



Seasonal swimming behaviour in the queen scallop (*Aequipecten opercularis*) and its effect on dredge fisheries

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Abstract

Modified dredges were used on *Aequipecten opercularis* (queen scallop) fishing grounds off the Isle of Man in the north Irish Sea to determine seasonal variability in swimming behaviour in queen scallops and its effect on dredge fisheries. Scallops, which evaded dredge capture by swimming up into the water column, were captured by a specially designed net deployed above the dredge gear. The gear was used over a 20-month period and the number and size distribution of queen scallops captured in both the net and dredges were recorded. A subsample of captured scallops was maintained in running seawater tanks and used to assess two components of swimming behaviour, the time taken to respond to stimuli and the number of valve adductions carried out until exhaustion. There was considerable seasonal variability in the proportion of queen scallops that avoided dredge capture by swimming. Very low numbers of queen scallops were found in the net during the winter and spring. Net capture increased in June, and was high throughout the summer and autumn when up to 42% of scallops greater than 55 mm in height, captured in dredges, swam over the dredge mouths. There was a strong positive correlation between seawater temperature and proportion of captured scallops found in the net. Swimming experiments in the laboratory indicated that the observed seasonal variability in net capture was probably a result of changes in the time taken to respond to stimuli, rather than changes in the ability to perform a large number of valve adductions. There was no relationship between reproductive state and the proportion of actively swimming scallops. Analyses of size distributions

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indicated limited swimming activity in the largest scallops but no effect of epifaunal load was found on the ability of scallops to avoid dredge capture.

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1. Introduction

The swimming behaviour of scallops is well documented. It occurs in response to a variety of biotic and abiotic factors, including escape from predators (Thomas and Gruffydd, 1971; Ordzie and Garofalo, 1980; Peterson et al., 1982; Jenkins and Brand, 2001), in selection or avoidance of habitat (Hartnoll, 1967; Winter and Hamilton, 1985), as a response to overcrowding (Howell and Fraser, 1984) and to disturbance from divers or fishing gear (Caddy, 1968; Chapman et al., 1979). Swimming is brought about by a series of rapid valve adductions, which force water from the mantle cavity and propel the animal ventral edge foremost. Typically, such action allows scallops to rise off the seabed at a steep angle before swimming horizontally for a short distance and then sinking passively to the seabed. Although the mechanism of swimming is similar in all scallop species, there are large interspecific differences in swimming ability (Brand, 1991). For example, in the north Irish Sea, the two commercially exploited scallop species, the great scallop *Pecten maximus* and the queen scallop *Aequipecten opercularis* differ in their propensity and ability to swim. *P. maximus* is generally sedentary and is usually found recessed in the sediment with the upper (left) valve level with the substrate. It is capable of effective swimming (e.g. Thomas and Gruffydd, 1971; Jenkins and Brand, 2001) but generally does so only in response to threat from predators (but see Hartnoll, 1967 for mobility on hard substrata). *A. opercularis* is generally considered to be a more mobile species which lies on top of the substratum; it swims readily in response to approaching divers and fishing gear (Chapman et al., 1979), and to predatory starfish (Stephens and Boyle, 1978). Chapman et al. (1979) investigated the swimming behaviour of *A. opercularis* in the field on the west coast of Scotland during summer and early autumn. Individuals showed a swimming response at up to 1.5 m away from approaching divers or fishing gear and attained a vertical height of between 0.1 and 0.7 m above the substratum, although occasionally they were observed up to 1.5 m in height.

The swimming behaviour of commercially exploited species has important implications for both fisheries and aquaculture. Bottom culturing or sea ranching, whereby juvenile scallops are seeded onto the seabed is a low-cost culturing method, but suffers from the potential loss of large numbers of scallops, not only through predation (e.g. Minchin, 1991), but also through dispersal from seeded areas by swimming (e.g. Freitas et al., 2000). In fisheries, the behaviour of scallops in response to fishing gear has important implications for gear design and use. For example, the recessing habit of *P. maximus* means this species can only be targeted effectively using toothed dredge gear that digs into the substratum. In contrast, more mobile species, such as *Amusium japonicum* (Dredge, 1988) and *A. opercularis* (e.g. Chapman et al., 1979), can be targeted by gears such as trawls, which utilise swimming behaviour to catch the scallops whilst in the water column.

A number of different gear types have been used to fish for the queen scallop *A. opercularis* in the north Irish Sea. Three main types are currently utilised, a toothed dredge, a skid dredge (a modification of the toothed dredge, with each dredge frame mounted on ski-like skids and the tooth bar replaced with a tickler chain) and bottom trawls. Although queen scallops may be fished all year round, most boats target the more lucrative *P. maximus* during the winter and only target the queen scallop during the *P. maximus* closed season (June–October inclusive). During this summer and autumn season, fishermen choose gear based on personal preference and experience, and the type of grounds targeted. In addition, the gear type chosen can be based on perceived seasonal differences in the behaviour of the queen scallop in response to gear. Dredges and skid dredges catch scallops on or near the seabed, whereas trawls rely on scallops swimming up into the water column in response to the approaching net. As water temperatures increase through the summer, the swimming activity of queen scallops is thought to increase and a number of boats change from dredge gear to trawls.

Little is known regarding the seasonal variability of scallop swimming. In general, it is known that swimming activity, both in the field (Parson and Dadswell, 1992; Carsen et al., 1995) and in the laboratory (Manuel and Dadswell, 1991; Jenkins and Brand, 2001), increases during the warmer part of the year. For example, Manuel and Dadswell (1991) demonstrated a correlation between swimming velocity and water temperature in the laboratory from June to December. As well as swimming activity, the time taken to respond to stimuli before swimming can vary with season. Ordzie and Garofalo (1980) found that the bay scallop *Argopecten irradians* took longer to respond to predators during October (water temperature, 12 °C) than in August (water temperature, 20 °C), although Jenkins and Brand (2001) found no seasonal variability in response time of *P. maximus*. Understanding of the implications of seasonality in swimming behaviour for the ecology of scallops, and to their exploitation in fisheries, is limited.

We aimed to assess seasonal variability in the response of queen scallops to fishing gear to provide an indirect measure of seasonality of swimming behaviour and more accurately understand the efficiency of different gears throughout the year. This was achieved by adapting conventional queen scallop dredge gear such that those individuals that avoided dredge capture by swimming upwards and passing over the dredge mouth were captured in a net. This gear was used over a 20-month period to determine the proportion of queen scallops avoiding dredge capture. In addition to this indirect field assessment of swimming activity, direct assessment of response times and number of adductions performed was made in the laboratory, to assess which component of swimming behaviour varied seasonally. The reproductive state of queen scallops was assessed throughout part of the study to determine any relationship with swimming activity.

2. Methods

2.1. Avoidance of capture by dredge gear

Dredge gear and modified dredge gear (skids) used in the Irish Sea to target the queen scallop typically have a mouth that extends approximately 20 cm above the substratum.

Any scallop individual, which swims upwards in the water column above this height, at the point the dredge mouth passes, will escape capture. To quantify the number of individuals that avoid capture in this way, a net (hereafter, called the 'top net') was developed which could be deployed above a gang of four queen scallop dredges. The top net had a rectangular-shaped mouth with an opening width of 4 m (the full width of a gang of four dredges) and height of 0.8 m. The net was set, so that when deployed, its mouth was extended vertically above the dredge. Thus, it captured all queen scallops which passed over the top of the dredge gang up to a height of approximately 1 m. The top net also incorporated a triangular-shaped section that extended forward, thus, deflecting the majority (though not all) of the scallops which swam higher than the net mouth. The way in which the top net affected dredge efficiency was not assessed, because this was the same throughout the study period. The top net had a diagonal-stretched mesh size of 70 mm with a 40-mm mesh cod end. Each dredge had a steel ring belly-collecting bag made up of 60-mm (internal diameter) rings and a netting back with diagonal mesh size of 65 mm. Thus, the size selectivity of the top net and dredge gear at the mesh and rings, respectively, were not comparable. However, both types of gear were expected to retain queen scallops above the general market size of 55 mm shell height with equal efficiency.

This gear was initially used during August 2000 at three queen scallop fishing grounds around the Isle of Man in the north Irish Sea (Fig. 1). The gear was deployed from the RV Roagan, a 24-m converted stern trawler. At each fishing ground, three tows of 2 nautical miles were made at a speed of 2.5–3 knots (4.6–5.6 km/h) in a direction parallel to the tidal flow. Tows were made both with and against the tide at each date. The number of queen scallops and great scallops captured in each dredge, and in the net, were counted at the end of each tow. A subsample of queen scallops was taken from the net, and from one dredge, and the shell height measured to the nearest millimetre. Following this successful trial, the same procedure was repeated at the Laxey fishing ground at between 4- and 15-week intervals over the following 20 months.

During the preliminary trials in August 2000, a subsample of queen scallops captured on the East Douglas ground was analysed to determine any difference in the level of epifaunal loading on shells of scallops caught in the net and in the dredge. Fifty individuals covering the observed size range were selected from each of the gear types and the shell height, total wet weight and shell weight, including the weight of attached epifauna, were determined in the laboratory.

2.2. Assessment of swimming ability in the laboratory

From March 2001, on each field sampling date, at least 50 queen scallops were taken alive to Port Erin Marine Laboratory where they were placed in running seawater tanks and allowed 7 days to recover from the dredging process. The swimming ability of at least 27 individuals (shell height 50–75 mm) at each date was tested in the laboratory using the procedure described in Jenkins and Brand (2001). A nylon nut was glued to the lower (right) valve of each queen scallop using Araldite Rapid™ adhesive. The head of a nylon bolt was glued to a brick so that the scallop could be quickly and easily screwed to the bolt and immobilised. Scallops were given at least 3 days to recover after the gluing procedure. A system of six circular experimental tanks (diameter × depth, 0.38 × 0.28 m), each with a

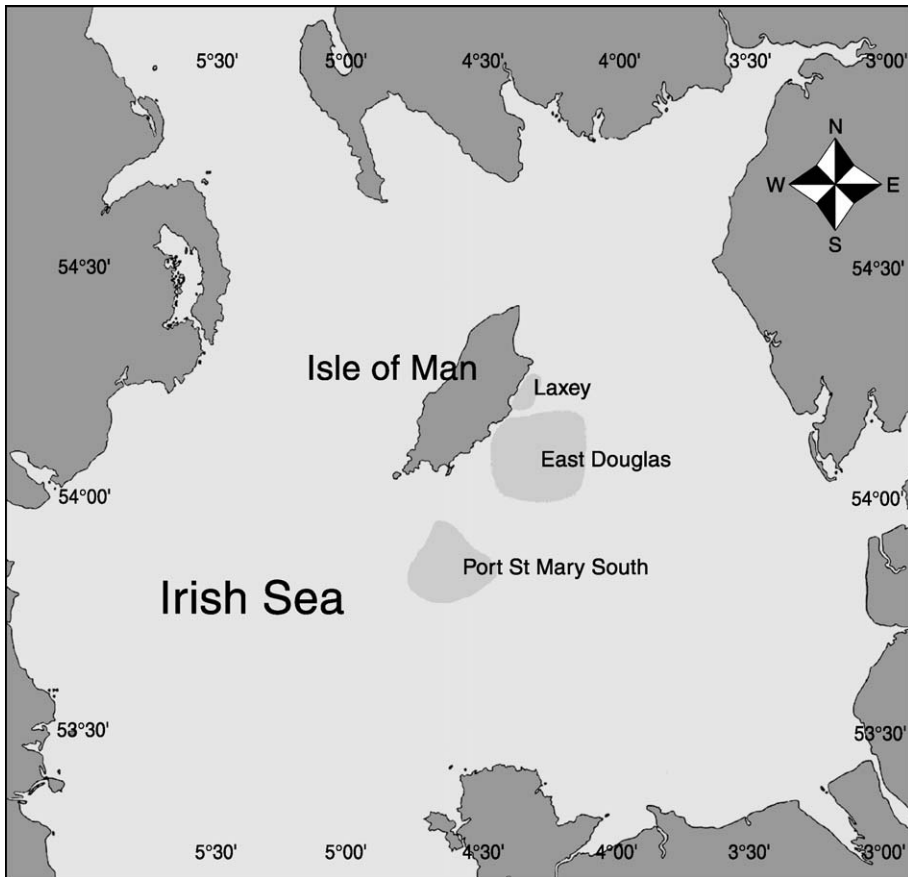


Fig. 1. Map showing position of the three queen scallop fishing grounds in the Irish Sea.

brick and bolt for immobilising a single scallop, was set up with running seawater. Six scallops at a time were transferred from storage tanks, and quickly screwed to a single brick in each experimental tank. This could be achieved underwater to avoid additional stress. Once immobilised in the experimental tanks, all scallops were given 15 min to recover from the handling process. After 15 min, scallops were stimulated to ‘escape’ using the predator *Asterias rubens*. A number of individuals of this species, of similar size (15–18 cm diameter), were maintained in seawater tanks, and a different individual used for each set of scallops. To stimulate an escape response, a starfish was introduced to a scallop so that the tube feet of a single arm touched the mantle edge. Care was taken to avoid creating shadows and displacing water, which could cause the scallop to close its valves before the starfish could be applied. The starfish arm was left in place until a response was initiated. The time from the first stimulation until an escape response was performed was recorded using a stopwatch, and the number of valve adductions counted. After valve adductions had ceased, the scallop was again stimulated in the same way, and

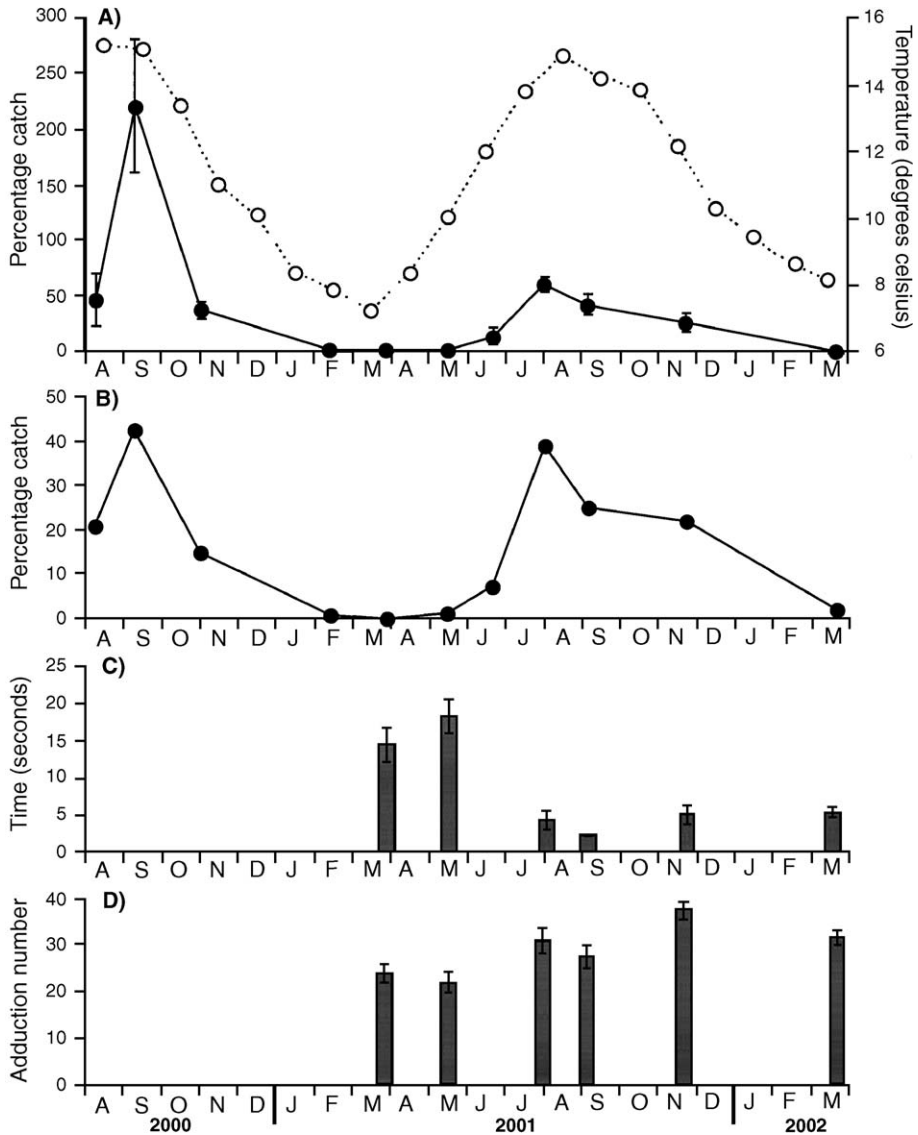


Fig. 2. Assessment of seasonal swimming behaviour in the queen scallop *A. opercularis*. (A) Number of queen scallops captured in the top net as a percentage of those captured in the dredges (closed circles) and mean monthly inshore surface water temperature measured at Port Erin in the south of the Isle of Man (open circles). (B) Number of queen scallops over 55 mm in shell height captured in the top net as a percentage of those captured in the dredges. (C) Response time in queen scallops induced to swim in the laboratory. (D) Total number of adductions before exhaustion in queen scallops induced to swim in the laboratory. Error bars = ± 1 SE.

the number of adductions counted. This was continued until the valves closed firmly or until there was no response after 60 s. In this way, a single response time (the time from the first stimulation until an escape response was performed) was recorded, plus a series of adductions.

2.3. Reproductive state of queen scallops

At each field sampling date from March 2001, the reproductive state of queen scallops caught in the dredges and caught in the net was assessed. Thirty queen scallops from the dredges (and on three occasions from both the dredges and net) were frozen, and subsequently, gonad and muscle dry weights were determined by drying at 60 °C until constant weight was achieved. These dry weight data were converted to a gonadosomatic index using the formula: (Dry weight gonad/Dry weight adductor muscle) × 100.

3. Results

3.1. Avoidance of capture by dredge gear

The number of queen scallops caught in the top net was calculated as a percentage of the total catch in the four dredges. There was very high seasonal variability in the proportion of individuals captured in the net and therefore avoiding dredge capture (Fig. 2A). In general, low numbers of queen scallops were found in the net during winter and spring (<3% of the dredge catch), but during summer and autumn, levels of net capture increased. Sampling was started too late to determine when queen scallops began actively swimming in the year 2000. During 2001, net capture (and therefore, presumably active swimming in response to the approach of gear) clearly increased between May and June (Fig. 2A). Peak levels of net capture occurred during late summer/early autumn. Owing to bad weather, it was not possible to sample frequently throughout the winter, and thus, it is not clear precisely when escape from the dredges ceased. In both 2000 and 2001, net capture was still high in November and declined to negligible levels by February and

Table 1

One-way ANOVA of swimming response variables of *A. opercularis* measured in laboratory experiments over six separate dates between March 2001 and March 2002

Source	<i>df</i>	MS	<i>F</i>	<i>P</i>
<i>(A) Response time (Log transformed. Cochran's C= 0.218, P>0.05)</i>				
Date	5	3.43	37.20	<0.01
Residual	156	0.09		
SNK test	March = May > July = November = March 02 > September			
<i>(B) Total adductions (Untransformed. Cochran's C= 0.248, P>0.05)</i>				
Date	5	850.83	6.55	<0.01
Residual	156	129.95		
SNK test	No interpretable pattern			

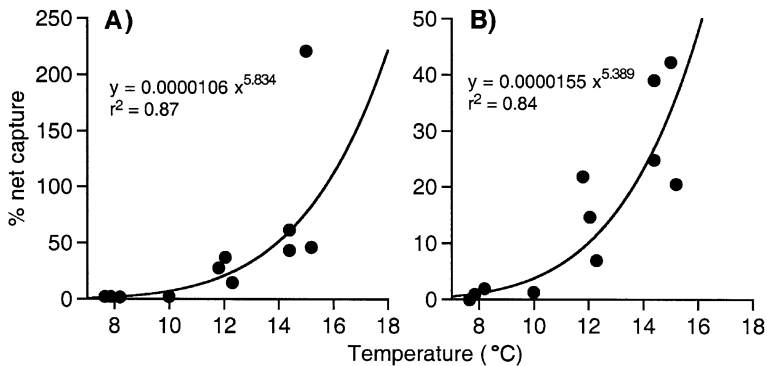


Fig. 3. Relationship between seawater temperature and the number of queen scallops captured in the top net as a percentage of those captured in the dredges (A) for all queen scallops and (B) for those queen scallops over 55 mm in shell height. Each point represents a single sampling date on the Laxey fishing ground. Sampling dates span a 20-month period.

March, respectively. To determine the proportion of marketable-sized queen scallops that avoid capture by the dredge, data were recalculated to include only those individuals over 55 mm in shell height (Fig. 2B). These data mirror the temporal trend described above, and show that the number of queen scallops of marketable size that avoid dredge capture by swimming over the top of conventional queen dredges can be as high as 42% of the number captured in dredges.

Swimming experiments in the laboratory revealed significant differences among dates in the response time and total number of adductions displayed by queen scallops (Table 1, Fig. 2C and D). The most marked change with time occurred from May to July when the time taken for individuals in the laboratory to show a swimming response following stimulation changed from 18 to 4 s. Over this same time period, there was a very marked increase in percentage of net capture from 1% of commercial-sized scallops in May to 39% of commercial-sized scallops in July.

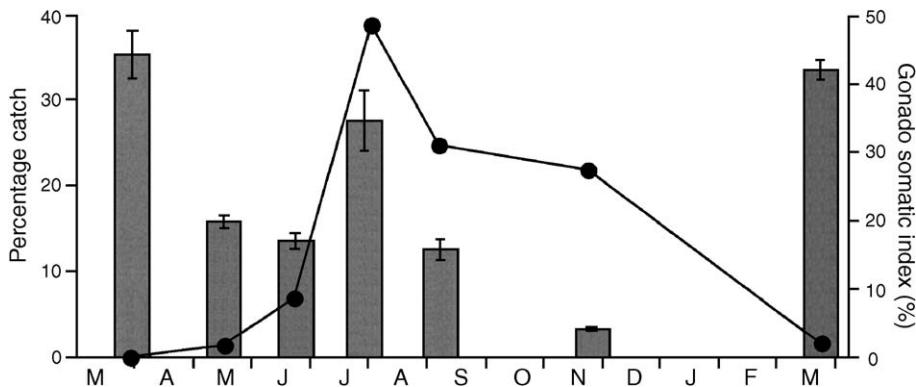


Fig. 4. Gonadosomatic index of queen scallops captured in dredges (columns) and percentage of dredge catch which were found in the top net (line) over a 13-month period from March 2000 to March 2001 on the Laxey fishing ground. Error bars = ± 1SE.

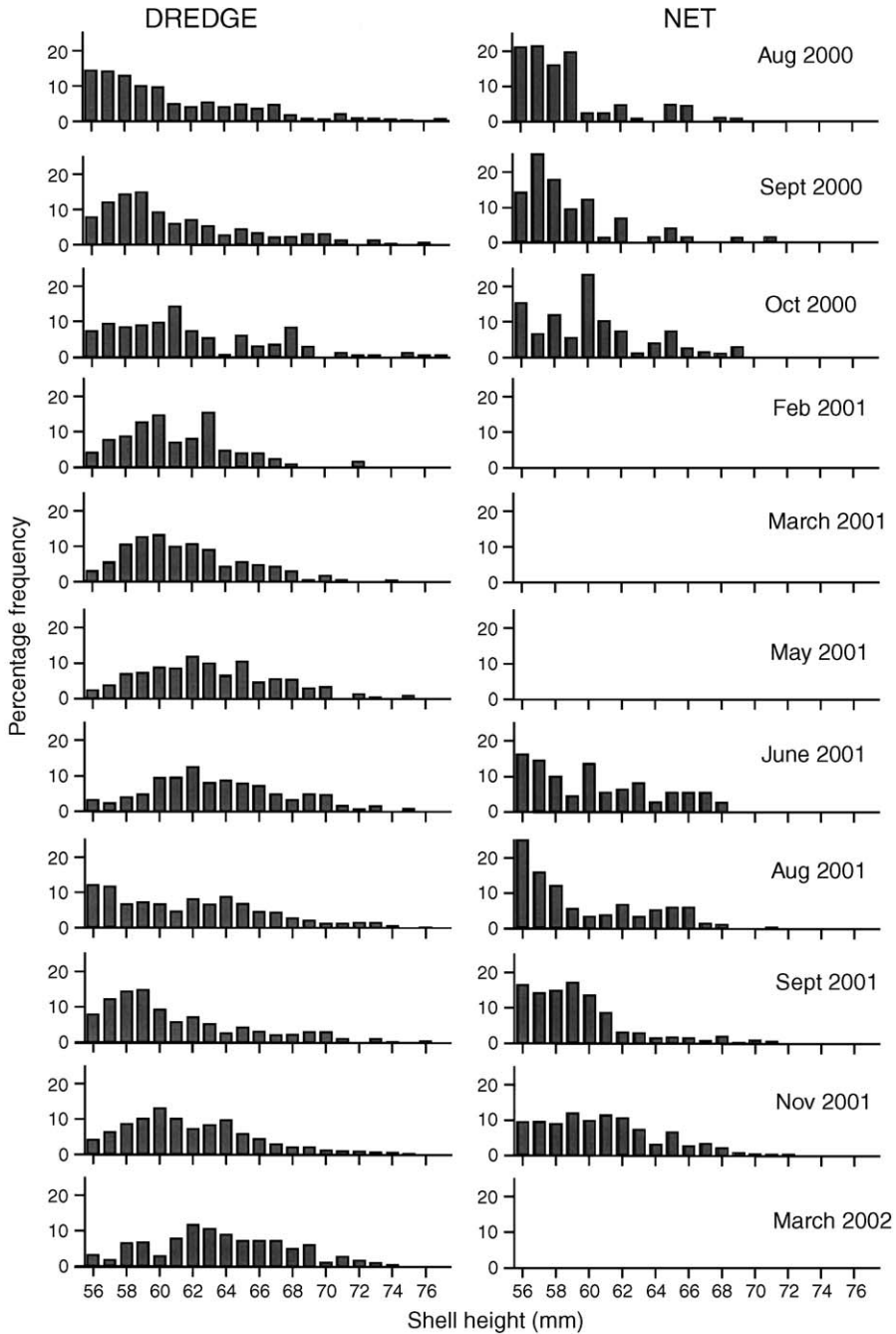


Fig. 5. Size frequency distribution of queen scallops above marketable size (>55 mm) captured in dredges and the top net at each sampling date from the Laxey fishing ground.

Table 2

Kolmogorov Smirnov two-sample test of size frequency distributions of *A. opercularis* of a marketable size (>55 mm shell height) captured in the dredges and the top net from August 2000 to November 2001

Date	Dredge (<i>n</i>)	Net (<i>n</i>)	<i>D</i>	<i>P</i>
August 2000	388	90	0.267	<0.01
September 2000	349	73	0.263	<0.01
October 2000	167	75	0.186	>0.05
June 2001	126	111	0.348	<0.01
August 2001	318	265	0.264	<0.01
September 2001	261	270	0.204	<0.01
November 2001	293	246	0.123	<0.05

Only sampling dates where over 150 individuals were captured in the top net were used. The value of *n* indicates the number of individuals measured from the total catch. Significant results in bold.

in July, indicating that the ability to respond quickly to stimuli may positively affect avoidance of dredge capture. Response times were rapid throughout summer and early autumn when dredge avoidance was high. However, this pattern was not consistent

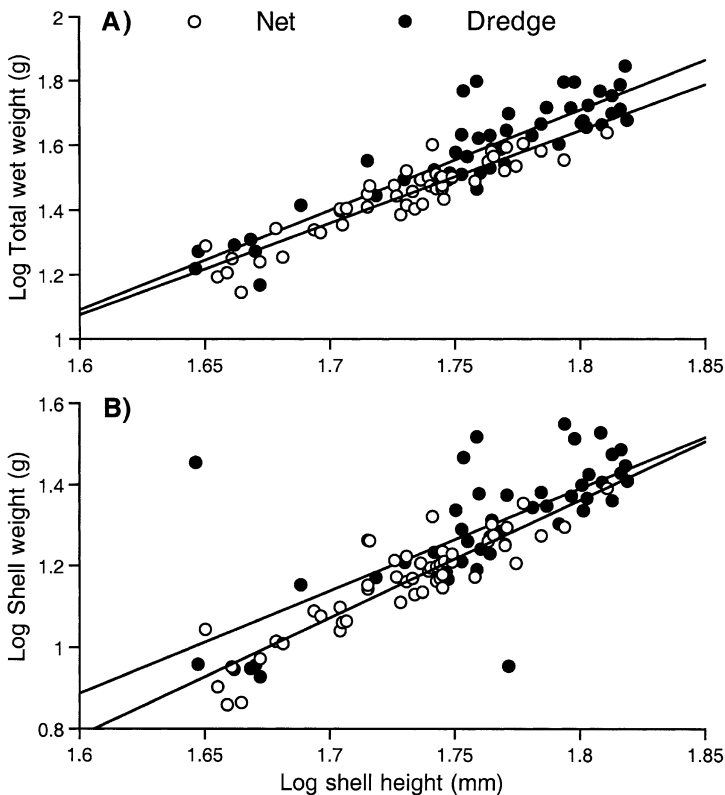


Fig. 6. Relationship between shell height and (A) total wet weight, (B) total shell weight including epifauna for dredge- and net-captured scallops on the East Douglas fishing ground in August 2000. All regression lines are significant at $P < 0.05$.

throughout the study. In March 2002, when dredge avoidance had declined to a minimum, response times remained rapid, significantly faster than the previous spring (Table 1). The total number of adductions performed showed no clear pattern over the sampling period although there were large significant differences among dates (Table 1), with mean values varying from a minimum of 21 to a maximum of 37.

The variability in level of net capture over time showed a strong relationship with seawater temperature (Figs. 2 and 3). The data were best fitted by a power function. Temperature explained over 80% of variability in net capture both for the total queen population and when only scallops over 55 mm were considered. Interestingly, there was no apparent relationship between seawater temperature and measurements of swimming responses in the laboratory. The reproductive cycle of queen scallops was followed during part of the study to assess whether reproductive state affected level of swimming activity. The reproductive cycle of the queen scallop was clearly seen by calculating a gonadosomatic index, with large declines in the index in May and in September indicating the time of the spring/summer and autumn spawnings, respectively (Fig. 4). There was no apparent relationship between the gonadosomatic index of dredge-captured scallops and percentage of net capture (Fig. 4). There was no difference in gonadosomatic index between dredge- and net-captured scallops on any of the three dates in which both were collected.

Differences in the size distribution of captured queen scallops between the dredges and the net may be a result of differences in behaviour between small and large queen scallops. However, owing to the difference in size selectivity between the two gears (70 mm diagonal mesh net versus 60-mm-diameter rigid steel rings), firm conclusions cannot be made. Queen scallops over 55 mm in shell height can reasonably be expected to be retained by both the dredge and net, and therefore, a comparison of size frequency of scallops over 55 mm in shell height captured by the two processes can be made. The frequency distribution of these queen scallops was skewed to the left in the net compared to the dredge, indicating lower numbers of the larger size classes swimming up in the water column (Fig. 5). Very few individuals of the largest size classes (>68 mm shell

Table 3

Analysis of covariance of total wet weight and shell weight (including epifauna) of *A. opercularis* captured in the two gear types, top net and dredge, at the East Douglas ground in August 2000

Source	df	MS	F	P
<i>(A) Total wet weight</i>				
Gear type	1	0.002	0.54	>0.4
Shell height	1	1.467	418.78	<0.001
Gear type × Shell height	1	0.002	0.70	>0.4
Residual	96	0.004		
<i>(B) Shell weight including epifauna</i>				
Gear type	1	0.007	0.84	>0.3
Shell height	1	1.228	154.53	<0.001
Gear type × Shell height	1	0.006	0.72	>0.3
Residual	96	0.008		

Shell height was used as the covariate.

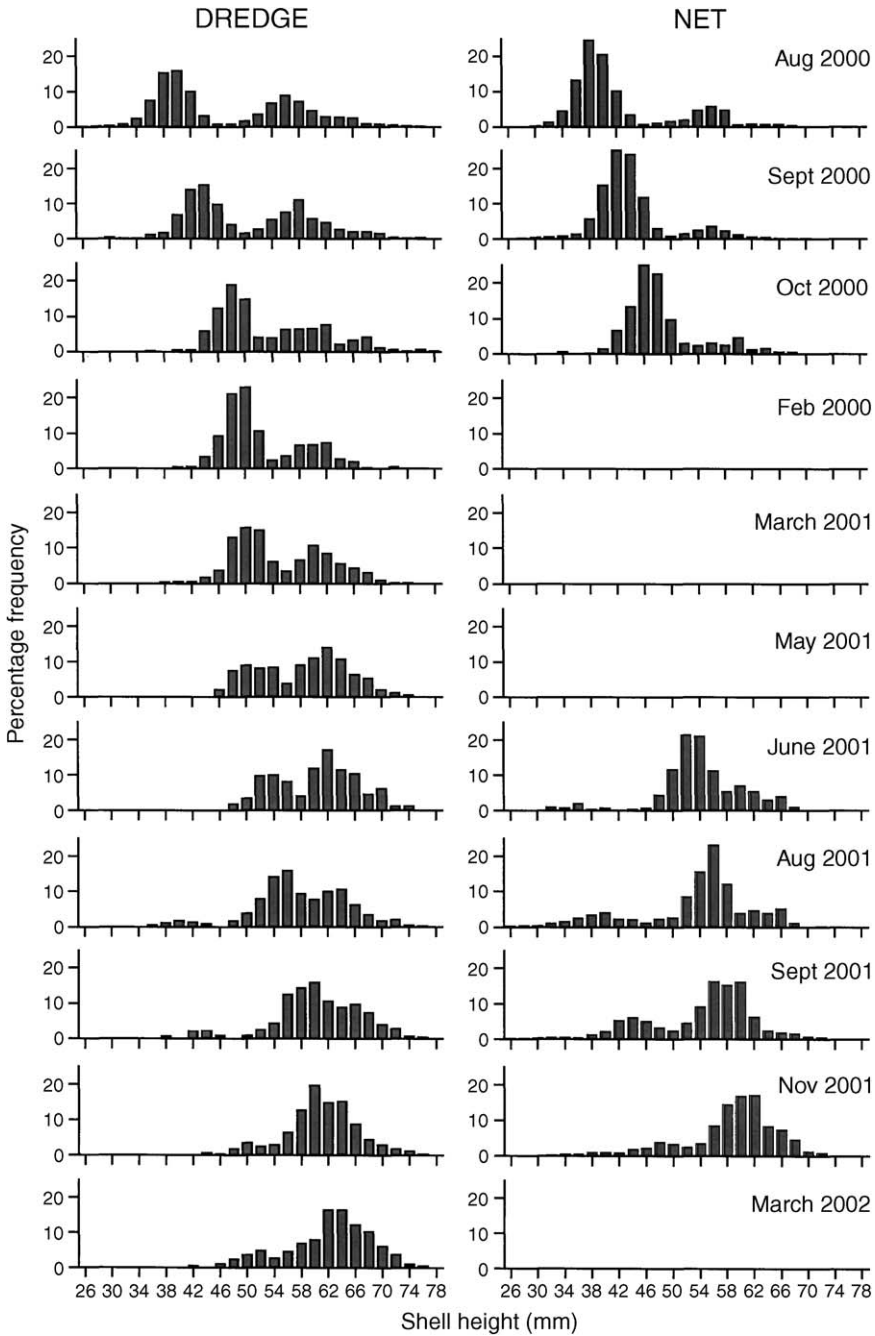


Fig. 7. Size frequency distribution of queen scallops of all sizes captured in dredges and the top net at each sampling date from the Laxey fishing ground.

height) were found in the net. Kolmogorov Smirnov two-sample tests showed significant differences between the size frequency distributions of marketable-sized queen scallops captured in the net compared to the dredges on all but one of the sampling dates analysed (Table 2). A subsample of queen scallops caught at the Douglas ground in August 2000 was analysed to determine any differences in body weight relationships between those captured in the dredge and the net (Fig. 6). ANCOVA showed no significant difference in the relationship between shell height and either total wet weight or shell weight (including weight of epifauna) (Table 3).

Examination of the size structure of the queen scallops captured over the study period shows a shift from a distinctly bimodal population structure in the summer of 2000 to a predominantly unimodal structure in the summer and autumn of 2001 (Fig. 7). These data indicate low levels of queen scallop recruitment during 2000 resulting in very low numbers of juveniles in 2001. The difference in the proportion of juvenile queen scallops in the population between years may have caused the large difference in the maximum proportion of queen scallops found in the top net between 2000 (maximum value = 221%) and 2001 (maximum value = 61%) (Fig. 2A).

4. Discussion

There was distinct seasonal variability in the number of queen scallops showing a strong swimming response to approaching dredge gear. The proportion of actively swimming queen scallops peaked in late summer/early autumn and was lowest during late winter and spring. Comparisons of scallop dispersion among seasons have demonstrated similar patterns of swimming activity in other species. For example, Carsen et al. (1995) showed that the movement of juvenile sea scallops (*Placopecten magellanicus*) from seeded sites of high density was significantly higher during autumn than spring. We showed a very clear positive relationship between queen scallop swimming activity in the field (as shown by the proportion of captured queen scallops in the top net) and seawater temperature. This relationship was best described using a power function. Correlation does not necessarily indicate causality, but it is likely that temperature will have a direct effect on the tendency to swim, and swimming performance, through effects on metabolic activity and nerve transmission. Experimental manipulation of temperature in the laboratory has shown a positive relationship of temperature with metabolic condition of the adductor muscle in *P. magellanicus* (Kleinman et al., 1996). Numerous studies have shown relationships between swimming behaviour and season, and attributed this to the effect of temperature. However, seasonal comparisons clearly confound temperature with several factors such as reproductive state and food supply. There is a need for controlled laboratory experiments to determine the direct effect of temperature on swimming behaviour.

Other factors likely to affect the swimming ability of scallops over the temporal scale investigated are the seasonal cycles of energy storage and utilisation (see Thompson and MacDonald, 1991 for review). The adductor muscle that is used in swimming activity serves as a site for storing reserves of glycogen and protein that are utilised during gametogenesis. However, we found no effect of reproductive state on the level of net

capture in *A. opercularis*. Similarly, Brokordt et al. (2000) showed that the stage of the reproductive cycle had no effect on the number and rate of valve claps performed by *Chlamys islandica* although there was a reduction in the ability to recover from exhausting swimming activity during gonadal maturation and spawning.

An index of ‘swimming activity’ incorporates a number of different components of swimming behaviour, including the time taken to respond to stimuli, the response threshold to stimuli, the strength and rate of valve claps (and therefore swimming velocity) and the total number of muscle adductions before exhaustion. Seasonal variability of one or a combination of these factors could have caused the observed patterns. Results from previous laboratory studies on temperature/seasonal effects on scallop swimming behaviour have been inconsistent (see Ordzie and Garofalo, 1980; Manuel and Dadswell, 1991; Parson and Dadswell, 1992; Jenkins and Brand, 2001). We investigated two behavioural components of swimming in the laboratory over a 12-month period. We found no clear seasonal pattern in the total number of adductions (or number of adductions in the first swimming response) shown by queen scallops on stimulation by a predator. Similarly, Jenkins and Brand (2001) found no differences between spring and autumn (minimum and maximum water temperatures) in the total number of adductions performed by the great scallop *P. maximus*. A clearer pattern was shown by the response times of queen scallops to stimuli. Response times to predators in the laboratory were slow during the spring of 2001, when the capture of scallops in the top net was low. Response times were significantly faster in July, coinciding with the time when capture in the top net peaked. Thus, the ability to respond quickly to oncoming gear and swim upwards before capture in the dredge mouth may have been an important factor in the high number of queen scallops captured in the top net in warmer months. However, this conclusion is by no means certain because, although response times remained rapid through the summer and early autumn of 2001, they were also rapid in March 2002 when capture rates in the top net were low.

Swimming behaviour and ability may vary with age and body size, although relationships are not straightforward and appear to differ among species (see Brand, 1991 for review). In general, large individuals swim less often, and require a higher threshold stimulus to elicit the swimming reaction (Brand, 1991). For example, Caddy (1968) found that *P. magellanicus* over 100 mm in shell length failed to show a swimming response to approaching dredge gear. However, in many species, including *A. opercularis* (Chapman et al., 1979), larger individuals can travel further per swimming event. In the present study, net-captured scallops of marketable size (>55 mm shell height) were generally smaller and lacking the largest size class. Thus, our data support the general model of larger individuals showing lower propensity to swim. Another factor likely to affect scallop swimming performance is the weight of epifauna attached to the shell (Chapman et al., 1979; Winter and Hamilton, 1985). Winter and Hamilton (1985) showed that weights, equivalent to the mass of a typical epifaunal load, attached to the shell of *A. irradians*, caused a marked reduction in the distance travelled per swimming burst. However, we found no effect of epifaunal load on the ability of scallops to swim above the dredge mouth.

Seasonality in the swimming behaviour of queen scallops has important implications for the capture efficiency of different gear types through the year. Chapman et al. (1979) made detailed underwater observations of queen scallop behaviour in response to otter

trawls in late summer/early autumn and showed that behaviour was a major factor in determining capture efficiency. Capture by demersal trawls relies on individuals being induced to swim upwards and pass over the foot rope of the approaching net. In contrast, dredge gear relies on queen scallops remaining on or close to the seabed. Our data show that between the latter part of July until the end of November, over 20% (and up to 42%) of the number of marketable-sized queen scallops captured in dredges escaped capture by swimming upwards in the water column. Thus, the capture efficiency of dredges and dredge-like gear used during this part of the year is compromised by swimming behaviour, and it is likely that trawl gear may be more efficient provided the seabed is suitable for trawls. Conversely, during the period from February to May when negligible numbers of queen scallops were caught in the top net, it is likely that trawl gear will show low capture efficiency owing to the lack of swimming activity.

Precise description of the seasonal variation in swimming activity may allow more effective and efficient use of different gear types. Improving the efficiency of demersal fishing techniques such as dredging, which is among the most damaging to benthic communities (Dayton et al., 1995; Collie et al., 2000), will allow lower fishing effort for the same yield. However, such scenarios require strong and effective management if highly efficient techniques are not to cause stock depletion. Such management is possible in scallop fisheries (see Arbuckle and Metzger, 2000 for description of a successful management model used in the *Pecten novaeselandiae* fishery in New Zealand). As well as providing insights into how fishing efficiency may be improved, our results have important implications for the use of catch rates (either from commercial fisheries or scientific surveys) as indicators of population abundance. A critical assumption made in stock assessments is that the catchability of the target species, defined as the proportion of a population captured per unit effort, remains constant. However, catchability may vary both spatially and temporally for a number of reasons, including improvements of fishing efficiency over time (e.g. Gulland, 1983) and changes in behaviour in different environments or seasons (see Smith and Page, 1996; Swain et al., 2000). Despite recognition of how changes in catchability can affect our ability to accurately predict fish and shellfish stocks, there are few studies that give a clear indication of how changes in behaviour affect the likelihood of capture. Our results give clear quantitative estimates of how the catchability of queen scallops using dredge gear will change over the seasonal cycle and hence may be used to improve the predictive ability of stock assessment procedures.

Ranching of shellfish rather than fishing natural populations has attracted increased interest in recent years. However, populations of seeded scallops have generally incurred high losses due to both predation and dispersal. A large research effort has investigated numerous aspects of reseeded in the sea scallop *P. magellanicus* and shown that dispersal occurs at a greater rate during warmer months (Carsen et al., 1995; Hatcher et al., 1996). Similarly, Fleury et al. (1996) concluded that autumn was the worst time for reseeded *P. maximus* because at this time of year, two thirds of juveniles were lost within 3 days. The present study confirms that similar seasonal patterns of dispersal are likely in *A. opercularis* owing to seasonal variability in swimming activity.

In conclusion, this study showed that avoidance of dredge capture may be used as a useful measure of swimming behaviour in the field. Swimming behaviour in *A. opercularis* was strongly seasonal which has important implications for the ecology of

the species and its exploitation. Swimming activity was closely correlated with seawater temperature but not with the reproductive cycle of *A. opercularis*. Confirmation of the direct role of temperature in causing seasonal variability in swimming activity requires the use of laboratory experiments to unconfound variability in seawater temperature with seasonal variability in metabolic status of animals, and determine which behavioural components of swimming contribute to the observed differences between seasons.

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