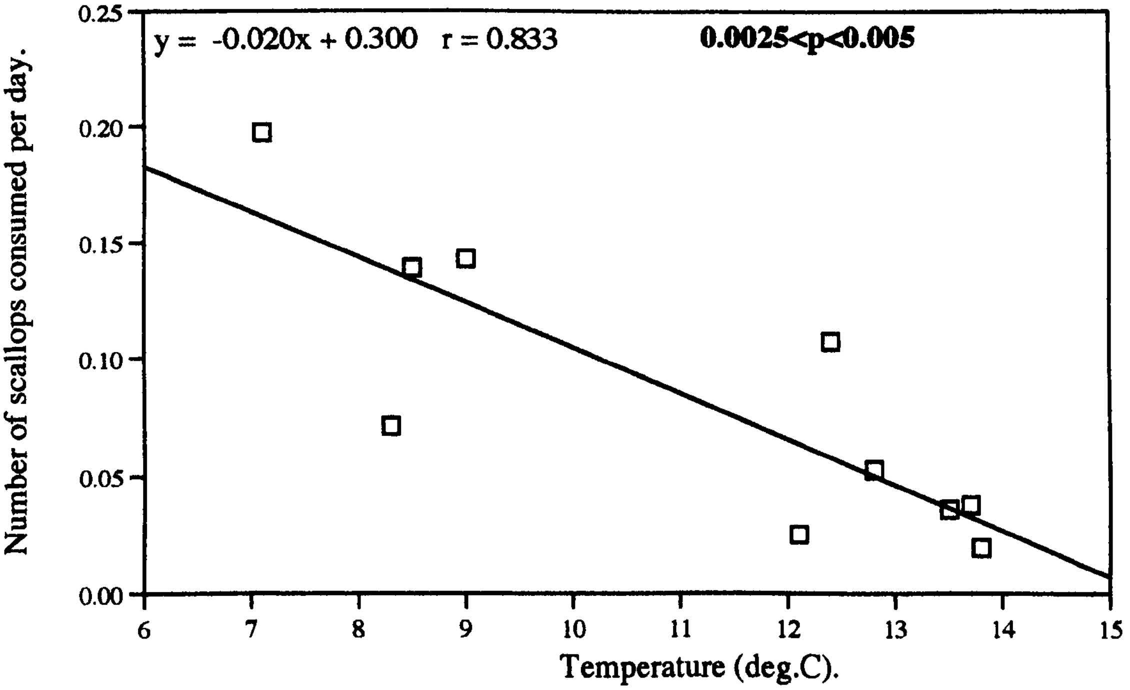


Figure 2.28b
Regression of small scallops consumed per day by starfish plotted against seabed temperature for the 1993/4 tethering experiments. Slope is negative and significant.

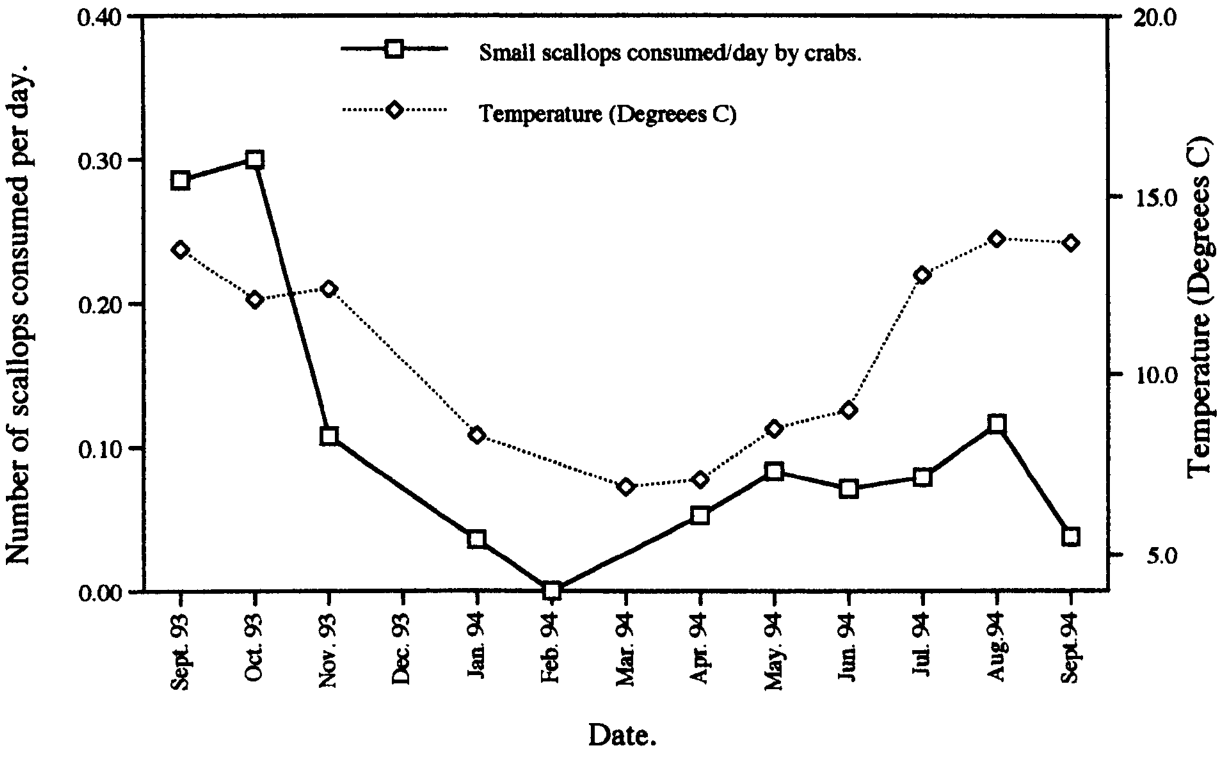


Figure 2.29a
Number of small scallops consumed per day by crabs plotted against date for the 1993/4 tethering experiments.Seabed temperature is also plotted.

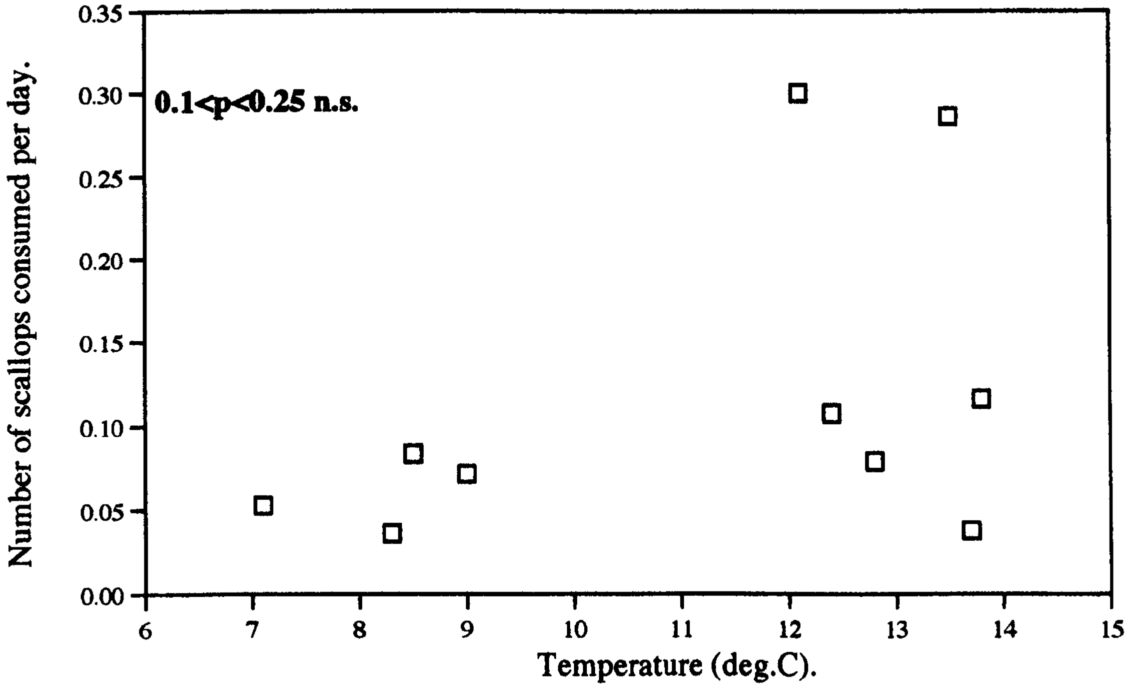


Figure 2.29b
Regression of small scallops consumed per day by crabs plotted against seabed temperature for the 1993/4 tethering experiments. The observed regression gives a positive slope but is not statistically significant.

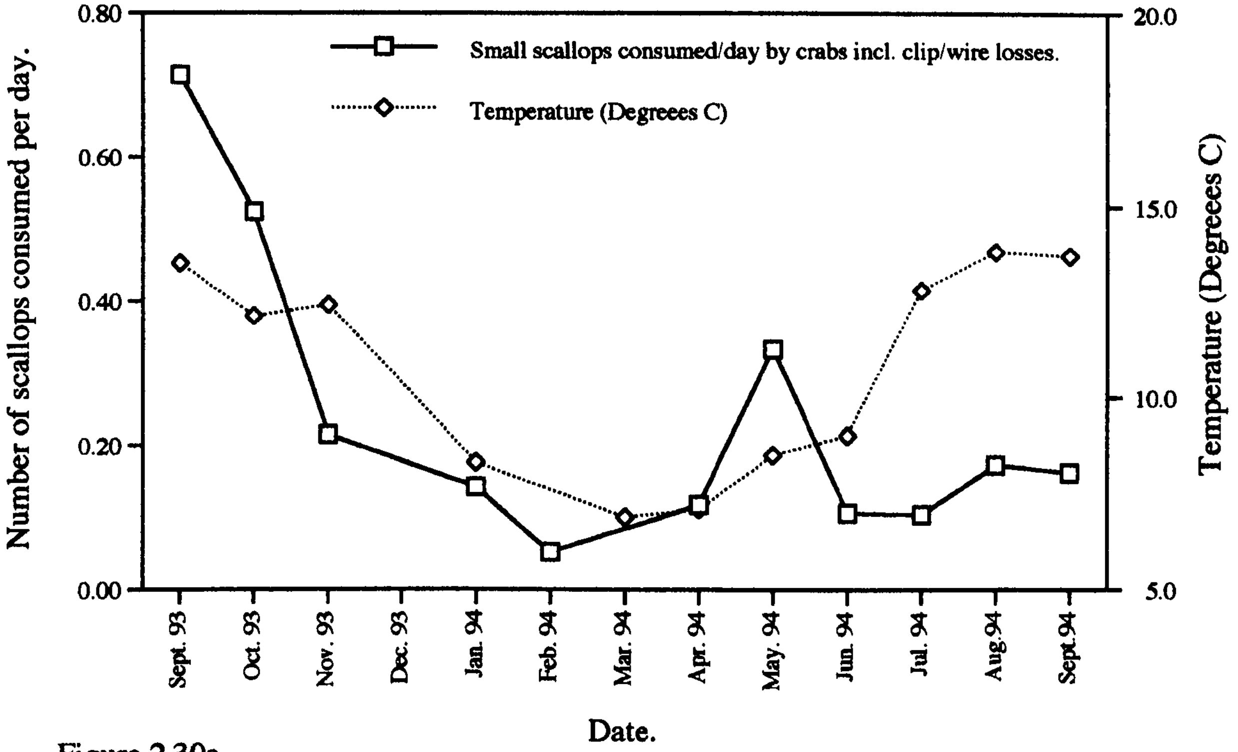


Figure 2.30a
Number of small scallops consumed per day by crabs plus losses whereclips/wires were retrieved plotted against date for the 1993/4 tethering experiments. Seabed temperature is also plotted.

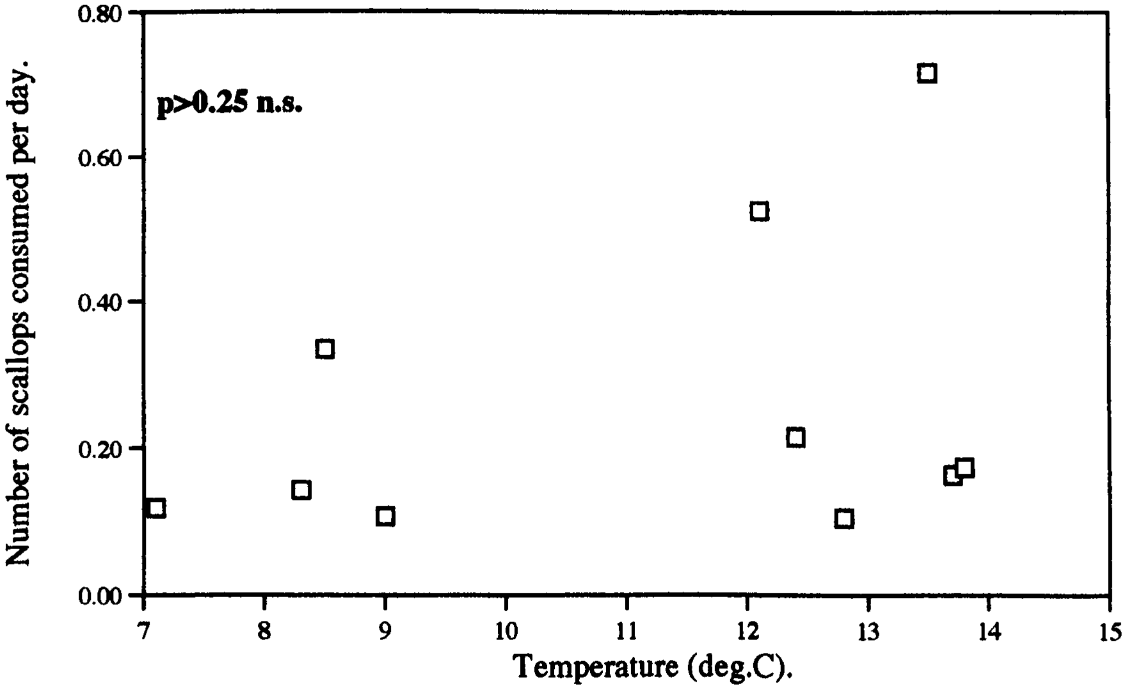


Figure 2.30b
Regression of small scallops consumed per day by crabs plus lost scallops where clips/wires were retrieved plotted against seabedtemperature for the 1993/4 tethering experiments. Slope is positive but not significant.

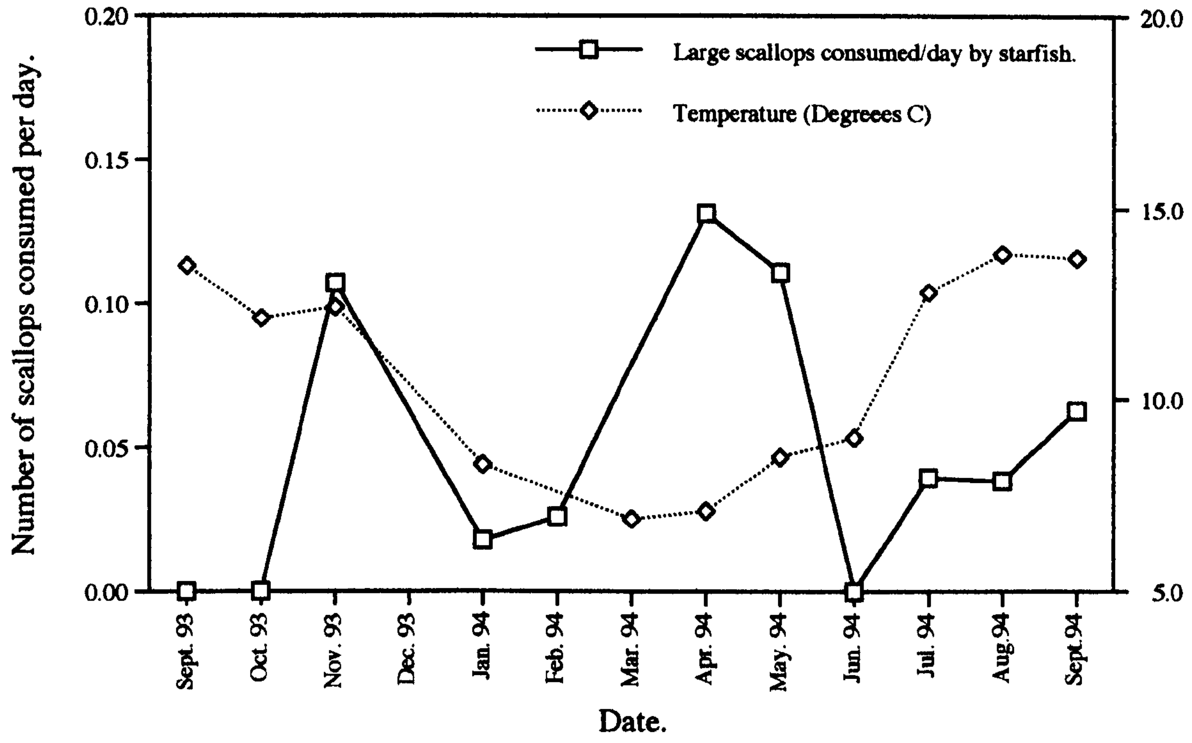


Figure 2.31a
Large scallops consumed per day by starfish plotted against date for the 1993/4 tethering experiments. Seabed temperature is also plotted.

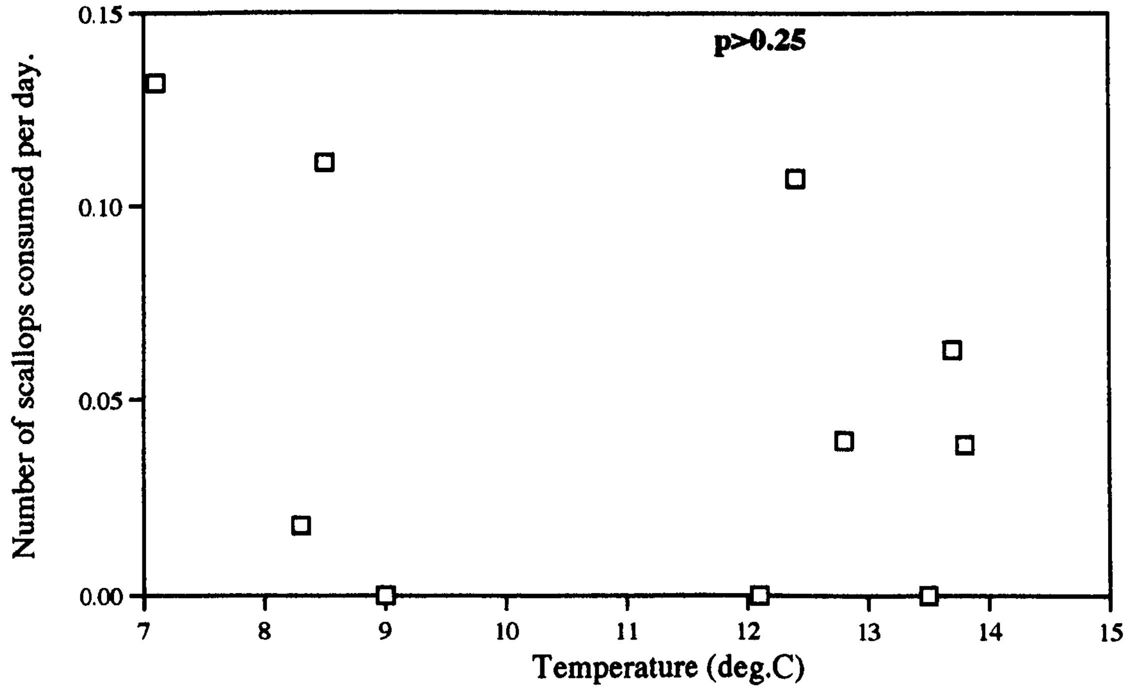


Figure 2.31b
Regression of large scallops consumed per day by starfish plotted against seabed temperature for the 1993/4 tethering experiments. Slope is negative but not significant.

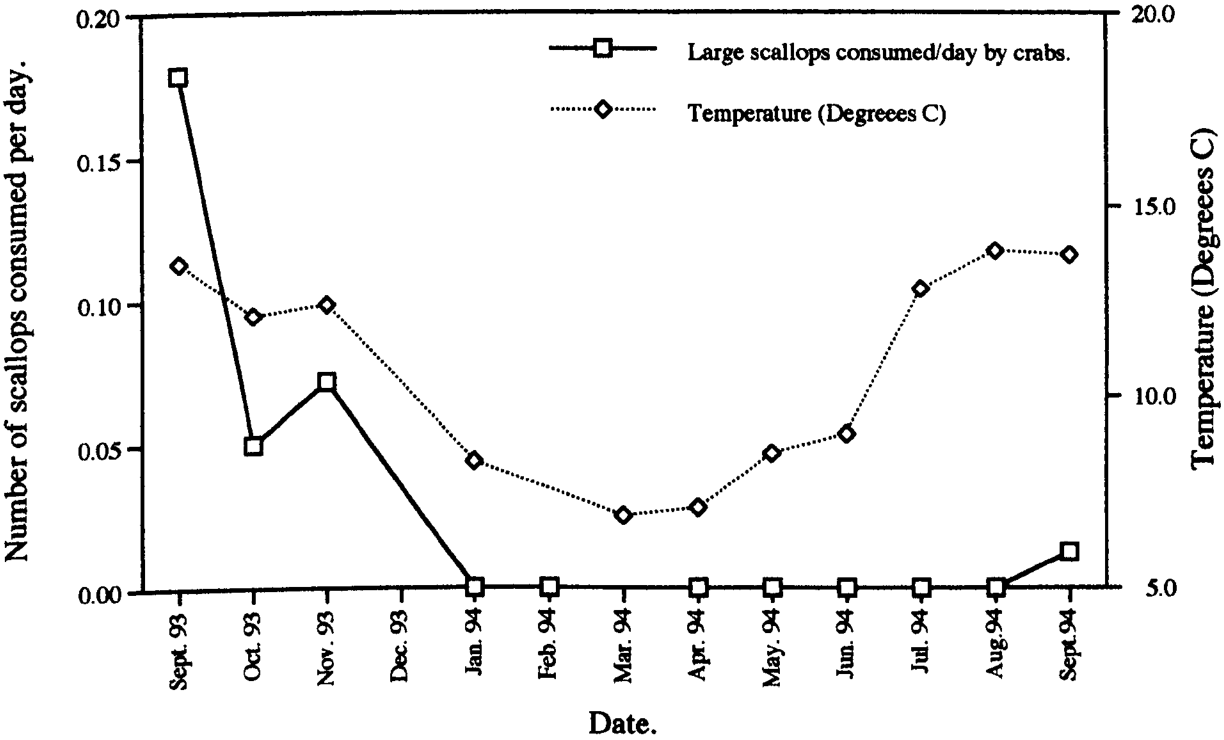


Figure 2.32a
Large scallops consumed per day by crabs plotted against date for the 1993/4 tethering experiments. Seabed temperature is also plotted.

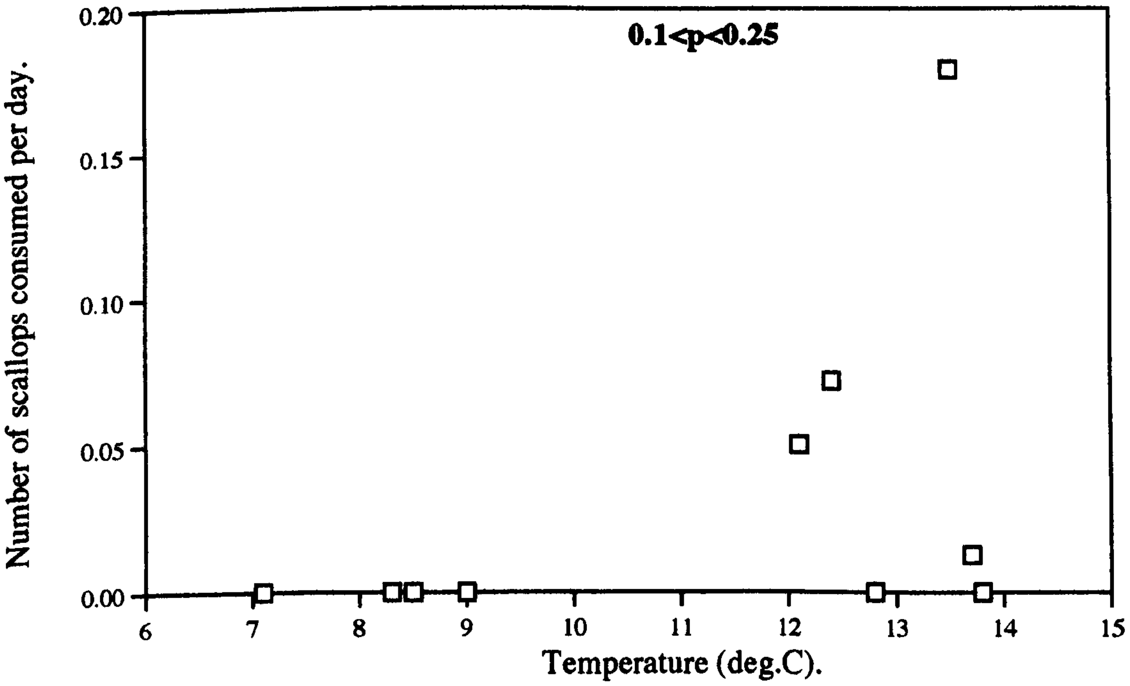


Figure 2.32b
Regression of large scallops consumed per day by crabs plotted against seabed temperature for the 1993/4 tethering experiments. Slope is positive but not significant.

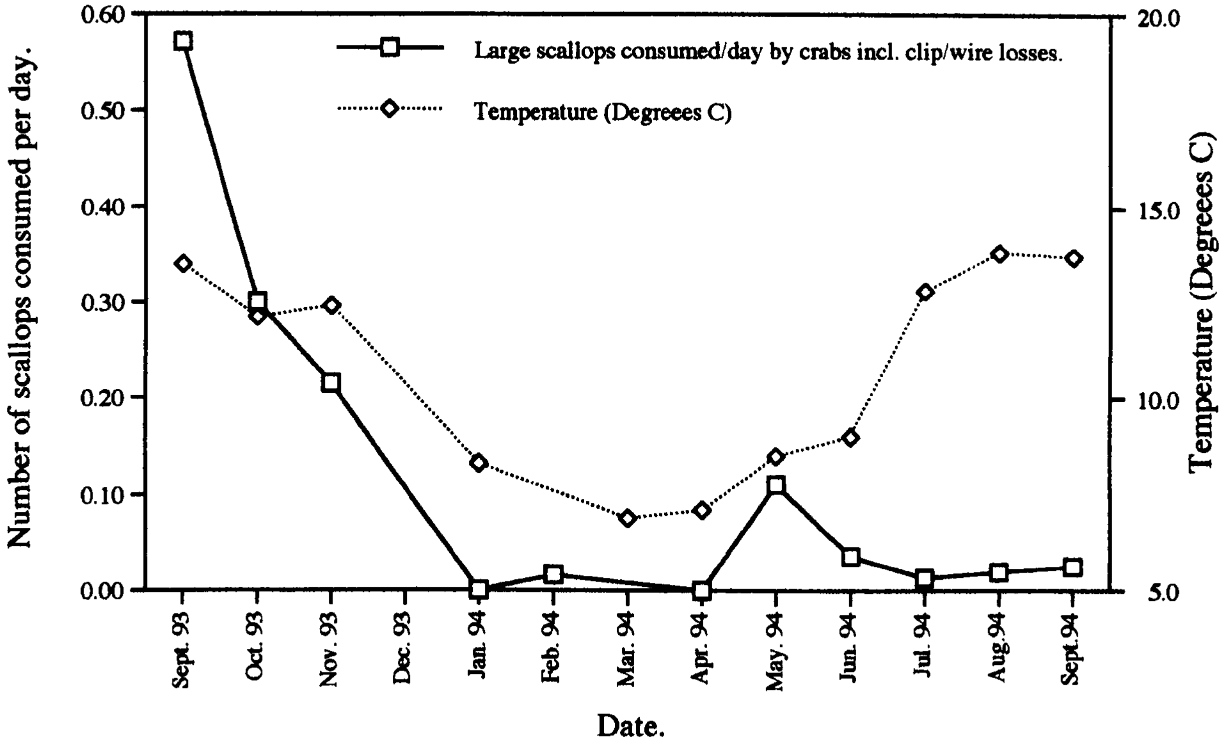


Figure 2.33a
Large scallops consumed per day by crabs combined with losses where clips/wires were retrieved plotted against date for the 1993/4 tethering experiments. Seabed temperature is also plotted.

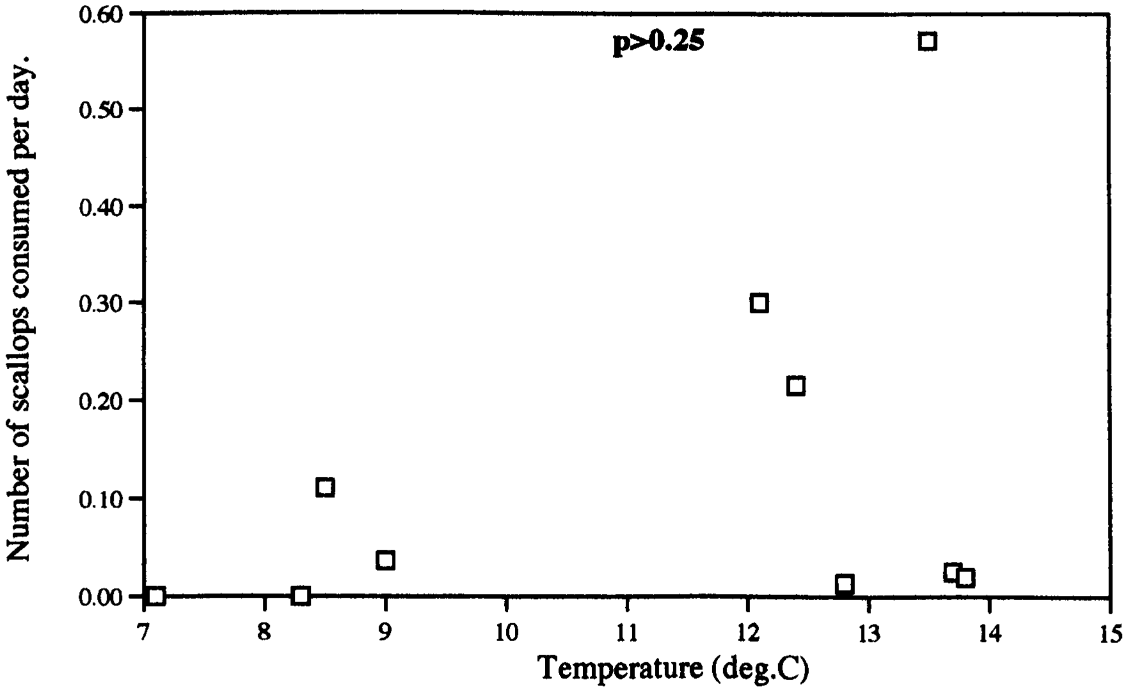


Figure 2.33b
Regression of large scallops consumed per day by crabs plus lost scallops where clips/wires were retrieved pltted against seabedtemperature for the 1993/4 tethering experiments. Slope is positive but not significant.

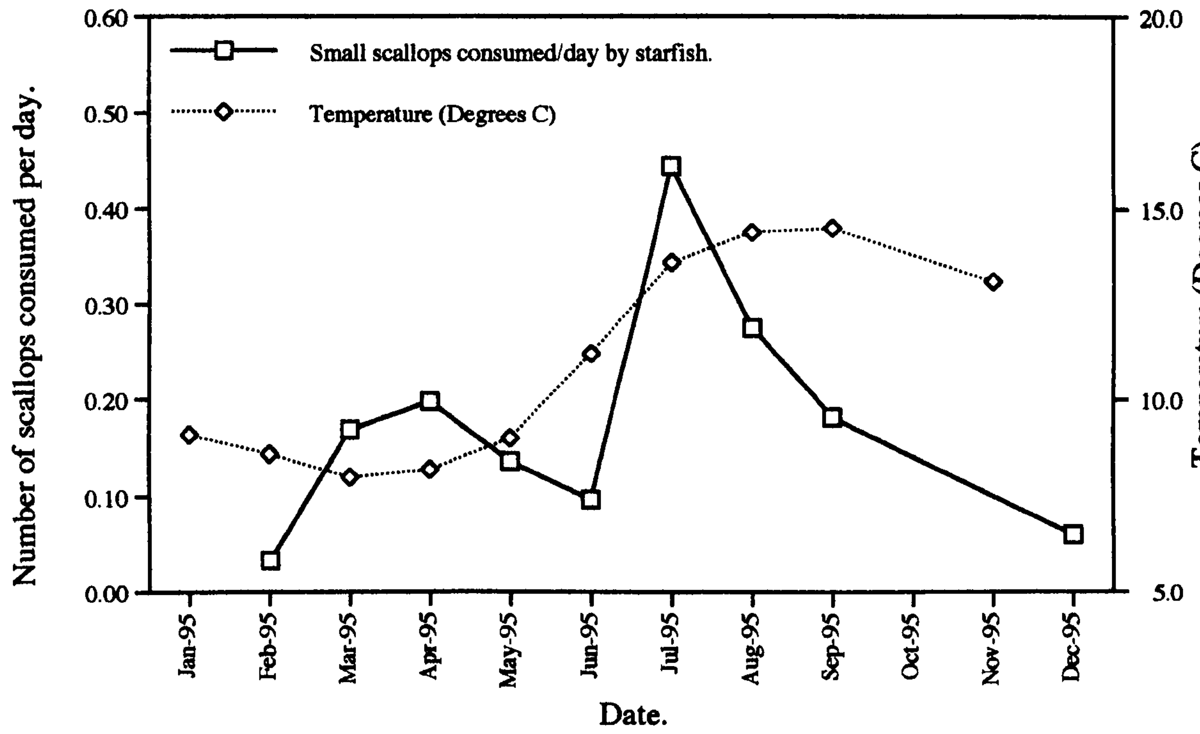


Figure 2.34a
Small scallops consumed per day by starfish plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

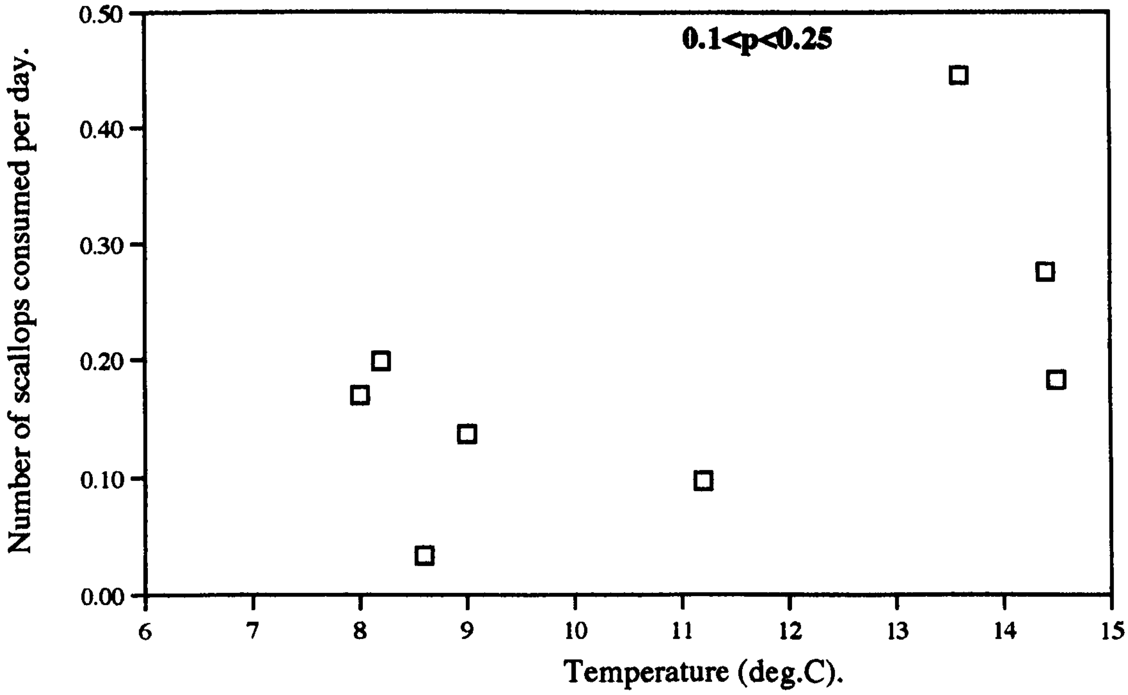


Figure 2.34b
Regression of small scallops consumed per day by starfish plotted against seabed temperature for the 1995 tethering experiments. Slope is positive but not significant.

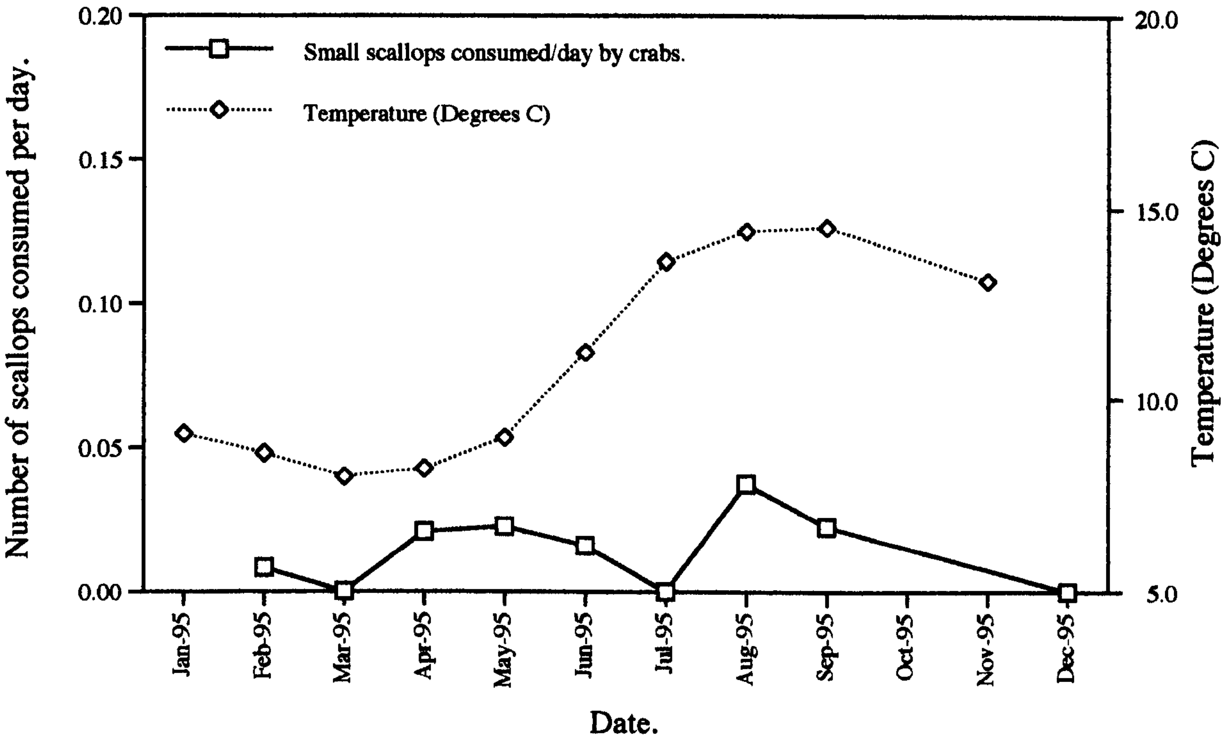


Figure 2.35a
Small scallops consumed per day by crabs plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

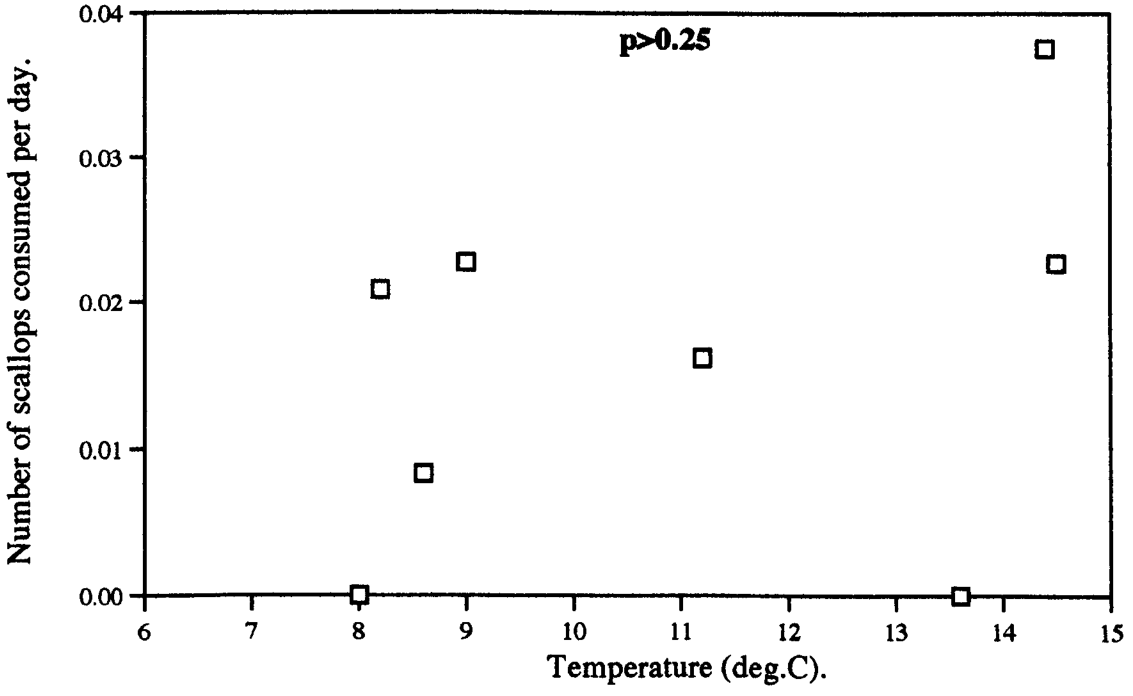


Figure 2.35b
Regression of small scallops consumed per day by crabs plotted against seabed temperature for the 1995 tethering experiments. Slope is positive but not significant.

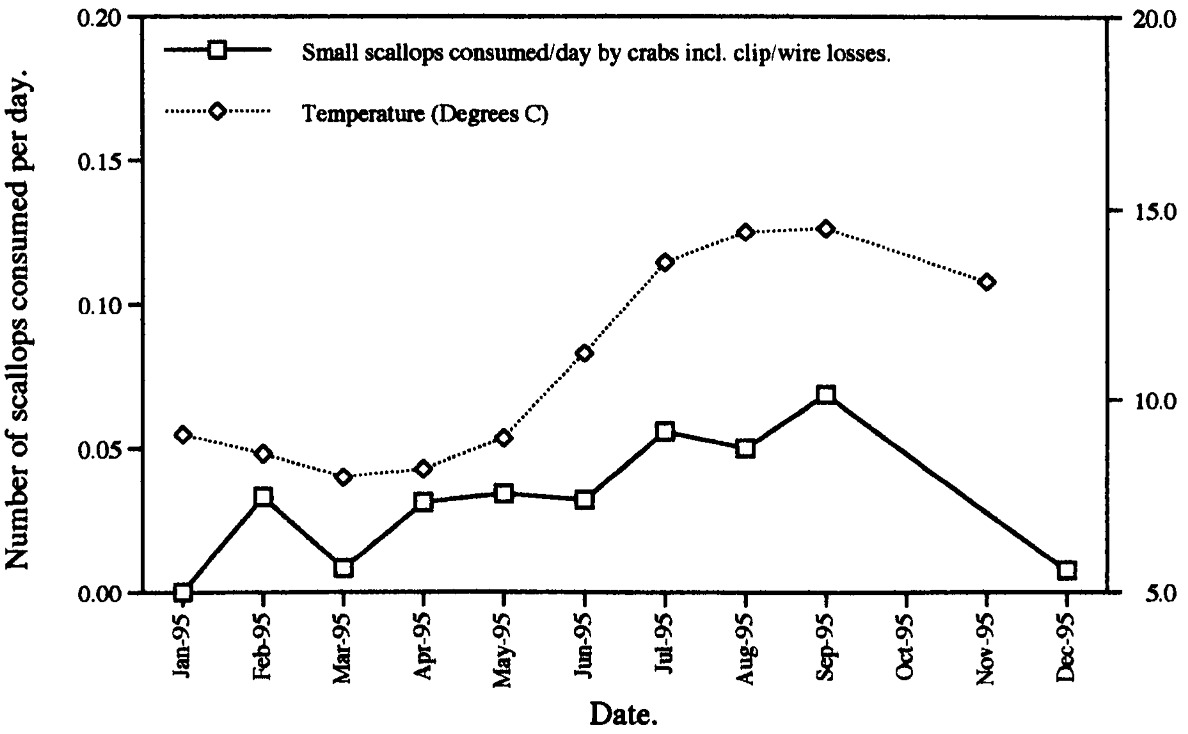


Figure 2.36a
Small scallops consumed per day by crabs plus losses where clips/wires were retrieved plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

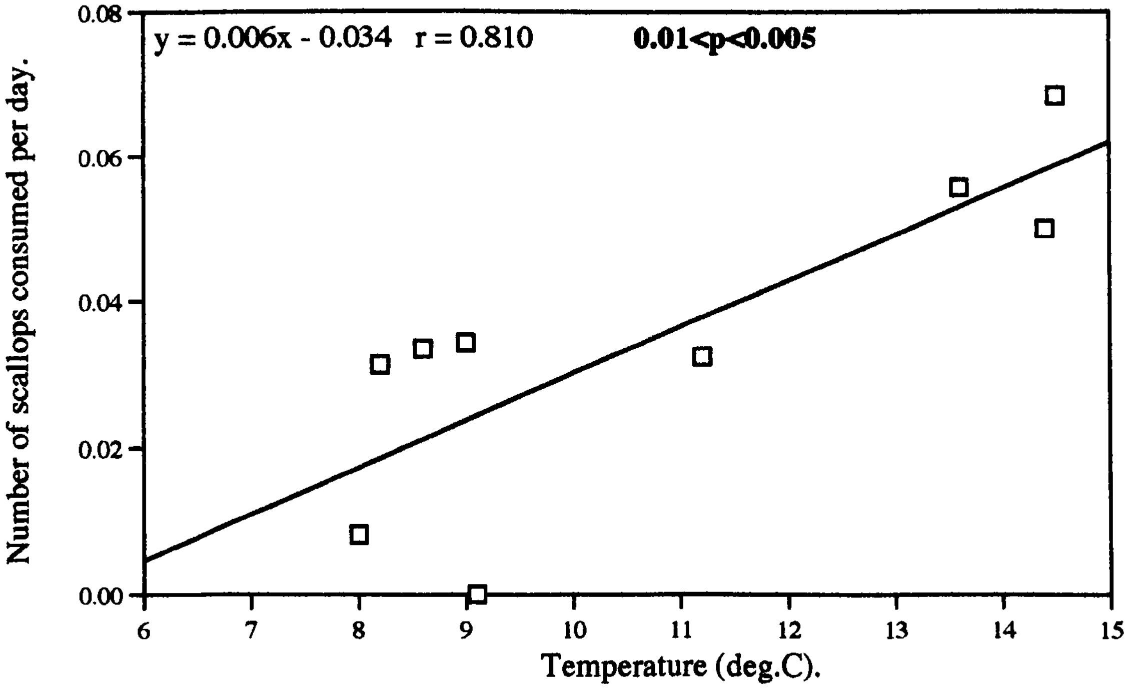


Figure 2.36b
Regression of small scallops consumed per day by Crustacean predators plus lost scallops where clips/wires were retreivedagainst seabedtemperature for the 1995 tethering experiments. Slope is positive and significant.

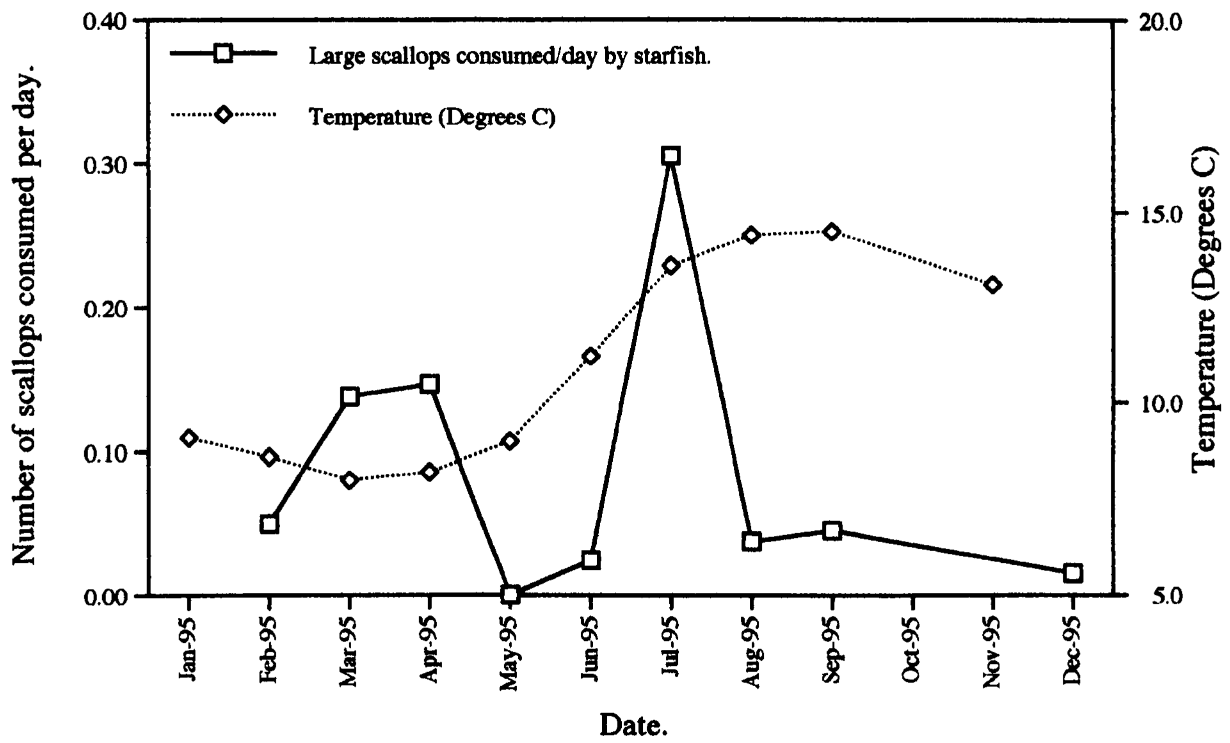


Figure 2.37a
Large scallops consumed per day by starfish plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

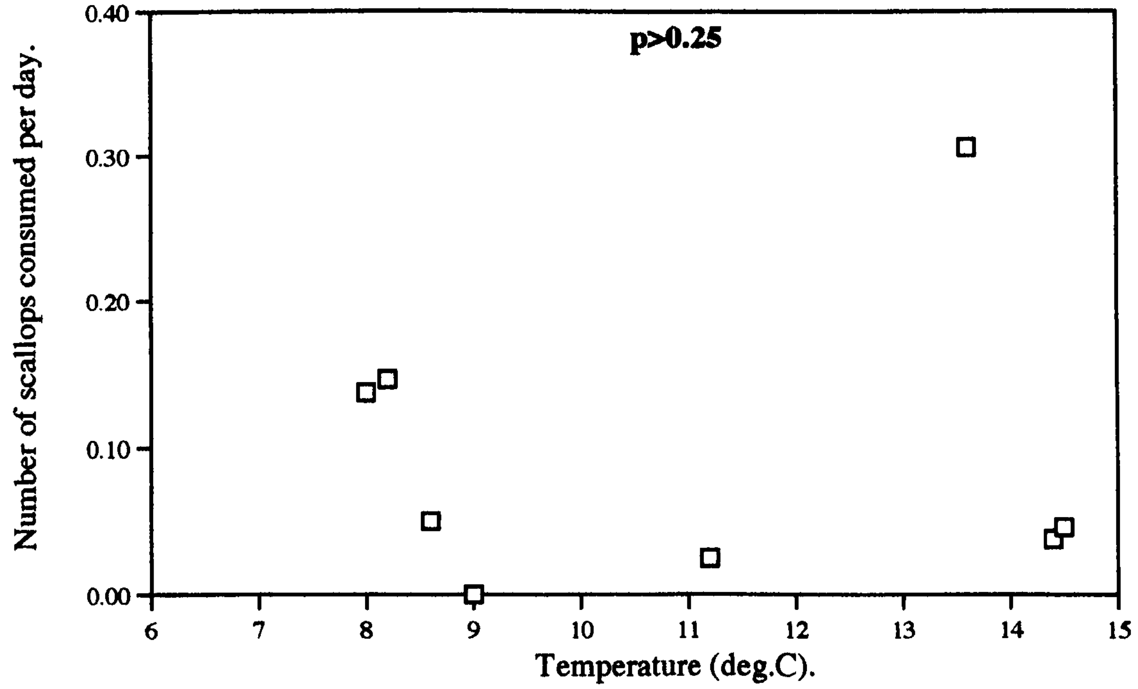


Figure 2.37b
Regression of large scallops consumed per day by starfish plotted against seabed temperature for the 1995 tethering experiments. Slope is positive but not significant.

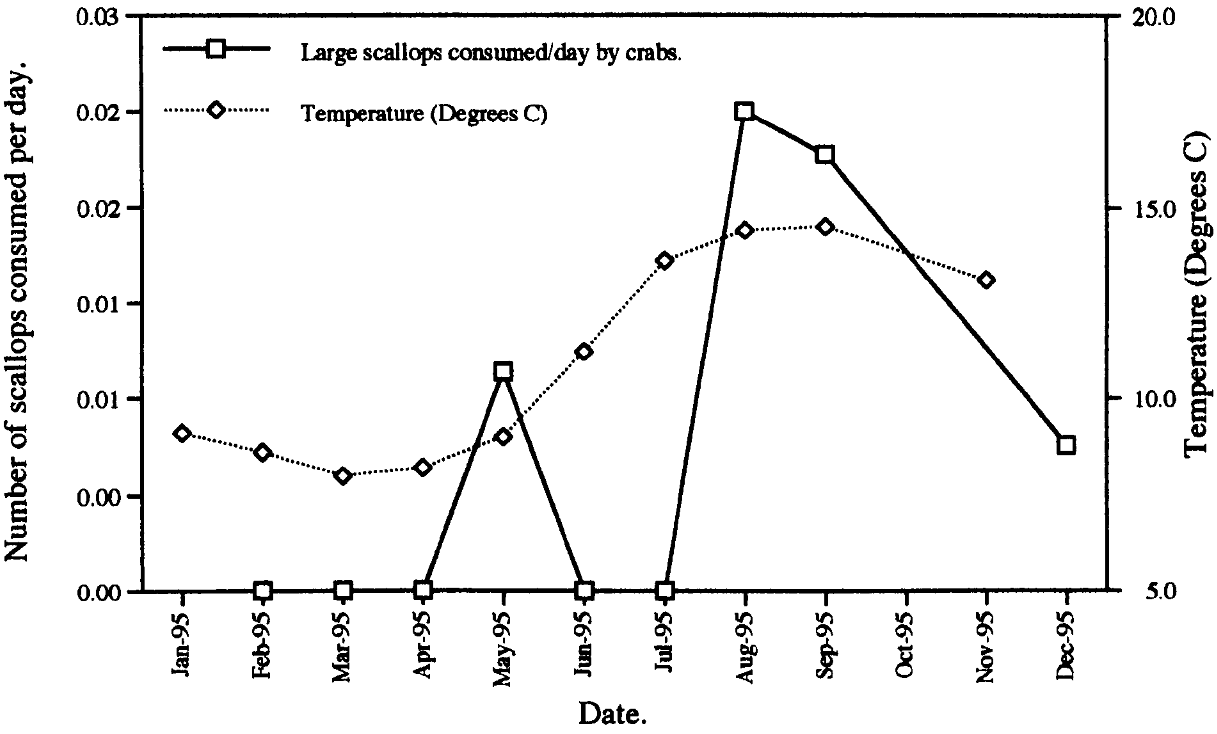


Figure 2.38a
Large scallops consumed per day by crabs plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

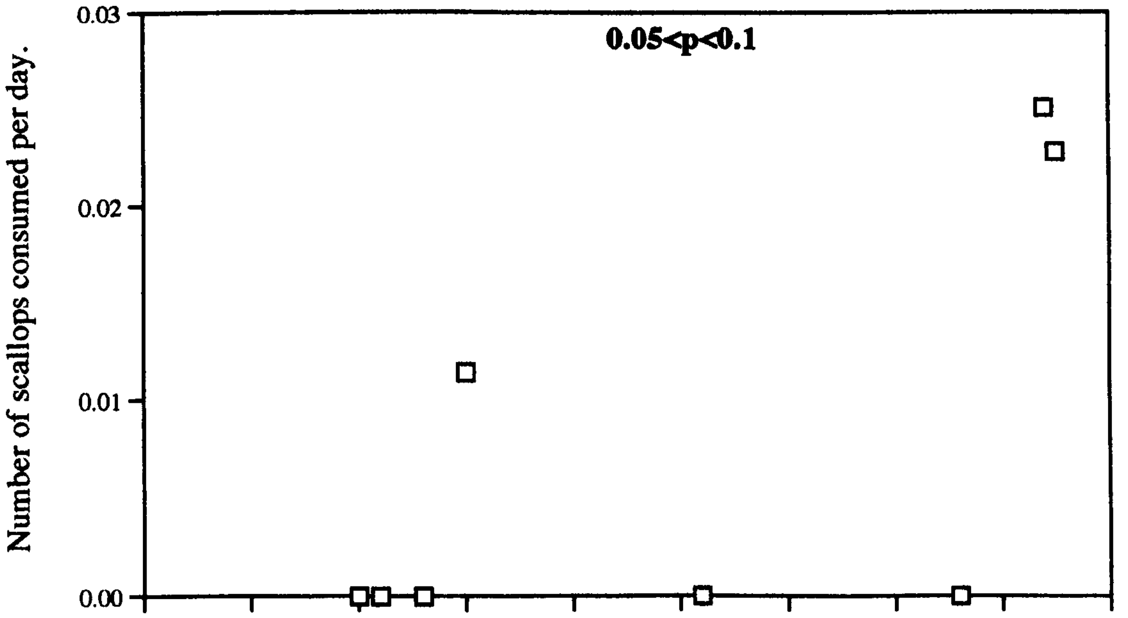


Figure 2.38b
Regression of large scallops consumed per day by crabs plotted against seabed temperature for the 1995 tethering experiments. Slope is positive but not significant.

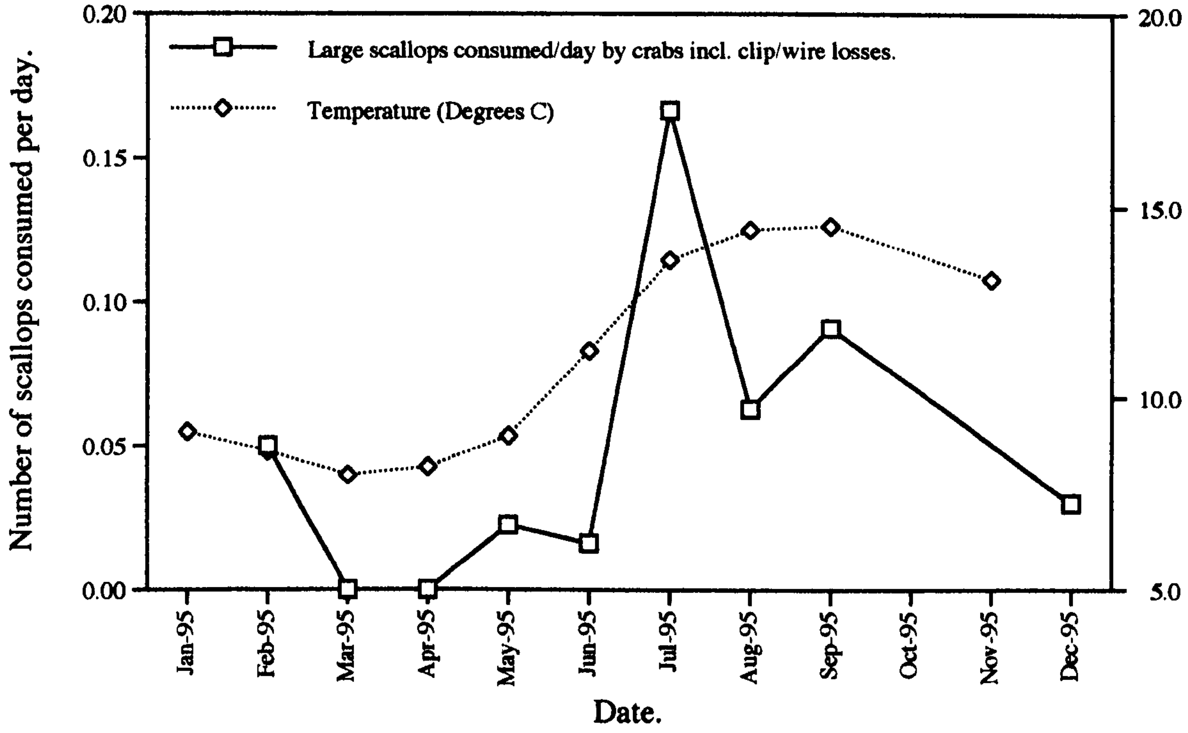


Figure 2.39a
Large scallops consumed per day by crabs plus losses where clips/wires were retrieved plotted against date for the 1995 tethering experiments. Seabed temperature is also plotted.

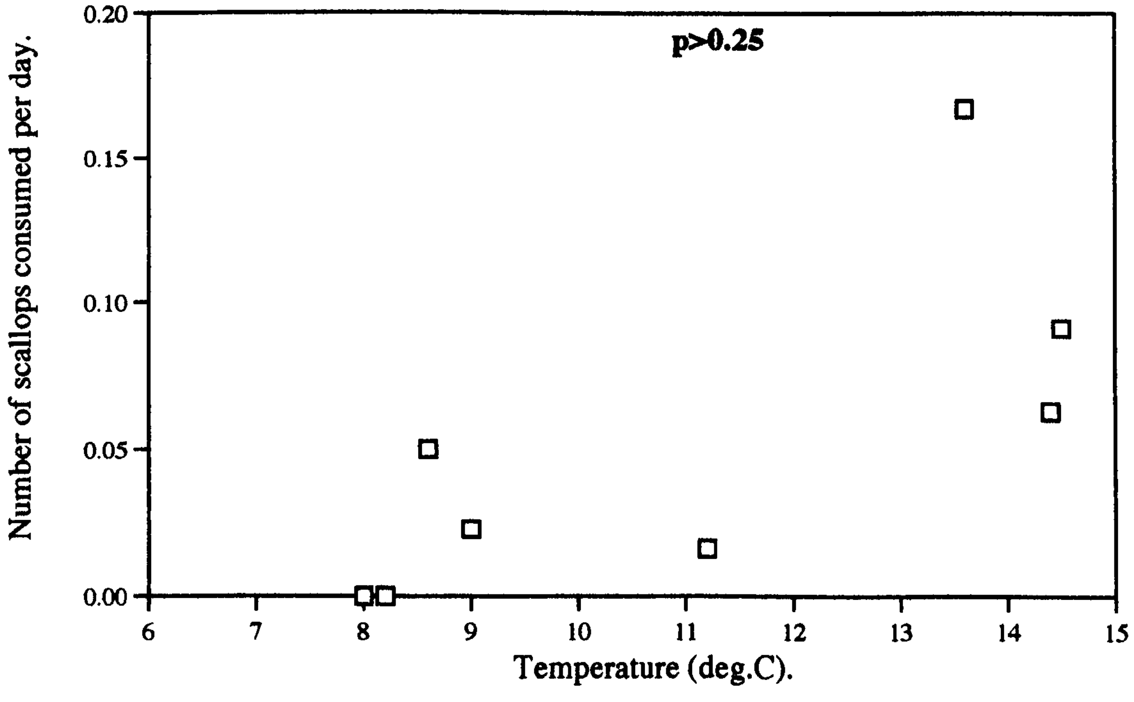


Figure 2.39b
Regression of large scallops consumed per day by crabs plus lost scallops where clips/wires were retrieved plotted against seabedtemperature for the 1995 tethering experiments. Slope is positive but not significant.

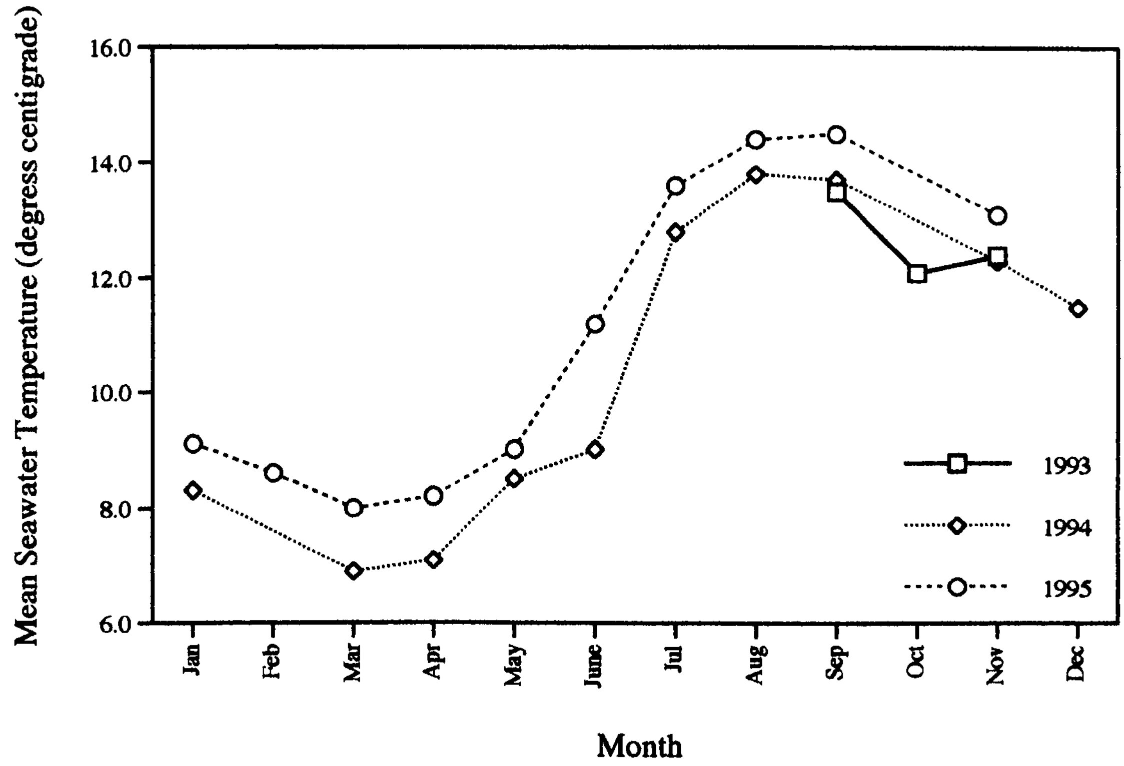


Figure 2.40
Comparison of mean monthly seawater temperatures during the 1993 -1995 tethering experiments. A paired sample t-test was used to show that the overall mean seawater temperature in 1995 was higher than the overall mean in 1994 ($p = 0.0004$, $a = 0.05$).

significant negative regression coefficient during the 1993/4 tethering experiments only. During the 1995 experiments the relationship between temperature and predation was positive but not statistically significant for starfish predators. This probably indicates that the response of starfish predators to water temperature is not a simple one. This is backed up by the bimodal feeding pattern observed during both sets of experiments for this predator type. This kind of pattern is not the result of a simple temperature dependency. The 1993/4 graphs show that, during parts of the year, starfish predation is high when temperature is high (October - November time) and high when temperature is low (March - April time). At other times the predation level does appear to be more or less temperature dependent (July - August onwards). This suggests different responses to temperature at different times of the year. Other factors besides temperature therefore appear to be acting to produce the observed pattern of predation.

Interestingly, both the 1993/4 and 1995 experiments indicate that the January/February period of low starfish predation does not coincide with the minimum water temperature - the minimum level of predation tends to occur about one to two months before the month of minimum water temperature (March/April). Both sets of experiments indicate a second period of low relative predation around June. This coincides with the expected period of spawning for *Asterias rubens* in Manx waters (Briggs, 1983). Subsequently, predation levels rise again to a second annual peak once spawning is complete and water temperature is rising. After this second peak starfish predation level falls away as temperature falls. The experiments suggest that the observed feeding pattern of starfish throughout the year is a result of the effects of temperature during the latter half of the year and the animals breeding cycle during the early part of the year. Given that the winter months show the lowest levels of starfish predation on tethered scallops, it may be sensible to initiate seabed re-seeding trials during the early part of the year as far as starfish predators are concerned. This would enable the scallops to settle and recess successfully with a reduced chance of early predation.

The effect of temperature on echinoderm predator activity did not appear to be as well defined as the response demonstrated by crustacean predators. Regression analysis of feeding rates with temperature yielded both positive and negative regression coefficients. The only statistically significant result was a negative regression coefficient for small scallops consumed by starfish during the 1993/4 tethering experiments. The variability in these results suggests that the relationship between starfish feeding activity and temperature is not straightforward. The observed bimodal feeding pattern indicates a more complex feeding pattern than one merely governed by ambient temperature.

When regression analysis was carried out between crab predation and water temperature all fitted slopes (regression coefficients r) were positive, however, only one was statistically significant at the 95% level. This significant result was for crab predation, combined with unattributable losses for small scallops during the 1995 experiments. The lack of significance of these coefficients was most likely a result of the relatively low level of replication used. The overall trend suggests that crab predation has a positive association with temperature.

Temperature is also known to affect the escape response of scallops (Barbeau & Scheibling, 1994b) which will make them more vulnerable to predators at certain times of the year. In the case of crabs this will also coincide with times of lower predator activity. The February feeding minimum of starfish predation observed during the 1995 tethering experiments will also coincide with this period. Starfish predation, however, did rise quickly after February which may indicate that temperature affected the ability of scallops to escape from starfish predators.

2.4 Discussion.

Previous studies suggest that tethering is a useful tool for investigating predation, especially for prey species which are sessile (Heck & Wilson, 1987; Eggleston, 1989; Auster & Malatesta, 1991) or capable of limited movement which could, potentially, remove them from an experimental monitoring area. Although the scallop *Pecten maximus* does have the ability to actively escape an attacking predator (Baird, 1957; Hartnoll, 1967), it has been suggested that it relies mainly upon cryptic colouration and recessing to evade predators. Thus scallops will tend not to move from their recessed state unless provoked by their more voracious predators (Thomas & Gruffydd, 1971). This behaviour may predispose this species for use in tethering experiments. Zimmer-Faust et al. (1994) suggested that predation rates on highly mobile prey are more likely to be exaggerated by tethering, compared with less mobile or cryptic prey. This argument was also employed by Auster & Malatesta (1991) in assessing predation on the infaunal bivalve *Mercenaria mercenaria* and by Heck & Wilson (1987) in their 5 year study of predation upon decapod Crustacea.

The results of diver monitored tethering experiments in Chapter 4 suggest that a high percentage (>75%) of surviving tethered scallops tend to be recessed in the sediment at between 5 and 6 days after experimental deployment. This percentage varied after the 5-6 day period, presumably because of disturbing influences causing scallops to move and subsequently recess again. However, the percentage of survivors that were recessed remained high, which suggests that the scallops used in these tethering experiments preferred to be recessed. This, however, does not indicate how many times a scallop actually moved, since a recessed animal may have moved and recessed elsewhere in between monitoring dives. The mere fact that *Pecten maximus* is capable of an escape response will introduce some bias into the estimation of predation rates. Any escape response initiated by the presence of a predator will be limited by any tethering method used, thus increasing the likelihood of predation. Also tethered scallops may not be as successful at initiating an escape response in the first place compared with an untethered animal. Despite this, the migration of free ranging *Pecten maximus* from a study areas can significantly reduce the amount of data retrieved from an experiment (Whittington, 1993; Wilson, 1994). The experimental animals do not have to move far to be undetectable to divers in all but the most exhaustive and time consuming searches. This problem was especially relevant at the depths encountered in the present study where dive times were severely restricted by decompression limits. Consequently, it was felt that, under the field conditions in the experimental areas, tethering was the only way of ensuring the collection of adequate amounts of data for subsequent analysis.

Previous work has shown that the importance of predation processes in populations of motile fauna in the marine habitat is virtually impossible to evaluate without some form of artificial manipulation such as tethering or caging (Peterson & Black, 1994). *Pecten maximus* is known to exhibit cryptic behaviour in the field (Thomas & Gruffydd, 1971) and, as a consequence, tethering should, theoretically, have less effect upon this species (Zimmer-Faust et al., 1984; Heck & Wilson 1987; Auster & Malatesta, 1991). However, it must be stressed that *Pecten maximus* is capable of an active escape response in the form of swimming (Baird, 1957; Hartnoll, 1967) and that, once this escape response has been initiated, the tether can potentially affect the likelihood of capture by a predator (Barbeau & Scheibling, 1994b; Zimmer-Faust et al., 1994).

The likelihood of predation upon tethered prey will also depend on the type of predator concerned and differential effects have been identified (Barbeau & Scheibling, 1994b; Zimmer-Faust et al., 1994). Barbeau & Scheibling (1994b) found that the effect of tethering of prey upon predation rate depended upon the type of predator and its mode of feeding. The scallop *Placopecten magellanicus* was used as the prey species. They found that for crabs encounter rate equalled predation rate therefore predation rate was independent of tethering since tethering could not affect encounter rate. For starfish, however, the probability of a seastar being able to detect the scallop was a major determinant of predation rate. Consequently, tethering significantly affected predation rate since the scallop, upon exhibiting its escape response, was limited in movement and could still remain within the area where the attacking starfish could detect it.

Heck & Thoman (1981) combined laboratory and field studies in an investigation of predator/prey interactions. Their field results indicated that predation on decapod Crustacea was higher in spring than in summer. Field tests using *Chlamys asperrima* and *Chlamys bifrons* tethered and untethered in cages with the starfish *Coscinasterias calamaria* allowed calculation of a statistically testable survivorship coefficient (Pitcher & Butler, 1987). Prey were not replaced as eaten, yielding a conservative estimate of the differences in susceptibility of tethered and untethered animals. As expected, tethered animals were found to be more susceptible to predation. This gives some indication of the effect of tethering on predation rate. Lake et al. (1987) used caging experiments to determine size refuge attainment in *Pecten maximus* from the crab *Cancer pagurus*. This work indicated a size refuge attained, albeit under very high densities of scallops and crabs compared to natural levels, at a scallop size of approximately 6-7cm shell length, using crabs of up to 14cm carapace width. These results were used as a rough guide in choosing suitable sizes of scallops to use in the current tethering study since, as this is a study of relative predation levels through the year, it would be pointless to choose a scallop size which the local predators would be incapable of attacking.

The larger size class of scallop (77.6mm ± 0.335 in 1993/4 and 74.7mm ± 0.16 during 1995) would seem to be the better of the two size classes used in the present study in terms of surviving predation and thus for re-seeding trials. Wilson (1994) showed, using a mathematical model, that seabed re-seeding could be financially viable with survival rates as low as 50% of re-seeded scallops surviving to marketable size. The results of the current study indicate that tethered scallops of 70-80mm show overall survival of 65.9% during 1993/4 and 52.2% during 1995 which may be conservative estimates given that tethering reduces the ability of the scallops to escape predators. The smaller size class of scallop demonstrated survival rates of 39% and 37.5% respectively during 1993/4 and 1995 experiments. These figures could well prove to be sufficient for viable re-seeding, given that untethered scallops would almost certainly have higher survival rates and that totally lost scallops may also have survived leading to conservative estimates of survival. Using smaller scallops would obviously lead to lower initial culture costs prior to re-seeding. However, it must be pointed out that the current study used only short term experiments which may mean that comparison with the data obtained by Wilson (1994) is not justified. If these magnitudes of survival could be demonstrated over longer time periods then the comparison would be justified. To clarify this would require long term experiments involving larger numbers of more widely distributed juvenile scallops.

Tethering is likely to restrict the degree of movement of the prey and thus result in raised predation rates compared with the totally natural situation. Tethers should therefore be designed to minimise their effect on prey mobility, allowing as much movement as possible within the confines of what is logistically feasible. There is also a problem with possible sequential encounter of prey by a predator when the tethered animals are close together. This effect could also lead to raised predation rates (Kuhlmann, 1992). This could apply to the present study where tethered scallops are set at intervals on lines along the seabed. Here also the prey density in the experimental area is almost certainly higher than in the area immediately adjacent, which could potentially attract more predators causing predator aggregation (Boulding & Hay, 1984; Hagen & Mann, 1992). Total loss of tethered prey (escape, broken tether) could potentially lead to artificially lowered estimates of predation rate if the lost animals were consumed. Conversely artificially raised estimates of predation rate would result if the lost animals survived but simply broke free. In this study, where total loss occurs, no form of predation was assigned and no conclusions regarding lost scallops could be drawn.

It therefore seemed sensible to test for differences in predation rate between tethered and untethered prey for each predator type. For comparison of different predators a factor would need to be calculated to take account of this difference. Zimmer-Faust et al. (1994) found that tethering affected different prey, with different modes of escaping, in different ways. Their conclusion was that tethering will greatly affect the rate of predation upon highly motile prey species that rely on motility as a means of escape from their predators. They recommended quantifying the impact of tethering on prey. Barbeau & Scheibling (1994b) suggested that tethering affects the likelihood of predation depending on the type of predator making an attack. Results from laboratory experiments carried out during the present study indicate that there was no statistically significant difference in the likelihood of predation between tethered and untethered scallops for starfish predators. Experiments were tried with crabs but were not successful because the crabs would not consume even very small scallops in the laboratory. It was felt that this finding reflected the confined nature of the experimental tanks rather than the true effect of tethering scallops. The size of tank used in this set of experiments left the scallops within detection range of the predators even when untethered. The tanks used were the largest available at the time.

Some account was taken of total losses in the present study by direct observation of predator aggregation experiments immediately after experimental deployment, before predation effects arose. The predator aggregation experiments were designed in exactly the same way as the main tethering experiments and are discussed in Chapter 4. Initially it was suspected that the most likely cause of total loss of prey items would be due to dragging along the seabed on deployment, as the boat drifts with wind and tide. The results of the monitoring dives made on the predator aggregation experiments immediately after deployment suggest that this factor is not a significant cause of total loss. No scallops were lost during any of the experimental deployments observed. This implies that total losses are most likely to result from predation and that total losses should be added to a final integrated total of predation since no firm conclusions about the type of predator causing the total loss can be drawn. Fortunately, in most cases, predators leave part of the prey item (shell broken or intact and/or viscera). From damage inflicted on the shell remains, the predator type may be determined upon recovery of the experiment (Elner & Jamieson, 1979; Fernandez et al., 1993 Whittington, 1993 and Barbeau & Scheibling, 1994b).

Various methods of tethering prey species have been employed by workers in the field. Wilson (1989) used monofilament fishing line and super glue to tether crabs in a predation experiment. The super glue was used to help retain part of the carapace upon predation thus leaving the vital evidence of part of the broken shell of the prey species as an indicator of predation. This method of tethering using super glue and monofilament line is common to several predation studies (Heck & Wilson, 1987; Heck & Thoman, 1981; Herrnkind & Butler, 1986). In the case of scallops the most straightforward and reliable means of attachment is thought to be by a small wire loop pushed through a hole drilled in the ear of the shell, as employed by Pitcher & Butler (1987) and Whittington (1993). This method was used in the current study and appeared to be successful in retaining whole shells, or fragments of shells, of scallops consumed by predators thus allowing suppositions about the types of predators inflicting the damage to be made (Elner & Jamieson, 1979; Whittington, 1993 and Fernandez et al., 1993).

It is possible that the tethering technique used could have affected the viability of the tethered animals and thus led to artificially raised estimates of relative predation. Zimmer-Faust et al. (1994) state that several investigators including Heck & Thoman (1981) and Aronson (1992) found no adverse effects of tethering upon the health of prey species in the absence of predators. This seems to be borne out in the present study where only two of the 176 animals tethered in pearl nets and attached to the shotlines of each tethering experiment during 1993/4 suffered mortality (1.14%). The corresponding figures for 1995 were 1 death out of 144 deployed in pearl net controls (1.4%). Also, animals prepared for tethering with drilled and wired ears were kept in holding tanks prior to deployment for periods up to 1 month alongside scallops not treated in this way. No difference in mortality was noticed between drilled and non-drilled animals but no statistical testing was performed.

The main drawback of tethering experiments, recognised by all authors of such studies, is that absolute rates of predation cannot be obtained, only relative rates. This assumes that there are no interactive artifacts associated with the experimental treatments. Peterson & Black (1994) state that any experiment in natural science necessarily intervenes in the natural system being studied. This runs the risk of introducing artifacts that may bias the outcome of such experiments. The most obvious examples of such intervention are laboratory experiments under highly artificial conditions, field caging experiments in ecological studies and field tethering experiments. The mere presence of an observer may create bias or alter the observed system. The tethering methods used in the present study may remove the need for direct observation by divers, thus removing the potential observer bias, but may introduce a tethering bias or artifact. Some attempt to quantify this type of bias should be made (Peterson & Black, 1994). Previous studies suggest that if the method of restraint, in whatever form, is applied equally across all treatments then the method will yield a comparative, relative level of predation (Peterson & Black, 1994). Peterson & Black (1994) reviewed previous tethering studies and found that a majority (55%) mentioned simple tethering artifacts, such as movement restriction, which were accounted for by stating that tethering could only produce a relative and not an absolute measure of predation rate. This would allow comparison of sites or dates treated in the same way, as carried out in this thesis.

The literature indicates that predation rates on tethered animals are raised, in some cases greatly, compared with natural levels, with some authors finding very high predation rates over very short experimental intervals (Watanabe, 1984). A minority of the papers reviewed mentioned potential tethering/treatment artifacts such as the possibility that different predators might dominate in different habitats (treatments) or that tethering a normally motile organism might lead to it being available to a predator that may not normally be capable of attacking that prey. Kuhlmann (1992) chose experimental areas with similar substrate (open sand) and other environmental variables as close as possible so that tether/treatment interaction would be minimal and relative predation rates would thus be more closely comparable. This approach was employed in the current study where two sites were chosen with similar depths, substrates, distances from nearby land and current regimes. Later experiments took place at a single site thus removing habitat as a potential factor affecting relative predation rates.

Peterson & Black (1994) also mentioned the possibility that tethering might induce attention attracting behaviour in the tethered animals. This review of the tethering literature found that most authors lack a complete assessment of the predators responsible for attacking the prey items used which would allow an evaluation of the degree to which artifacts of tethering may have varied between treatments. Predator surveys were also carried out for known or likely predators, as is the case with other authors (Pohle et al., 1991 and Kuhlmann, 1992), where it is considered a highly important part of the assessment of predation as a whole. In the present study predator surveys were carried out as detailed in Chapter 3.

Heck & Wilson (1987) suggested that predation intensity would vary owing to changes in characteristics of predator populations, changes in habitat and changes in characteristics of prey species. Their results showed predation varying from location to location and from generation to generation. Other environmental and biological parameters shown to be of importance were investigated to attempt to elucidate any differences in relative rates of predation e.g. sediment composition (Arnold, 1984; Gibbons, 1984; Fouke & Lawton, 1990; Sponaugle & Lawton, 1990); temperature (Bennett & Brown, 1983; Gibbons, 1984); prey size and predator size (Gibbons, 1984; Lake et al., 1987). In this instance prey size only can be manipulated in the field but both prey and predator sizes and types can be manipulated in the laboratory. Predator size can be investigated using predator surveys but cannot be manipulated experimentally.

Peterson & Black (1994) concluded that the need for addressing the problem of tethering artifacts depends upon the incidence and consequence of such artifacts. There appear to be no examples of empirical testing of experimental artifacts in the literature and our understanding of complex interactions involved in community ecology is inadequate, at present, for the application of a deductive approach employing community ecology theory. Their aim was not to provide a means of testing for non-additivity of artifacts, but simply to bring the problem to the attention of the experimentalist and encourage them to evaluate the importance of non-additivity within the contexts of their own work. Peterson & Black (1994) state that, for any response variable, the non-additive artifacts of intervention will be trivial if the artifacts are small compared with the treatment effects. One way around the problem would be to employ treatment by treatment intervention controls. This, however, would not only be self defeating but also, by definition, virtually impossible to do since, if the experiments could have been conducted without the intervention (in this case tethering), then they would have been thus removing the risk of an intervention artifact in the first place. The constraints placed on the tethered prey are a necessary intervention for the experiment to be viable, since without such intervention the prey could potentially be lost to subsequent monitoring regimes. Peterson & Black (1994) also mention sampling frequency as a potential source of intervention artifacts and tested for this by employing a control where the sampling frequency was halved. They stated that it is not possible to accept unchallenged the assumption that because all treatments in an experiment may have been applied identically the effect is necessarily constant.

Splitting the prey into the two size classes shows starfish to be more successful at consuming larger scallops, while smaller scallops appear equally susceptible to both predators. Starfish may have this increased success with larger prey because of their mode of feeding which does not require the scallop shell to be broken (Jangoux, 1982). Crabs, on the other hand, need to be capable of crushing or chipping the shell to gain access to the soft body parts. It is thought that a limiting factor to crabs is the risk of claw damage while attempting to break the shell of the prey (Juanes, 1992). Crabs might rapidly cease attacking a prey item if the risk of claw damage is high.

The 1993/4 results show that assumed echinoderm predation accounted for 10.7% of large the scallops and 15.9% of the small scallops presented. During the 1995 experiments echinoderm predators accounted for 48.6% of small scallops but only 23.7% of large scallops. The differential between consumption of large and small scallops thus increased for echinoderm predators during 1995. Both size classes of scallop experienced increased predation by echinoderms during the 1995 experiments.

The 1993/4 experiments showed that the predation rate of crabs on small scallops was the same as that for starfish on small scallops (15.9%). The corresponding rates for predation of large scallops by crabs was 3.3% and by starfish was 10.7%. This suggests that crabs were more affected by prey size than were starfish during the 1993/4 experiments.

The predation rate for echinoderm predators during the 1995 experiments was greater than the predation rate for crabs. An overall comparison of crab and starfish predation suggests that crab predation fell from 1993/4 to 1995 while starfish predation rose from 1993/4 to 1995. In both sets of experiments starfish consumed more scallops than crabs except for small scallops during 1993/4 when the rate for crabs equalled the rate for starfish. These results therefore suggest that the starfish *Asterias rubens* poses a greater threat to re-seeded juvenile scallops than does the crab *Cancer pagurus* on these grounds. They also indicate that echinoderm predators are affected less by the size of scallop presented than are crabs. This result is consistent with the findings of other studies (Lake et al., 1987; Juanes, 1992) which identified prey size as a limiting factor in crustacean predation. The results of the current study are also consistent with the fact that starfish do not need to physically break the shell apart given their ability to externally digest prey by everting their stomachs through very small shell apertures (Jangoux, 1982). This means that they are less limited by prey size, although wastage of digestive juices and/or digested material if the starfish is not able to completely engulf its prey could lead to a size refuge from starfish. It has been suggested that starfish are capable of determining prey size when they wrap themselves around shellfish. In this way they might be able to determine whether the prey item encountered is within their handling capabilities and thus decide whether to continue an attack or not. This type of behaviour was observed during laboratory experiments but was not analysed.

During the course of this study a static video camera was used to record predator/prey interactions on the seabed using a time lapse video recorder. Approximately 10-12 days and nights of video tape were analysed and during this time only starfish (*Asterias rubens*) and crabs (*Cancer pagurus*) were observed attacking or attempting to attack tethered scallops. This does not prove that other predators are not active with respect to *Pecten maximus* but it does suggest that these two predators constitute the main threat to scallops in the field. Consequently, this study has concentrated only on these two predators while realising that other predators may be capable of consuming scallops. No evidence of this was found during the tethering experiments as shells were carefully examined for damage, particularly damage which may have been inflicted by octopus (bore holes and beak marks). Ambrose (1986) mentions the octopus as a potential predator of bivalves and that a distinctive drill hole was left in the shells of molluscs eaten by this predator. Initial results using an octopus in a holding tank suggest that damage inflicted on bivalve prey by this predator appears to be in the form of complete, undamaged but disarticulated valves which is very similar to the damage resulting from starfish predation. This could lead to the scallops consumed by octopus being assigned to starfish by mistake. The results of the static seabed video surveys suggest that this was not the case as no octopus were observed attempting to attack tethered scallops. Evidence from diver surveys in similar areas both to the tethering experiments and to the static video camera suggest that octopus were present in the area although not in large numbers. Observations made by divers during small scale re-seeding trials indicated that octopus did take and eat juvenile scallops (U.A.W. Wilson, pers comm.)

2.4.1 Conclusions.

This chapter has shown that starfish had two main feeding peaks during both sets of tethering experiments. The timing of the peaks varied between experiments with the 1995 experiments giving later peaks. For both sets of experiments the early peak was smaller than the later peak in starfish predation.

From the observations made starfish were less affected by prey size than were crabs. This would have important implications for re-seeding trials. Starfish appear to be capable of overcoming prey size refuges both by their method of feeding and by attacking prey in numbers which has been observed both during diver surveys (Chapter 4), and video surveys (Chapter 3), and in the laboratory (Chapter 4). Crabs, on the other hand, have to break the shell of scallops in order to consume them and are therefore more limited by the size and relative shell strength of scallops.

Starfish also were seen to be the main threat to tethered scallops, consuming far more than crabs, especially during the 1995 tethering experiments. There was no evidence of other predators attacking tethered scallops during these experiments or during other experiments carried out for this study. This does not mean that other predators were or are not active in the experimental area. The types of damage observed were consistent with echinoderm and crustacean predation. If one ignores the results of the seabed video surveys then these damage categories would simply be attributable to echinoderms in general and crustaceans in general. However, the result from the static seabed video camera showed that *Asterias rubens* was the only type of starfish to attack tethered scallops in the field of view of the camera. Similarly, *Cancer pagurus* was the only species of crustacean to attempt to attack the tethered scallops. This is not, of course, conclusive proof that these are the only two predators attacking *Pecten maximus* but it does indicate that the most common species attacking the Manx scallop appear to be *Asterias rubens* and *Cancer pagurus*. Lower crab predation during the 1995 tethering experiments may have resulted from increased crab fishing activity in the Port Erin area resulting in lower densities of crabs. However, diver surveys failed to identify a reduction in crab density so another factor may be acting to reduce crab predation. The diver surveys carried out during these experiments took place at different times of the year during the years sampled. This combined with crab migratory behaviour may explain why differences in crab density were not observed. Diver surveys may also miss crabs beacause they are mostly active at night. Low levels of replication would not have helped either.

Temperature was a factor in determining levels of predation on tethered scallops but the effect was not as marked as may have been expected. This contrasts with the findings of Barbeau et al. (1995), where starfish predation was found to increase with temperature. Barbeau et al. (1994) found that crab predation correlated positively with temperature at some of their experimental sites but showed no relationship at other sites. During the present study, crab predation showed a consistently positive association with seawater temperature but with only one of statistical tests proving significant. Barbeau et al. (1994) found that starfish predation on scallops was dependent mainly upon temperature and scallop size. Results of the current study indicate that starfish predation did not show any clear association with temperature but was probably affected by the reproductive cycle of the starfish itself and by scallop size during 1995. Allison (1994) found that meat weights (abductor muscle) of scallops varied significantly throughout the year which could lead to variation in the ability of scallops to escape predators. This is discussed in greater detail in Chapter 5.

Chapter 3 - Surveys of Predator Populations.

3.1 Introduction.

It has been mentioned by several authors (Dare, 1982; Auster & Haskell, 1988; Himmelman & Dutil, 1991; Minchin, 1991) that an integral part of any field study of predation rate upon a given prey species should be a local survey of the potential predator populations. Results from these surveys could help to explain any observed differences or variations in predation rates and, possibly, any interactions between predators and their prey. This illustrates the importance of obtaining sufficient data to attempt to define basic predator population parameters, such as mean densities and sizes, during different periods of the year in order to explain any observed differences in levels of predation. In connection with this, it is also important to have some knowledge of predator population dynamics, not just in terms of numbers present (Elner & Lavoie, 1983; Lake et al., 1987; Lind, 1987), but also whether any seasonal activity changes occur (Castilla, 1972; Gibbons, 1984) and whether any seasonal migratory behaviour is displayed (Edwards, 1979; Brown & Bennett, 1980; Bennett & Brown, 1983). Large area surveys could go at least some way to elucidating the reasons for changes in predation levels throughout the year. Such surveys might show how predator populations respond to the varying environmental conditions at different times, assuming that the surveyor has knowledge of the expected behavioural responses of the target organisms. The problem is how to quantitatively survey large areas for widely distributed, motile species.

Up until the late 1960s and early 1970s quantitative methods of sampling the marine benthos advanced most rapidly for the infauna of particulate sediments (Holme, 1964), with most sampling methods being modifications of the Petersen grab which rarely sampled areas greater than $0.5m^2$ (Caddy, 1970). Larger, mobile epifaunal species, such as the crabs and starfish surveyed during this study, often occur at densities much less than $1m^{-2}$. Consequently they would very rarely, if ever, show up in such a discrete sampling method. This illustrates the need to cover larger areas quantitatively in order to estimate more accurately overall mean densities of such species (Caddy, 1970; Franklin et al., 1980).

Attempts have been made to quantify what are effectively qualitative techniques such as the naturalist's dredge, beam trawl and scallop dredge including attachment of odometer wheels to quantify the area of seabed swept by the gear (Gunter, 1979). Divers have also been used to observe and survey dredges and their tracks to assess efficiency (Bourne, 1966; Chapman et al., 1977). These methods of surveying widely dispersed, mobile epifaunal species and the attempts to quantify them have been considered unsatisfactory for a number of reasons. Dredges may become clogged changing the efficiency during a tow (Cameron, 1955;

Chapman et al., 1977). Mesh selectivity captures certain species but not others (Bourne, 1966). Animals being surveyed may actively avoid capture (Caddy, 1968). Dredge gear may not remain in contact with the seabed throughout a tow (P. Crebbin pers comm.). Only totally integrated samples can be obtained with no idea of where or when the animals were caught during the tow (Holme & McIntyre, 1971) and dredges, especially, are known to have low efficiencies (Holme & McIntyre, 1971). All of these factors mean that only relative or comparative investigations can be made using dredge sampling. To add to these problems very little or no work has apparently been done on the efficiency of dredges with respect to non-target or by-catch species such as the main predators of scallops - *Cancer pagurus* and *Asterias rubens*. Comparative video and dredge survey data obtained during this study could provide such data, for the areas surveyed at least. Dredging is thought to be useful as a qualitative or semi-quantitative survey method, assuming the low efficiency and selective nature of such surveys (Holme & McIntyre, 1971; Wilson, 1994).

Wilson (1994) stated that broad scale dredging surveys can provide important data regarding relative densities of predators throughout the year. Such surveys can help to explain observed differences in predation rates, and can provide samples of species for size frequency analysis which can be used to estimate prey size refuges. Consequently, for the purposes of this study dredging is used as a semi-quantitative survey method for determining relative densities of predator populations. The same, standard, methodology is applied to all surveyed sites so that comparisons between sites, at least, should be justified. It is hoped that the dredge survey results coupled with video and diver surveys will go some way to explaining observed differences in relative predation levels derived from field prey tethering experiments. Wilson (1994) also stated that it would be of great interest to know the gender of crabs caught in dredges off the coast of the Isle of Man. This would clarify whether the presence of these predators at different densities throughout the year on the local scallop grounds is due to normal foraging activity or to the annual migrations undertaken by females as part of their breeding cycle. These data can easily be obtained from the catches made. Inferences could then be made regarding the importance of that species in consuming a commercially important fishery species. Of great interest are the size frequency distributions of the predator populations since this will determine at what point prey species are likely to achieve a size refuge, if at all (Blankley & Branch, 1984; Tettelbach, 1986; Lake et al., 1987; Minchin, 1991). In this respect, dredge surveys have an advantage over the other methods employed in that samples of the predator populations are retrieved and can be analysed to provide these data.

Other methods for surveying widely dispersed, mobile epifaunal species exist including SCUBA diving (Caddy, 1968; Larsson, 1968; Mingoa & Menez, 1988; Himmelmann and Dutil, 1991); video surveying (Franklin et al., 1980) and submersibles (Caddy, 1970).

SCUBA diving is limited in scope for carrying out prolonged surveys, even at moderate depths (Myreberg, 1973), decompression times limiting divers to two half hour dives per pair per day at depths as shallow as 20-25m. Diving does, however, have the advantages of direct observation, by a trained scientist and the method can be made quantifiable using the correct equipment. Submersibles are, of course, highly expensive, require skilled operators and considerable surface support but have been demonstrated as a viable, quantifiable method of surveying widely dispersed, if not highly motile, bivalve mollusc stocks (Caddy, 1970).

The need to quantitatively survey populations of the crab *Cancer pagurus* and the starfish *Asterias rubens* off the west coast of the Isle of Man meant that a sled mounted video camera towed by a small research vessel would be a useful method of undertaking these surveys. The 1950s saw the first use of television systems underwater by the U.S. and Royal Navies (Barnes, 1963). It was at this point that scientists realised the potential of underwater television in general and the method came to be accepted as a valid tool for underwater research. Observation of benthic fauna was considered the single most useful application of underwater television in terms of both static, undisturbed experiments (LaPointe & Sainte-Marie, 1992) and towed transect surveys using sleds (Machan & Fedra, 1975; Holme & Barrett, 1977; Franklin et al., 1980; George et al., 1985). No other marine sampling instrument produces so much information so rapidly and with such a low requirement for support (Machan & Fedra, 1975; George et al., 1985). Underwater television and video produce data over sufficient areas and times that meaningful analyses are assured (Myreberg, 1973). Large areas can be covered and substrate characteristics, animal counts and distributions can be monitored (Barnes, 1963). Experiments can be placed in the field of view of a static camera on a frame. Underwater television is particularly suited to long periods of continuous observation. The technology and data analysis for such systems has been improving ever since (Caddy, 1970; Franklin et al., 1980; Auster et al., 1989, 1991).

Caddy (1970) rightly states that, before the use of underwater television for transect surveys can be accepted by the scientific community as a usable survey tool, the technique must be made quantifiable. This requirement has since been largely fulfilled. Michalopoulos et al. (1992) also mention that video and manned submersible transect methods require a stable platform, free from pitch and roll such that the field of view maybe quantified. This point is also considered by Buchannan (1971) who states that attachment of a camera to a sled removes uncertainty associated with the field of view and consequently the area observed at any time, thus path width of the transect can be determined easily. With the use of odometer wheels the method is also rendered quantifiable in terms of distance travelled (Machan & Fedra, 1975; Holme & Barrett, 1977; Franklin et al., 1980). The on-screen spotting method can be used as a backup should there be any problems with the odometer wheel.

The aims of the predator survey work were to provide data on the local predator populations around the Isle of Man. Detailed, non destructive survey work (diving and video surveys) were carried out around areas where tethering experiments were located to investigate how density of predators might affect predation rates. Dredge surveys provided predator size frequency data which can be used to assess at what point *Pecten maximus* might be expected to achieve a size refuge on different grounds around the Island. Tentative predictions about the likely risk of predation on other grounds were made using the size and relative density data collected from the dredge samples. Given the low efficiency of dredges, the video and diver surveys made during the present study will be used to estimate the efficiency of the dredges in terms of the two predator species and scallops where surveys are coincident.

3.2 Materials and Methods.

3.2.1 Dredge surveys.

Dredge sampling was carried out on several grounds around the Isle of Man. The approximate co-ordinates of the central points of these sites are summarised in Table 3.0a. A diagrammatic representation of the locations of the survey sites can be seen in Fig. 3.0.

Table 3.0a

Locations of the central points of all of the dredge survey grounds investigated by PEML around the Isle of Man.

Ground surveyed	Latitude (N)	Longitude (W)
Bradda Inshore	54° 07.80'	04° 48.00'
Bradda Offshore	54° 06.00'	04° 54.00'
Peel	54° 13.80'	04° 45'00'
Targets	54° 25.20'	04° 42.00'
Point of Ayre	54° 32.40'	04° 18.00'
Ramsey	54° 19.80'	04° 21.00'
Laxey	54° 13.12'	04° 18.00'
East Douglas	54° 06.00'	04° 18.00'
South East Douglas	53° 59.40'	04° 12.60'
Chickens	53° 59.40'	04° 54.00'
10 Miles South PSM	54° 01.80'	04° 43.80'
20 Miles South PSM	53° 55.20'	04° 43.48'

For this study the starfish and crab by-catch were used to obtain relative estimates of predator density and mean size to enable comparison of the sites sampled. Owing to the fact that dredges are known to be inefficient, qualitative tools (Holme & McIntyre, 1971), no absolute density or size estimates could be obtained. However, since the same methods were employed for all sites, a relative comparison between sites seemed justified.

Generally the queen dredges were used for sampling as they tend to catch more animals and, as such, demonstrate a greater efficiency than the scallops dredges in terms of sampling by-

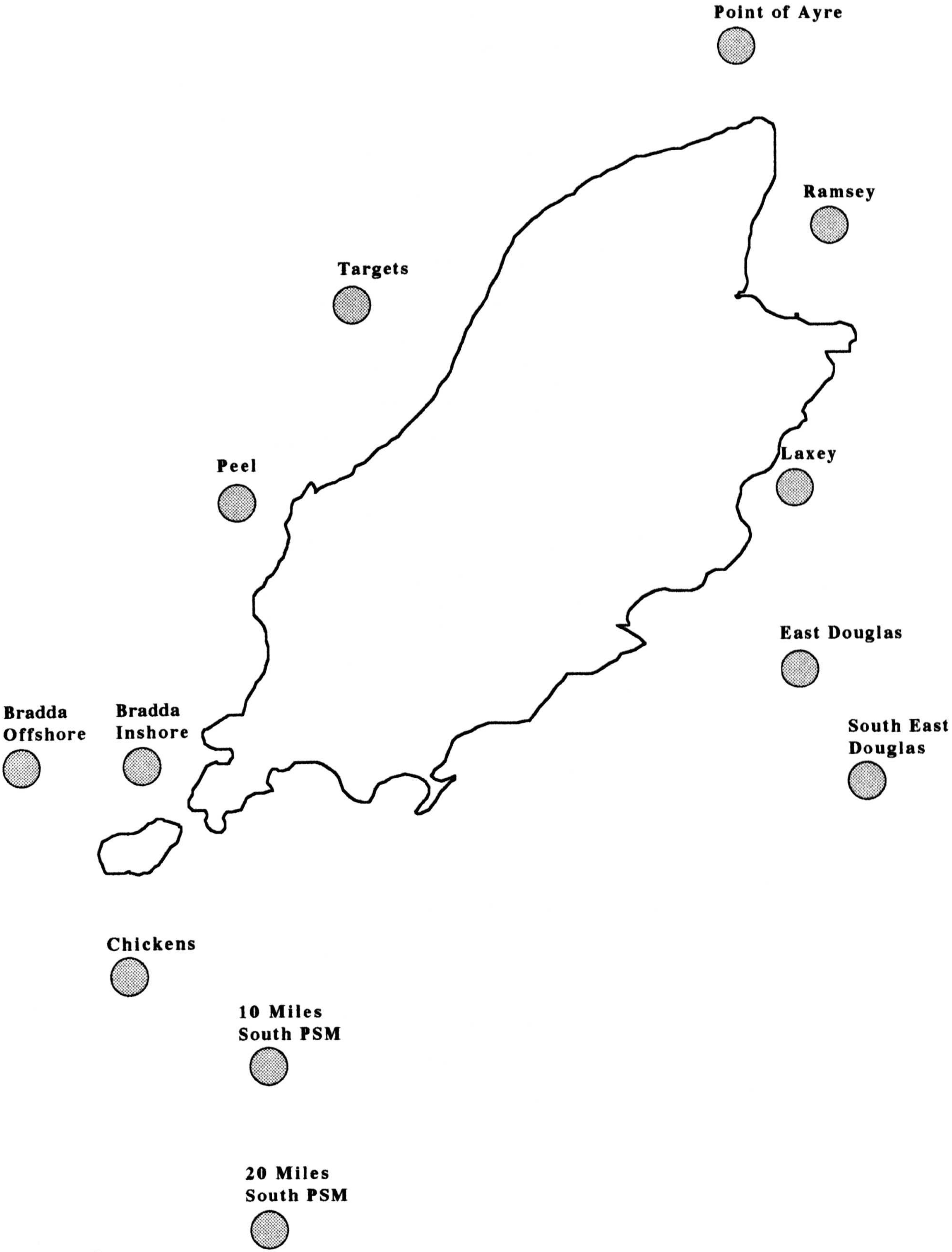


Fig. 3.0
Diagrammatic representation of the locations of the dredge survey sampling sites around the Isle of Man used during this study.

catch species (Wilson, 1994). Scallop gear is designed to minimise by-catch and trash and to maximise the numbers of larger scallops caught, which is less preferable when investigating by-catch species. The only exception to this was made for the crab size estimates since crabs were caught in relatively low numbers so a pooled mean from the scallop and queen dredges was used to obtain more accurate mean sizes. For both crabs and starfish the differences between the two gear types in terms of mean sizes and mean numbers of animals caught were tested using t-tests. This information was used to determine whether data could be pooled from both gear types or data from only the queen dredges used.

3.2.1.1 Analysis of predator size data from dredge samples.

After each 2 mile tow the contents of the queen dredges (queen and scallop dredges for crabs) were emptied onto the deck, keeping the contents of each dredge separate, to be sorted, counted and measured. Size data from the Bradda Inshore and Offshore grounds were collected from October 1993 to October 1996. Collection of predator size data was extended to all surveyed grounds during the October 1995, June 1996 and October 1996 surveys.

Crabs were caught in low enough numbers to be counted and measured on board the boat. Sex and size across the carapace at its widest point were noted. Higher relative densities of starfish meant that they had to be bagged and returned to the laboratory for freezing and measurement at a later date after being counted and the dredge totals recorded on deck. Mean sizes of starfish samples (≈200 animals where possible) were determined by measuring the longest arm of each animal in the sample (Briggs, 1983). Starfish were collected until approximately 200 had been caught and all these animals were then measured to ensure there was no bias in the sizes of the animals that were measured. All starfish were measured where less than 200 animals were collected. Mean sizes for each sample of starfish were then calculated using tows as replicates.

ANOVA techniques were employed to test for differences in mean sizes of the predators caught at each grounds during each survey and to test for differences in size over time within grounds. A two-way ANOVA was applied to the Bradda Inshore and Offshore size data to determine whether significant differences occurred between the two sites and between the dates sampled for both predator species because these were the sites closest to the prey tethering experiments. For crabs, only females were caught in sufficient numbers for analysis.

The predator size data obtained from all grounds between October 1995 and October 1996 were analysed using a one-way ANOVA with ground as the factor. One-way ANOVAS with date as the factor in each case were applied to the predator size data from within each ground where grounds were sampled on more than one date. Where significant differences were identified, a Tukey multiple comparison test was employed to identify where the differences occurred. All data were tested for normality and homoscedascity prior to application of ANOVAs. Any data which could not be transformed to meet the criteria required by ANOVA were analysed using non-parametric Kruskal-Wallis tests. Equivalent non-parametric multiple comparison tests were then employed to identify where differences occurred.

3.2.1.2 Estimation of relative densities from dredge samples.

The PEML RV Roagan was used and data collected from the biannual scallop surveys . RV Roagan is a 25m converted beam trawler. The gear set-up for the scallop survey had four 2 ft 6 in scallop dredges on the starboard side of the boat and four 2 ft 6 in queen dredges on the port side as illustrated in Fig. 3.1. The standard method employed on the survey was to perform between three and four 2 nautical mile tows along specified Decca transects for each site. The same Decca transects were used from year to year. The June 1995 survey encompassed all the grounds that have ever been surveyed (13 in total) and data from the Microplot navigation system were used from this set of surveys to calculate mean tow lengths for each ground. These tow length data were used to calculate mean relative densities of by-catch species and scallops for all surveys used in this study since the same transects were used from year to year. This would lead to some error as tow lengths could vary slightly but this error should be small in comparison to overall tow lengths.

Each set of four tows using eight dredges took a day to complete and sort. Data from previous surveys back to 1982 were also employed. These earlier surveys were less detailed with only numbers of animals being recorded. A summary table (Table 3.7, section 3.7) shows the mean tow lengths for each site. These tow lengths were then used for all surveys, to simplify calculations, as the same transects were used from year to year. Any variation in tow lengths from year to year would tend to be small in comparison with the overall mean tow lengths calculated from the Microplot data. The dredge widths (4 x 2 ft 6 in or 4 x 0.762m) were used in conjunction with the relevant tow lengths to calculate the area swept by the dredges during each tow assuming constant contact with the seabed. Since the dredges were towed parallel to one another they could not be considered to be independent of one another. Consequently, the figures from the four queen dredges were integrated and the total swept area for four dredges used to produce an average value of relative density of predators at each site with tows being employed as replicates so that means and standard deviations could be calculated.

Relative density calculations were carried out assuming that the efficiency of the dredges remains constant from ground to ground and tow to tow. Once figures were obtained for each species in each tow at each ground the data were standardised to give relative estimates

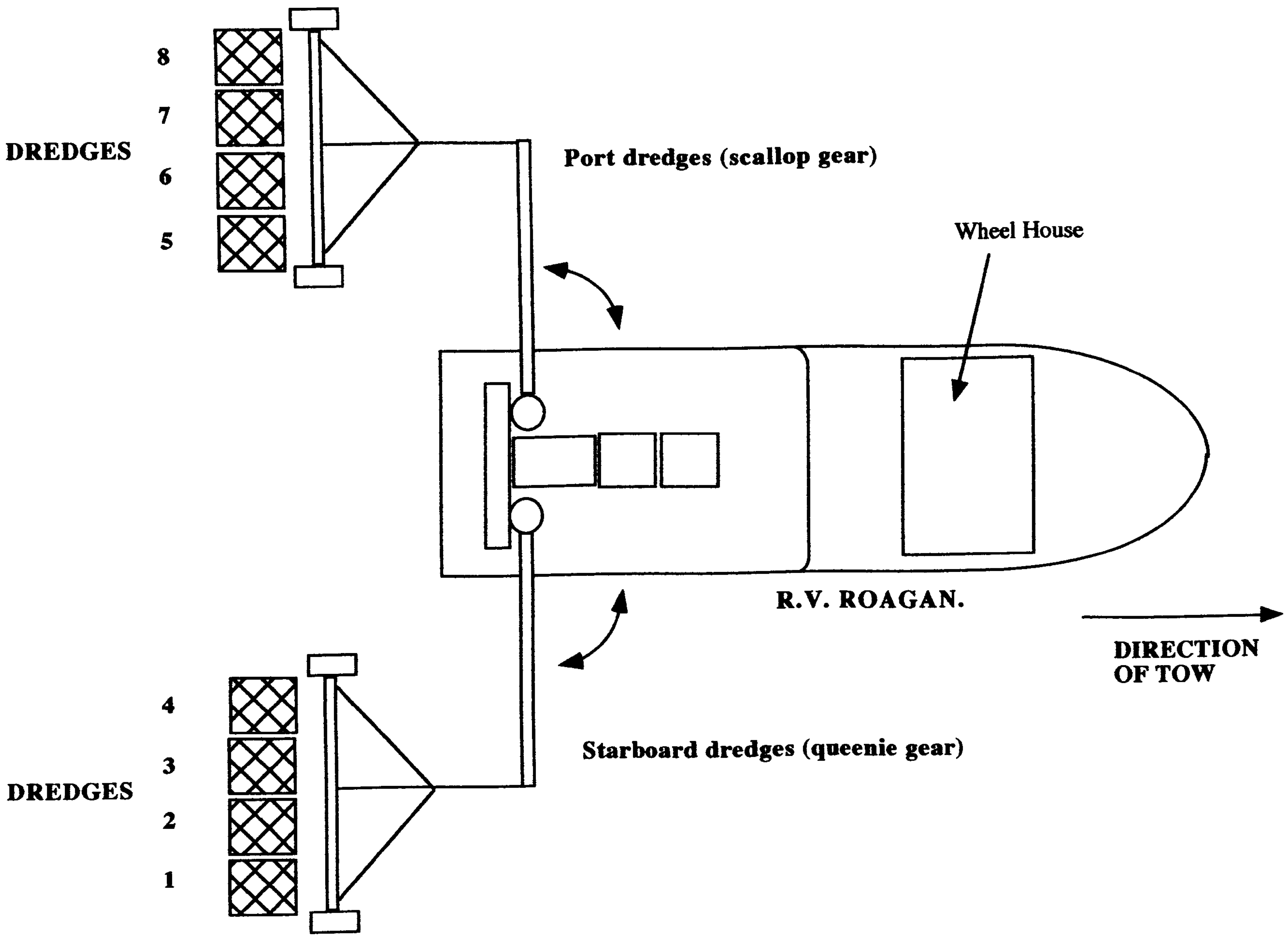


Figure 3.1.
Layout of RV Roagan during dredge surveys - viewed from above.

of animals per square metre of seabed (swept area). Data from each tow were used to calculate means for each ground for each survey. For each survey date ANOVA techniques were used to assess whether any significant differences were identifiable in mean relative densities between grounds. This entailed applying a one-way ANOVA with relative density as the response and ground as the factor to each of the surveys where data were collected.

Where significant differences in size were identified, a Tukey multiple comparison test was used to determine where these differences lay. Assessment of changes in mean relative density within a site were carried out using data from a single site taken over several surveys. A one-way ANOVA was used employing date as the factor and mean relative density as the response for each site tested. Where significant differences in mean relative density were identified, a Tukey multiple comparison test was used to find where these differences occurred. All data were tested for normality and homoscedascity and any data which failed to meet the criteria for parametric ANOVA were analysed using non-parametric methods.

3.2.2 Estimating predator densities using video surveys.

Part of this project involved the design and construction of a video sled usable from a small research vessel for epibenthic surveys. A Rovtech Ltd Seacam system was available and the sled was designed around this. The casing of the camera consists of a plain steel tube for which a mount was designed so that the camera could be securely attached to the sled. The camera mount consisted of an aluminium tube split length ways with a flange welded along the length of each side of each half (Fig. 3.2). This could then be sandwiched around the camera using neoprene rubber cushions as shock absorbers and friction retainers. Pinch bolts through the flanges secured the mounting to the sled and tightened it around the camera. The mounting tube also effectively protected the camera from impact damage.

Once the mounting was made a prototype sled was made up using Dexion (type 225 right angled with M8 13mm nuts and bolts) from an original design by Ken Collins of Southampton University Department of Oceanography (SUDO) for use with a housed camcorder. This design was adapted and miniaturised for use with the much smaller Seacam system. This prototype was tested using divers in shallow water in Port Erin Bay thus ensuring that all dimensions were correct and that the camera angle was sufficient to give a usable field of view. The prototype was then taken to a local metal workshop where a sled was constructed to the same dimensions in galvanised steel tubing (34mm external diameter, 3mm wall thickness), with a variable tilt camera mount to give some flexibility to camera angle (Fig. 3.3). The sled was first tested in Spring 1993 and used for the first epibenthic survey in September 1993.

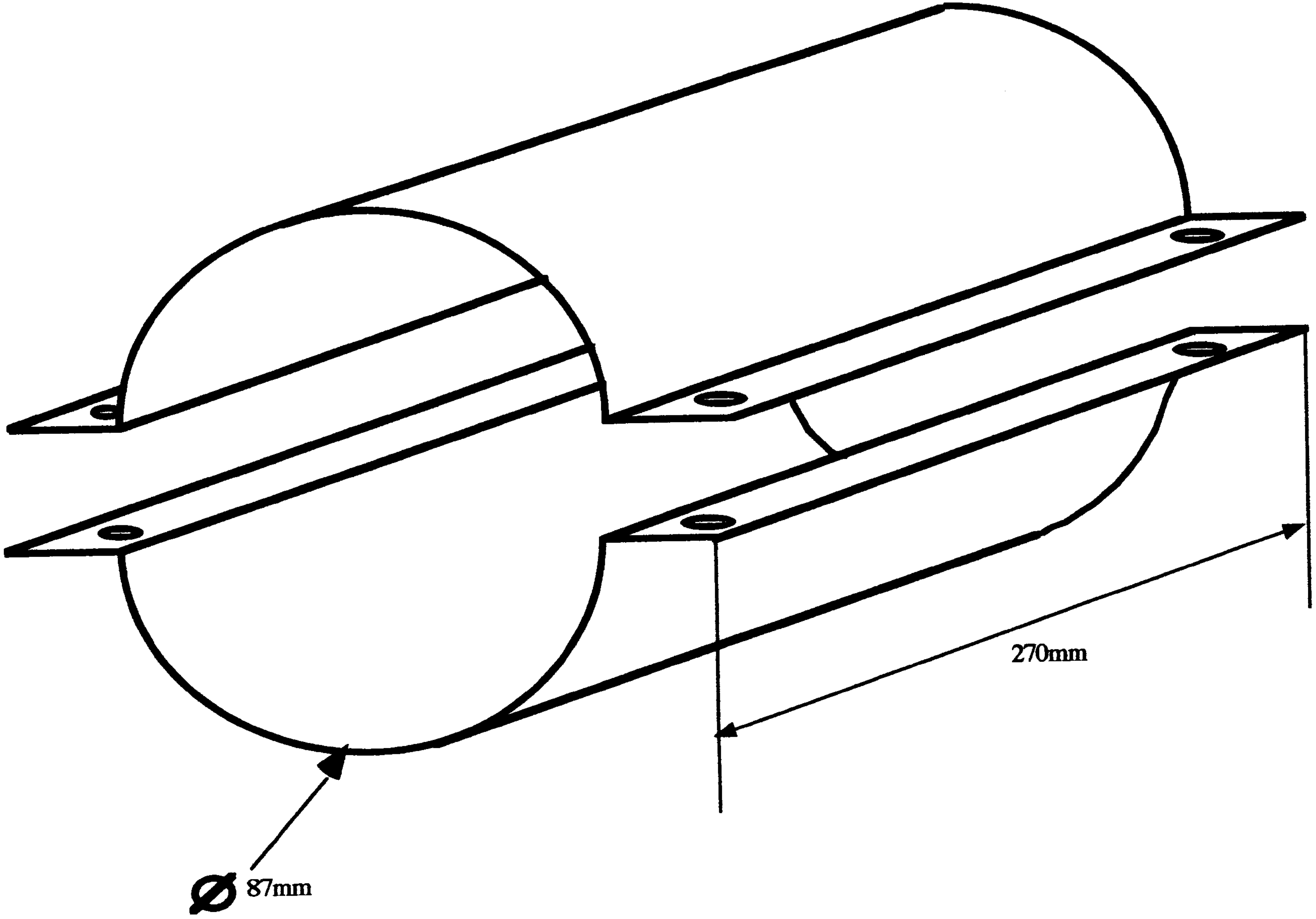


Figure 3.2.
Diagram of the aluminium mount made for the Seacam Industries Ltd black and white, underwater camera used for the video surveys made during this study.

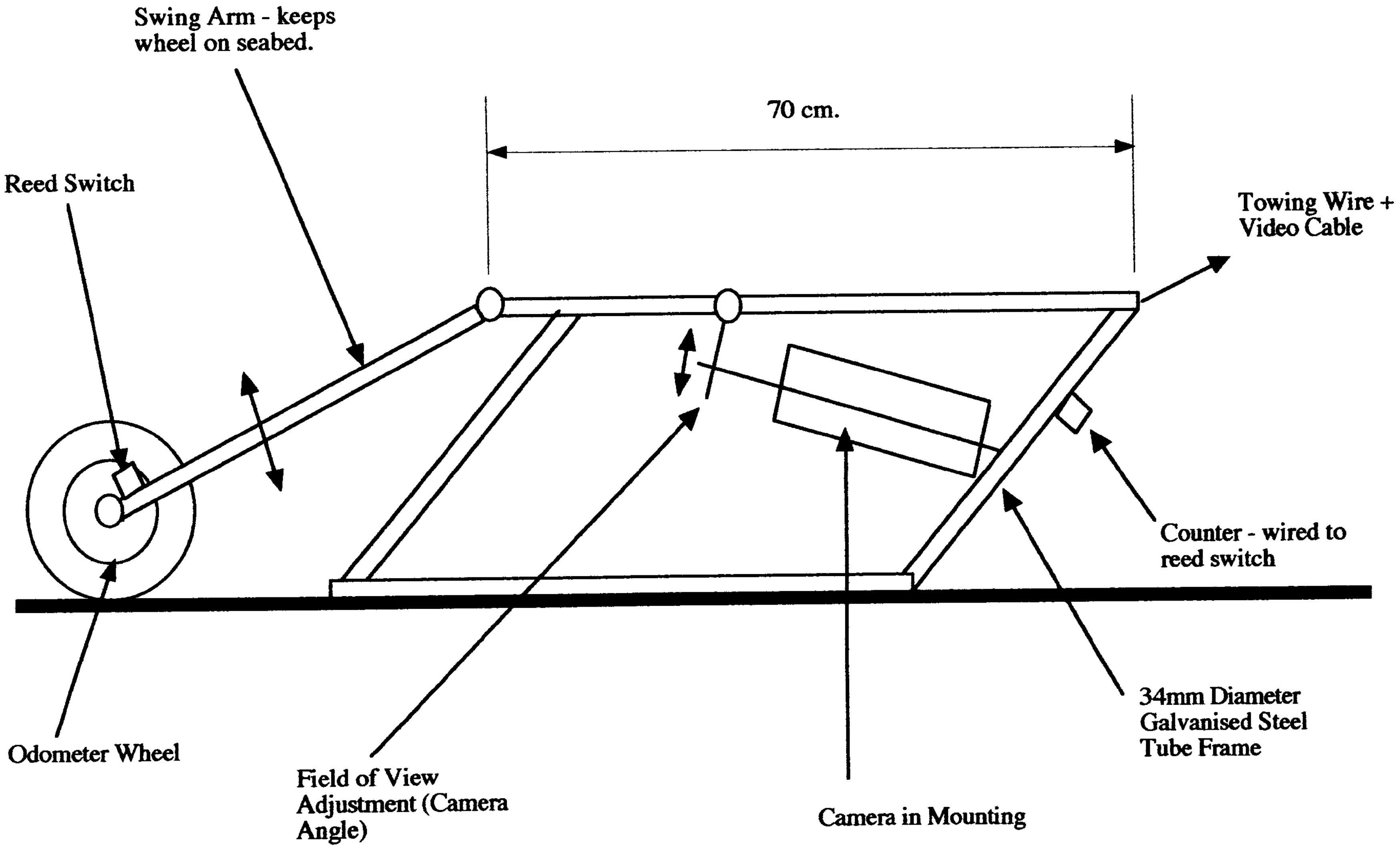


Figure 3.3.
Diagram of the video sled used to makethe seabed video surveys carried out during this study..

To be able to accurately quantify the video data in terms of tow length required an odometer wheel (Caddy, 1970; Holme & Barrett, 1977; Franklin et al., 1980) connected to an on-screen (real time) counter display. For this study a system was designed using a swinging arm pivoted at the back end of the top rail of the sled (Fig. 3.3). It was 70cm long and had a 24cm diameter plastic wheel with a solid rubber tyre, cut to provide improved grip on sand, at the other end. The weight of the swing arm ensured that the wheel remained on the seabed and a short piece of 6mm polypropylene rope attached to the swing arm and the rear cross rail of the sled ensured that it did not rise more than 37cm above the seabed with the sled runners horizontal. The bottom of the wheel could fall 20cm below the bottom rail of the sled, again with the sled runners horizontal.

A magnet (RS part no. 339-768) was attached to the wheel between the hub and tyre using electrical cable ties. A reed switch (RS part no. 339-746, normally open form) embedded in fibreglass resin (RS part no. 561-628) was attached to the right hand strut of the swing arm. Several washers were used as spacers on the wheel axle to maintain the required distance between magnet and reed switch such that the magnet closed the reed switch each time one revolution of the wheel was completed. The output from the reed switch was fed forwards along electrical cable attached to the swing arm and top rail of the sled to a counter positioned on a bracket within the top of the field of view of the camera. A watertight battery tube containing 2 x 1.5 volt C cells was suspended below the top rail of the sled and wired up to the counter to provide power. The counter was designed and built by Hugh Bridge Designs and, after testing, was set in a block of epoxy resin prior to mounting on the sled. All wire connections were made by first soldering the relevant wires, taping them with insulating tape individually and then as a group and then covering the connection in silicone sealant. Each junction was then plastic coated using heat shrink material. Fig. 3.4 shows the wiring diagram of the counting system which incremented the counter by one for each revolution of the odometer wheel (0.746m).

Video surveys were carried out on the dates and at locations shown in Table 3.0b. The start and finish points for each survey are also tabulated. Diagrammatic representations of the video survey areas are shown in Fig. 3.5.

For each survey the camera was mounted in the sled and the power/picture cable (200m total length) connected up to the monitor unit which provided a real time image on a portable T.V. via a video recorder. Power was provided by a portable Honda generator. A marker buoy with 50-60m of 6mm polypropylene line attached to the back of the top rail of the sled was first paid out. This provided enough drag to keep the sled upright as it was lowered, the sled

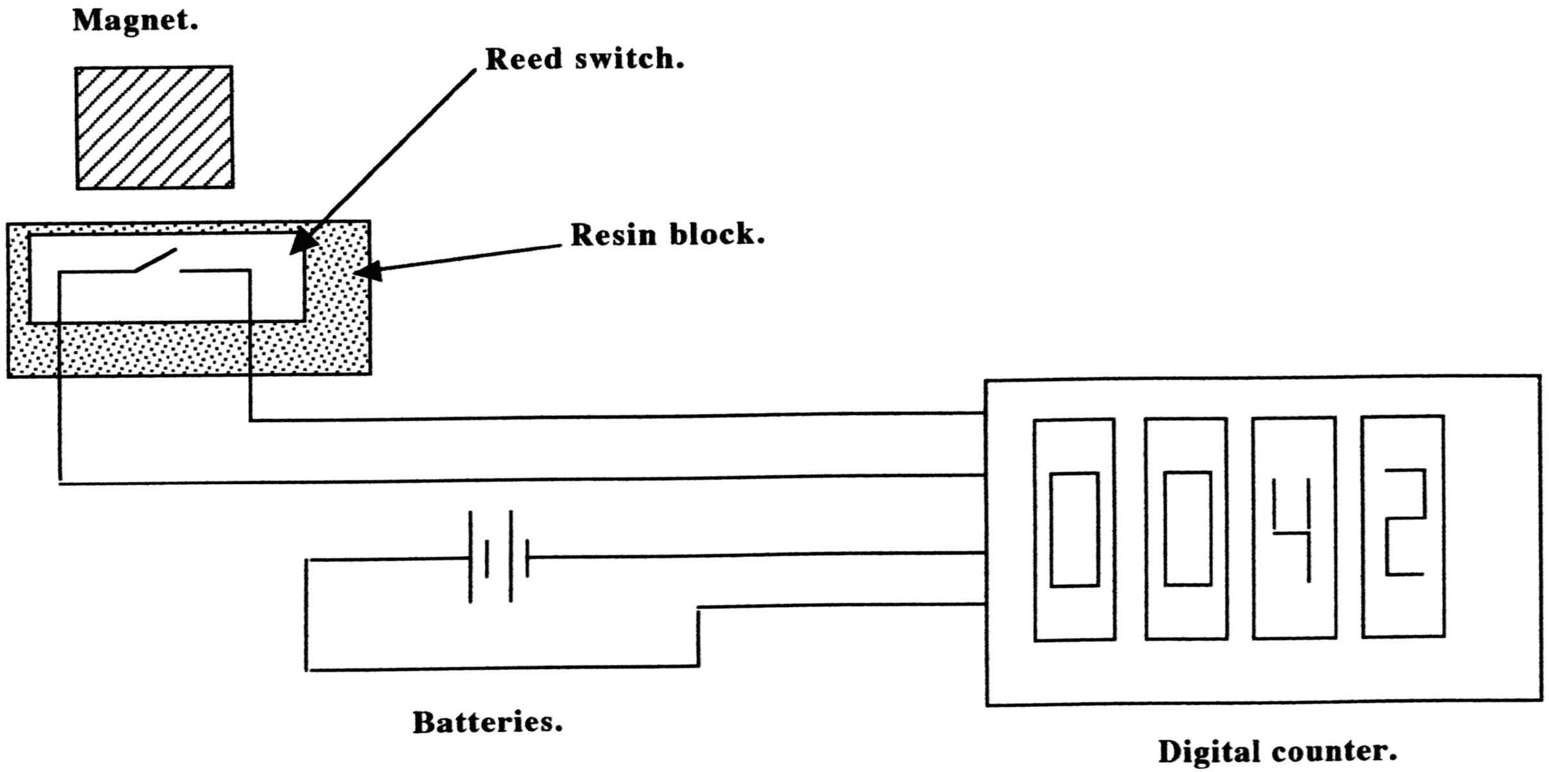


Figure 3.4.
Diagram of the basic layout of the circuit used to operate the on-screen counter on the video sled which was used to quantify results in terms of distance travelled.

Table 3.0b

Dates and start/finish points of the predator surveys carried out using a sled mounted video camera. Latitude and longitude for each start finish/point are detailed.

Date.	Site.	Start.		Finish.	
1/9/93	Bradda Head	54° 06.01'N	04° 46.96'W	54° 05.25N	04° 47.19'W
	Exclusion Zone	54° 05.16'N	04° 46.68'W	54° 04.47N	04° 47.86'W
19/10/93	Bradda Head	54° 05.75'N	04° 47.00'W	54° 06.78N	04° 45.92'W
	Exclusion Zone	54° 04.53'N	04° 47.70'W	54° 05.61N	04° 46.96'W
16/2/94	Bradda Head	54° 06.56'N	04° 46.49'W	54° 05.96N	04° 47.15'W
	Exclusion Zone	54° 05.36'N	04° 46.86'W	54° 04.81N	04° 47.00'W
7/7/94	Exclusion Zone	54° 04.31'N	04° 47.71'W	54° 04.31N	04° 47.71'W
	Exclusion Zone	54° 04.98'N	04° 47.79'W	54° 05.60N	04° 48.18'W
	Bradda Head	54° 05.80'N	04° 47.03'W	54° 06.44N	04° 46.94'W
2/9/94	Exclusion Zone	54° 04.63'N	04° 46.51'W	54° 05.35N	04° 46.70'W
	Bradda Head	54° 05.73'N	04° 47.21'W	54° 06.33N	04° 46.99'W
	Bradda Head	54° 06.35'N	04° 46.77'W	54° 05.63N	04° 46.89'W
14/12/95	Exclusion Zone	54° 05.58'N	04° 46.55'W	54° 05.16N	04° 46.59'W
	Exclusion Zone	54° 05.18'N	04° 46.60'W	54° 04.64N	04° 46.66'W

pivoting around the top rail suspended between the towing wire and the buoy drag line. This system also helped righting the sled when it overturned on the seabed, the sled only needing to be pulled clear of the bottom to right it. This was usually achieved either by hauling in the towing cable a short distance or by a brief increase in boat speed.

Once the drag line was out the sled was lowered to the seabed using the winch and wire aboard the R.V. *Sula*, the video cable being paid out simultaneously from a large plastic tank. The video cable was stored in figure of eight loops to avoid kinking. The sled was then towed slowly into the tide while videoing the images of the seabed sent back for later analysis in the laboratory. The video cable was attached to the towing hawser during lowering using electrical cable ties at 5-10m intervals to avoid undue strain. Tows lasted one hour and one or more such tows were made, on the dates indicated in Table 3.3, parallel to the coast in the general areas of the two sites used for tethering experiments. Retrieval was the reverse of deployment with the video cable being cut free from the towing wire as it came into the boat and coiled into its box, again in figures of eight.

The field of view of the camera at a set angle was determined in a water tank using a video recorder and meter rulers and the video sled set up in the same way as for a survey. A 50x60cm quadrat was made and placed in the tank ahead of the camera. It was then moved until the bottom edge (50cm) of its image on the monitor screen just touched both edges of the monitor screen. The corners of the quadrat were touched in turn with a white metre ruler so that the position of each corner was clearly recorded on the video tape. A mask was then made for the viewing monitor, as detailed by (Auster et al., 1989), for a perspective quadrat of sides 50x60cm using this video tape.

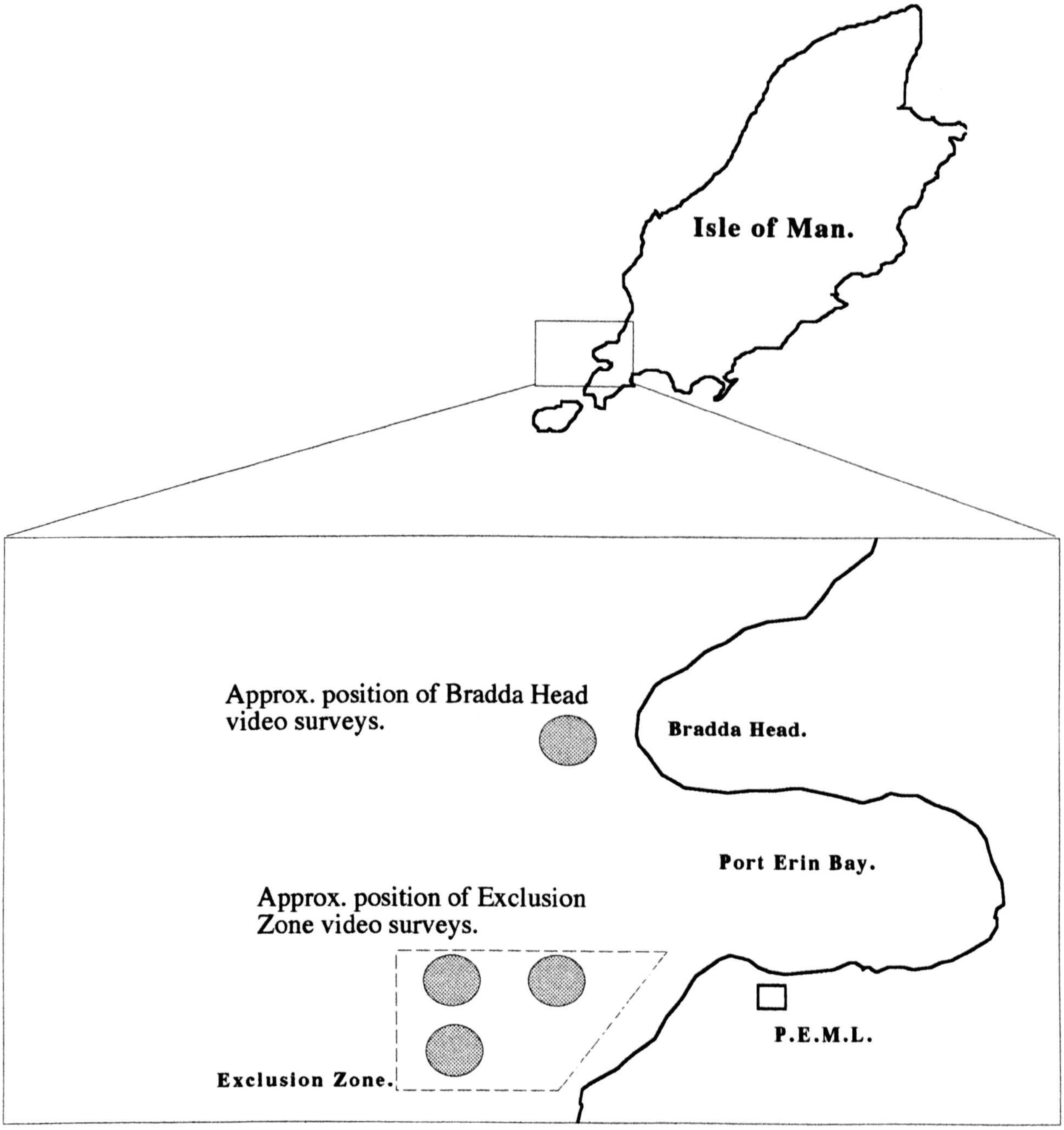


Figure 3.5.
Diagrammatic representation of the locations of video surveys with the locations of PEML, Bradda Head, Port Erin Bay and the Exclusion Zone marked.

Analysis of the video tape data involved splitting each transect into contiguous quadrats using either the on-screen count given by the odometer wheel and reed switch system operating the digital counter, or by on-screen spotting (Auster et al., 1989) using slow play-back and obvious seabed features along the transect, usually numerous and obvious white stones or shell fragments. Using slow replay and the quadrat mask for the T.V. screen a stone or shell fragment was spotted and followed from the top of the mask to the bottom. This constituted one quadrat and this process was repeated for each video tow in turn thus building up a series of adjacent quadrats. This method was employed while the odometer wheel was being designed and if it failed to work for any reason. Using either quadrat counts or the digital on-screen counter an estimate of the area covered by each video survey was determined. This estimate, combined with a count of predator species (starfish and crabs) for the survey was used to provide an estimate of predator density for each video survey. A diagrammatic representation of this method of analysing video tapes is shown in Fig 3.6.

The video survey results were used to determine differences in predator densities between the Bradda Head and Exclusion Zone survey sites. Estimated density data were compared using t-tests using all video surveys from each site for the test in order to provide an adequate number of replicates.

Video survey results were also used to provide estimates of dredge efficiency in catching predator species. This information would prove useful in quantifying the results of dredge surveys since dredges are known to have low efficiency in catching benthic macrofaunal species. Estimation of dredge efficiency for catching predator species was made by comparing Bradda Inshore dredge survey data with video survey data made at similar times of the year. Comparisons were made between video surveys carried out in July and September 1994 with dredge survey results from June and October 1994 and between video surveys carried out in September and November 1993 with dredge survey results from June and October 1993.

This method assumes that video surveys have a 100% efficiency and that surveys made at different sites/times may be comparable. For this study it was impractical to perform both dredge and video surveys over the same seabed and at exactly the same times. This was because I was required to be present throughout the whole scallop survey, encompassing all grounds round the Isle of Man, which meant that he was unavailable for making video surveys for this period. The same was also true of diver surveys.

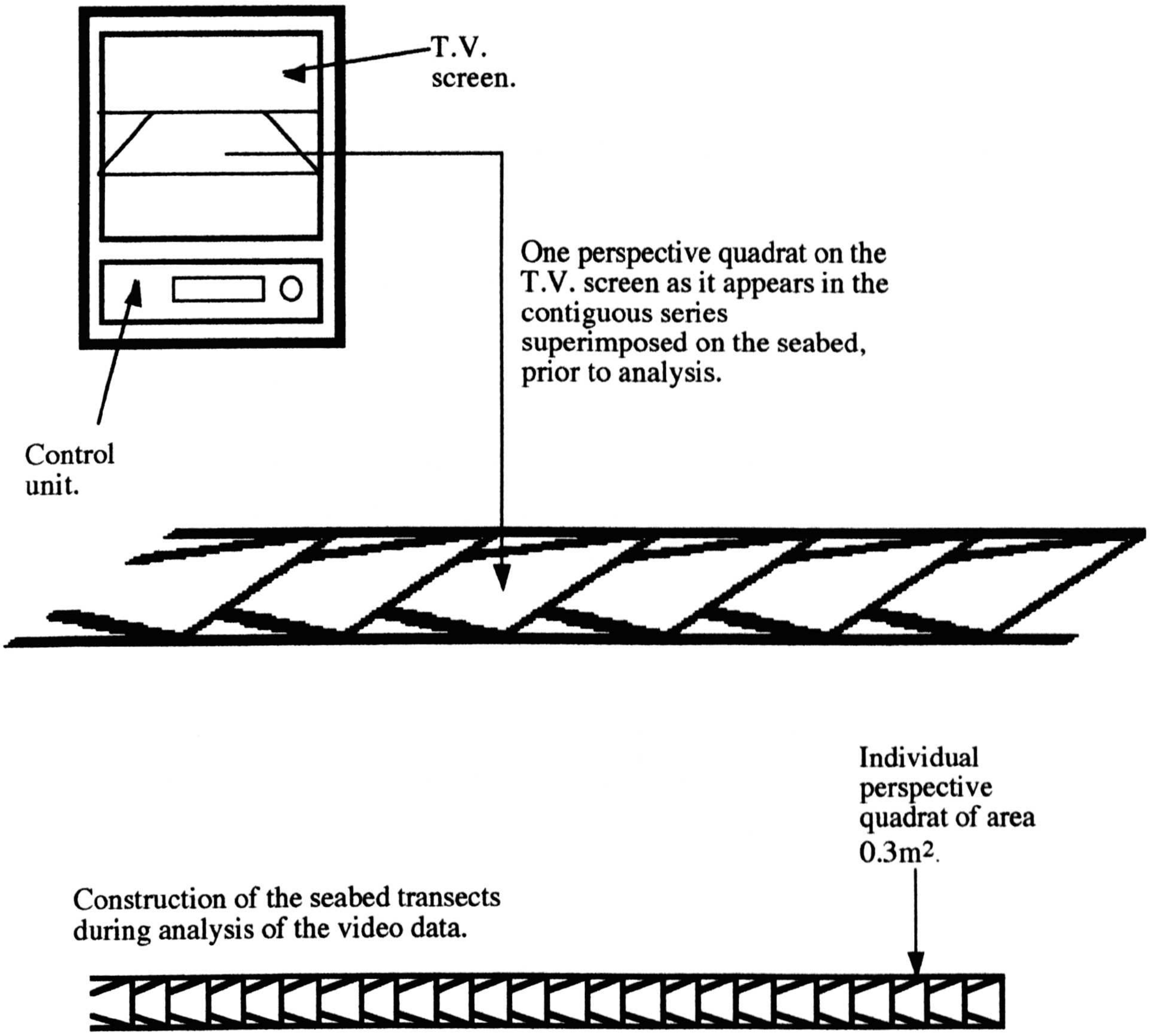


Figure 3.6.
T.V. monitor with perspective quadrat, acetate overlay in position. Screen scrolling or odometer counts were used to construct the contiguous series of perspective quadrats, as represented below, for each video survey. These methods were used to quantify distances travelled during video surveys.

3.2.3 Estimating predator densities using diver surveys.

Diver surveys were carried out, in conjunction with the dredging and video surveys, to monitor predator densities. These were performed at sites adjacent to the positions of the tethering experiments and video surveys. Diver surveys were used to provide a comparative, quantitative method for obtaining density estimates of predators. Locations and dates of all diver surveys carried out for this study are detailed in Table 3.0c.

The method of diver survey used follows that of Wilson (1994). A concrete sinker and buoyed shot line were deployed from RV *Sula* at the Decca co-ordinates listed in Table 3.0c, and shown in Fig. 3.7. Divers then descended with a four meter long Durapipe pole with a 50m reel of line at its centre and two writing slates attached 1m either side of the reel (Fig. 3.8). The free end of the reel line was clipped to the shot weight and the line reeled out slowly as the divers swam over the seabed maintaining a steady compass bearing using compasses attached to the slates. Divers noted the presence of any species of interest and general sediment characteristics falling within the two meter wide strip defined by their half of the pole between its end and the reel. Thus each pair of divers covered 200m^2 in one dive (approx. 15min). The direction of the survey was noted and usually determined by the direction of the tidal stream.

Data from each individual survey are summarised in the relevant results section. The overall mean numbers and associated standard errors of crabs, starfish and scallops per square metre were calculated using each diver survey as one replicate. Comparisons with dredge surveys were carried out as follows: April/May 1994 diver surveys were compared with June 1994 dredge survey data; June/July 1996 diver surveys were compared with the June 1996 dredge survey data and the August/September 1996 diver surveys were compared with the October 1996 dredge survey data. Since all diver surveys were carried out within the Exclusion Zone the Bradda Inshore dredge survey site was used for all comparisons being the closest dredge survey site geographically.

The diver surveys were also used to compare species densities over time using the same groupings of diver surveys as those described in the previous paragraph. A one-way ANOVA was carried out to test for significant differences in mean species density for the three sampling periods employed. The three species analysed were *Asterias rubens*, *Cancer pagurus* and *Pecten maximus*.

The data obtained from the diver surveys, in terms of densities of predators and prey species, were also compared, graphically, with the results obtained from the other survey methods used during this study, where surveys coincided spatially and temporally.

Table 3.0c

Co-ordinates and dates of diver surveys carried out in the Exclusion Zone.

Date.	Survey.	Latitude (N).	Longitude (W).
11/4/94	1	54° 04.92'	04° 46.63'
	2	54° 05.08'	04° 46.61'
18/4/94	1	54° 04.06'	04° 47.60'
	2	54° 04.57'	04° 47.12'
	3	54° 04.54'	04° 46.54'
20/4/94	1	54° 04.03'	04° 47.44'
	2	54° 04.03'	04° 47.33'
21/4/94	1	54° 04.01'	04° 47.46'
	2	54° 05.03'	04° 47.77'
9/5/94	1	54° 04.93'	04° 47.39'
	2	54° 05.09'	04° 47.24'
16/5/94	1	54° 04.65'	04° 47.78'
	2	54° 04.65'	04° 47.92'
17/5/94	1	54° 05.00'	04° 48.00'
	2	54° 04.63'	04° 47.08'
	3	54° 04.63'	04° 47.40'
	4	54° 04.75'	04° 47.27'
19/5/94	1	54° 04.92'	04° 47.84'
25/6/96	1	54° 05.47'	04° 47.16'
27/6/96	1	54° 05.25'	04° 47.16'
	2	54° 05.31'	04° 47.57'
	3	54° 05.54'	04° 47.16'
18/7/96	1	54° 04.94'	04° 47.80'
	2	54° 04.65'	04° 47.31'
19/7/96	1	54° 04.79'	04° 47.06'
26/7/96	1	54° 04.87'	04° 46.70'
	2	54° 04.85'	04° 46.89'
30/7/96	1	54° 05.05'	04° 46.61'
	2	54° 05.14'	04° 45.77'
2/8/96	1	54° 05.05'	04° 46.17'
8/8/96	1	54° 05.05'	04° 46.61'
	2	54° 05.15'	04° 47.00'
14/8/96	1	54° 04.73'	04° 47.51'
	2	54° 05.02'	04° 46.76'
15/8/96	1	54° 04.61'	04° 47.34'
	2	54° 05.10'	04° 46.86'
16/8/96	1	54° 05.06'	04° 46.81'
25/9/96	1	54° 05.31'	04° 47.16'

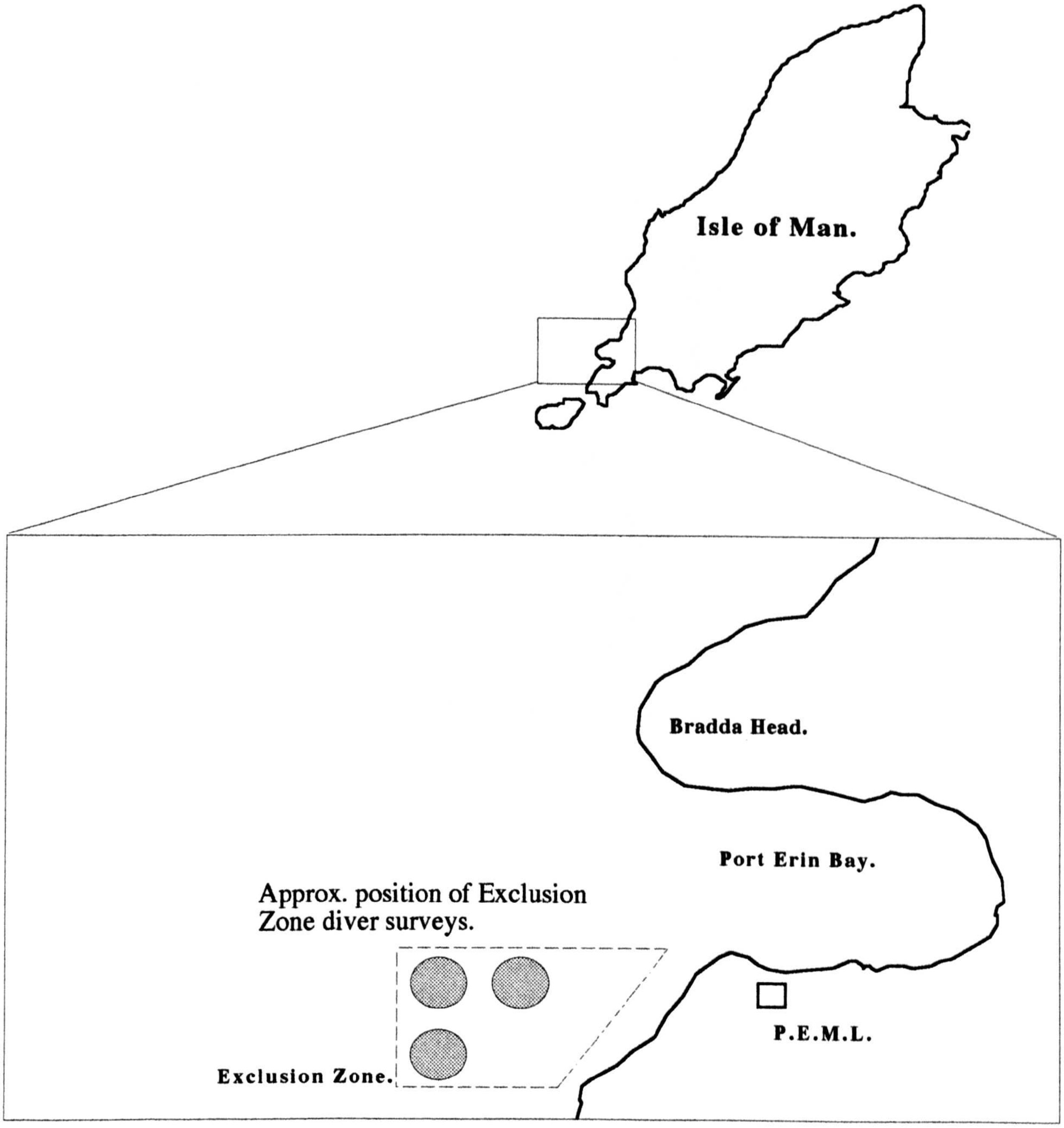


Figure 3.7.
Diagrammatic representation of the locations of diver surveys.

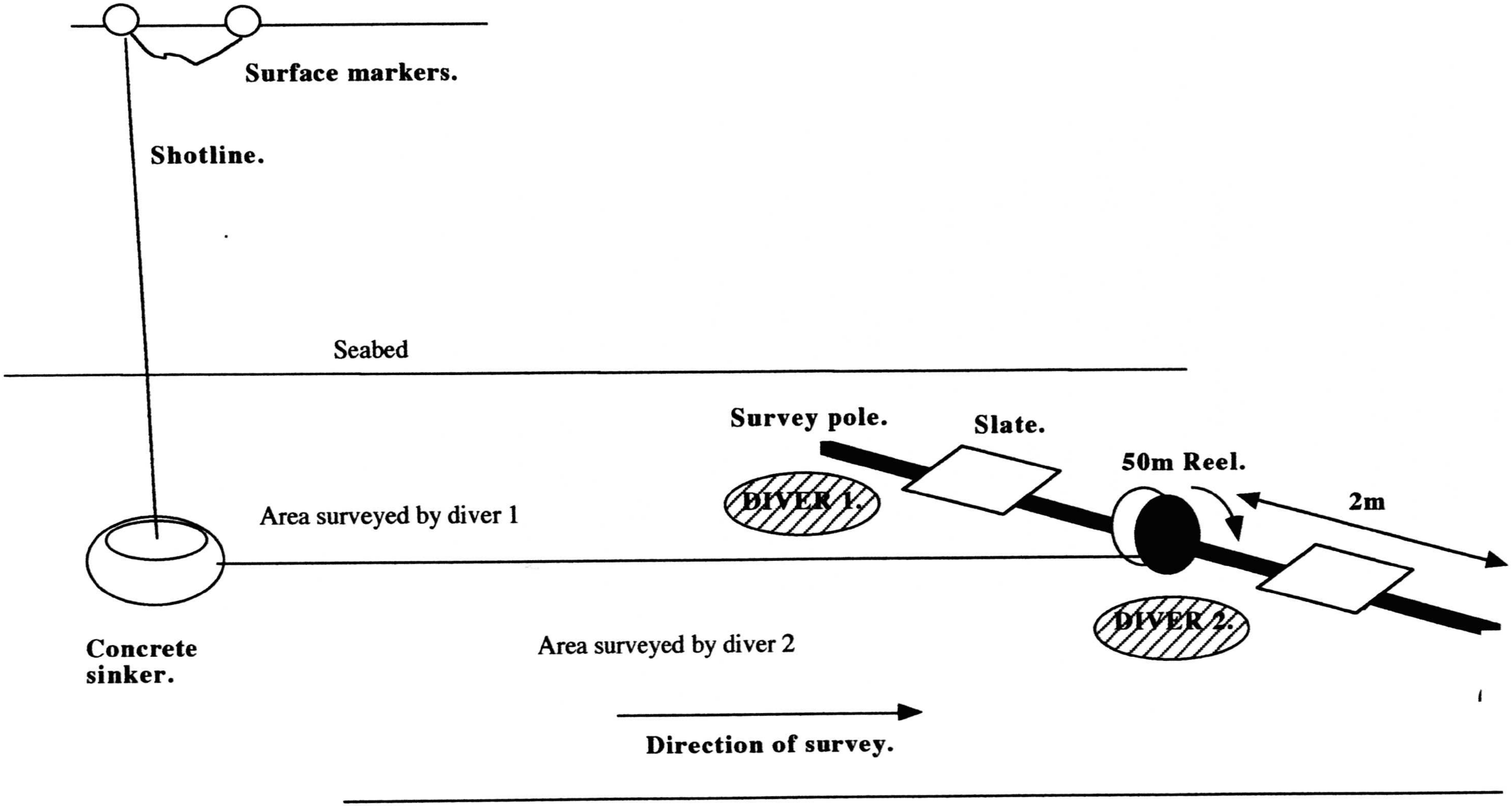


Figure 3.8.
Diagrammatic representation of diver survey method.

3.2.4 Comparison of video, diver and dredge survey data.

Where video and diver surveys coincided at the Bradda Inshore ground dredge surveys comparisons were made and dredge efficiency for predator species estimated. Dredge efficiency was calculated by assuming that both diver and video surveys had an efficiency of 100% in identifying the relevant species within their area of survey.

3.3 Results.

3.3.1 Starfish sizes at the Bradda Inshore and Bradda Offshore sites.

For each site surveyed, separate records were kept of the mean sizes of starfish caught in the queen and scallop dredges. 1 tailed t-tests were used to determine whether mean sizes of starfish caught in the queen dredges were significantly different from the mean sizes of starfish caught in the scallop dredges within each site tested during the June and October 1996 surveys. Sites were chosen to correspond with the sites where the same analysis was performed for crabs - Bradda Inshore, Bradda Offshore and Laxey. Twenty miles south of Port St. Mary was also used to include a site to the south of the island - no crabs were caught here so no analysis for gear differences for crabs could be carried out. The results of this analysis are summarised in Table 3.1a. The null hypothesis used in each case was:

H_O: The mean size of starfish caught in the queen dredges is the same as the mean size of starfish (maximum arm length in mm) caught in the scallop dredges.

The results summarised in Table 3.1a show that significant differences exist between the mean sizes of starfish caught in scallop and queen dredges. In all cases the mean size of starfish caught in the queen gear was greater than those caught in the scallop gear. The observed difference probably results from the larger ring size of the scallop dredges which will allow more smaller starfish to be lost. Analyses involving starfish carried out in the remainder of this chapter therefore use data from the queen dredges only.

The results of the two-way ANOVA applied to the Bradda Inshore and Bradda Offshore starfish size data are summarised in Table 3.1b. Size data were collected for the Bradda Inshore and Bradda Offshore sites from October 1993 onwards to June 1996. Size data were collected from all sites from October 1995 onwards. The data were found to be normally distributed and so were not transformed prior to analysis. The null hypotheses used were:

H_{O1}: There are no significant differences in the mean sizes of starfish caught at the Bradda Inshore and Bradda Offshore sites.
H_{O2}: There are no differences in the mean sizes of starfish caught on different dates at the Bradda Inshore and Bradda Offshore sites.
H_{O3}: There is no interaction between the two factors, site and date.

Table 3.1b indicates that H_{O1} and H_{O3} should be rejected ($p<0.0001$ in both cases) and that H_{O2} should be accepted ($p = 0.053$). Therefore there are no significant differences in mean sizes over the dates sampled at either site but there are significant differences in mean sizes of starfish at the two sites and there is a significant interaction between the two factors. The significant interaction term means that a multiple comparison test must consider differences between the cell means in order to identify where the detected differences occur in the data. The results of the Tukey multiple comparison test applied to the Bradda Inshore and Bradda Offshore data and a graphical summary of the mean starfish sizes for each site and each sampling date are summarised in Table 3.1c and Fig. 3.9.

The results of the Tukey test summarised in Table 3.1c completely separates the Inshore and Offshore site in terms of mean sizes of starfish caught. Also, in general, at the Offshore site the starfish caught in the October surveys were smaller than these caught in the June surveys with the exception of the October 1993 survey which yielded the largest mean size of starfish caught at the offshore site. At the Inshore site the reverse generally appeared to be true with the smaller starfish caught in the June surveys. The exceptions here are the June 1996 survey, which yielded the largest mean starfish size, and the October 1993 survey which yielded the smallest. The results indicate that, at the Bradda Inshore and Offshore sites the populations of starfish are fairly dynamic in terms of mean sizes. The population mean sizes are not stable but change with time. At both sites the changes over the sampling period have been following general trends with a consistent fall in mean size at the Bradda Offshore site and a consistent rise at the Bradda Inshore site. The consistency of these changes is surprising, considering the flexible, food determined growth patterns of the starfish *Asterias rubens*. The results show that there are significant differences in mean sizes of starfish at the two sites sampled and that this, in turn, might lead to differences in the risk of predation of re-seeded, juvenile scallops by starfish.

Fig. 3.9 shows mean starfish size against sampling date. The mean sizes of starfish at the Bradda Inshore and Bradda Offshore sites were quite similar in October 1993. However, from this point onwards the mean sizes of starfish fell at the Bradda Offshore site while they rose at the Inshore Bradda site. The difference increased with time up to the June 1996 survey. This rise in mean starfish size at the inshore site with time and the associated fall at the offshore site probably accounts for the detection of significant interaction between the two factors of the two-way ANOVA ($p<0.0001$). This raises the interesting question that starfish sizes at the two sites, separated by several miles, are linked in some way possibly by some migratory activity. Examination of starfish relative densities may help to clarify this question.

Table 3.1a

Summary of t-test results comparing the mean sizes of starfish caught in queen and scallop dredges from the June and October 1996 scallop surveys. Sites sampled are listed.

Site	Date	1 tail t-test result (p)	Conclusion
Bradda Offshore	June 1996	$p < 0.0001$	Reject H_0
Bradda Inshore	June 1996	$p = 0.0003$	Reject H_0
20 Miles S PSM	June 1996	$p < 0.0001$	Reject H_0
Bradda Offshore	October 1996	$p = 0.0479$	Reject H_0
Bradda Inshore	October 1996	$p = 0.0382$	Reject H_0
20 Miles S PSM	October 1996	$p < 0.0001$	Reject H_0
Laxey	October 1996	$p < 0.0001$	Reject H_0

Table 3.1b

Results of the two way ANOVA applied to the mean starfish size data from the Bradda Inshore and Bradda Offshore dredge surveys between October 1993 and June 1996. Site and survey date were used as the factors with mean starfish size as the response variable.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	1	516133	516133	1226.81	<0.0001
Date	6	5242	874	2.08	0.053
SitexDate	6	114485	19081	45.35	<0.0001
Error	4290	1804850	421		
Total	4303				

Table 3.1c Summary of the Tukey Multiple comparison test applied to the Bradda Inshore and Offshore dredge survey data for mean starfish size. Starfish were measured by maximum arm length and samples were taken from the June and October surveys from 1993 to 1996. Underlined sites/dates indicate no significant differences between those sites/dates. Gaps represent statistically significant differences between sites/dates.

Site	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Inshore	Inshore	Inshore	Inshore	Inshore	Inshore	Inshore
Date	Oct-94	Oct-96	Oct-95	Jun-96	Jun-94	Jun-95	Oct-93	Oct-93	Jun-94	Jun-95	Oct-95	Oct-96	Oct-94	Jun-96
Mean	48.96	50.64	51.67	51.98	57.19	57.33	67.00	73.36	75.82	79.80	84.29	84.36	87.53	89.3

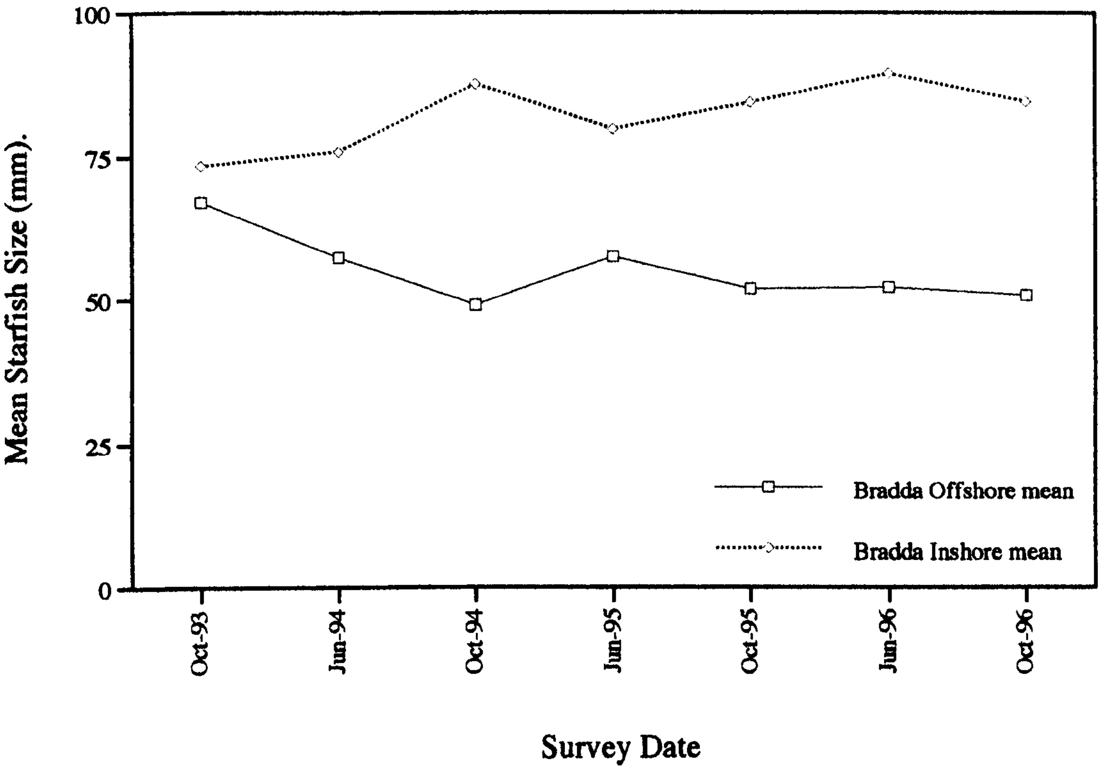


Figure 3.9
Comparison of mean starfish sizes (maximum arm length) at the Bradda Inshore and Bradda Offshore dredge survey sites.

3.3.2 Starfish sizes at all grounds around the Isle of Man.

The results of testing for differences in mean sizes of starfish at all grounds sampled during the October 1995, June 1996 and October 1996 scallop surveys are summarised in Tables 3.2a - f. The starfish mean size data from these three scallop surveys were all analysed for between site differences using a one-way ANOVA and the null hypothesis:

H_O: There are no significant differences between the mean sizes of starfish at different sites during the October 1995 scallop survey sampled using queen gear.

Table 3.2a indicates that the null hypothesis is therefore rejected and it is concluded that, for the October 1995 scallop survey sites, there are significant differences in mean sizes of starfish found at these sites ($p<0.0001$). A summary of the Tukey multiple comparison test carried out to identify where these differences lay is summarised in Table 3.2b.

Table 3.2b indicates that, for the October 1995 survey, the sites sampled to the east of the Isle of Man had significantly larger starfish present then those to the south and west. Unfortunately the most northerly site sampled was Targets (TA) which had a greater mean size than most of the southern sites apart from the two Douglas grounds. To determine a north-south pattern would require more northern sites to be sampled. The Bradda Offshore (OSB) site had the smallest mean size of starfish sampled.

The results of the between sites analysis of mean starfish size for the June 1996 survey, using the same method and null hypothesis as above, are summarised in Tables 3.2c and d. Table 3.2c shows that the null hypothesis that mean sizes of starfish at all grounds sampled during the June 1996 scallop survey were identical is therefore rejected ($p < 0.0001$). The results of the subsequent Tukey test are summarised in Table 3.2d.

The June 1996 survey covered more sites (12) then the October 1995 survey (9). Table 3.2d shows a similar pattern in mean sizes of starfish caught during the October 1995 survey. The East Douglas and Ramsey grounds have the highest mean sizes of starfish, while the Bradda Offshore and Chickens grounds have the smallest. Generally the eastern sites have higher mean size starfish than western sites, and the northern sites, with the possible exception of Laxey, have larger starfish than southern sites.

The results of the between sites analysis of mean starfish size for the October 1996 survey, using the same method and null hypothesis as above, are summarised in Tables 3.2e and f. Table 3.2e shows that the null hypothesis that mean sizes of starfish at all grounds sampled during the October 1996 scallop survey were identical is therefore rejected ($p < 0.0001$). The results of the subsequent Tukey test are summarised in Table 3.2f.

Table 3.2a

Summary of the one way ANOVA performed on mean starfish size data from all grounds sampled during the October 1995 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	8	594467	74308	106.39	<0.0001
Error	2321	1621110	698		
Total	2329	2215577			

Table 3.2b

Summary of the Tukey multiple comparison test applied to the starfish mean size data from all grounds sampled during the October 1995 scallop survey. Underlined sites showed no statistical difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

<table>
<tr><th>Site</th><th>OSB</th><th>CH</th><th>10S</th><th>PL</th><th>ISB</th><th>20S</th><th>TA</th><th>ED</th><th>SD</th></tr>
<tr><td>Av. size (mm)</td><td>51.7</td><td>71.8</td><td>74.0</td><td>76.7</td><td>84.3</td><td>93.6</td><td>94.4</td><td>111.8</td><td>125.0</td></tr>
<tr><td>N</td><td>190</td><td>432</td><td>149</td><td>266</td><td>564</td><td>205</td><td>287</td><td>158</td><td>79</td></tr>
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</table>

Site abbreviations used in Table 3.2b:

OSB	Offshore Bradda	SD	South East Douglas	PL	Peel
10S	10 Miles South of P.S.M.	ISB	Inshore Bradda	TA	Targets
20S	20 Miles South P.S.M.	ED	East Douglas	CH	Chickens

Table 3.2c

Summary of the one way ANOVA performed on mean starfish size data from all grounds sampled during the June 1996 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	11	630807	57346	66.52	<0.0001
Error	2383	2054393	862		
Total	2394	2685200			

Table 3.2d

Summary of the Tukey multiple comparison test applied to the starfish mean size data from all grounds sampled during the June 1996 scallop survey. Underlined sites showed no statistical difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

Site	OSB	CH	PL	10S	ISB	LX	20S	PA	TA	SD	ED	RY
Av. size (mm)	52.0	73.9	82.9	88.3	89.3	90.8	93.5	95.2	97.7	98.5	111.9	125.4
N	242	238	229	172	212	211	235	215	214	194	149	84
					———	———	———	———	———	———	———	———
				———	———	———	———	———	———			
	———	———	———	———	———	———						

Site abbreviations used in Table 3.2d:

OSB	Offshore Bradda	PL	Peel	LX	Laxey
ISB	Inshore Bradda	TA	Targets	SD	South East Douglas
10S	10 Miles South of P.S.M.	CH	Chickens	RY	Ramsey
20S	20 Miles South P.S.M.	PA	Point of Ayre		

Table 3.2e

Summary of the one way ANOVA performed on mean starfish size data from all grounds sampled during the October 1996 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	4	284024	71006	142.21	<0.0001
Error	1239	618619	499		
Total	1243	902644			

Table 3.2f

Summary of the Tukey multiple comparison test applied to the starfish mean size data from all grounds sampled during the October 1996 scallop survey. Underlined sites showed no statistical difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

<table>
<tr><th>Site</th><th>OSB</th><th>CH</th><th>LX</th><th>ISB</th><th>SD</th></tr>
<tr><td>Av. size (mm)</td><td>50.6</td><td>64.7</td><td>83.1</td><td>84.4</td><td>87.5</td></tr>
<tr><td>N</td><td>330</td><td>212</td><td>224</td><td>232</td><td>246</td></tr>
<tr><td></td><td>———</td><td>———</td><td colspan="3">—————————</td></tr>
</table>

Site abbreviations used in Table 3.2f:

OSB	Offshore Bradda	LX	Laxey	SD	South East Douglas
CH	Chickens	ISB	Inshore Bradda		

Table 3.2f indicates that statistically significant, higher mean sizes of starfish were found on the South East Douglas, Bradda Inshore and Laxey grounds. The smallest starfish were found on the Bradda Offshore and Chickens grounds. Although far fewer sites were sampled, primarily due to poor weather and research vessel commitments, the results appear to be consistent with those for the October 1995 and June 1996 surveys. This suggests that there is consistency in the mean sizes of starfish within sites from year to year. If this is the case then the results of the dredge surveys carried out by PEML every year could be used to identify the best sites for re-seeding trials. The best sites should have the lowest densities of small predators.

3.3.3 Comparison of Mean Starfish Sizes Within Sites.

Of the sites analysed above, Bradda Inshore, Bradda Offshore, South East Douglas and Chickens were sampled during all three surveys. The results of one-way ANOVAs applied to test for differences in mean starfish sizes within each site respectively over the three sampling dates (October 1995, June 1996 and October 1996) are detailed in Tables 3.3a - i. The null hypothesis used in each case was:

H_O: There are no differences in mean starfish sizes at the site tested between the three sampling dates.

Table 3.3a shows that the null hypothesis is accepted ($p = 0.639$) and the mean sizes of starfish at the Bradda Offshore ground sampled on October 1995, June 1996 and October 1996 can be considered to be equal. The mean sizes (± 1 s.e.) are 51.7mm±1.23mm, 51.98mm±1.24mm and 50.64mm±0.92mm for these three sites respectively.

Table 3.3b shows that the null hypothesis is rejected ($p = 0.009$) and the mean sizes of starfish at the Bradda Inshore site show significant differences over the three survey dates. A summary of the Tukey multiple comparison test used to determine where these differences lay is detailed in Table 3.3c which shows that the June 1996 survey yielded a significantly larger mean starfish size than either of the other two surveys.

Table 3.3d shows that the null hypothesis is rejected ($p < 0.001$) and the mean starfish sizes from the different survey dates are significantly different at the Chickens site. The results of the Tukey multiple comparison test are detailed in Table 3.3e. Table 3.3e shows that the October 1996 survey yielded a significantly smaller mean starfish size than either of the other two sampling dates at the Chickens survey site. No obvious trend is evident in the data.

Table 3.3a

Summary of the results of the one way ANOVA testing for differences in mean starfish sizes from year to year within the Bradda Offshore site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	281	141	0.45	0.639
Error	759	238419	314		
Total	761	238700			

Table 3.3b

Summary of the results of the one way ANOVA testing for differences in mean starfish sizes from year to year within the Bradda Inshore site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	4174	2087	4.7	0.009
Error	1005	6550	444		
Total	1007	724			

Table 3.3c

Summary of the Tukey multiple comparison test applied to the starfish mean size data from the Bradda Inshore ground sampled during the October 1995, June 1996 and October 1996 scallop surveys. Underlined dates showed no statistical difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

Survey date	Oct-95	Oct-96	Jun-96
Mean size (mm)	84.3	84.4	89.3
N	564	232	212

Table 3.3d

Summary of the results of the one way ANOVA testing for differences in mean starfish sizes from year to year within the Chickens site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	10507	5254	9.99	0.000
Error	879	462102	526		
Total	881	472610			

Table 3.3e

Summary of the Tukey multiple comparison test applied to the starfish mean size data from the Chickens ground sampled during the October 1995, June 1996 and October 1996 scallop surveys. Underlined dates showed no statistical difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

Survey date	Oct-96	Oct-95	June-96
Mean size (mm)	64.7	71.8	73.9
N	212	432	238
	———	—————————	—————————

Table 3.3f

Summary of the results of the one way ANOVA testing for differences in mean starfish sizes from year to year within the South East Douglas site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	84072	42036	40.48	0.000
Error	516	535859	1038		
Total	518	619932			

Table 3.3g

Summary of the Tukey multiple comparison test applied to the starfish mean size data from the South East Douglas ground sampled during the October difference in mean starfish size. Gaps in the underlining show statistical differences in mean starfish sizes.

Survey date	Oct-96	Jun-96	Oct-95
Mean size (mm)	87.5	98.5	124.95
N	246	194	79
	———	———	———

Table 3.3h

Summary of t-tests carried out to determine whether mean starfish sizes varied between surveys at sites which were sampled twice during the course of this study.

Site	Dates	t	df	p	Conclusion
Laxey	Jun.96-Oct.96	3.02	423	0.0027	Reject Ho
Targets	Oct.95-Jun-96	-1.06	433	0.29	Accept Ho
East Douglas	Oct.95-Jun-96	-0.03	303	0.98	Accept Ho
20 M South	Oct.95-Jun-96	0.04	433	0.96	Accept Ho
10 M South	Oct.95-Jun-96	-3.82	311	0.0002	Reject Ho
Peel	Oct.95-Jun-96	-2.83	472	0.0049	Reject Ho

Table 3.3i

Summary of mean starfish sizes (maximum arm length in mm) obtained from October 1995, June 1996 and October 1996 dredge surveys.

Site	Date	Mean size (mm)	S.E. Mean
Laxey	June 1996	90.8	1.9
	October 1996	83.1	1.7
Targets	October 1995	94.4	1.9
	June 1996	97.7	2.5
East Douglas	October 1995	111.8	2.8
	June 1996	111.9	2.5
20 M South	October 1995	93.6	2
	June 1996	93.5	2
10 M South	October 1995	74	2
	June 1996	88.3	2
Peel	October 1995	76.8	1.4
	June 1996	82.9	1.6

Table 3.3f shows that the null hypothesis is rejected ($p < 0.001$) and that the mean starfish sizes from the three survey dates are significantly different. The results of the Tukey multiple comparison test are summarised in Table 3.3g.

Table 3.3g shows that, at the South East Douglas site, the mean starfish sizes obtained from the three survey dates are all significantly different from one another. There is a trend of decreasing size with time at this site.

The remaining sites (Laxey, Targets, East Douglas, 20 Miles and 10 Miles South of Port St. Mary and Peel) were each sampled on 2 out of the three surveys. Differences in mean starfish sizes on different dates were assessed using t-tests, the results of which are summarised in Table 3.3h. The null hypothesis used in each case is that there is no significant difference in mean starfish size between the survey dates at the site in question.

At half the sites the null hypothesis is rejected and at the other half it is accepted. No pattern is evident from the locations of these sites around the island. The results probably reflect the flexible growth pattern of the starfish which will alter significantly according to local, prevailing conditions. A summary of the mean sizes of starfish obtained during each survey are summarised in Table 3.3i.

3.3.4 Crab sizes at the Bradda Inshore and Bradda Offshore sites.

The low numbers of crabs caught meant animals caught in both gear types (scallop and queen dredges) were used in calculating mean sizes for each site. 1 tailed t-tests were used to determine whether mean sizes of crabs caught in the queen dredges were significantly different from the mean sizes of crabs caught in the scallop dredges within each site. These tests were used to assess whether pooling data from the two gear types was justified. Only sites where crabs were caught in sufficient numbers during the two 1996 surveys were analysed in this way as crabs were kept and measured separately for each gear type during these surveys. The results of the 1 tailed t-tests are summarised in Table 3.4a. The null hypothesis used in each case was:

H_O: The mean size of crabs caught in the queen dredges is the same as the mean size of crabs (carapace width) caught in the scallop dredges.

Table 3.4a

Summary of the results of t-tests used to determine whether statistically significant differences existed between the mean sizes of crabs caught in queen and scallop dredges used during scallop surveys.

Site	Date	1 tail t-test result (p)	Conclusion
Bradda Offshore	June 1996	$p = 0.383$	Accept H_0
Bradda Inshore	June 1996	$p = 0.153$	Accept H_0
Bradda Offshore	October 1996	$p = 0.0081$	Reject H_0
Bradda Inshore	October 1996	$p = 0.41$	Accept H_0
Laxey	October 1996	$p = 0.39$	Accept H_0

Table 3.4b

Summary of the results of the two factor ANOVA applied to the mean crab size data form the Bradda Inshore and Bradda Offshore surveys between October 1993 and June 1996. Site and survey date were used as the factors with mean crab size as the response variable.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	1	432.1	432.1	2.04	0.153
Date	6	13305.4	2217.6	10.49	<0.0001
SitexDate	6	2375.2	395.9	1.87	0.083
Error	685	144794.2	211.4		
Total	698				

Table 3.4c

Summary of the Tukey multiple comparison test applied to the crab mean size data from the Bradda Inshore and Bradda Offshore sites from October 1993 to June 1996. Underlined dates showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes.

Sampling date	**Oct-95**	**Oct-93**	**Jun-96**	**Jun-94**	**Oct-96**	**Oct-94**	**Jun-95**
Mean size (mm)	148.75	151.19	156.76	160.82	160.94	161.31	164.14
N	68	176	25	39	213	143	35

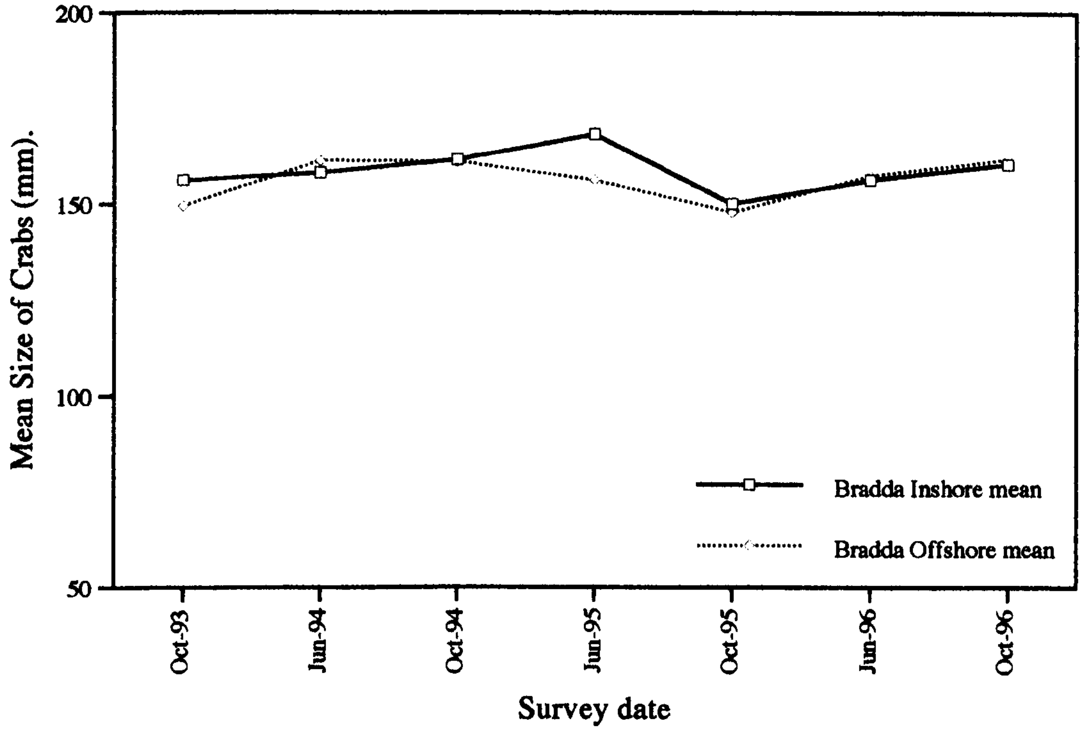


Figure 3.10a
Comparison of mean crab sizes (carapace width) at the Bradda Inshore and Bradda Offshore dredge survey sites.

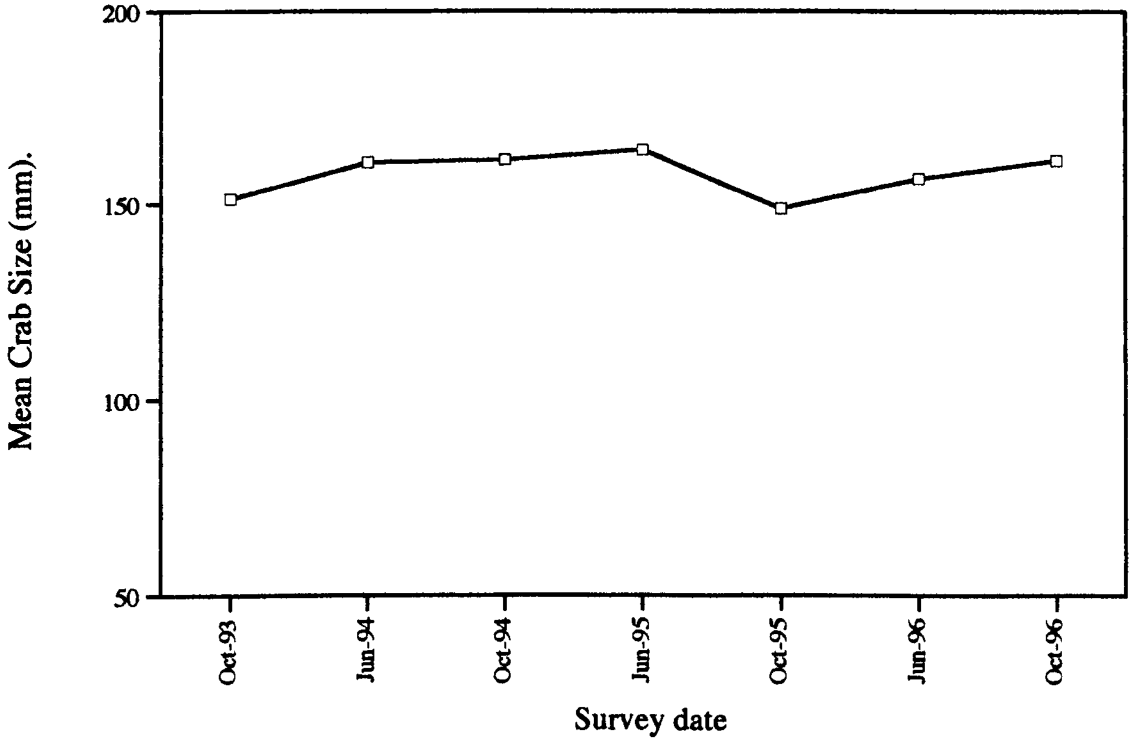


Figure 3.10b
Combined Bradda Inshore and Bradda Offshore mean crab siz data integrating all crabs caught at both sites for each survey..

Table 3.4a shows that, generally, there were no differences in mean sizes of crabs caught in queen and scallop dredges. The only exception was the Bradda Offshore site during the October 1996 survey where the crabs caught in the queen dredges were significantly larger than those caught in the scallop dredges.

The limited time available on the boat for counting and measuring meant that the crabs were generally measured and grouped together with no separate records kept for the sizes obtained from different gear types. The exceptions to this were the two 1996 surveys used here. The results of the t-test analyses within each site show that in most cases the gear types provide the same estimates of mean sizes of crabs with only the one exception. This probably results from the fact that crabs are hard shelled animals and that only very small juveniles would be able to pass through the rings of either type of dredge. If more time had been available the gear type might have been treated separately given the one significant result.

The results of the two way ANOVA applied to the Bradda Inshore and Bradda Offshore crab size data from October 1993 to June 1996 are summarised in Tables 3.4b. The test was applied to determine whether there were any significant differences in mean crab sizes at the two sites over the dates sampled. The data used were from pooled queen and scallop dredge catches. The data were not transformed prior to analysis. The null hypotheses used in each case were:

H_{O1}: There are no significant differences in the mean sizes of crabs caught at the Bradda Inshore and Bradda Offshore sites.
H_{O2}: There are no differences in the mean sizes of crabs caught on different dates at the Bradda Inshore and Bradda Offshore sites.
H_{O3}: There is no interaction between the two factors, site and date.

Table 3.4b indicates that H_{O1} and H_{O3} should be accepted ($p = 0.153$ and 0.083 respectively) and that H_{O2} should be rejected ($p<0.0001$). Therefore there are no significant differences in mean crab sizes at the Bradda Inshore and Bradda Offshore sites but there are significant differences in mean sizes of crabs between sampling dates. There is no significant interaction between the two factors tested ($p = 0.083$). A Tukey multiple comparison test was thus carried out comparing the differences in mean sizes between different sampling dates using pooled inshore and offshore data. The results of the Tukey multiple comparison test applied to the pooled Bradda Inshore and Bradda Offshore data for the dates sampled are summarised in Table 3.4c.

Table 3.4c shows that the October 1995 and October 1993 surveys yielded mean crab sizes that were significantly smaller than the mean sizes obtained during all other surveys apart from June 1996. Differences in size between sampling dates do occur but with no recognisable pattern. However, plotting the mean crab size with time reveals a pattern of successive growth between several surveys followed by a sharp reduction in mean size in turn followed by successive increase once more. Smaller mean predator sizes occurring on a regular or predictable basis might improve survival chances of juvenile, re-seeded scallops. A graphical summary of the mean crab sizes for each site and each sampling date are summarised in Figs. 3.10a and b.

3.3.5 Crab sizes at all grounds around the Isle of Man.

The results of testing for differences in mean sizes of crabs at all grounds sampled during the October 1995, June 1996 and October 1996 scallop surveys are summarised in Tables 3.6.5a - f. In each case surveys were analysed for between site differences in mean crab size using a one-way ANOVA and the null hypothesis:

H_O: There are no significant differences between the mean sizes of crabs at different sites around the Isle of Man sampled using scallop and queen gear.

Table 3.5a shows that H_O is rejected and it is concluded that significant differences in mean crab size exist among the different sites sampled. The results of the Tukey multiple comparison test used to determine where these differences lay are detailed in Table 3.5b.

Table 3.5b shows that mean crab sizes at Peel, Bradda Offshore, Chickens, Bradda Inshore and 10 Miles South of Port St. Mary are significantly larger than the mean crab size at the South East Douglas site. The test lacks the power to discern further differences among the data. Differences in mean crab sizes among the sites sampled do not appear to be as marked as the differences among mean starfish sizes.

The results of the between sites analysis of mean crab size for the June 1996 survey, using the same method and null hypothesis as above, are summarised in Tables 3.5c and d. Table 3.5c shows that the null hypothesis is therefore rejected ($p = 0.006$) and that significant differences in mean crab sizes exist between the sites sampled. The results of the subsequent Tukey test are summarised in Table 3.5d.

Table 3.5d shows some change in the ordering of sites by mean crab size compared to the October 1995 survey. There are still no detectable differences between the Bradda Inshore, Bradda Offshore and Targets sites while the Laxey site appears to have significantly smaller crabs than any other site sampled. The Laxey site did have a small mean size compared to the other sites during the October survey but no significant difference was detected then. Fewer sites were sampled or had enough crabs caught for analysis during the June 1996 survey which may have affected the results. Alternatively the mean size at Laxey may have reduced or the mean sizes at the other sites increased.

Table 3.5a

Summary of the one way ANOVA performed on mean crab size data from all grounds sampled during the October 1995 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	8	8139	1017	4.90	0.000
Error	190	39482	208		
Total	198	47621			

Table 3.5b

Summary of the Tukey multiple comparison test applied to the crab mean size data from all grounds sampled during the October 1995 scallop survey. Underlined sites showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes (carapace width in mm).

Site	**SD**	**LX**	**ED**	**TA**	**PL**	**OSB**	**CH**	**ISB**	**10S**
Mean size	127	130.6	136	141.1	147.3	147.8	148.9	150.1	162
N	9	11	6	15	69	40	19	28	2

Site abbreviations used in Table 3.5b:

OSB	Offshore Bradda	PL	Peel	LX	Laxey
CH	Chickens	ISB	Inshore Bradda	TA	Targets
10S	10 Miles South of P.S.M.	ED	East Douglas	SD	South East Douglas

Table 3.5c

Summary of the one way ANOVA performed on mean crab size data from all grounds sampled during the June 1996 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	3	3107	1036	4.99	0.006
Error	35	7269	208		
Total	38	10378			

Table 3.5d

Summary of the Tukey multiple comparison test applied to the crab mean size data from all grounds sampled during the June 1996 scallop survey. Underlined sites showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes (carapace width in mm).

Site	**LX**	**ISB**	**OSB**	**TA**
Mean size (mm)	134.7	156.3	157.4	160.7
N	7	15	10	7
	—	————	————	————

Key to abbreviations used in Table 3.5d:

LX	Laxey	ISB	Bradda Inshore	TA	Targets
OSB	Bradda Offshore				

Table 3.5e

Summary of the one way ANOVA performed on mean crab size data from all grounds sampled during the October 1996 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	4	5026	1257	5.66	0.000
Error	135	29974	222		
Total	139	35001			

Table 3.5f

Summary of the Tukey multiple comparison test applied to the crab mean size data from all grounds sampled during the October 1996 scallop survey. Underlined sites showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes (carapace width in mm).

Site	**SD**	**LX**	**ISB**	**OSB**	**CH**
Mean size	133.5	139.9	160.8	161.8	164.9
N	2	7	35	72	24
			―――	―――	―――
	―――	―――	―――		

Key to abbreviations used in Table 3.6.5f:

SD	South East Douglas	LX	Laxey	ISB	Bradda Inshore
CH	Chickens	OSB	Bradda Offshore		

The results of the between sites analysis of mean crab size for the October 1996 survey, using the same method and null hypothesis as above, are summarised in Tables 3.5e and f. Table 3.5e shows that the null hypothesis is therefore rejected ($p < 0.0001$) and that mean crab sizes differ significantly between the sites sampled. The results of the subsequent Tukey test are summarised in Table 3.6.5f.

Table 3.5f shows that the mean sizes of crabs at the Chickens and Bradda Offshore sites were significantly greater than those at the South East Douglas and Laxey sites. The results from the three surveys above suggest that sites to the south and west of the island (Bradda Inshore, Bradda Offshore and Chickens) tend to have larger mean crab sizes than sites to the north and east (South East Douglas and Laxey) although these differences are not always detectable statistically. Generally crabs appear to show less distinct differences in mean size between sites than starfish do. The low numbers of crabs caught does not help in the statistical analysis of differences between grounds.

3.3.6 Comparison of mean crab sizes within sites.

Of the sites analysed above, Bradda Inshore, Bradda Offshore and Laxey were either sampled during all three surveys or yielded a high enough number of crabs for analysis. The results of one-way ANOVAs applied to test for differences in mean crab sizes within each site respectively over the three sampling dates (October 1995, June 1996 and October 1996) are detailed in Tables 3.6a - f. The null hypothesis used in each case was:

H_O: There are no differences in mean crab sizes at the site tested between the three sampling dates.

Table 3.6a shows that the null hypothesis is therefore rejected ($p < 0.0001$) and it is concluded that there are significant differences in mean crab size between the three survey dates. The results of the Tukey multiple comparison test to determine where these differences lay are summarised in Table 3.6b.

Table 3.6b shows that the mean crab size at the Bradda Offshore site was significantly greater during the October 1996 survey than it was during the October 1995 survey. The mean size of crabs caught during the June 1996 survey was not found to be significantly different from mean sizes caught during the other two surveys. There is a trend of increasing crab mean size with time at this site.

Table 3.6c shows that the null hypothesis of no differences between mean crab sizes over the dates sampled is therefore rejected ($p = 0.024$) and that significant differences exist between the mean sizes of crabs on the dates sampled at the Bradda Inshore site. The results of the

Table 3.6a

Summary of the results of the one way ANOVA testing for differences in mean crab sizes from year to year within the Bradda Offshore site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	5000	2500	11.85	<0.0001
Error	119	25105	211		
Total	121	30105			

Table 3.6b

Summary of the Tukey multiple comparison test applied to the crab mean size data from the Bradda Offshore ground sampled during the October 1995, June 1996 and October 1996 scallop surveys. Underlined dates showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes (carapace width in mm).

Sample date	Oct-95	Jun-96	Oct-96
Mean size	147.8	157.4	161.8
N	40	10	72
		———	———
	———	———	

Table 3.6c

Summary of the results of the one way ANOVA testing for differences in mean crab sizes from year to year within the Bradda Inshore site using data from the October 1995 to October 1996 scallop surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	1782	891	3.91	0.024
Error	75	17101	228		
Total	77	18884			

Table 3.6d

Summary of the Tukey multiple comparison test applied to the crab mean size data from the Bradda Inshore ground sampled during the October 1995, June 1996 and October 1996 scallop surveys. Underlined dates showed no statistical difference in mean crab size. Gaps in the underlining show statistical differences in mean crab sizes (carapace width (mm).

Sample date	Oct-95	Jun-96	Oct-96
Mean size	150.1	156.3	160.8
N	28	15	35
		———	———
	———	———	

Table 3.6e

Summary of the results of the one way ANOVA testing for differences in mean crab sizes from year to year within the Laxey site using data from the October 1995 to October 1996 scallop surveys.

Source	Degreed of Freedom	Sum of Squares	Mean Square	F	p
Survey date	2	365	182	0.79	0.466
Error	22	5081	231		
Total	24	5446			

Table 3.6f

Summary of results of t-tests used to identify whether there were any differences in mean crab sizes within sites for October 95 and June, October 96.

Site	Dates	t	df	p	Conclusion
Targets	Oct.95-Jun.96	-3.85	19	0.0011	Reject Ho
Chickens	Oct.95-Oct.96	-3.44	30	0.0017	Reject Ho
S.E. Douglas	Oct.95-Oct.96	-1.04	8	0.33	Accept Ho

Tukey multiple comparison test used to determine where these differences lay are summarised in Table 3.6d. Table 3.6d shows that the mean crab size at the Bradda Inshore site was significantly greater during the October 1996 survey than it was during the October 1995 survey. The mean size of crabs caught during the June 1996 survey was not found to be significantly different from mean sizes caught during the other two surveys. There is a trend of increasing crab mean size with time at this site.

Table 3.6e indicates that the null hypothesis should be accepted ($p = 0.466$) and it was therefore concluded that there were no significant differences in mean crab size at the Laxey site over the three survey dates.

The remaining sites tested (Targets, Chickens and South East Douglas) were only sampled on two out of the three survey dates. T-tests were used to determine whether any differences in mean crab sizes occurred within these sites over the dates tested and the results are summarised below. The null hypothesis used in each case was that there was no difference between the two mean sizes being tested. Any other sites sampled were only surveyed once and therefore could not be tested for within site differences. The results of these t-tests are summarised in Table 3.6f.

Table 3.6f shows that significant differences in mean crab size occurred on the two dates surveyed for the Targets and Chickens sites but not for the South East Douglas site. The mean sizes (±1 s.e.) of crabs at the Targets site were 141.1mm ± 3.9mm and 160.7mm ± 3.2mm from the October 1995 and June 1996 surveys respectively. The mean sizes of the crabs caught during the surveys at the Chickens site were 148.9mm ± 4mm and 164.9mm ± 2.4mm from the October 1995 and October 1996 surveys respectively. Both sets of figures suggest a trend of increasing size with time at the two sites. The South East Douglas site gave mean crab sizes of 127mm ± 6.1mm and 133.5mm ± 1.5mm from the October 1995 and October 1996 surveys respectively. The trend, again, was increasing mean size with time but in this instance it was not statistically significant.

Both the ANOVAs and t-tests of mean crab sizes generally suggest increasing crab size within sites. The differences from survey to survey were often statistically detectable. The more structured nature of these results compared to those obtained from the starfish data reflect the more structured growth patterns of crabs compared with starfish. Growth in size of crabs would have to be taken into account when planning re-seeding trials as larger crabs would be able to successfully attack juvenile scallops over a greater scallop size range.

3.3.7 Densities of predators at different sites around the Isle of Man.

Mean tow lengths obtained from the June 1995 survey (first three tows measured) are summarised in Table 3.7.

3.3.7.1 Numbers of starfish caught in queen and scallop dredges.

Results of the analysis of differences between numbers of starfish caught in the two different gear types are summarised in Table 3.8. Sites were chosen to represent, where possible, grounds from the north, south east and west of the island where 3 or more tows were made. Tows were used as replicates and data from each gear type were integrated within each tow. Data from three different surveys (June 1994, October 1994 and June 1995) were used to ensure that observed results were consistent from survey to survey. The null hypothesis used in each paired sample t-test was:

H_O: there is no difference in the mean number of starfish caught in the scallop and queen dredges at this site during this survey.

Table 3.8 shows that in all cases there was a significant difference in the mean totals of starfish caught in each gear type. Subsequent analyses used only data obtained from the queen gear which sampled greater numbers of starfish and which can therefore be assumed to have a greater efficiency in catching starfish.

3.3.7.2 Densities of starfish at the Inshore and Offshore sites.

The results of the two-way ANOVA applied to the Bradda Inshore and Bradda Offshore starfish relative density data are summarised in Table 3.9a. Surveys from October 1993 to June 1996 were used to coincide with the analysis performed on the size data. The data were found to be normally distributed when tested and so were not transformed prior to analysis. The null hypotheses used were:

H_{O1}: There are no significant differences in the mean, relative densities of starfish caught at the Bradda Inshore and Bradda Offshore sites.
H_{O2}: There are no differences in the mean, relative densities of starfish caught on different dates at the Bradda Inshore and Bradda Offshore sites.
H_{O3}: There is no interaction between the two factors, site and date.

Table 3.9a shows the that mean relative densities of starfish are significantly different at the two Bradda sites and that mean relative densities vary with sampling date ($p = 2.36 \times 10^{-10}$ and $p = 0.00011$ respectively). There is significant interaction between these factors ($p = 0.0128$) which means that cell means must be compared using a Tukey multiple

Table 3.7

Summary of mean tow lengths for each site surveyed during the June 1995 scallop survey which covered 12 out of the 13 sites that are surveyed round the Isle of Man.

Site	Mean tow length (m)	S.D.
Peel	3784.2	46.6
Point of Ayre	3734.2	57.4
10 Miles South PSM	3790.4	21.3
20 Miles South PSM	3988.0	267.9
Maughold	3852.1	26.2
Laxey	3704.0	26.1
Ramsey	3759.3	52.8
Bradda Offshore	3747.2	42.8
Bradda Inshore	3827.5	111.7
South East Douglas	3723.8	63.1
Chickens	3728.7	21.4
Targets	3778.1	115.7
East Douglas	3706.5	27.8

Table 3.8

Summary of the results of the t-tests used to determine differences in the mean numbers of starfish caught in the two gear types used during scallop surveys.

Survey site	Survey date	t	p	Conclusion
Bradda Inshore	Jun-94	5.01	0.019	Reject H_O
	Oct-94	4.65	0.022	Reject H_O
	Jun-95	3.10	0.045	Reject H_O
Bradda Offshore	Jun-94	3.67	0.034	Reject H_O
	Oct-94	8.12	0.039	Reject H_O
	Jun-95	4.82	0.020	Reject H_O
10 Miles South	Jun-94	5.30	0.007	Reject H_O
	Oct-94	3.76	0.017	Reject H_O
	Jun-95	12.86	0.001	Reject H_O
East Douglas	Jun-94	7.72	0.002	Reject H_O
	Oct-94	9.90	0.001	Reject H_O
	Jun-95	4.10	0.013	Reject H_O

Table 3.9a

Summary of the results of the two way ANOVA using site and date as the factors and mean density of starfish as the response variable.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	1	0.0021153	0.00211533	107.76741	2.3559×10^{-10}
Date	5	0.0008238	0.00016478	8.3947636	0.0001055
SitexDate	5	0.0003626	0.000072521	3.6946557	0.01274857
Error	24	0.0004710	0.000019629		
Total	35	0.0037729			

Table 3.9b

Summary of the Tukey multiple comparison test applied to the starfish mean density data obtained from the October 1993 to June 1996 survey data. OS represents the Bradda Offshore site and IS represents the Bradda Inshore site.

Site	OS	OS	OS	OS	OS	OS	IS	IS	IS	IS	IS	IS
Date	6/94	10/93	6/95	10/95	10/94	6/96	6/95	6/94	10/93	10/94	10/95	6/96
Mean (x10^{-3})	1.5	2.8	8.3	9.7	10.4	11.1	12.3	18.1	21.4	21.5	27.1	35.3
n	3	3	3	3	3	3	3	3	3	3	3	3

comparison test rather than using factor means. The results of the Tukey multiple comparison test between cell means are summarised in Table 3.9b. OS represents the Bradda Offshore site and IS the Bradda Inshore site.

Table 3.9b shows that there are apparent trends within the data concerning both sites which the statistical test suggests but lacks the power to prove outright. There does not appear to be any pattern in the June/October data within any particular year so, in order to increase the level of replication and the power of the multiple comparison test, the June/October data were integrated for each year to try to elucidate any year to year pattern in the data at these sites.

3.3.7.3 Testing combined June/October starfish density data.

Mean starfish density data obtained from June and October surveys are treated as replicates from the same year and analysed as in section 3.3.7.2 above using two way ANOVA with site and date as the factors and mean starfish density as the response. The null hypotheses were the same as those in section 3.3.7.2 above. The two sites are Bradda Inshore and Bradda Offshore and the survey years used were 1994, 1995 and 1996. Table 3.10a summarises the results of this two way ANOVA.

Table 3.10a shows that mean relative densities of starfish are significantly different at the two Bradda survey sites and that mean relative densities vary with sampling date ($p = 1.077 \times 10^{-9}$ and $p = 0.000271$ respectively). There is significant interaction between these factors ($p = 0.0152$) which means that cell means, rather than the factor means must be compared using a Tukey multiple comparison test. The results of the Tukey multiple comparison test between cell means are summarised in Table 3.10b.

Table 3.10b shows that the relative densities of starfish observed at both the Bradda Inshore and Bradda Offshore sites is increasing with time over the period surveyed. Between 1994 and 1996 the estimated, relative density of starfish at the Bradda Offshore site rose from 0.0059 animals per square metre to 0.0107 however, the test was not powerful enough to identify this change as significant. At the Bradda Inshore site 1994 and 1995 showed similar estimated, relative densities of 0.0197 and 0.0198 animals per square metre while 1996 showed a 1.77 times increase above the average of these values. Therefore, according to these relative density calculations the starfish population has increased significantly at the Bradda Inshore site between 1994 and 1996. Table 3.10b also shows that the Bradda Offshore site has significantly lower densities of starfish then the Bradda Inshore site in all years except 1996.

Table 3.10a

Summary of the two way ANOVA using survey site and date as the factors and mean starfish density as the response variable.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	1	0.00239	0.00239	75.548	1.077×10^{-9}
Year	2	0.000692	0.000346	10.938	0.000271
SitexYear	2	0.000306	0.000153	4.827	0.0152
Error	30	0.0009495	0.0000317		
Total	35	0.00434			

Table 3.10b

Summary of the results of the Tukey multiple comparison test. Underlined dates showed no statistical difference in mean starfish density. Gaps in the underlining show statistical differences in mean starfish density.

Site	**Bradda Offshore**	**Bradda Offshore**	**Bradda Offshore**	**Bradda Inshore**	**Bradda Inshore**	**Bradda Inshore**
Year	1994	1995	1996	1995	1994	1996
n	6	6	6	6	6	6
Mean	0.0059	0.0090	0.0107	0.0197	0.0198	0.0350
			———	———	———	———
	———	———	———			

3.3.7.4 Densities of starfish at all sites around the Isle of Man.

Results of the one-way ANOVAs comparing relative densities at different sites and subsequent Tukey multiple comparison tests (where appropriate) are summarised in Table 3.11. Low and high density sites represent sites where significant differences in starfish densities were identified and where low and high relative densities occurred respectively. F statistics and p values obtained from the ANOVA show where significant differences were identified. Sites where no definite conclusions about differences could be drawn are not included in this summary for brevity.

Table 3.11 shows that significant differences in relative densities of starfish were identified between surveyed sites in every survey made. Generally the Bradda Inshore and Point of Ayre sites had the highest relative densities of starfish. The multiple comparison test lacked the power to determine differences between many of the sites surveyed.

The June 1995 and June 1996 surveys grouped most of the sites sampled together, indicating no statistical difference between the grouped sites. In most cases the differences in relative starfish density would appear to be small enough that only the minimum and maximum relative densities yield a significant difference. Therefore most sites, with the exception of 10 Miles South of Port St. Mary (low density), Bradda Inshore and Point of Ayre(high density), could be deemed to have the same overall relative densities of starfish assuming equal dredge efficiency and tow lengths at all sites.

The second factor to consider when assessing suitability of a site for re-seeding is possible differences in relative densities on different sampling dates within a site - seasonal changes within the year. This factor is tested in section 3.3.7.5.

3.3.7.5 Densities of starfish within sites on different dates.

Results of the one-way ANOVAs comparing relative densities within sites on different survey dates and subsequent Tukey multiple comparison tests (where appropriate) are summarised in Table 3.12. Low and high density table columns represent dates where significant differences in starfish densities were identified and where low and high relative densities occurred respectively. F statistics and p values obtained from the ANOVA show where significant differences were identified. Dates where no definite conclusions about differences could be drawn are not included in this summary. The Bradda Inshore and Bradda Offshore sites have been analysed in section 3.3.7.2.

Table 3.11

Summary of all the one way ANOVAs and Tukey multiple comparison tests used to identify differences in mean starfish density between sites for each dredge survey.

Survey Date	Calculated F	p Value	Low Density	High Density
October 1993	29.03	6.74×10^{-12}	10S, BO	PA
June 1994	19.26	5.22×10^{-10}	BO	BI, PA
October 1994	9.17	2×10^{-4}	10S	BI
June 1995	10.92	7.47×10^{-8}	10S,LX,SD,PL,CH, 20S,TA,BO,ED	RY
October 1995	16.07	1.09×10^{-8}	10S	BI
June 1996	40.53	1.24×10^{-15}	10S,SD,LX,20S,ED, PL,CH,BO	PA,BI

Key to abbreviations used in Table 3.11:

20S	20 Miles South of P.S.M	SD	South East Douglas	TA	Targets
10S	10 Miles South of P.S.M	ED	East Douglas	LX	Laxey
PA	Point of Ayre	RY	Ramsey	PL	Peel
CH	Chickens	BO	Bradda Offshore	BI	Bradda Inshore

Table 3.12

Summary of all the one way ANOVAs and Tukey multiple comparison tests used to identify differences in mean starfish density within each site and between June and October dredge surveys.

Survey Site	Calculated F	p Value	Low Density	High Density
Chickens	14.85	4.25×10^{-6}	June: 95	October: 93,95
Peel	8.83	2×10^{-4}	June: 94	June: 96 October: 93
10 Miles South	1.23	0.334	No differences	-
20 Miles South	3.32	0.028	No differences*	-
Targets	7.76	1.4×10^{-3}	June: 94,95	June: 96
Point of Ayre	2.69	0.127	No differences	-
Ramsey	3.20	0.180	No differences	-
Laxey	6.66	7×10^{-3}	June: 94 October: 96	June: 96
East Douglas	16.21	4.08×10^{-6}	June: 95	October: 93
South East Douglas	12.28	2.77×10^{-5}	June: 94,95,96 October: 95,96	October: 93

Table 3.12 shows that sites where no differences were identified were: 10 and 20 Miles South of Port St. Mary; Point of Ayre and Ramsey. Surveys made at 20 Miles South of Port St. Mary yielded a significant result from the ANOVA with survey date as the factor ($p= 0.028$). The subsequent Tukey multiple comparison however, failed to determine where these differences lay. This is a consequence of the ANOVA test having a greater power than the Tukey test which sometimes leads to the conclusion of significant differences between means when no difference is detectable by multiple comparison. This appears to be the case for this site.

Table 3.12 does not show any particular pattern between June and October surveys in terms of mean starfish densities. The observed differences are either likely to be a result of natural fluctuations in density within the sites sampled or are a result of a pattern of fluctuation which could only be investigated by making a larger number of surveys throughout the year. The latter course of investigation was not viable given the cost, manpower and time constraints involved in using the R.V. Roagan for such surveys.

3.3.7.6 Densities of crabs at the Inshore Bradda and Offshore Bradda Sites.

Results of the analysis of differences between numbers of crabs caught in the two different gear types are summarised in Table 3.13a. Sites were chosen to represent, where possible, grounds from the north, south east and west of the island where 3 or more tows were made. Tows were used as replicates and data from each gear type were integrated within each tow. Data from three different surveys (June 1994, October 1994 and June 1995) were used to ensure that differences or lack of differences were consistent. Different sites were used compared to the same analysis for starfish due to the lack of crabs at some of the sites. The null hypothesis used in each paired sample t-test was:

H_O: there is no difference in the mean number of crabs caught in the scallop and queen dredges at this site during this survey.

Table 3.13 shows that, in all cases, there was no significant difference in the mean totals of crabs caught in each gear type. Subsequent analyses used pooled data obtained from both gear types with tows used as replicates.

The results of the two-way ANOVA applied to the Bradda Inshore and Bradda Offshore crab relative density data are summarised in Table 3.13b. Surveys from October 1993 to June 1996 were used to coincide with the analysis performed on the size data. The data were not transformed prior to analysis. The null hypotheses used were:

Table 3.13a

Summary of the results of the t-tests used to investigate differences in the mean numbers of crabs caught in queen and scallop dredges during the June 1994 to June 1995 dredge surveys.

Survey site	Survey date	t	p	Conclusion
Bradda Inshore	Jun-94	-0.76	0.26	Accept H_0
	Oct-94	1.63	0.12	Accept H_0
	Jun-95	1.51	0.14	Accept H_0
Bradda Offshore	Jun-94	-1.51	0.14	Accept H_0
	Oct-94	-0.82	0.28	Accept H_0
	Jun-95	-1.96	0.09	Accept H_0
Targets	Jun-94	0.00	0.5	Accept H_0
	Oct-94	No survey	No survey	No survey
	Jun-95	0.73	0.26	Accept H_0
East Douglas	Jun-94	0.88	0.22	Accept H_0
	Oct-94	0.79	0.24	Accept H_0
	Jun-95	-0.78	0.25	Accept H_0

Table 3.13b

Summary of the two way ANOVA used to determine differences in mean crab densities between the Bradda Inshore and Bradda Offshore sites during the October 1993 to June 1996 dredge surveys. Site and date were used as the factors and mean crab density as the response variable.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Site	1	$6.172x10^{-7}$	$6.171x10^{-7}$	12.409	0.0015
Date	6	$6.955x10^{-6}$	$1.159x10^{-6}$	23.304	$1.11x10^{-9}$
SitexDate	6	$1.272x10^{-6}$	$2.121x10^{-7}$	4.264	0.00358
Error	28	$1.393x10^{-6}$	$4.974x10^{-8}$		
Total	41	$1.024x10^{-5}$			

Table 3.13c

Summary of the results of the Tukey multiple comparison test applied to the data analysed in Table 3.13b. OS represents the Bradda Offshore site and IS represents the Bradda Inshore site.

Site	**OS**	**IS**	**IS**	**OS**	**IS**	**OS**	**IS**	**IS**	**OS**	**IS**	**OS**	**OS**
Date	6/95	6/94	6/95	6/96	6/96	6/94	10/93	10/95	10/95	10/94	10/93	10/94
n	3	3	3	3	3	3	3	3	3	3	3	3
Mean ($x10^{-4}$)	1.86	2.34	3.79	3.86	4.52	4.86	7.15	7.30	8.00	11.38	16.14	16.93

H_{O1}: There are no significant differences in the mean, relative densities of crabs caught at the Bradda Inshore and Bradda Offshore sites.
H_{O2}: There are no differences in the mean, relative densities of crabs caught on different dates at the Bradda Inshore and Bradda Offshore sites.
H_{O3}: There is no interaction between the two factors, site and date.

Table 3.13b indicates that relative density is affected by both factors and that there is significant interaction between the two factors. A summary of the Tukey multiple comparison test is detailed in Table 3.13c.

Table 3.13c shows that the between sites differences in crab density are of less importance than differences in crab density by sampling date. The relative densities of crabs are significantly lower in the June surveys than in the October surveys. The test lacks the power to define differences between other sampling dates. During the June surveys there was little difference between mean inshore and offshore relative crab densities (3.55 and 3.53×10^{-4} crabs m^{-2} respectively). However, the inshore and offshore relative means obtained from the October surveys differed more markedly (8.61 and 13.69×10^{-4} crabs m^{-2} respectively). Therefore the relative densities of crabs appears to differ between the Bradda Inshore and Bradda Offshore sites to a much greater extent in October than it does in June. This difference is probably responsible for making the interaction term significant.

The data were re-analysed using inshore and offshore data as replicates to determine whether the June/October pattern persisted and whether any trends with time existed. The integration of the inshore and offshore data meant that a one-way ANOVA was used with survey date as the factor. The purpose of this was to increase the level of replication and power of the ANOVA and subsequent multiple comparison test. The results must be treated with caution as this involves integration of surveys where differences have been shown to exist. Ideally a greater number of replicates would have been made during each individual survey however, logistically this was not possible. The results of the ANOVA test are summarised in Table 3.13d.

Table 3.13d shows that survey date is a significant factor affecting observed mean densities of crabs during these surveys. The data were compared using a Tukey multiple comparison test summarised in Table 3.13e.

Table 3.13e shows that crab densities were lowest and not significantly different during the June surveys. Crab densities are higher during the October surveys but the only significant difference identified was in the October 1994 survey. Although inconclusive, the October

Table 3.13d

Summary of the one way ANOVA investigating differences in mean crab densities (m^{-2}) between dates for the combined Bradda Inshore and Bradda Offshore dredge surveys from October 1993 to June 1996.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Date	5	$6.57x10^{-6}$	$1.31x10^{-6}$	13.849	$4.81x10^{-7}$
Error	30	$2.84x10^{-6}$	$9.48x10^{-8}$		
Total	35	$9.41x10^{-6}$			

Table 3.13e

Summary of the Tukey test used to investigate differences in mean crab densities (m^{-2}) between dates for the combined Bradda Inshore and Bradda Offshore dredge surveys from October 1993 to June 1996.

Date	**Jun-95**	**Jun-94**	**Jun-96**	**Oct-95**	**Oct-93**	**Oct-94**
n	6	6	6	6	6	6
Mean $(x10^{-4})$	2.83	3.60	4.19	7.65	11.65	14.16
					———	———
				———	———	
	———	———	———	———		

survey data suggests a reduction in crab numbers with time. The October 1996 data were then checked to determine whether this trend continued. This gave an average relative density of 10.10×10^{-4} crabs m^{-2} (2.85 times the June average).

Mean crab density from the June surveys was 3.54×10^{-4} animals m^{-2}. The 1993, 1994 and 1995 October surveys yielded crab densities of 3.29, 4.00 and 2.16 times greater than the June average respectively. This trend appeared to continue in October 1996 though with some recovery to 2.85 times the June average. The reduction in crab numbers could be a result of increased activity in the crab fishery locally over the last 18 months to 2 years. Many more crabs have been landed through Port Erin all of which are locally caught.

3.3.7.7 Densities of crabs at all sites around the Isle of Man.

Results of the one-way ANOVAs comparing relative densities at different sites and subsequent Tukey multiple comparison tests (where appropriate) are summarised in Table 3.14. Low and high density sites represent sites where significant differences in crab densities were identified and where low and high relative densities occurred respectively. F statistics and p values obtained from the ANOVA show where significant differences were identified. Sites where no definite conclusions about differences could be drawn are not included in this summary.

Table 3.14 indicates that there are higher relative densities of crabs inshore to the south west of the Isle of Man and lower relative densities to the north and east and offshore to the south. The differences observed also became more clearly defined statistically in the October 1995 and June 1996 surveys. In these latter two surveys the mean relative densities at the high density sites were 5.37 and 8.65 times greater than the mean relative densities at the low density sites respectively. The high density sites (generally Peel, Bradda Inshore and Bradda Offshore) showed higher crab densities during October surveys compared to June surveys. This factor is tested in section 3.3.7.8.

3.3.7.8 Densities of crabs within sites on different dates.

Results of the one-way ANOVAs comparing relative densities within sites on different survey dates and subsequent Tukey multiple comparison tests (where appropriate) are summarised in Table 3.15. Low and high density table columns represent dates where significant differences in crab densities were identified and where low and high relative densities occurred respectively. F statistics and p values obtained from the ANOVA show where significant differences were identified. Dates where no definite conclusions about differences could be drawn are not included in this summary. The Bradda Inshore and Bradda Offshore sites have been analysed in section 3.3.7.6.

Table 3.14

Summary of all the one way ANOVAs and Tukey multiple comparison tests used to identify differences in mean crab density between sites for each dredge survey.

Survey Date	Calculated F	p Value	Low Density	High Density
October 1993	45.02	$1.23\text{x}10^{-13}$	20S, 10S, SD, TA	BI, BO
June 1994	19.08	$5.83\text{x}10^{-10}$	10S, 20S, LX, SD	PL, BO
October 1994	21.68	$9.06\text{x}10^{-7}$	10S, RY, LX, ED	PL, BO
June 1995	19.5	$5.97\text{x}10^{-11}$	20S, SD, PA, 10S, RY, LX, ED, TA, CH	PL
October 1995	26.94	$3.05\text{x}10^{-11}$	20S, 10S, SD, ED, TA, LX, CH	BI, BO, PL
June 1996	14.79	$1.35\text{x}10^{-9}$	10S, LX, RY, 20S, SD, PA, TA, CH, ED	BO, BI, PL

Key to abbreviations used in Table 3.14:

20S	20 Miles South of P.S.M	SD	South East Douglas	TA	Targets
10S	10 Miles South of P.S.M	ED	East Douglas	LX	Laxey
PA	Point of Ayre	RY	Ramsey	PL	Peel
CH	Chickens	BO	Bradda Offshore	BI	Bradda Inshore

Table 3.15

Summary of all the one way ANOVAs and Tukey multiple comparison tests used to identify differences in mean crab density within each site and between June and October dredge surveys.

Survey Site	Calculated F	p Value	Low Density	High Density
Chickens	7.03	0.001	No differences*	-
Peel	13.26	$1.65\text{x}10^{-5}$	June: 94, 96, 95 October: 93	October: 94, 95
10 Miles South	1.53	0.229	No difference	-
20 Miles South	0.547	0.739	No difference	-
Targets	2.63	0.0763	No difference	-
Point of Ayre	0.556	0.659	No difference	-
Ramsey	16.32	0.0038	June: 95, 96	October: 94
Laxey	8.77	0.0008	June: 96	October: 94
South East Douglas	0.99	0.443	No difference	-
East Douglas	2.369	0.081	No difference	-

Table 3.15 shows that, where differences occurred within a site, the relative densities of crabs were generally higher during the October surveys than during the June surveys. Most sites showed no differences in crab densities between the June and October surveys.

The Chickens surveys yielded a significant result from the ANOVA with survey date as the factor (p= 0.001). The subsequent Tukey multiple comparison however, failed to determine where these differences lay. This is a consequence of the ANOVA test having a greater power than the Tukey test which sometimes leads to the conclusion of significant differences between means when no difference is detectable by multiple comparison. This appears to be the case for this site.

3.3.8 Video survey results .

Results of the video surveys carried out during this study are presented in terms of densities of animals per metre square of seabed for the Bradda Head site (Table 3.16a) and for the Exclusion Zone site (Table 3.16b).

The results summarised in Tables 3.16a and b were analysed using a t-test to determine whether any statistically significant difference existed in mean crab and starfish densities between the two sites sampled. Results of this t- test analysis are summarised in section 3.3.8.1.

3.3.8.1 Bradda Head and Exclusion Zone video surveys.

Comparing densities of starfish at the two sites showed that, for the dates surveyed, the Bradda site had a significantly greater density of starfish than the Exclusion zone site: ($p = 0.0036$, $t_{crit} = 2.178$, $t = 3.604$ using MS Excel Analysis Tools).

Testing the estimated densities of crabs observed at the two sites showed that, for the dates surveyed, no significant difference existed between the two sites ($p = 0.325$, $t_{crit} = 2.178$, $t = 1.026$ using MS Excel Analysis Tools).

3.3.9 Estimating dredge efficiency using video surveys.

Comparisons between video and dredge surveys of estimated mean densities of animals were only carried out for the predator species, *Asterias rubens* and *Cancer pagurus*. The video surveys did not provide enough definition to confidently identify the scallop *Pecten maximus* using the equipment available. Diver surveys (section 3.3.10) were used to estimate dredge efficiency for scallops.

Table 3.16a

Summary of predator densities (animals per square metre) for crabs and starfish obtained from the Bradda Head video surveys. Figures in bold indicate where estimates were made using quadrat counts only where the digital counter failed.

Date	Cancer m^{-2}	Asterias m^{-2}
1/9/93	0.0115	0.1286
19/10/93	0.0118	0.1361
16/2/94	**0.0018**	**0.1052**
7/7/94	0.0000	0.1001
2/9/94	0.0061	0.0388
2/9/94	0.0027	0.0994

Table 3.16b

Summary of predator densities (animals per square metre) for crabs and starfish obtained from the Exclusion Zone video surveys. Figures in bold indicate where estimates were made using quadrat counts only where the digital counter failed.

Date	Cancer m^{-2}	Asterias m^{-2}
1/9/93	0.0091	0.1152
19/10/93	0.0016	0.0359
16/2/94	**0.0000**	**0.0209**
7/7/94	0.0000	0.0084
7/7/94	0.0055	0.0073
2/9/94	0.0050	0.0213
14/12/95	**0.0056**	**0.0446**
14/12/95	**0.0000**	**0.0041**

Tables 3.17a (for crabs) and b (for starfish) summarise the results of the comparison of dredge and video surveys taken at approximately equivalent times of each year surveyed. Estimates of dredge efficiency, assuming that video surveys were 100% efficient and were calibrated correctly, are also included.

Table 3.17a indicates that dredge efficiency in catchin crabs is low and variable (between 3.9 and 26.1%). Dredge efficiency in catching starfish is low (Table 3.17b) but appears to be less variable than the estimates made for crabs (Table 3.17a).

3.3.10 Estimating dredge efficiency using diver surveys.

All dredge surveys were carried out at the Bradda Inshore site for these comparisons. Diver surveys took place within the Exclusion Zone. Comparisons were made between: the June 1994 dredge survey and April/May 1994 diver surveys (Table 3.18a); the June 1996 dredge survey and the June/July 1996 diver surveys (Table 3.18b) and between the October 1996 dredge survey and the August/September 1996 diver surveys (Table 3.18c). Estimates of dredge efficiency are summarised in Tables 3.18d assuming 100% efficiency of diver surveys in estimating density.

A summary of estimated dredge efficiency calculated by comparing the results of diver surveys with dredge surveys at similar times of year is included in Table 3.18c. Dredge efficiency estimates were made using the data from Tables 3.18a - c. These efficiency estimates are summarised in Table 3.18d.

Table 3.18d indicates that dredge efficiency in sampling crabs is consistently lower than 10%. This compares with the variable results obtained using comparison with video surveys (Table 3.17a). This difference was not expected because diver surveys are effectively point surveys where one might expect there to be greater variability because of the patchy distribution of animals on the seabed. Video surveys, using long linear transects similar to dredge surveys, would have been expected to produce more consistent results when comparing data with dredge surveys. Further differences between diver and video estimates of dredge efficiency are highlighted when surveying starfish. The video surveys indicate low efficiency (16.3 - 24.9%, Table 3.17b) whereas diver surveys indicate consistently higher efficiency of dredges in sampling starfish (48.5 - 79.4%, Table 3.18d). Table 3.18d also gives an estimate of greater than 100% efficiency for starfish which arose because the locations of the diver and dredge surveys were not exactly coincident. This fact, combined with the patchy distribution of benthic macrofauna may explain the observed variability in reaults.

Table 3.17a

Summary of the comparison of video and dredge surveys carried out during 1993 and 1994 comparing densities of crabs and estimating dredge efficiency in collecting crabs. For both survey methods, surveys made within a particular year were combined to yield a reasonable number of replicates for calculating means. All figures are animals per square metre.

Survey Type **Dates**	**Video** **Jul+Sept 94**	**Dredge** **Jun+Oct 94**	**Video** **Sept+Nov 93**	**Dredge** **Jun+Oct 93**
	0.0000	0.0003	0.0115	0.0012
	0.0061	0.0003	0.0118	0.0014
	0.0027	0.0000	-	0.0000
	-	0.0010	-	0.0000
	-	0.0017	-	0.0003
	-	0.0013	-	0.0003
	-	-	-	0.0000
Mean	**0.0029**	**0.0008**	**0.0117**	**0.0005**
Est. efficiency %	**26.14**		**3.92**	

Table 3.17b

Summary of the comparison of video and dredge surveys carried out during 1993 and 1994 comparing densities of starfish and estimating dredge efficiency in collecting starfish. For both survey methods, surveys made within a particular year were combined to yield a reasonable number of replicates for calculating means. All figures are animals per square metre.

Survey Type **Dates**	**Video** **Jul+Sept 94**	**Dredge** **Jun+Oct 94**	**Video** **Sept+Nov 93**	**Dredge** **Jun+Oct 93**
	0.1001	0.0129	0.1286	0.0228
	0.0388	0.0173	0.1361	0.0194
	0.0994	0.0240	-	0.0221
	-	0.0182	-	0.0231
	-	0.0301	-	0.0197
	-	0.0162	-	0.0150
	-	-	-	0.0285
Mean	**0.0794**	**0.0198**	**0.1324**	**0.0215**
Est. efficiency %	**24.91**		**16.26**	

Table 3.18a

Summary of the comparison of diver and dredge surveys carried out during spring 1994 comparing densities of crabs, starfish and scallops. All figures are animals per square metre.

	Diver Surveys - Apr/May 94			Dredge Surveys - June 94		
	Crabs.	**Starfish.**	**Scallops.**	**Crabs.**	**Starfish.**	**Scallops.**
	0.015	0.015	0.015	0.0003	0.0129	0.0207
	0	0.025	0.045	0.0003	0.0173	0.0158
	0.005	0.03	0.02	0.0000	0.0240	0.0157
	0.01	0.025	0.015	-	-	-
	0.025	0.015	0.055	-	-	-
	0	0.015	0.01	-	-	-
	0	0.01	0	-	-	-
	0	0.005	0.025	-	-	-
	0	0.02	0.07	-	-	-
	0	0.005	0.005	-	-	-
	0	0.015	0.015	-	-	-
	0	0	0.01	-	-	-
	0	0.01	0.02	-	-	-
	0	0.005	0.015	-	-	-
	0	0.045	0.005	-	-	-
	0.02	0.125	0.035	-	-	-
	0.005	0.045	0.01	-	-	-
	0	0	0.04	-	-	-
Mean (m^{-2})	**0.0044**	**0.0228**	**0.0228**	**0.0002**	**0.0181**	**0.0174**

Table 3.18b

Summary of the comparison of diver and dredge surveys carried out during spring 1996 comparing densities of crabs, starfish and scallops. All figures are animals per square metre.

	Diver Surveys - Jun/Jul 96			Dredge Surveys - June 96		
	Crabs.	**Starfish.**	**Scallops.**	**Crabs.**	**Starfish.**	**Scallops.**
	0	0.095	0.005	0.0005	0.0367	0.0068
	0.005	0.06	0.01	0.0003	0.0343	0.0068
	0.005	0.035	0.01	0.0006	0.0350	0.0058
	0.02	0.16	0	-	-	-
	0	0.025	0.07	-	-	-
	0	0.015	0.02	-	-	-
	0.01	0.12	0	-	-	-
Mean (m^{-2})	**0.0057**	**0.0729**	**0.0164**	**0.0005**	**0.0353**	**0.0065**

Table 3.18c

Summary of the comparison of diver and dredge surveys carried out during autumn 1996 comparing mean densities of crabs, starfish and scallops. All figures are animals per square metre.

	Diver Surveys - Aug/Sept 96			**Dredge Surveys - Oct 96**		
	Crabs.	**Starfish.**	**Scallops.**	**Crabs.**	**Starfish.**	**Scallops.**
	0.005	0.02	0.01	0.0009	0.0339	0.0105
	0.02	0.03	0.03	0.0010	0.0327	0.0094
	0.01	0	0.05	0.0006	0.0374	0.0073
	0	0.03	0.005	-	-	-
Mean (m^{2})	**0.0088**	**0.0200**	**0.0238**	**0.0009**	**0.0347**	**0.0091**

Table 3.18d

Summary of the calculated estimates of dredge efficiency in collecting crabs, starfish and scallops assuming that diver surveys were 100% efficient. Data from Tables 3.18a - c above.

Date.	**Crabs.**	**Starfish.**	**Scallops.**
Dive Mean Apr/May 94	0.0044	0.0228	0.0228
Dredge Mean June 94	0.0002	0.0181	0.0174
Estimated Dredge Efficiency	**4.5%**	**79.4%**	**76.3%**
Dive Mean Jun/Jul 96	0.0057	0.0729	0.0164
Dredge Mean June 96	0.0005	0.0353	0.0065
Estimated Dredge Efficiency.	**8.5%**	**48.5%**	**39.6%**
Dive Mean Aug/Sept 96	0.0088	0.0200	0.0238
Dredge Mean Oct 96	0.0009	0.0347	0.0091
Estimated Dredge Efficiency.	**9.8%**	**>100%**	**38.3%**

3.3.11 Variation in species density over time in the Exclusion Zone.

All diver surveys took place in the Exclusion Zone during the course of this study. The sampling periods were spring 1994, summer 1996 and Autumn 1996. The results of one-way ANOVAs testing for differences in mean density between sampling dates are included for crabs (Table 3.19a), starfish (Table 3.19b) and for scallops (Table 3.19c). Time of year of sampling is used as the factor with species density per metre square as the response variable in each case. The null hypothesis used for each test was:

H_O: There are no significant differences in mean species densities between sets of diver surveys.

Tables 3.19a - c show that the only species demonstrating significant differences in density between sampling periods was *Asterias rubens* ($p = 0.01$ in Table 3.19b). The results of the Tukey multiple comparison test for this species are summarised in Table 3.19d.

The null hypothesis used was:

H_O: There is no difference between mean starfish density for the three periods sampled.

Table 3.19d shows that starfish densities are significantly lower in the autumn 1994 sampling period than in the summer 1996 period. Ambiguity of results may stem from low replication plus small sampling area of diving surveys combined with a patchy distribution of the species.

3.4 Discussion.

Initial analysis showed that significant differences existed in the mean sizes of starfish caught in queen and scallop gear. Queen gear was therefore used to make comparisons between sites of starfish sizes following the reasoning and methods of Wilson (1994). Similarly, the numbers of starfish caught in the two gear types and used for calculating relative densities were found to be significantly different. Again this meant that the queen gear were used for making comparisons. Significant differences between numbers and sizes of starfish caught in the two different gear types probably result from the more delicate, soft bodied nature of starfish compared with crabs. Smaller starfish would be far more likely to pass through the larger belly rings of the scallop gear than through the smaller rings of the queen gear thus increasing the mean size of animals caught in the scallop gear. The relatively delicate nature of starfish means that they are fairly readily broken up in the dredges as they are towed along the seabed. Broken and damaged starfish were found in dredge contents and these pieces would suggest that many starfish were lost from the dredges or were not in a fit state to be

Table 3.19a

Summary of the one way ANOVA testing for differences in mean crab density between diver surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Time of Year	2	6.1929E-05	3.0964E-05	0.50805346	0.60751578
Error	26	0.00158462	6.0947E-05		
Total	28	0.00164655			

Table 3.19b

Summary of the one way ANOVA testing for differences in mean starfish density between diver surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Time of Year	2	0.01361327	0.00680664	5.49536471	0.01021988
Error	26	0.03220397	0.00123861		
Total	28	0.04581724			

Table 3.19c

Summary of the one way ANOVA testing for differences in mean scallop density between diver surveys.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Time of Year	2	0.00022925	0.00011463	0.27055132	0.76508031
Error	26	0.01101558	0.00042368		
Total	28	0.01124483			

Table 3.19d

Summary of the Tukey multiple comparison test applied to the starfish mean density (m^{-2}) data from the diver surveys made in autumn 1994, spring 1996 and summer 1996.

Time of Year	Autumn 94	Spring 96	Summer 96
n	4	18	7
Mean Density	0.2	0.0228	0.0729

measured once caught. If particular sizes of starfish are more susceptible to damage then this will affect the mean sizes of starfish calculated from the catch data. This combined, with gear selectivity, means that all size and density estimates can only be relative. Comparisons between sites and dates can be made assuming equal efficiency of gear and equal within dredge effects (breaking of animals and clogging of the belly rings for example) for each survey site and date. These assumptions may not be correct but they are the only way of obtaining comparative data between sites on such a large scale. For these reasons all mention of size and density differences in this thesis refer only to relative differences and are not to be taken as absolute measures of population mean sizes and mean densities. A far more detailed and exhaustive survey regime would be required to obtain absolute estimates and even these figures could be cast in a doubtful light given the patchy distributions of animals on the seabed. All sampling gear will be selective to some degree. The compromise lies in covering sufficient areas with sufficient accuracy in the time allowed by logistical constraints.

No statistically significant difference was found between dredge types in terms of sizes of crabs caught except at the Bradda Offshore site in October 1996. It was considered that, given the time and manpower restrictions involved in working at sea, pooling the size data from both gear types was justified for crabs. In a majority of the surveys tested this was found to be a valid method and also served to increase the accuracy of calculated means by increasing the number of crabs caught and measured. There was no significant difference between dredge types in the numbers of crabs caught. Consequently, given the low densities of crabs encountered during the surveys, results from the two dredge types were pooled and a larger swept area employed in calculating relative densities.

The lack of significant differences in the size and numbers of crabs caught in the two different dredge types probably reflects the fact that crabs are of a large size compared with the targeted scallops. Coupled with their epibenthic habit on open seabed and with the fact that their legs frequently get tangled in the belly rings and mesh backing of both dredge types, this will lead to their capture by both gear types with equal efficiency. Differences in size selectivity do not occur because most crabs are larger than the maximum ring size of the scallop gear which determines the minimum size of hard shelled animals caught. Differing teeth length does not apparently alter the number of crabs caught either otherwise the numbers caught in the two dredge types would have differed. True densities of crabs could not be estimated from these dredge surveys as crabs have some ability to avoid dredges by movement and the dredges may not always be in contact with the seabed or may become clogged. General observations on deck, however, suggest that at most sites using the tow lengths detailed the dredges were not usually clogged during the tow lengths used. The selectivity of dredge gear for crab size has not been investigated but undoubtedly small crabs could be lost through the dredge belly rings, thus shifting the size distribution towards a larger mean size than actually present in the population sampled. Further investigation of selectivity and efficiency of dredges in catching non target species would be extremely useful in calibrating dredges as a means of surveying predator populations.

Comparison of starfish sizes at the Bradda Inshore and Bradda Offshore sites revealed a significant difference between sites and significant interaction between sites and dates but no significant differences between dates within each site. The Bradda Offshore site showed a generally decreasing trend in mean starfish size with time, while the Bradda Inshore site showed a generally increasing trend. Combining this information with the density data obtained from the same sites allows conclusions to be drawn regarding the potential threat posed by starfish to juvenile scallops in these areas. This information, in turn, could be used to explain observed trends in relative predation rates on tethered scallops.

Comparison of all sites over three surveys (October 1995, June 1996 and October 1996) suggests that, with the exception of Laxey, sites to the east of the Isle of Man have larger mean relative sizes of starfish than sites to the west and south of the island. The South East Douglas and East Douglas sites consistently gave significantly higher mean relative starfish sizes than the other sites surveyed during October 1995, June 1996 and October 1996.

Statistically significant within site variations in mean relative starfish sizes were identified. The sites where starfish sizes have remained stable throughout the October 1995-October 1996 surveys were: Targets, East Douglas and 20 Miles South of Port St. Mary. Laxey, Chickens and South East Douglas each showed a significant decrease in mean relative starfish size while 10 Miles South of Port St. Mary and Peel showed significant increases with time. These findings demonstrate the rather flexible nature of starfish growth patterns which tend to be determined by food supply. Some sites had stable mean starfish sizes over the surveys made while some increased and some decreased. This could make predictions regarding future trends complicated if not impossible.

The analysis of starfish densities showed that the Bradda Inshore site generally had a greater density than the Bradda Offshore site but with only a few statistically significant differences. A greater level of replication would have been preferable but logistic constraints would not allow this. The plots of relative starfish density from the Bradda Inshore and Bradda Offshore sites show increasing trends at both sites. In summary then, from October 1993 to June 1996 there appears to have been an increase in mean starfish density and an increase in mean starfish size at the Bradda Inshore site. Over the same period there was an increase in mean starfish density but a decrease in mean starfish size at the Bradda Offshore site. These results suggest that, over the period surveyed, the Bradda Inshore site became a higher risk area for re-seeding juvenile scallops in terms of mean starfish numbers and sizes. Comparatively, the Bradda Offshore site should presented a lower risk to re-seeded scallops than the Bradda Inshore site as it had a lower mean density and size of starfish, despite the fact that mean density appears to be increasing.

Mean relative starfish densities were consistently, significantly higher at the Point of Ayre and Bradda Inshore sites while the other sites surveyed showed little or no differences. The combination of higher mean relative starfish densities to the east and higher mean relative starfish sizes to the north suggest that a site for re-seeding trials should be located to the south west of the island, considering the risk of starfish predation in isolation from other factors. The sites giving a combination of the lowest mean relative densities and sizes of starfish would include: 10 Miles South of Port St. Mary, Peel, Chickens and Bradda Offshore. From a monitoring point of view the Bradda Offshore site would be the most convenient being situated only 5 miles from PEML. This does not take into account the differences in fishing intensity experienced by these sites which could disturb re-seeded stocks of scallops.

Within site changes in mean relative densities of starfish also show significant differences between survey dates. Sites where decreases in mean relative density of starfish have occurred with time include: Chickens, East Douglas and South East Douglas. Increasing trends in mean relative starfish density occurred at Laxey, and at Targets and Peel an initial drop in density from a high point was followed by a recovery. 10 and 20 Miles South of Port St. Mary, Point of Ayre and Ramsey showed no significant changes in mean relative starfish density. Some sites show trends which may be found to be cyclic if further surveys were to be analysed. Alternatively, the trends could be merely random fluctuations in the starfish populations at different sites dependent on factors such as larval production/success rates, spat settlement success and food supply. If the trends could be shown to have a cyclic aspect then the timing of scallop re-seeding could be adjusted to coincide with minimum sizes and densities of predators.

Analysis of mean crab sizes at the Bradda Inshore and Bradda Offshore sites revealed significant differences between dates but not between the two sites. No significant interaction was detected. Re-analysis of the data combining the two sites showed that the October 1993 and October 1995 surveys yielded significantly smaller mean crab sizes than the June 1994 and 1995 and the October 1994 and 1996 surveys. No conclusions could be drawn regarding the October 1995 survey. When data were plotted a cyclic pattern became evident. From the October 1993 survey the mean crab size (151.2mm± 1.1 mm) increased steadily to the June 1995 survey (164.1mm± 2.9 mm). The mean size at the following survey then dropped to 148.8mm± 1.6 mm and then began another steady increase to a high of

161.4mm± 1.5 mm in October 1996. This might indicate a cycle of increasing crab size with time over a 2 year period followed by a sudden, significant drop in mean size which is in turn followed by a steady increase. The data from the June 1997 and subsequent surveys may confirm whether this pattern is regular or not. If this turns out to be a regular pattern then any re-seeding trials could be carried out at a time when crab mean sizes are predicted to be low. This pattern could be generated either by smaller crabs migrating in to the survey area every 2 years or by larger crabs migrating out of the survey area or by both of these occurring. There is no known reason why this should happen in a two year cycle however.

Significant differences in mean crab sizes between sites were identified. During the October 1995 survey the South East Douglas site had a significantly smaller mean crab size than Peel, Chickens, 10 Miles South of Port St. Mary and Bradda Inshore and Bradda Offshore. During the June 1996 survey, Laxey had a significantly smaller mean crab size than Targets, Bradda Inshore and Bradda Offshore. The October 1996 survey gave significantly smaller mean crab sizes at South East Douglas and Laxey compared with Bradda Offshore and Chickens. The results suggest that sites off the east coast of the Isle of Man have crab populations with smaller mean sizes than sites to the south and west of the Isle of Man. Again, a higher level of replication would help to clarify these differences. Viewed in isolation this information might suggest that sites to the east of the Isle of Man may be more suitable for re-seeding trials.

Significant within-site differences in mean crab sizes were identified from the October 1995 to October 1996 surveys. Most sites showed steady increases in crab sizes with time although one (South East Douglas) was not statistically significant. Sites where significant increases with time occurred were: Bradda Offshore, Bradda Inshore, Targets and Chickens. Only Laxey suggested no change at all. These data reflect the more structured growth patterns of the edible crab compared with the starfish where regular growth patterns were impossible to detect. Crabs are known to show regular, yearly increments in growth (Edwards, 1979) with growth following a relatively predictable curve throughout the life of each crab. The parameters involved in this growth curve will obviously depend upon environmental parameters such as temperature, food supply and genetic factors. Starfish, on the other hand, are know to exhibit unpredictable growth patterns (Smith, 1940) with growth dependent upon the abundance and type of food available. Starfish have been observed to stop growing for long periods (several months) under starvation conditions. Growth is resumed once food becomes available leading to erratic growth curves. These patterns of growth mean that surveying crab populations in potential re-seeding area will be useful in predicting future trends in crab size at that site assuming that the population of crabs does not migrate elsewhere. Starfish, with their less predictable growth patterns, will not lend themselves easily to simple survey methods in order to predict future trends in starfish size.

Consequently, given the preliminary results of predator clearance experiments in chapter 4, it is considered that removal of starfish from trial re-seeding sites maybe the only way to significantly reduce starfish predation. Alternatively a site should be chosen which has a very low natural density of starfish

Analysis of the crab densities at the Bradda Inshore and Bradda Offshore sites showed significant differences between both dates and sites, and a significant interaction between these two factors. The differences in mean relative crab densities between dates was greater than that between the two sites. June mean relative crab densities were less than those in October, while the June figures showed little difference between Bradda Inshore and Bradda Offshore sites and the October figures showed greater difference, with the Bradda Inshore site having a lower mean relative crab density than the Bradda Offshore site. This probably results from the offshore migration of female crabs in the autumn to areas beyond the Bradda Offshore site. The October surveys must coincide with the time when the crabs have left the Inshore site and are moving out through the Bradda Offshore site towards soft muddy areas beyond. The reduced difference between sites during the June surveys probably results from the Bradda Inshore and Bradda Offshore sites being well inshore of the muddy, offshore beds where the female crabs go to brood their eggs. The crabs thus appear to spread themselves evenly between the two sites surveyed during spring and summer resulting in little difference in estimated relative densities. The lower relative densities observed in June, compared with October surveys suggest that the inshore migration of crabs is still occurring during June.

The plots of mean relative crab densities for the June surveys show that in 1994 the Bradda Offshore site had a higher density than the Bradda Inshore site, while this situation was reversed in both June 1995 and 1996. This may indicate that the inshore migration occurred later in 1994 than in the two subsequent years. This was checked against temperature records for these years and it was found that every month during 1994 gave consistently lower seawater temperatures than the corresponding months in 1995 (Fig. 2.40 in Chapter 2). If the migratory behaviour of *Cancer pagurus* is in some way mediated, or affected to some degree by, environmental temperature then this could explain the observed differences in crab densities from year to year between the Bradda Inshore and Bradda Offshore sites. Similar plots for the October surveys show the Bradda Offshore site having a consistently higher mean relative density of crabs than the Bradda Inshore site and that the difference between sites is greatest in October 1993.

When all sites were analysed, relative crab densities were significantly higher at the inshore south west grounds (Peel, Bradda Inshore and Bradda Offshore) than at the north, east and offshore south grounds (10 and 20 Miles South of Port St. Mary, South East and East Douglas, Point of Ayre, Ramsey, Laxey and Targets). The starfish data suggested that some of the sites found to have high crab densities might be suitable for scallop re-seeding trials. This would probably mean having to time the re-seeding to occur after the offshore migration of the female crabs. This would also have the advantage of coinciding with lower activity levels of any crabs remaining inshore in the colder, winter months.

Within-site differences in crab densities were not generally statistically significant. Where differences were identified the relative densities were generally highest in the October surveys. Many of the sites where no significant differences were identified had extremely low populations of crabs anyway so differences would be very difficult to identify. Greater levels of replication would be needed to clarify any differences. It would probably be best to cover a few selected sites in more detail than to carry out smaller surveys at many sites for this type of study.

The video survey data showed that there were no significant differences in crab density between the Bradda Head and Exclusion Zone survey sites. There was, however, a significant difference in starfish density between these two sites, using this survey method, with the Exclusion Zone having a much lower mean density of starfish. This could possibly be attributable to dredge disturbance effects. In this case the churning effect of scallop dredges on the seabed might attract starfish to the Bradda Head site, whereas the less disturbed Exclusion Zone might be less attractive to starfish. Crabs are also known to range fairly widely during foraging activity and therefore are more likely to be evenly distributed between two relatively close areas experiencing different levels of dredging. Starfish are much slower moving and are therefore more likely to be affected by dredging activity. To some extent the fact that starfish occur at higher density in a dredged, compared to an undredged, area is unexpected since dredging can damage or remove starfish predators. However, if the starfish are hardy enough to survive dredging (the by-catch is generally returned to the sea) and dredging itself attracted more starfish into an area, then this might lead to an increase in starfish density. Dredging may also expose a greater percentage of food resources to starfish because benthic invertebrates are disturbed and damaged making them more vulnerable to both detection and attack. Collie et al. (1997) found that sites disturbed by fishing gear were dominated by hard shelled molluscs, scavenging crabs and echinoderms. Other studies have shown that disturbance by fishing gear does not necessarily cause predator aggregation but does lead to an increase in the proportion of predators feeding in the disturbed area (Ramsey et al., 1998). Disturbance by fishing gear has also been shown to affect the ability of otherwise undamaged molluscs (whelks) to perform escape responses when confronted by a predator (Ramsey & Kaiser, 1998). The combined effects of increased predator activity and impaired prey escape response could lead to high prey mortality rates without predator aggregation occurring. This leads to the conclusion that re-seeding should take place in areas which are, at least initially, closed to fishing in order for the re-seeded scallops to become established. Between site variability in the effects of fishing gear on the seabed have been identified (Ramsey et al., 1998). This implies that each site which is being considered for re-seeding would have to be assessed individually for the potential effects of fishing activity if the site were not closed to fishing.

Estimation of dredge efficiency in terms of predator species was estimated using video surveys taken at similar times to dredge surveys. Estimated efficiency for crabs was between 3.9% and 26.1% and for starfish between 16.3% and 24.9%. These data compare with estimates of dredge efficiency for scallops (Chapman et al., 1977) of between 13.4 and 14% overall using spring loaded dredges of a similar design to those used in the present study. McLoughlin et al. (1991) and Dolmer et al. (1999) calculated estimated dredge efficiencies for scallops and mussels of 11.6% and 17% respectively. This indicates that dredges have a similar, low and variable efficiency in collecting non-target species as well as target species. Obviously, given the circumstances of the comparisons made in the current study, these are only very approximate estimates as the surveys took place at only approximately similar times and at approximately similar sites. Given greater resources, perfect sampling conditions and more manpower a more accurate estimate could be made using specified survey areas which could be intensively surveyed by video and divers after which a dredge survey could be immediately carried out.

The results of the diver surveys suggest that the only species showing a significant difference over different sampling periods was the starfish. Diver surveys taken in autumn 1994 gave a significantly lower mean density of starfish than surveys taken in summer 1996. This may indicate an increase in density over time from 1994 to 1996 or it could indicate that starfish density increases in summer compared with spring and autumn. Unfortunately, the limited number of suitably qualified research divers, weather and constraints on boat time often precluded diver surveys which led to the low number of surveys carried out.

Comparison of diver surveys with dredge surveys were also used to estimate dredge efficiency in terms of predator species and scallops. Estimated dredge efficiency varied between 4.5% and 9.8% for crabs and between 48.5% and 79.4% for starfish with one set of dredge surveys yielding a higher estimated mean density than the corresponding diver survey. This illustrates the need for caution in interpreting these estimates. This latter point is backed up by the unrealistically high estimates of dredge efficiency for scallops of between 38.3% and 76.3%. Although the figures for crabs were the most consistent it must be remembered that diver surveys can only cover relatively small areas of seabed compared with dredges and that species distribution will undoubtedly be patchy (Pennington, 1996). This will lead to the discrepancies observed when comparing two very different survey methods. The video survey method is, by its nature, more likely to yield comparable results given the large areas that can be surveyed and the linear nature of the survey method. In the current study comparisons were made between sites using the same methods at each site and it is recognised that the data provide only relative estimates of density from site to site. If one is interested in absolute estimates of species density then one must consider both dredge efficiency and species distribution on the seabed when calculating overall species densities for particular areas. Estimates of dredge efficiency are available from published literature (Chapman, 1977; McLoughlin et al., 1991; Dolmer et al., 1999) and Pennigton (1996) suggests a model which may be useful in quantifying survey data from patchily distributed species.

3.4.1 Conclusions.

Higher densities of crabs have been found at inshore and south west sites compared with offshore and north east sites. Mean crab sizes are smaller at the eastern sites compared with the western sites. Therefore, generally speaking, there were more larger crabs at sites to the south and west of the Isle of Man and fewer, smaller crabs to the east and north of the Isle of Man.

Starfish occurred throughout the surveyed sites at much higher densities than crabs. Higher densities of starfish were found at the northern end of the Island but generally there was far less variability between sites compared with the crab data. Lower densities of starfish were found to the south and east of the Island and at offshore sites - Bradda Offshore, 10 and 20 Miles South of Port St. Mary - than at inshore sites. Mean starfish sizes were greater at sites to the east of the Isle of Man than to the west.

In terms of the best sites for re-seeding juvenile scallops these results appear to be conflicting since the best site for reduced crab predation (lowest sizes and densities of crabs at eastern and northern sites) will not generally be the best site for reduced starfish predation (lower densities and sizes of starfish at the southern and offshore sites). However, one cannot gain a complete picture of the predation risk to re-seeded scallops from such data viewed in isolation. One also has to consider the behavioural aspects of predator species. Crab migrations and reduced activity during the colder months will play a key role in the timing of re-seeding activity. Since starfish densities do not appear to be as variable as crab densities, and are much higher, it would seem sensible to attempt re-seeding at sites where starfish sizes and numbers are lowest at a time when the threat from crabs is lowest. Starfish are likely to pose the greatest threat to re-seeded and naturally occurring juvenile scallops as they occur in far greater numbers than crabs and they are not reduced in number by a fishery as crabs are. There is also the problem of starfish winter feeding peaks which would be best avoided. There is also the possibility of predator aggregation to consider. Sufficiently high densities of juvenile shellfish are known to attract predator species. These behavioural aspects were discussed in greater detail with regard to seasonal patterns in predation obtained from tethered scallop experiments in Chapter 2.

Video surveys revealed no differences in crab densities between the Bradda Head and Exclusion Zone sites but did show greater numbers of starfish at the Bradda Head site which was exposed to dredging. Diver surveys showed that there may be a pattern in starfish densities with time through the year but more surveys would have to be made to confirm this.

Some estimates of dredge efficiency have been made by comparing different survey results with dredge surveys. It is considered that video surveys provide the most reliable comparison in this context given the large area surveyed and the linear, transect style nature of the survey method which is more similar to a dredge survey than is a diver survey. It would be better to use a colour camera system with artificial lighting in order to collect data on scallop densities since the black and white system used in the current study was unable to reliably identify scallops.

Chapter 4 - Predator Aggregation and Laboratory Work.

4.1 Introduction.

The first part of Chapter 4 assesses whether the tethered scallop experiments, detailed in Chapter 2, could attract or aggregate predators, thus yielding artificially high predation mortality rates. The tethering experiments themselves constitute a relatively high density patch of prey and previous work (Pyke et al., 1977; Hughes, 1980; Wilson, 1994) suggests that such high density patches will tend to aggregate predators until a point is reached where the experiment or patch achieves a density of prey equal to that of the natural surroundings. Prey are thus 'depressed' by predator activity until such time as the likelihood of encountering prey equals that of the surrounding area. At this point the predators should disaggregate (Charnov et al., 1976). This is known as the marginal value theorem (Pyke et al., 1977). Predator aggregation will thus be an important consideration when planning seabed reseeding trials and the correct seeding density, which will minimise the risk of predator aggregation and increased mortality due to predation, will have to be determined. The ability of scallops to recess in the seabed was also investigated as this is one of the methods that scallops employ to avoid predation.

Predator aggregation was also investigated using a static, time lapse video system mounted in a frame situated on the seabed in the Exclusion Zone. Surveys of this type have shown variations in activity patterns of crabs (Nickell & Sayer, 1998) using hourly frequency of occurence analysis. This type of survey will also be useful in determining which predators are most active in the area where the tethering experiments (Chapter 2) were carried out (Nickell & Sayer, 1998; Burrows et al., 1999), and in determining the activity patterns of those predators.

The second part of Chapter 4 to investigates the interactions of predator size and prey size for scallops (*Pecten maximus*) and their main predators (*Cancer pagurus* and *Asterias rubens*). These experiments were carried out in aquarium tanks in the hatchery area of PEML. Only preliminary investigations were made but the basis of the experiments with *Asterias rubens* follow, approximately, those of Lake et al. (1987) in their investigation of different size classes of crab feeding on different size classes of scallop. The experiments with *Cancer pagurus* were basically designed to illustrate the type of damage inflicted upon scallop shells by this predator, the predator size/prey size interaction already having been investigated by Lake et al. (1987). Experiments to illustrate any differences between tethered and untethered scallops in terms of predator success rates were also carried out for both predators.

The octopus *Eledone cirrhosa* has also been cited as a predator of bivalve molluscs among (Ambrose, 1986) and, as such, could present a threat to seabed re-seeded, juvenile scallops. Although difficult to work with under laboratory conditions some feeding trials with this predator were carried out, primarily to determine the type of shell damage inflicted and to determine possible size ranges of prey available to this species.

The third and final part of this Chapter 4 to investigates whether the tethering method used and described in Chapter 1 has a significant effect upon the ability of scallops to escape attacks by predators. These experiments were carried out in tanks in the hatchery area of PEML. Work carried out by Barbeau & Scheibling (1994b) and by Zimmer-Faust et al. (1994) suggest that tethering will have little effect where mobile, sight-oriented predators are concerned - predation rate will equal encounter rate. However, if non-visual, chemosensory predators are present, the scallop will be unable to escape the area over which prey detection and capture can occur and this may lead to higher than expected predation rates for this type of predator. This section attempts to investigate this theory by using tethered and untethered scallops in large experimental tanks using different types of predator.

The aims of the field work described in this chapter are firstly to determine if the tethering methods used in this study caused any significant predator aggregation since the tethering experiments each represent a higher than normal density of scallops compared to the surrounding seabed. Secondly, the static seabed video camera was used to determine predator activity patterns on a diurnal/nocturnal basis and to determine the foraging strategies of predator species. Diver surveys carried out around the static video camera were used to determine whether these experiments caused predator aggregation.

The aims of the laboratory work described in this chapter are firstly to determine the degree of interaction between scallop size, predator size and the ability of predators to consume scallops. Secondly, laboratory experiments were employed to investigate the potential effect of tethering upon predation rates which would help to determine how accurate a representation the tethering experiments are of the natural scallop/predator interaction on the seabed.

4.2 Materials and Methods.

4.2.1 Predator aggregation experiments.

4.2.1.1 Location and dates of predator aggregation experiments.

The tethering experiments described constituted relatively high density patches of prey compared to the area surrounding the experiments. This could potentially result in predator aggregation and subsequent disaggregation according to the marginal value theorem (Pyke et al., 1977). A preliminary investigation of this theory was carried out using further tethering experiments with daily monitoring by divers. Lines of tethered animals were deployed at a site on the northern edge of Port Erin Bay at 54 05.71N, 04 46.35W (Fig. 4.1) on 23/8/94, 6/9/94, 26/9/94 and 14/10/94.

4.2.1.2 Experimental methods.

Tethering systems identical to those described in Chapter 1 were used, the set up and deployment methods being described in that chapter. One size class of scallop was used with a mean size of 77.68 ± 0.42mm shell length (mean ± s.e.). Two tethering systems were deployed at a time, at the experimental site on the dates indicated, to minimise survey times so that access to the research vessel was not limiting. These systems were monitored by divers at daily intervals for a period of two weeks, or as often as the weather allowed. Once the systems had been deployed for two weeks they were retrieved and the next set deployed. Four sets of two lines were deployed on the dates indicated but those deployed on the 26/9/94 could not be monitored because of poor weather conditions.

4.2.1.3 Estimating natural densities of predators at the experimental site.

Background densities of predators and scallops were estimated by making diver survey transects identical to those described in Chapter 3. These surveys were performed at the same site as the predator aggregation experiments on three occasions, two prior to and one after the deployment of the experiments.

A concrete sinker was deployed from which two divers began the survey using a reel of line 50m long in the middle of a 4m pole which were used to gauge the length and width of the transect respectively. The free end of the 50m transect line was clipped to the sinker and the line reeled out keeping the pole perpendicular to the direction of travel. Presence of predators, naturally occurring scallops and crab pits were noted by each diver for his/her side of the survey pole over the 50m transect. Upon completion of a transect the divers returned to the sinker and began another survey at an angle of 120° to the direction of the first survey. This process was repeated until three surveys had been completed, each at an angle of 120° to one another and each covering 200m^2. The direction of each survey was noted. These surveys covered an area of 600m^2 each and 1800m^2 in total.

4.2.1.4 Monitoring experiments with divers.

During the monitoring dives the length of each system was swum by two divers and the state of each scallop along the lines noted, including whether each animal had recessed into the substrate or not. A visual survey was made, by each diver, to a distance of 2m either side of the ground line to which the scallops were tethered. This covered an area of approximately

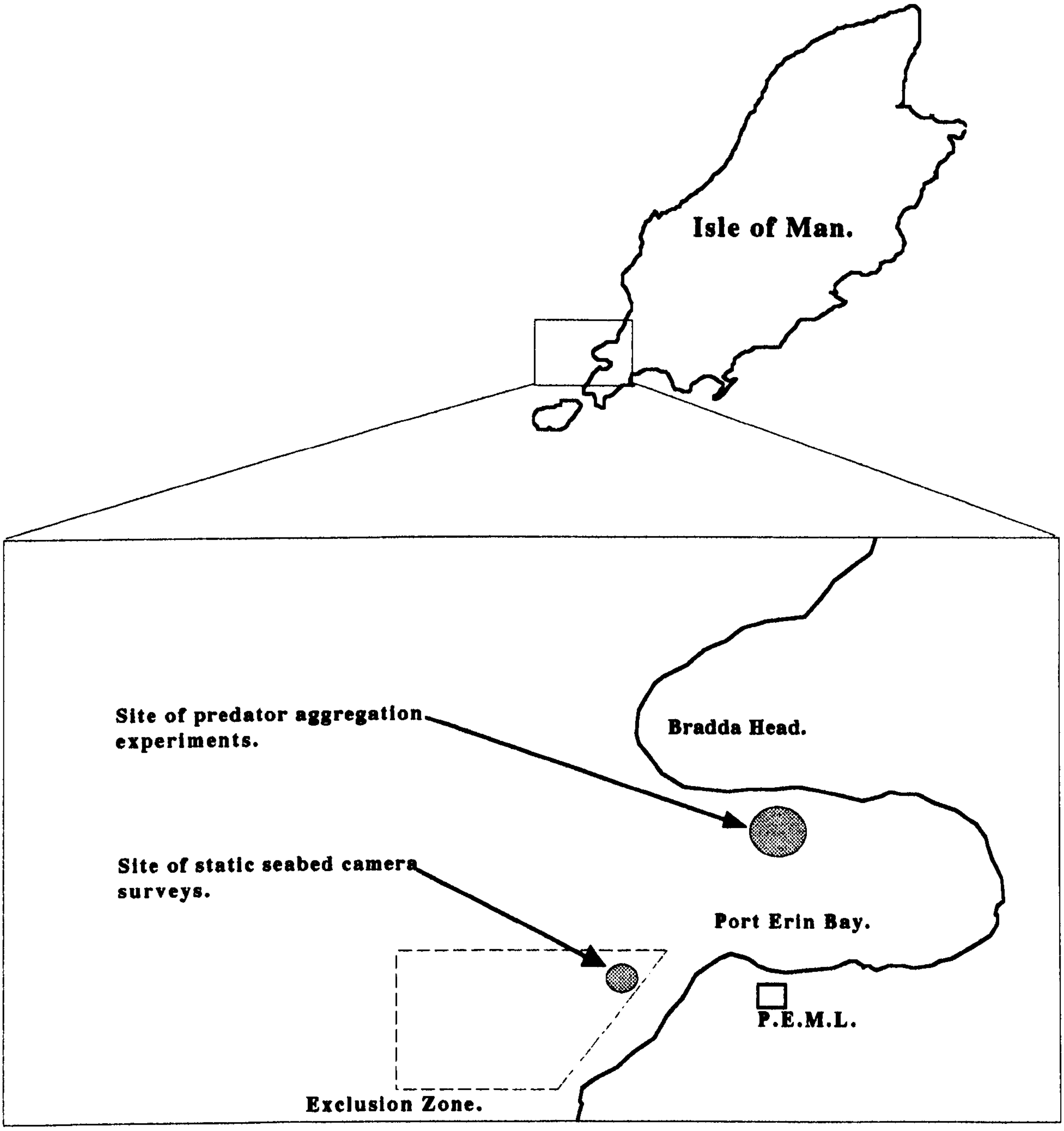


Figure 4.1.
Diagrammatic representation of the locations of the predator aggregation experimental sites.

148m^2. Presence of predators such as crabs (*Cancer pagurus*) and starfish (*Asterias rubens*) were noted, plus any naturally occurring scallops. Occurrences of crab pits were also noted as possible evidence of crab activity. The water temperature and depth were recorded for each dive plus any other points of interest, such as prey escape responses while tethered. The results of these diver surveys were used to calculate day to day variations in predation rate, predator aggregation, if it occurred, and how long the scallops took to recess in the substrate.

4.2.1.5 Predator densities around the aggregation experiments.

Each individual line of tethered animals was employed as a replicate for calculating mean densities of predators around the tethered scallops for each day after deployment. The unpredictability of the weather meant that monitoring could not be carried out every day after deployment for every experiment. Consequently, each day was not replicated to the same extent. The actual numbers of replicates obtained for each day following deployment are summarised in table 4.0 below.

Density estimates were calculated by taking the number of predators or crab pits observed along a line of tethered scallops and dividing that number by the area surveyed by the divers = 148m^2. The values obtained were then used to calculate means for each day after deployment using the numbers of replicates for each day surveyed as indicated above.

4.2.1.6 Statistical methods applied to the predator aggregation data.

The grouped means of estimated densities for crabs, starfish and crab pits for each day surveyed after deployment were checked for normality using the Nscores function of Minitab 8.1 (Wilson, 1994). This function calculates a normal score for each data point based on all the other data points in the dataset one is testing for normality. These normal scores are then correlated with the original dataset which produces a correlation coefficient. This coefficient is then compared with tabulated values which vary with the number of data points in the dataset. If the calculated correlation coefficient exceeds the tabulated value then the dataset is not normally distributed and parametric tests may not be applicable.

The diver surveys carried out when no tethered animals were deployed were used to calculate normal or background densities of each predator type. The daily monitoring dives on the aggregation experiments were used to calculate means of predator densities for starfish and crabs for each day monitored. The means calculated for each day were grouped, then tested

Table 4.0

Summary of the number of days surveyed after deployment of each predator aggregation experiment. (x) marks where a survey was carries out and (-) marks where surveys could not be carried out for each experiment.

Experiment starting on 23/8/94	Experiment starting on 6/9/94	Experiment starting on 26/9/94	Experiment starting on 14/10/94	Days After Deployment	N
x	x	-	-	1	4
-	-	-	x	3	2
-	x	-	x	5	4
-	x	-	-	6	2
x	x	-	x	7	6
x	x	-	-	8	4
x	x	-	-	9	4
-	x	-	-	14	2
-	x	-	-	15	2
x*	x	-	-	16	2
-	-	x*	-	21	

(*) indicates where predation level was measured upon retrieval of the experiment - no diver survey was carried out.

(N) represents final number of replicates employed in calculating mean predator densities for each day (two lines per experimental deployment).

using the one sample t test function of Minitab 8.1 against the background mean calculated from the diving surveys using the null hypothesis:

H_O: $\mu_a \leq \mu_b$ and the alternative hypothesis H_O: $\mu_a > \mu_b$.

where μ_a = the mean predator density around the aggregation experiments.
μ_b = the mean predator density encountered naturally (background density).

This process was carried out for starfish, crabs and crab pits in turn to assess whether the densities estimated around the aggregation experiments were any different from natural, background levels at the experimental site.

4.2.1.7 Calculating day to day differences in predation rates.

The diver surveys provided information about the number of scallops eaten by the same assumed predator types as for the main tethering experiment over 1-2 day periods. Predation rates were calculated for each assumed predator type simply by dividing the number of scallops eaten by the number of days over which those scallops were eaten.

4.2.1.8 Calculating relative rates and levels of recessing.

Diver surveys of the experiments provided data on recessing of the scallops into the sediment. The 23/8/94 experiment did not yield any data on scallop recessing as the experimental lines landed on a stony patch of seabed. Each scallop on each line was assessed, in terms of recession, during the diver surveys. By determining when each scallop became recessed after deployment and by noting when scallops became unrecessed and then recessed again, a mean time for scallops of this size to recess in this sediment type could be calculated with the minimum observable time to recess being determined by the time between surveys. Data from both of the usable surveys were pooled to produce a plot of mean number of scallops recessed (as a proportion of the total number surviving) for each day after deployment.

The absolute number of recessed scallops observed during each monitoring dive were used to calculate ratios of recessed scallops to total surviving scallops for each survey day. These values were then used to calculate mean ratios of recessed to surviving scallops for each of the two experimental periods used. The series of ratios obtained from each experiment were then plotted against survey day. The data from both surveys were then combined, where survey days for both coincided, to obtain total mean ratios (n = 4 for days 3, 5 and 7 and n = 2 for the remainder). These data were plotted against survey day.

4.2.2 Seabed video camera - predator aggregation and behaviour.

This set of experiments involved setting up a frame on the seabed in which was housed a colour video camera and a pair of lights. A cable providing power to the camera and lights was run from PEML out to the camera on the seabed. This cable also brought back the video signal which was recorded on a time lapse video recorder. Experiments were placed in front of the camera and monitored over a number of days to determine predator activity in the area of the experiment. Initially, the cable was run from PEML to the edge of a gully in the nearby coast. A steel pipe was bolted to the rocks in the gully and the video cable run through this pipe to beneath the intertidal zone. This meant that wave action would not damage the cable where it would be most vulnerable. Next the R.V. *Sula* was used to pull the end of the cable out to sea and into the Exclusion Zone. The end of the cable was buoyed so that it could be found later. Finally, a frame and video camera were taken out to sea, again using the RV Sula, to the buoy on the end of the video cable. Here the frame was taken to the seabed by divers and securely anchored using large sinker weights made from concrete filled tyres. The camera was then hooked up to the video cable making the setup complete.

Diver surveys were carried out at the beginning and end of each experiment to determine whether any changes in density or distribution of predators had occurred. The diver surveys involved descending to the camera on the seabed with a reel of line which was knotted at 3m, 6m and 9m intervals. One diver remained at the frame/camera assembly while the second diver reeled out 3m of line and performed a circular sweep noting the numbers of predators and naturally occurring scallops. Once complete, the next 3m of line was reeled out and a second sweep performed, this time surveying between 3m and 6m from the camera. Once completed a final sweep was made to survey 6m to 9m from the camera. Start and finish points for each sweep were determined by the diver using compass bearings. Fig. 4.2 gives a diagrammatic representation of this survey process and shows the areas surveyed for each 360 degree sweep. Predator densities were calculated for each 3m wide zone around the camera both before and after each experiment was run. These results were used to determine if the experiments caused any change in the distribution of predators within the areas surveyed.

Experiments consisted of tethering either two or four scallops in the field of view of the camera, using the same tethering technique described in Chapter 1. The differences here were that the tethers were much shorter (typically 4-6cm) and that the scallops were tethered to alloy pegs driven into the seabed. The tethers were designed to maintain the scallops within the field of view of the camera so that reasons for mortality could be determined from the video footage. This type of experimental setup was of use to other researchers at PEML so constraints were placed on the number and timing of these experiments. This meant that

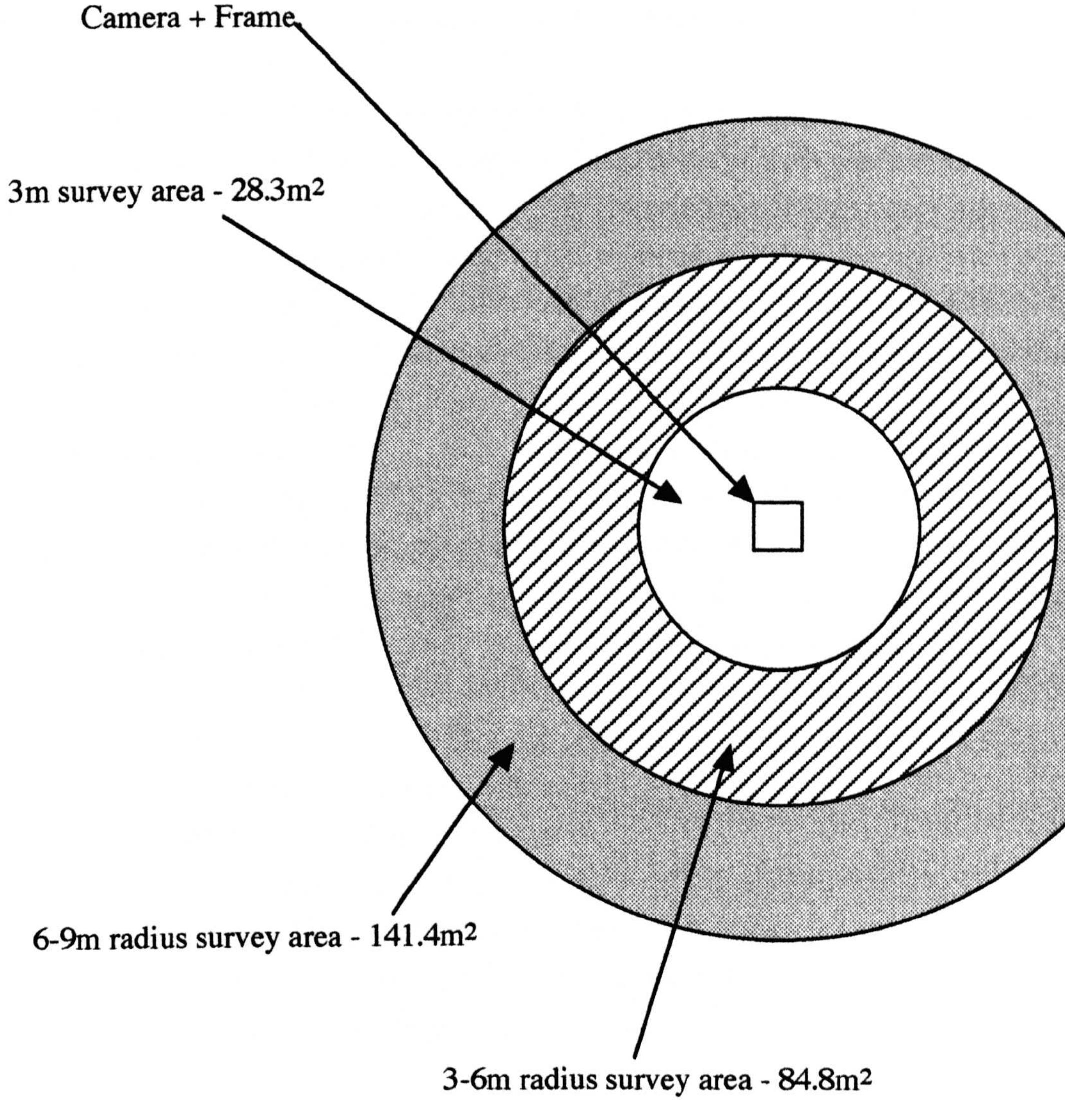


Fig 4.2.
Diver survey areas around the static video camera experiment.

only a limited amount of time was available for theses experiments. Consequently no effective replication could be carried out to determine differences in predator densities or levels of prey mortality between two and four scallop experiments. Diver surveys could not be replicated since this would require more than one identical camera setup. Consequently only qualitative observations could be made using these methods during the present study.

All experiments were carried out during 1996. From 4 September to 6 September two scallops were deployed in front of the camera. Diver surveys were carried out as described above, before and after this experiment. On 7 September four scallops were placed in front of the camera with the experiment finishing on 9 September. Diver surveys were carried out before and after this experiment. On 13 September four scallops were placed in front of the camera and the experiment concluded on 16 September. Diver surveys were carried out before and after. On 19 September as many predators as possible were cleared from the immediate vicinity of the camera to assess whether predator clearance might affect the survival of tethered scallops. After predators were cleared to a distance of approximately 15m radius, four scallops were placed in front of the camera for three days. On 10 October four scallops were placed in front of the camera for three days. Estimated densities of predators for each diver survey band around the camera were plotted against survey date.

Experiments run were:

1 4/9/96 - 6/9/96 (two scallop experiment)
2 7/9/96 - 9/9/96 (four scallop experiment)
3 9/9/96 - 11/9/96 (four scallop experiment)
4 13/9/96 - 16/9/96 (four scallop experiment)
5 19/9/96 Predator clearance (four scallop experiment)
6 10/10/96 - 13/10/96 (four scallop experiment)

Diver surveys carried out were:

1 Pre 4/9/96 experiment
2 Post 4/9/96 and pre 6/9/96 experiment
3 Pre 13/9/96 experiment
4 19/9/96 post 13/9/96 experiment
5 13/10/96 post 10/10/96 experiment

The static seabed video camera was also used to estimate predator activity over several days for both main predator types. This was carried out by counting the total number of predators entering the camera field of view during each hour of each day surveyed. The number of predators entering the field of view were then plotted against hour of the day using midnight as zero. Each day was treated separately although the continuous nature of the recordings

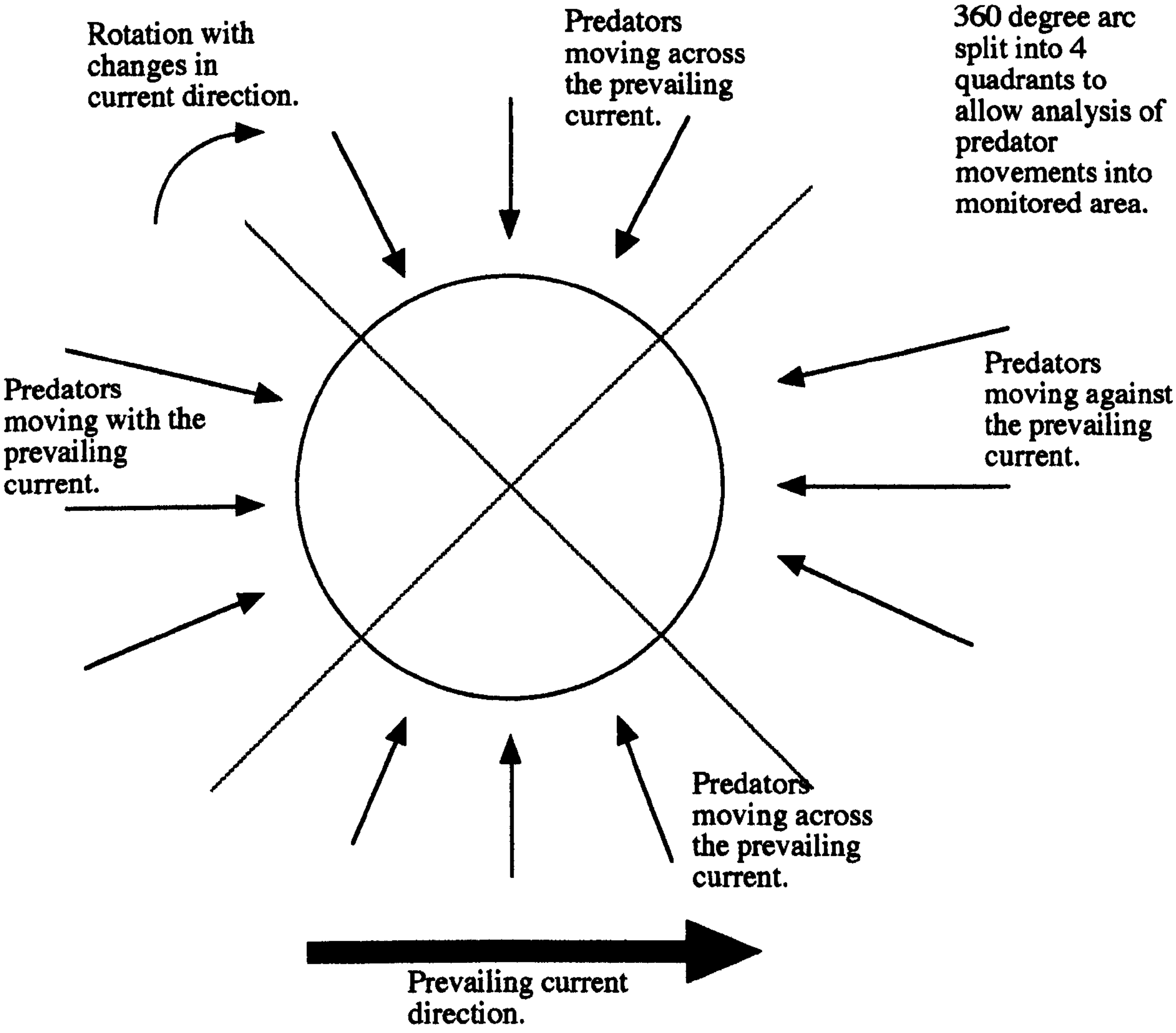


Figure 4.3
Diagrammatic representation of the categories of predator movement in releation to prevailing current direction used during the analysis of the static seabed video data. This diagram clearly shows that, if predators move in random patterns across the seabed, twice as many would be expected to enter the field of view of the camera from cross current than from either upstream or downstream.

(carried out over 48 or 72 hours) meant that results for each day cannot be considered to be truly independent. For this reason the results are merely observational and cannot be tested for statistical significance.

The direction of travel of predators, particularly starfish, in relation to local current direction is also of interest. Starfish have been shown to travel mainly across current or against tidal currents as this gives them the best chance of detecting prey by sensing chemical signals emitted by prey (Rochette et al., 1994). This theory was tested by counting how many starfish entered the field of view from downstream, upstream and across stream for each day surveyed. Current direction was determined by observing the orientation of shoals of fish in the camera field of view - fish tend to swim into the current. The monitored area was split into four quadrants (90 degrees each) in order to assess directions of predator movements into the field of view (Fig. 4.3). The orientation of these quadrants varied with current direction and were assessed by eye. Fig. 4.3 shows that, if predators move in a random manner across the seabed, they will be twice as likely to enter the field of view across the prevailing current direction than from either upstream or downstream directions. Therefore, if predator movements are random, cross current entry into the field of view should be greater than entry from upstream or downstream. If this does not prove to be the case then this would indicate that the predator concerned is not moving in a random manner in relation to current direction.

4.2.3 Laboratory Work - Materials and Methods.

4.2.3.1 The effect of predator and prey sizes on predation rate.

Four aquarium tanks were used during the course of this experiment. Each tank had dimensions of 65cm length, 33cm width and 37cm depth. Each set of experiments (four tanks) lasted for approximately two weeks. Clean, abiotic builders sand was placed in each tank to a depth of about 1-2cm. The tanks were filled and continually supplied with unfiltered seawater at a mean flow rate of 1.3 litres min^{-1}. Each tank was aerated by a single tube connected to a pumped air supply and terminated with an aeration block. The tanks were emptied of water and new seawater allowed to fill them at the beginning and end of each experimental period and at 4-5 day intervals during the experimental periods to ensure that stagnation did not occur. Starfish were obtained by dredging in Laxey Bay using scallop and queen dredge gear of the same specifications as those used for the dredge surveys described in Chapter 3. Only undamaged, healthy individuals were used for feeding experiments.

Three starfish of a similar size were placed in each of the four tanks and left for one week without food. Different size classes were placed in each of the tanks with the size classes used ranging from 80 to 150mm maximum arm length in 10mm increments.

Five scallops were then introduced into each of the tanks, one size class per tank but with different size classes of scallop placed in each tank. The scallops were not tethered but they were drilled and the same wire loops fitted as those used in the main tethering experiment described in Chapter 1. This was to examine whether or not the scallops could exhibit a normal escape response with the wire fitted in this manner. The tanks were then monitored daily over the next fourteen days. Numbers of scallops eaten per day were noted each morning for each tank during the monitoring period. Scallops were replaced as they were eaten and any damage inflicted upon the shell and whether the shell was still articulated or not was noted. This gave an indication of the validity of the assumption that undamaged shells retrieved during the main tethering experiment were attributable to starfish predation.

Once the monitoring period was complete the starfish and scallops were removed and a new set of starfish placed in the tanks, again with one size class per tank. These animals were again left for one week and then scallops introduced. Monitoring and prey replacement then continued for fourteen days. In some cases very few scallops of a particular size class were available. Where this was the situation three scallops at a time were introduced into the experimental tanks and the experiments run for as long as was practicable.

Once each experiment was completed the daily and overall (two week) means of predation rate were calculated. Daily consumption rates were calculated by dividing the number of scallops eaten on that day by the number of predators. Overall predation rates were calculated by taking the total number of scallops eaten over the two week period and dividing that figure by the number of days (14) and by the number of predators (3) to obtain an overall predation rate in terms of scallops eaten per day per predator over each two week experimental period.

Individual daily rates of predation were plotted with time to determine if any pattern emerged from the data or if there were any noticeable differences between experimental regimes. Overall predation rates for each predator size class/prey size class interaction were used to make a 3D plot of predator size against prey size (X_1 and X_2) against overall predation rate per predator per day (Y). This plot was then used to assess at what prey size class, if any, the prey achieves a size refuge from the different size classes of *Asterias rubens* employed (Lake et al., 1987). These experiments were carried out in such a way as to cover as many predator and prey sizes as possible. This was designed as a preliminary study and time did not allow for replication of experiments to be carried out. The main aim of this experiment was to demonstrate the feasibility or otherwise of such an experiment before carrying out a more detailed study.

The same aquarium tanks were used for the experiments involving *Cancer pagurus* as those described above. The only difference being that they had to be blacked out since feeding behaviour in *Cancer pagurus* is known to be inhibited by light (Whittington, 1993). This was achieved using black plastic sheeting made from heavy duty plastic dustbin liners cut to size and placed around the aquarium tanks. One crab was placed in each tank and left for 24 hours. Crab of 150mm carapace width were used to reflect the mean size identified in the local, inshore crab population during the dredging surveys. In darkness, five 65mm shell length scallops were introduced into the tanks. The tanks were then left for five days and then checked for signs of damage to the scallops. This gave an indication of the validity of the assumption that damaged or crushed shells and single valves retrieved during the main tethering experiment were attributable to crab predation. Five experiments of this type were run in total. Different sizes of crab were not used in these experiments because this type of comparison had been carried out already by Lake et al. (1987) and because crabs proved extremely difficult to work with under laboratory conditions.

4.2.3.2 The effects of tethering on the likelihood of predation.

Three 150cm x 150cm x 20cm plastic tanks were filled to a depth of 4-5cm with clean builders sand. A crab or starfish was placed in each of two of these tanks, depending upon the experimental regime being undertaken. The third tank contained no predator to act as a control to assess normal scallop mortality under experimental conditions. During each experiment the two predators were left in the tanks for 24h after which time four tethered or untethered scallops were introduced, again depending on the experiment being carried out. In the case of tethered scallops one animal was placed in each corner on a 75cm tether of the same design as used in the field tethering experiments. Untethered scallops were placed in the same positions as tethered animals were but were subsequently free to move within the tank. Once the scallops were placed in the three tanks they were monitored for tether damage and predation every day for two weeks. Animals that were eaten were replaced. The same sizes of predators and prey were used throughout.

Since only three tanks were available, replicates had to be carried out in sequence with the crab experiments taking place in the summer months and starfish in the winter months to coincide with peak feeding times suggested by the literature and experimental results. Each replicate consisted of one control tank, one tank containing tethered scallops and one tank containing untethered scallops.

Over each three week period an average feeding rate per predator per day was calculated and the replicates used to obtain mean feeding rates for the tethered and untethered scallops for each predator. Treating each predator separately the tethered and untethered scallop data were then analysed using a t-test to determine whether the mean feeding rate on tethered scallops was significantly different from the feeding rate upon untethered scallops. The ability of tethered and untethered scallops to recess into the sediment in the tanks was also tested. This was achieved by counting the number of days during each experiment where one or more scallops in each tank were observed to be recessed.

4.2.3.3 Assessing the prey size capabilities of *Asterias rubens.*

It had been noted during the predator size/prey size tank experiments that several starfish were capable of attacking and consuming the same large scallop. This behaviour was also observed during the static video camera experiments and on dives made by the author. It was therefore decided to test whether prey size refuge could potentially be overcome in this way.

The same four aquarium tanks described in section 4.2.3.1 were used for this experiment. Each experiment consisted of the four aquarium tanks into which were placed three scallops of 85mm shell length and different numbers of starfish of mean arm length 90-100mm. In the first tank there were no starfish, in the second tank one starfish, in the third tank two starfish and in the fourth tank three starfish. Four replicate sets of such experiments were run. Numbers of scallops consumed per day were calculated for each tank during each experimental run. The tank with no predators in acted as a control to determine any natural mortality of scallops under experimental conditions. Results were analysed using single factor ANOVA with predator number as the factor and number of scallops consumed per day as the response variable. Scallops were replaced as they were consumed. Water temperature was also measured within each tank during each experiment.

The null hypothesis used was:

H_{01}: Starfish number has no effect upon the number of scallops consumed per day.

Any significant results were further investigated using a Tukey multiple comparison test. After all experiments, starfish were returned to the sea alive.

4.2.3.4 Assessing predation by the octopus *Eledone cirrhosa.*

A large hatchery tank (1m x 2m x 1.5m) was used for a brief investigation of octopus predation on scallops. Five experiments were carried out using octopus caught during the dredge surveys described in Chapter 3. For each experiment an octopus was placed in the tank and left without food for 24 hours. Five 65mm shell length scallops were then dropped into the tank. Observations were made of how many scallops were consumed over a five day period and of the type of shell damage inflicted on the scallop shells. Scallops were replaced after being consumed. The size of the octopus was impossible to determine accurately without killing the animal. Octopus were chosen to be of a similar size when judged by eye. All octopus were returned to the sea alive, where possible.

The method of capture (by dredging) of octopus is likely to have caused damage and/or stress to the animal which may affect their behaviour and therefore the results obtained.

4.3 Results.

4.3.1 Predator aggregation experiments.

4.3.1.1 Natural densities of predators at the experimental site.

Table 4.1 indicates a mean background density of starfish equal to $0.00056m^{-2}$; a mean background density of crabs equal to $0.0011m^{-2}$ and a mean background density of crab pits equal to $0.00056m^{-2}$. These figures were then used for comparison with identical surveys carried out during monitored tethering experiments.

4.3.1.2 Densities of predators around the aggregation experiments.

Table 4.2 suggests that the mean starfish density around the tethering experiments increases after deployment with some fluctuation. This type of increase would be expected of a relatively slow moving species that has identified a relatively high density patch of prey. The mean density of crabs tends to be more variable which would be expected for a highly mobile species like *Cancer pagurus*.

4.3.1.3 Assessing predator aggregation.

T-tests were used to compare mean predator densities with background densities. The results of these t-tests are summarised in Table 4.3. The null hypothesis used in turn for starfish, crabs and crab pits was :

H_O: $\mu_a \leq \mu_b$ and the alternative hypothesis H_O: $\mu_a > \mu_b$.

where μ_a = the mean predator density around the aggregation experiments.
μ_b = the mean predator density encountered naturally (background density).

Table 4.3 shows that, for starfish and crab pits the null hypothesis of density around aggregation experiments being less then or equal to background densities can be rejected ($p = 0.0078$ and $p = 0.036$ respectively). For crabs the null hypothesis is accepted ($p = 0.42$). Therefore the mean densities of both starfish and of crab pits around tethering experiments are significantly greater than the observed background densities.

Table 4.1.

Summary of the results of the diver surveys made while no aggregation experiments were deployed. Entries represent:- numbers of starfish / numbers of crabs / numbers of crab pits.

Survey.	21/8/94.	22/8/94.	21/10/94.
1	0/1/0	0/1/0	0/0/0
2	0/0/0	0/0/1	0/0/0
3	1/0/0	0/0/0	0/0/0
Area (m^2).	600	600	600

Table 4.2

Summary of the mean estimated densities of starfish and crabs for each diver survey made after deployment of aggregation experiments. All figures in terms of animals m^{-2}.

Day.	Starfish.	Starfish s.e.	Crabs.	Crab s.e.
1	0.0017	0.0017	0.0017	0.0017
3	0.0034	0.0034	0.0000	0.0000
5	0.0000	0.0000	0.0034	0.0020
6	0.0000	0.0000	0.0000	0.0000
7	0.0056	0.0044	0.0011	0.0011
8	0.0034	0.0020	0.0000	0.0000
9	0.0034	0.0020	0.0034	0.0020
14	0.0034	0.0034	0.0000	0.0000
15	0.0000	0.0000	0.0000	0.0000
16	0.0067	0.0000	0.0024	0.0034

Table 4.3

Results of the one sample t-test applied to the grouped daily means of estimated densities compared to the respective background means for starfish, crabs and crab pits.

	N	t	P	Result.
Starfish.	10	2.98	0.0078	Reject Ho
Crabs.	10	0.22	0.42	Accept Ho
Crab pits.	10	2.04	0.036	Reject Ho

4.3.1.4 Predator densities around predator aggregation experiments.

The densities of predator species found by divers around the predator aggregation experiments are summarised in the Figs. 4.4 - 4.5.

4.3.1.5 Day to day differences in predation rates.

The diver surveys provided information about the number of scallops eaten by the same assumed predator types as for the main tethering experiment. The data obtained from the surveys are summarised in Table 4.4.

Table 4.4 suggests that both crab and starfish predation rates increase with time during the course of the tethering experiments. This indicates that either more predators are attracted to the experiments as time progresses or that the predators that are there consume greater numbers of scallops per day with time. The results of section 4.3.1.3 suggest that the former is more likely to be the case. Predators increase in number around the tethering experiments leading to increasing predation rates with time.

4.3.1.6 Calculating relative rates and levels of recessing.

Diver surveys of the experiments provided data on recession of scallops into the sediment. The 23/8/94 experiment did not yield any data on prey recession as the experimental lines landed on a stony patch of seabed and the 26/9/94 experiment was not monitored due to adverse weather.

Rates of recession were calculated for each scallop which demonstrated a cycle of recession and subsequent movement. Scallops which remained unrecessed were also noted as were scallops which recessed, moved and remained unrecessed. Where no definite recession time could be attributed a range or maximum time taken was calculated. Result are summarised in Table 4.5.

Table 4.5 shows that, out of the four experiments surveyed, 9 scallops remained recessed while only five remained unrecessed throughout all surveys. The 6/9/94 experiment shows five scallops recessing after 1 days deployment with one further scallop recessing between 1 and five days after deployment. This gives a total number 11 recessed scallops for this experiment. The 14/10/94 experiment shows 6 scallops recessing between 1 and 2 days after deployment plus a further 6 scallops within 4 days giving a total of 16 recessed scallops for this experiment. Graphs of the numbers of recessed scallops against time are presented in Figs. 4.6 - 4.7. Fig. 4.6 shows that the proportion of surviving scallops that were recessed in

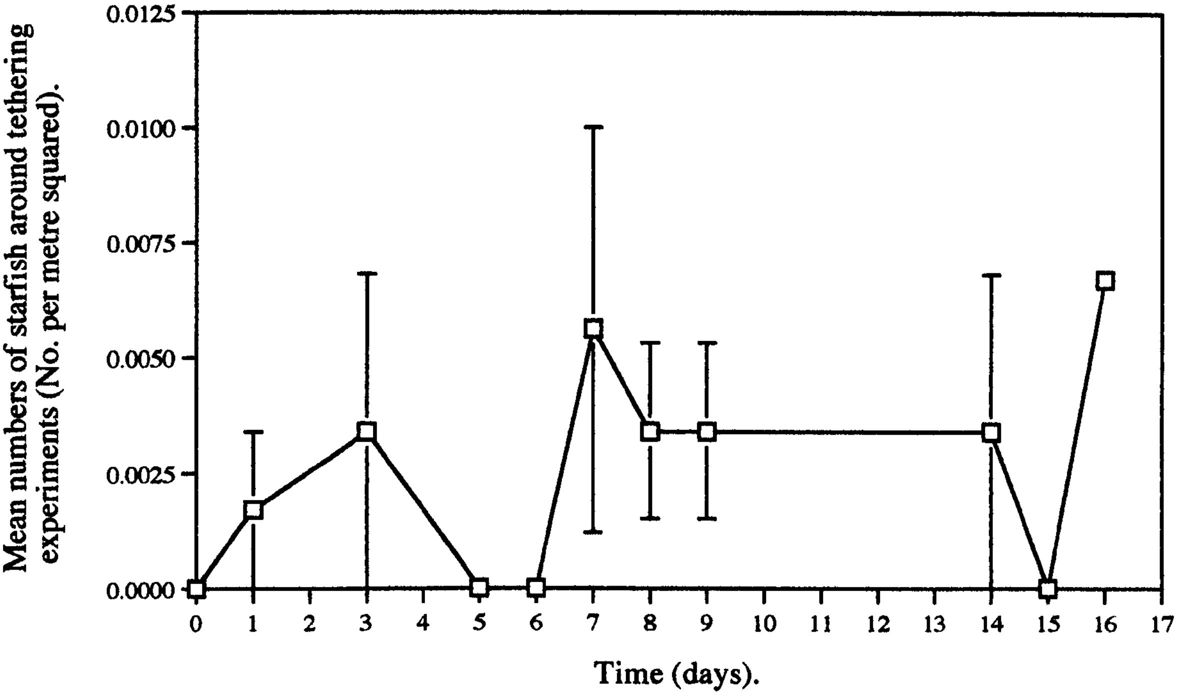


Figure 4.4
Mean densities of starfish around aggregation experiments for each day after deployment. Error bars ± 1 s.e.

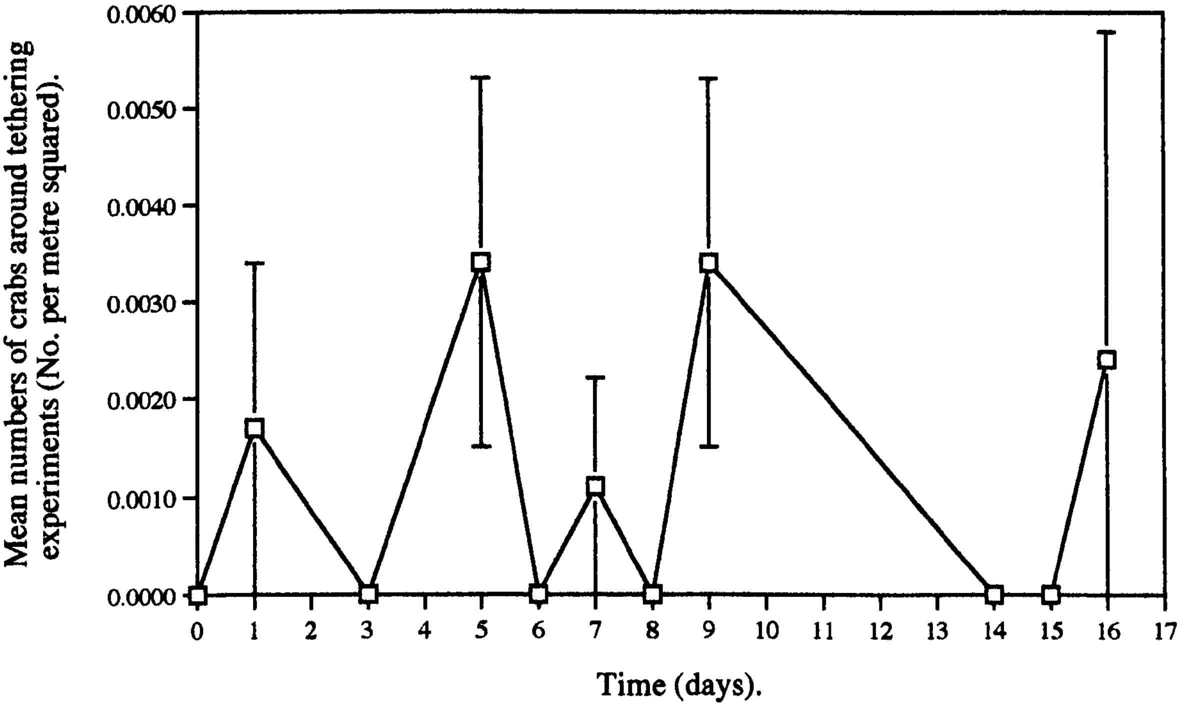


Figure 4.5
Mean densities of crabs around aggregation experiments for each day after deployment. Error bars ± 1 s.e.

Table 4.4

Day to day predation rates calculated from diver monitored aggregation experiments. All figures are scallops consumed per day.

Day.	Crab.	Crab s.e	Starfish.	Starfish s.e.
1	0.000	0.000	0.250	0.250
3	1.500	0.500	2.000	1.000
5	0.750	0.478	2.000	0.816
6	0.500	0.500	1.000	1.000
7	1.667	0.333	1.833	0.477
8	1.750	0.478	1.250	0.250
9	2.000	0.408	1.250	0.250
14	2.500	0.500	2.000	0.000
15	4.000	0.000	2.000	0.000
16	3.250	0.478	1.500	0.288
19	4.500	0.500	2.500	0.500
21	5.500	0.500	5.000	2.000

Table 4.5

Recession rates in scallops used in aggregation experiments. Values in this table refer only to scallops which demonstrated recession at some point (excludes those scallops which never demonstrated recessing behaviour). Replicates are combined to give totals for each set of experiments.

Days After Deployment	6/9/94 Tethering Experiments - Number Recessesd	14/10/94 Tethering Experiments - Number Recessed
1 Day.	5	0
1-2 Days.	0	6
1-5 Days.	1	0
2 Days min.	0	1
4 Days min.	0	5
8 Days.	0	0
Never recessed.	5	0
Always recessed.	5	4

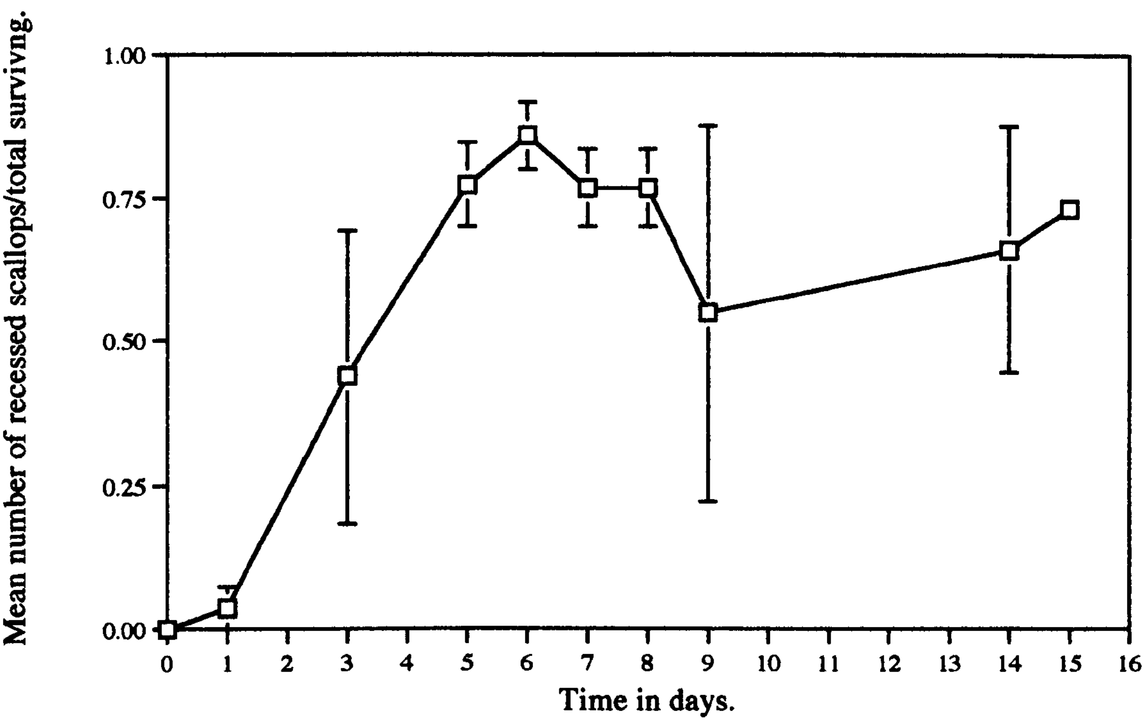


Figure 4.6
Mean number of recessed scallops, expressed as a proportion of the total number surviving, against time in days for the second set of aggregation experiments. Error bars ±1 s.e.

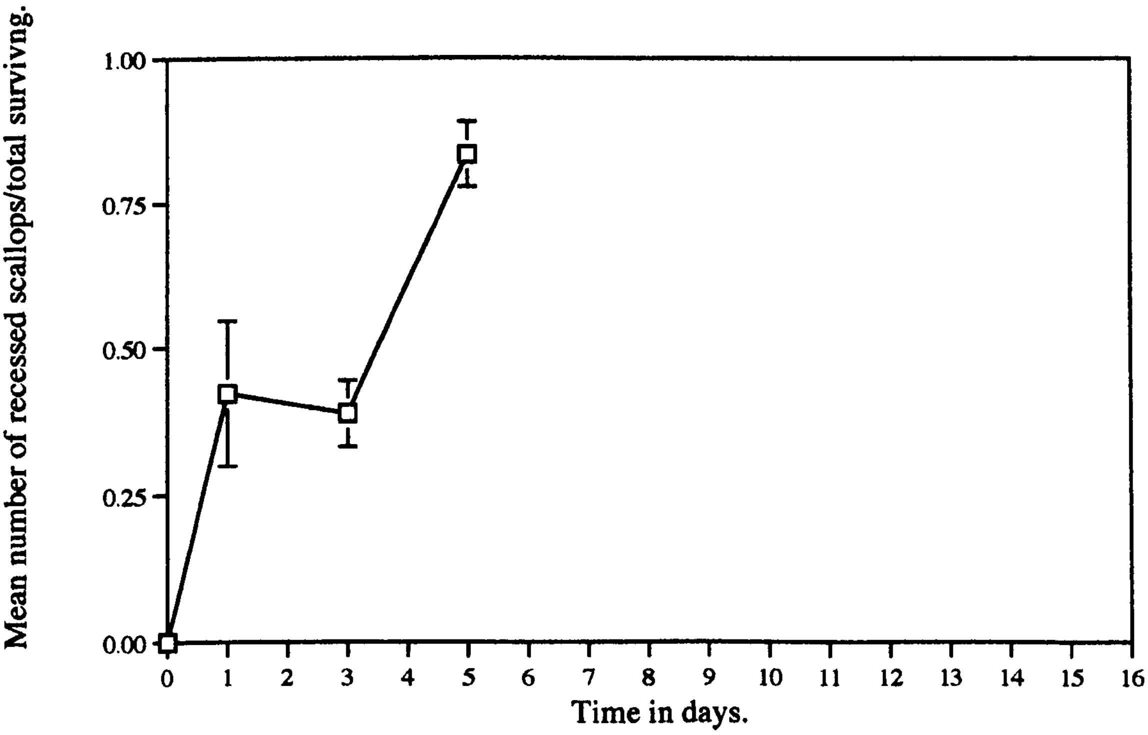


Figure 4.7
Mean number of recessed scallops, expressed as a proportion of the total number surviving, against time in days for the fourth set of aggregation experiments Error bars ±1 s.e.

the second set of tethering experiments increased steadily to just above 75% by the 6th day after deployment thereafter fluctuating between 50 and 75% up to day 15. Fig 4.7 shows a similar trend in the fourth set of tethering experiments. Here the proportion of surviving scallops that were recessed increased steadily to just above 75% within five days. No further surveys could be carried out on this set of experiments because of bad weather.

4.3.2 Static seabed video camera results.

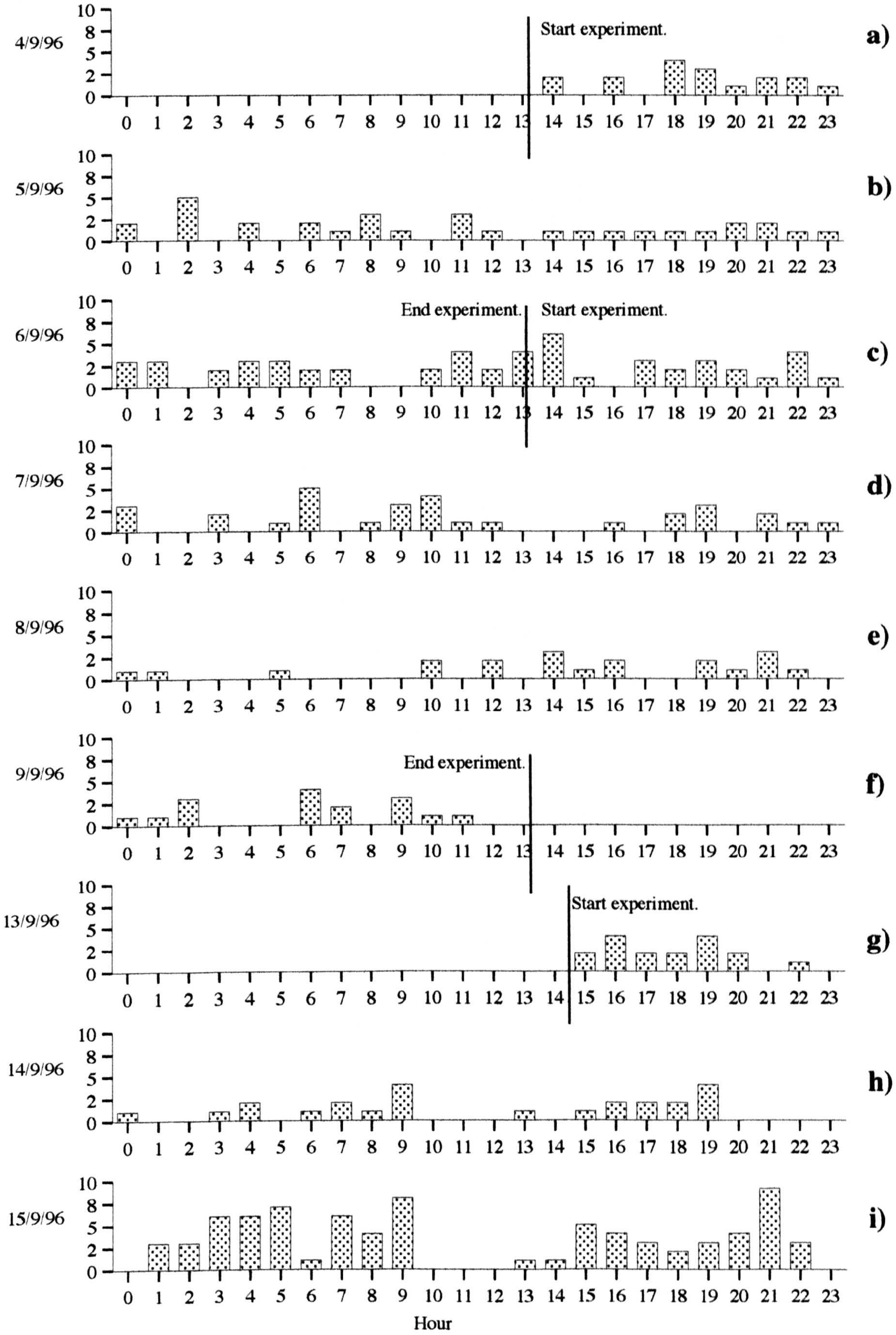
Bar charts showing predator activity in terms of crabs and starfish entering the field of view of the camera per hour are represented in Figs. 4.8a - m (for starfish) and 4.9a - m (for crabs).

Figs. 4.8a - c show the results for starfish activity for 4 September to 6 September 1996. These figures show that, during this experiment, starfish were active throughout the monitoring period with no obvious activity pattern apparent.

Figs. 4.8c - f show the results for starfish activity for 6 September 1996 to 9 September 1996. These figures again show no obvious pattern in activity of starfish. They do suggest lower overall levels of activity compared to the 4 September experiment.

Figs. 4.8g - j show the results for starfish activity for 13 September 1996 to 16 September 1996. These figures show that there may be a pattern in starfish activity. There appear to be greater levels of starfish activity between 1 and 9 a.m. and between 3 and 7 p.m. on 14 September and between 3 and 10 p.m. on 15 September. Both of these days show a reduction in starfish activity between 10 a.m. and 2 p.m (Figs 4.8h and i). Fig. 4.8j also indicates higher levels of starfish activity between 2 a.m. and 12 a.m. but with a much smaller rise at 3 p.m. compared to the previous two days. These results may indicate that starfish tend to be active mostly during the early morning followed by a reduction in activity during the middle of the day followed in turn by higher levels of activity from mid afternoon to late evening. Further experiments would have to be carried out to confirm or refute the existence of these patterns. Limited time meant that further experiments were not possible.

Figs 4.8k - m show the results for starfish activity for 10 October 1996 to 12 October 1996 after predator clearance had taken place. These figures show greatly reduced starfish activity throughout the period of the experiment. Further experiments would be required to ascertain at what point starfish numbers and activity returned to the same levels as those observed before predator clearance took place. These figures indicate that predator clearance could be a very useful tool in preparing an area prior to re-seeding with scallops.



Figures 4.8a - i
Bar charts showing starfish activity over 24 hours for days monitored using the static seabed video camera. Number of starfish entering field of view (Y) against time of day (X).

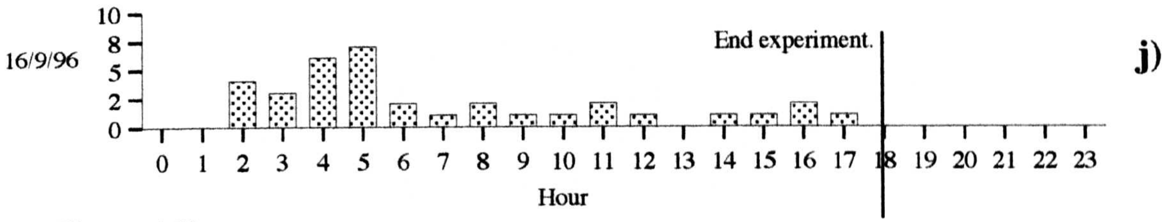
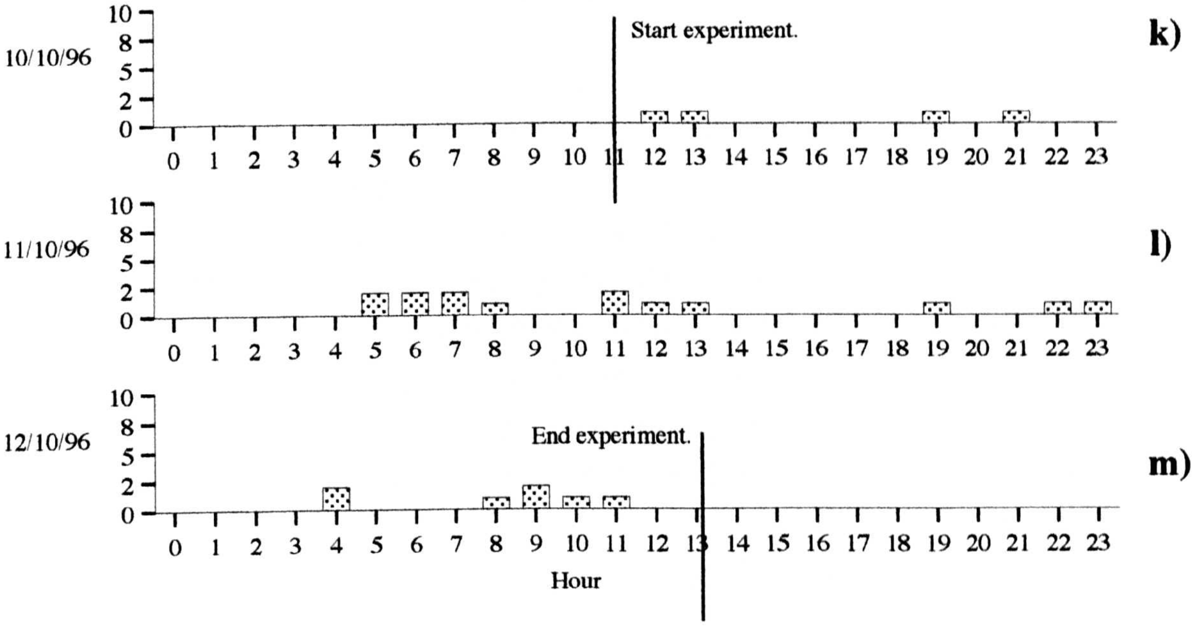


Figure 4.8j
Bar chart showing starfish activity over 24 hours for days monitored using the static seabed video camera.Number of starfish entering field of view (Y) against time of day (X)



Figures 4.8k - m
Bar charts showing starfish activity over 24 hours for days monitored using the static seabed video camera where predator clearance was carried out prior to monitoring.

Figs. 4.9a - c show the results for crab activity for 4 September to 6 September 1996. These figures show that, during this experiment, crabs were far less active than starfish throughout the monitoring period with no obvious activity pattern apparent. Very few crabs were captured by the camera. Those that were observed were active between 4p.m. and midnight.

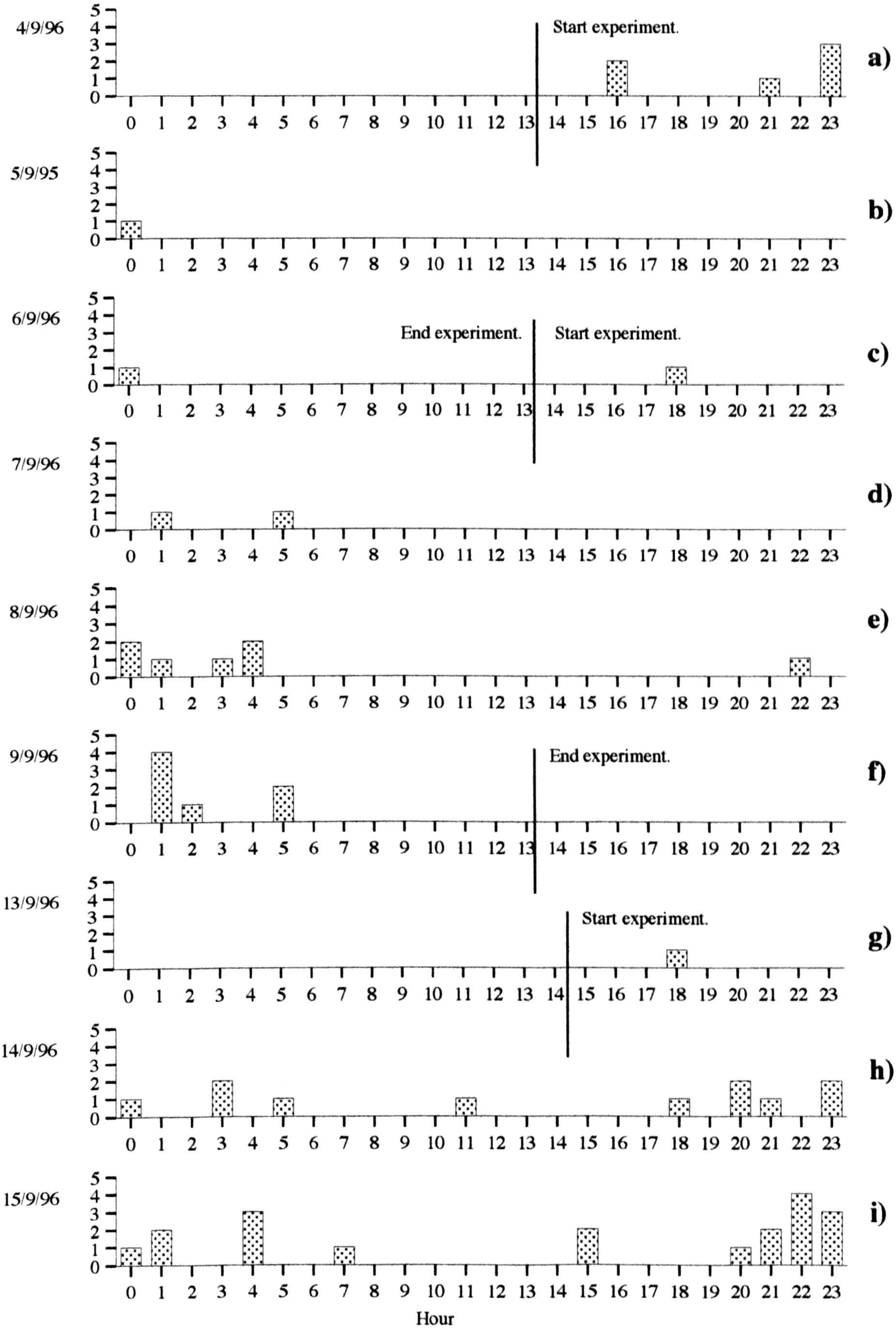
Figs. 4.9c - f show the results for crab activity for 6 September 1996 to 9 September 1996. These figures again show very low levels of crab activity with crabs being observed only between 6 p.m. and 5 a.m. No crabs were observed moving into the camera field during daylight hours.

Figs. 4.9g - j show the results for crab activity for 13 September 1996 to 16 September 1996. These figures show greater crab activity compared to the previous days experiments. This activity is mostly confined to the hours of darkness with a couple of exceptions. Diving surveys made between experiments suggested that crabs began to use the camera frame and anchor weights as a daytime refuge, much as they would use a patch of reef. This might explain why crab activity rose during this later experiment. As crabs move around the seabed they would come across the camera and may choose to remain there during the day while foraging at night. This behaviour would lead to an increase in the number of crabs in the vicinity of the camera and thus to an increase in observed activity by the camera. This is probably an example of the experimental method causing interference with the observations made during the experiment itself.

Figs 4.9k - m show the results for crab activity for 10 October 1996 to 12 October 1996 after predator clearance had taken place. These figures show greatly reduced crab activity throughout the period of the experiment. Again crab activity was confined to the hours of darkness. All of the observations involving crabs suggest a nocturnal activity pattern. Further experiments would be required to ascertain at what point crab numbers and activity returned to the same levels as those observed before predator clearance took place. These figures indicate that predator clearance could be a very useful tool in preparing an area prior to re-seeding with scallops.

The results of the analysis of starfish approaching the camera field of view relative to current direction are summarised in Table 4.6. All figures are for number of starfish approaching from one of three directions per hour surveyed for each days survey. Direction of approach was classified in three ways: against the current, with the current and across the current.

Table 4.6 indicates that starfish approach the monitored area against the prevailing current more frequently than either with or across the current. The results of the one-way ANOVA



Figures 4.9a - i
Bar charts showing crab activity over 24 hours for days monitored using the static seabed video camera. Number of crabs entering field of view (Y) against time of day (X).

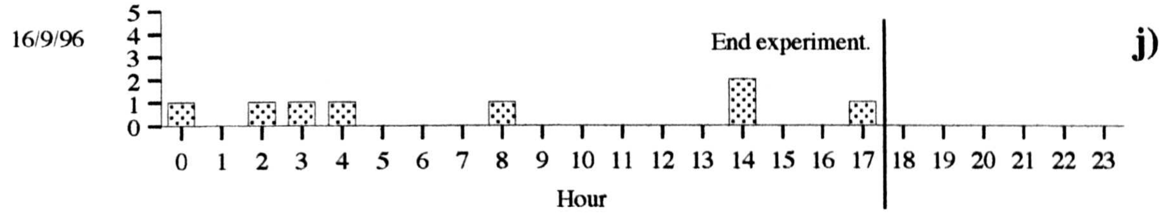
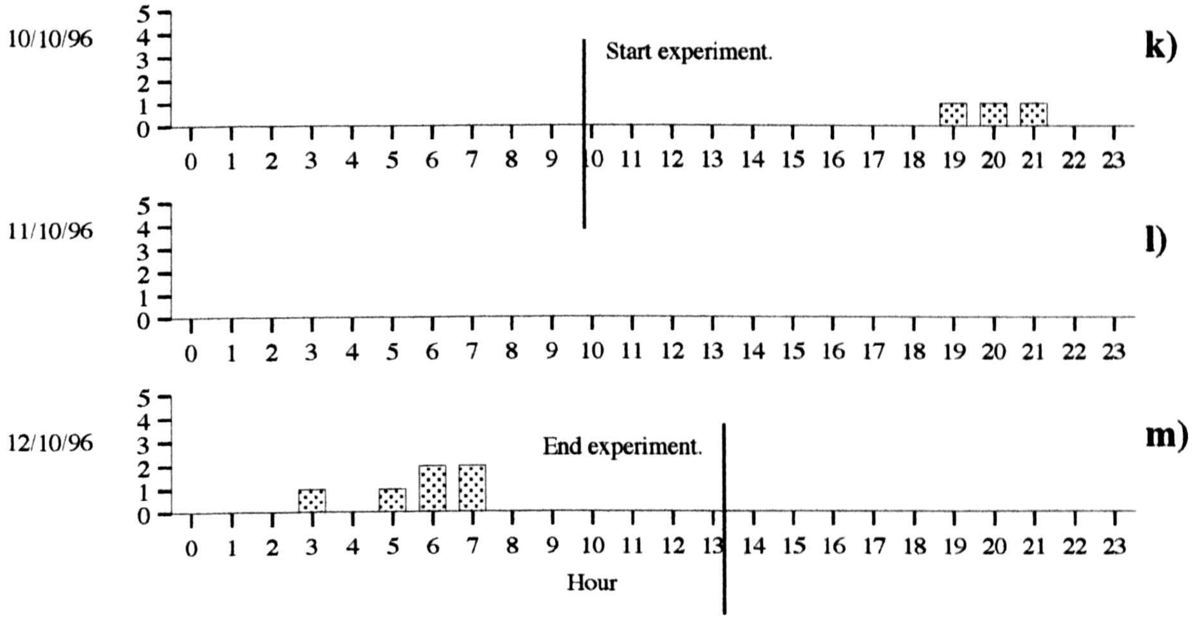


Figure 4.9j
Bar chart showing crab activity over 24 hours for days monitored using the static seabed video camera.Number of crabs entering field of view (Y) against time of day (X)



Figures 4.9k - m
Bar charts showing crab activity over 24 hours for days monitored using the static seabed video camera where predator clearance was carried out prior to monitoring.

Table 4.6

Summary of the direction of approach of starfish into the fieled of view of the seabed video camera expressed as animals entering the field of view per hour relative to prevailing current direction.

Date	Starfish approaching against the current per hour	Starfish approaching with the current per hour	Starfish approaching across the current per hour.
4/9/96	1.00	0.30	0.40
5/9/96	0.83	0.29	0.38
6/9/96	1.17	0.29	0.75
7/9/96	0.42	0.50	0.25
8/9/96	0.63	0.08	0.13
9/9/96	0.50	0.29	0.36
13/9/96	0.89	0.44	0.67
14/9/96	0.63	0.08	0.29
15/9/96	2.04	0.58	0.67
16/9/96	0.89	0.56	0.33
10/10/96	0.00	0.00	0.00
11/10/96	0.42	0.08	0.08
12/10/96	0.33	0.08	0.17

Table 4.7

Summary of the one way ANOVA applied to the starfish direction of travel data. The direction of travel of starfish into the monitored area was used as the factor with number of starfish per hour entering the field of view as the response variable.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	P-value
Direction of Approach	1.702	2	0.851	7.412	0.002
Error	4.134	36	0.115		
Total	5.836	38			

Table 4.8

Summary of the Tukey test applied to the data analysed in Table 4.7. Underlined means indicate no statistically significant difference those means. Breaks in the underline indicate where statistical differences occur.

Direction	With Current hr^{-1}	Cross Current hr^{-1}	Against Current hr^{-1}
Mean	0.276	0.344	0.749
	————————	————————	————————

to determine whether the direction of travel of starfish relative to prevailing current direction are equally likely are summarised in Table 4.7. Direction of travel of starfish was noted as either with the current, against the current or across the current using 4 quadrants as described in Fig. 4.3. Using this method means that starfish approaching across current should occur with twice the frequency of starfish approaching with the current or against the current if starfish move randomly across the seabed. The null hypothesis used was:

H_o: $\mu_{\text{with current}} = \mu_{\text{against current}} = \mu_{\text{across current}}$

Table 4.7 indicates that the null hypothesis is therefore rejected. A Tukey test was then performed to determine where the differences lay. The results of this test are summarised in Table 4.8.

Tukey test results:
SE = 0.094 Error df = 36 n = 13 k = 3 ($q_{0.05,3,30}$= 3.486 $q_{0.05,3,40}$= 3.442)

Table 4.8 indicates that significantly more starfish approach the camera field of view travelling against the current than either with or across the current direction. No difference was identified between mean numbers of starfish approaching with the current and across the current direction. Given that one would expect twice as many starfish to approach the field of view of the camera across current rather than with or against the current these results show that starfish do not move across the seabed randomly but tend to use the current in order to detect food by chemosensory means. Dale (1999) determined that starfish use differences in odour concentrations between rays or arms to detect the direction of prey. Prey odours are naturally carried by currents therefore one would expect starfish to approach prey from down current.

4.3..2.1 Results of the diver surveys carried out between video surveys.

Densities of predators in circular bands 3m, 6m and 9m from the video camera are summarised in Figs. 4.10a - b.

Figure 4.10a shows starfish densities falling in all three areas surveyed around the video camera. This effect may be a result of other, unrelated experiments carried out prior to this experiment where bags of dredge by-catch were place in front of the camera to determine predator aggregation and dispersal. The tethered scallop experiments were made with as long a gap as possible after these dredge catch experiments, but time constraints on the use of the video system and the need to bring the camera in before winter meant that tethering experiments had to be carried out soon after these experiments. It would appear that starfish were still undergoing dispersal after initial aggregation observed during the dredge catch

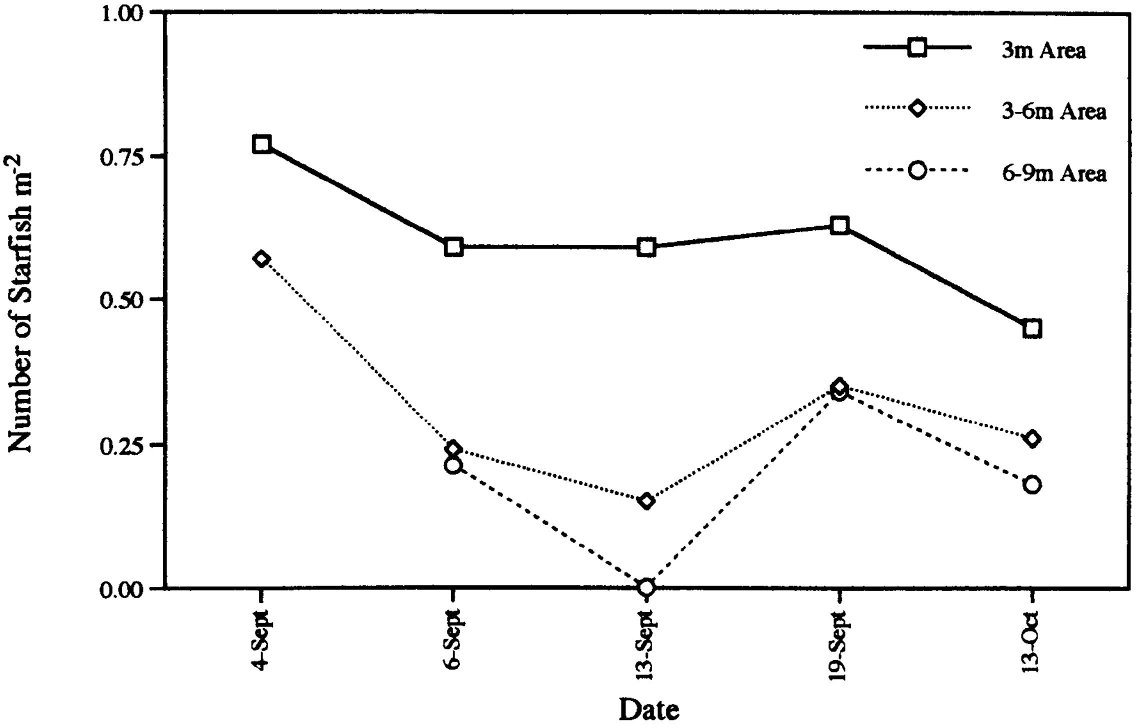


Figure 4.10a
Densities of starfish on different survey dates at different radii around the static seabed video camera.

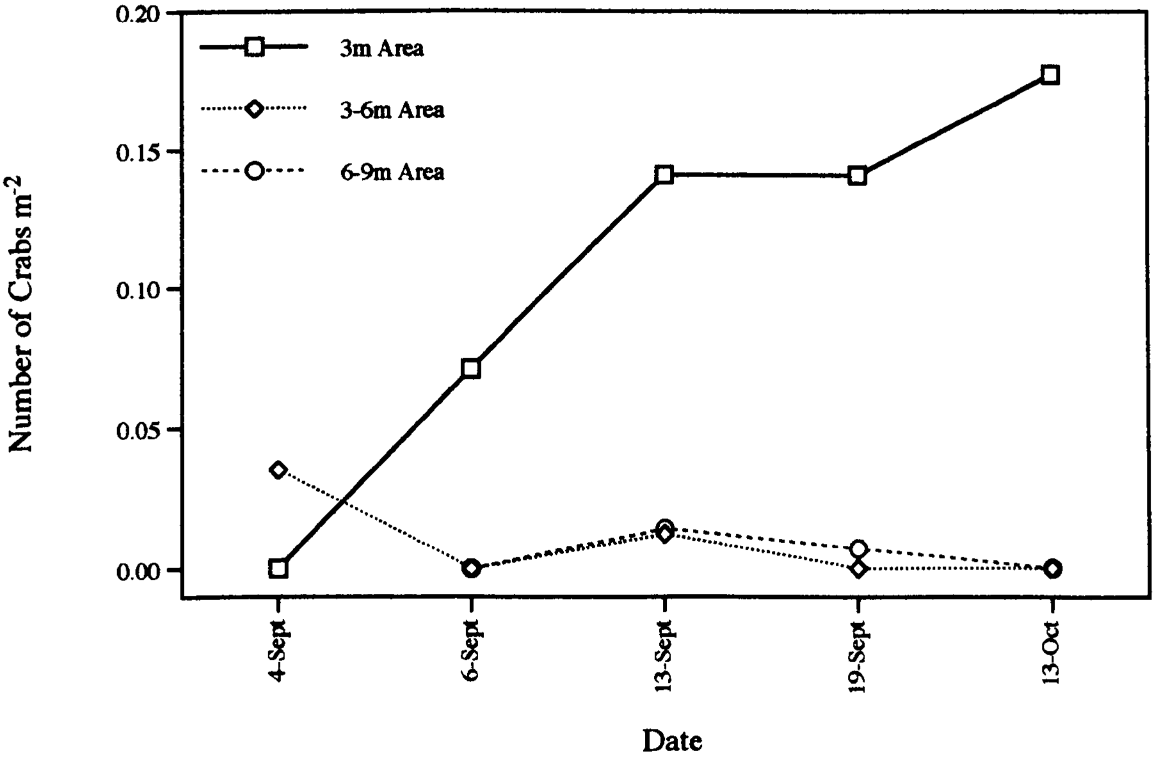


Figure 4.10b
Densities of crabs on different survey dates at different radii around the static seabed video camera.

experiment which probably masked any effect of the tethering experiments which would be small in comparison.

Figure 4.10b shows crab density remaining low and relatively constant between 3 and 9m from the camera. The surveys carried out within 3m however, show a marked increase in crab density with time. This was mainly due to finding crabs on the seabed within the confines of the frame supporting the video camera. The crabs appeared to be using the frame and block anchors for shelter during the daytime. The rising trend of the graph suggests that the frame is acting as an aggregation point for the crabs since this rising trend is not repeated further away from the frame. This aggregation of crabs did not appear to affect the tethered scallops in the camera field of view because non were consumed by crabs. All tethered scallops that did not survive experiments were consumed by starfish. This indicates that starfish pose more of s threat to juvenile scallops in the field than do crabs in the area where these experiments were carried out especially since these experiments were carried out at a time of year when one would expect crabs to be relatively active. This autumn peak of crab activity was identified by the tethering experiments described in Chapter 2.

4.3.3 Laboratory Work Results.

4.3.3.1 Predator size/prey size interaction.

A summary of all of the predator size/prey size experiments is presented in Fig 4.11 in the form of a three dimensional plot using scallop (prey) size, starfish (predator) size and number of scallops consumed per predator per day as the three axes of the graph. MS Excel charting tools were used to produce this graph.

Figure 4.11 shows that larger scallops are consumed with less frequency by starfish. 45mm shell length scallops were most vulnerable to attack but once starfish size exceeded 110mm arm length predation on this size class fell. This could be the result of handling difficulties for a large starfish attacking a small scallop or a result of energetic considerations, the scallop being too small to yield sufficient energy. 65mm shell length scallops show a steady increase in numbers consumed per day with increasing starfish size. This size of scallop is therefore both susceptible to attack over a range of starfish sizes and sufficiently attractive to maintain an increase in consumption. 75mm shell length scallops show a similar trend to 65mm shell length scallops but at a reduced daily consumption rate. This indicates that this size of scallop is attractive to the range of starfish used but that these starfish either find it harder to attack or take longer to consume this size of scallop. Once 85mm scallop shell length is reached the starfish need to be 120mm arm length or greater in order to successfully attack this size of scallop. 95 and 105mm shell length scallops were attacked very infrequently by the size range of starfish used in this experiment.

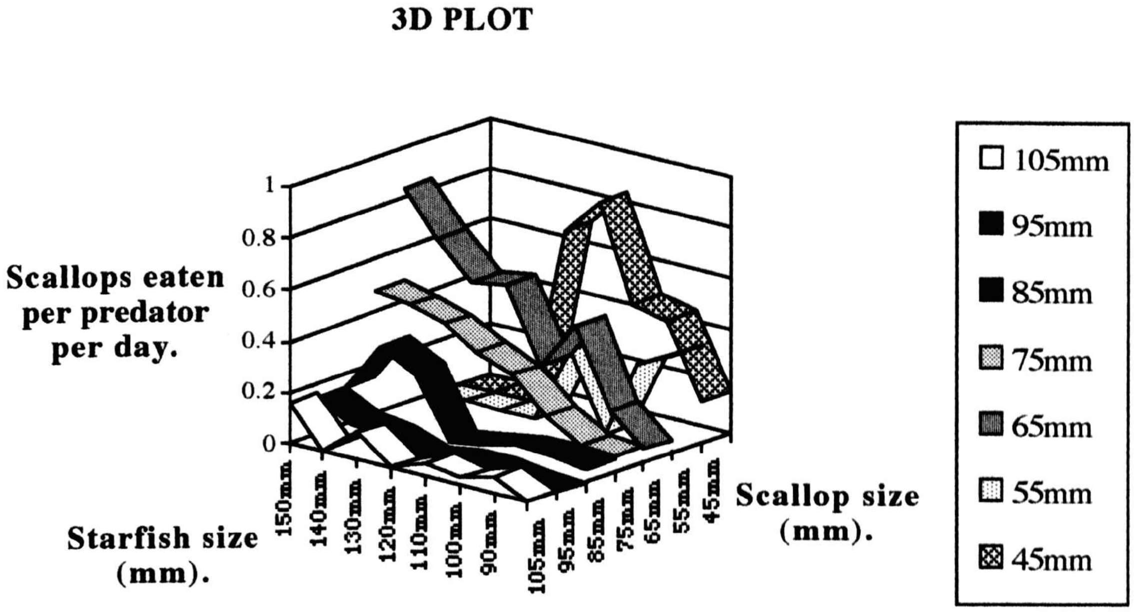


Figure 4.11
Three dimensional plot of scallops consumed per starfish per day against scallop size and starfish size. This plot indicates the sizes of scallop that different sizes of starfish can successfully handle and where scallops of a specific size may expect to achieve a size refuge from specific sizes of starfish.

These results give an indication that scallops achieve a size refuge from starfish at around 75 - 85mm shell length under the experimental conditions imposed. It must be stressed that these conditions probably represent a worst case scenario given that these experiments were carried out in relatively small tanks with high densities of both predators and prey. Consequently, in the field, one would expect this size refuge to be lower given that scallops are capable of successfully evading starfish predators with a strong escape response. This would mean that re-seeding trials could use scallops smaller than 75mm shell length which would reduce the cost of culture prior to re-seeding. In every case where starfish consumed scallops during this experiment they left behind two, clean, joined shells which were undamaged. Where small starfish had attacked scallops at the limit of their size capabilities there were often soft body parts remaining in the shell. These results back up the assumption, made in Chapter 2, that articulated, undamaged, empty shells retrieved during tethering experiments were attributable to starfish predation.

A similar experiment conducted with crabs gave no satisfactory results because, in general, the crabs would not eat under experimental conditions even when blacked out tanks were used. One crab (150mm carapace width) did successfully attack and consume a 55mm scallop. The damage inflicted on the shell was consistent with the assumption that crustacean predators crush and break the shell of the scallop in order to consume the soft body parts within. This backs up the assumption used during the tethering experiments (Chapter 2) that shells retrieved showing this kind of damage indicated predation by crabs.

4.3.3.2 The effects of tethering on predation and recessing of scallops.

The t-test carried out to determine if there was a difference in mean predation rate on tethered and untethered scallops indicated that there was no difference in mean predation rate for the two treatments under the experimental conditions imposed ($p = 0.772$, $a = 0.05$ $n = 8$). This suggests that tethering has no effect upon predation rate for starfish predators. However, the tanks that these experiments were carried out in were relatively small. This probably constitutes a manner of tethering in itself. The escape response of the untethered scallops in the tank will be restricted and the scallops would remain exposed to detection by starfish for periods long enough so that the escape response would be weakened and the scallop would eventually succumb to an attack. This type of experiment would need to be carried out in much larger tanks if tethering effects are to be investigated. The tanks used were the largest available at the time. All shell damage inflicted by starfish was consistent with the assumption made in Chapter 2 that undamaged, articulated shells were attributable to starfish predation.

The same experiments carried out using crabs proved unsuccessful, again because the crabs would not feed under experimental conditions. During five experiments, each of three replicates only one crab (150mm carapace width) consumed a single scallop (55mm shell length). The damage inflicted on the shell was consistent with the assumptions made in Chapter 2 regarding crustacean predation. Lake et al., 1987 performed similar experiments with crabs with more success. They only used crabs up to 140mm carapace width, however. Most sites surveyed around the Isle of Man gave larger mean crab sizes than this.

It was also found that the ability of scallops to recess in the sediment in the tanks was not affected by the tethering method used ($P = 0.121$, $a = 0.05$). Again, this applies under the experimental conditions imposed.

4.3.3.3 Prey size capability of *Asterias rubens.*

The results of the one way ANOVA carried using starfish number as the factor and square root transformed prey consumed per day as the response are summarised in Table 4.9. 85mm scallops were used as prey with starfish measuring 90-100mm maximum arm length. This combination of predator and prey size, chosen using the results of section 4.3.3.1, should mean that individual starfish would struggle to attack scallops of this size but starfish attacking in numbers could overcome the size refuge. The null hypothesis used was:

H_O: starfish numbers do not affect the number of scallops consumed per day

Table 4.9 shows that the null hypothesis is rejected (P = 0.01899) and that the number of starfish present in the experimental tanks significantly affects the number of scallops consumed. A Tukey multiple comparison test was then used to determine where the identified differences lay.

The results of the Tukey multiple comparison test applied to the starfish number data are summarised in Table 4.10.

$SE = 0.0769$ Error $df = 9$ $n = 4$ $k = 3$ $q_{0.05,9,3} = 3.949$

Table 4.10 indicates that, when more than one starfish is present in the experimental tanks, more scallops were consumed per day. It appears that there is no difference between having two or three starfish in experimental tanks. This means that, when starfish attack scallops in numbers, they are capable of overcoming a size refuge which applies to a single starfish attacking a scallop.

4.3.3.4 Octopus - *Eledone cirrhosa.*

The results of the experiment using octopus as the predator were relatively inconclusive. The octopus proved to be difficult to work with. Experimental animals often did not survive very long and if they did survive they tended not to eat under experimental conditions. On only two occasions were octopus observed to consume scallops during these experiments. In both cases (different octopus) the scallop shell was left broken into separate valve with no meat left attached to either valve. There was no other evidence of damage to the shells. This experiment showed that the octopus *Eledone cirrhosa* was capable of successfully attacking and consuming scallops and that the shell damage inflicted could potentially be confused with the damage inflicted by starfish. No conclusions could be drawn about predator/prey size interactions because of the difficulties experienced in handling this predator. On two occasions octopus actually escaped from the tank the experiment was held in and were not recovered. The method of capturing octopus (dredge survey by-catch) may not have helped this situation because the octopus used may have been damaged and highly stressed.

Table 4.9

Summary of the one way ANOVA used to determine whether significant differences existed between the numbers of scallops consumed by different numbers of starfish.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	P-value
Starfish Number	0.615	2	0.307	6.358	0.01899
Error	0.435	9	0.048		
total	1.0496	11			

Table 4.10

Summary of the Tukey multiple comparison test analysing where statistical differences lie in the data analysed in Table 4.9 above.

Number of Starfish	1 Starfish	2 Starfish	3 Starfish
Mean Scallops Consumed/day	0.164	0.642	0.645

The very low frequency with which lesser octopus were caught in dredge surveys may reflect a very low mean density or may reflect their ability to move very quickly and avoid dredges, or both. More detailed investigation into the dynamics of this predator would be needed in order to determine the threat posed to juvenile, re-seeded scallops.

4.4 Discussion.

Comparison of predator densities around tethered scallop experiments with background densities of predators indicate that these experiments do tend to attract predators. The marginal value theorem suggests that predators will aggregate at sites of high prey density and subsequently disaggregate from that area when prey density equals that of the surrounding area. The results for starfish and crab pits both show that predator aggregation occurred at tethering experiments. Crabs themselves showed no significant difference from background densities but these tend to be nocturnal predators which would not fall within normal, daytime diver surveys. Evidence of crab activity in the form of pits is taken as relatively strong evidence of increased crab activity around the tethering experiments. The graphs of predators surveyed suggest that starfish increase in density around the tethering experiments after deployment and remain at a relatively stable density with some fluctuation. Crabs show a far more erratic pattern, varying more widely from day to day. These patterns may result from the "snapshot" nature of a diver survey. Given ideal conditions and resources, several surveys would have been carried out each day to yield more accurate, averaged results.

Tethering experiments have proved to be a very useful tool in assessing patterns of predator activity, but it must be borne in mind that they will almost certainly yield quite high estimates of mortality given their attractiveness to predators. This in itself could be encouraging for re-seeding trials since scallops would be seeded at much lower densities than were used here and would not have the restriction of a tether. This could lead to much higher survival rates than those observed during the tethering experiments.

During the predator aggregation experiments, observations were made of scallops recessing into the sediment. The results suggest that after five days of deployment about 75% of surviving scallops were recessed in the sediment. This suggests that scallops prefer to be recessed as opposed to not recessed and that the tethering method used does not interfere with this behaviour.

Results of the static seabed video camera surveys suggest that starfish are active throughout the day, with a possible bias towards increased activity during the morning and evening or dawn and dusk periods. The only criteria for estimating predator activity was number of predators entering the field of view of the camera. Crabs were observed to be most active in the early hours of the morning or very late evening. Starfish were observed to enter the field of view of the camera mostly travelling against the current. This would be expected for a chemosensory predator since any chemical trails from potential prey would be carried to them with the current. The average direction of travel of starfish into the field of view of the camera therefore changed with the prevailing current direction. Current direction during these surveys was determined by the orientation of shoals of fish which tended to swim into the current.

The 3D plot of prey size and predator size against prey consumed per predator per day (Fig. 4.11) shows *Pecten maximus* possibly achieving a size refuge from *Asterias rubens* at about 75mm shell length for starfish up to 100mm in arm length. The mean size of starfish recovered from the dredge surveys indicates a local, average starfish size of 60 - 80mm arm length which suggests that scallops could safely be re-seeded at a size smaller than the size refuge identified above. Indeed, the size refuge identified for 80mm starfish is 65mm. The size refuges identified may be artificially high for reasons detailed below. Further tethering experiments may be able to show that the size refuge identified in the laboratory is higher than the actual prey size refuge achieved in the field by using different sizes of scallops. It was also observed that very small (45mm) scallops were consumed at much lower rates by starfish above 100mm. This could be due to handling difficulties associated with a large predator trying to consume a very small prey item. Either the small scallop is not detected by larger starfish or the larger starfish make a decision not to consume very small prey for reasons of efficiency. Very large scallops (95 - 105mm) showed very low mortality in these experiments but were susceptible to attacks by more than one starfish. Such attacks were observed on a number of occasions during the course of these experiments and in the field by divers. Barbeau & Scheibling (1994c) found that seastars consumed more small scallops than large scallops in choice experiments. They found that this was because smaller scallops were more vulnerable to attack, not because the seastar made an active selection of smaller prey. Barbeau & Scheibling (1994c) also found that the probability of seastars catching scallops was relatively low.

A feeding *Asterias rubens* can stimulate other individuals in close proximity to begin feeding (Blankley & Branch, 1984). Field observations of more than one starfish attacking a single prey species have been made (Blankley & Branch, 1984) and up to three predators have been observed attacking one scallop in experiments carried out in the present study. This is not necessarily confounding since the object of the experiment is to demonstrate the prey size handling capability of the predator to which end a further stimulus to feed may be an advantage. If no feeding occurred, then no results would be obtained. The results cannot, therefore, be regarded as reflecting true feeding rates and the highly artificial conditions under which they were conducted reinforce this view. Artificially high densities of predators and prey confined in a small tank could be regarded as a worst case scenario in terms of actual predation rate. True values in the field would almost certainly be lower. This could also be true of the predator/prey size interaction with high densities of both in a confined space leading to predators potentially attacking larger prey than they might ordinarily in the field. If this is the case then the presence of more than one predator in each tank might have the effect of producing an artificially high prey size refuge.

There is also the possibility that scallop size will affect the ease with which an escape response can be stimulated by a predator. Parsons & Dadswell, (1992) found that 76% of juvenile scallops were moving after seeding onto the seabed. This factor will effectively be masked by the confined nature of the experimental tanks which maintained scallops in close proximity to their predators. In field reseeding trials this could lead to higher survival rates among smaller scallops but would be very difficult to assess as the scallops would be more likely to move away from a monitored re-seeding experiment. Best and worst case estimates of survival could be made (Wilson, 1994) by assuming that all scallops not recovered or surveyed were alive and then calculating survival assuming all were dead. The possibility that smaller scallops could be used in reseeding trials is better for the prospects of a reseeding programme as this would minimise the cost of the initial growth period in hanging culture and its associated labour costs. This, coupled with the tethering data which can be used to pick the time of reseeding so as to minimise predation, may make seabed restocking a viable proposition.

Laboratory experiments to determine whether tethering significantly affects mortality rates of scallops indicated that no significant difference was apparent between tethered and untethered treatments. This was probably due to the nature of the experimental environment since the tanks that the experiments were carried out in effectively tethered all scallops within a small area anyway. Consequently, even untethered scallops would be unable to escape a determined attack under these conditions. Ideally, much larger tanks should have been used had they been available.

The observations made regarding multiple starfish attacks on individual scallops strongly suggests that scallops of 85mm shell length have successfully achieved a size refuge from individual starfish of maximum arm length 90-100mm. however, these starfish were entirely capable of overcoming this size refuge by attacking scallops in numbers. Observations were made during this experiment of up to three starfish attacking the same scallop.

Very limited success was achieved using either crabs or octopus as predators of scallops in laboratory experiments. The results of the experiments were able to confirm only the type of shell damage expected from crustacean predators and that octopus were capable of consuming scallops. The two scallops consumed by octopus during these experiments also exhibited a very similar type of shell damage to starfish. It is possible then that, in the field tethering experiments , some of the predation assigned to starfish could have been due to octopus predation instead.

4.4.1 Conclusions

This chapter has shown that the tethering experiments used and described in Chapter 2 cause predator aggregation and could, therefore, lead to artificially high estimates of predation. This is encouraging in terms of re-seeding because the relatively high survival rates obtained from some of the tethering experiments, admittedly over short periods of time, would be higher assuming that re-seeding would take place at much lower densities and without the effects of tethers. The results have also shown that the tethering method used does not affect the ability of scallops to recess into the seabed. The seabed video footage showed that starfish tended to be active throughout the day and night while crabs, as expected, were active mainly nocturnally. This footage also indicated both that starfish were more numerous than crabs and that starfish were probably more important as predators of scallops than crabs. This is also backed up by the results of the tethering experiments which show that many more tethered scallops were consumed by starfish than by crabs. The dredge, diver and video surveys also show starfish to be more numerous on the seabed but this may be a result of the nocturnal activity pattern of the crab. Laboratory experiments carried out show that scallops may achieve a size refuge from starfish at around 75mm shell length. It is felt that this threshold could be lower in the field where mean sizes of starfish identified by the dredge surveys were lower than the minimum size used in these experiments.

Chapter 5 - A Brief Investigation of Scallop Growth Rates.

5.1 Introduction.

Fairbridge (1953) stated that differences in growth rates between geographical areas are a characteristic of lamellibranchs. The reasons postulated for these differences include: currents (Gutsell, 1930; Fairbridge, 1953); temperature (Coe & Fox, 1944); food availability and type (Broom & Mason, 1978) and seabed type (Fairbridge, 1953). Gibson (1956) found that scallops on sheltered beds grew more quickly than those on exposed beds suggesting that excessive particle loads may interfere with feeding processes. Mason (1957) found that Manx scallops growing on shallow beds grew faster than those on deeper beds. He suggested that this is probably a result of temperature differences since the bottom temperature at the deeper site was significantly lower than that at the shallow site. Given that the scallop beds around the Isle of Man lie at varying depths, may have different degrees of exposure, different seabed types and different current regimes, it is possible that scallops may be found to grow at different rates at different sites. This would mean that, looking at growth rate in isolation, re-seeded scallops at one ground could potentially achieve a size refuge from predators more quickly than scallops at another ground. It is the aim of this chapter to discover whether this is true and how great are the differences between grounds if such differences occur.

Growth rates of the bivalve *Pecten maximus* have been studied around the coast of the Isle of Man over a number of years (Tang, 1941; Mason, 1957; Allison, 1993). Assessment of growth rates are important in the context of the present study assuming that the scallop can achieve a size refuge from its major predators. PEML has biannual scallop survey records dating back to the early 1990s which can be used to estimate annual variations in growth rates at different grounds around the island using size measurements and ageing using ring counts (Brand & Wilson, 1991). The suitability of different grounds for re-seeding could be usefully investigated through growth rates of scallops. If a ground consistently demonstrated higher growth rates then it may be considered more suitable for re-seeding since scallops could achieve a size refuge more quickly.

Pecten maximus , in common with many bivalves, lends itself readily to study of length and age structure since it lays down annual rings in its shell. In the case of *P. maximus* in Manx waters these rings are laid down in spring prior to commencement of the main yearly growth period (Mason, 1957). Growth increases in the months March to May and is most rapid from June to September or October. Growth then more or less ceases from November or December to the following spring (Gibson, 1956; Mason, 1957). More recently, very accurate methods of aging bivalve shells have been developed using oxygen isotope ratios of gases found in minute pockets within the structure of the shells (Deling et al., 1990). These methods have been used to verify annual nature of the shell rings. These methods are complex, very expensive and beyond the scope and requirement of this study.

Data from two sources were used in this study. Firstly, records of scallop ages and shell lengths from scallop surveys made prior to this study (1992 - 1995) were used to create Ford-Walford plots for each ground surveyed. These records only provided data for the length of each scallop at the time of the survey since only the overall scallop size was measured, not individual ring sizes. The dredges used in the scallop survey only tend to catch scallops of age 2 years or greater and 2 year old scallops are caught in very low numbers making average size estimates for this size class less accurate. Since only overall length at age data is recorded it is preferable to only use scallops at the end of the annual growth period with the growth ring at the very edge of the shell. This occurs during the June surveys (surveys being carried out bi-annually in June and October). Consequently the data obtained from the October 1992 - 1995 scallop surveys were not used in these analyses. Secondly, scallop surveys carried out during the course of the present study (June 1996 survey) were used to obtain animals of different age classes: these were used to obtain back-calculated growth curves by measuring shell lengths and growth increments at each annual ring. Different aged animals were used to determine growth rates for different cohorts in order to determine year to year variations in growth rates. This method has the advantage of allowing estimates of scallop sizes at less than 2 years of age, given that clear rings are laid down on an annual basis (Tang, 1941; Mason, 1957; Brand & Wilson, 1991).

The main aims of this chapter are to investigate the growth rates of scallops at different grounds round the Isle of Man using archive data and dredge samples with back measured growth rings. The data obtained by Mason (1957) are also employed as a comparison with the contemporary Inshore Bradda and Chickens data. The results will be discussed in the context of the achievement of a size refuge from predators and the consequent potential for re-seeding on different scallop grounds around the Isle of Man. The possibility of the effects of intensive fishing for scallops on scallop growth rates will also be discussed.

5.2 Materials and Methods.

5.2.1 Scallop survey data from past scallop surveys.

Data were obtained from the PEML scallop survey database using data from the June scallop surveys carried out between 1992 and 1995. 2 year old scallops from the 1992 survey (the 1990 year class, the smallest scallops caught in this survey) were used as a starting point. The data on the size of these animals were extracted and used to calculate a mean sizes for 2 year old scallops separately for all the grounds surveyed. This process was repeated for subsequent June surveys for 3, 4, 5, 6 and 7 year old scallops respectively for each ground surveyed. The data obtained were then used to create Ford-Walford growth plots from 2 to 7 years of age for scallops from the same year-class (1990) from each ground surveyed. These plots were used to compare growth rates of scallops on grounds around the Isle of Man to assess whether any significant differences exist. The aim of this analysis is to try to identify areas with the greatest potential for seabed re-seeding in terms of the highest growth rates.

The archive data obtained from the scallop survey database, analysed using the method described above, provides an equivalent method to that used by Hancock (1965) where measurements were made over several years of different scallops (Hancock's method (1a)) for plotting Ford-Walford graphs. This method allows comparison of K values - K being the coefficient representing the rate at which the growth curve approaches the asymptote L_∞ in the growth equation:

$$L_t=L_\infty(1-e^{-K(t-t_o)}) \qquad \text{(Equation 5.1)}$$

where L_t = length at time t
L_∞ = asymptotic length
K = Coefficient of catabolism (von Bertalanffy 1938)
t = time
t_o = theoretical time where length equals zero

The larger the K value the faster the asymptote is approached and the faster the animal is growing.

Generally, only animals 2 years old or older are caught during the scallop surveys and no records of shell ring sizes at previous ages were kept. Consequently, the data retrieved from the scallop survey archives prior to this study only provide data for scallops of age 2 years or greater. The low number of 2 year old scallops caught may also lead to problems with this method.

5.2.2 Scallop biometric data from the June 1996 scallop survey.

During the 1996 scallop surveys 5, 6 and 7 year old scallops (the 1991, 1990 and 1989 year-classes respectively) were collected at each ground surveyed (30 animals of each age, where possible). The grounds surveyed are shown in Fig 5.1. The shell lengths of the annual rings of each animal were measured using calipers and the measurements used to plot growth curves for the different cohorts that the different aged animals represented i.e. the 5 year old scallops would yield a growth curve for scallops which settled on the seabed in 1991; 6 year old scallops would yield data for the 1990 settlement and the 7 year old scallops would yield

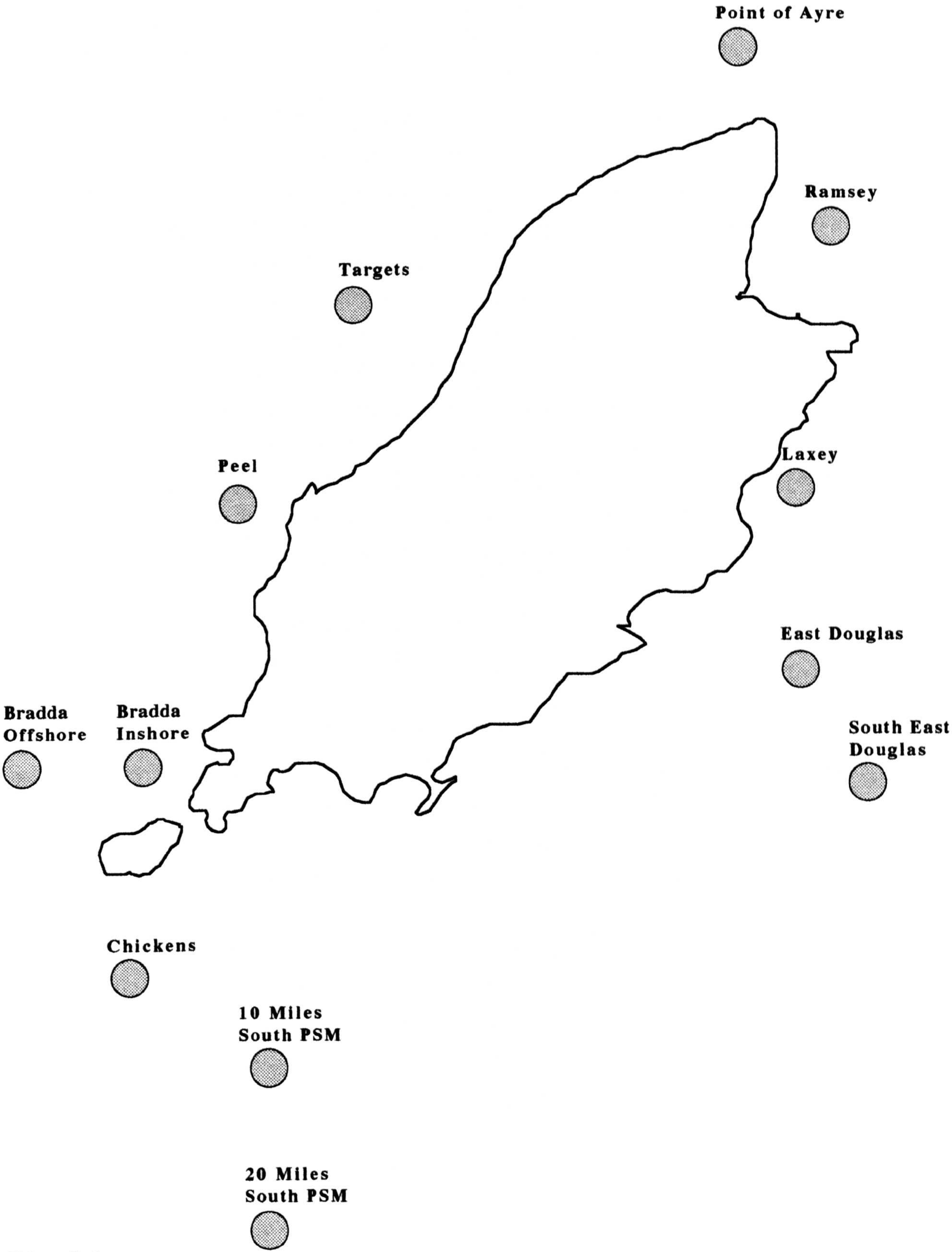


Fig. 5.1
Diagrammatic representation of the locations of the dredge survey sampling sites around the Isle of Man used during this study.

data for the 1989 settlement. These data provided a year to year comparison of growth rates within different grounds around the island. The 6 year old scallops also provided a convenient comparison with the archival data which took 2 year old scallops in 1992 as a starting point for the growth curve - these scallops would also have settled in 1990.

The most relevant section of the growth curves obtained from these measurements is from settlement to about 3 years of age because it is during this stage of the growth curve that the scallops are likely to achieve a degree of size refuge from their main predators (around 70-80mm shell length). The growth curve from this shell length up to the Minimum Legal Landing Size (110mm shell length) will also be of interest because sites could be identified where commercial size is achieved quickly. The shell length measurement data were first tested for homoscedascity and normality using the Minitab 8.1 statistical analysis package to determine whether a test for linearity could legitimately be carried out. Relevant transformations of the data were applied where required. The growth curves for each year-class at each site were then tested for linearity since it is far easier to test for differences between straight lines than curves. The tests of linearity were carried out according to methods detailed in Zar (1984). Growth curves over this age range that were found to be linear were then tested to determine whether there were any significant differences between:

i) year-class growth rates (slope of the growth curve) on individual scallop grounds and
ii) growth rates on different scallop grounds.

using the methods detailed in Zar (1984). Where cohorts on a single ground showed no statistical difference in growth rate the data were pooled for testing between different grounds. An ANOVA could then be applied to the growth rate data to determine differences between sites if linearity was established. The analysis methods applied to the data where linearity was not identified are detailed in sections 5.2.2.1 - 4 below.

5.2.2.1 Differences in growth rates within and between sites.

The ring measurements from the 5, 6 and 7 year old scallops detailed in section 5.2.2 above were used to obtain mean sizes at age 3 years for each year-class at each site. The data were root transformed and tested for normality and homoscedascity. Firstly a one-way ANOVA was applied to each site in turn to determine whether there were any differences in mean sizes at age 3 years between the 5, 6 and 7 year old scallops. Where no differences were identified the data were then pooled and tested, again by one-way ANOVA, for differences between sites in mean size at age 3 years.

5.2.2.2 Testing for differences between total growth curves.

Where linearity of the growth curves between 1 and 3 years could not be proven then other methods of growth analysis were applied. This involved using the length at age data for plotting Ford-Walford graphs (Ricker, 1975; Pitcher & Hart, 1982) to determine growth parameters which were used to solve the growth equation:

$L_t = L_\infty(1-e^{-K(t-to)})$

This provides an equivalent method to that used by Hancock (1965) where measurements were made over several years of different cockles (Hancock's method 2) for plotting Ford-Walford graphs. This method was also employed to compare bivalve growth rates by Warwick & Price (1975). Hancock (1965) states that better approximations to straight lines in Ford-Walford plots are obtained using older animals as these yield more points on the graph. Consequently growth curves and Ford-Walford plots were made for the 7 year old scallops only (Figs. 5.4a - l and 5.5a - l respectively).

The coefficients involved in this equation have been described above. Solution of this equation at each site will then enable the time taken to achieve a size refuge to be determined. In this equation L_∞ = the maximum expected length and K = the coefficient of catabolism (von Bertalanffy, 1938) which describes the rate at which the asymptotic length of the growth curve is reached. Calculations of K values were made for each year-class at each site (3 K values per site) and these data were used in a one-way ANOVA to determine whether there were any statistically significant differences in this parameter between sites. The parameter K was calculated from the slope of the Ford-Walford plot (Hancock, 1965) which was, in turn, derived from the equation of the line fitted to the data by the Cricket Graph III graphical analysis software package (linear model: $y = Mx + C$) using:

Slope = $e^{-K} = M$ from the linear model. (Hancock, 1965)

and

$L_\infty = C/(1 - e^{-K}) = C/(1- M)$. (Hancock, 1965) (Equation 5.2)

The calculated coefficients are summarised in section 5.3.3. The only other parameter involved in the growth equation is t_0. This is the theoretical time t at which length equals zero and it is required as an initial value for non-linear regression analysis. This parameter was calculated by rearranging the growth equation, described below, and solving it for time t =1 using the other parameter values already calculated from the Ford-Walford plots.

$$L_t = L_\infty(1 - e^{-K(t-t0)})$$
$$L_t/L_\infty = (1 - e^{-K(t-t0)})$$
$$1 - (L_t/L_\infty) = e^{-K(t-t0)} = e^{-Kt} e^{Kto}$$
$$[1 - (L_t/L_\infty)]/e^{-Kt} = e^{Kto}$$

$$t_0 = Ln\ \{[1 - (L_t/L_\infty)]/e^{-Kt}\}/K \qquad \text{(Equation 5.3)}$$

Values of t_0 obtained by solving equation 5.1 for $t = 1$ are included in the summary table of the other growth parameters.

5.2.2.3 Determining the differences between K values at different sites.

Analysis was applied to K values obtained from 7 year old animals (the 1989 year-class) only as these animals should yield the most accurate Ford-Walford plots. The measurements from each individual scallop from a site were used to construct Ford-Walford plots which were in turn used to calculate K values. The calculated K values were used as replicates in a one way ANOVA testing for differences between sites in terms of this growth parameter of the von Bertalanffy growth model. Since this method yields a higher level of replication among calculated K values it is better able to define any differences between sites by producing greater power in the statistical tests used to compare K values from the different sites. This method also uses Ford-Walford plots derived from the oldest animals sampled. According to Hancock (1965) this should provide the most accurate estimates of growth parameters.

5.2.2.4 Solution of the general growth equation.

The growth equation was then rearranged to provide an estimate of the time taken to achieve a specified length in order to estimate a time to an assumed size refuge for the sites sampled.

$$L_t = L_\infty(1 - e^{-K(t-t_o)})$$
$$Lt/L_\infty - 1 = -e^{-K(t-t_o)}$$
$$1 - Lt/L_\infty = e^{-K(t-t_o)}$$
$$(Ln[1 - Lt/L_\infty])/-K = t - t_o$$
$$\{(Ln[1 - Lt/L_\infty])/-K\} + t_o = t$$

The parameters calculated for each site from 7 year old scallops were then substituted in this rearranged equation for calculating times to specified lengths for each site. The specified lengths used were 65, 75, 85 and 110mm which provided a best case, average case and worst case time respectively for scallops attaining a size refuge from predation at each site assuming that a size refuge is attained somewhere between 65 and 85mm shell length. 110mm was also used to determine the time taken for scallops to reach the Minimum Legal Landing Size.

5.2.3 Comparisons with historical growth data.

Mason (1957) sampled scallop grounds around the south of the Isle of Man during the mid 1950s. Some of his data correspond to sites where sampling took place during the present study. The two sites where samples were coincident are the Bradda Inshore and Chickens grounds. The methods described above can be applied to these data to determine whether any long term changes in the growth rates of scallops could be detected. The results are discussed in the light of data on fishing effort and its possible effect on any differences which may be observed. Growth curves from all of Mason's sampling sites are also presented.

Mason (1957) took measurements of scallop length, height and thickness and found significant correlation between all three dimensions in the scallops around the Isle of Man. Most of his sampling data were measurements of height (umbo to growth ring apex) so a conversion factor had to be applied to his data to provide estimates of shell lengths. This conversion factor was calculated as the average ratio of mean length to mean height ratio over all ages sampled using the data from table 2 in his 1957 paper. The calculated correction ratio for converting breadth to length was 1.1017. This factor was used to convert, by multiplication, the breadth data from stations 5 (Chickens) and 4 (Bradda Inshore) to length data - data obtained from table 3 in his paper. Mason's corrected data were then used to construct growth curves and Ford-Walford plots which were, in turn, used to determine growth parameters as described above. These parameters were then used in a comparison with contemporary data. The contemporary data were derived from ring measurements of the 7 year old (1989 year-class) scallops caught during the 1996 scallop survey at the Chickens and Bradda Inshore sites.

5.3 Results.

5.3.1 Analysis of scallop survey archives: 1992 - 1995.

Ford-Walford plots obtained from the scallop survey database records for scallops of the 1989 year-class caught in the June scallop surveys between 1992 and 1995 are presented in Figs. 5.2a - j. These plots were used to calculate the growth parameters for scallops at each site around the Isle of Man. A summary of the most relevant parameters is included in Table 5.1.

The Ford-Walford plots each have an additional line plotted (dashed line) where X = Y. The point at which the dashed line intersects the Ford-Walford plot gives an estimate of L_∞ reading from the X axis. These figures indicate that there is variability in growth rates between sites both in terms of L_∞ and K (the coefficient of catabolism).

5.3.2 Growth parameters obtained from scallop survey archives.

A summary of the parameters calculated from the Ford-Walford plots (Figs. 5.2a - j) are presented in Table 5.1. Parameters were calculated using the straight line equations calculated using the Cricket Graph III graphical analysis software package.

Table 5.1 indicates that highest K values occur at the two offshore south sites. Generally, however, the figures for L_∞ would appear to be unrealistically low or high, with the possible exceptions of Bradda Offshore, Chickens, Targets and East Douglas. The problem with this method of analysis is probably that there are not sufficient data points for a realistic estimate of parameters to be made. Most of the Ford-Walford plots are made using 3 data points (4 scallop surveys) while some are made with only 2 data points. This will inevitably lead to spurious results which can only be rectified by including more surveys to obtain more data points. These data should not be relied upon in their present state to provide accurate estimates of growth parameters. If further surveys were conducted and included in the analysis then this situation could be reconsidered. The results of this analysis were not used in subsequent estimates of scallop growth or for determining which sites might be most suitable for re-seeding.

5.3.3 June 1996 scallop survey - 5, 6 and 7 year old scallops.

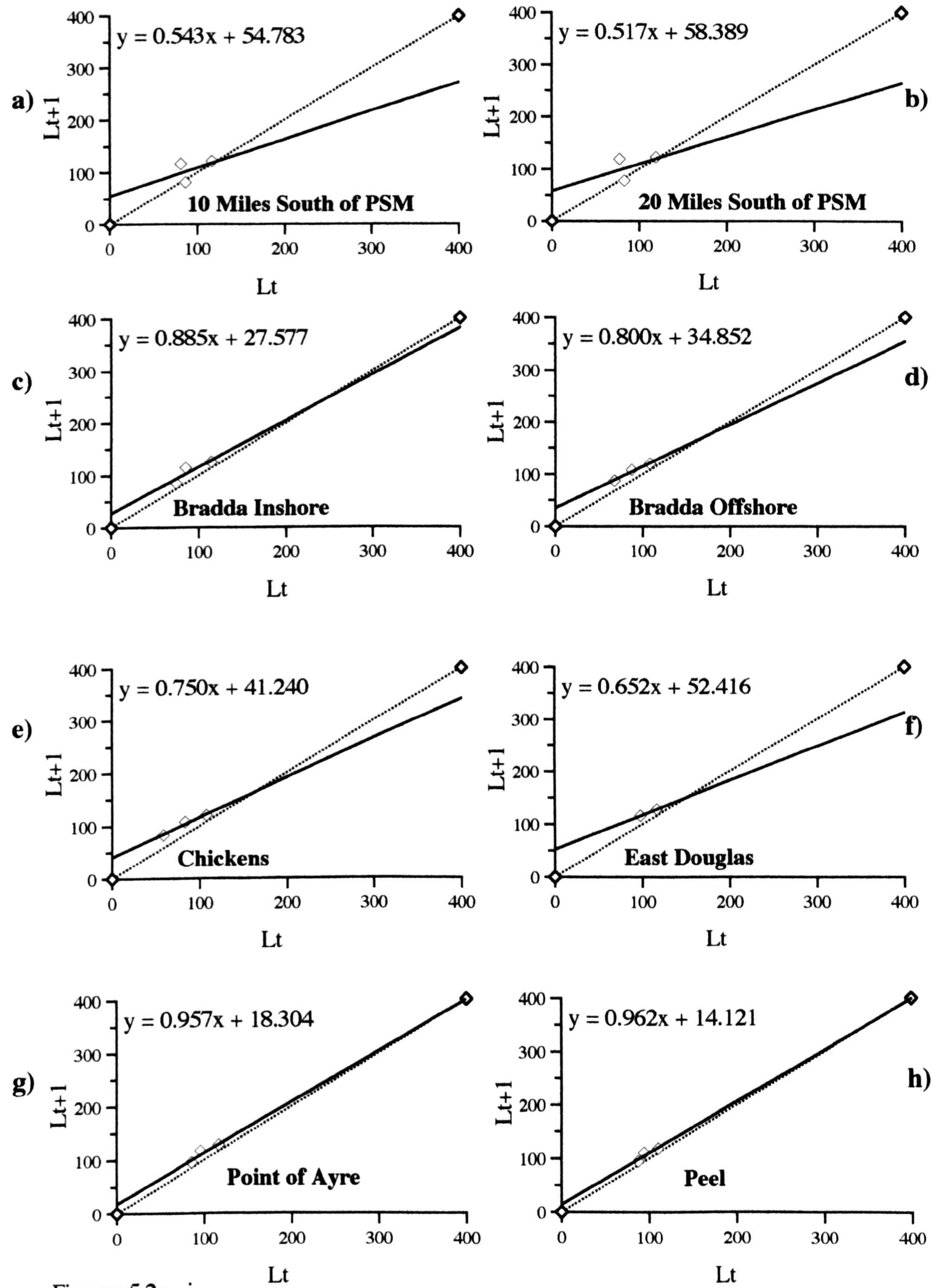
None of the growth curves from age 1 to 3 years were found to be linear. Consequently, growth rates (slopes) could not be directly compared. A different approach was required to identify whether statistically significant differences existed within sites and between sites and the results of the analyses used are detailed in sections 5.3.4 - 7.

5.3.4 Differences between shell lengths at 3 years of age within sites.

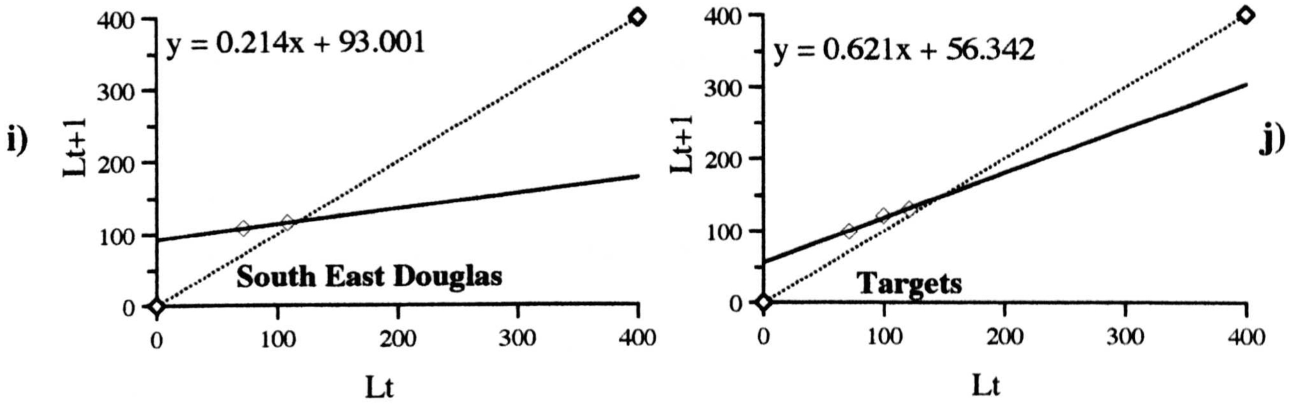
Results of a series of one way ANOVAs testing for year to year, within site differences between the mean sizes of 5, 6 and 7 year old scallops at age 3 years are summarised in Table 5.2. The data were square root transformed. The null hypothesis in each case is:

H_O: There are no differences in root transformed mean lengths at age 3 years for the 3 year classes measured at this site.
H_A: There are significant differences in the root transformed lengths at age 3 years for the 3 year classes measured at this site.

Table 5.2 suggests that there were no significant differences between the year-classes analysed in terms of mean shell lengths of scallops (measured at age 3 years) at the following sites: Peel, Chickens, Bradda Inshore and Offshore, East Douglas, Point of Ayre and Targets. This means that the majority of sites show no significant difference in growth rate up to year 3 from year to year between the year-classes measured. The Laxey sample suffered from low replication (number of animals caught) in the 7 year old cohort which may explain why



Figures 5.2a - j
Ford-Walford plots obtained from archived scallop survey records for 7 year old scallops (1989 year-class). Each figure refers to the site labelled in that figure. Lines of X = Y are included in each plot to indicate the derivation of L_∞



Figures 5.2a - j (continued)
Ford-Walford plots obtained from archived scallop survey records for 7 year old scallops (1989 year-class). Each figure refers to the site labelled in that figure. Lines of X = Y are included in each plot to indicate the derivation of L_∞

differences were identified at this site. Most of the sites where differences were significant appear to be to the east and offshore to the south of the Isle of Man.

The fact that several sites appear to show year to year variations in scallop growth is probably one of the factors causing the inaccuracies in growth parameter estimates observed in section 5.3.2.

Data from the sites where no differences between year-classes were identified were pooled for a one-way ANOVA to test for differences in mean lengths at age 3 years between these sites. The results of the ANOVA are summarised in Table 5.3.

H_O: There are no differences between root transformed mean lengths at age 3 at the sites tested.
H_A: There are significant differences between root transformed mean lengths at age 3 at the sites tested.

Table 5.3 shows that the null hypothesis is rejected and it is concluded that, at age 3 years, scallops grow to significantly different mean sizes at different sites. Since three years of age is approximately the age at which a size refuge from predators will be expected to be achieved it is therefore important to know at which sites the largest 3 year old scallops occur. This information will allow conclusions about the best sites for re-seeding to be drawn on the basis of where scallops are likely to achieve a size refuge fastest. Results of a Tukey multiple comparison test on the above data are detailed in Table 5.4. The critical value of the q statistic used in the comparisons was:

$q_{0.05,\infty,7} = 4.170$.

Table 5.4 shows that 3 year old scallops, at all sites analysed, grow to a larger mean length than they do at the Chickens ground. Also the mean lengths achieved at the East Douglas and Targets are significantly larger than those at Bradda Inshore, Bradda Offshore and Peel. The test lacks the power to discern any differences between the other sites. This appears to indicate that scallops might achieve a size refuge fastest on the East Douglas and Targets grounds and slowest at the Chickens ground. The sites where the 3 year old scallops achieve the largest mean size appear to be found around the northern half of the Isle of Man off the east and west coasts, whereas the smaller 3 year old scallops are found to the south and west of the island for the sites tested. The above data are summarised graphically in Fig. 5.3.

Table 5.1

Summary of the growth parameters K (coefficient of catabolism) and L_∞ asymptote of the growth curve) calculated from the Ford-Walford plots (Figs. 5.2a-j).

Site	K	L_∞(mm)
10 Miles South P.S.M	0.611	119.88
20 Miles South P.S.M	0.660	120.76
Bradda Inshore	0.122	239.80
Bradda Offshore	0.223	174.26
Chickens	0.288	164.96
Peel	0.039	371.61
Targets	0.476	148.66
East Douglas *	0.428	150.62
South East Douglas *	1.54	118.32
Point of Ayre	0.044	425.67

* Denotes sites where only 2 points were obtained for the Ford-Walford plot.

Table 5.2

Summary of one way ANOVAs testing for significant differences in mean scallop shell lengths at 3 years of age within each site sampled.

Site	Conclusion	Probability
Peel	Accept H_O	$P = 0.214$
Chickens	Accept H_O	$P = 0.079$
10 Miles South P.S.M	Reject H_O	$P = 0.005$
20 Miles South P.S.M.	Reject H_O	$P = 0.001$
Bradda Inshore	Accept H_O	$P = 0.221$
Bradda Offshore	Accept H_O	$P = 0.257$
East Douglas	Accept H_O	$P = 0.898$
Laxey	Reject H_O	$P = 0.01$
Point of Ayre	Accept H_O	$P = 0.301$
South East Douglas	Reject H_O	$P < 0.001$
Targets	Accept H_O	$P = 0.097$
Ramsey	Reject H_O	$P < 0.001$

Table 5.3

Summary of the one way ANOVA testing for differences in scallop mean lengths between sites sampled round the Isle of Man.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	P
Site	6	48.251	8.042	54.05	P < 0.001
Error	461	68.592	0.149		
Total	467	116.843			

Table 5.4

Summary of the results of the Tukey multiple comparison test applied to the data analysed in Table 5.3.

Site	Chickens	Peel	Bradda Offshore	Bradda Inshore	Point of Ayre	East Douglas	Targets
n	77	90	60	59	71	64	47
Root mean	8.7612	9.0583	9.2175	9.4047	9.5397	9.6416	9.7142

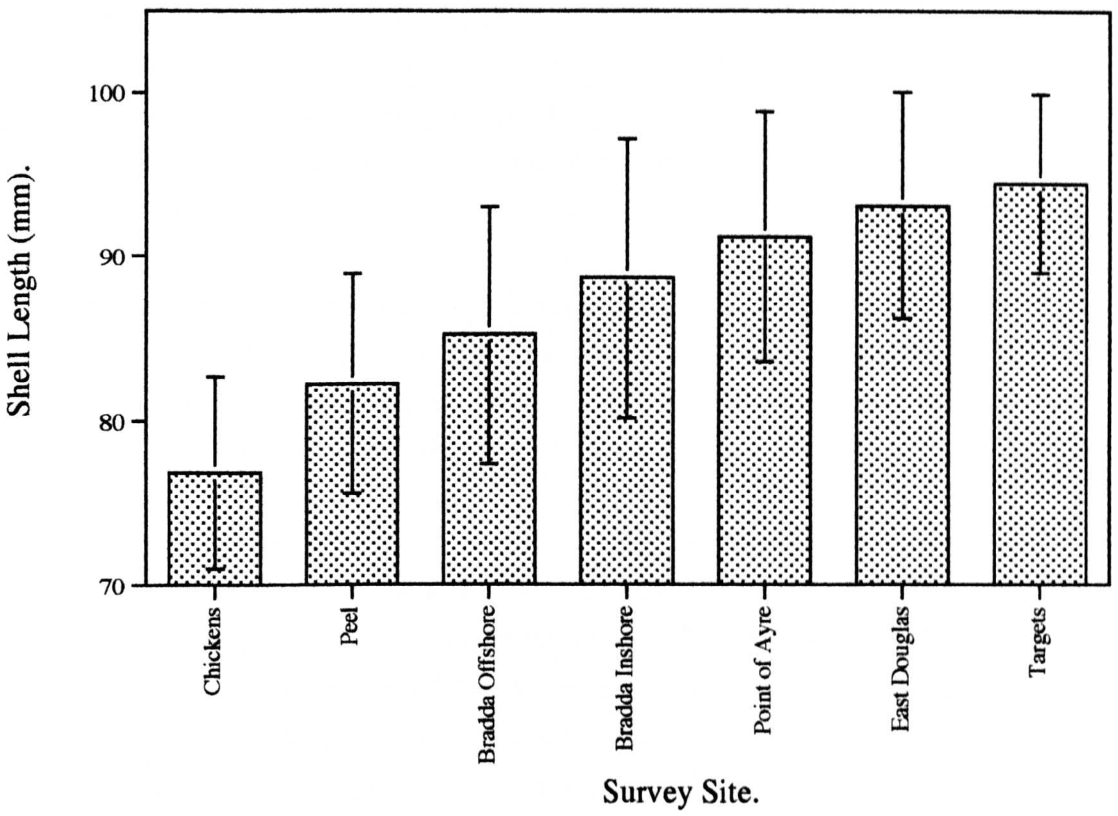


Figure 5.3
Mean shell lengths of scallops at 3 years of age. Data pooled within sites where no differences were identified between year-classes at that site. Error bars ± 1 S.D and length shown from 70mm and above for clarity of comparison.

5.3.5 Differences between growth parameters.

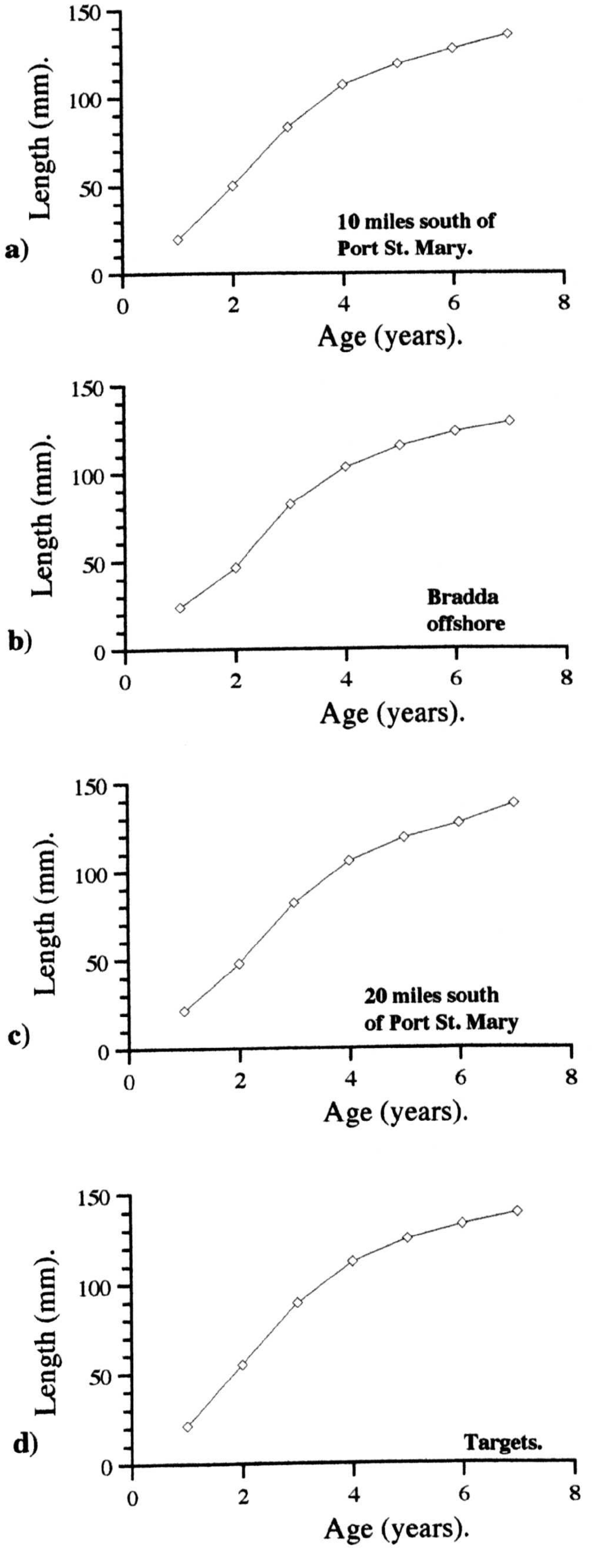
Growth curves for 7 year old scallops at each ground surveyed are presented in Figs. 5.4a - l. Each growth curve has its associated Ford-Walford plot adjacent to it (Figs. 5.5a to l). The Ford-Walford plots provide estimates of the growth parameters which are summarised in Table 5.5 following the graphs.

The Ford-Walford plots each have an additional line plotted (dashed line) where X = Y. The point at which the dashed line intersects the Ford-Walford plot gives an estimate of L_∞ reading from the X axis. These figures indicate that there is variability in growth rates between sites both in terms of L_∞ and K (the coefficient of catabolism).

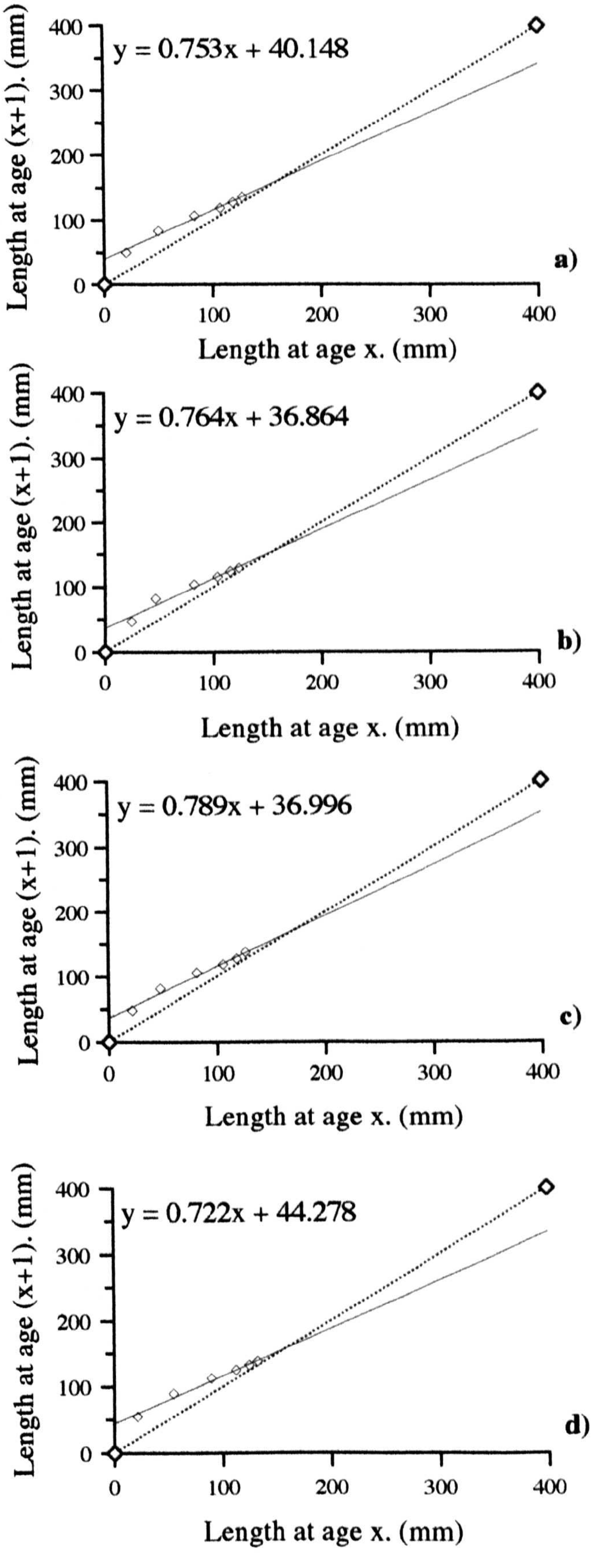
The K values summarised in Table 5.5 are of most interest since they represent the rate at which the original growth curve approaches its asymptote. A one-way ANOVA was used to test for differences between K values at different sites using each age class or cohort as replicates within a site. The data were found to be normally distributed but no transformation could be found which would equalise the variances. This, however, should not cause a problem to an ANOVA as this type of statistical test is known to be robust enough to handle heteroscedascity (Zar, 1984). The results of the one way ANOVA are summarised in Table 5.6.

Table 5.6 shows that a significant difference exists between the sampled K values. A Tukey multiple comparison test was then carried out to identify where these differences lay. The results of this test are summarised in Table 5.7.

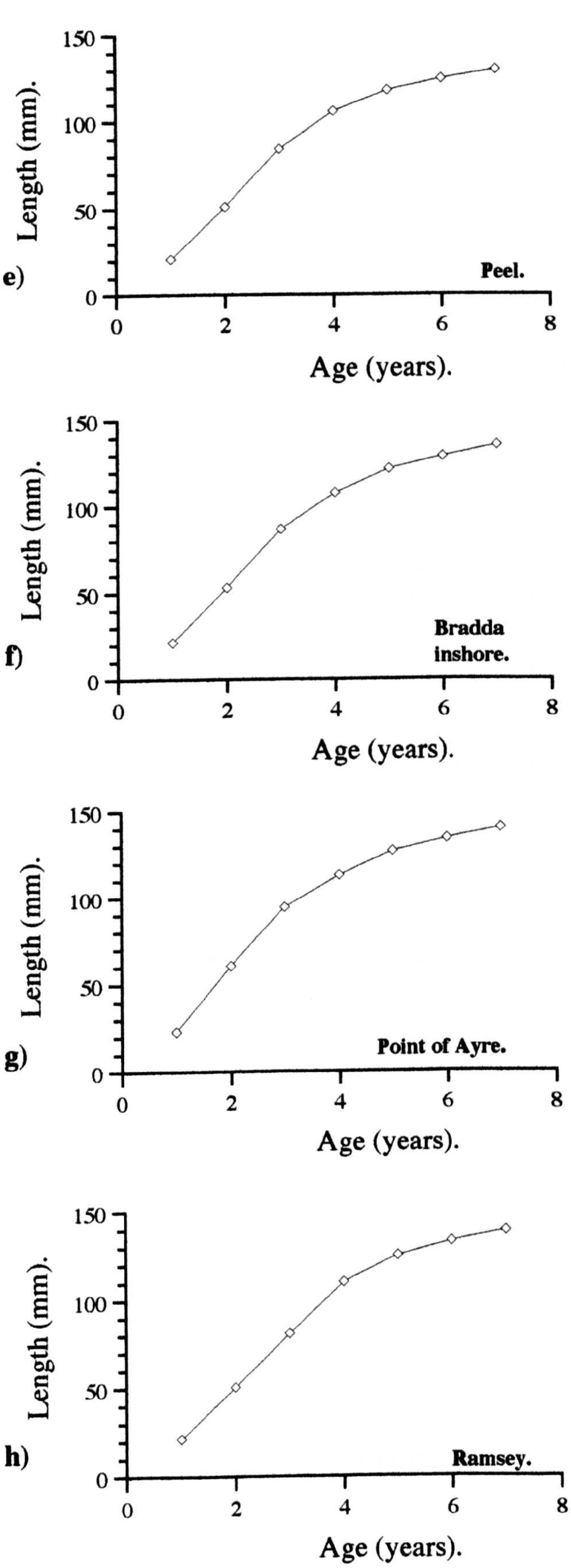
Table 5.7 shows that the Tukey test only identifies statistically significant differences between the East Douglas (high K value) and the Chickens and 20 Miles South of Port St. Mary sites (low K values). This is probably due to the low level of replication (n=3 where 5 is generally considered to be the minimum) and high number of sites involved (12) which may lead to confusion. Examining more year-classes could clarify any other differences which may exist. The problem with this, however, is that younger scallops yield less accurate Ford-Walford plots and it becomes less easy to measure ring lengths of scallops older than 7 years accurately. The low level of replication (3 year-classes analysed so n = 3 in case) means that the Tukey test lacks power in determining differences between sites. This low level of replication was addressed by using a different method described in section 5.3.6.



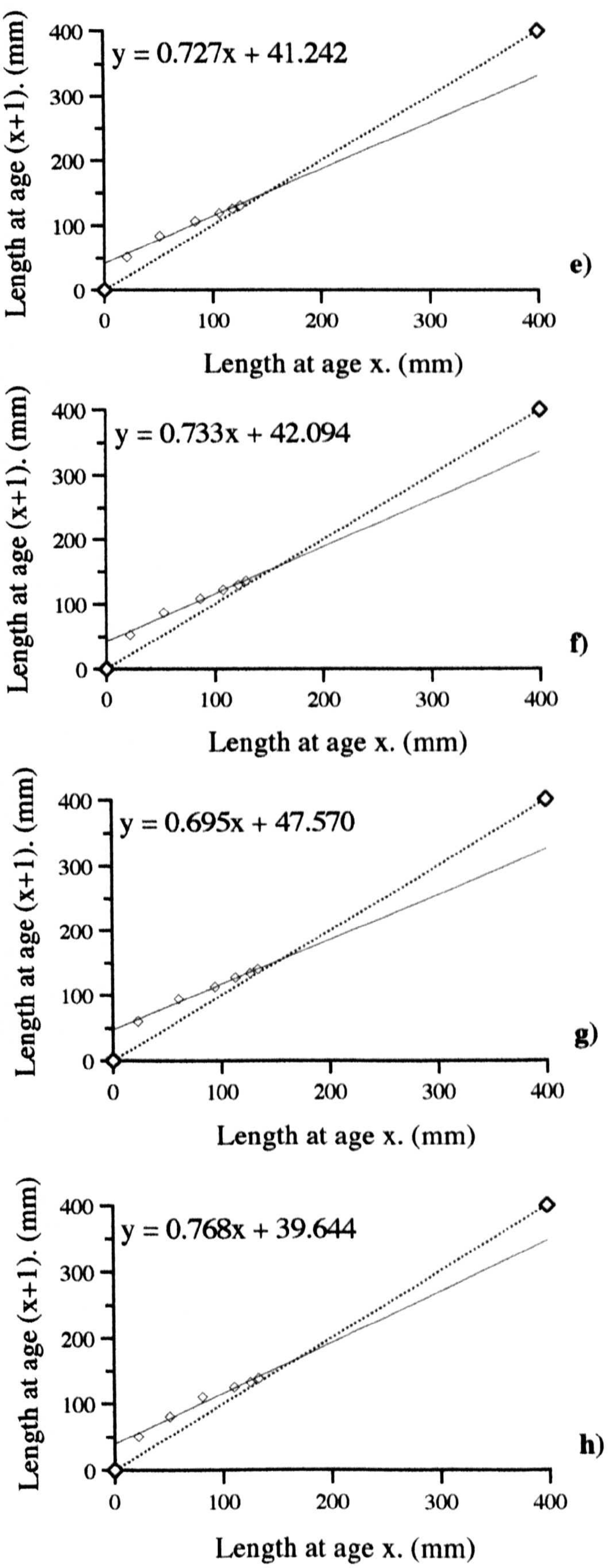
Figures 5.4a - d
Growth curves for the 7 year old scallops obtained during the June 1996 scallop survey.



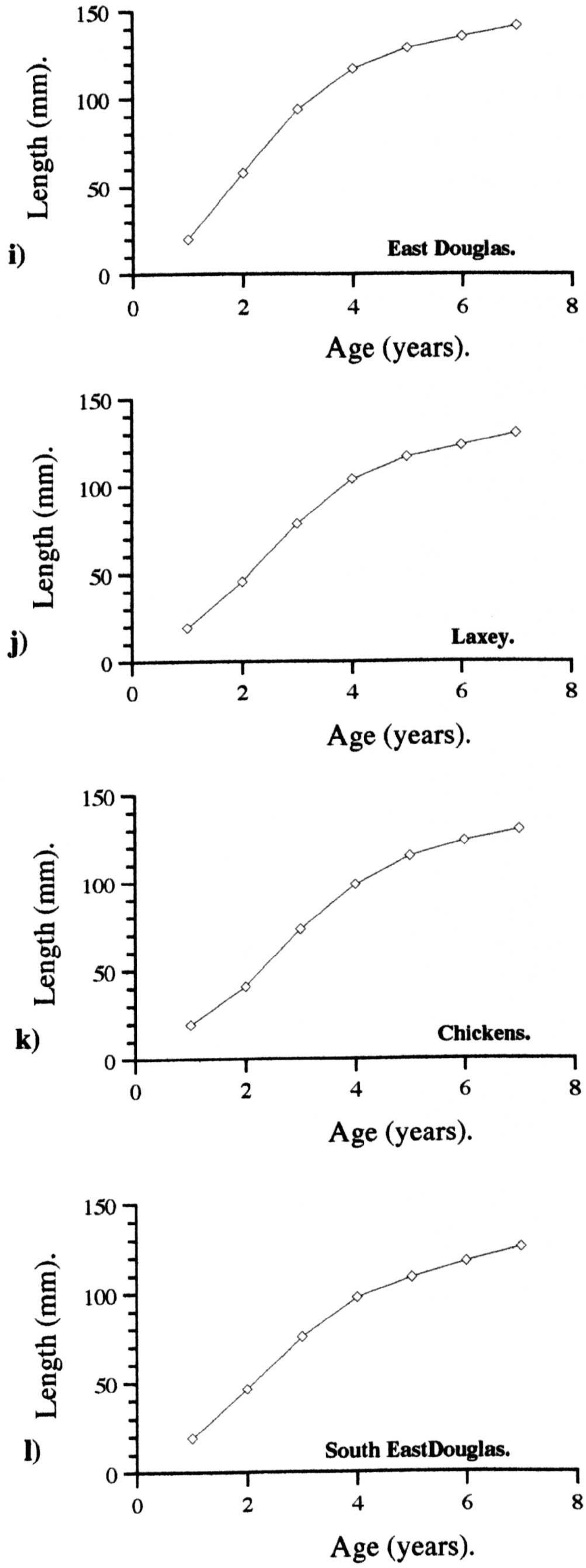
Figures 5.5a - d
Ford-Walford plots obtained from the data in Figs. 5.4a - d. Line of X=Y included to show derivation of L_∞



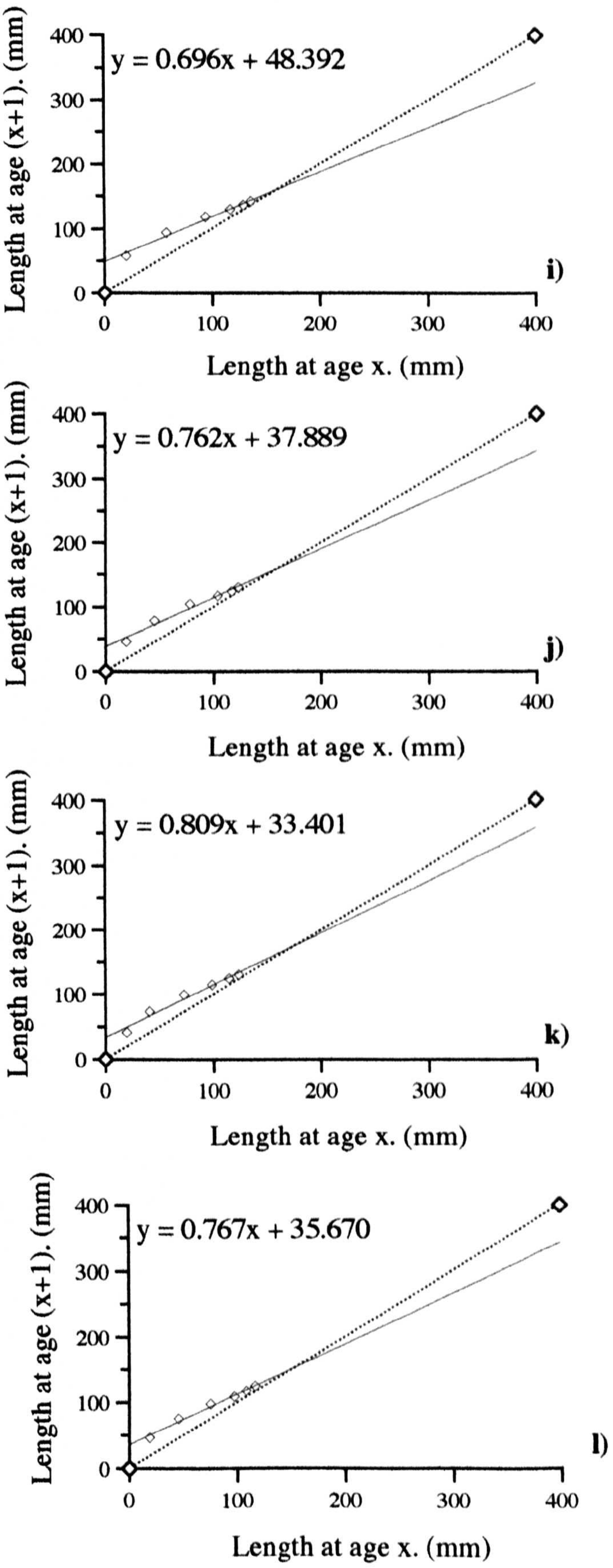
Figures 5.4e - h
Growth curves for the 7 year old scallops obtained during the June 1996 scallop survey.



Figures 5.5e - h
Ford-Walford plots obtained from the data in Figs. 5.4e - h. Line of X=Y included to show derivation of L_∞



Figures 5.4i - l
Growth curves for the 7 year old scallops obtained during the June 1996 scallop survey.



Figures 5.5i - l
Ford-Walford plots obtained from the data in Figs. 5.4i - l. Line of X=Y included to show derivation of L_∞

Table 5.5

Summary of the growth parameters calculated using the Ford-Walford plots (Figs. 5.5a - l) for each site sampled. Parameters were calculated for all three year-classes but only growth curves and Ford-Walford plots for the 7 year old scallops (1989 year class) are included in this section.

Site	Age	K	L_∞(mm)	t_0
East Douglas	7yr	0.362	159.18	0.629
	6yr	0.334	160.73	0.529
	5yr	0.315	168.31	0.570
Laxey	7yr	0.272	159.20	0.528
	6yr	0.351	142.31	0.546
	5yr	0.282	159.37	0.555
10 Miles south PSM	7yr	0.284	162.54	0.547
	6yr	0.203	192.29	0.486
	5yr	0.153	241.89	0.455
20 Miles south PSM	7yr	0.237	175.33	0.446
	6yr	0.179	209.54	0.413
	5yr	0.126	271.34	0.397
Ramsey	7yr	0.264	170.88	0.482
	6yr	0.203	193.87	0.418
	5yr	0.402	148.69	0.608
Peel	7yr	0.319	151.07	0.534
	6yr	0.284	158.71	0.516
	5yr	0.290	175.50	0.607
Bradda Inshore	7yr	0.311	157.66	0.527
	6yr	0.269	170.42	0.473
	5yr	0.265	179.68	0.483
Bradda Offshore	7yr	0.269	156.20	0.380
	6yr	0.300	159.48	0.505
	5yr	0.226	185.44	0.407
Targets	7yr	0.326	159.27	0.561
	6yr	0.348	160.51	0.558
	5yr	0.304	174.21	0.551
South East Douglas	7yr	0.265	153.09	0.492
	6yr	0.211	167.84	0.447
	5yr	0.134	233.11	0.398
Chickens	7yr	0.212	174.87	0.342
	6yr	0.197	186.74	0.316
	5yr	0.113	280.61	0.215
Point of Ayre	7yr	0.364	165.24	0.544
	6yr	0.312	173.35	0.463
	5yr	0.269	177.05	0.456

Table 5.6

Summary of the one way ANOVA used to determine whether differences existed between K values (coefficient of catabolism) for different populations of scallops around the Isle of Man.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	P-value
Site	0.10969808	11	0.00997255	3.67478616	0.00371376
Error	0.06513067	24	0.00271378		
Total	0.17482875	35			

Table 5.7

Summary of the Tukey multiple comparison test applied to the data analysed in Table 5.6.

Site	CH	20S	SD	10S	BO	BI	RY	PL	LX	PA	TA	ED
N	3	3	3	3	3	3	3	3	3	3	3	3
Mean K	0.174	0.181	0.203	0.213	0.265	0.282	0.290	0.298	0.302	0.315	0.326	0.337

Abbreviations used in Table 5.7:

CH	Chickens	20S	20 Miles South of PSM	BO	Bradda Offshore
LX	Laxey	10S	10 Miles South PSM	BI	Bradda Inshore
RY	Ramsey	SD	South East Douglas	PL	Peel
TA	Targets	PA	Point of Ayre	ED	East Douglas

5.3.6 Estimating growth parameters using 7 Year old scallops.

A further examination of the K parameter was carried out using measurements of individual, 7 year old scallops to obtain K values. Between 5 and 30 individual 7 year old scallops were collected from all sites surveyed during the June 1996 scallop survey. This yielded a higher level of replication among calculated K values than that obtained in section 5.3.5 and used only older animals for more accurate estimates of growth parameters. A one factor ANOVA, summarised in Table 5.8, was used to determine whether differences existed in K values between sites. The higher level of replication should mean that the statistical tests used have greater power in discerning differences between sites.

Table 5.8 indicates that there are significant differences between sites ($P = 1.53 \times 10^{-5}$) in terms of the coefficient of catabolism K obtained from 7 year old scallops. The results of the Tukey test to determine where these differences lay is summarised in Table 5.8.

Table 5.9 shows that there is no significant difference in K values between East Douglas and Point of Ayre and that there are no significant differences between Chickens, 20 Miles South of Port St. Mary and South East Douglas. However, the former two sites have significantly higher mean K values than the latter three sites. No conclusions can be drawn regarding the other sites as the test is not powerful enough to discern differences. It is highly unlikely that there will be any significant differences observable in growth rates of scallops at these sites if the test cannot determine exactly where differences lie.

Comparing tables 5.7 and 5.9 indicates that the increased level of replication has led to an increase in power of both the ANOVA and the Tukey multiple comparison test. The sites are more clearly segregated by the test although the difference is not great. Table 5.9 indicates significant differences between East Douglas/Point of Ayre and Chickens/South East Douglas/20 Miles South of PSM while Table 5.7 only identifies significant differences between East Douglas and Chickens/20 Miles South of PSM. The majority of sites in both tables are identified as having no significant differences in K value for their scallop populations.

5.3.7 Solution of the general growth equation.

The general growth equation was solved using the parameters obtained from the 7 year old scallops analysed in section 5.3.6. Estimated ages at lengths 65, 75, 85 and 110mm were calculated for each site and are summarised in Table 5.10.

Table 5.8

Summary of the one way ANOVA test used to determine between site differences in K values using back-calculated growth data from 7 year old scallops (1989 year-class) collected during the June 1997 scallop survey.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	P Value
Site	11	0.2444	0.0222	4.2271	1.53×10^{-5}
Error	169	0.8882	0.0053		
Total	180	1.1326			

Table 5.9

Summary of the Tukey multiple comparison test applied to the data analysed in Table 5.8.

Site	CH	20S	SD	LX	RY	10S	BO	BI	PL	TA	ED	PA
N	7	22	27	4	12	31	10	11	25	4	8	14
Kav	0.218	0.235	0.269	0.279	0.285	0.286	0.308	0.314	0.322	0.339	0.367	0.369

Key to abbreviations used in table 5.12:

CH	Chickens	20S	20 Miles South of PSM	SD	South East Douglas
LX	Laxey	RY	Ramsey	BO	Bradda Offshore
BI	Bradda Inshore	10S	10 Miles South of PSM	PL	Peel
TA	Targets	ED	East Douglas	PA	Point of Ayre

Table 5.10

Summary of the estimated time taken for scallops to achieve specified sizes as estimated by the growth equation (Equation 5.1). The data are arbitrarily ordered by estimated age at 65mm shell length.

Site	Estimated age at 65mm (yrs)	Estimated age at 75mm (yrs)	Estimated age at 85mm (yrs)	Estimated age at 110mm (yrs)
Point of Ayre	2.13	2.43	2.77	3.89
Targets	2.24	2.56	2.91	4.03
Ramsey	2.25	2.57	2.93	4.04
East Douglas	2.25	2.56	2.90	4.02
Inshore Bradda	2.38	2.74	3.15	4.49
20 Miles South PSM	2.39	2.78	3.21	4.52
10 Miles South PSM	2.43	2.80	3.22	4.56
Offshore Bradda	2.47	2.86	3.30	4.78
Peel	2.48	2.86	3.29	4.74
Laxey	2.53	2.90	3.32	4.66
South East Douglas	2.62	3.06	3.57	5.24
Chickens	2.64	3.07	3.53	4.96

The sites are ordered by estimated age in years at 65mm as this is felt to be the most likely starting point for a size refuge given the results of tethering and aquarium experiments. Table 5.10 shows that scallops from the three most northerly sites and the East Douglas site attained a size of 65mm most quickly. The Chickens and South East Douglas sites appear to be the sites at which scallops attain a size of 65mm the slowest. These results generally agree with the ANOVA summary (Table 5.9) which identified significant differences in K values between Point of Ayre/East Douglas and Chickens/20 Miles South PSM/South East Douglas. The other sites were identified as having no significant differences in K values and gave a range of ages at 65mm shell length of 2.38 years (Bradda Inshore) to 2.53 years (Laxey).

These results will be discussed in relation to re-seeding potential and in relation to the potential threat posed by the relative sizes and densities of predators found at these sites during scallops surveys.

5.3.8 Comparisons of contemporary and historical datasets.

The growth curves and Ford-Walford plots obtained from the historical dataset (Mason, 1957) and from the corresponding sites sampled during the June 1996 scallop survey (7 year old scallops) are presented. The growth parameters calculated from the Ford-Walford plots are compared in Table 5.11.

At both sites, the coefficients of catabolism K have fallen slightly in the contemporary dataset while the estimated values of L_∞ have increased. The differences between these figures cannot be tested statistically because the data presented by Mason (1957) were only presented as mean values. The underlying data would be required in order to test for statistical differences in the data. If, however, the differences were significant then some factor may have caused this reduction over time. Alternatively the observed reduction may be due to natural fluctuations in environmental parameters affecting growth rate with one sampling period coinciding with a time of more suitable environmental factors for growth. Of course a further alternative is that there are no detectable differences between the figures.

The Bradda Inshore ground gives a higher K value than the Chickens ground in both historical and contemporary datasets. This difference was not identified as being statistically significant during the current study (ANOVA summary Table 5.9). However, the magnitude of the observed difference in K values between these two sites is 2.6 times larger in the historical dataset compared with that observed in the contemporary samples analysed above (7 year old scallops). This means that for the sites and dates analysed the difference in K values derived from scallops caught at the Bradda Inshore and Chickens grounds has

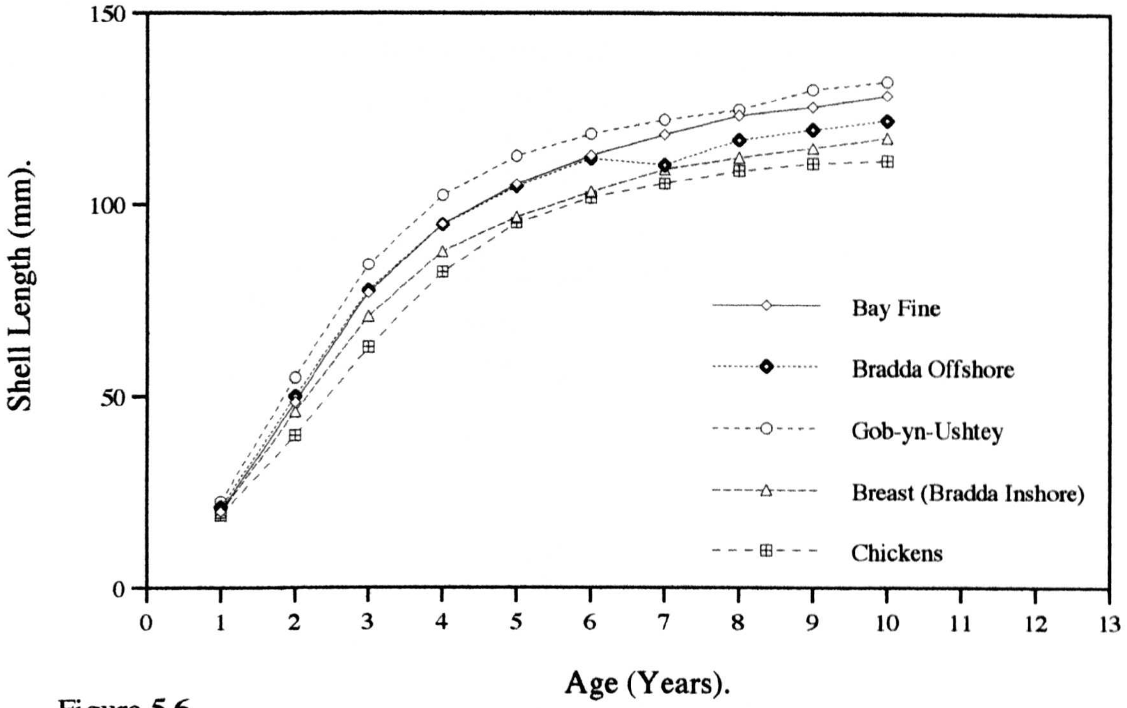


Figure 5.6
Data from Mason, 1957 showing umbo to growth ring lengths at different sites around the Isle of Man.

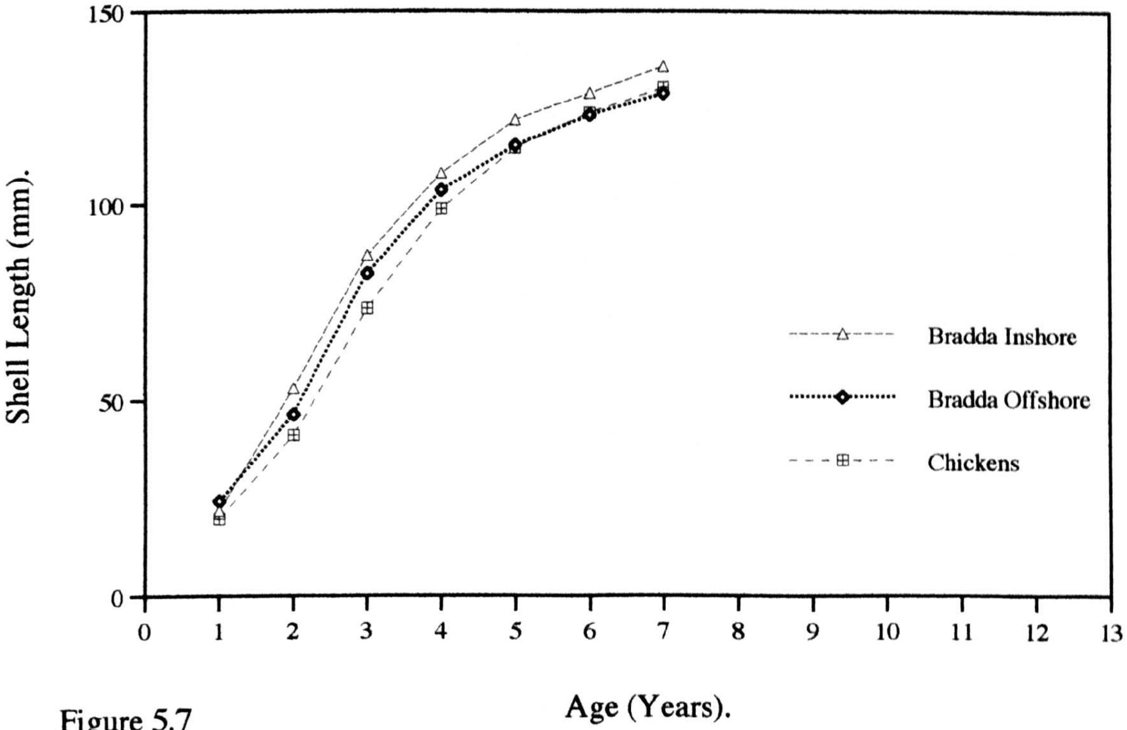


Figure 5.7
Data from 7 year old scallops from the June 1996 scallop survey. Sites were chosen which most closely corresponded to the sites sampled by Mason, 1957.

Table 5.11

Summary of the comparison of growth parameters (K values, L_∞ and t_0) including calculations which show the changes in K values between 1957 and 1996.

	K	%Change in K	L_∞	t_0
Contemporary data				
Chickens	0.212	down 27.4%	178.87	0.456
Bradda Inshore	0.311	down 5.8%	157.66	0.527
Historical data - Mason, 1957				
Chickens	0.292	-	133.47	0.483
Bradda Inshore	0.330	-	135.81	0.533

increased by a factor of 2.6. Although K values at both sites appear to have fallen over time the largest drop has occurred at the Chickens site. This has contributed most to the increased difference in K values between the two sites. Possible factors that may have contributed to the observed differences in this growth parameter are discussed in the section 5.4. It is possible that the differences in K values observed in the historical dataset maybe significant although, unfortunately, this was not statistically testable.

5.4 Discussion.

Analyses based on past scallop survey records revealed highest K values (fastest approach to theoretical maximum length) at the two offshore sites to the south of the Isle of Man. However, the estimates for maximum theoretical lengths obtained from the Ford-Walford plots appear to be unrealistically low or high except for 4 of the 10 sites analysed. The maximum measured scallop size obtained during an average survey at most sites would be expected to be approximately 160-180mm. The problem with some of the calculations undoubtedly stems from the low numbers of surveys carried out at some of the sites leading to inaccuracies in the Ford-Walford plots. The fact that the sampling gear was only able to catch 2 year old scallops and older also reduced the data available for constructing Ford-Walford plots. The nature of this method of analysis means that more accurate results are obtained when longer time periods/older animals are used. In this case 2 year old animals in 1992, 3 year old animals in 1993, 4 year olds in 1994 and 5 year olds in 1995 were used. In each case this will yield a maximum of 3 data points for each Ford-Walford plot. Further analysis of scallop survey data would therefore be required in order to increase the accuracy of these results. The results obtained using this method of analysis should , therefore, be treated with caution.

Most sites demonstrated no significant differences between sizes of 3 year old scallops from year to year. This suggests that, within a particular site, conditions for scallop growth remain relatively stable. Three years of age was chosen as a general point of comparison both between and within sites as this was the age at which laboratory experiments showed that a size refuge from predation was most likely to be attained. Significant differences in sizes of three year old scallops were, however, identified between different sites round the Isle of Man. This suggests that scallops will tend to achieve a size refuge from predation faster at some sites than at others. The Chickens and Peel sites gave the lowest mean sizes of 3 year old scallops, while the highest mean sizes were found at the East Douglas and Targets sites. These results suggest that the Chickens and Peel sites would be least suitable for re-seeding trials taking only growth up to 3 years of age into account.

The comparison of coefficients of catabolism (K values) obtained from the Ford-Walford plots for 5, 6 and 7 year old scallops (1989 - 91 year-classes) showed that significant differences existed between sites. Significant differences were identified between the East Douglas (high K value, high growth rate) and the Chickens and 20 Miles South of Port St. Mary sites (low K values, low growth rates). The data for 7 year old scallops were also re-analysed and identified similar trends in the data this time with Point of Ayre and East Douglas as high K value (high growth rate) sites and Chickens, 20 Miles South of PSM and South East Douglas as low K value sites. The analyses suggest that differences in K values between sites were not great which is also reflected in the estimated times that scallops at different sites would be expected to achieve different sizes (Table 5.10).

Times taken to achieve 65, 75 and 85mm shell lengths were calculated using growth equations and ring measurements of three year-classes from the June 1996 scallop survey. 75mm equates to the most likely size at which a size refuge is attained as identified in Chapter 4. The most rapid attainment of 75mm shell length occurs at the Point of Ayre site while the slowest occurs at the Chickens site. The difference in estimated time to achieve 75mm between these two sites is 0.64 years or just under 8 months. This is a considerable difference which should be investigated in greater detail should re-seeding be considered.

Table 5.10 includes estimates of how long scallops at each site might be expected to take to reach the Minimum Legal Landing Size of 110mm. The Point of Ayre site is identified as the site where scallops would achieve this size most quickly (3.89 years) while the South East Douglas site gives the longest estimated time (5.24 years), a difference of 1.35 years or 1 year and 4 months. This result indicates that the growth curves at these two sites must diverge as scallops get older because the differences in time to attain specific sizes increases with scallop age. At all of the other sites one would expect newly settled scallops to take at least 4 years to reach the Minimum Legal Landing Size. If scallops could be successfully re-seeded at 65mm shell length then one would expect these scallops to be available to the fishery between 1.76 years (Point of Ayre) and 2.62 years (South East Douglas) after re-seeding assuming that re-seeded scallops achieved the same growth rates. These figures could be reduced if re-seeded scallops grew more quickly.

Several questions remain regarding scallop growth rates in relation to re-seeding: why such large differences in apparent, estimated growth rates?; would these estimated growth rates hold for re-seeded animals?; is there a genetic difference between scallop stocks at different sites which might explain the observed differences?; could different hydrographic and hydrodynamic parameters be responsible?; would the observed differences in growth rates between sites be a more important factor than mean predator sizes or densities when choosing a site for re-seeding? The reality is most likely that a combination of several factors contribute to the observed differences in estimated growth rates.

Allison (1994) devised a growth model for scallops which identified seasonal fluctuations in aductor muscle and gonad weights. Once scallops exceed 4 years of age these fluctuations become larger than the annual growth increments for *Pecten maximus*. The seasonal changes in aductor muscle weight (decreasing during winter) could have implications for escape responses from predators. The decrease in muscle weight could reduce the effectiveness of an escape response. Fortunately this appears to coincide with a minimum in predator activity identified by the tethering experiments in Chapter 2. Use of the growth model devised by Allison (1994) was felt to be unecessary in this preliminary investigation of scallops growth rates at different sites around the Isle of Man.

The graphs comparing the data presented by Mason (1957) and the data from the June 1996 survey where 7 year old scallops were measured appear to indicate possible differences between historical and contemporary growth curves. Taking 3 years of age as an example in both datasets, the historical data give a fairly broad range of sizes at different sites with the upper sizes being about 80mm and the lower sizes around 60mm. The June 1996 data give a much narrower range of sizes at age 3 years with a similar upper limit of around 80mm but with a raised lower limit nearer to 75mm. A brief examination of the graphs (Figs 5.6 and 5.7) suggests that the greatest change has occurred at the Chickens sampling site where the mean size of 3 year old scallops appears to have risen. The full Mason dataset would have to be examined in order to test whether this observed difference is statistically significant. It is very difficult to see any reason for this change over time. The finding that growth rates of scallops have fallen at two commercial fishing grounds to the south of the Isle of Man over a period of approximately 40 years may be of concern to the local scallop fishery if this is identified as a continuing trend. Although this could not be tested statistically, the drop in estimated K value at the Chickens site over the last 40 years was 27.4% and at the Bradda Inshore site the drop was 5.8% (Table 5.11).

5.4.1 Conclusions.

Prey growth rates vary significantly at different sites around the Isle of Man which may influence the siting of re-seeding trials. Historical data indicate that variations in growth rates of scallops also occurred in the 1950s at sites equivalent to some of those sampled in the present study. Some of the sites sampled during 1996 demonstrate year to year variations in growth rates. These variations may be more likely to be a result of differing environmental conditions from year to year assuming a consistent source of spat. In the present study the best growth rate achieved was at the Point of Ayre site where it was estimated that scallops could potentially achieve a size of 75mm at 2.43 years after settlement. Conversely the worst estimated growth rate was observed at the Chickens site - 75mm attained in an estimated 3.07 years after settlement. Re-seeded scallops of 65mm shell length, assuming growth rates equivalent to those observed in the natural populations, would potentially be available to the fishery at between 1.76 and 2.62 years after re-seeding depending upon the site chosen.

Chapter 6 - General Discussion.

The tethering experiments described in this thesis suggest that July would be the best month to seed scallops in a re-seeding trial as this would provide the re-seeded animals with approximately 2-3 months of lower predation pressure. Seeding could take place in the early morning to provide the best chance of avoiding nocturnally active predators during the stressful initial period. This time of year might expose the re-seeded scallops to the threat of crab predation but observations made during 1995, when there was a significant increase in crab landings suggest that this may have been a factor in reducing crab predation on tethered scallops to almost nil. Thus predator removal in this manner could not only enhance the income to the local crab fishing fleet but would also be beneficial to any re-seeding trials. More work would be required to determine whether such a link exists between crab fishing and reduced predation by crabs on scallops.

A bimodal feeding pattern in starfish identified by Doering (1982) was also observed during both 1993/4 and 1995 tethering experiments, as was a winter minimum in feeding also identified in work by Castilla (1972). The drop in starfish feeding in late winter/early spring is thought to be associated with spawning (Milekovskiy, 1969; Jangoux, 1977; Doering, 1982). Feeding then recommences after spawning takes place creating the second peak.

Statistically, starfish consumed the same number of small and large scallops during the 1993/4 tethering experiments, but consumed more small scallops than large during the 1995 experiments. This may indicate a change in activity or in overall predator density/size. The presence of more starfish might mean that multiple attacks would be more likely and that consequently more scallops could be consumed. The results from the dredge surveys indicate that starfish densities at the Bradda Inshore site remained constant (statistically) during 1994 and 1995, but rose significantly during 1996 after completion of the tethering experiments. Diver surveys showed a rise in starfish density actually around the tethering sites from autumn 1994 to summer 1996. The mean size of starfish at the Bradda Inshore site did, however, increase from 1993 to 1995, with an observed increase in mean size from 73.4mm to 84.3mm. This size increase may well have been sufficient to allow the starfish to attack the smaller scallops more successfully. The tethering results appear to bear this out since the level of starfish predation on small scallops increased threefold between 1993/4 and 1995. The corresponding increase for larger scallops was smaller but was still a twofold increase. The dredge survey results must be treated with a certain degree of caution, given that the dredge survey site and the tethering experiment sites were geographically separate. This was unavoidable since, to minimise loss of data, the tethering experiments were carried out in areas closed to dredging. Video and diver surveys, being non-destructive, were carried out at the same sites as the tethering experiments.

Crabs were more affected by prey size presented during the tethering experiments. More small scallops than large scallops were consumed by crabs during both sets of experiments. This probably reflects the mode of feeding of crabs where the shell of the scallop being attacked has to be physically broken. Starfish appear to be more flexible in their ability to cope with larger prey. The level of crab predation during both sets of tethering experiments was far lower than that recorded for starfish indicating that starfish are probably the more important predator on the Manx scallop beds. This was especially true of the 1995 experiments where a huge increase in crab fishing effort may have resulted in significantly fewer crabs in the local area. There was a fourfold reduction in crab predation on small scallops from the 1993/4 experiments, compared with the 1995 experiments. Dredge results for the Bradda Inshore survey site show that crab densities were significantly lower during the June surveys of 1994, 1995 and 1996 compared with October surveys of 1993, 1994 and 1995. Part of this difference is probably a result of the migratory behaviour of crabs. However, the October 1995 survey does give a significantly lower density than the October 1994 survey, which suggests that crab density fell from 1994 to 1995 at the Bradda Inshore site. Further monitoring and analysis of dredge survey results would confirm or refute this observed trend.

The results of the current study indicate that tethered scallops of 70-80mm show overall survival of between 52 and 66% and that the smaller size class showed survival of between 38 and 39% overall. These estimates are likely to be conservative, given that tethering reduces the ability of the scallops to escape predators. These figures, although derived from short term experiments, could well prove to be sufficient for viable re-seeding given that untethered scallops would almost certainly have higher survival rates. This, combined with the fact that at least some of the scallops lost from these experiments may also have survived, all tends to suggest that these experiments provide conservative estimates of survival. Using smaller scallops would obviously lead to lower initial culture costs prior to re-seeding.

Paine (1976) states that the significance of size limited predation is that predators and prey can co-exist and that surviving prey can attain a large size. This therefore allows survivors to make a disproportionately large reproductive contribution to the prey population compared with their abundance. The problem in a heavily fished area is that these large individuals are removed by fishing therefore depriving the local prey population of at least some of its reproductive capability. Table 5.10 suggests that, if scallops were re-seeded at 65mm shell length, they would achieve market size in 1.76 years or 1 year 9 months at the Point of Ayre site where the fastest growth rates were identified. At the Chickens site the same increase in growth would be expected in 2.32 years or 2 years 4 months. During the time taken to achieve market size the re-seeded scallops could potentially be dredged up and damaged or killed before reaching market size. This could be used as an argument for closing areas after re-seeding, allowing the scallops to mature and contribute reproductively to the local population, and then open the area to fishing again.

Although *Pecten maximus* is known to exhibit cryptic behaviour in the field (Thomas & Gruffydd, 1971) and, as a consequence, tethering should, theoretically, have less effect upon this species (Heck & Wilson 1987; Auster & Malatesta, 1991; Zimmer-Faust et al., 1994), it must be stressed that *Pecten maximus* is capable of an active escape response in the form of swimming (Baird, 1957; Hartnoll, 1967). Other marine invertebrates are also known to perform active escape responses (Harrold, 1982; Legault & Himmelman, 1993). Once an escape response has been initiated, artificial tethers can potentially affect the likelihood of capture by a predator (Barbeau & Scheibling, 1994a; Zimmer-Faust et al., 1994). Tethering experiments probably represent a worst case scenario - producing high densities of low motility prey as well as causing aggregation of predators. Given this, it would be expected that re-seeded scallops might exhibit higher survival rates than those observed during these experiments. This would appear encouraging, given that the survival of tethered scallops (large size class) reached 66% during the 1993/4 experiments, admittedly over short periods of deployment. Survival rates of re-seeded scallops would also depend on the timing of deployment of such scallops. Legault & Himmelman (1993) found that the intensity of the escape response among shellfish increased with the threat posed by various predators. The more dangerous a predator was perceived to be, the more intense was the response initiated. To some degree this was observed during the static seabed video surveys. On several occasions crabs were seen to approach scallops and even handle them with no escape response initiated. If a starfish touched, or even closely approached a scallop, some degree of escape response or shell clamping behaviour was stimulated. The tethering experiments also suggest that starfish are 'higher risk' predators than crabs, which may explain the different responses observed.

Both the tethering experiments and the static seabed video data strongly suggest that starfish are by far the main predator of scallops in the areas where the tethered scallops were deployed. This suggests that densities and mean sizes of starfish population are probably the most important factors to consider, in terms of predators, for any re-seeding trial. The dredge surveys indicate that sites to the south and west of the Isle of Man would be best in this respect. Given low densities of small starfish, culture/importation costs could be minimised by using the smallest possible shell length for re-seeding. Laboratory work has shown that starfish are capable of overcoming a 'one to one predator to prey' size refuge by attacking scallops in groups. This behaviour enables two smaller starfish to successfully attack larger scallops than either would individually. An advantage for small scallops would therefore be gained in areas where starfish were smaller and less numerous, since smaller starfish would be less able to attack scallops, and the chance of two small starfish attacking the same scallop would be reduced because of the lower overall density of starfish. This could be tested using tethering experiments at the Bradda Inshore and Offshore sites, where marked differences in starfish density and mean sizes were observed.

The static seabed camera showed that, overall, starfish were potentially active throughout the day, but had peaks of activity on some days during the early morning and early to mid evening periods. Such crepuscular activity has not been previously reported for *Asterias rubens*. These videos also gave an insight into the foraging strategy of starfish in the field. Starfish tend to travel against the current more than any other direction which ties in with the fact that they are known to follow chemical trails to their prey (Dale, 1999). Rochette et al. (1994) found that asteroid predators move across currents when no prey are present to maximise chances of encountering chemical trails from potential prey. They also found that once an odour plume was detected starfish moved upstream towards the source, which in turn tends to minimise the chance of the prey species detecting the approach of the predator. Rochette et al. (1994) also postulated that faster currents lead to better spatial definition of odour plumes. This would allow starfish to locate prey more easily. If this was confirmed then re-seeding trials during neap tides would allow juvenile scallops a better chance of remaining undetected on the seabed during the initial, potentially stressful first few hours and days after release.

Crabs were active almost exclusively at night and generally in the early hours of the morning. The predator clearance carried out prior to the last experiment indicates that scallop survival can be enhanced in the short term using this method. These results were, however, obtained from a very small area of seabed and over a short period of time. Further investigations of this type would be required to generate an overall picture of predator activity patterns. Seabed structures are known to attract crustacean species which suggests that this method may be of use since attracted crabs would be captured in the camera field of view - allowing activity to be judged.

Dredge surveys provided estimates of densities for the two main predator species of the scallop around the Isle of Man. Comparison of all sampled sites over three scallop surveys (October 1995, June 1996 and October 1996) suggests that sites to the east of the Isle of Man, with the exception of Laxey, have larger mean relative sizes of starfish than sites to the west and south of the Island. The South East Douglas and East Douglas sites consistently gave significantly higher mean relative starfish sizes than the other sites surveyed during October 1995, June 1996 and October 1996. These findings tend to demonstrate the rather flexible nature of starfish growth patterns which are determined by food supply. Some sites had stable starfish population sizes, some increased and some decreased, which could make predictions regarding future trends difficult if not impossible. These results suggest that, over the period surveyed, the Bradda Inshore site was becoming a higher risk area for re-seeding juvenile scallops in terms of mean starfish numbers and sizes. Comparatively, the Bradda Offshore site presents a lower risk to re-seeded scallops than the Bradda Inshore site as it has a lower mean density and size of starfish, despite the fact that mean density appears to be increasing. To determine the extent and pattern of starfish population dynamics further monitoring would be required. Mean relative starfish densities were consistently, significantly higher at the Point of Ayre and Bradda Inshore sites, while the other sites surveyed showing little or no differences. The combination of higher mean relative starfish densities to the east and higher mean relative starfish sizes to the north suggest that a site for re-seeding trials should be located to the south west of the island, considering starfish in isolation from other factors and excluding the Bradda Inshore ground. The sites giving a combination of the lowest mean relative densities and sizes of starfish would include: 10 Miles South of Port St. Mary, Peel, Chickens and Offshore Bradda. From a monitoring point of view, the Offshore Bradda site would be the most convenient being situated 5 miles from PEML. This does not take into account the differences in fishing intensity experienced by these sites which could disturb re-seeded stocks of scallops. Some sites showed trends which may be cyclic in nature, if further surveys were to be analysed. Alternatively, the trends could merely be random fluctuations in the starfish populations at different sites, dependent on factors such as larval production/success rates, spat settlement success and food supply. If the trends are cyclic, then the timing of re-seeding could be adjusted to coincide with minimum sizes and densities of predators.

Dredging also provided an estimate of mean crab sizes at the Bradda Inshore and Bradda Offshore sites. Results indicate a cycle of increasing crab size with time over a 2 year period, followed by a sudden, significant drop in mean size which was, in turn, followed by a steady increase. The data from the June 1997, and subsequent surveys may confirm whether this pattern is regular or not. If this is a regular pattern, then any re-seeding trials could be carried out at a time when crab mean sizes are predicted to be reduced.

Dredge surveys carried out at all sites suggest that sites off the east coast of the Isle of Man have crab populations with smaller mean sizes than sites to the south and west of the Isle of Man. Again, a higher level of replication would help to clarify these differences. Most sites showed steady increases in crab sizes with time, although for one (South East Douglas) this was not statistically significant. Sites where significant increases with time occurred were: Bradda Offshore, Bradda Inshore, Targets and Chickens. Only Laxey suggested no change at all. These data indicate the yearly incremental growth pattern of the edible crab, compared with the starfish where regular growth patterns were not detected. Viewed in isolation, this information suggests that sites to the east of the Isle of Man may be more suitable for re-seeding trials. Given the observations of the tethering and static video camera, crabs would appear to be far less important as predators of the scallop than starfish. Therefore, the observed sizes and densities of starfish suggest selecting a site for re-seeding trials to the south and west of the Isle of Man with the exception of the Bradda Inshore ground.

Crab sizes and corresponding prey size capabilities are available from the results of Lake et al. (1987). These data only cover crab sizes up to 140mm carapace width. Most sites round the Isle of Man appear to have larger mean crab sizes than this. Crabs would appear to be more successful predators of small scallops of 55mm shell length or less. The expected size refuge of scallops obtained from Lake et al. (1987) are summarised in Table 6.1.

The difficulty of working with crabs in the laboratory was highlighted during the current study. Experiments with crabs of 140mm and greater carapace width were run to attempt to address the issue of larger mean crab sizes in Manx waters. None of the experiments worked, and only two crabs to consumed individual scallops under laboratory conditions. All experimental tanks were blacked out since bright light is known to be one factor causing such behaviour but to no avail.

Dredge surveys showed that relative crab densities were significantly higher at the inshore south west grounds (Peel, Bradda Inshore and Bradda Offshore) than at the north, east and offshore south grounds (10 and 20 Miles South of Port St. Mary, South East and East Douglas, Point of Ayre, Ramsey, Laxey and Targets). The starfish data suggested that some of the sites found to have high relative crab densities might be suitable for re-seeding trials. This would probably mean having to time the re-seeding to occur after the offshore migration of the female crabs. This would also have the advantage of coinciding with lower activity levels of any crabs remaining inshore in the colder, winter months. The static video and tethering data obtained indicate that crabs are far less important as predators of scallops compared with starfish. This may be encouraging for re-seeding trials, given that the Inshore Bradda site was identified as an area of high crab density yet showed crabs to be attacking and consuming very low percentages of tethered scallops. This evidence suggests that when considering re-seeding trials, the main predation risk would be from starfish and that the mean local size and density of these predators are more likely to determine where re-seeding takes place or is more likely to succeed.

In summary, higher densities of crabs have been found at inshore and south west sites, compared with offshore and north east sites. Mean crab sizes are smaller at the eastern sites

Table 6.1

Summary of mean crab sizes at different sites around the Isle of Man including the expected size refuge of scallops.

Site	Mean Crab Size (mm)	Expected Scallop Re-seeding Size.
South East Douglas	130	60mm
Laxey	135	60mm
East Douglas	136	60mm
Targets	150	>60mm
Peel	147	>60mm
Offshore Bradda	155	>60mm
Chickens	156	>60mm
Inshore Bradda	155	>60mm
10 Miles South P.S.M.	162	>60mm

Table 6.2

Summary of mean starfish sizes at different sites around the Isle of Man including the expected size refuge of scallops.

Site	Mean Starfish Size (mm)	Expected Scallop Re-seeding Size.
Offshore Bradda	51	55-65mm
Chickens	70	55-65mm
10 Miles South P.S.M.	81	55-65mm
Peel	79	55-65mm
Inshore Bradda	87	55-65mm
20 Miles South P.S.M.	93	65-75mm
Targets	96	65-75mm
East Douglas	111	75mm+
South East Douglas	102	75mm+
Laxey	86	55-65mm
Point of Ayre	95	65-75mm
Ramsey	125	75mm+

Table 6.3

Results of the Tukey multiple comparison test identifying differences in mean sizes of three year old scallops at different sites around the Isle of Man.

Site	LX	PL	CH	BO	10S	BI	SD	20S	ED	TA	RY	PA
n	44	62	190	127	68	87	134	44	30	141	85	14
Mean	84.9	89.3	89.3	93.0	94.0	95.2	97.4	98.1	98.9	103.4	103.5	106.4
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compared with the western sites. Therefore, generally speaking, there were more larger crabs at sites to the south and west of the Isle of Man and fewer, smaller crabs to the east and north of the Isle of Man.

Estimated mean starfish size for dredge survey sites plus corresponding trial re-seeding size obtained from laboratory experiments, averaged over the October 1995, June 1996 and October 1996 dredge surveys are summarised in Table 6.2.

The initial cost of culturing or importing scallops for re-seeding could potentially be reduced considerably by choosing a site where smaller scallops could be used (Table 6.2). Growth in culture times would be far less for sites like Chickens or Offshore Bradda compared with sites like Ramsey or the two sites east of Douglas. The results of the investigation into growth rates of naturally occurring scallops indicate that the Chickens site gave the fastest rate of growth of natural stocks of scallops. If this could be extrapolated to re-seeded stocks one would have an area where small scallops could be seeded, thus minimising preparatory costs, and where rapid growth rates could be expected. This would be an ideal combination for re-seeding, both in terms of minimising costs and minimising exposure to the risk of predation. Since crabs appear to be more efficient at consuming scallops <55mm in shell length it would be sensible to set the minimum re-seeding size to 60 or 65mm to minimise the impact of crustacean predators. Then one has to consider only echinoderm predators.

Starfish occur throughout the surveyed sites at much higher densities than crabs. Higher densities of starfish were found at the northern end of the Island but generally there was far less variability between sites compared to the crab data. Lower densities of starfish were found to the south and east of the Island and at offshore sites - Bradda Offshore, 10 and 20 Miles South of Port St. Mary - than at inshore sites. Mean starfish sizes were found to be greater at sites to the east of the Isle of Man than to the west.

Minchin (1995) states that areas where rapid scallop growth occur should be prioritised in re-seeding trials. Analysis of growth rates of scallops during the current study indicate that the best mean growth rate achieved was at the Point of Ayre site where it was estimated that scallops could potentially achieve a size of 75mm in 2.43 years. Conversely the worst estimated growth rate was observed at the Chickens site - 75mm attained in an estimated 3.07 years. These results, compared with Table 6.2, show that the best site for re-seeding trials based solely on growth rates of scallops will not necessarily be the best site in terms of mean predator sizes or densities. Age/size data from the June 1995 scallop survey were analysed because of the high percentage of sites covered (12 out of 13, only missing Maughold Head). A one way ANOVA was used to determine differences between mean sizes of 3 year old scallops for these 12 sites. The results indicated highly significant differences between sites ($P<0.0001$) and the subsequent Tukey test (Table 6.3) shows where these differences occur.

Table 6.3 indicates that three year old scallops are significantly larger at Ramsey, Targets and Point of Ayre than they are at South East Douglas and 20 Miles South of Port St. Mary. These two sites, in turn, have larger 3 year old scallops than Bradda Offshore, Chickens, Laxey and Peel. Therefore, in terms of scallops growth rates, the best sites for re-seeding would appear to be the three most northerly sites surveyed while the least suitable would be Peel, Chickens and Laxey. Whether this difference is sufficient to overcome the effect of predator density or mean size locally is debatable but it is a factor which has to be considered. Growth rates would certainly have a bearing on the economic viability of any large scale re-seeding programme, given that smaller scallops are cheaper to produce in culture and that more could potentially survive if they were able to achieve a size refuge from predators more quickly. One factor which would bear further investigation would be whether the observed differences in growth rates of scallops between sites were due to environmental conditions or genetic structure of the populations within each site (or both). Further work needs to be carried out into the relative importance of growth rates, predator size and predator densities on the likelihood of survival of re-seeded or juvenile scallops.

In terms of the best sites for re-seeding, these results appear to be conflicting since the best site for reduced crab predation (lowest sizes and densities at east and north) will not generally be the best site for reduced starfish predation (lower densities and sizes to south and offshore). However, one cannot gain a complete picture of the predation risk to re-seeded scallops from such data viewed in isolation. One also has to consider the behavioural aspects of predator species. Crab migrations and reduced activity during the colder months will play a key role in the timing of re-seeding activity. Since starfish densities do not appear to be as variable as crab densities, and are much higher, it would seem sensible to attempt re-seeding at sites where starfish sizes and numbers are lowest at a time when the threat from crabs is lowest. Starfish are likely to pose the greatest threat to both re-seeded and naturally occurring juvenile scallops as they occur in far greater numbers than crabs and they are not reduced in number by a fishery. There is also the problem of starfish winter feeding peaks which would be best avoided. The possibility of predator aggregation also has to be considered when re-seeding juvenile scallops. Sufficiently high densities of juvenile shellfish are known to attract predator species (Schmitt, 1987; Barbeau et al., 1995).

Landenberger (1968) showed that larger asteroid predators tend to consume larger shellfish prey species. He also found that there was a certain minimum size below which larger starfish would not tend to attack shellfish prey. Leviten (1976) also states that there is a minimum food/prey size below which consumers will not feed for energetic reasons. Both authors put this down to the fact that smaller prey can take more energy to capture and consume than they actually yield. Leviten (1976) further states that there will be a maximum size of prey above which consumers will be unable to successfully feed upon prey species. The starfish must therefore have some means of gauging the size of its prey before commencing an attack in order to determine whether the prey item is either too large to consume successfully or too small to be energetically worth the effort of consumption. Behaviour of this nature has been observed during the current study, both in laboratory aquaria and by the static video camera in the field. In both cases, starfish were observed to wrap an arm or arms around the perimeter of a scallop shell after initial contact was made. In some cases, where the arm or arms were unable to reach fully round the shell, the attack was broken off. These observations are only anecdotal and would certainly bear further investigation. The laboratory work carried out also showed that predation rate on the smallest scallops used (45mm) peaked and then dropped off as predator size increased. This would tend to support Landenbergers' findings. This presents an interesting possibility: iIf very small, juvenile scallops were re-seeded in an area of high starfish mean size would early survival be enhanced? The larger predators may actually ignore the smaller prey. Of course, as the scallops grew they would become more attractive to the predators so mortality may only be delayed.

Some estimates of dredge have been made by comparing different survey results with dredge surveys. Video surveys probably provide the most reliable comparison in this context given the large area surveyed and the linear, transect style nature of the survey method which is more similar to a dredge survey than is a diver survey. Estimated dredge effieciency ranged from 3.9 to 26.1% for crabs and from 16.3 to 24.9% for starfish. This indicates that dredges have similar low and variable efficiency in catching predator species as they do in catching scallops, the main target species.

The video survey data showed no significant differences in crab density between the Bradda Head and Exclusion Zone survey sites. Crabs are known to range fairly widely during foraging activity and therefore are more likely to be evenly distributed between two relatively close areas experiencing different levels of dredging. Starfish are much slower moving and are therefore more likely to be affected by dredging activity. The video surveys identified a significant difference in starfish density between Bradda Head and the Exclusion Zone, with the latter having a much lower average density of starfish. This could possibly be attributable to dredge disturbance effects. In this case the churning effect on the seabed and damage to benthic organisms might be attracting starfish to the Bradda Head site whereas the less disturbed Exclusion Zone might be less attractive to starfish. Research has found that disturbance by fishing gear can cause increased predation in disturbed areas but that this was often a result of increased feeding activity and not predator aggregation (Barbeau et al., 1994;

Barbeau et al., 1996; Ramsey & Kaiser, 1998). If reduced predator densities did occur at undisturbed sites then this could be proposed as a method of reducing predator numbers prior to re-seeding trials. The area to be used would have to be closed to dredging for some time prior to re-seeding commencing. Further work would have to be carried out to investigate whether this was a consistent, testable phenomenon or whether the observed results merely reflected natural variability in the local starfish population. To some extent the fact that starfish occur at higher density in a dredged area, compared with an undredged area, is unexpected since dredging can damage or remove starfish predators. However, if the starfish were hardy enough to survive dredging (by-catch generally being returned to the sea), and dredging itself attracted more starfish into an area, then this might lead to an increase in starfish density in dredged areas. Dredging may also expose a greater percentage of food resources to starfish because shellfish are disturbed and damaged making them more vulnerable to both detection and attack. Field tethering work (Barbeau et al., 1998) has also shown that increasing densities of scallops stimulates increased feeding activity among predators but may not always cause predator aggregation.

Diver surveys made around tethering experiments showed that these experiments attracted predators, presumably because of higher than background prey densities. This suggests that the tethering experiments used constitute a 'worst case' scenario where predators are attracted to high density, low motility prey. Given that this is true, the rates of survival of tethered scallops was surprisingly high during certain months of the year. This in turn suggests that re-seeding trials in a carefully chosen area might experience even higher levels of scallop survival.

Laboratory experiments to determine whether tethering significantly affects mortality rates of scallops indicated that no significant difference was apparent between tethered and untethered treatments. This was probably due to the nature of the experimental environment since the tanks that the experiments were carried out in effectively restricted all scallops within a small area anyway. Consequently, it would be difficult even for untethered scallops to escape a sustained attack under these conditions. Ideally, much larger tanks would have been used had they been available. Barbeau & Scheibling (1994) state that tethering effects are likely to affect different predators in different ways. For instance, it was found that for crabs, encounter rate roughly equalled predation rate so tethering makes little difference. For starfish, predation rate was found to be much lower than encounter rate because of the more successful escape response. Crabs will often see an escaping scallop whereas starfish rely on chemosensory means to detect prey and may be unable to detect a scallop that swims downstream. Thus a scallop escape response can more easily evade attack by starfish than by crab. Consequently, tethering scallops is more likely to have an effect on starfish predation rate (it will rise) than on crab predation rate (it will stay approximately the same). During the course of this study it was found to be virtually impossible to get crabs to feed under laboratory conditions so this theory could not be tested for crabs. It is, however, likely that the confines of the experimental tanks available for use in these experiments would mask any effects of tethering. The dimensions of the tanks themselves act as an effective means of 'tethering' even untethered prey by restricting movement. The ability of scallops to perform an escape response is also known to decrease with increasing water temperature (Barbeau & Scheibling, 1994c) which implies that the timing of re-seeding will be important in maximising the chances of scallop survival.

Barbeau & Caswell (1999) state that success of scallop re-seeding efforts depends upon mortality, growth and dispersal of scallops. They ranked the order of importance of factors influencing final scallop survival as: Reducing predator densities; increasing the size of seeded scallops; changing the initial density of seeded scallops; changes in the dimensions of the site and season of re-seeding. Other work suggests that sea water temperature has significant effects upon scallop escape response (Barbeau & Scheibling, 1994c) implying that season will have an effect upon scallop survival. The results of the present study indicate that season may well effect survival of scallops re-seeded on grounds round the Isle of Man since observed levels of predation on tethered scallops varied significantly throughout the year. Significant differences in predator densities at different sites around the Isle of Man have also been identified leading to the conclusions that sites to the south and west of the island may be most suitable for re-seeding and that July would be the best month for commencing trials. Initial results indicate that predator clearance would be a useful tool in maximising scallop survival. Combining this with fishing activity restrictions would help to enhance survival of re-seeded scallop stocks. Growth rates of naturally occurring scallops have been found to vary significantly between grounds around the Isle of Man. Further work needs to be carried out to determine whether re-seeded scallops could take advantage of these differences i.e whether the observed differences in growth rate result from hydrodynamic or genetic differences. This work has been able only to identify survival rates for juvenile scallops over short periods. The results have been encouraging but longer term experiments would have to be carried out in order to determine overall survival rates for re-seeded stocks. Further investigation into predator/prey interactions for crabs larger than 140mm carapace width and for starfish handling different scallop sizes would be required. In conclusion it is felt that seabed re-seeding could potentially be a very useful tool in enhancing scallop stocks in Manx waters and other areas.

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