Discarding in the Isle of Man Queen Scallop, *Aequipecten opercularis*, Fishery

The effect of on-deck sorting processes upon the survival potential of undersized queen scallops

MSc Marine Biology

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Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted for any degree.

This dissertation is being submitted in partial fulfillment of the requirement of M.Sc. Marine Biology.

This dissertation is the result of my own independent project work, except where otherwise stated.

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Abstract

Indirect fishing mortality is now recognised as a major force undermining the sustainability of exploited populations and, with the current drive towards ecosystem management, its role must be accounted for when designing new management strategies. The present study focuses upon the sustainability of Isle of Man queen scallop (*Aequipecten opercularis*) fisheries, as defined by the Marine Stewardship Council. Consequences of discarding include direct damage, which can cause mortality, and stress, which undermines defences against predation and disease. Queen scallops around the Isle of Man can be caught in trawls or dredges. Once on deck they are currently sorted by a mechanical process, though before this development the catch was sorted by hand. Each of these processes may have different effects upon discard survivorship.

The results show significantly higher levels of damage are caused by dredging in comparison to trawling. The mechanical sorting process is also demonstrated to cause higher levels of shell damage than the hand sorting process. These differences are proposed to be due to the higher levels of physical contact with metal elements of the fishing gear experienced during both dredging and mechanical sorting. However, the higher levels of physical damage inflicted on deck during the mechanical sorting process do not appear to be accompanied by higher levels of stress. An investigation into vigour of the predation avoidance response showed no discernable difference between the two sorting processes. No difference in survival, short or long term, was found as a result of using mechanical sorting rather than hand sorting.

The type of by-catch affected by different fishing methods was investigated. The community structure affected by dredging was distinct to that affected by trawling. Composition of by-catch caught in trawls was found to vary geographically, possibly due to water column features such as surface temperature or wave action.

Introduction

The massive expansion of the human population since the Industrial Revolution and the subsequent pressure exerted upon natural systems mean that ensuring the sustainability of natural resources and food production has become an international priority (Agardy 1994). Marine resources constitute an important source of animal protein, particularly in developing countries where much population expansion is occurring. In 2002 it was estimated that the world's population was increasing at a rate of 1.14%, meanwhile exploitation of marine resources is widely believed to have peaked. Capture fisheries provided an estimated 106 million tonnes of food fish in 2004 and currently exhibit a growth rate of 0.4% (SOFIA 2006). Over 75% of world fish stocks are now believed to be either fully or overexploited, thus little potential exists for the expansion of marine capture fisheries and cautious management is now required to maintain a supply of animal protein for the expanding human population (SOFIA 2006). The Marine Stewardship Council specifies three major objectives which must be achieved in order to classify a fishery as sustainable:

- Ensure the sustainability of the exploited stock.
- Be managed in a manner that maintains ecosystem structure, function and biodiversity.
- Engage in a responsible management strategy that adheres to local, national and international legal institutions.

As part of the current drive towards MSC eco-label certification for the Isle of Man queen scallop (*Aequipecten opercularis*) fishery, this review aims to characterise the effects of different fishing processes upon the survivorship of the non-harvested queen scallop stock.

Since the 1970s, after the collapse of the herring fishery, fishing for the great scallop (*Pecten maximus*) and queen scallop has constituted a major industry for the Isle of Man. Over 80% of the first sale value within the fishing and processing industries on the island has been generated by the great and queen scallop fisheries (Brand & Prudden 1997).

There are current no specific management restrictions for queen scallop fisheries in the Isle of Man beyond the minimum landing size of 40mm. However, fishing for these animals tends to be seasonal, taking place in the summer months. Indeed, trawl fisheries for this species are largely restricted to the summer months as they rely upon warm summer temperatures to promote the swimming behaviour of the queen scallops, by which means they are captured in trawl nets (Jenkins *et al*. 2003). The area of Bay Fine is set aside as a marine reserve, permanently closed to both trawling and dredging, and therefore provides some kind of refuge for exploited species. However, the efficacy of temperate marine reserves in providing fisheries benefits is of some debate (Kaiser 2005).

In the Isle of Man queen scallop fishery, both dredges and trawls are used and the effect of fishing activity is largely dependent upon the type of gear used (Jones 1992). After fishing, the catch is hauled on board and sorted using a mechanical system in the form of a rotating drum with apertures of 50mm which sorts out queen scallops of manageable size and returns that portion of the catch to be discarded directly to the sea. The fishery is situated on grounds of primarily gravelly sediments, which exhibit high levels of habitat and community heterogeneity (Bradshaw *et al*. 2000).

Indirect Fishing Mortality

In order to achieve sustainability of an exploited stock, both direct and indirect fishing mortality must be managed. Direct fishing mortality is managed through a variety of methods, including quotas, spatial and temporal fishery closures and gear restrictions. However, such measures are insufficient to completely support exploited populations. A major factor in ensuring the health of the exploited stock is protecting potential recruits to the fishery (Gruffydd 1972). Thus the effects of indirect fishing mortality must also be considered whilst designing management strategies. In some cases, this indirect mortality may even exceed that of the catch mortality (Alverson 1994). It has therefore been proposed that if the indirect mortality caused by fishing could be eliminated then some severely depleted stocks may be able to recover (Kell & Bromley 2004).

There are two major components of indirect fishing mortality; the mortality of individuals that are caught and subsequently discarded and the mortality of individuals that come into contact with fishing gear and are subsequently damaged by it without being caught (Jenkins & Brand 2001). Within these two indirect fishing mortality factors, discarding is generally believed to be the greater force in driving mortality in non-harvested populations. The levels of damage observed on the seabed in individuals that come into contact with fishing gear but are not caught is generally low and highly dependent upon the nature of the gear used (Jenkins & Brand 2001).

The FAO defines discards as 'that portion of the catch which is returned to the sea' for whatever reason and worldwide may comprise 7.3 million tonnes per year (Kelleher 2005). In ICES Subarea VII, including the English Channel, Western Approaches, Celtic and Irish Seas, 24500 tonnes of a total of 72000 tonnes of fish caught each year are estimated to be discarded, with trawling being responsible for approximately 90% of these discards (Enever *et al*. 2007). A range of estimates of the level of indirect fishing mortality exerted upon the non-exploited portion of scallop stocks have been produced, ranging from 10% (Caddy, 1973), 20% (Curry & Parry, 1999) through to up to 92% (Messieh *et al*. 1991). Thus in designing a management strategy to decrease levels of indirect fishing mortality, the most efficient use of resources may be to decrease the level of discarding or ameliorate the impact of the fishing process upon individuals that are to be discarded (Broadhurst *et al*. 2006). During fishing activity, discards may suffer physical damage (Medcof & Bourne 1964) and experience high levels of stress which may increase their susceptibility to predation or disease (McLoughlin *et al*. 1991).

Capture in fishing gear and subsequent on-deck sorting processes have the potential to exert both sub-lethal and fatal damage upon captured individuals. Damage caused by capture and discarding can detrimentally impact the survival potential of discards in several ways. Severe damage can result in mortality directly, it can increase the predation risk for discarded individuals (Jenkins *et al*. 2004) and it may also negatively impact upon growth and reproduction as available energetic resources are directed away from these uses and are instead invested in shell repair.

Beyond the direct physical damage suffered during the fishing process, removal from their habitat and subsequent discarding from the fishing vessel once sorted is a highly stressful experience. Stress is 'the reaction of an organism by a disturbed physico-biological balance to an abnormal impact to the environment' (Dhert 1996). It is most commonly studied through the use of a variety of biochemical, behavioural and physiological indices which may represent the response of an animal to environmental conditions (Maguire *et al*. 1999*a*). The recent development of behavioural indices in the study of stress has been particularly useful as it represents a non-destructive method of observing the stress response.

In scallops, predation avoidance behaviours are often used as a behavioural marker for stress, in particular swimming or righting and recessing behaviour. The energetic cost of these behaviours means that individuals that are highly stressed are unable to expend the additional energy required in order to perform them (Minchin *et al*. 2000). Thus stress may negatively affect the swimming ability of species such as the queen scallop (Maguire *et al*. 1999*b*).

As a consequence of the inability to perform swimming or recessing behaviours, highly stressed individuals may suffer higher levels of predation once returned to their natural environment (Thompson 1980). This risk of predation is compounded by the attraction of high levels of scavengers and predators to sites where discarding has occurred. Veale *et al*. (2000) demonstrated that up to 200 times the background number of scavengers may aggregate at discarding sites. Thus an increased predation risk may compound the effects of indirect fishing mortality.

The consideration of indirect fishing mortality in catch mortality models such as that of Chopin *et al*.(1996) may be seen in a wider context as a move towards ecosystem-based fishery management, which looks beyond the management of single exploited species and instead considers the wider impact of the fishery (Sinclair & Valdimarsson 2003). Maintenance of benthic marine habitats is important, marine ecosystems cover over 70% of the Earth's surface and provide an array of vital goods and services, including nutrient cycling to support species of commercial importance (Constanza 1997).

Impact of Fishing upon the Wider Ecosystem

Dredging and trawling have various effects upon the wider marine ecosystem, which must be modulated in order to meet MSC standards for sustainability within a fishery. The design of demersal gears ensures some contact with the seabed, which may result in sediment resuspension, ploughing of the benthos or changes in community structure (Jones 1992). A variety of other species are also captured and discarded as by-catch as part of the queen scallop fishery and fishing may impact upon the marine environment itself.

The non-exploited species most commonly impacted by commercial fishing are larger members of the epibenthos, which are of sufficient size to be retained by the fishing gear (Kaiser *et al*. 1998). Such animals may also suffer outright physical damage or a degree of stress as a result of capture and discarding, which may result in a heightened risk of predation or simply impose an energetic cost as resources are directed to recovery rather than to growth or reproduction (Mensink *et al*. 2000). Demersal fishing has the potential to alter the structure of benthic communities, removing the largest species and larger-bodied individuals (Ball *et al*. 2000) whilst smaller-bodied or burrowing species tend to be less vulnerable (Brey 2001). This shift in community composition can lead to changes in the diversity and productivity of the ecosystem as a whole. It may also impact upon commercially important species, as many benthic invertebrates provide an important food source and support ecosystem processes (Hiddink *et al*. 2006).

It has been estimated that demersal fishing may impact upon over 50% of seabed habitats each year (Hall 2002), though habitats may differ in their sensitivity to such impacts. Sensitivity may be described as the degree to which features of the environment (in the current context, habitats) respond to stresses, where stresses are deviations of environmental conditions beyond the expected range (Zacharias & Gregr 2005). More sensitive habitats tend to be characterised by relatively low levels of natural disturbance, including wave erosion, with an abundance of relative large and long-lived individuals (Hall 1999). Understanding the sensitivity of a habitat is important in devising an ecosystem-approach to fisheries as any collateral ecological damage must be accounted for whilst achieving sustainability of a target species (Kaiser *et al*. 2002). However, such understanding can only be achieved through detailed fishery-specific studies. Predicting the damage caused to an ecosystem by fishing may result in the development of management measures such as quotas based upon the degree of ecological 'expense' caused by fishing a particular habitat (Holland & Schnier 2006).

Aim of the Study

The present study aims to investigate the impact of different fishing practices upon the survivorship of queen scallop discards in the fishery around the Isle of Man. Specifically, it seeks to characterise the levels of physical damage and stress induced by two different on-deck sorting processes; hand sorting and processing by a mechanical riddle. The riddle is a rotating drum with apertures through which undersized individuals fall and are returned to the sea. Survival potential is demonstrated through a study of shell damage levels, behavioural responses to predation and direct mortality, both long-term and on-deck. It is hypothesised that the mechanical process will be a more traumatic procedure, which will result in higher levels of physical damage and stress than the supposedly less traumatic hand sorting process, and therefore will cause higher levels of indirect fishing mortality within the queen scallop fishery. The impact of fishing upon other species caught in the queen scallop fishery as by-catch will also be investigated as part of the characterisation of the indirect impacts of fishing. It is hoped that as a result more effective management protocols can be designed in order to minimise the effects of this indirect fishing mortality and therefore enhance the sustainability of the queen scallop stock, assisting in the current drive towards MSC eco-label certification.

Specific Objectives and Hypotheses

- The length structure of the discarded and retained queen scallop catch will vary according to the sorting method used to process those individuals hauled on board.

At present, the principal method of conserving the queen scallop stock is a minimum legal landing size restriction of 40mm. Thus ensuring effective management requires that this size is adhered to and that this effectively preserves the future stock. Any potential changes to the sizes of queen scallops harvested as a result of changing fishing practices must also be investigated.

- The level of physical damage exhibited by an undersized queen scallop will vary according to the gear with which it was captured. Dredging will result in higher levels of physical damage than trawling.

- The level of physical damage shown by undersized queen scallops will vary according to the on-deck sorting process to which they are exposed. Those individuals sorted by hand will suffer lower levels of damage than those subjected to a mechanical sorting treatment.

The extent of physical damage suffered during fishing has an important influence upon the survival of discarded individuals. It is therefore important to investigate how different fishing methods may impact upon the level of physical damage inflicted as part of designing optimal fishery management strategies in order to maximise the survival potential of discarded animals and therefore increase the probability of their effective recruitment to the adult fishery.

- The ability of an undersized queen scallop to respond to the threat of predation will be impaired according to the level of stress exerted upon it by on-deck sorting processes. Hand-sorting will be less traumatic and therefore hand-sorted queen scallops will be better able to respond to simulated predation threats than mechanically-sorted individuals.

Once returned to the benthos, there is abundant evidence that discards suffer higher levels of predation as a result of the attraction of large numbers of predators and scavengers to discard sites, particularly to energetically-valuable queen scallops. In order to for queen scallop discards to survive once thrown back, they must therefore be able to effectively respond to the threat of predation through the initiation of an escape response. If mechanical sorting is a particularly stressful process, then individuals treated by this method will be less able to initiate the energetically expensive escape response upon interaction with a predator and therefore will suffer reduced survival in comparison to those which have undergone less stressful on-deck processes.

- The ability of undersized queen scallops to survive the stress of exposure on-deck after sorting will vary according to the stress endured during the sorting process.
- Survival of queen scallop discards over the long term once returned to the benthos will be affected by the stress endured on-deck and will therefore vary according to the type of sorting process experienced.

Perhaps the most direct effect of stress upon indirect fishing mortality is its ability to decrease both short and long-term survival (Bremec *et al*. 2004). If these mortalities can be reduced by promoting less stressful on-deck sorting processes, then the overall fishing mortality within the exploited population may be reduced and its sustainability therefore enhanced.

- The composition of the by-catch obtained as a result of fishing for queen scallops will vary according to the type of fishing gear used.
- The composition of the by-catch obtained as a result of trawling for queen scallops will vary according to the location of the fishing activity around the Isle of Man.

The impacts of fishing often extend beyond the exploited population. In consideration of the wider ecosystem effects of fishing, the mortality caused in non-target species should be investigated. Several species of both commercial and non-commercial importance may be found in the by-catch of queen scallop fisheries and fishing may therefore impact upon the environment and other commercially important fisheries. Thus it is important to characterise the types of communities and species affected by fishing activity in order to be able to design management strategies to reduce the impact of fishing upon these species.

Methodology

Collection of Samples: Trawling and Dredging

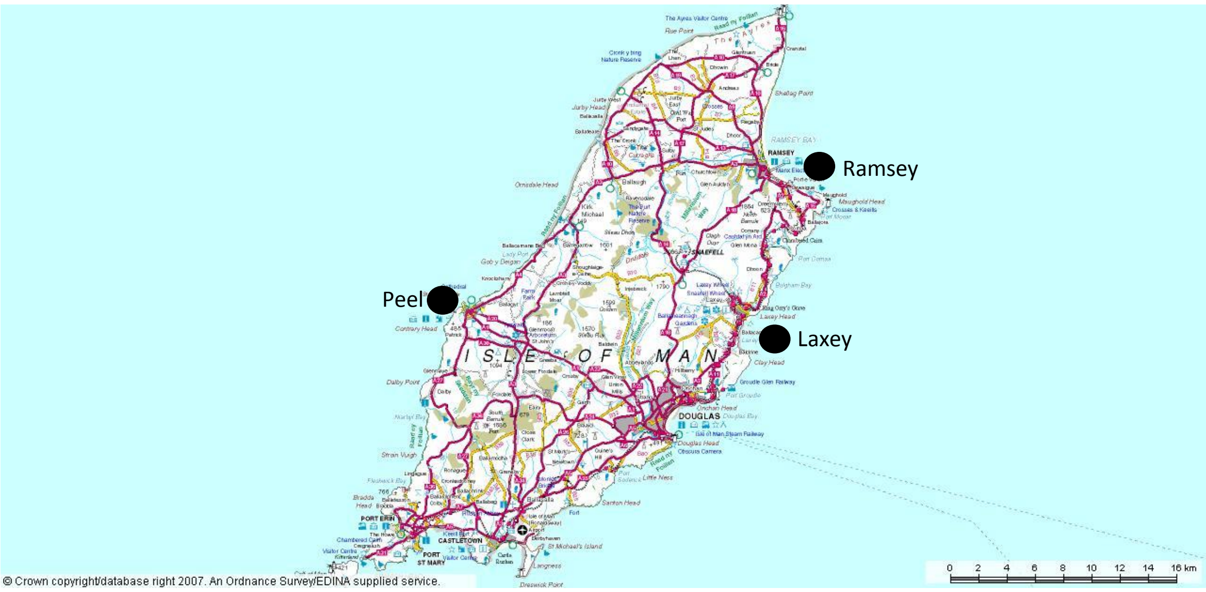

Figure 1 Map of the Isle of Man showing general location of trawling and dredging activities in Peel, Ramsey and Laxey. (Taken from www.digimap.com)

For the queen scallop discard work, trawls were conducted in June 2008 on board the *Silver Viking* off the east coast of the Isle of Man in fishing grounds off Peel, south of the Targets fishing ground, using trawl gear with a diamond mesh size of 80mm, gear width 48ft and weight approximately 3 tonnes. Dredging was carried out on board the *Cair Vie* out of Ramsey and Douglas using 4 dredges each of 0.76m width and approximately 500kg. For both trawling and dredging, tow length was approximately 2 nautical miles, carried out at a speed of 2.5-3 knots (duration approximately 45 minutes).

After being hauled on the board, the trawled catch was treated in one of two ways. Half the catch of queen scallops was sorted according to current commercial practices, being shovelled into a rotating mechanical drum with apertures of 50mm in order to separate those individuals of marketable size from those which would usually be returned to the benthos. The other half of the catch was sorted by hand, with undersized individuals being picked out manually. Those queen scallops caught in the dredges were sorted by hand once on board as no mechanical alternative was available.

For the by-catch survey, trawl data were collected alongside the queen scallop experimental work off Peel, plus an additional 8 trawls were conducted off the west coast of the island on board the *Helena M.* covering grounds classified for the purpose of this study as Laxey and Ramsey. By-catch data are also presented from dredging activities on board the *Cair Vie* at Laxey and Ramsey. As the queen scallop catch was sorted, individuals of by-catch species were picked out, identified to the highest possible taxonomic resolution, and their abundances recorded.

Size-Frequency Analysis

Hypothesis One: The length structure of the discarded and retained queen scallop catch will vary according to the sorting method used to process those individuals hauled on board.

Methods

The minimum legal landing size for queen scallops in Isle of Man fisheries is 40mm shell height. To investigate the size structure of the queen scallop population caught for market, or caught and subsequently discarded, a size-frequency analysis was conducted. 200 queen scallops, which had been sorted form the catch by hand, were measured, 100 being of a size considered marketable and 100 which were to be discarded. The process was repeated for 200 queen scallops that had been through the mechanical sorting process.

The length-frequency data were pooled into 5mm categories for both discarded and retained individuals and a size-frequency chart constructed to visually compare the size frequencies of those queen scallops preferred for market and those discarded for each sorting treatment.

After visualising the data, a chi square analysis was performed to test the null hypothesis that size-frequencies of discarded queen scallops was the same for each sorting method. This analysis was then repeated to test the null hypothesis that the sizes of queen scallops retained for sale was the same for each of the two sorting methods.

Results

Of the 200 individuals sampled in the analysis of mechanically-sorted queen scallops, only 5% were found to be below the minimum legal landing size, all of which were found in the discarded catch. The size-frequency analysis of mechanically-sorted individuals found that the average size of those individuals retained for sale is 67mm. The average size of those queen scallops caught and then discarded after being mechanically sorted is 48mm. The size-frequency distribution of the catch and discards are shown in Figure 2. The mechanical riddle was constructed with apertures of 50mm, thus individuals below this size should fall into the discarded category whilst those above this size should be kept for market. However, the analysis found that some individuals above 50mm were found in the discarded catch. The minimum size which was kept for market was 56mm and the maximum size of queen scallop that went through the sorted process to be discarded was 70mm, there is therefore some degree of overlap in the size-frequency distributions of kept and discarded individuals. Figure 2 clearly illustrates two different cohorts of queen scallops, the larger being targeted for market and the smaller being thrown back to recruit to the fishery later.

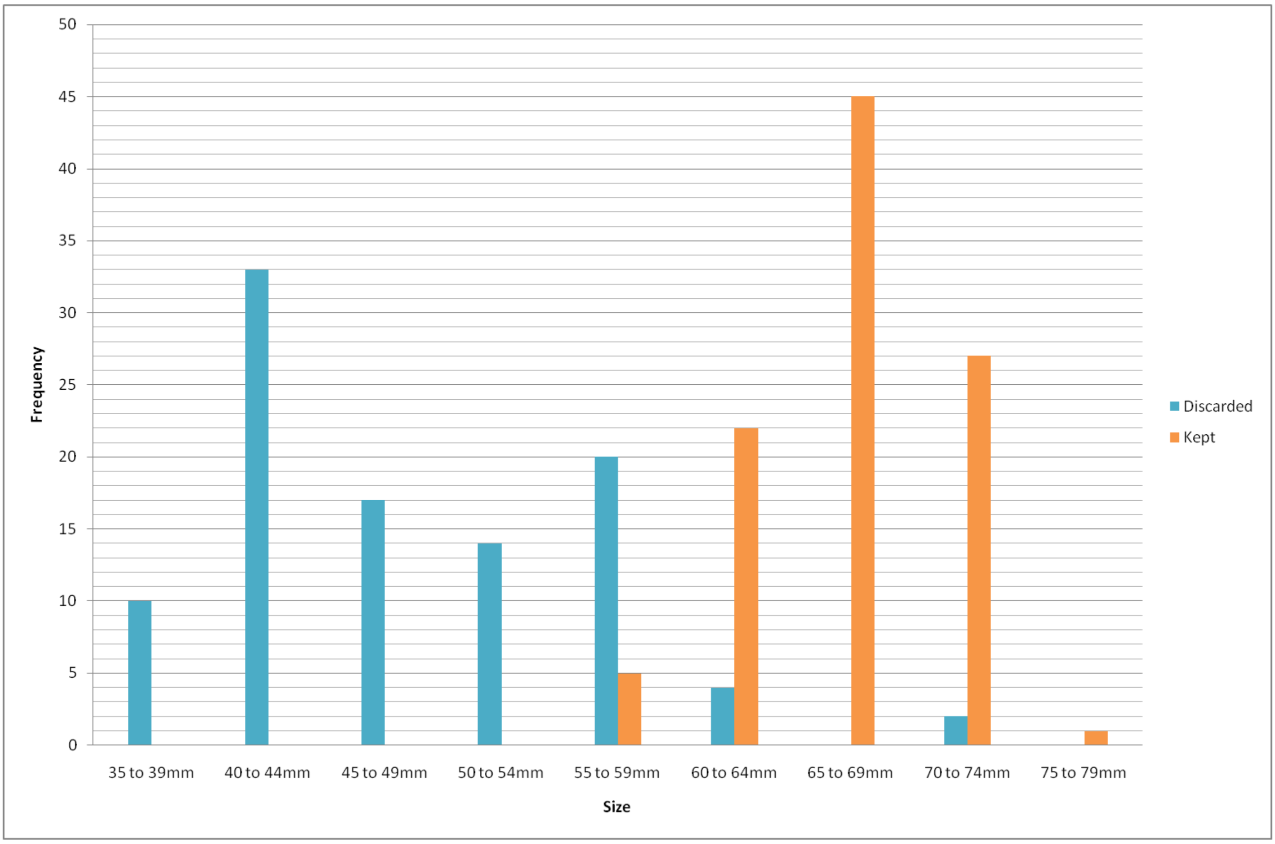

Figure 2 Size-frequency analysis results of mechanically-sorted queen scallops, both kept and discarded, clearly showing a cohort of adult animals and one of undersized animals which will later recruit to the fishery. There is some degree of overlap in size between discarded and harvested individuals.

Only 7% of those queen scallops sorted by hand were below the legal landing size of 40mm, all of which were found in the discarded catch. The average size of individuals kept for market was 67mm, whilst that of those sorted out by hand for discarding was 48mm. As for the mechanically-sorted distribution, Figure 3 shows two cohorts of queen scallops; one harvested and the other discarded. The size distributions of discarded and harvested scallops overlap, thus meaning that the system is not 100% efficient.

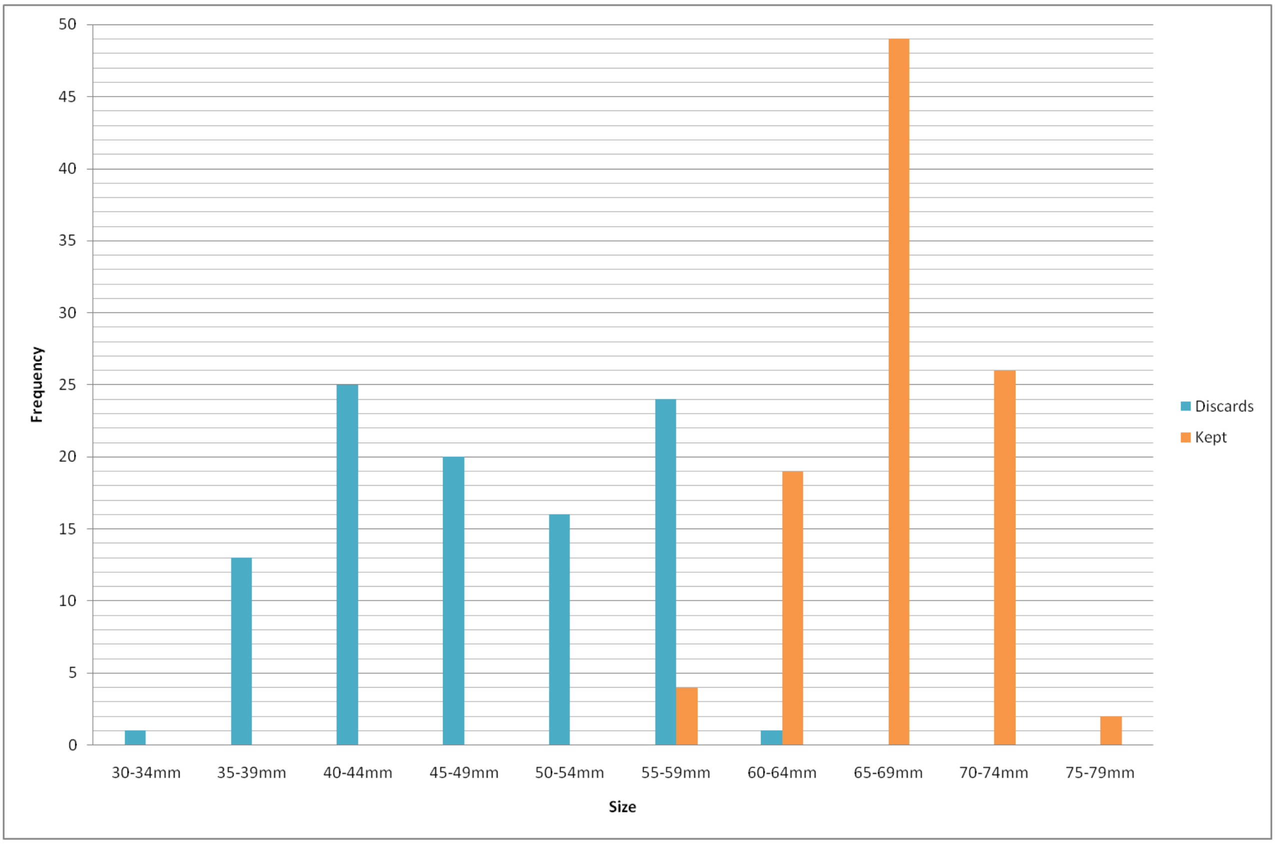

Figure 3 Size-frequency distribution of hand-sorted queen scallops, showing a flatter distribution than that of their mechanically-sorted counterparts. Again, there is some overlap in size of harvested and discarded individuals and two clear cohorts can be seen.

Chi square analysis showed no significant difference in the size-frequency distributions of either the discarded individuals of the two sorting processes (X^2=17.889, p=0.929, *df*=28) or that of the individuals from each sorting method kept for sale (X^2=12.272, p=0.906, *df*=20). Thus the null hypotheses are accepted and the size-frequency distributions of queen scallop catches and discards do not vary according to the sorting method by which individuals are processed on deck.

Damage Scores

<u>Hypothesis One: The level of physical damage exhibited by an undersize queen scallop will vary according to the gear with which it was captured. Dredging will result in higher levels of physical damage than trawling.</u>

Method

Queen scallops in the Isle of Man may be caught by either dredging or trawling. A damage assay was conducted whereby a sample of 50 individuals which were to be discarded were taken from each of 6 dredge tows and 15 trawls, all of which had been sorted out from the wider catch by hand. Each individual was scored for damage level according to the method outlined in Jenkins *et al.* (2001), detailed in Table 1.

Table 1 Scoring system to characterise damage level in queen scallops, following Jenkins *et al*. (2001)

Score	Damage Level
1	None/Negligible
2	Minor (shell shipped)
3	Major (large cracks)
4	Lethal

A chi square analysis was conducted to test the null hypothesis that the proportion of queen scallops in each of the four damage score categories would be the same for the two fishing methods.

Results

Figure 4 shows the average damage scores for each fishing method. Dredging produced an average score of 1.43±0.04, whilst the average damage level in trawled queen scallops was 1.32±0.02. The chi square analysis showed a significant difference in damage levels between the two fishing methods (X^2=14.036, p=0.003, *df*=3). Thus the level of physical damage exerted on the undersized queen scallops was higher if they had been captured in dredging gears, with significantly more individuals having a score of only 1 in the trawled population.

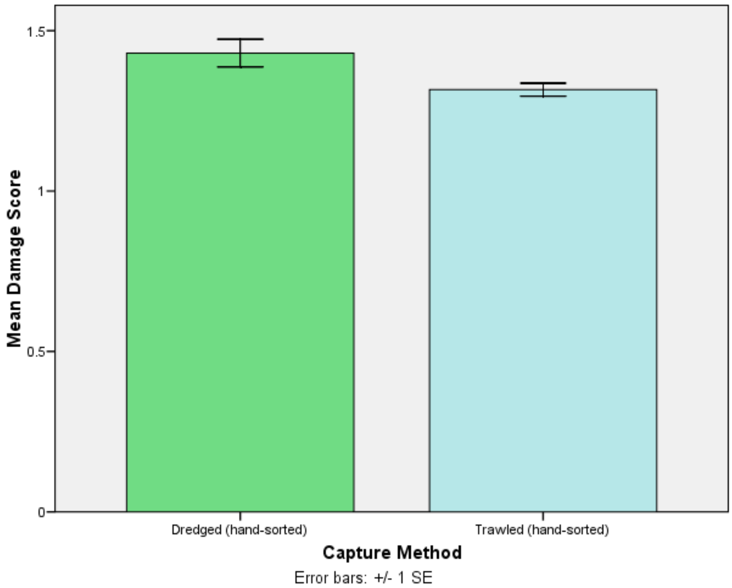

Figure 4 Bar chart showing the average damage score in dredged and trawled queen scallops, sorted by hand, with error bars representing one standard error. Level of damage in dredged individuals is higher than that in trawled.

<u>Hypothesis Two: The level of physical damage shown by undersized queen scallops will vary according to the on-deck sorting process to which they are exposed. Those individuals sorted by hand will suffer lower levels of damage than those subjected to a mechanical sorting treatment.</u>

<u>Methods</u>

100 queen scallops were sampled from each of 15 trawls. A sample of 50 individuals was taken from the population of queen scallops which had been sorted from the catch by hand and were considered below marketable size. An equivalent sample was taken from the queen scallops which had been put through the mechanical sorting process. Each of these individuals were visually assayed for physical damage and scored according to the system outlined previously by Jenkins *et al*. (2001).

To test for an association between damage levels and on-deck sorting process, a chi square analysis was performed, investigating the null hypothesis that there would be no difference in damage level regardless of the sorting process used.

<u>Results</u>

Figure 5 shows the average damage levels in queen scallops exposed to each sorting treatment. The average damage level in those individuals sorted by hand was 1.32±0.02, whilst those put through the mechanical process on average scored 1.53±0.03.

The chi square analysis showed a significant difference in the damage levels observed in queen scallops from the two sorting processes (X^2=44.798, p<0.001, *df*=3). Thus the null hypothesis can be rejected and it can be observed that there is an association between the hand-sorting treatment and the presence of lower levels of physical damage.

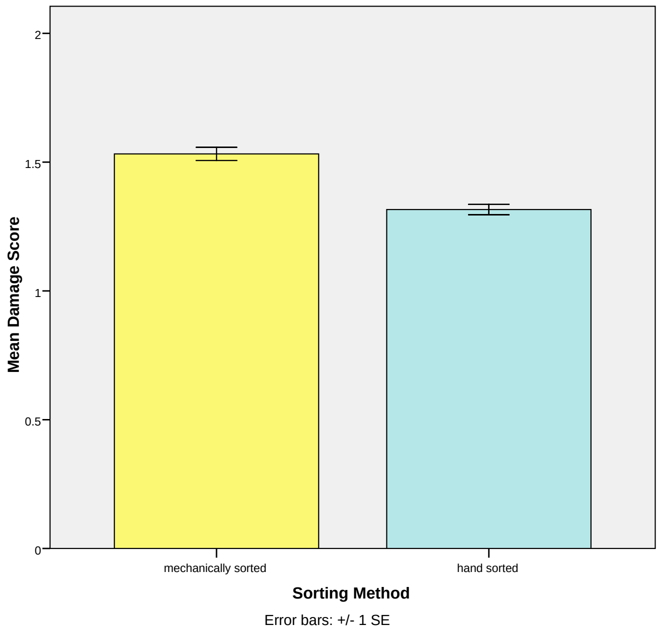

Figure 5 Bar chart showing the average damage score observed in queen scallops from each sorting treatment. Error bars represent one standard error. The mean damage level in mechanically-sorted queen scallops is significantly higher than that in hand-sorted individuals.

Behavioural Assay

Hypothesis One: The ability of an undersized queen scallop to respond to the threat of predation will be impaired according to the level of stress exerted upon it by on-deck sorting processes. Hand-sorting will be less traumatic and therefore hand-sorted queen scallops will be better able to respond to simulated predation threats than mechanically-sorted individuals.

Methods

Queen scallops were sampled from 8 trawls. Preliminary observations of fished queen scallops appeared to indicate that the majority of individuals required a recovery period of 2 hours before recommencing feeding activity when held in tanks on-deck. The trawled queen scallops were therefore transferred to holding tanks after being put through one of the two sorting treatments and left for 90 minutes before any experimental work was performed upon them.

5 trials were conducted, each being carried out 15 minutes apart to cover a total period of one hour. In each trial, 4 queen scallops from each treatment were transferred to separate experimental chambers filled with fresh seawater. Care was taken such that these individuals were not removed from the seawater during this process to minimise any additional stress to the animals. For each trial, a new set of test individuals was used, thus ensuring the independence of the data from each subsequent test. Repeat measures were therefore avoided. Each of these 8 individuals was then assaulted with a simulated predation threat by touching the mantle with the leg of a starfish (*Asterias rubens*). The response to this assault was noted by counting the number of valve adductions performed by the queen scallop as part of a predation avoidance strategy. A total of 20 samples were tested over the 5 trials for each treatment and this was repeated for 8 replicate trawls.

The manner in which the response to predation changed over time and how the response varied according to sorting treatment was therefore ascertained.

To ascertain the manner in which the behavioural response of queen scallops from both treatments varied over time, linear regressions were performed on the response data across each trial to show any change in the number of valve adductions attempted according to the amount of recovery time experienced after capture.

ANCOVA was performed to highlight any differences between the two sorting treatments in their effect upon the ability of the queen scallops to respond to the threat of predation, whilst taking into account any effect of the time allowed for recovery upon the strength of the predator avoidance response elicited as a covariate.

The number of individuals able to respond to the threat of predation was also investigated. Linear regressions were used to elucidate any relationship between the number of respondents and recovery time. These were then used to calculate the point at which 50% of the catch would be able to effectively respond if returned to the benthos and exposed to predation threats.

Results

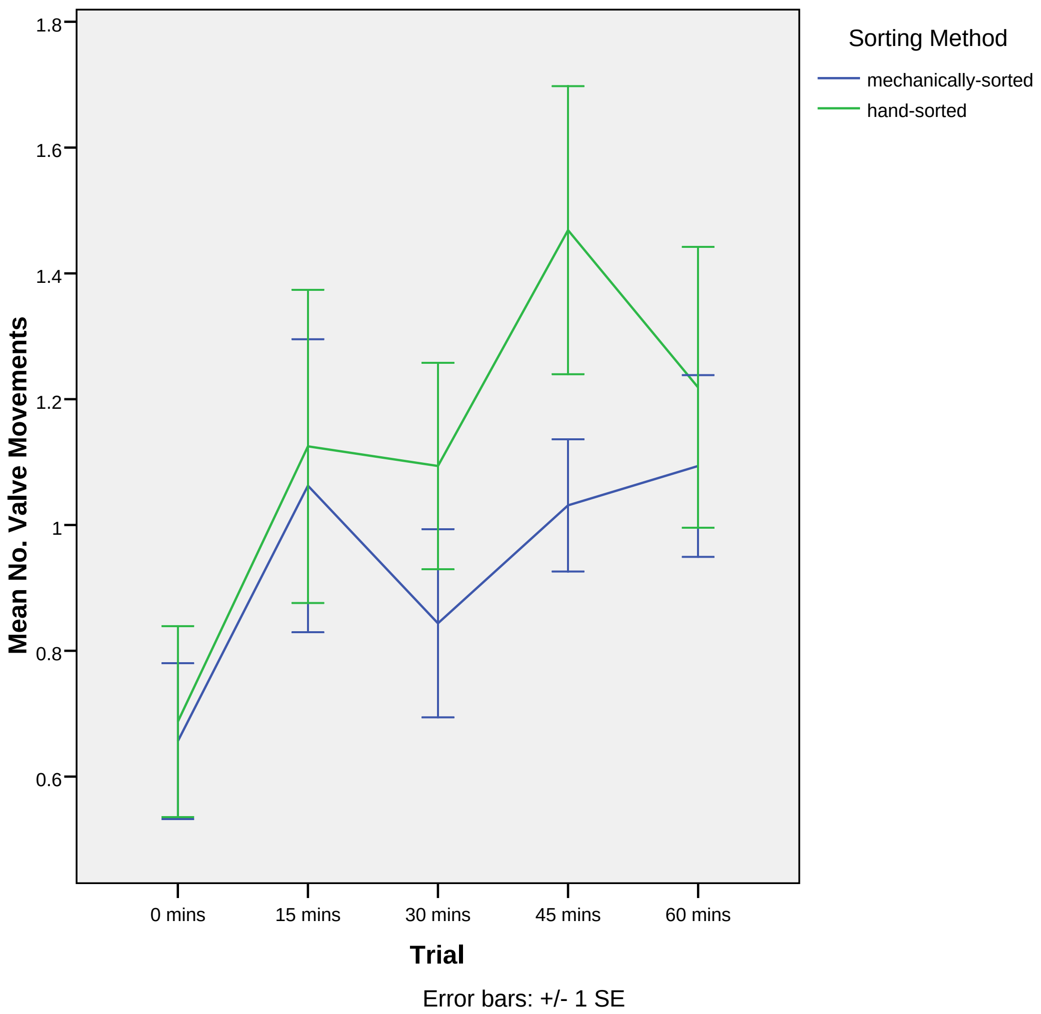

Figure 6 Graph showing the mean number of valve movements performed by queen scallops from both sorting treatments over time. Error bars represent one standard error and can be observed to be overlapping at some points. Hand-sorted individuals tended to respond more vigorously to a simulated predation threat.

Table 2 Table showing the average number of valve movements performed and the associated standard error for each trial of the two sorting treatments.

	Hand-Sorted		Mechanically-Sorted	
Trial	Average No. Claps	St. Error	Average No. Claps	St. Error
1 (0mins)	0.69	0.15	0.66	0.12
2 (15mins)	1.13	0.25	1.06	0.23
3 (30mins)	1.09	0.16	0.84	0.15
4 (45mins)	1.47	0.23	1.03	0.11
5 (60mins)	1.22	0.22	1.09	0.15

Figure 6 shows a plot of the number of valve adductions performed over time by queen scallops from the two treatments, the average number of valve movements at each trial and the standard errors for that trial are shown in Table 2. A general increase in the vigour of the response to a simulated predation threat may be seen.

The results of the linear regression reported that those individuals sorted by hand did show a significant positive change in their responsiveness over time, with the response increasing as the number of trials progressed (r^2=0.028, p=0.033). However, the low R-value indicates that only a relatively low proportion of the variation in response magnitude is accounted for by the regression equation. In contrast, those individuals sorted by the mechanical process did not show a significant increase in their responsiveness over the experimental period (r^2=0.018, p=0.092). ANCOVA showed no significant difference between the sorting treatments in their effects upon the behavioural response to predation in the queen scallops (Table 3).

Table 3 Results of ANCOVA testing for differences between sorting treatments in the ability of queen scallops to respond to a predation threat. No significant difference between sorting methods is seen.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	10.728(a)	2	5.364	4.972	0.007
Intercept	27.751	1	27.751	25.721	0.000
Trial	8.100	1	8.100	7.507	0.006
Sorting Method	2.628	1	2.628	2.436	0.120
Error	342.019	317	1.079		
Total	691.000	320			
Corrected Total	352.747	319			

a R Squared = .030 (Adjusted R Squared = .024)

The number of individuals responding over time for each treatment is shown in Figure 7, average number of responsive individuals in each trial and the standard errors for each trial are given in Table 4.

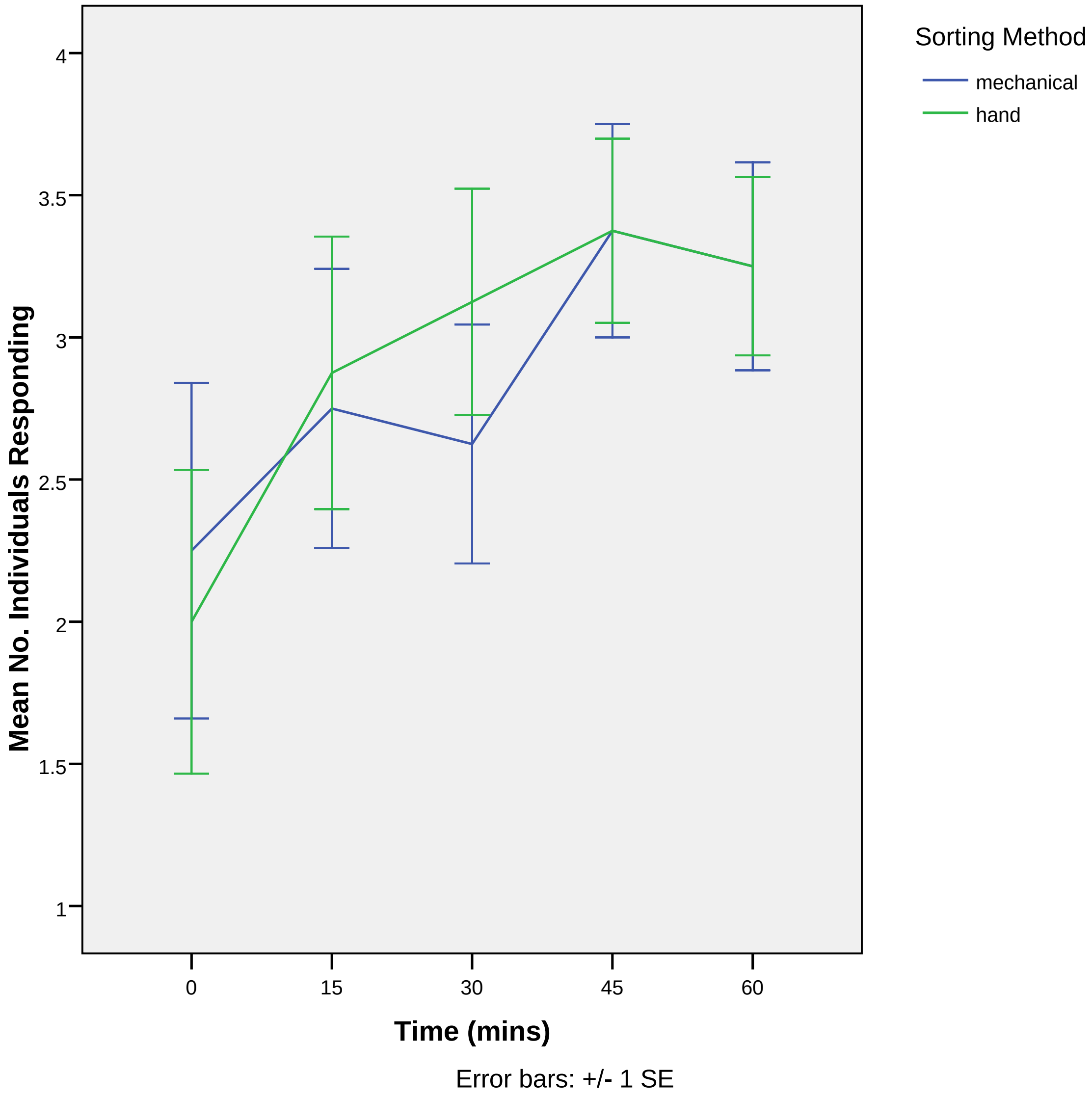

Figure 7 Graph showing the average number of individuals responding to the simulated predation threat in each trial. The error bars are one standard error and are overlap for each treatment. There is an increase in the number of individuals responding over time.

Table 4 Table showing the average number of queen scallops responding to the threat of predation at each time interval and the associated standard errors for each sorting treatment.

	Hand-Sorted		Mechanically-Sorted	
Trial	Average No. Responding	St. Error	Average No. Responding	St. Error
1 (0mins)	2.00	0.53	2.25	0.59
2 (15mins)	2.88	0.48	2.75	0.49
3 (30mins)	3.13	0.40	2.63	0.42
4 (45mins)	3.38	0.32	3.38	0.38
5 (60mins)	3.25	0.31	3.25	0.37

Linear regressions were fitted to these data for both treatments. A significant relationship existed between the number of hand-sorted queen scallops responding to the threat of predation and the time they had been left to recover (r^2=0.123, p=0.027). The number of mechanically-sorted queen scallops which were able to respond to the predation threat did not change significantly over time (r^2=0.085, p=0.069), though this relationship was close to being significant.

Using the regression lines so calculated, an attempt was made to decipher the point at which 50% of the sorted individuals from each treatment would be able to respond to the threat of predation. The regression lines were extrapolated back to were 50% of individuals in a trial showed some kind of respond to the starfish (where n=2). For the hand-sorted queen scallops, the point at which 50% responsiveness occurred 79 minutes after sorting. For the mechanically-sorted individuals, 50% responsiveness occurred 76 minutes after sorting.

On Deck Survival

Hypothesis One: The ability of undersized queen scallops to survive the stress of exposure on-deck after sorting will vary according to the stress endured during the sorting process.

Methods

Queen scallops were sampled from 14 trawls conducted.

To investigate the survival of queen scallops when left exposed on-deck after sorting, 10 individuals were taken from each of the mechanically and hand-sorted treatments and left aside to assay their survival over time. The number surviving was counted every 10 minutes over a period of an hour. The process was repeated for 14 replicate trawls.

The relationship between survival and time were plotted for each treatment and a linear regression analysis performed to investigate the relationship between the number of individuals surviving and the time for which they were left exposed on deck.

ANCOVA was carried out to investigate whether any differences occurred in the patterns of on-deck survival over time between the two sorting processes, also taking into account the effect of the different weather conditions in which the experiments were conducted.

Results

The relationship between the numbers of queen scallops from each treatment surviving over time is shown in Figure 8, the average number of survivors at each time interval and the standard errors are given in Table 5. Mortality increases with increasing exposure time. Linear regressions showed a significant decrease in the number of hand (r^2=0.530, $p<0.001$) and mechanically-treated (r^2=0.526, $p<0.001$) individuals. In each case, over 50% of the variation in the number of queen scallops surviving was accounted for in the regression equation, indicating a good fit to the data. ANCOVA revealed that the two sorting processes did not result in any significant difference in the patterns of on-deck survival observed (Table 6), though survival did decrease significantly with increasing exposure time and varied according to the day on which the experiment was conducted (most probably due to weather conditions at the time of exposure).

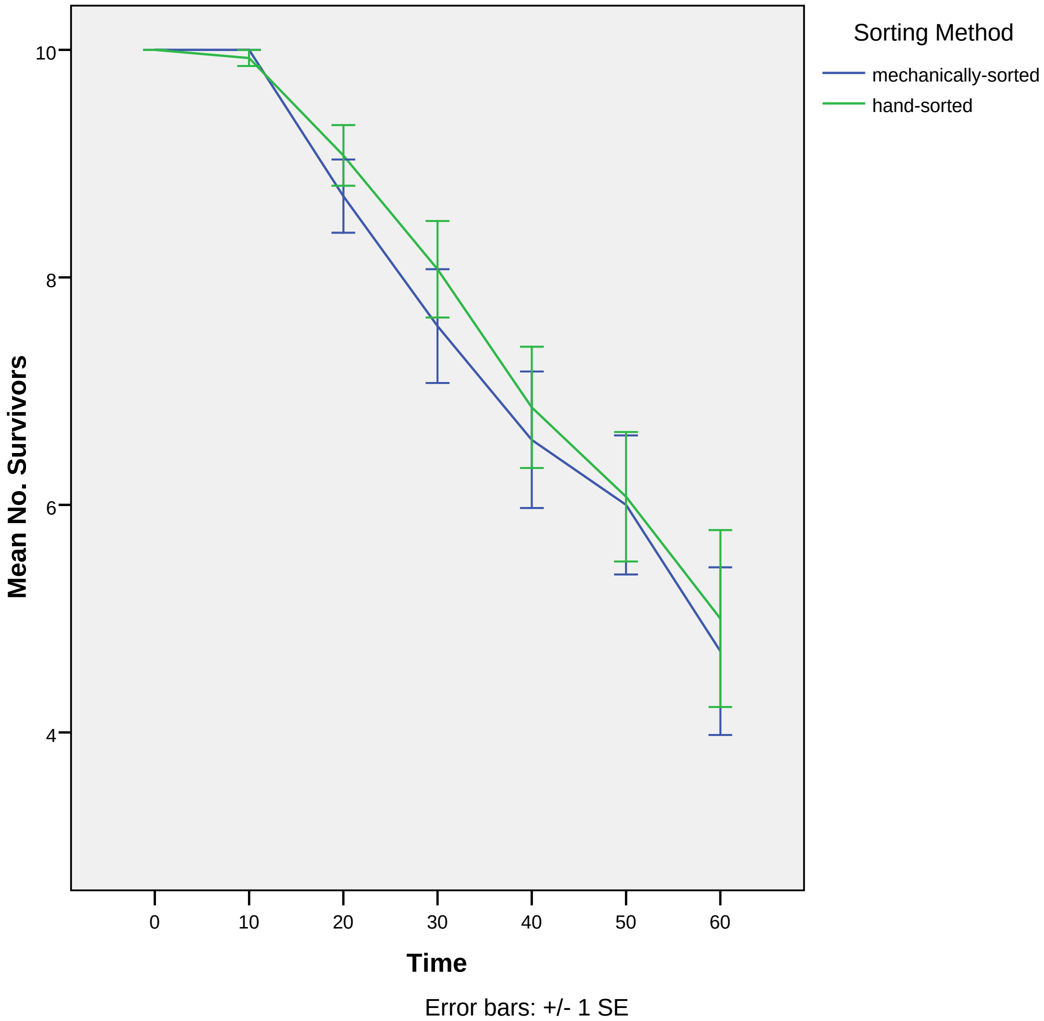

Figure 8 Graph showing the average number of queen scallops from two on-deck sorting processes surviving at 10 minute intervals over a period of an hour. Error bars show one standard error. The two lines follow each other closely, survival decreasing as exposure time increases.

Table 5 Table showing average number of individuals surviving at each time interval and the associated standard errors for each sorting process.

	Hand-Sorted		Mechanically-Sorted	
Time	Average No. Surviving	St. Error	Average No. Surviving	St. Error
0mins	10.00	0.00	10.00	0.00
10mins	9.93	0.07	10.00	0.00
20mins	9.07	0.27	8.71	0.32
30mins	8.07	0.43	7.57	0.50
40mins	6.86	0.53	6.57	0.60
50mins	6.07	0.57	6.00	0.61
60mins	5.00	0.78	4.71	0.74

Table 6 Results of ANCOVA testing for differences between sorting processes in the ability of queen scallops to survive on deck. No significant difference is observed between sorting processes in their effect upon survival.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	737.619(a)	3	245.873	95.829	0.000
Intercept	987.375	1	987.375	384.828	0.000
Time	648.430	1	648.430	252.725	0.000
Day (Weather)	87.149	1	87.149	33.966	0.000
Sorting Method	2.041	1	2.041	.795	0.374
Error	492.625	192	2.566		
Total	13018.000	196			
Corrected Total	1230.245	195			

a R Squared = .600 (Adjusted R Squared = .593)

Long-Term Survival

Hypothesis One: Survival of queen scallop discards over the long term once returned to the benthos will be affected by the stress endured on-deck and will therefore vary according to the type of sorting process experienced.

Method

A flowing seawater tank system was set up at the Manx Mariculture facility to investigate the long-term survival of 200 queen scallop discards. 100 individuals were taken from each sorting treatment during one trawl, 50 being damaged and 50 being undamaged. These were taken from a trawl and kept in cold seawater during transfer to the holding tanks at Manx Mariculture. The samples were split across 20 replicate tanks, 5 being designated for each of 4 categories (hand-sorted and damaged, hand-sorted and undamaged, mechanically-sorted and damaged, mechanically-sorted and undamaged), 10 individuals of each category being housed in each tank. Damaged and undamaged individuals were kept separately to prevent confounding the results with an effect of additional mortality. The tanks were maintained over a two week period with flowing seawater filtered to 8 microns and, with any mortality being noted over this time.

The data were investigated for any trends present in the level of mortality between sorting treatments and these displayed visually.

Results

Over the two week period for which the sampled queen scallops were studied, no mortality was experienced.

3. By-catch Composition in Queen Scallop Fisheries.

By-catch data were collected from a total of 24 trawls, 8 on the east coast and 16 on the west coast of the island, and 6 dredges from the east coast. Trawling and dredging was carried out under the same conditions as described for the queen scallop discard work. Multivariate statistical analyses were performed using the PRIMER package (Clarke & Warwick 2001) in order to highlight patterns in by-catch composition or species abundance according to the type of fishing gear used.

Prior to use in analysis, raw abundance data were standardised to show the number of individuals of each species present per square kilometre, such that the effects of tow duration or gear width upon the number of individuals obtained were accounted for.

Abundance data were imported into PRIMER and square root transformed before any statistical tests were carried out, so that the influence of extreme outliers upon the results obtained was reduced and the contributions and rare and abundant species to the community analysis became more balanced.

A Bray-Curtis similarity matrix was generated from these data and subsequently used to assess the degree of similarity or dissimilarity between tows.

An ANOSIM was first performed with an *a priori* specification of groups in order to test the null hypothesis that no differences were present between species assemblages obtained by different fishing methods (either trawling or dredging or location of fishing). The R value so obtained by a randomisation permutation technique represents the degree of dissimilarity between groups (Clarke 1993).

A CLUSTER analysis was carried out from the similarity matrix, whereby the relative similarity of the species composition of tows could be visualised in the form of a dendrogram using the group-average linkage method.

Non-metric multi-dimensional scaling (MDS) was carried out on the data in the similarity matrix. This analysis was performed in order to map the tows into two-dimensional space according to their relative similarity or dissimilarity, thus highlighting any potential groupings between tows according to the species present and their abundances.

Once the species abundance data from the tows had been visualised using the CLUSTER analysis and MDS plot, with potential differences between groups of tows being determined, a SIMPER analysis was performed, which utilised the Bray-Curtis similarity matrix in order to calculate those species of the greatest importance in driving similarities within groups of samples and differences between them.

For the analysis of the trawls carried out at different geographic locations, the species assemblage data were used to produce dominance plots, which may serve as an indicator of the level of environmental stress acting within an assemblage. Traditionally, the presence of few, highly dominant species is considered indicative of a highly disturbed or stressed system in which only a few well-adapted species are able to thrive.

PRIMER was used to calculate the total number of species present in each tow and the Shannon-Weiner Index for each tow. These indices were analysed using univariate statistical methods. The data were tested for normality and homogeneity of variance, using a Kolmogorov-Smirnov test and Cochran's test and found not to meet the assumptions of ANOVA. SPSS was therefore used to conduct a non-parametric Kruskal-Wallis test to investigate whether any difference existed in these diversity indices between groups.

Trawling Vs. Dredging

<u>Hypothesis One: The composition of the by-catch obtained as a result of fishing for queen scallops will vary according to the type of fishing gear used.</u>

<u>Methods</u>

Species abundance data from 8 trawls conducted on the east coast (Laxey and Ramsey) and 6 dredges also carried out on the east coast were included in the analysis to compare the by-catch assemblages caught by the two gears whilst removing the possible influence of geography, Multivariate analysis was conducted as detailed previously.

<u>Results</u>

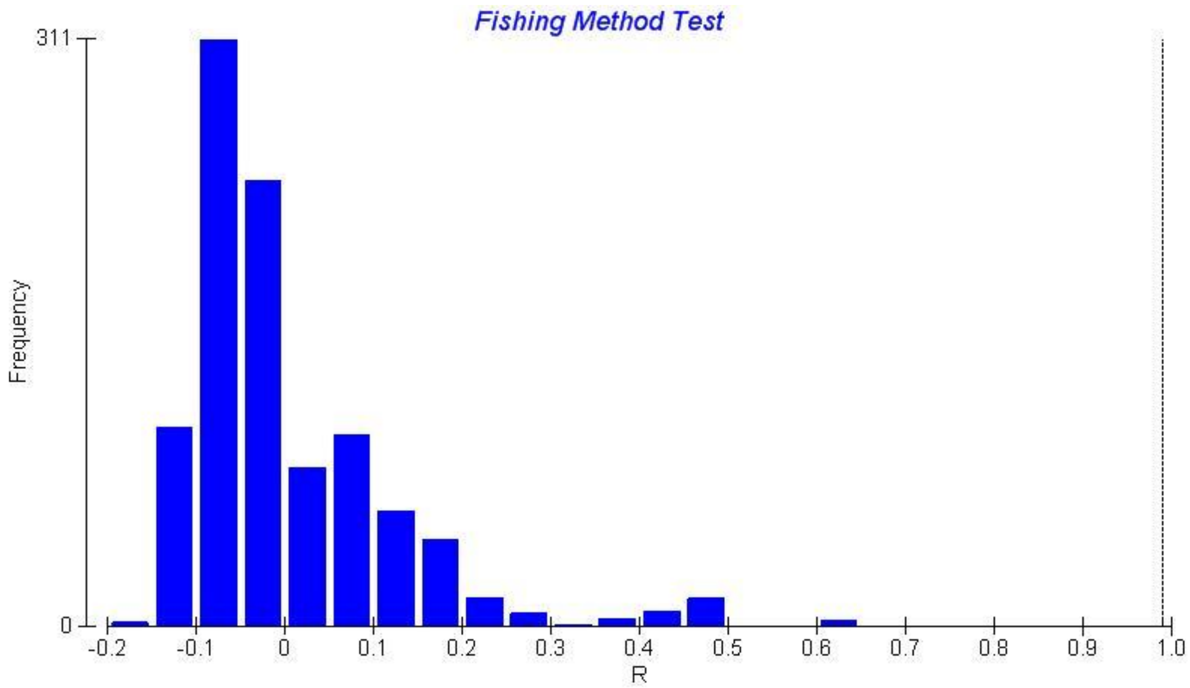

Figure 9 Results of ANOSIM showing a Global R value of 0.99, therefore indicating a significant difference between fishing methods in terms of the by-catch assemblages caught.

ANOSIM gave a Global R value of 0.99 (p=0.001), which rejects the null hypothesis and indicates that there is a significant and high degree of dissimilarity between by-catch species assemblages according to the type of fishing gear used (Fig. 9).

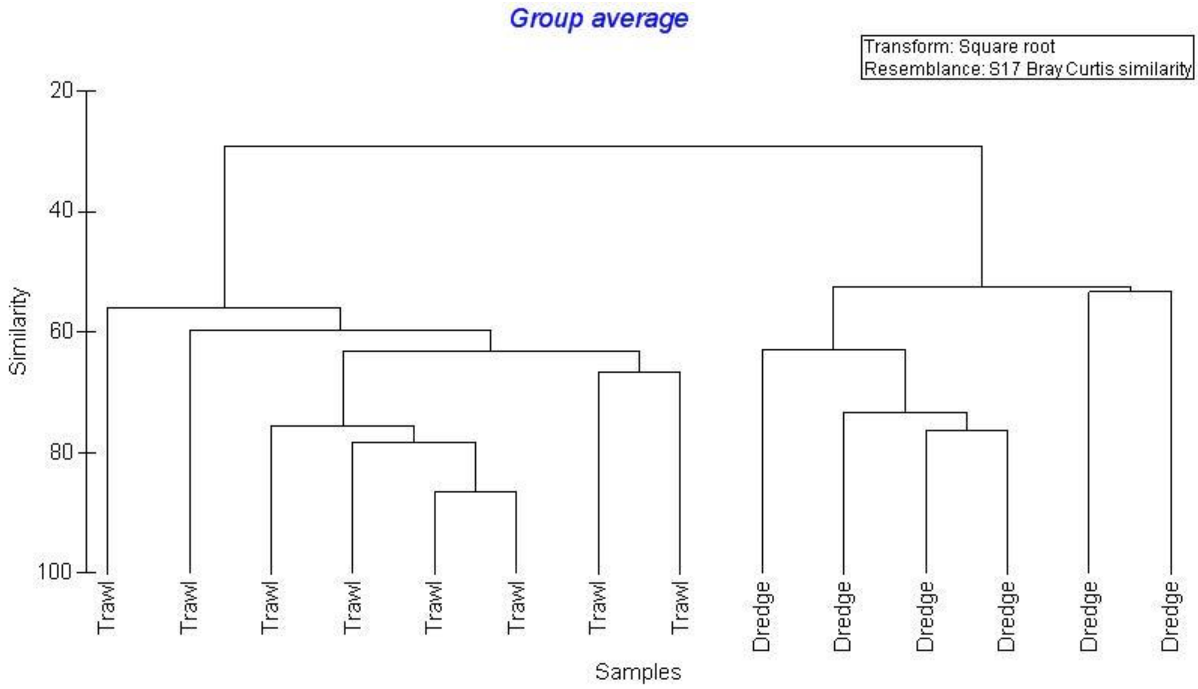

Figure 10 Results of CLUSTER analysis showing the degree of relatedness between tows of different fishing gears. The primary grouping can be observed to split the by-catch assemblages according to the fishing method used, thus grouping together trawling events separately from dredging.

The dendrogram produced by the cluster analysis illustrates a clear separation of tows into two groups according to the fishing method used (Fig. 10). There is therefore a clear distinction between the by-catch composition of trawling gear and that of dredging gear.

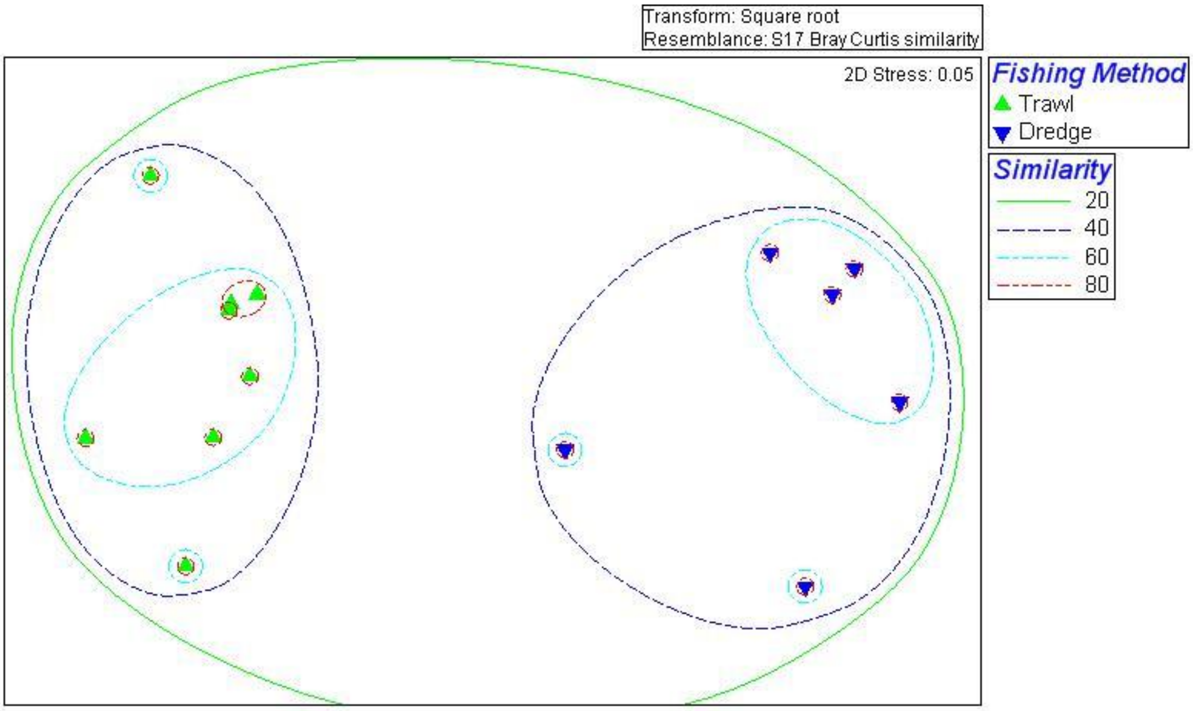

Figure 11 MDS plot highlighting the grouping pattern of the communities studied. The by-catch assemblages of the trawls group separately from those of the dredges.

The pattern highlighted by the CLUSTER analysis is re-enforced by the results shown in the MDS plot (Fig. 11). Tows are segregated into two primary groups according to the fishing gear used, though there is some spread within each group.

The results of the SIMPER analysis are given in Table 7.

Table 7 Results of SIMPER analysis looking for species driving differences between the types of assemblage found in dredges and that found in trawls. The most important species are listed first, and tend to be benthic invertebrates.

	Group Trawl	Group Dredge				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Common Starfish (*Asterias rubens*)	27.27	84.49	9.62	2.13	13.58	13.58
Dead Mens Fingers (*Alcyonium digitatum*)	3.46	44.77	6.72	1.38	9.48	23.06
Hermit Crab (*Pagurus sp.*)	2.15	41.43	6.44	3.54	9.08	32.14
Whelk (*Buccinum undatum*)	4.47	33.73	5.08	2.64	7.17	39.31
Ophiuroidea	0	31.69	5.01	1.32	7.07	46.38
Urchin (*Echinus esculentus*)	24.62	50.15	4.1	1.84	5.78	52.16
Dogfish (*Scyliorhinus sp.*)	35.86	11.3	4.02	2.09	5.67	57.84
Red Gurnard (*Aspitrigla cuculus*)	18.78	1.61	2.96	2.37	4.17	62.01
Unknown bivalve	0	16.5	2.4	0.68	3.38	65.39
Astropecten irregularis	0.55	14.28	2.2	1.88	3.1	68.49
Cuckoo Ray (*Raja naevus*)	1.94	13.84	2.18	1.22	3.08	71.56
Liocarcinus holsatus	1.38	12.74	1.95	1.2	2.75	74.32
Plaice (*Pleuronectes platessa*)	7.92	10.26	1.55	1.25	2.18	76.5
Sun Star (*Crossaster papposus*)	4.31	10.78	1.53	1.78	2.16	78.66
Grey top shell (*Gibbula cineraria*)	0	8.74	1.4	1.32	1.98	80.63
Pout Whiting (*Trisopterus luscus*)	7.63	0	1.18	0.46	1.66	82.29
Bloody Henry Starfish (*Henricia oculata*)	0	6.71	1.02	0.66	1.44	83.74
Long-legged crab (*Macropodia sp.*)	0	5.9	0.88	0.68	1.24	84.98
Grey Gurnard (*Eutrigla gurnardus*)	4.99	0	0.84	1.34	1.18	86.16
Ascidians	0	4.92	0.81	0.7	1.14	87.3
Whelk egg mass	0	5.16	0.8	0.63	1.12	88.42
Edible Crab (*Cancer pagurus*)	0	4.78	0.74	0.65	1.04	89.46
Dab (*Limanda limanda*)	0	3.41	0.67	0.66	0.94	90.4

The average dissimilarity between the species composition of trawls and that of dredges was 70.9%. 23 species accounted for over 90% of the differences between the tows using fishing methods. It can be seen in Table 7 that the species which account for the greatest part of the dissimilarity between fishing groups tend to be benthic invertebrates that are found in greater abundance in dredges than in trawls, for example *Asterias rubens* and *Acyonium digitatum*.

The average number of species found in trawls was 13 and that in dredges was 15. Kruskal-Wallis showed no significant difference between trawls and dredges in terms of the average number of species found per tow (X^2=1.689, p=0.194). The average value of the Shannon Index for the trawls carried out was 1.7, whilst that for dredges was 1.8. Again, Kruskal-Wallis indicated no significant difference in this diversity index according to fishing method (X^2 = 1.067, p=0.302).

Effect of Location in Trawling By-Catch

<u>Hypothesis Two: The composition of the by-catch obtained as a result of trawling for queen scallops will vary according to the location of the fishing activity around the Isle of Man.</u>

<u>Methods</u>

Species abundance data obtained from 8 trawls along the east coast of the island and 16 trawls from the west coast of the island were analysed using multivariate methods as outlined previously.

<u>Results</u>

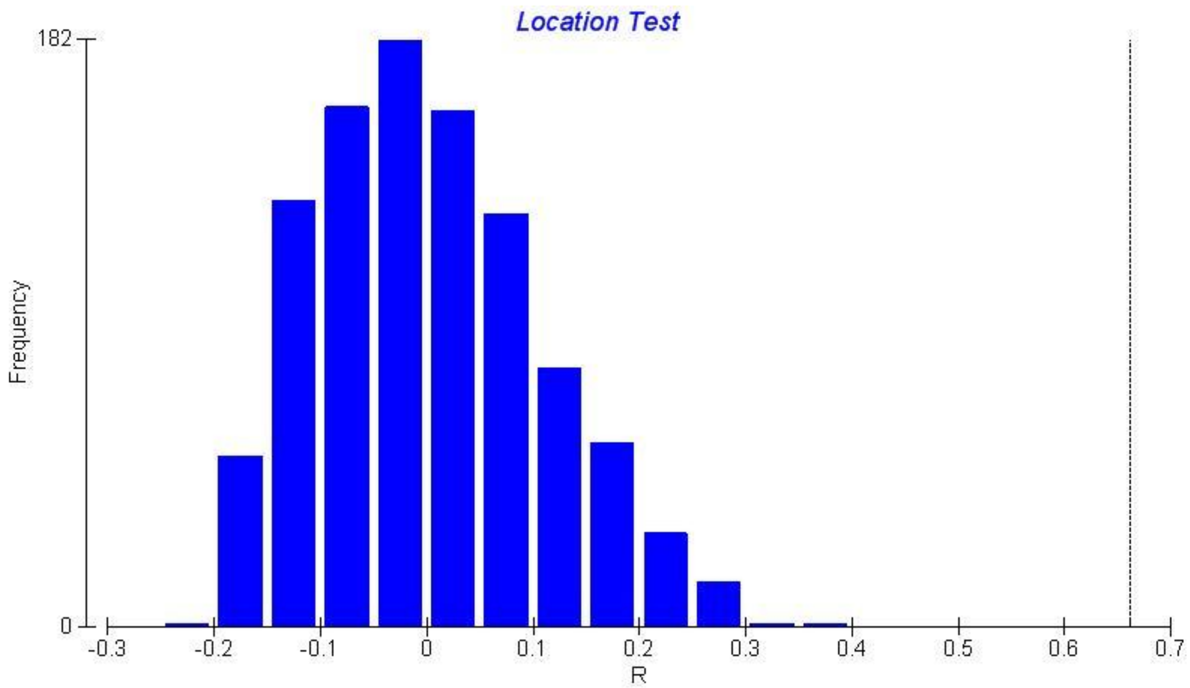

Figure 12 Results of ANOSIM showing a Global R of 0.662, meaning a significant difference exists between the by-catch assemblages of different trawling locations.

ANOSIM gave a Global R value of 0.662 (p=0.001) and therefore indicates that there is a highly significant degree of difference between samples based on the groups specified *a priori*, which represented three different locations around the island. There is thus a spatial influence upon by-catch composition (Fig. 12).

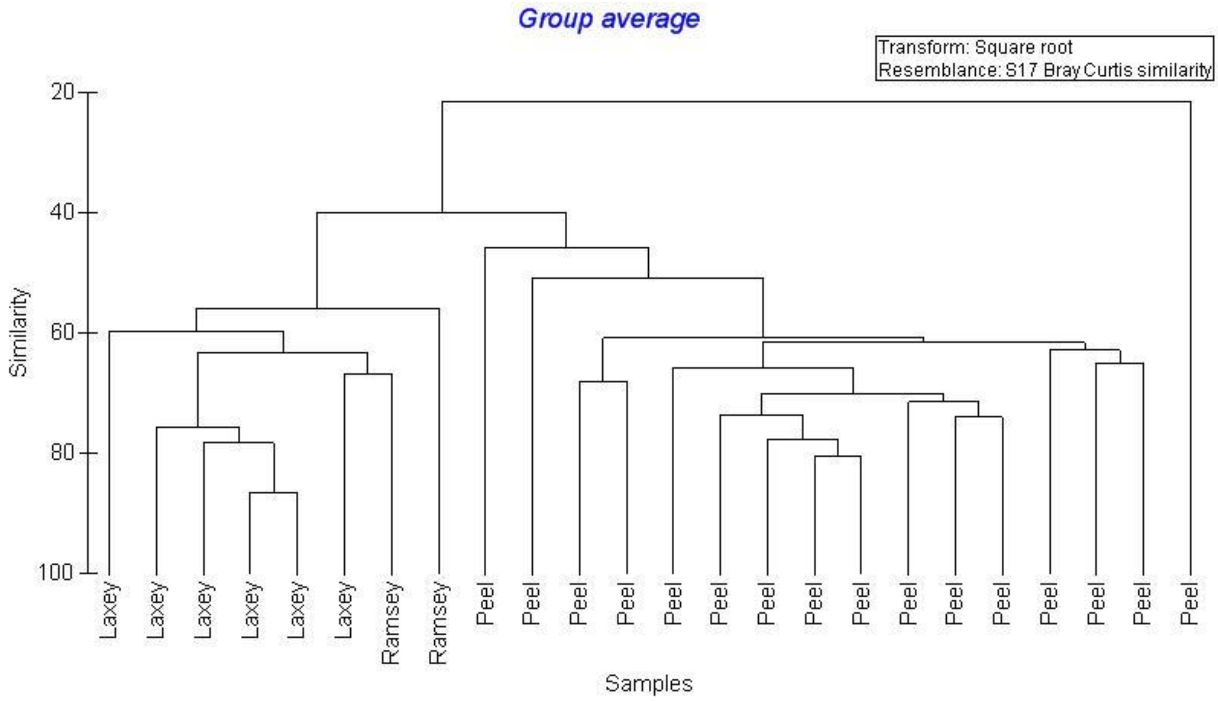

Figure 13 CLUSTER analysis of trawling by-catch. The assemblages from the east coast are more similar to each other than to those of the west coast, which also group together.

The CLUSTER analysis produced the dendrogram shown in Figure 13. Figure 13 illustrates that the primary division of samples occurs along a large-scale spatial division; the dendrogram splits to separate east and west coast samples. Any patterns at smaller spatial scales are unclear as a result of low levels of replication. One sample from Peel, seen far right, appears to be an outlier.

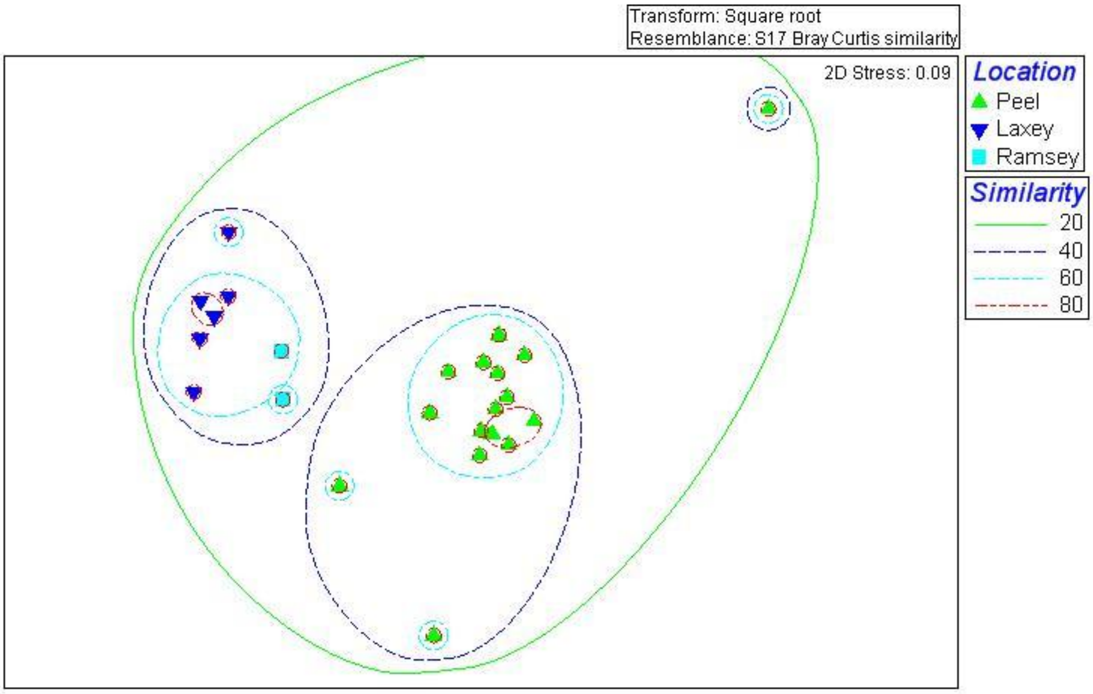

Figure 14 MDS plot showing grouping of by-catch data according to geographic location; east coast trawls group together, as do west coast trawls. Once trawl form the west coast is seen to be an outlier.

The MDS plot again highlights a split between east and west coast samples. The higher level of replication of the west coast samples results in a larger degree of spread and one sample is clearly an outlier (Fig. 14).

Given that the primary grouping pattern present in the data appears to be that of east versus west coast, the SIMPER analysis was performed using 'coast' as the grouping factor. The results are shown in Table 8. Whiting were found to contribute most to the dissimilarity between trawls grouped according to geographic location.

Table 8 SIMPER results showing species important in driving differences between trawl by-catch assemblage structure on the east and west coast of the Isle of Man.

	Group West	Group East				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Whiting (*Merlangius merlangus*)	30.12	0.71	6.45	2.24	10.5	10.5
Common Starfish (*Asterias rubens*)	75.12	27.27	6.27	0.41	10.2	20.7
Urchin (*Echinus esculentus*)	5.84	24.62	4.64	1.73	7.55	28.25
Dab (*Limanda limanda*)	13.68	0	3.25	3.43	5.29	33.54
Dogfish (*Scyliorhinus sp.*)	23.72	35.86	3.1	1.4	5.05	38.59
Red Gurnard (*Aspitrigla cuculus*)	7.82	18.78	2.7	1.83	4.39	42.98
Scallop (*Pecten maximus*)	11.32	1.44	2.28	1.84	3.71	46.7
Plaice (*Pleuronectes platessa*)	14.34	7.92	2.2	1.19	3.59	50.28
Dead Mens Fingers (*Alcyonium digitatum*)	7.44	3.46	1.91	0.81	3.11	53.4
Dragonette (*Callionymus lyra*)	9.15	1.72	1.85	1.94	3.02	56.41
Velvet Swimming Crab (*Necora puber*)	7.05	0	1.64	3.02	2.66	59.07
Squid (*Alloteuthis media*)	8.45	2.63	1.61	1.38	2.62	61.69
Pout Whiting (*Trisopterus luscus*)	0	7.63	1.58	0.46	2.58	64.27
Hermit Crab (*Pagurus sp.*)	6.53	2.15	1.33	1.33	2.17	66.43
Astropecten irregularis	5.09	0.55	1.23	1.12	2	68.43
Cuckoo Ray (*Raja naevus*)	4.55	1.94	1.07	1.51	1.74	70.18
Liocarcinus holsatus	4.46	1.38	1.06	1.02	1.73	71.91
Whelk (*Buccinum undatum*)	1.08	4.47	1	1.08	1.63	73.54
Grey Gurnard (*Eutrigla gurnardus*)	3.77	4.99	0.96	1.24	1.57	75.11
Sun Star (*Crossaster papposus*)	1.44	4.31	0.94	1.13	1.53	76.64
Cod (*Gadus morhua*)	3.89	0	0.91	0.91	1.48	78.12
Spotted Ray (*Raja montagui*)	0.9	3.92	0.87	1.1	1.42	79.54
Anemone	3.67	0.5	0.87	0.82	1.42	80.96
Cuckoo Wrasse (*Labrus mixtus*)	3.6	0	0.86	0.98	1.4	82.36
Hairy Crab (*Pilumnus hirtellus*)	3.33	0	0.8	0.9	1.3	83.66
Brittlestar (*Ophiura sp.*)	0.61	2.86	0.71	0.81	1.15	84.82
Aurelia auretia	3.15	0	0.71	0.55	1.15	85.97
Cyania lamarkii	2.55	0	0.68	0.68	1.11	87.08
Ling (*Geypterus blacodes*)	3	0	0.68	1.2	1.1	88.18
Spider Crab (*Hyas sp.*)	2.43	1.22	0.67	0.9	1.08	89.26
John Dory (*Zeus faber*)	0	2.67	0.66	0.91	1.08	90.34

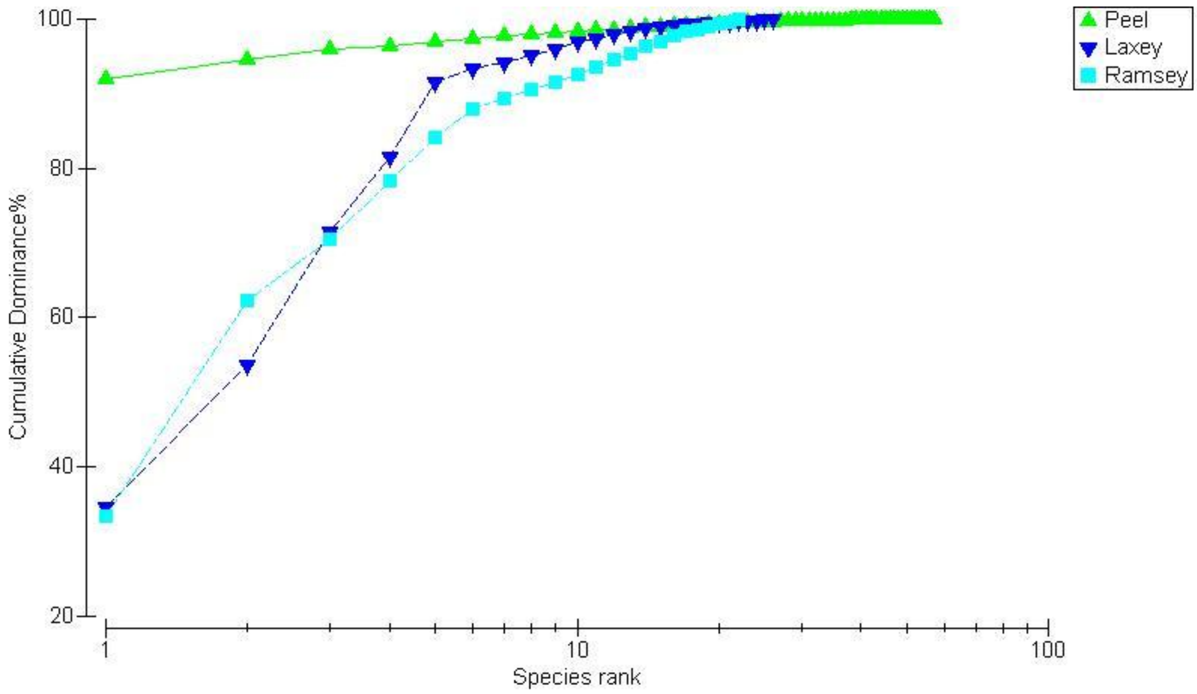

Figure 15 Dominance plot for the 3 sites sampled during trawling. The dominance patterns for the east coast sites are broadly similar and both are different to that for the west coast site.

Averages were taken for the abundance of species at each site and a dominance plot produced (Fig. 15). Clear differences can be seen in the patterns of dominance across the three areas sampled. The two east coast sampling areas (Laxey and Ramsey) display a similar curve-pattern, whilst the dominance pattern of Peel on the west coast is almost linear.

The average number of species found on the west coast was 22, that on the east coast was 13. Kruskal-Wallis showed a significant difference between the two coasts in terms of the total number of species found (X^2=13.589, p<0.001). The average value of the Shannon Index for the west and east coast were 2.1 and 1.7 respectively. Kruskal-Wallis revealed that the level of species diversity found in the by-catch varied significantly according to geographic location (X^2=9.375, p=0.002).

Discussion

Size-Frequency Distribution

The minimum legal landing size for queen scallops currently stands at 40mm shell height. The function of this restriction is to protect younger queen scallops from exploitation and therefore help preserve the stocks of potential recruits. The minimum size of those individuals kept for market was found to be 56mm, which may serve to indicate that the minimum landing size is somewhat redundant as a fishing restriction, as the market already dictates that queen scallops of a larger size are preferred for sale. Of the total 400 queen scallops studied, only 12% of those caught were below this size, and all of those were discarded. That so few queen scallops below the minimum landing size were caught may serve to indicate that the current preferred gear sizes are working effectively to modulate the size of animal caught by the trawl fishery. Whilst there are currently no stringent restrictions upon gear size, the market preference for larger individuals and the fact that fishers often operate to catch different species at different times of the year (especially in the trawl fishery, which is unable to capture large volumes of queen scallops over winter) influence gear size selection. The mesh size of the net in this study was 80mm. Alternatively, it may be that the area of the Irish Sea sampled in this study contains a generally low level of smaller queen scallops. If other areas (such as inshore Laxey Bay) were analysed for the size frequency of queen scallops caught, a higher proportion of smaller individuals may be found.

The size-frequency charts (Fig. 2 & 3) demonstrate a certain degree of overlap between the sizes of queen scallops kept and that of those discarded. Thus, a certain proportion of the catch which is of marketable size is being returned to the ocean after going through the riddle. There is therefore scope to increase the efficiency of the sorting equipment used within the fishery. However, this would have relative little benefit unless the processing industry would accept queen scallops of smaller sizes than currently preferred.

When the size-frequency distributions of the discarded catch of hand-sorted and mechanically-sorted queen scallops are compared, it can be seen that a higher proportion of the hand-sorted individuals fall into slightly larger size classes. The size-distribution of discarded, hand-sorted scallops is flatter. This may indicate that hand-sorting results in the return of a greater proportion of larger queen scallops to the benthos. However, no statistically significant difference between sorting methods was found in terms of size-structure. That no difference exists would seem to infer that no additional conservation benefit is to be found in terms of the return of undersized individuals to the benthic population through alterations to on-deck sorting processes.

The results shown here indicate that the current gear size restrictions are efficient in conserving potential recruits to the fishery as the size-frequency charts clearly show a younger cohort being returned to the benthos after sorting. There is no significant difference between the two sorting processes in this respect. In addition, market forces act to ensure that only larger queen scallops are taken from the catch, as the factory processing procedure favours only those queen scallops over at least 50mm.

Damage Levels

The results presented in this study show a clear relationship between the type of fishing process applied to a population of queen scallops and the level of physical damage which can be identified in that population.

Dredged queen scallops exhibit on average a significantly higher degree of shell damage than their trawled counterparts. The effect of gear type upon damage level results from the different strategies for removing the queen scallops from their benthic environment employed by the different gear types. The use of tickler chains with trawl gears encourages queen scallops to swim up into the water column, from where they are then caught in the net. Thus a high level of physical interaction between the scallops and the heavy metal elements in the fishing gear is avoided. In contrast, dredges rake the sea bed and therefore physically remove the queen scallops directly from their habitat. This method results in a greater frequency of contact between the captured individuals and heavy parts of the gear before being moved into the net and thus increases the probability of physical damage being inflicted by the capture process (Shephard *et al.* 2008). Unfortunately, these results represent only the levels of damage caused by the fishing gear itself and no inference as to the effect of sorting method can be made as only hand-sorted dredged queen scallops were available. Given that both dredging and trawling are used as methods of capture for queen scallops at different times of year around the Isle of Man and mechanical sorting is the most common method by which the organisms are handled on deck, future work may wish to enhance these results by directly comparing scallops caught in trawls and dredges, both being sorted mechanically for what may perhaps be a more realistic representation of the difference in damage level caused by dredging versus trawling.

Those queen scallops caught by trawling were subsequently subjected to one of two sorting treatments; mechanical or hand. The individuals sorted by mechanical equipment as described previously showed a higher level of physical damage than those trawled and then sorted by hand. This is unsurprising given the physicality of the mechanical sorting process, which offers many more opportunities in which the scallops may experience different levels of shell damage as they are rotated through the metal gear. It is possible that the results showing the level of shell damage in the hand-sorted individuals are confounded by an observer effect, in that the act of observing how fishers would sort their catch by hand may change as a result of the presence of observers on deck and the manner in which the catch was handled may have at times been less vigorous than would be usual.

Attempts have been made to ameliorate the level of damage caused by capture upon queen scallops, principally through the re-design of traditional gears. For example, the hydrodredge utilised the deflection of water by cups upwards to capture great scallops, which resulted in significantly lower levels of lethal damage to the exploited stock (Shephard *et al.* 2008). This therefore illustrates the role of dredging, in particular contact with the dredge teeth, in inflicting damage upon the shell of captured individuals.

It is possible that the area in which the fishery is situated may exert some influence upon the levels of shell damage observed. In particular, the sedimentary environment may play an important role. The presence of large rocks in the catch composition will result in a higher probability of damage being suffered due to collisions in the net or in the riddle (Shephard & Auster 1991). The area around Peel in which the trawling damage study was conducted consisted of largely gravelly sediment without large rocks or boulders. Dredge gears were previously used on smoother substrates, however, recent developments in the design of spring-toothed dredges have allowed this gear to exploit rougher ground, with a greater proportion of stones at the surface, which may affect the level of trauma experienced by the catch during fishing (Brand *et al*. 1991).

Behaviour

Predation avoidance behaviours, such as the valve movements counted in this study, are energetically costly and it may therefore be supposed that scallops which have expended large amounts of energy during the fishing process would be unable to perform these actions (Thompson 1980). Given that the mechanical sorting process constitutes an additional period of high stress it may be that these scallops are less able to perform these behaviours.

ANCOVA demonstrated that no significant difference exists between scallops treated by the two different sorting processes in their ability to respond to a simulated predation threat. However, the reliability of the results is undermined by the size of the error bars produced, indicating that perhaps a difference exists but the experimental method or level of replication were insufficient to highlight any difference (Fig. 6).

The ability of hand-sorted individuals to respond to predation increased significantly over the experimental period. That of the mechanically-sorted scallops did not, though the plotted results did seem to indicate a positive trend (Fig. 6).

The point at which 50% of individuals were able to respond to the threat of predation occurred 76 minutes after sorting for mechanically-treated individuals and 79 minutes after sorting for those sorted by hand when being kept in seawater tanks on deck. These results would imply that, given discarded individuals may suffer a higher rate of predation due to scavenger-accumulation once returned to the seabed, survivorship of the discards may be enhanced by maintaining individuals in seawater tanks for a period of roughly 80 minutes before discarding occurs. However, the reliability of these results may be compromised as they were obtained by extrapolation beyond the data set actually obtained (the assay having begun 90 mintues after sorting).

Scavengers may be attracted to discarded material as a result of chemosensory cues (Dayton & Hessler 1972). Studies of scavenger attraction have shown that even undamaged queen scallops may attract up to seven times the background abundances of predators such as *Asterias rubens* to the location of discarded individuals (Veale *et al*. 2000). Thus discards need not be damaged to attract predators, but instead high concentrations of metabolites released from areas of high concentrations of discards may be sufficient to attract predators and scavengers. Queen scallops have been found to be particularly attractive as a result of their high energetic value.

The high degree of spatial specificity of many predator aggregation studies makes it impossible to estimate the predation rate to which the discarded queen scallops will be exposed (Veale *et al*. 2000). The gravelly sediments around the Isle of Man are highly heterogenous in their distribution of epifauna and therefore extensive work would be required to characterise the prevalence of scavengers and predators. The distribution of discards is also highly variable in time and space according to the intensity of fishing activity and will therefore also influence the risk of predation (Rijnsdorp *et al*. 1996). So whilst this study has been able to characterise the response of fished queen scallops to predation, it is not possible to interpret these results in terms of direct risk of predation, as the density of predators at each specific location was not determined.

Survival: Short Term

Air exposure has been demonstrated to be a significant stressor to queen scallops (Maguire *et al*. 1999*b*) and therefore may undermine their survival both on deck and once returned to the benthos. Exposure thus constitutes an additional challenge to the survivorship of these organisms, beyond that of on-deck processes and it was hypothesised that those individuals which are already highly stressed may not be able to cope with this.

In this study, there was no significant difference between the two sorting processes in the survival of scallops from either treatment on-deck. The effect of weather upon the survival of individuals once on deck was significant. It may therefore be that the magnitude of the stress caused by exposure dwarves that caused by on-deck sorting processes and the survival of individuals once left on deck will be largely determined by environmental conditions.

Survival: Long Term

None of the scallops moved to holding tanks and observed over 14 days suffered any mortality. Thus the results obtained were the same for scallops sorted by both treatments. These results are consistent with those of Bremec *et al*. (2004), who also studied the effects of mechanical sorting upon the survival of the Patagonian scallop. Bremec *et al*. (2004) found no difference between control and processed scallops exposed to different lengths of time in air and returned to the seabed for between 5 to 12.5 days. Valero & Lasta (2008) criticised these results in part for not considering the mortality of undersized scallops separately from those of a legal marketable size. However, this study concentrated solely on those queen scallops which would be discarded and also showed that the minimum legal landing size means relatively little as the gear is selective for scallops of larger size and the market demands dictate more the size of scallop retained for sale. Valero & Lasta (2008) also noted that the effect of different levels of damage was not accounted for, as the level of shell damage may have a significant effect upon mortality (Gruffydd 1972). The present study also separated damaged and undamaged scallops for observation, yet found no discernable difference in the long-term survival of either type.

It is possible that the experimental period of 14 days for which the scallops were observed in this study was insufficient to highlight the effects of protracted mortality upon the discarded population. McLoughlin *et al*. (1991) found that the highest levels of mortality in the Australian scallop fishery (*Pecten fumatus*) occurred 8 months after the cessation of fishing activity. It was also not possible to account for the effects of repeated fishing, which would be possible at peak times or possible environmental effects upon the general health and survivorship of the individuals studied, all of these being from a single area.

Immunology

Queen scallops may respond to stress in a variety of ways. In this study, changes in predation-avoidance behaviour and overall survival were considered. More subtle effects may be observed in the physiological response of these organisms to stress. A key effect of stress is its ability to increase the susceptibility of normally healthy organisms to disease (Boyd & Burnett 1999). In many cases therefore, the immune system of bivalves has been studied as a marker of the level of environmental stress to which the organisms studied have been exposed (King *et al*. 2006). Recent work has allowed the development of a variety of immunological markers, which may serve as indicators of the manner in which environmental stress can affect the ability of an individual to cope with immune challenges, including reactive oxygen species production, hemocyte mortality and phagocyte activity (Chen *et al*. 2007).

An increase in the level of environmental stress experienced by an animal increases its vulnerability to pathogenic attack (de Zwaan & Babarro 2001). Various environmental stresses are experienced during the fishing processes including air exposure and physical trauma during sorting. Long-term stress can result in an overall loss of condition and accumulation of microorganisms (LaCoste *et al*. 2001).

The immune system of bivalves and other invertebrates differs fundamentally from that of vertebrates as a result of the absence of any adaptive immune response (Lee & Soderhall 2001). These organisms are therefore reliant upon a contingent of more simple innate responses to any invading pathogen. Studies of the immune function in bivalves most often consider changes in the activity or abundance of a few key cells. Principally these include the number of hemocytes found in the blood, the relative proportions of different types of hemocytes and the degree of phagocytic activity performed by these cells. Phagocytes comprise a key component of the immune response. Upon contact with foreign pathogens these cells extent psuedopods from the cytoplasm which wrap around the foreign particle and engulf it (Bayne 1990). The resulting phagosome is then fused with lysosomes within the phagocyte, which release phagocytic enzymes that digest the pathogen, thus neutralising it.

The immune system may also play an important role in promoting the healing of physical damage caused by fishing practices, thus impairment of immune function as a result of fishing-induced stress may confound the negative impacts of fishing by preventing individuals from effectively repairing shell damage caused during the sorting process (Monari *et al*. 2000), which in turn may make them more vulnerable to pathogenic attack.

The assays available by which the immune function of scallops under differing environmental stress regimes include quantification of the number of different types of hemocytes and the percentage level of phagocytic activity as well as any changes in the oxidative ability of immune cells (LaCoste *et al*. 2002).

Epibionts

In addition to the active swimming response, queen scallops possess other mechanisms by which they avoid predation. It has been shown that the epibionts found encrusting queen scallop shells may play a role in allowing them to avoid detection by predators. The queen scallops investigated in this study were observed to display several different types of epibionts; sponges and barnacles were the most commonly observed.

The encrustation of scallop species by sponges is widely considered as a mutualism, with the sponge providing protection from predation either as a result of them preventing tube-foot adhesion by starfish or giving tactile camouflage to the scallop (Schejter & Bremec 2007).

In contrast, some epibionts may decrease the survival potential of encrusted individuals, with barnacle encrustation having been described as effectively a case of 'shared doom' as they may hinder the escape reflex by weighing a scallop down and therefore prevent the necessary speed to stay in the water column from being achieved. Farren & Donovan (2007) reported that in predation experiments, more individuals from the scallop species *Chlamys hastata* were taken by the starfish predator if encrusted with barnacles than if covered in a sponge epibiont.

Trawling and mechanical on-deck sorting are both traumatic physical processes. The results reported in this study have shown a significantly higher level of physical damage is inflicted upon queen scallops as a result of mechanical sorting in comparison to that caused by hand sorting. It is therefore reasonable to expect that similar types of damage could be inflicted upon the sponge epibionts covering these individuals. Thus if the sorting process damages the sponge coating of discarded individuals then they may reasonably be expected to be more vulnerable to predation as a result of a loss of camouflage or as a result of being more easily picked up by a starfish if their sponge coating is lost. It is possible that a loss of sponge covering may increase the space for settlement by barnacle spat. Thus repeated trawling and discarding may result in a shift in the epibiont community within the queen scallop population and possibly result in the population as a whole therefore being at a greater risk of predation. Further work is required to elucidate the nature of the mutualism between queen scallops and their sponge epibionts and to quantify the level of damage inflicted upon these epibionts as a result of the fishing process. It may be hypothesised that the patterns of damage to epibionts may follow the patterns of shell damage, with the more traumatic processes of dredging and mechanical sorting resulting in greater levels of epibiont damage.

By-catch

The full effect of fishing, in terms of its wider environmental impact to non-target species and benthic habitats, therefore varies according to the type of gear used. Demersal gears remove both target and non-target fauna and have the potential to alter the structure of the habitat (Kaiser *et al*. 1996). Trawls have the potential to reduce the abundance of fauna present by up to 55% in a single fishing event (Collie *et al*. 2000).

A clear distinction can be seen between the by-catch assemblages caught as a result of dredging versus that obtained by trawling. This is due to the action of the gears used. The trawling gear caught a wider variety of fish species as it moved through the water column, with relatively fewer invertebrates being included in the catch. Dredging produced a wider variety of invertebrate fauna as it was dragged along the sea floor.

The results presented here are not consistent with those of Kaiser *et al*. (1996), which found that trawling was found to capture a greater number of non-target taxa in its by-catch than dredging. In the present study, dredging captured on average a greater number of species and a greater diversity of species, though the differences between the two fishing methods in these respects were not found to be significantly different. Kaiser *et al*. (1996) also found that dredging resulted in the capture of a greater biomass of non-target fauna. Unfortunately, the scope of this study did not extend to a measurement of the biomass of the by-catch obtained and therefore this aspect of the impact of the two fishing gears within the queen scallop fishery remains untested. Both gears resulted in an overall decrease in the number of benthic organisms present. Results of multivariate analysis highlighted the tendency of dredges to pick up larger numbers of benthic invertebrates, most probably due to its action whilst being dragged along the sea floor. That both gear types result in alterations to the benthic environment is also reported by Collie *et al*. (2000), though they contend that the initial impact of dredging upon the seabed is greater due to penetration of the gear deeper into the sediment.

The by-catch obtained in trawls differed according to the geographic location in which the trawl was conducted, specifically multivariate analysis showed a distinction between those trawls conducted on the east coast versus those carried out on the west coast. A variety of environmental parameters vary latitudinally across the island within the marine ecosystem. A few of these are shown in Figures 16-18. Summer surface temperature, shelf mixing depth and a variety of water column characteristics differ between the east and west coasts of the island. There is also some degree of difference in the sedimentary composition of the marine environment in the sites studied. Any or a combination of these factors may conspire to result in the changes in the types and abundances of species found in trawl by-catch in these areas. The dominance plots produced as a result of the multivariate analysis show differences in the pattern of dominance within the assemblages found according to geographic location; the dominance pattern observed in Peel is distinct from that of Laxey and Ramsey. These patterns may serve to indicate that the environment in Peel is more stressful than that on the east coast, possibly due to the more dynamic nature of the sandier sediments in this region (Holt *et al*. 1990). More stressful environments lead to greater levels of dominance by fewer species, as few species are sufficiently adapted to cope with the difficulties posed by existence in these habitats (Connell 1978).

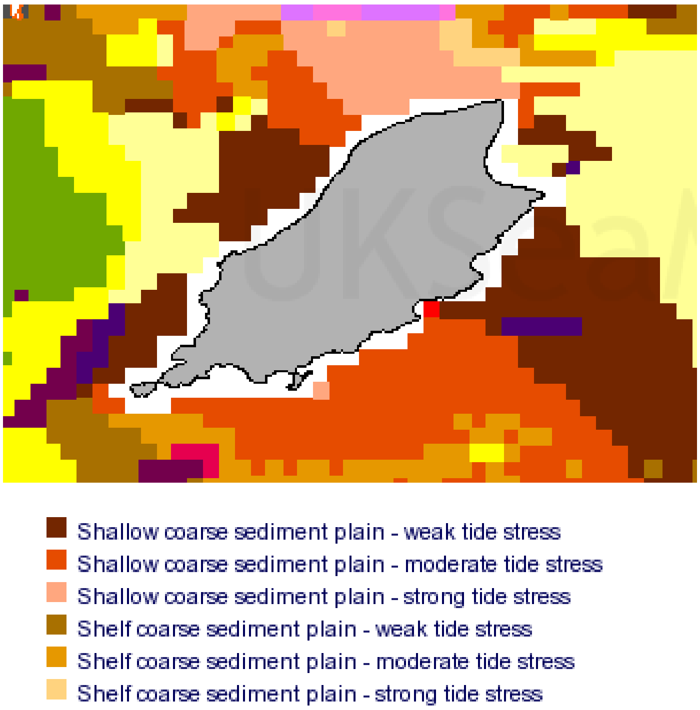

Figure 16 Map showing the sedimentary environment around the Isle of Man, the environments studies fall primarily into the categories of shallow coarse sediment with weak tide stress and shelf coarse sediment plain with strong tide stress. From www.jncc.gov.uk.

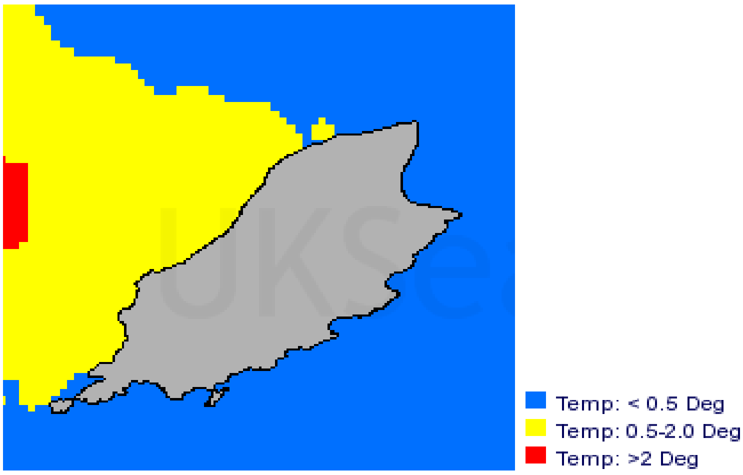

Figure 17 Map showing the surface to sea bed temperature difference in waters around the Isle of Man during the summer season. From www.jncc.gov.uk.

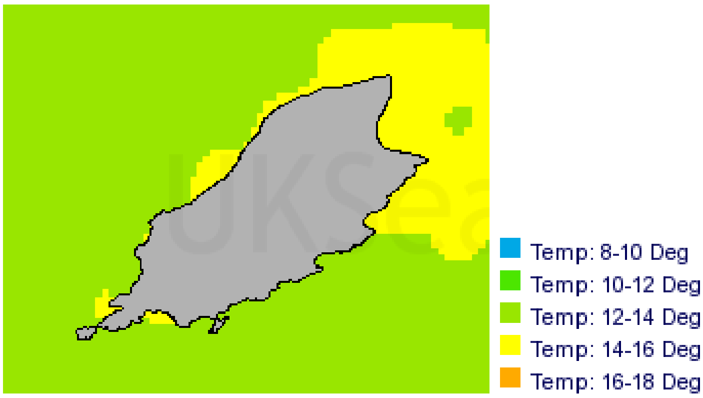

Figure 18 Map showing the summer surface water temperatures around the Isle of Man. From www.jncc.gov.uk.

The patterns of assemblage distribution presented in this study are consistent with those expected in geographic distribution around the Isle of Man. Veale *et al*. (2001) studied the distribution and abundance of by-catch in queen scallop fisheries around the island and concluded two geographically distinct assemblages of by-catch could be found in scallop dredges. The by-catch found to the south west of the island differed from that found in the north, south and east. They proposed a number of explanations for this pattern including differences in the sedimentary environment, there being a higher proportion of sand and consequently less gravel to the west than in other grounds (Holt *et al*. 1990). A seasonal gyre exists in the western Irish Sea, which may enhance recruitment of benthic species through retention of planktonic larvae in the area (Hill *et al*. 1997). Patterns of exploitation could also contribute to this pattern, the western grounds having been exploited over a longer time period (Brand *et al*. 1991). Such factors may contribute to the greater diversity of species found from the trawls conducted in the area of Peel, compared to that found in Laxey and Ramsey.

The results obtained by any study looking at the wider ecological effects of fishing tend to be highly variable and specific to the area studied, as a result of specific habitat features, sediment characteristics and the spatial heterogeneity of the fauna present (Jennings *et al*. 2005). It is therefore not possible to generalise these results to the scale of the island as a whole.

The scope of the by-catch assessment in this study is limited to the abundance of species found. Extensions to this could consider the potential effects of the removal of this abundance of species from the wider ecosystem, including potential shifts in community composition which have been widely documented as a result of fishing activity (Veale *et al*. 2000). These may be manifest as an increase in the number of scavengers (Kaiser & Spencer 1994), decreasing numbers of epifaunal filter feeders (Bradshaw *et al*. 2003), a change in the life-history composition of the assemblage (Dickie *et al*. 1987), changes in the body sizes of individuals found (Ball *et al*. 2000) and even changes in habitat structure (Trimmer *et al*. 2005). Continual monitoring of community composition over time would be necessary to determine the presence or absence of such trends within this fishery.

When considering the potential impact of fishing upon by-catch species it may also be prudent in future to consider the level of damage caused to these species by both the capture method and on-deck sorting process, as fish or invertebrates returned to the sea damaged by fishing will suffer both an energetic cost in directing available resources to recovery, which could otherwise be invested in growth or reproduction (Clapp & Clarke 1989), and will risk suffering higher levels of predation (Kaiser & Spencer 1994) or disease (McLoughlin *et al*. 1991) in much the same way as the queen scallops in this study may. High levels of fishing-induced mortality in megafaunal species that come into contact with fishing activities may have a cascade effect and ultimately result in changes to the overall community structure (Jennings & Kaiser 1998). Given that species of both commercial and conservation interest were found to be present in by-catch assemblages, the indirect mortality of these species may be notable factors in designing management strategies.

Conclusions

The results of the present study indicate that mechanical on-deck sorting processes result in higher levels of physical damage being inflicted upon queen scallops which are subsequently discarded and may therefore be viewed as a more physically traumatic process. However, this physical trauma is not necessarily translated into decrease survivorship of queen scallops sorted mechanically in comparison to those sorted by hand as no differences in behavioural response to predation, on-deck survival or long-term survival were observed between the two groups. In the future, other indices of stress may be used to give more quantifiable data, such as immune parameters, or demonstrate alternative impacts of the fishing process, such as the effects upon epibionts. At present, whilst it could be proposed that a shift in management to favour hand-sorting over mechanical-sorting would reduce the levels of damage observed in the exploited stock, it could not be confirmed that this would translate into increase survival of undersized individuals or recruitment to the adult fishery.

Analysis of the by-catch found within the Isle of Man queen scallop fishery confirms previous results that show the importance of gear type in determining the species captured. The spatial heterogeneity of by-catch assemblages around the island has also been demonstrated, which may be linked to a variety of environmental parameters. In order to fully characterise the impact of fishing upon non-target communities it would be necessary to include estimations of the biomass taken as part of fishing processes and to consider the survivorship of animals caught and discarded along with the effect of the fishing method upon the environment itself.

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