# Survivability of target species discards in the Isle of Man Queen Scallop (*Aequipecten opercularis*) fishery

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# <u>Abstract</u>

For effective fisheries management it is important to know the environmental impacts of employed management strategies. In 2010 the Isle of Man Fisheries Directorate introduced a minimum landing size of 50 mm (shell width) to the Queen scallop (*Aequipecten opercularis*) fishery operating in Manx territorial waters. This was carried out with the intention of improving recruitment to the population and followed the assumption that all target species discards survive. The presented study evaluates this assumption by quantifying the discard rates and discard mortality rates of *Aequipecten opercularis* within each gear type prosecuting the fishery. Three way factorial survivability experiments were set up to investigate the effect of minor damage, shell width and gear type on long term direct mortality rate and predation response. Long term mortality tests were deployed at sea in shrimp creels for 10 days, after which the number surviving was assessed. Predation response experiments were carried out in situ via predation simulation by *Asterias rubens*.

For each gear type target species discard quantities were estimated to be very low and this was especially true for undersized individuals, as they comprised < 7% of the discard composition. The results from the survivability study were combined with known mortality rates of severely damaged scallops to give an overall mortality rate for each gear type, trawl: 13.06%; skid dredge: 35.33%; modified dredge: 18.54%. The dredgers displayed the highest discard mortality as a result of a greater proportion of discards suffering severe damage. Undersized scallops suffered less mortality as a result of them experiencing minimal severe damage during the fishing procedure. Also better predation avoidance indicated they were less likely to suffer indirect mortality compared to their larger counterparts. For all sizes and gear types, low discard rates and low mortality rates specified that the number of discarded *A. opercularis* suffering mortality was negligible relative to landings in the fishery.

# **DECLARATION & STATEMENTS**

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 fulfilment of the requirement of M.Sc Marine Biology

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

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

I hereby give consent for my dissertation, if accepted, to be made available for photocopying and for inter-library loan, and the title and summary to be made available to outside organisations.

Christ all

Signed ...... (Candidate)

Date .....07/10/2011.....

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# **Abbreviations**

CPUE	-	Catch per unit effort, number of individuals caught per hectare
DPUE	-	Discards per unit effort, number of individuals discarded per hectare
кс	-	King Challenger, modified dredger
LPUE	-	Landings per unit effort, number of individuals landed per hectare
MLS	-	Minimum landing size
MP	-	Maureen Patricia, trawler
NM	-	Nautical miles
QV	-	Q Varl, skid dredger
VMS	-	Vessel monitoring system
D1, 2, 3 or 4	-	Damage category 1 – 4
S1 or 2	-	Size category 1 - 2
#	-	Number

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#### Introduction

Marine fisheries are a globally important industry with a total annual value of more than US\$200 billion (Dyck and Sumaila, 2010). However due to its invasive nature, fishing can have numerous negative effects on the marine environment. These can be direct, through overexploitation of the targeted population or indirect, through habitat degradation and bycatch (Dayton *et al.*, 1995; Jennings and Kaiser, 1998). Bycatch can be defined as the capture of undersized target species and non-target species that are retained and sold or discarded (Clucas, 1997). Discarding is a particularly pertinent issue as it can result in high discard mortality (Broadhurst *et al.*, 2006) which has negative effects on populations and ecosystem function (Kelleher, 2005), as well as posing considerable economic losses (Pascoe, 1997). Bycatch and subsequent discarding is a problem in almost all commercial fishing operations due to the difficulties associated with selectively fishing for a target species. It is estimated that discards represent 8% of the global catch, equating to 7.3 million tonnes per annum (Kelleher, 2005). As a result of its prevalence and its current importance in fisheries management (Alverson and Hughes, 1996; Bellido *et al.*, 2011) the European Commission has recently proposed a ban on discards as part of the suggested reform to the European Union Common Fisheries Policy (EU COM, 2011).

An outright ban on discards across all fisheries may not be the most effective management technique because the quantity of discards and ultimate discard mortality are fishery specific, depending on target species, fishing gear and species discarded (Alverson *et al.*, 1994). Also the return of by-caught undersized target species to the sea can be very important for stock recruitment, provided they survive.

For effective ecosystem based management it is important for fisheries managers to know the environmental impacts of their fishing techniques. The fate of target species discards is particularly important for the management of the stock population. Despite its importance there is still considerable uncertainty surrounding the fate of discards and management decisions continue to overlook it (Davis, 2002).

This is equally true for the Isle of Man Queen Scallop, *Aequipecten opercularis* fishery. In 2010 the Isle of Man Government Fisheries Directorate increased the minimum landing size of *A. opercularis* (from 40 mm to 50 mm, shell width) in order to increase protection of recruitment and early spawning. However the success of this endeavour is dependent on the survival of undersized discards which are unknown (but see, Montgomery, 2008).

Within the literature one of the only estimates of discard mortality in the Isle of Man Queen scallop fishery is a study by Allison and Brand (1995) which calculated very high incidental fishing mortality rates in June 1985. Very high levels of incidental mortality have been recorded in other scallop fisheries as well (Naidu, 1988; McLoughlin *et al.*, 1991). However, discard mortality is just a sub-component of incidental fishing mortality, which includes all unaccounted fishing mortalities, for example mortality caused by encounter with fishing gear that does not result in capture.

For the problem of target-species discard mortality to be addressed properly it needs to be studied independently.

# **Target species discards**

Discards of target species usually refer to undersized individuals, these are considered bycatch because they are uneconomical and their removal from the population can have recruitment implications and result in losses in future catches. For example Saville (1980) identified that undersized target species discards in the Gulf of Maine ground-fish fisheries were contributing to a reduction in populations. However, bivalves consistently show high survival relative to other taxa such as ray-finned fish and cephalopods (Kaiser and Spencer 1995; Hill and Wassenberg, 2000; Broadhurst *et al.*, 2006) so it is unclear the effect discard mortality will have in the *A. opercularis* fishery. If survival is high the return of juveniles is particularly important in species with few year classes (such as *A. opercularis*) because the population is largely dependent on the strength of recruitment each year (Csirke *et al.*, 1980; Vause *et al.*, 2007).

The quantity of undersized target species being caught and discarded is determined by the selectivity of the fishing gear. Where gear selectivity is poor the composition of catch that is undersized can be very high in scallop fisheries and in some cases can be the majority of the catch. Jenkins and Brand (2001) showed that an average catch in the Isle of Man king scallop (*Pecten maximus*) fishery consisted of 35% undersized scallops, with a maximum of 75% on some fishing grounds. Similar values were found in other scallop fisheries such as the Queensland saucer scallop (*Amusium balloti*) fishery (Courtney *et al.*, 2001). Making gear modifications or changing gear type can result in increased catch efficiency and selectivity (Cook, 2003; Graham *et al.*, 2007; Hinz *et al.*, 2009) and thus reduction in undersized discards.

As well as discards of undersized target species, target species of above minimum landing sizes can also be discarded. This is usually a result of inefficiency in the sorting procedure or damage (Maguire *et al.*, 2002). If discarding of target species (undersized and landable) results in unaccounted fishing

mortality it may result in underestimates of fishing mortality in a fishery and lead to management inaccuracies.

#### **Discard mortality**

The overall effect discard quantity has on a fishery is dependent on the mortality rate of the discards. Discard mortality is a result of physical or physiological stress experienced by the fishing process and it can be immediate or delayed. It manifests itself for a number of different reasons and can be a direct or indirect result of the fishing process.

Direct mortality includes death caused by physical damage and/or physiological stress, such as energetic exhaustion, desiccation and siltation (Medcof and Bourne, 1962; Brand, 2006b). The cumulative stress of these interacting factors is thought to contribute towards direct mortality, or if not lethal, sub-lethal stress (Davis, 2002).

In addition, survivability of discards are jeopardised further by the possibility of indirect mortality. This encompasses mortality that is an indirect result of the sub-lethal stress experienced by discards. For example sub-lethal damage and physiological stress have been shown to make individuals more susceptible to predation either through reduced escape response (Ramsey and Kaiser, 1998; Jenkins and Brand, 2001) or as a result of reduced protection caused by shell damage (Jenkins *et al.*, 2004). Risk of infection from bacteria, viruses and parasites has also been shown to increase with fishing related stress (McLoughlin *et al.*, 1991). However disease is unlikely to inflict high mortality rates here as it is thought to be of low importance in mortality of *A. opercularis* around the Isle of Man (Brand, 2006a). Whilst the risk of predation is probably greater because there is a high abundance of the predatory species, *Asterias rubens* in this area (Hill *et al.*, 1999) which commonly aggregate at discard sites (Kaiser and Spencer, 1996; Veale *et al.*, 2000). The latter risk is compounded by this relatively resilient predator being part of the discard assemblage (Kaiser and Spencer, 1995; Veale *et al.*, 2001).

The extent of physical damage is significantly related to discard mortality in scallop fisheries (Medcof and Bourne, 1962) and is dependent on impacts with components of the catch, the fishing gear, and the sorting procedure (Broadhurst *et al.*, 2006). In scallop fisheries catch components such as stone and catch volume are positively related to the extent of damage due to the increased chance of impact and potential for scallops to interlock valves (Pranovi *et al.*, 2001; Veale *et al.*, 2001; Campbell *et al.*, 2010). Where damage is severe mortality has been shown to be high in *A. opercularis* (Veale *et al.*, 2001) however the effect of minor damage on long term mortality is unknown.

The effect of discard size may also interact with mortality rate because undersized scallops can be more vulnerable to exhaustion, predation risk and desiccation (Barbeau and Scheibling, 1994; Gasper and Monteiro, 1999; Maguire *et al.*, 2002). Moreover, damage and thus mortality may be greater in small scallops because bivalves are more fragile when they are younger (Gruffydd, 1972).

# Aim of study

This study aimed to measure the quantity and survivability of target species discards in the Isle of Man Queen scallop fishery with a particular focus on undersized individuals (< 50 mm). It compared all gear types prosecuting *A. opercularis* with the intention of making a holistic assessment of discarding within the fishery. The primary purpose of this project was to evaluate the assumption that undersized scallops survived and to provide management advice to the Isle of Man Government Fisheries Directorate.

The effect that gear type, damage and shell width had on direct mortality rates were measured in order to investigate potential differences in survival of discards with the intention of assisting management recommendations. Predation response was also assessed in order to indicate any differences in abilities to escape predation and avoid indirect mortality. This is one of very few studies on the direct and indirect mortality of both undersized and landable *A. opercularis* discards (but see Montgomery, 2008) and it is hoped the study will provide a valuable insight into the uncertain and understudied fate of discards.

# Hypotheses

- The extent of physical damage suffered by *A. opercularis* will differ between gear types. Specifically dredgers will cause higher damage than trawlers
- Direct mortality rates and predation response of *A. opercularis* will differ between gear type. Specifically dredgers will cause a higher mortality than trawlers because they are predicted to be more damaging to target species.
- Direct mortality rates and predation response of *A. opercularis* will differ between undamaged and minor damaged individuals \*. Specifically those individuals suffering minor damage will show higher mortality and a reduced ability to respond to predation because damage is known to negatively influence survival.

\* only minor damage will be assessed because it is conclusive that severe damage causes mortality (Veale *et al.*, 2001).

• Direct mortality rates and predation response of *A. opercularis* will vary according to size (shell width). It hypothesised that smaller scallops will suffer higher mortality and a reduced ability because they are thought to be physically and physiologically more sensitive.

# **Specific objectives**

The primary objective of this study was to determine the extent of mortality in target species discards particularly undersized *A. opercularis* (< 50 mm), and make comparisons between the gear types operating in the fishery.

Sub-components of this objective included,

- 1. Determine quantity of target species discards from each gear type
- 2. Assessment of the size (shell width) and level of damage incurred on target species discards
- 3. Investigate the effect of fishing gear, size and damage had on the, a) direct survivability b) indirect survivability (predation response).
- 4. Consider the impact the whole fishing fleet has on of survivability of target species discards on the fishery.

## **Overview of Isle of Man Queen scallop fishery**

The Isle of Man Queen scallop (*Aequipecten opercularis*) fishery operates in Manx territorial waters (within 12 nautical miles of the island) and it is managed by the Isle of Man Government Fisheries Directorate. Vessels registered both inside and outside the Isle of Man have jurisdiction to fish these waters but they must all adhere to the management legislation of the directorate (Box 1).

At present there are three types of fishing gear operating in the fishery. These comprise otter trawls and two different types of modified toothless dredge, one with skids that has tickler chains instead of teeth and one which has larger dredges that have rubber flaps instead of teeth (detailed descriptions of these can be found in the methods section). For the remainder of the report these gears will be referred to as 'trawl', 'skid dredge' and 'modified dredge' respectively. In 2011 the number of vessels in the queen scallop fishing fleet regularly using each gear type was unequivalent, trawl: 27; skid dredge: 1; modified dredge: 3.

For management purposes these gears are split into the trawl and the dredge fishery. The trawl fishery is believed to be sustainable and to this effect has been given Marine Stewardship Council (MSC) accreditation (Andrews *et al.*, 2011) and has received the Billingsgate School Sustainable Seafood Award 2011. The dredge fishery is not deemed sustainable as a result of the large bycatch quantities and habitat degradation associated with dredging (Kaiser *et al.*, 2006). However Kaiser *et al.* (2006) looked specifically at toothed dredgers and a recent study by Hinz *et al.* (2009) showed the modified dredge operating in this fishery caught a similar amount of non-target species to that of the trawl, although damage to the sea bed was significantly more.

Most queen scallop fishing occurs between the 1<sup>st</sup> June and 31<sup>st</sup> October when the more profitable *Pecten maximus* fishery is closed and also when *A. opercularis'* increased swimming activity, associated with higher water temperatures, can be exploited by trawlers (Jenkins *et al.* 2003). Landings from this fishery represent a significant proportion of total annual Queen scallop landings in Europe (Brand 2006; FAO 2010) but exact quantities of landings vary from year to year. In recent times, 2007-2009 landings equated to approximately 4000t (tonnes) per annum (Murray *et al.* 2009), although in 2010 landings had increased to 12,800t (Murray and Kaiser, 2011). Most landings come from the dredge fishery. In 2010 landings were divided into Dredge: 10,700t and Trawl: 2000t. However it is important to note that the majority of queen scallops caught around the Isle of Man are landed by modified dredgers (8700t), assuming most dredge landings to the UK are by this gear type. The landings values reported here relate to ICES statistical rectangles 36 E5 and 37 E5 and are not exclusively within Manx territorial waters. A substantial amount of dredge landings are caught outside territorial waters because they are closed to dredgers between 1<sup>st</sup> June and 31<sup>st</sup> August.

Box 1 Management legislation enforced by the fisheries directorate for the A. opercularis fishery

- minimum legal landing size of 50 mm (shell width)
- seasonal closure from 1<sup>st</sup> April to 31<sup>st</sup> May
- Dredgers are not permitted to fish in territorial waters between 1<sup>st</sup> June and 31<sup>st</sup> August
- strict fishing hours of 6:00-20:00 GMT within 12NM\* and 6:00-18:00 GMT within 3NM\*
- vessel and gear restrictions including a ban on toothed dredges
- recommended total allowable catch (TAC) of 4000 tonnes per annum

(Personal communication with Fisheries Directorate; Department of Environment, Food and Agriculture, 2010)

\*NM = nautical miles

# **Method**

# Study site

The East Douglas fishing grounds, Isle of Man (Figure 1), were selected as the study site because this area was exploited by all gear types operating in the Queen scallop fishery (see Murray *et al.* 2009 for maps of fishing effort). The approximate GPS coordinates in decimal degrees for the area fished was N: 54.01769 W: -4.3701 (calculated from the mean of the start points of each tow). In this area the substrata is classified as gravelly or sandy and the community assemblage is characterised by *Aequipecten opercularis* and other species such as brittle stars, hermit crabs and hydroids (Hinz *et al.* 2010).



**Figure 1** Isle of Man and the East Douglas fishing grounds (encircled in grey). The 12 nautical mile boundary for the Isle of Man territorial waters is displayed as the solid black line surrounding the island. Figure adapted from Murray *et al.*, 2011.

# **Gear description**

In this study, three vessels each operating a different gear type were used. These were the King Challenger (modified dredge, Skipper: Dougie White), the Q Varl (skid dredge, Skipper: Steve Hatton) and the Maureen Patricia (trawl, Skipper: Craig Woodbridge).

The dimensions and properties of these gears differed considerably.

The King Challenger (KC) was equipped with ten large dredges (five either side) each 2m wide (total gear width: 20m). The dredges used were modified toothed dredges equipped with 'rubber flappers' instead of teeth and with metal bars across the dredge opening to prevent entry of large boulders (Figure 2a). A traditional metal belly bag (1.5m in length) was used as the catching bag and it had a mesh size of 60mm.

The Q Varl (QV) used 16 skid dredges (8 either side) each 0.76m wide (total gear width: 12.16m). The dredges were mounted on ski like runners with tickler chains fixed at the base of the dredge mouth (Figure 2b). A traditional metal belly bag (1 metre in length) collected the catch and had a mesh size of 60mm.

The Maureen Patricia (MP) deployed a single otter trawl that was equipped with a rock hopper but without a tickler chain (Figure 2c). The net had a foot rope length of 18.3m and a cod end mesh size of 85mm. These dimensions and properties were typical of most trawlers in the Queen scallop fishery (Duncan, 2009).



**Figure 2** Vessels and their gear types **a.** King Challenger (gear type: 'modified dredge'), modified dredge with rubber flaps at the base of the dredge mouth and metal bars across it. **b.** Q Varl (gear type: 'skid dredge'), modified dredge equipped with skids and a tickler chain at the base of the dredge mouth. **c.** Maureen Patricia (gear type: 'trawl'), otter trawl with rock hopper and floatation devices (buoys) attached to the head rope.

After the catch is brought on deck it is graded using sorting devices. QV and KC had similar grading machines (Figure 3a). Here the catch was automatically released into a two-layered vibrating riddle. The first layer sorted large items (e.g. rocks, starfish and fish) from the rest of the catch, by preventing them from passing through the riddle and then transferring them into a discard chute. The second layer sorted *A. opercularis* of a commercial size from the remainder of the catch and conveyed them to the fish room at the base of the boat where they were bagged. All small items of the catch (e.g. undersized *A. opercularis*, sediment and small non-target species) passed through this layer into a second discard chute, which was either separate from (QV) or joined onto (KC) the first discard chute. MP used an automated rotating riddle drum (Figure 3b). The catch was manually shovelled into the hopper at one end of the rotating drum. The riddle then selected for size allowing undersized scallops and small bycatch to pass through into a discard chute. Commercial sized scallops were retained and bagged after a final manual sort to remove large bycatch.



**Figure 3** Grading machines used by each vessel **a.** Two-layered vibrating riddle used by QV and KC (Photograph of KC grading machine, also shows photograph of inside the machine to display two-layered riddle) **b.** Rotating drum riddle used by MP (Photograph is of a similar grading machine, acquired from Duncan, 2009)

# **Tow properties**

As well as differences in fishing gear and graders there were differences in the operation of each vessel. For each individual tow, tow properties were recorded. These variables included tow duration (minutes), tow speed (knots), tow distance (metres), air exposure of catch (minutes), catch composition, number of bags of *A. opercularis* landed (each bag was approximately 40kg) and the geographic coordinates at the start and end of each tow (degrees, minutes and seconds for latitude and longitude).

Catch composition was defined as the proportion of catch that were *A. opercularis* (both legal and undersized individuals), bycatch species, rocks and other debris. This was determined by randomly sampling two standard fishing baskets of catch and weighing each assigned grouping separately each tow. The exact quantity of subsampled *A. opercularis* and by-caught species was also counted. Due to effort constraints catch composition could not be determined for every tow, but was carried out frequently.

Most of the tow properties were provided by on-board electronic equipment or from measurements taken *in situ*. However some variables were determined post field work. Speed had to be calculated using the vessel monitoring system (VMS) data for the MP as it was not recorded on the vessel. Tow distance (metres) was calculated as the multiple of tow duration (converted to seconds) and tow speed (converted to metres per second). Air exposure of catch (minutes) was estimated from the length of time between consecutive gear hauls. The estimated air exposure is defined as the maximum potential air exposure discarded *A. opercularis* can receive before being discarded.

Fishing effort was calculated for each tow as the area swept. Swept area calculations used the total gear widths of each vessel (see gear descriptions).

Area swept 
$$(m^2)$$
 = gear width  $(m)$  \* tow distance  $(m)$ 

Area swept  $(m^2)$  was then expressed in hectares (1ha = 10,000m<sup>2</sup>) and then converted to area swept (hectares, ha).

Landings per unit effort (LPUE) were specified as the number of individuals landed per hectare swept. To calculate this, the individual weight of an *A. opercularis* was determined from the weight and quantities of *A. opercularis* in the subsampled catch (see later in methods) and the number of individuals landed per bag was inferred. This was then extrapolated for each tow to the number of individuals landed per hectare covered by the fishing gear.

# Size frequency

The size distribution of scallops being caught, landed and discarded was determined. For selected tows a sub-sample of approximately 50 individuals were measured from either the catch (before it was processed), the landed bags or discards. The shell width (anterior-posterior axis) of each individual sampled was measured to the nearest millimetre using a measuring board.

The method of extracting samples of discards differed for each vessel due to the differences in boat design, sorting equipment and waste chute configurations. On the QV a thin seedling tray was placed underneath the sorting machine collecting discards before they passed through the discard chute back to sea. On the KC the tray was unable to fit under the sorting machine so a modified paint bucket with holes to allow water drainage was tied to a rope and lowered to the end of the discard chute. This was pulled out when full and queen scallops were selected. In the trawler a fishing basket was held over the side of the boat and placed underneath the discard chute, this was possible because the MP had a shallow bulwark and the discard chute was more than a metre above the water line. In all vessels when the specific collection device was full it was removed and the queen scallops were collected, this process was repeated until enough individuals had been sampled or collected.

# Estimation of absolute catch

Average catch per unit effort (CPUE, # individuals caught/ha) needed to be estimated for each vessel in order to evaluate the proportion of catch being discarded. The number of individuals discarded/ha (DPUE) is the difference between CPUE and LPUE (# individuals landed/ ha). It was predicted that CPUE could be estimated by determining a threshold size that was discarded, from assessing differences in size frequencies of landings and discards (see Montgomery, 2008). However expectations of the sorting machines efficiency in selecting specific threshold sizes to discard were incorrect. CPUE therefore had to be estimated by matching the cumulative frequency profiles of sizes caught (catch profile) generated from known average % size frequency distributions with a catch profile generated from an estimated quantity of absolute catch. Specifically, this involved converting the average absolute landings/ ha (LPUE) for each vessel into absolute numbers landed within each size class. This was done by using the vessel specific average % size frequency distribution of landings data.

# = LPUE (# individuals/ ha) \* proportion in each size category

An absolute number discarded/ ha was then estimated (based on qualitative observations in the field) and distributed across the size classes based upon average % size frequency distribution of discards data.

# = estimated number individuals discarded/ ha \* proportion in each size category

From this estimate of discards an estimate of the number of queens in the total catch was calculated as the sum of absolute discards and landings for each size class. The estimated absolute catch was then graphically illustrated as a % cumulative frequency plot (to display the profile of sizes caught) alongside the % cumulative frequency plot of the average % size frequency distribution of total catch data. The estimated absolute number discarded/ ha was then altered in a trial and error process until these two profiles matched as closely as possible. When a comfortable match was determined the estimated CPUE and number individuals discarded/ ha was noted and the percentage of target species discarded was calculated and assumed.

## Physical damage assessment

The extent of physical damage incurred by discarded queen scallops from the fishing procedure (both from the fishing/catching and sorting processes) was recorded. This involved visual assessment of the shell and mantle of each individual in the sub-sample of discards and scoring them with a damage category. The shell damage scoring system was adapted from methodologies used by Veale *et al.* (2001), shown in Table 1. Mantle damage included a positive or negative assessment of intrusions into the mantle cavity from catch debris (e.g. small stones, shell fragments, sediment or other queen scallops).

Score	Damage Level
1	No damage
2	Chips in shell edge
3	Large chips, cracks or holes
4	Crushed or broken hinge

 Table 1 Scoring system categorising A. opercularis damage level, adapted from Veale et al. (2001)

# Direct survivability of discarded A. opercularis

Direct survivability of discarded *A. opercularis* was investigated by keeping samples in shrimp creels (surface area  $\approx 80 \times 40 \text{ cm}$ ) at sea for the a period of 10 days (although some individuals were left for 16 days due to logistical difficulties) and assessing the number still alive after this set time.

A three way factorial experimental design was set up in order to determine potential differences in survivability with vessel (fishing technique), size (shell width) and damage (minor damage only, see below). For each vessel four treatment levels were adopted which comprised two size categories (S1 and S2) and two damage categories (D1 and D2), S1:D1, S1:D2, S2:D1 and S2:D2.

The size categories chosen for this experiment were, S1: queen scallops below the legal landing size (< 50 mm, shell width) and S2: those above the legal landing size (> 50 mm). This size separation was chosen in order to make an informed assessment of the minimum landing size management strategy and also because many queen scallops discarded were not actually undersize by definition. Although there was no buffer separating the size categories the two sizes were significantly different from one another (Mean size, S1: 58.55mm s.e.±0.19; S2: 41.38mm s.e.±0.19, KRUSKAL-WALLIS ANOVA  $\chi^2 = 1051.94$ , d.f. = 1, P < 0.001) with at least 17mm between the means.

At their normal fishing locations undersized individuals were very rare in discard compositions of QV and KC. In order to sample undersized *A. opercularis* (< 50 mm) for survival assessments tow locations had to be spatially manipulated to areas with a high abundance of juveniles. These areas were not usually fished by the fishing vessels because of the reduced catch efficiency and quality of catch associated with processing many undersized individuals. The data collected from these tows was therefore not used in the analysis because it was not representative of the usual operations in the fishery.

Damage categories chosen for this experiment included D1: undamaged (damage category 1) and D2: chipped on shell edge (damage category 2). It excluded other damage categories because they were either very rare and therefore were not representative of the fishery (e.g. damage category 3).

or mantle damage) or unnecessary due to inevitable mortality caused by high damage (damage category 3 and 4) (Veale *et al.*, 2001). These experiments therefore only looked at the effect of minor damage on survival. On the QV it was possible to get an assessment of survival from scallops with mantle damage as this was a slightly more common damage level on this vessel. However not enough samples could be collected to have size categories so these survival figures could not be analysed quantitatively with other treatment levels.

The stratified samples were taken in the same way as discard size frequency samples, meaning that discarded queen scallops were extracted from each fishing vessel immediately before discarding took place but after the sorting procedure had happened, this was to ensure the queen scallop had undergone the stress of the entire fishing process (with the exception of stress once returned to sea/ seabed).

A minimum of five replicates of 20 individuals were taken for each treatment level. Due to shortages in equipment and resources, shrimp creels were divided into two compartments and replicates were placed in compartments (surface area  $\approx$  40 x 40 cm). Scallops did not overlap in the creels and the stock density of 20 per compartment was unlikely to have an effect on survival as they are known to occasionally occur in very high densities in the wild (Personal communication with Belinda Vause and Andrew Brand). Also in aquaculture, *A. opercularis* are kept at higher densities without affecting survival (Roman *et al.* 1999).

Entrances to creels were covered with netting to prevent entry of large predators. On assessment of survival small scavengers found in the creels were noted and dead scallops were investigated to see if flesh had been consumed (e.g. if it was present).

Shrimp creels were deployed in Douglas Bay using the chartered lobster potter boat The Persevere (Skipper: Tony Bridson). Shrimp creels were deployed 10-13 to a line with a space of 2 metres between each creel. 20 metres of rope was provided either end of the line and each end had a buoy attached for precaution, in case one buoy was lost. Lines comprised a mixture of species as this study was carried out in conjunction with another study looking at survival of non-target species (Policarpo, 2011). The habitat profile was similar to where queens were extracted but sufficiently close to shore so that they could be accessed quickly. The area used in Douglas Bay ranged from 10-15 metres chartum depth and was well mixed with a sandy substrate (Personal communication with Tony Bridson).

# Indirect survivability

The *A. opercularis* predator escape response behaviour was utilised to assess indirect mortality associated with increased predation risk caused by the fishing procedure. This behaviour is a reaction to predation which propels the individual away from a predator via a series of valve adductions and ejections of water from the dorsal side (Thomas and Gruffydd, 1971).

The common starfish, *Asterias rubens* was used to simulate predation because it was a known predator of *A. opercularis* (Kaiser and Spencer, 1996; Veale *et al.*, 2000) and it was commonly available in the bycatch of all vessels (Policarpo, 2011). In order to study escape response the arm of a starfish was rested against the outer edge of the shell of a test individual and response parameters were measured. These parameters included the time (seconds) it took for an initial response, the initial number of valve adductions and the number of valve adductions until exhaustion (valve closure or gasping). The maximum length of time allowed for individuals to respond was 60 seconds, beyond this time the individual was recorded as a non-response. If the individual did respond within 60 seconds the same maximum time limit was applied between valve adductions and when it failed to re-respond after 60 seconds the individual was assumed to be exhausted and the test was ended.

For each vessel the same treatment levels from direct survivability tests were applied to these tests (S1:D1; S1:D2; S2:D1; and S2:D2). Other damage categories were not tested due to their rarity in the discards or on account of them already being dead (damage category 4). Pilot studies on damage category 3 and those scallops suffering mantle damage showed a response, and for the latter foreign bodies were occasionally ejected.

There were a minimum of 5 replicates per treatment level with a minimum of 4 individuals for each replicate. Each individual was placed separately in water-tight buckets (2 litre capacity) full of fresh sea water and left for 1 hour before performing predation simulation to allow them time to recover from the fishing process. The buckets were also placed in an area of the boat where there was low activity in order to prevent disturbance.

It was decided that a recovery period of at least 1 hour was required as pilot experiments on discarded scallops showed no immediate response to predation (immediately, 0 hours, after discarding). The recovery period could not be extended to longer periods due to limited time and resources available.

# Proportion of discards suffering mortality

To assess the proportion of discarded scallops suffering mortality, mortality rates were assigned to each damage category and then collaborated with the proportions of discarded individuals within each damage category. This was done separately for each vessel in order to get vessel specific mortality rates and it was carried out for discards of both size classes and for undersized (< 50 mm) alone. The assigned mortality rates were based on this study's findings from the direct survival assessments and on informed assumptions for mortality in high damage levels (see Veale *et al.*, 2001).

In order to exhibit the effects of discard mortality on the wider fishery the quantity of target species discards dying per unit effort (per hectare swept) and in one year was estimated.

To estimate the effect per unit effort, the overall mortality rates for each vessel were applied to the DPUE (# individuals discard/ha) to infer the number of discarded individuals suffering mortality per unit effort (per hectare swept). This was also carried out for the discarded undersized (< 50 mm) scallops alone as the former includes both undersized and landable size scallops.

To get an estimate of the effect in one year, the overall mortality rates were applied to 2010 landings data to estimate the total weight (tonnes) of target species discards suffering mortality in one year. Again this was also carried out for undersized (< 50 mm) scallops alone.

The 2010 landings data was taken from the 'Queenie Landing Figures (01/06/2010-31/05/2011)' summary sheet provided by the Isle of Man Government (Appendix 1). The estimates of discard mortality for 2010 rely on the following assumptions,

- All dredge landings to the UK were by modified dredgers (KC and similar vessels) and all dredge landings to the Isle of Man were by skid dredgers (QV and similar vessels)
- All landings were originally caught in Isle of Man territorial waters
- There was no difference between discard rates and discard mortality between similar vessels operating in the fishery
- The estimates of discard rates and mortality rates presented in this study are accurate

# Data analysis

All statistical analyses were conducted using R version 2.12.0. Where parametric tests were used the prerequisite assumptions (normality and homogeneity) were checked and where required dependent variables were transformed.

To compare size distributions between stages of the fishing method (catch, landings and discards) and between vessels tow-sample Kolmogorov-Smirnov tests were performed.

Generalised linear models (GLMs) using quasi-binomial error structures were applied to proportional data. Here the effect of size class and vessel was tested on the proportion of individuals in each damage category. The mortality experiments were also analysed with this test. The effect of damage category, size class and vessel were tested on the direct mortality rate and the indirect mortality indices (response rate, reaction time (seconds), initial number of adductions and total number of adductions). To assess which variables significantly affected the response, non-significant predictors were removed from the models beginning with the interactions, until only significant factors remained in the model. To analyse how factors affected the response in the GLMs *post hoc* Tukey's HSD tests were carried out on all GLMs.

Throughout analysis basic descriptive statistics such as mean are used to display the results also ANOVA and the non-parametric equivalent, Kruskal-Wallis tests were used to examine differences in the tow properties and landings per unit effort between vessels.

# **Results**

When data is presented as a mean in this section it is followed by the standard error (s.e.±) and then the sample size (n) in parenthesis.

# **Tow and LPUE properties**

In the study a total of 112 tows were performed in the East Douglas fishing grounds (Figure 4). Of these tows, 29 were spatially manipulated to be in areas with a high abundance of undersized *A. opercularis* (< 50 mm) for sampling requirements of the survival assessments.



**Figure 4** Tow locations in the East Douglas fishing grounds, Isle of Man. Tows are represented by coloured circles and vessels (gear type) are distinguished by colour, black – King Challenger (modified dredge), white – Maureen Patrica (otter trawl), grey – Q Varl (skid dredge). The manipulated tows carried out for sampling undersized *A. opercularis* are encircled in grey. The territorial waters are marked by a dark solid grey line.

Aside from gear type, fishing techniques differed considerably between vessel. The mean tow properties for each vessel are displayed in Table 2. MP towed its gear for the longest duration, mean tow length 80.06 minutes s.e. $\pm$  2.87 (n=17), and in doing so swept almost double the area the other

vessels did, mean area swept per tow 9.95 ha s.e.± 0.36 (n=17). QV and KC towed their gears for a similar amount of time (38.69 and 35.12 minutes respectively) but QV towed fastest and covered a greater distance whilst KC swept a large area in a small distance because of its large gear width. The dredgers both contained a significant proportion of stones in the catch (QV:37.83% and KC:18.78%) whilst none were found in the trawler. QV was the least selective gear with highest proportion of stones and bycatch in the catch (Policarpo, 2011). Maximum air exposure for the discards was greatest on the MP (50.38 minutes) and approximately the same for QV and KC (28.84 and 30.12 minutes). Also although catch volume was not quantified, it was observed that the MP's net reached full catch capacity on multiple tows.

The individual weight of *A. opercularis* caught was not significantly different between vessels (ANOVA  $F_{2,23} = 2.117$ , P = 0.143). Mean individual weight was therefore calculated over each tow irrespective of vessel and equated to 55.17g s.e.± 1.07. Thus a 40kg bag of *A. opercularis* approximately contained 725 individuals. This figure was then combined with number of bags landed per hectare to calculate the absolute number of individuals landed per hectare for each vessel (Table 2).

LPUE differed significantly between vessels (KRUSKAL-WALLIS ANOVA  $\chi^2$  = 59.375, d.f. = 2, P < 0.001) and *post hoc* pairwise comparisons showed these differences were significant between all vessels (MP:QV, P <0.001; MP:KC, P < 0.001; QV:KC, P < 0.001). Mean LPUE for KC was the largest, being six times greater than MP and three times greater than QV.

**Table 2** Mean tow properties for each vessel with ± standard error and sample size (n). Comparable data was not collected for every tow so not all means comprise the same sample size.

Vessel	Tow Time (mins)	Tow Distance (km)	Tow Speed (m/s)	Area Swept (ha)	Number of Bags landed	LPUE (individuals/ha)	Proportion of stones (%)	Air Exposure (mins)
MP	80.06	5.47	1.13	9.95	21.47	1604.25	0.0	50.38
	s.e.± 2.87	s.e.± 0.20	s.e.± 0.00	s.e.± 0.36	s.e.± 1.38	s.e.± 103.42	s.e.± 0.00	s.e.± 2.87
	n = 17	n = 17	n = 23	n = 17	n = 19	n = 14	n = 17	n = 21
QV	38.69	4.18	1.80	5.08	36.51	5366.94	37.83	28.84
	s.e.± 1.01	s.e.± 0.11	s.e.± 0.00	s.e.± 0.13	s.e.± 1.28	s.e.± 242.55	s.e.± 5.80	s.e.± 1.59
	n = 42	n = 42	n = 43	n = 42	n = 41	n = 40	n = 8	n = 43
KC	35.12	2.62	1.24	5.23	67.76	10229.58	18.78	30.12
	s.e.± 2.10	s.e.± 0.16	s.e.± 0.03	s.e.± 0.32	s.e.± 4.30	s.e.± 1117.73	s.e.± 5.36	s.e.± 2.10
	n = 17	n = 17	n = 17	n = 17	n = 17	n = 17	n = 7	n = 17

#### Size frequency distributions

The mean size (mm) of *A. opercularis* caught by each vessel was, MP: 69.62 s.e. $\pm$  0.25 (n=14); QV: 70.19 s.e. $\pm$  0.30 (n=8); KC: 70.22 s.e. $\pm$  0.19 (n=7). The mean size represents the mean of the average size from each tow, this also applies to landings and discards. No significant difference was found between vessels (ANOVA F<sub>2,26</sub> = 1.848, P = 0.178). Of those caught the average size landed by each

vessel was, MP: 70.26 s.e. $\pm$  0.22 (n=13); QV: 69.85 s.e. $\pm$  0.18 (n=10); KC: 69.89 s.e. $\pm$  0.31 (n=6). These were also found not to be significantly different from each other (ANOVA F<sub>2,26</sub> = 1.102, P = 0.347). The average sizes of the scallops discarded were considerably smaller than those caught and landed, MP: 61.06 s.e. $\pm$  0.46 (n=18); QV: 59.09 s.e. $\pm$  0.50 (n=13); KC: 62.44 s.e. $\pm$  1.04 (n=11). Vessel type was found to significantly affect the discard size (ANOVA F<sub>2,39</sub> = 3.542, P = 0.039), Tukey HSD *post hoc* tests showed that QV was significantly different to KC but that no other significant differences were found (MP:QV, P = 0.156; MP:KC, P = 0.601; QV:KC, P = 0.036).

The size frequency distribution of *A. opercularis* sampled from the catch, landings and discards of each vessel are shown in Figure 5. Across all vessels the proportion of caught *A. opercularis* that were undersized (< 50 mm) was very low, MP: 0.25%, QV: 0.48% and KC: 0.18% and this proportion only increased marginally in the discards *A. opercularis*, MP: 4.50%, QV: 5.65% and KC: 6.90%.



**Figure 5** Size frequency distributions of catch, landings and discards. The sizes are categorised into 5 mm groups (e.g. the 47.5 group contains *A. opercularis* that are within the 45 - 49 mm range). The size frequencies displayed are the mean proportion of individuals within each group of each tow. Error bars represent the  $\pm$  standard error of these mean proportions. **a.** MP = Maureen Patricia (otter trawler), **b.** QV = Q Varl (skid dredge), and **c.** KC – King Challenger (modified dredge).

Two-sample Kolmogorov-Smirnov tests comparing these size distributions explicated that there was no difference between size distributions of catch and landings within each vessel, but there were highly significant differences between discards of both catch and landings, Table 3a. Two-sample Kolmogorov-Smirnov analyses of size distributions between vessels explained that catch and landings did not differ between vessels Table 3b. However the size distribution of *A. opercularis* discarded from KC was found to be significantly different to both MP and QV discards. There was no difference shown between MP and QV discards. KC had a higher frequency of larger sized discards than the other vessels, the model size category of discarded *A. opercularis* for each vessel were, MP: 55-59; QV: 55-59; KC: 65-69.

**Table 3** Two-sample Kolmogorov-Smirnov tests outputs, assessing differences in frequency distributions. The test groups, test statistic (Z) and the p values (P) are displayed. **a.** Compares size distribution of stages within the fishing procedure (catch, landings and discards) for each individual vessel. **b.** Compares size distribution of catch, landings and discards between vessels. \* = significant.

				b.			
essel	Size Distributions Compared	Z	Р	Vessel	Size Distributions Compared	Z	Р
/IP - Trawl	Catch:Landings	0.354	1.000	Catch	MP:QV	0.556	0.90
	Catch:Discards	3.677	>0.001*		МР:КС	0.559	0.9
	Landings:Discards	3.960	>0.001*		QV:KC	0.210	1.0
۷۷ -	Catch:Landings	0.566	0.906	Landings	MP:QV	0.636	0.8
redge	Catch:Discards	4.525	>0.001*		MP:KC	0.480	0.9
	Landings:Discards	4.596	>0.001*		QV:KC	0.311	1.0
C - Dredge	Catch:Landings	0.340	1.000	Discards	MP:QV	0.849	0.4
	Catch:Discards	2.867	>0.001*		MP:KC	1.485	0.0
	Landings:Discards	2.936	>0.001*		QV:KC	1.909	0.0

#### Estimation of absolute catch and discards

Using size frequency data and landings data the average CPUE (# individuals caught/ ha) and average DPUE (#individuals discarded/ ha) for each vessel was estimated as, MP: 1754 and 150; QV: 5607 and 240; KC: 10510 and 280. The percentage of queen scallops that were discarded therefore amounted to, MP: 8.55%; QV: 4.28%; KC: 2.66%. Using the proportion of undersized discards values (shown previously) the absolute number of undersized individuals was estimated per hectare, MP: 4.50, QV: 13.56, KC: 19.32.

This also coincided with field observations as sampling of discarded *A. opercularis* was much more frequent on MP. It was also evident that MP discard had the greatest quantity of undersized *A. opercularis* because no request was needed to fish at the juvenile scallop grounds when sampling from the MP.

# Damage

The level of damage to discarded *A. opercularis* varied considerably between vessels. Figure 6 displays a detailed picture of the proportion of scallops in each damage category for the separate gear types. As a result of the categorical nature of the damage data each damage category had to be analysed separately.

The mean proportion of scallops that were undamaged (damage score 1) by the fishing process varied between vessels, MP=15.16% s.e. $\pm$ 1.57 (n=18), QV=22.13% s.e. $\pm$ 4.21 (n=11), and KC=26.54% s.e. $\pm$ 2.64 (n=9). As was done with size the mean proportion of each damage category represents the mean of the mean proportion of that damage category within each tow, the sample size (n) therefore equates to the number of replicate tows. A generalised Linear Model (family = quasibinomial) showed this difference was significant (F<sub>2,39</sub> = 5.633, P = 0.007\*) and a Tukey HSD *post hoc* test explained this difference was significant between both the dredgers (QV and KC) and the trawler (MP) but insignificant between the two dredge types (MP:QV, P = 0.009\*; MP:KC, P = 0.028\*; QV:KC, P = 0.996; QV:KC > MP). Although a relatively small difference clearly the dredgers are discarding more undamaged scallops than the trawler and therefore the trawler fishing procedure seems to be causing more damage to scallops than the dredgers.

Minor shell chipping (damage score 2) was the most common damage category across all the vessels (see Figure 6). The proportion of scallops displaying this damage category for each vessel was, MP=81.91% s.e. $\pm$ 1.87 (n=18), QV=47.59% s.e. $\pm$ 5.31 (n=11), and KC=56.48% s.e. $\pm$ 6.35 (n=9) and these were found to be significantly different (GLM (quasi-binomial) F<sub>2,39</sub> = 37.465, P < 0.001\*). Tukey HSD *post hoc* tests showed all gears were significantly different from each other (MP:QV, P <0.001\*; MP:KC, P<0.001\*; QV:KC, P = 0.017\*; MP>KC>QV). The MP (trawler) has a greater quantity of this damage level than both the dredgers combined and within the dredgers the KC has a significantly higher proportion than the QV.

The proportion of scallops incurring large cracks or holes (damage score 3) was very low, MP = 0.79% s.e. $\pm$ 0.24 (n=18), QV = 0.82% s.e. $\pm$ 0.46 (n=11) and KC = 0.70% s.e. $\pm$ 0.51 (n=9). This was the lowest represented damage level for all vessels and there was no statistical difference between vessels (GLM (quasi-binomial) F<sub>2,39</sub> = 0.108, P = 0.898).

Scallops that were completely crushed or with split hinges (damage score 4) were observed more frequently in the dredgers and were not common in the trawler, MP = 2.13% s.e. $\pm$ 0.61 (n=18), QV = 29.46% s.e. $\pm$ 4.83 (n=11), and KC = 16.28% s.e. $\pm$ 6.07 (n=9). Within the dredgers QV exhibited more scallops in this damage category than KC. These differences were found to be significant (GLM (quasi-binomial) F<sub>2,39</sub> = 40.739, P < 0.001\*) and Tukey HSD *post hoc* test showed all gears significantly differed from one another (MP:QV, P <0.001\*; MP:KC, P<0.001\*; QV:KC, P = 0.004\*; QV>KC>MP).



**Figure 6** Proportion of *A. opercularis* exhibiting each shell damage category for the separate gear types. MP n=18, QV n=13, and KC n=11. Colour of the shapes denotes whether there is significant difference (if colours differ there is significant difference). Error bars represent  $\pm$  standard errors of the mean proportion. Legends represent vessels MP = Maureen Patricia (otter trawler), QV = Q Varl (skid dredge), and KC – King Challenger (modified dredge).

Although difficult to estimate for all individuals, scallops found to have mantle damage were uncommon however they were more frequently observed in the dredgers than the trawler and out of the dredgers most common in the QV, MP = 0.11% s.e. $\pm$ 0.11 (n=18), QV = 1.59% s.e. $\pm$ 0.62 (n=13), KC = 0.92% s.e. $\pm$ 0.53 (n=11) (see Figure 7). The difference between vessels was found to be significant (GLM (binomial) F<sub>2,39</sub> = 29.659, P < 0.001\*) but Tukey HSD *post hoc* test confirmed this difference was only significant between the QV and the MP (MP:QV, P = 0.018\*; MP:KC, P=0.130; QV:KC, P = 0.603; QV>MP).



**Figure 7** The proportion of *A. opercularis* exhibiting mantle damage in the discards for each vessel. MP n=18, QV n=13, and KC n=11. Error bars represent  $\pm$  standard errors of the mean proportion. MP = Maureen Patricia (otter trawler), QV = Q Varl (skid dredge), and KC = King Challenger (modified dredge).

# Damage and size

To test whether the size of scallop affects the likelihood of inflicted damage, scallops were grouped into those above and below minimum landing size (< 50 mm and > 50 mm) and the generalised linear model (family =quasi-binomial was carried out for each damage category (Table 4). When scallops are grouped into size categories (< 50 mm and > 50 mm) it appears the amount of inflicted damage is size dependent (Figure 8). For instance it is clear that undersized *A. opercularis* (< 50 mm) are more likely to be undamaged (damage score 1) by fishing gears than the larger *A. opercularis* (> 50 mm) and it is also evident that what-ever the extent of damage (damage category 2-4), larger scallops are more likely to be damaged. Generalised linear models (family =quasi-binomial) confirmed that shell width significantly affects the proportion of scallops in each damage level (Table 4). This analysis includes data from dredger tows in the small area as it contained more undersized scallops.



**Figure 8** Proportion of discarded *A. opercularis* within each damage category for those less than 50 mm and those greater than 50 mm. Sample sizes: MP n=18, QV n=19, and KC n=20. Error bars represent +/- standard errors of the mean proportion. Maureen Patricia (otter trawler), QV = Q Varl (skid dredge), and KC = King Challenger (modified dredge).

Vessel type was also seen to be significant and Tukey *post hoc* test showed that the trawler was significantly different from the dredgers (but not between dredgers) showing that there was proportionally more undamaged queens in the dredgers. However the difference between trawlers and dredgers may be obsolete and inaccurate because the data used in this analysis includes 29 dredge tows which were carried out in an area of the sea bed with a high proportion of juveniles.

**Table 4** Output of generalised linear models (family =quasi-binomial), proportion of discarded scallops ~ size + vessel + size\*vessel. \* = significant.

Dependent Variable	Factor	F	d.f.	Р
Damage Score 1	Size	97.004	1,102	<0.001*
	Vessel	14.963	2,100	<0.001*
	Size:Vessel	0.018	2,98	0.982
Damage Score 2	Size	55.219	1,102	<0.001*
	Vessel	47.498	2,100	<0.001*
	Size:Vessel	0.866	2,98	0.424
Damage Score 3	Size	9.386	1,102	0.003*
	Vessel	0.152	2,100	0.859
	Size:Vessel	0.000	2,98	1.000
Damage Score 4	Size	13.176	1,102	<0.001*
	Vessel	46.063	2,100	<0.001*
	Size:Vessel	0.808	2,98	0.449

# **Direct mortality**

For the Q Varl survival assays, five replicates (treatment levels: > 50 mm: damaged (n=4) and > 50 mm: undamaged (n=1)) were left at sea for 16 days rather than the designated 10 days. The mean mortality rates for these combined treatment levels were 10 days: 11.30% s.e.±1.10 (n=12) and 16 days: 25.59% s.e.±5.31 (n=5) which suggested the longer the time replicates were left at sea the greater mortality rate. This difference was confirmed to be significant by a generalised linear model (GLM (family=binomial)  $F_{1,15}$ =8.860 P=0.0142\*). As a precaution replicates left for 16 days at sea were removed from the analysis. The effect of duration had on survival was anticipated so enough replicates had been measured at the designated 10 days (minimum of 5 replicates per treatment level).

Mortality rates for the treatment levels investigated ranged from 3.28% to 17.39% but high standard errors suggested a large degree of uncertainty in these mortality estimates (Table 5). A generalized linear model found neither vessel, damage, shell width or their interactions significantly explained differences between mortality rates (Table 6). However the effect of damage was found to be almost significant (P=0.080, Table 6) and despite the large variation in mortality estimates there was a clear difference between mean mortality rates of undamaged scallops and scallops with minor shell chipping, D1 = 7.89% s.e. $\pm$  1.74 (n=34) and D2 = 13.26% s.e. $\pm$  2.69 (n=30). This implies damage may increase the probability of mortality.

Damaga	Cina	Vessel			
Damage	Size	MP	QV	КС	
	< 50 mm	10.36% s.e.±8.03	3.28% s.e.±2.01	5.78% s.e.±3.01	
Undamagod	< 30 mm	(n=6)	(n=5)	(n =5)	
Unuannageu	> 50 mm	11.17% s.e.±4.11	11.26% s.e.±1.88	4.39% s.e.±3.44	
	> 30 mm	(n=5)	(n=7)	(n=6)	
	< 50 mm	14.79% s.e.±8.25	15.91% s.e.±5.00	7.22% s.e.±4.94	
Minor Chips	< 50 mm	(n=5)	(n=5)	(n=3)	
		17.39% s.e.±12.29	11.35% s.e.±0.68	10.67% s.e.±3.02	
	> 30 mm	(n=6)	(n=5)	(n=6)	

**Table 5** Proportion of discards suffering mortality (Without those at sea for 16days and without replicates of mantle damage) Error bars represent ± standard errors of the mean proportion, (sample size in parenthesis).

Factor	F	d.f.	Ρ
Damage	3.178	1,62	0.080 □
Size	0.334	1,61	0.565
Vessel	1.170	2,59	0.317
Damage*Size	0.307	1,58	0.582
Damage*Vessel	0.088	2,56	0.916
Size*Vessel	0.016	2,54	0.985
Damage*Size*Vessel	0.955	2,52	0.391

**Table 6** Output of generalised linear models (family =quasi-binomial), proportion of A. opercularis that died ~size + vessel + size\*vessel.  $\circ$  = almost significant.

Survival assays on scallops suffering mantle damage could only be carried out on samples collected from the Q Varl. Unfortunately only three replicates could be acquired and these could not be separated into size categories due to the rarity of this damage category. The mean mortality rate of these replicates was 53.76% s.e.± 7.51 (n=3). This damage category could not be included in the generalised linear model as it was only obtained for one vessel and did not include size categories, therefore can only be analysed qualitatively.

On assessment of survival 92.14% of dead scallops recorded were only shell. Small scavengers were thought to have consumed the flesh of these dead scallops and some scavenger species were recorded in the shrimp creels. These included *Galathea squaiifera*, *Palaemon serratus*, *Liocarcinus-deruptor*, *Ophiuria albida*, *Archidoris pseudoargus*, *Inachus phalangium*, *Neballa bipes*, *Lepadogaster lepadogaster* and *Gibbula spp*..

# Indirect mortality

Not all scallops responded to stimulated predation and the proportion of individuals responding varied between treatment levels. A generalised linear model (family=quasi-binomial) informed that predation response was significantly affected by the factors of shell width and vessel. The outcome of this analysis is shown in Table 7. The mean proportion of scallops responding within each size category equated to, < 50 mm: 77.60% s.e. $\pm$  5.58 (n=32) and > 50 mm: 52.50% s.e. $\pm$  4.54 (n=49). Thus explaining undersized scallops were more likely to respond to predation than scallops above the minimum landing size.

The mean proportion of scallops responding to predation within each vessel was, MP: 58.85% s.e. $\pm$  5.29 (n=29), QV: 80.42% s.e. $\pm$  5.99 (n=20), and KC: 54.45% s.e. $\pm$ 6.83 (n=32). This shows that scallops

discarded from the QV are more likely to respond to predation threats than those discarded from the other vessels. Tukey *post hoc* tests confirmed this by showing that the proportion of response on the QV was significantly different from both MP and KC but that there was no difference between KC and MP (QV:MP, P = 0.018; QV:KC, P = 0.017; MP:KC, P = 0.999; QV>MP:KC).

Damage also appeared to affect the predation response with a higher proportion of undamaged scallops responding than damaged. The mean proportion responding to predation within each damage category was, D1: 69.82% s.e.± 5.48 (n=37), and D2: 56.19% s.e.±5.03 (n=44). However this relationship was found not to be significant (Table 7).

Table 7 Output of generalised linear	<ul> <li>models (family =quasi-binomial),</li> </ul>	proportion reacting ~	' size + vessel +
size*vessel. * = significant = almost s	significant.		

Factor	F	d.f.	Р
Size	22.250	1,77	<0.001*
Vessel	4.312	2,77	0.017*
Damage	3.791	1,76	0.055 -
Damage*Size	0.650	1,75	0.422
Damage*Vessel	0.778	2,73	0.463
Size*Vessel	1.927	2,71	0.153
Damage*Size*Vessel	0.758	2,69	0.473

Analysis was then carried out specifically on those scallops that reacted to stimulated predation. This was to assess if damage, shell width and vessel affected the extent of the escape response. The escape response parameters, response time (seconds), initial number of valve adductions and total number of valve adductions were separately analysed using general linear models.

All escape response parameters showed a significant relationship with shell width and the total number of valve adductions was also significantly influenced by vessel (Table 8, Table 9). No other factors were seen to influence the escape response parameters measured. Smaller undersized scallops responded quicker and performed more valve adductions both initially and in total than larger scallops (Table 10).

**Table 8** Escape response parameters (response time, initial number of claps, total number of claps) expressed as means within each size category. Error bars represent ± standard errors of the mean proportion, (sample size in parenthesis).

Escape Response Parameter	Small (< 50 mm)	Large (> 50 mm)
Mean Response Time (seconds)	7.58 s.e.± 2.33 (n=32)	14.41 s.e.± 1.62 (n=49)
Initial Number of Claps	5.73 s.e.± 0.65 (n=32)	3.73 s.e.± 0.43 (n=49)
Total Number of Claps	20.49 s.e.± 1.26 (n=32)	15.24 s.e.± 1.16 (n=49)

In response to predation simulation scallops discarded from the Q Varl performed more valve adductions before they were exhausted than those from the other vessels, MP: 16.65 s.e. $\pm$ 1.64 (n=27), QV: 21.48 s.e. $\pm$ 1.62 (n=20) and KC:14.81 s.e. $\pm$ 1.17 (n=25). A tukey HSD *post hoc* test confirmed this difference (QV:KC, P<0.001; QV:MP, P=0.001; MP:KC, P=0.769).

 Table 9 Output of generalised linear models (family =quasi-binomial) response parameters ~ size + vessel + size\*vessel

Dependent Variable	Factor	F	d.f.	Р
Ln (Response time)	Size	12.058	1,58	<0.001*
	Vessel	0.141	2,58	0.869
	Damage	0.116	1,58	0.735
	Damage*Size	2.853	1,58	0.097
	Damage*Vessel	1.129	2,58	0.331
	Size*Vessel	1.397	2,58	0.256
	Damage*Size*Vessel	1.172	2,58	0.317
Ln (Initial number of valve	Size	8.737	1,60	0.005*
adductions)	Vessel	0.832	2,60	0.440
	Damage	2.944	1,60	0.091
	Damage*Size	1.852	1,60	0.179
	Damage*Vessel	2.722	2,60	0.074
	Size*Vessel	0.388	2,60	0.680
	Damage*Size*Vessel	1.259	2,60	0.291
Ln (Total number of valve	Size	7.920	1,60	0.007*
adductions)	Vessel	5.112	2,60	0.009*
	Damage	2.336	1,60	0.132
	Damage*Size	0.536	1,60	0.467
	Damage*Vessel	0.168	2,60	0.847
	Size*Vessel	0.237	2,60	0.789
	Damage*Size*Vessel	0.897	2,60	0.413

# Proportion of discards suffering mortality

The mortality rates designated to each damage category were as follows. For damage category 1 and 2 the mortality rate assigned was the mean mortality rate across all treatment levels in the survival

assays, 10.41% s.e.± 1.59 (n=64). This was carried out over all treatment levels because no variable was found to significantly affect mortality. The mortality rate of scallops suffering damage category 3 and 4 was assumed to be 100% due to the high level of damage associated with these categories. This assumption is confirmed by experiments in Veale *et al.* (2001) that show mortality was 100% in these categories after 72 hours in aquaria. Those suffering mantle damage were assigned the mortality rate of 53.76% s.e.± 7.51 (n=3). This figure was based on the three replicates taken from the QV for this damage category and so follows the assumption that vessel does not affect survival.

From the assigned mortality rates for each damage category the proportion of discards suffering mortality was calculated for each vessel (Table 10). The trawler experienced the lowest amount of mortality as a result of it having the lowest proportion of scallops being discarded at high damage levels (category 3, 4 and mantle damage) and the QV suffered the highest proportion of mortality in the discards due a large proportion of the discard being damage category 4 (crushed or hinge broken). If undersized scallops are assessed alone mortality is reduced as a result of individuals less than 50 mm incurring no or less severe damage (damage category 1 or 2) (Table 10).

Vessel	Proportion of target species discards suffering mortality (includes all sizes)	Proportion of undersized target species discards suffering mortality (only < 50 mm)
MP	13.06%	10.40%
QV	35.33%	18.61%
КС	18.54%	10.40%

**Table 10** Total proportion of *A. opercularis* discards suffering mortality and proportion of undersized suffering mortality. Values based on mortality rates of each damage level and the proportion of discards within each damage level. No error can be assigned to these figures.

# Discard suffering mortality per hectare swept

Applying these discard mortality rates to the absolute number of individuals discarded (/ha) (see p. 30) shows the number of discards suffering mortality (/ha) to be very minimal (Table 11a), especially alongside the LPUE (# individuals landed/ha). LPUE is also the accounted for fishing mortality. The number of undersized scallops suffering mortality is a fraction of the total discard mortality, shown in parenthesis in Table 11a.

# Discards suffering mortality in 2010

a.

The discard mortalities were then applied to the 2010 landings data (Table 11b). Here the full extent of discard mortality (both for undersized and total discards) on the fishery can be seen.

**Table 11** Wider effects of discard mortality rates (values in parenthesis equate to undersized < 50 mm) a.</th>Number of individuals landed, discarded and that suffered mortality, per hectare swept b. Weight (tonnes) in2010 landed, discarded and that suffered mortality. No error could be assigned to these values apart fromLPUE where ± standard error and sample size (n) is presented.

# In DPUE, # Individuals Discarded/ha		# Individuals discarded predicted	LPUE, # Individuals landed/ha
VC33C1	(represents undersized, < 50 mm)	(represents undersized, < 50 mm)	
MP	150 (6.75)	19.59 (0.70)	1604.25 s.e.± 103.42 n = 14
QV	280 (13.56)	84.79 (2.53)	5366.94 s.e.± 242.55 n = 40
КС	240 (19.32)	51.91 (2.01)	10229.58 s.e.± 1117.73 n = 17
b.			
Vessel Total Discards (tonnes) in 2010 (represents undersized, < 50 mm)		Total Discards suffering mortality (tonnes) in 2010 (represents undersized, < 50 mm)	Total Landings (tonnes) in 2010
Trawl	190.2 (8.6)	24.8 (0.9)	2034
Skid Dredge	89.9 (5.1)	31.8 (1.0)	2010
Modified Dredge	239.0 (16.5)	44.3 (1.7)	8747
Total	519.1 (30.2)	100.9 (3.6)	12791

# **Discussion**

*A. opercularis* discard quantities and discard mortality rates were studied within each gear type operating in the Isle of Man Queen scallop fishery.

# **Discard quantities**

Within each vessel type the size distributions for catch and landings were almost identical with no statistical difference (Figure 5). Therefore following the reasonable assumption that discards are selected for by shell size this strongly suggests the proportion of discards was very low in all vessels. Furthermore all vessels studied were united in having low catch quantities of undersized *A. opercularis* (comprising < 0.5% of all *A. opercularis* caught) indicating that there were minimal undersized discards from all vessels.

Estimates of discard quantities based on the catch profiles of each vessel confirmed a low discard rate but also showed the exact proportion of discards differed between vessels (MP: 8.55%; QV: 4.28%; KC: 2.66%). MP had the greatest proportion of target species discards. A potential cause was that the rotating riddle of MP was less efficient at grading *A. opercularis* than the two-layered sorting machines of the dredgers, allowing more scallops of landable sizes to pass through (of which there were many, see below). Secondly qualitative observations indicated catch density in MP was larger than other vessels and often at full net capacity; this may have blocked the net and prevented undersize scallops escaping.

A previous study by Duncan (2009) assessed the bycatch in the same trawl fishery and quantified the proportion of target species discarded at 21% of the catch, whilst the estimate from this study was 8.55% for MP. Duncan's value for proportion discarded comes from an average of eleven different trawlers whilst this study just shows data from one trawler, this and that the fact different methodology was used to calculate discard proportion give possible explanations for the difference in discard quantity. The quantified discard proportions in this study should be interpreted with caution as a result of the discard proportions being estimates. These estimates are highly dependent on the accuracy of size distributions of catch, discards and landings. The size distributions presented in the results appear reliable though as they show Gaussian distribution and have low standard errors. A further study is needed to be carried out to accurately quantify the proportion of discards in the Isle of Man Queen scallop fishery. Suggested methods for this are presented in Duncan (2009).

# **Discard size frequencies**

For all vessels the discard size frequencies showed that target species discards not only include undersized *A. opercularis* but also landable sizes (> 50 mm). In fact the vast majority of discards were of landable size, MP: 95.50%, QV: 94.35% and KC: 93.10%. Although there was the occasional undersized scallop (ranging from 30-50 mm) in the discards (Figure 5), it is clear for all vessels that the graders efficiency for size selection was imprecise and is leading to some accidental discarding of marketable catch. Despite many discards being the same size as those scallops landed, discards quantities can still be assumed to be low. This is because discard and landed size frequencies are different and therefore if a large proportion of landable sized scallops had been discarded it would have created a difference between the catch and landings distributions.

Discards from KC were larger (Mode size categories: MP: 57.5, QV: 57.5 and KC: 67.5) and the distribution was more skewed to the right with respect to the other vessels discard frequency distributions (Figure 5). This was most likely a result of the two-layered sorting machine which firstly removed large items, occasionally including very large or heavily fouled *A. opercularis*, and then removed small items such as undersized *A. opercularis* and occasionally those of legal size which were thinner than usual or crushed. Both this waste (large and small) went out the same chute and this was the chute that the discarded *A. opercularis* were sampled from. For the MP these results are understandable because large waste was sorted by hand so large scallops were always landed. The difference between QV and KC discard size frequencies is difficult to explain as the QV also used a two-layered sorting machine, so theoretically there should have been large sizes discarded from the QV as well. Large *A. opercularis* discards were not sampled as there were two separate discard chutes for large and small waste and only the small waste chute was sampled. This under-sampling in QV highlights a limitation in the methodology.

# Damage of discards

Discards from the dredgers exhibited more serious damage than the trawler, with approximately 30% (QV) and 17% (KC) of discards suffering serious damage compared to 3% in the trawler. A greater probability of mantle damage was also seen in dredgers, MP = 0.11%, QV = 1.59% and KC = 0.92%, although only significantly greater between QV and MP. This supports the hypothesis and is consistent with studies showing damage to captured species is substantial in dredges (Medcof and Bourne, 1962; Jenkins *et al.*, 2001; Veale *et al.*, 2001). However these studies looked at toothed dredges not toothless dredges and on comparison with similar damage categories used by Veale *et al.*, (2001) damage appears to be a lot more extensive in toothed dredges, with 90% experiencing

severe damage. Further confirmation of these findings comes from a study by Montgomery (2008) that shows severe damage is limited in trawlers with the majority of the catch being either undamaged or slightly chipped. This is similar to this study's findings although it could not be compared quantitatively as a result of Montgomery (2008) reporting the mean damage score. This was not reported in this study because means from category data are often meaningless and can obscure results.

A study by Mcloughlin *et al.* (1993) showed that fishing on rocky substrate resulted in a high proportion of the scallops caught being smashed. The high rock content seen in the catch composition of the dredgers in this study was therefore a likely factor in the high severity of damage also seen in this study (Percentage rock composition, MP: 0%, QV: 37.83% and KC: 18.78%). Another reason could be the components of the dredge gears were harder (i.e. metals as opposed to netting) therefore leading to more forceful collisions within or on entry of the gear. The fact there was a greater proportion of rocks in the catch composition of QV suggest a reason for a higher proportion of seriously damaged scallops too. This may also have been a result of QV's high tow speed

(QV: 1.8 m s<sup>-1</sup> compared to KC: 1.24 m s<sup>-1</sup> and MP: 1.13 m s<sup>-1</sup>). Maguire *et al*. (2002) has shown tow speed is determining factor in mortality of scallops.

It is worth mentioning that minor damage was significantly greater in the trawler and as a result trawler discards showed a significantly smaller proportion of undamaged scallops (MP: 15.16% compared to QV=22.13% and KC=26.54%). This is probably a result of the high catch volume in trawler which would have resulted in a high collision rate between scallops and increasing potential for minor shell chipping.

It was clear from this study that shell size was related to damage level. Undersized scallops were found to be less damaged than scallops larger than 50 mm. This contradicts predictions that damage would be greater as a result of younger scallops having more fragile shells. A probable reason for undersized scallops being less damaged is hypothesised as small individuals being less obtrusive within the gears and sorting machines. Being relatively smaller in total area will reduce their probability for collisions in the fishing procedure.

# Survival

# Direct survivability experiments

Overall, survival from survivability assessments was high, 89.59% s.e.± 1.59. This was consistent with the survival rates from similar studies on the same species (Kaiser and Spencer, 1995; Montgomery,

2008) and on different scallop species (Wassenberg and Hill, 1993; Kaiser and Spencer, 1995; Campbell, 2010). Montgomery (2008) actually found 100% survival but these experiments were carried out in controlled aquaria so samples were not under the same stresses as they would have been if discarded at sea. Arguably the results reported in this study are a better representation of the fate of discards at sea. Also the Montgomery (2008) study was unclear on what damage levels were tested for survivability.

This study is the first, I am aware of, to look at the survivability of juvenile (or undersized, < 50 mm) A. opercularis after discarding compared with commercially landable (> 50 mm) individuals, and it showed that there was no discernable effect of size. In fact there was found to be no significant effect of vessel, minor damage or size on the direct mortality rate of discarded A. opercularis. This was largely unexpected and all three hypotheses looking at the effect of these variables on direct survivability were rejected. Explanations for this could be that stresses from fishing and subsequent discarding only lead to sub-lethal effects in the treatment levels chosen. For instance stress was not great enough for the sensitivity of undersized scallops (Gasper and Monteiro, 1999; Maguire et al., 2002) to be expressed. Similar reasons can explain the null effects of vessel, here different levels of stress provided by each vessel may not have transpired to direct mortality as a result of the resilient nature of scallops. The negative effect of shell chipping is probably sub-lethal and has been shown not to effect mortality in the past (Gruffydd, 1972). However the survival experiments indicated there could be a relationship between minor shell damage and mortality rate and this was almost significant (P < 0.1). A follow up study using more replication may be required to confirm or refute this effect. Whilst minor shell damage did increase mortality slightly it is assumed that as nonsignificant this variable is unlikely to have a large impact on the direct survival rate.

It is important to stress that the damage variable in this experiment only includes the two categories, undamaged scallops and scallops with minor damage. Damage levels of greater severity (for example, mantle damage, major cracks and chipping, and crushed) significantly reduce chances of survival. Veale *et al.* (2001) showed that *A. opercularis* suffering major cracks or crushing (damage category 3 and 4) died within 72 hours and preliminary experiments in this study on scallops with mantle damage show 53.76% s.e.± 7.51 mortality. Mortality caused by mantle damage is likely to be dependent on the size and rigidity of the objects entering the mantle cavity and observations during this study show *A. opercularis* can clear its mantle of foreign bodies by performing valve adductions.

Estimates of the total discard mortality rate (includes all damage levels) showed greater discard mortality than the survivability study and found clear differences between vessels (Overall discard mortality, MP: 13.06%; QV: 35.33%; KC: 18.54%). Total discard mortality was highest for the

dredgers in particular the skid dredge, QV. This was a cause of discards from the QV experiencing the most severe damage,  $\approx$ 32% (% of severe damage: damage categories 3,4 and mantle damage combined) which exhibited instantaneous mortality. KC also had a higher mortality than the trawl because it had more discards suffering severe damage,  $\approx$ 18%, although not as much as the QV. For undersized scallops the discard mortality is even lower (MP: 10.40%; QV: 18.61%; KC:10.40%) as a result of there being very few or no discarded individuals suffering high damage levels (MP:0%, QV:15%, KC:0%). Again QV has the highest rate of mortality.

The overall mortality rates show the proportion of target-species discards suffering mortality is dependent on the damage experienced by the discards. It therefore can be concluded that vessel and size may be confounding variables of damage in this study. Note that mortality estimates do not include the increased risk of predation qualified in this study (see below). The overall discard mortality therefore only represents direct mortality rates of discarding.

Overall direct discard mortality for each vessel was relatively low compared to mortality rates of *A*. *opercularis* from other gears, Veale *et al*. (2001) found a mortality rate of 90% from toothed dredges (also see, Allison and Brand, 1995). These rates are also low compared to other species from the same gear types (Policarpo, 2011) and different gear types (Kaiser and Spencer, 1995; Gasper *et al*. 2001). This was particularly true for undersized scallops as they were largely less damaged.

High overall survival following capture and discarding is likely a result of the robust nature of *A. opercularis*, like most bivalves they have two hard valves that surround their body providing them with protection. Kaiser and Spencer (1995) suggested mortality rate from discarding was dependent on an individual species' physiological and physical characteristics, showing molluscs, *Buccinum undatum, Nucella antiqua, Pecten maximus* and *A. opercularis* had higher survival rate (90-100%) after discarding than other taxa such as *Pleuronectes platessa* (40%), *Psammechinus miliaris* (38%), *Raja naevus* (59%) and *Liocarcinus depurator* (50%). High survival may also be a result of a scallop's resilience to desiccation, as seen in a study on *Pecten maximus* by Maguire *et al.* (1999) which showed air exposure of 12 hours did not affect survival.

The length of time given to assess delayed mortality (10 days) was a limitation in this study. Protracted mortality is important to measure as organisms can suffer postponed mortality after discarding. It is however unclear what the most informative length of time at which survivability should be measured. Wassenberg and Hill (1993) reported that 4 days was sufficient to measure direct mortality and Bergmann and Moore (2001) showed mortality could be protracted up to 3 weeks after the discarding event. Significant differences in mortality rate between 10 and 16 days shown in this study indicate this study did not allow long enough to test the full effect fishing had on delayed mortality. It may be that the effect of vessel, damage and size is not expressed within 10 days.

The fact there were scavengers found inside the creels suggests further potential limitations of this methodology as it is probable mortality rate included the uncontrollable factor of predation pressure albeit from small scavengers. It can be argued however that this makes the experiment more representative of what actually occurs at discard sites and it is unlikely that being in creels increased predation risk compared to what it would have been at the discard site. There was plenty of space for the scallops to escape predation and most of the predators found were quite fast movers e.g. fish, shrimp and squat lobsters so it is unlikely escape response in a larger area would have improved survival.

A final limitation to this experiment is that there were no conventional controls (i.e. scallops which had not been fished) to test the effect of the creels on mortality. At the start of the study the assumption was made that the trawler would be a control for this experiment due to the study by Montgomery (2008) which indicated 100% survival in a trawler operating in the same fishery. However the scallops sampled from MP exhibited some mortality suggesting that the conditions at the sea bed are causing mortality in MP, not fishing. However the conditions the creels were kept in were assumed to be good with high flow of water providing circulation, food availability and the stock density was lower than densities exhibited in the wild and in aquaculture. It is likely the increased mortality is a result of the combination of fishing stress and pressures at sea for example predation mentioned above. It is therefore suggested the increased mortality rates shown in this study (relative to Montgomery, 2008) are a cause of them being deployed at sea rather than a cause of the conditions of the creels.

#### Indirect Survivability Experiments

As a result of the complexity of the escape response in scallops (see review, Brand, 2006b) the results of these experiments are more of an indicator to the fishing effects on predation risk.

Experiments looking at the ability of *A. opercularis* to respond to predation after discarding showed a unanimous effect of size (shell width) (Table 10). Scallops less than 50 mm were significantly better at avoiding predation after discarding (Table 9). This was unexpected as smaller individuals are believed to be more sensitive to the stress of fishing procedures (Gasper and Monteiro, 1999; Maguire *et al.*, 2002). The results shown here are probably a result of physiological differences between small and large *A. opercularis*, which lead to energetic deficiencies in larger scallops (Philipp

*et al.*, 2008). *A. opercularis* in the smaller size category are also thought to be the most hydrodynamically efficient with the best swimming capacity of any other size (Schmidt *et al.*, 2008). Whether fishing had an added effect on the difference in predation response with size is unknown without experimental controls (i.e. scallops not fished). Previous studies have shown fishing reduces the ability of discarded individuals to respond to predation (Ramsey and Kaiser, 1998; Jenkins and Brand, 2001) and this may be less likely to affect undersized scallops as result of them incurring less damage when captured (overlooked when formulating hypothesis). Although the reasons are unclear it is apparent that undersized scallops are better adapted at avoiding predation after discarding than their larger counterparts.

Response rate and total number of adductions was significantly greater in scallops being discarded from the Q Varl (Response Rate, MP: 58.85% s.e.± 5.29; QV: 80.42% s.e.± 5.99; KC: 54.45% s.e.±6.83 and Total adduction number, MP: 16.65 s.e.±1.64; QV: 21.48 s.e.±1.62 ; KC:14.81 s.e.±1.17). Indicating they were more likely to react and had a higher energetic capability. This was counter to the hypotheses as dredgers are believed to cause more physiological and physical stress (Medcof and Bourne, 1962; Jenkins *et al.*, 2001; Veale *et al.*, 2001) which reduces predation response (Ramsey and Kaiser, 1998; Jenkins and Brand, 2001). Possible reasons behind this are unclear. From an assessment of the tow properties measured it is unlikely that scallops underwent less physiological stress during this fishing procedure than those in other vessels. Lower air exposure results in increased swimming activity (Jenkins and Brand, 2001). Although air exposure was less than MP it was roughly the same as KP. The tow speed and the proportion of stones and bycatch in the catch (Policarpo, 2011) was greatest in the QV. Further study is required to disentangle the reasons for differences found between gears; this would also be interesting as will quantify reasons for difference in damage.

The proportion of scallops unable to respond to predation was greater in scallops with shell damage, although found to be insignificant. This is probably a cause of increased energetic stress experienced from the impacts that lead to the shell damage. Further study is required to confirm this relationship.

As mentioned previously the response parameters measured are only an indicator of predation risk. The only way to accurately measure predation risk would be to setup simple mesocosm experiments with discards and predators in the same locations and measure their interaction and mortality rates. However the parameters of escape response measured in this study were thought to be representative indices for predator avoidance. Response rate and reaction time are particularly important because they will reduce the ability of *Asterias rubens* gaining a firm hold of the shell. Beyond this point escape response is ineffective and the starfish has the ability to force open the scallops valves (Jangoux, 1982). Secondly the initial number of adductions carried out determines the initial swimming distance. This is important because if the scallop moves a significant distance away from the predator the threat of predation will end in the short term, provided the predator is slow moving (Jenkins and Brand 2001). The measurement of total number of adductions until exhaustion is probably not representative of true predator-prey interactions as it is unlikely discarded scallops will be subjected to repeated predation stimulation, but it provides a comparable estimate of the energetic ability of discarded scallops to respond to predation.

Due to time and effort constraints escape response was only measured one hour after discarding. This short recovery time gives a conservative estimate of the ability to respond to predation as peak predator aggregation at a similar discard site occurs approximately 24 hours post discard (Kaiser and Spencer, 1996; Jenkins *et al.*, 2004). Although findings from a previous study on *Pecten maximus* by Jenkins and Brand (2001) implied escape response would not change much over this length of time as it showed little difference between response parameters 1 hour after and 24 hours after simulated dredging. Another limitation includes not controlling for epibiont cover as this can affect the ability of scallops to swim (Donovan *et al.*, 2003; Dijkstra and Nolan, In press). This may have confounded the results, although it was unlikely to have affected response in small scallops as observations in the field implied they were rarely fouled.

# Wider effects of target species discard mortality on the fishery

The effect that discard mortality has on the fishery is dependent on the absolute quantity of target species being discarded. As a result of low discard rates and low discard mortality rates the absolute number of individuals (/ha) suffering discard mortality were relatively small for each vessel. In fact the estimated numbers suffering mortality appear negligible when related to the number of individuals landed per hectare (LPUE, otherwise known as the accounted for fishing mortality), this was especially true for undersized scallops (Table 11a).

This suggests discard mortality will have limited effect on the population of *A. opercularis* around the Isle of Man and the fact there were so few undersized scallops dying suggests discarding will have very minor effects on recruitment in the fishery. However these statements depend on the scale of the fishery and the fishing effort of each gear type. Applying the discard quantities and their mortalities to fishery landings data (Appendix 1) gave estimates for total quantities of scallops (both undersized and landable sizes) perishing in the year 2010. Again these appear negligible relative to total landings (Table12b). The total weight of target-species discards experiencing mortality in 2010

was estimated at 100.9 tonnes, with 3.6 tonnes of this representing undersized scallops, this is an insignificant amount compared to the sum of all landings (12,790 tonnes). It should also be noted that 2010 will provide a high estimate of the number of discards suffering mortality per annum as the landings in 2010 were the highest they have been since the fishery opened (Murray and Kaiser, 2011)

Although trawls discarded the greatest quantities of target species they caused the least mortality per hectare which also transcended to the least per annum as well. Skid dredges had second the highest discard rate but caused the highest discard mortality per hectare. However the total mortality per annum was not highest. Modified dredges showed the lowest discard rate and although did not cause the highest discard mortality per hectare they did cause the highest mortality per annum as a result of this gear landing over four times the quantity of either of the other gears.

However due to low discard mortality and a negligible quantity of discards there is no reason to rank the effect of gear type. According to the figures presented in this study, mortality as a result of discarding is less than 1% (100.9/12,790 tonnes) of the total accounted for fishing mortality (including those suffering mortality through discarding) in one year of fishing. Of this 0.03% (3.6/12,970 tonnes) represents the proportion of undersized scallops suffering mortality through discarding. This means that relative to the total mortality in the fishery, discarding is unlikely to be having a noticeable negative effect on the population especially on recruitment to population.

# **Further limitations**

Values calculated from the proportion of discard quantities (e.g. mortality per hectare and mortality per annum) should be interpreted with caution as they are estimates (see limitations of Discard Quantities, above). Also caution should be placed on the skid and modified dredge figures for the total landings of *A. opercularis* caught in Isle of Man territorial waters in 2010. These boats are restricted to fish in territorial waters between the 1<sup>st</sup> June and 31<sup>st</sup> August so it is unlikely all landings are caught inside Manx waters. Also they were assumed to be respectively equal to the total dredger landings in the Isle of Man and the total dredger landings into UK. This can only be inferred because it is known the Kirkcudbright fishing fleet which operates these dredgers almost always lands in UK (Kirkcudbright) and the skid dredger almost always lands on the Isle of Man (Douglas). However accurate estimates of fishing effort and total landings are required for accurate predictions of the wider effects discard mortality. Measurements of fishing effort could be created from vessel monitoring system (VMS) data, as all vessels operating in the Isle of Man *A. opercularis* fishery

contain a satellite-tracking device. Using fishing effort from VMS data will provide a much more accurate picture of the exploitation and discard mortality in Isle of Man waters.

Although extrapolated to the wider fishery, data presented in this report only represents one fishing ground in Manx territorial waters. The East Douglas ground was chosen to avoid confounding habitat differences as all fishing gear types exploited this area and also because it was the most fished area in 2011 (Murray and Kaiser, 2011). Other fishing grounds may contain more undersized *A. opercularis* and discard mortality may have a greater effect on the pre-recruit population in these areas. It is important to look at habitat effects on mortality as this has been shown to effect scallop mortality in past studies (Shepard and Auster, 1991; Currie and Parry, 1999). Further studies should investigate the effect of habitat on mortality and in order to more accurately assess the wider impact discarding has on the population.

# **Further study suggestions**

Vause *et al.* (2007) has shown that fluctuations in the population density of *A. opercularis* are dependent upon the strength of recruitment. The negligible effects of discard mortality on undersized *A. opercularis* populations shown in this study suggest that discard mortality is unlikely to affect strength of recruitment in the fishery. Recruitment probability is affected by many other things including larval predation and starvation, oceanographic processes, and spawning population. Overfishing of stock population are probably more important issues and other factors such as abiotic (temperature, salinity, habitat) and biotic (food availability, predator abundance and competition) (Vause *et al.*, 2007). The combined effect of these factors will perhaps better explain recruitment variations, further study is required to disentangle these effects in order to understand how best to increase recruitment.

This study did not attempt to investigate other forms of collateral mortality associated with fishing that can result unaccounted fishing mortality. These include mortality as result of contact with the fishing gear either through target species passing through the gear or the gear passing over them on the sea bed (Broadhurst *et al.*, 2006). Jenkins *et al.* (2001) showed that levels of *P. maximus* damage on the sea bed were equal or greater than those captured and discarded, although their study was looking at toothed dredges. Other fisheries operating in this area may also be causing unreported mortality in *A. opercularis* populations. In particular the *P. maximus* fishery is the largest fishery operating in the Isle of Man territorial waters and it frequently catches *A. opercularis* as bycatch (Veale *et al.*, 2001). Also toothed dredges which are used in this fishery are known to be very destructive (Collie *et al.*, 2000; Kaiser *et al.*, 2006) and high mortality in the catch and on the sea bed is associated with this gear type (Medcof and Bourne, 1962; Shepard and Auster, 1991; Allison and

Brand, 1995; Jenkins *et al.*, 2001; Veale *et al.*, 2001). Veale *et al.* (2001) showed *A. opercularis* were always damaged with 80% of individuals sampled from bycatch have large cracks or holes (damage category 3 in this study). In this study and in Veale *et al.* (2001) individuals suffering this damage category were assumed to all suffer mortality. It is therefore likely discard mortality from this fishery will have an impact on the population density and recruitment of *A. opercularis*. Further studies should be carried out to quantify the proportion of *A. opercularis* discards from the *P. maximus* fishery and also look at mortality for a longer duration than was performed in Veale *et al.* (2001). Future studies could adopt the same methods as this study in order to quantify direct discard mortality of discarded *A. opercularis* including undersized.

#### **Management recommendations**

- Keep or increase minimum landing size
- Further study on survival of discarded A. opercularis from the King scallop fishery

The reasoning behind the first recommendation are that mortality was found to be low in this study especially for undersized scallops as they experienced less severe damage. Returning juveniles to the populations means they are likely to recruit to the population improving yield of the fishery.

Although the proportion of discards in this study were found to be low it is important to put in place controls such as minimum landing size (MLS) in case fishery practices change, e.g. processors request smaller queen scallops, overfishing and population reduction results in fishing down the year classes.

There is also an argument for increasing the MLS in order to further improve recruitment and improve quality of catch. For instance if a the MLS was increased to 55 mm, which is largely considered the minimum marketable size, the smallest *A.opercularis* (55 mm) would be at least 2 years old (Taylor and Venn, 1978). Therefore will have been more likely to have contributed to population and maintained yield as *A. opercularis* are reproductively active after 1 years old (Soemodihardjo 1974).

# Conclusions

In summary, this study revealed that whilst target species discards from the dredgers do incur the highest discard mortality, the low discard rates (although estimates) show this may have very little impact on the wider fishery. This is especially true for undersized scallops as there were very few in the discards and mortality rates were smaller as a result of small scallops suffering less damage.

Undersized scallops were also seen to be better adapted at avoiding predation after discarding further reducing their likelihood of mortality.

It is recommend that the minimum landing size (50 mm) is kept or even increased to further improve recruitment but also to protect undersized scallops if demand for smaller scallops increases. In conjunction with other studies (Wassenberg and Hill, 1993; Kaiser and Spencer, 1995; Montgomery, 2008) these findings further highlight that scallops suffer low discard mortality rates as well as showing differences in survival between gears. It is therefore suggested that the outright ban on discarding recently proposed in all fisheries operating under the EU Common Fisheries should be reviewed with respect to the fishing gears and species being discarded.

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# Appendix

Appendix 1. Isle of Man Government Fisheries Directorate summary document for the A. opercularis landings in 2010 (01/06/2010 – 31/05/2011)

Queenie Landing Figures 1st June 2010 - 31st May 2011 in kg's Liveweight						
IOM LAP	NDINGS OF QUEENS 5 and E5 37 on IoM System	UK LANDINGS OF QUEENS in E5 36 and E5 37 on UK system	PRECAUTIONARY LANDING FIGURES Advised by Bangor University	TOTAL LANDINGS TO DATE	LOW RISK LANDINGS REMAINING	% LOW RISK LANDINGS REMAINING
TOTAL	3578666.9	9211853.5	3970000	12790520.4	-8820520.4	-222.18
DREDGE	2009602.5	8746854.7		10756457.2		
TRAWL	1569064.4	464998.8		2034063.2		

The recommended precautionary landings of 4,000 tonnes is based on the stable abundance of queenies seen in surveys 2008 - 2010. An increase in recruitment in 2010 may mean that this figure can be increased. However with average or below average recruitment, catches over 4000 tonnes may endanger the abundance of the stock and lead to a reduced recomended landings figure in 2011, reduced catch rates and loss of MSC accreditation.



# Appendix 1. Summary document continued



# CD contains data and photos

End...