A dissertation submitted in partial fulfilment of the requirements for the Master of Science (MSc) in Marine Environmental Protection

1884

PRIFYSGOL
BANGOR
UNIVERSITY

Trialling innovative disruptive technology to reduce bycatch in the Isle of Man queen scallop (*Aequipecten opercularis*) trawl fishery

By Lucy Southworth
BAHons Fine Art 2015 Bath Spa University

School of Ocean Sciences Bangor University Gwynedd, LL57 2UW, UK

www.bangor.ac.uk Submitted in October 2017

DECLARATION

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

Candidate:

Date: 28/10/2017

STATEMENT 1

This dissertation is being submitted in partial fulfilment of the requirements for the degree of Master of Science

Candidate:

Date: 28/10/2017

STATEMENT 2 This thesis is the result of my own work/investigations, except where otherwise stated.

Candidate:

Date: 28/10/2017

STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available to outside organisations.

Candidate:

Date: 28/10/2017

Abstract

In the Isle of Man queen scallop fishery, bycatch species such as haddock cod and whiting have the potential to *choke* the fishery once the EU *landings obligation* is enforced in 2019. This study provides evidence that target catch can be maintained while reducing bycatch species. Commercial trials to develop species-selective trawl gear were conducted using a paired tow design whereby a control net is towed parallel to a treatment net with either: 1) a square mesh panel or; 2) a square mesh panel incorporating six white LED lights inserted into a traditional all diamond mesh otter trawl. The square mesh panel was found to be most effective in medium depths (29-40m) with high ambient light levels, significantly reducing lesser spotted catshark by 34% (P= 0.004) and whiting by 82% (P=0.008). While in these depths the net with both the panel and the lights observed reductions of whiting bycatch by 77% (P=0.01) and haddock by 55% (P=0.06). The panel plus lights in deep water (45-95m) with low ambient light levels, reduced bycatch of lesser spotted catshark by 48% (P= 0.04), flatfish by 26% (P=0.002) and haddock by 55% (P=0.001). Water depth was found to have a significant influence on the effectiveness of the devices to reduce bycatch of haddock (P=0.004). Strong but opposite linear relationships of haddock bycatch were detected between the two treatments with increasing depth. The square mesh panel incurred increases of haddock bycatch, while substantial reductions occurred with the addition of lights to the panel in deeper waters (P=0.005). However, no reductions of cod bycatch were observed in either treatment. These results indicate the importance of understanding species-specific responses to bycatch reduction devices and that determining the influence environmental parameters have on species catchability is key to establishing appropriate technical modifications to reduce bycatch.

Acknowledgements

I would like to express my gratitude to my supervisors, Professor Michel Kaiser and Dr Isobel Bloor, for their excellent guidance and support throughout the project, from conception to completion. Thanks also for the co-operation and efforts of the Manx Fish producers Organisation, in particular Dr David Beard for organising and assisting with logistical challenges during the sea trials and also skippers Melvyn Reid, Marshal Thompson and their crews for their tireless efforts and insight. The project would not have been feasible without the friendship and laughter that came alongside the stress and early mornings when working with the dream team both on the vessels and in the office – Frances Ratcliffe, Sian Morgan, Claire Lambden and Jack Emmerson. Special thanks go to Jack Emmerson for his motivational support and for lifting my spirits through the thick and thin. Thanks also to Adam Delargy and Jack Emmerson for their patience when helping me to get to grips with R. Finally, I would like to give a million thanks to my family and friends for their never-ending support and encouragement during the production of this thesis.

Table of Contents

List of tables

List of figures

Abbreviations

AICc	Akaike information criterion
ANOSIM	Analysis of similarities
ANOVA	Analysis of variance
BRD	Bycatch reduction device
CFP	Common fisheries policy
CHI	Chickens
CPUA	Catch per unit area
DEFA	Department of Environment, Food & Agriculture
EBM	Ecosystem based management
EDG	East Douglas
EU	European Union
FMA	Fisheries Management Agreement
GIS	Geographic information systems
GLM	Genearlised linear model
GPS	Global positioning system
ICES	International council for the exploration of the seas
IoM	Isle of Man
LED	Light emitting diode
LogRR	Log Response Ratio
MDS	Multi-dimensional scaling
MFPO	Manx Fiah Producers Organisation
MLS	Minimum Landing Size
MMS	Minimum Mesh Size
OSJ	FV Our Sarah Jane
QSC	Queen Scallop (*Aequipecten opercularis*)
RAM	Ramsey
RR	Response Ratio
SE	Standard error
SIMPER	Similarity of percentages
SMP	Square mesh panel
SMP+L	Square mesh panel and lights
TAC	Total allowable catch
TAR	Targets
TG	FV Two Girls
TL	Total Length (mm)
UTC	Coordinated Universal Time
WPUA	Weight per unit area

1. Introduction

The global issue of bycatch and discards

Current fisheries management advocate the use of the *ecosystem based management* (EBM) and part of that approach is the consideration of the issue of *bycatch*. *Bycatch* or *incidental catch* refers to the accidental capture of non-target marine animals and undersized target species, which typically cannot be avoided through technical spatial or temporal management measures, as target species live among other organisms (Crowder and Murawski 1998; Garcia 2003; Davies *et al.* 2009; Gilman *et al.* 2014; Boyle *et al.* 2016). The capture of these species subsequently results in the process of *discarding*; the release of unwanted animals of commercial and non-commercial value back into the sea alive, dead or dying (Catchpole *et al.* 2005b).

Principally, there is concern over discards as a waste of consumable and economic resources and a source of increased undocumented fishing mortality(Sigurðardóttir *et al.* 2015). Discards may negatively impact a fishery ecologically in the long-term, with unforeseen economic consequences (Grazia Pennino *et al.* 2014; Pennino *et al.* 2017; Kelleher 2005). The removal of non-target species can result in a shift in community structure, negatively affecting the total biomass, species composition and richness in the area (Bellido *et al.* 2011; Kelleher 2005; Pennino *et al.* 2017).

Fishers resort to discarding for a variety of reasons, which can be broadly categorised as a result of; 1) regulatory restrictions: for example quota may have been reached or no quota may be available, minimum landing sizes (MLS) or protected status attributed to certain species; 2) quality of catch: individuals may be contaminated or unfit for human consumption or they may be damaged on deck and; 3) value: the target-species catch may have little or no market value, resulting in *high grading* (when lower value catch are tactfully discarded to free up quota for higher-value catch to maximise profits (Clucas 1997; Kelleher 2005; Gilman *et al.* 2014).

In recent decades, the *bycatch/discards* issue has become a global economic and ecological concern. In 1994 Alverson *et al.* estimated that ~27 million tonnes of bycatch were generated annually. Although the apparent decline may be due to the differences in their calculations, an updated fishery-by-fishery study by Kelleher (2005) revealed that global fisheries bycatch was significantly less with an estimation of 7.3 million tonnes (8%) discarded annually, with over 50% of discards generated by trawl fisheries for demersal finfish and prawns.

The bycatch/discards process is currently in the hands of the individual fishers, through the decisions they make on how and where they fish, as well as the component of the catch they land or discard (Catchpole *et al.* 2005a; Catchpole and Gray 2010). However, ecosystem-based management requires that fishery managers quantify, analyse and incorporate the bycatch elements of a fishery into the management system to ensure sustainability. In light of this, the European Union have responded through implementing the *landings obligation* for all fisheries within EU waters, into the common fisheries policy (CFP) whereby the process of discarding *quota species* (which includes all fish and shellfish species that are managed by catch-limits set by the EU), will be banned by 2019 (EU Regulation No. 1380/2013 Article 26; EC 2013). This legal requirement aims to increase the documentation of bycatch as all target and non-target catch will be landed, so stocks can be managed realistically and to encourage fishers to avoid generating bycatch and subsequently reduce discards mortality.

This legislation requires the industry to either; i) hold sufficient quota to land the bycatch of quota species, ii) prove that the survivability rates of species once discarded is high enough to permit continued discarding of certain species (*survivability exemption*) or; iii) implement bycatch reduction strategies to eliminate or significantly reduce rates of bycatch (*de minimis exemption).* If the industry fails to achieve one of the three options, the accumulation of bycatch quota-species caught and landed under the obligation with insufficient quota, will result in the early closure of that fishery- a circumstance termed *choked*.

Effective ways to drastically reduce bycatch levels must be sought by both fishers and managers. In addition to bycatch restrictions such as the *landings obligation,* there are various mechanisms to reduce the capture of unwanted species such as; move on rules, real time closures, spatial closures, stricter enforcement and surveillance measures, as well as economic incentives for fishers to reduce discarding and retain their currently unwanted catch through expanding markets for lower value catch as a resource for animal consumption, fish meal/oils and aquaculture (Condie *et al.* 2014).

One method to reduce bycatch is the implementation of technological modifications to fishing gear to improve selectivity and avoid the capture of undesired species (Graham *et al.* 2007). These modifications to fishing gear are termed bycatch reduction devices (BRDs) and are utilized with the aim to encourage innovative shifts in traditional fishing methods, to reinvent the way in which target species are harvested to secure sustainable exploitation of the world's oceans (Net Positive Fishing 2016). Although, there has been an evident decline in discards over recent years, Hall and Mainprize (2005) estimated that it would be possible to further reduce bycatch from of 25% to 64% if the catching sector of the fishing industry utilize gear modifications demonstrated to successfully reduce bycatch in experimental studies.

BRDs in trawl fisheries to eliminate gadoid bycatch

There is increasing concern that trawl fisheries have poor target-species selectivity, with high rates of incidental catch. As a result, there are numerous studies that have trialled BRDs to reduce the bycatch of both undersized target species and non-target species (Broadhurst 2000; Hannah and Jones 2012). BRDs can be designed to manipulate the species of concern by one or a combination of two strategies, either i) select species *mechanically*, eliminating species by size or; ii) encourage escapement through exploiting differences in species *behaviour* (Broadhurst 2000). BRDs that select fish mechanically generally involve simplistic designs through modifying the geometry of the net, to separate larger and smaller species, through inserting panels or grids which exclude fish larger than the apertures of the openings within them (Broadhurst 2000).

Square mesh codends

The principal method in changing the selectivity through mechanical means is to modify the shape of the mesh, from knotted diamond to knotless square mesh, enabling bycatch to escape through the mesh (Robertson and Stewart 1988; Walsh *et al.* 1992). The way the two mesh designs stretch under load differs during trawling; diamond mesh tends to close up, whereas square mesh is hung in such a way that while towing the mesh stays open even under tension (Robertson and Stewart 1986). Robertson (1983) and Isaksen and Valdemarsen (1986) found that square mesh codends reduced the retention of juvenile haddock, cod and whiting. BRDs have variable effects according to the species in question, meaning a one-size-fits all approach to BRDs is not appropriate, particularly in mixed fisheries, where BRDs should be considered on a site and species-specific basis, as responses differ across species and fisheries. For instance, Robertson (1983) found that bycatch of whiting were reduced substantially more than that of haddock, which may be a result of whiting's body shape. Furthermore, a study to reduce juvenile plaice revealed that the square mesh codend consistently had a lower selection factor than the diamond mesh net, which resulted in an increase in discards (Walsh *et al.* 1992). In fisheries such as the Queensland scallop trawl fishery, square mesh codends have reduced total bycatch by 40%, while retaining the target catch (Courtney *et al.* 2008).

Square mesh panels

Square mesh panels (SMP) are another form of BRD that incorporates a combination of square and diamond mesh into the net in the form a strategically placed panel, typically in the top of the net. SMPs eliminate bycatch through both behavioural and mechanical manipulation, through exploiting the physiologies of target and non-target species. Bycatch species, such as gadoids have a higher motor ability than target catch such as scallops or prawns, allowing them to locate the panel and escape through it while the target catch remain in the lower sections of the net (Briggs 1992; Broadhurst 2000; Courtney *et al.* 2008). SMPs have been successful in reducing bycatch for over two decades, in North Atlantic, European and Australian fisheries (Karlsen and Larsen 1989; Broadhurst and Kennelly 1996; Broadhurst 2000; Brčić *et al.* 2016).

BRDs and the use of artificial light

The use of artificial light incorporated into BRDs such as SMPs in trawls has further reduced bycatch, through manipulating fish behaviour to increase net selectivity and increase the escapement of species (Lomeli and Wakefield 2014; Elliott and Catchpole 2015). Fish utilise visual stimuli for breeding, feeding and survival instincts (Lythgoe 1979). Lights may be used to either attract the animals towards the light (Ben-Yami 1988) or illuminate the BRDs to guide them out of the escape panels (Lomeli and Wakefield 2014). The use of light has been found to have a mixed effect in reducing fish bycatch and appears to be a tool that is very sensitive to species and site variations, as well as the configuration of the lights. For example, both Hannah *et al.* (2015) and (Maynard and Gaston 2010) conducted trials in which the bycatch species were increased by >50%. The increases in bycatch were attributed to the position of the lights on the nets, with the lights either rigged facing down on the footrope towards the seabed (Maynard and Gaston 2010) or the lights attached to the escape grate of a shrimp net (Hannah *et al.* 2015). However, when Hannah *et al.* (2015) attached the lights to the headrope of the net, they observed a 91% reduction in bycatch. These contrasting findings highlight the importance of undertaking research on a fisheries-by-fisheries and species-specific basis, as species behaviours differ between areas. Hannah *et al.* (2015) utilized green artificial light, as light absorption decreases in colours furthest away from the red end of the visible spectrum. Although absorption levels can be affected by aquatic particles like chlorophyll, algae, or plankton, minimal absorption is achieved with green and blue light (Schill *et al.* 2004). Therefore, blue or green LED lights have the advantage that they are more visible at longer distances compared to white light. However coloured lights have been found to repel fish (Marchesan *et al.* 2005), whereas fish tend to be attracted to white lights and therefore white light has the potential to guide fish through escape panels (Ben-Yami 1976; Lomeli and Wakefield 2014; Elliott and Catchpole 2015).

Bycatch in the IoM Queen scallop fishery

Discard rates are a function of each specific fishery and are determined by a combination of the gear utilized, the geographical area of deployment and the target species (Kelleher 2005). Studies have found that prior to the selection of the BRDs that will be most effective in mitigating bycatch on a site and fisheries specific basis, initially the quantification of bycatch compositions and discard rates of the fishery in question need to be obtained (Broadhurst 2000). The Isle of Man (IoM) is situated within the Irish Sea. The primary fisheries target shellfish using various fishing gears, including demersal otter trawls, dredges and pots. The Queen scallop (*Aequipecten opercularis*; QSC) fishery is targeted mainly using demersal otter trawls and is the second most valuable fishery to the islands economy. In 2015 a total of ~3,814 tonnes were landed from within ICES area VIIa (ICES rectangles 36E5, 37E5 and 38E5) with a value of £2,381,563 (MFPO *pers comms.,* 2017).

The IoM, although it is not a member of the European Union (EU), is a Crown dependency of the United Kingdom (UK) and has a fisheries management agreement (FMA) with the UK and by extension is subject to the EU's CFP and consequently the fishery will have to comply with the *landings obligation* from January 2019. The QSC fishery is managed by catch-limits set by the local Scallop Management Board (SMB), however it is not presently a *quota-species* within the EU. However, several EU quota species are incidentally captured in varying quantities in the IoM QSC fishery which makes it liable to conform with the *landings obligation*.

According to an assessment conducted in 2012 in the IoM QSC trawl fishery, bycatch levels as a percentage of overall catch including target species was relatively low at 7.4% (Boyle *et al.* 2012). However, under the *landings obligation* if this level is not reduced *as much as practically possible*, which would result in a *de minimus* exemption, there is a high risk that

the fishery will be *choked* and the fishery will close early or close altogether, due to low or unavailable quota for several species in the Irish Sea (ICES area VIIa).
The priority *choke* species (species with high levels of bycatch, for which the fishery holds insufficient quota) ranked in order from highest concern are skates and rays (*rajiformes)*, whiting *(Merlangius merlangus)*, cod *(Gadus morhua)*, Dover sole *(Solea solea)*, plaice *(Pleuronectes platessa)*, and haddock *(Melanogrammus aeglefinus)* (*pers comms* MFPO, 2017). However, skates and rays and flatfish species are considered to have high survivability and are likely to be exempt from the obligations through a *survivability exemption*. Subsequently, the remaining gadoid species whiting, cod and haddock are of highest concern due to high bycatch and low survivability. Therefore, experimental trials assessing the effectiveness of implementing an SMP were considered most appropriate for the IoM QSC fishery as an effective tool in reducing gadoid bycatch, with the addition of artificial light technology to facilitate escapement through the SMP. The SMP was chosen over an all square mesh codend, as the minimum mesh size (85mm) is larger than the MLS (55mm) for QSC. As a consequence, the use of square meshes in the entire circumference of the codend may have resulted in a loss of marketable catch.

Boyle *et al.* (2016) found that bycatch rates and composition differ from site to site within the IoM territorial sea, with significant differences found across all four of the fishing grounds with regards to mean weight of target catch, bycatch and species composition. This indicates that bycatch differs in each fishing ground and is influenced by the environmental parameters attributed to that ground (Michalsen *et al.* 1996). Therefore, this reinforces the importance in assessing the effectiveness of the BRDs on a site-specific basis.

Objectives and hypothesis

The objectives of the experiment are to test the effectiveness of different BRDs relative to a conventional QSC otter trawl. The BRDs utilized were:

1) a square mesh panel inserted in an all diamond mesh QSC otter trawl,
2) a square mesh panel with 6 white lights, inserted into an all diamond mesh QSC otter trawl.

Catches were quantified for the retention of target species and also key potential choke species: whiting *(Merlangius merlanus)*, cod *(Gadus morhua)* and haddock *(Melanogrammus* *aeglefinus).* Other bycatch species groups analysed were *Gurnard spp., Shark spp., Ray spp.* and *non-commerical roundfish.*

Hypotheses

H_1 Inserting a square mesh panel into the diamond mesh otter trawl will reduce overall bycatch abundance and weight of cod, whiting and haddock and the abundances of species groups *Gurnard spp., Shark spp., Ray spp.* and *non-commerical roundfish* relative to the standard commercial *control* net.

H_2 Inserting a square mesh panel into the diamond mesh otter trawl will change the length distributions of species including cod, whiting and haddock relative to the standard commercial *control* net.

H_3 Inserting a square mesh panel into the diamond mesh otter trawl will change catch rate by weight of queen scallop relative to the standard commercial *control* net.

H_4 Inserting a square mesh panel into the diamond mesh otter trawl will change the length distributions and proportions of undersized queen scallop relative to the standard commercial *control* net.

H_5 Attaching artificial lights into the square mesh panel will further increase escapement of bycatch species in both abundance and weight of cod, whiting and haddock and the abundances of species groups *Gurnard spp., Shark spp., Ray spp.* and *non-commerical roundfish* relative to the SMP-net and standard commercial *control* net.

H_6 Environmental parameters such as fishing ground, community assemblages, depth and ambient light levels, will change the catch rates of non-target bycatch, and individual quota bycatch species such as whiting, cod and haddock in both the SMP net and the SMP + lights net, relative to the standard commercial *control* net.

2. Methodology

2.1 Site selection

The commercial bycatch reduction trials took place within the IoM territorial sea across three QSC fishing grounds. The sites selected were Targets and Chickens, which are well recognised well recognised QSC fishing grounds, fished on a regular basis by the industry. Trials were also conducted within Ramsey Bay Marine Reserve which is a commercial fishing ground and currently contains high densities of QSC as the result of the management systems that pertains in the area.

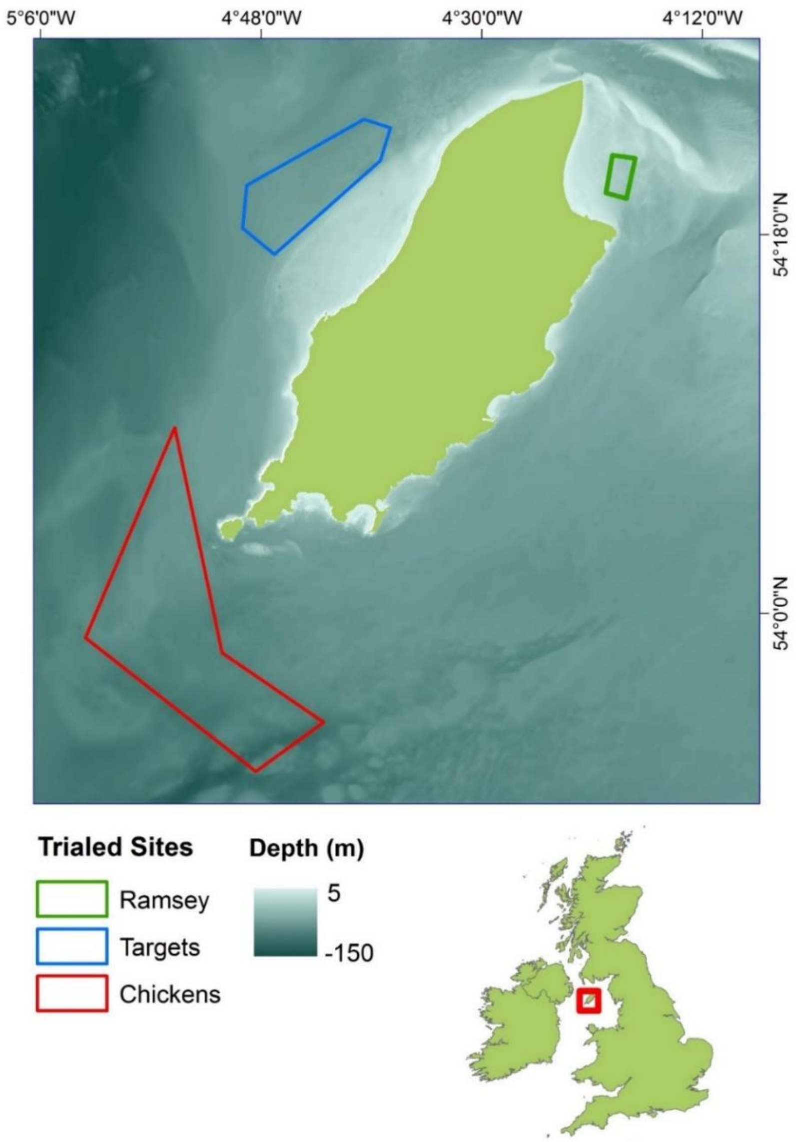


Figure 3 *Map illustrating the areas surveyed within the three fishing grounds (Ramsey, Targets and Chickens), the boxes indicate the area in which the tows were conducted during the commercial gear trials (data sourced from GPS loggers used on board the vessels). Bathymetry data is also shown as Depth (m) (Sourced from EMODnet.EU).*

2.2 Bycatch reduction device selection and configuration

After evaluating various forms of BRDs, the SMP was selected for the commercial trials in the IOM QSC fishery. The MFPO expressed confidence in the device as it had proved successful in other Irish sea trawl fisheries (such as the Irish Nephrops fishery), the Baltic sea and the North sea in reducing commercial gadoids such as cod, haddock and whiting (Briggs 1992; O'Neill *et al.* 2006; Herrmann *et al.* 2015), which from an industry perspective are the bycatch species of highest concern for the fishery. A small scale preliminary trial in 2016 investigated the effectiveness of a SMP (10x12 panel, of 150mm stretched square meshes) in IoM waters and indicated that the SMP could reduce the bycatch of round fish (cod and whiting) in comparison to similar boats using standard nets in the same ground. Although these findings were neither scientifically controlled nor published, they are considered anecdotal, the preliminary trial indicated that the SMP had the potential to reduce gadoid bycatch and thus prompted further investigation in a scientific commercial trial. The simplistic design of the SMP was considered beneficial, as it is more economically viable and practical to install.

Two configurations of SMP were implemented throughout the trial (Figure 3 b & c). The original SMP was manufactured by Atlanticweave Ltd. with a configuration of 20 meshes long and 12 meshes wide and this configuration was used throughout Targets and Ramsey. The vessels fished with this configuration during the commercial season, when the experiment was not taking place. During this period, the nets incurred significant damage when target catch-rates were increased. The increased pressure on the nets changed the configuration of the net such that the net chafed on the seabed and needed repair on a regular basis. As a result, the SMP design was modified and reduced to 8 meshes wide (20 x 8 meshes) (Figure 3c.), through lacing together 4 lengths of square mesh for the duration of the trial at the final site, Chickens. The size of the square mesh were 300mm stretched from knot to knot (150mm x 150mm). The forward perimeter of the SMP began 1.8m aft of the centre of the headrope and the aft perimeter of the panel was situated 0.5m from the anterior section of the codend (Figure 3b.). Previous commercial trials using SMP to reduce the catch of small whitefish have found that placement of the SMP nearer to the codend to be most effective in increasing fish escapement, as they tire and fall back into the codend (Broadhurst *et al.* 2002; Graham *et al.* 2003; Herrmann *et al.* 2015). Some studies inserted the SMP within the central column of the codend. However, when determining the optimum SMP position, the prevention of the loss of target catch through the larger meshes had to be considered. Due to the small scale of the QSC net and codend, placement within the codend was not feasible for our study, as the risk in loosing target catch was too high, resulting in the SMP being inserted just anterior to the codend (Broadhurst *et al.* 2002).

The LED lights were selected through discussions with SafetyNet Technologies Ltd. © (the fishing light manufacturers) and a literature search into the effect various light frequencies, colour and strobing have in manipulating the behaviour of gadoid species. The lights were programmed to emit constant white light (luminous intensity 33 cd (candela); voltage 3.1V). Six lights were deployed evenly within the SMP to ensure an even spread of illumination was emitted across the panel (Figure 3c). The LED lights were also chosen for several practical reasons. Due to their small, compact nature, they were clipped within the SMP without reducing the aperture of the square meshes, ensuring escapement rates would not be directly affected (Figure 2). The clipping system made the removal and attachment of the lights between tows an easy and quick procedure. The DPY100 casings were robust and had been previously trailed at depths greater than the IoM fishery operates (~700m), therefore the pressure rating for the units were reliable. The cases were also robust enough to withstand the net handling procedure used on the commercial vessels. The lights were inexpensive, with long lasting battery life of >25 hours in cold water.

***Figure 4** The white LED lights, and clipping system used to attach the lights to the square meshes within the SMP (Left; example of the LED lights and housing used) (pers comms SafetyNet Technologies), and the position in which the lights were attached the meshes (Right; photograph taken on board TG during the trials).*

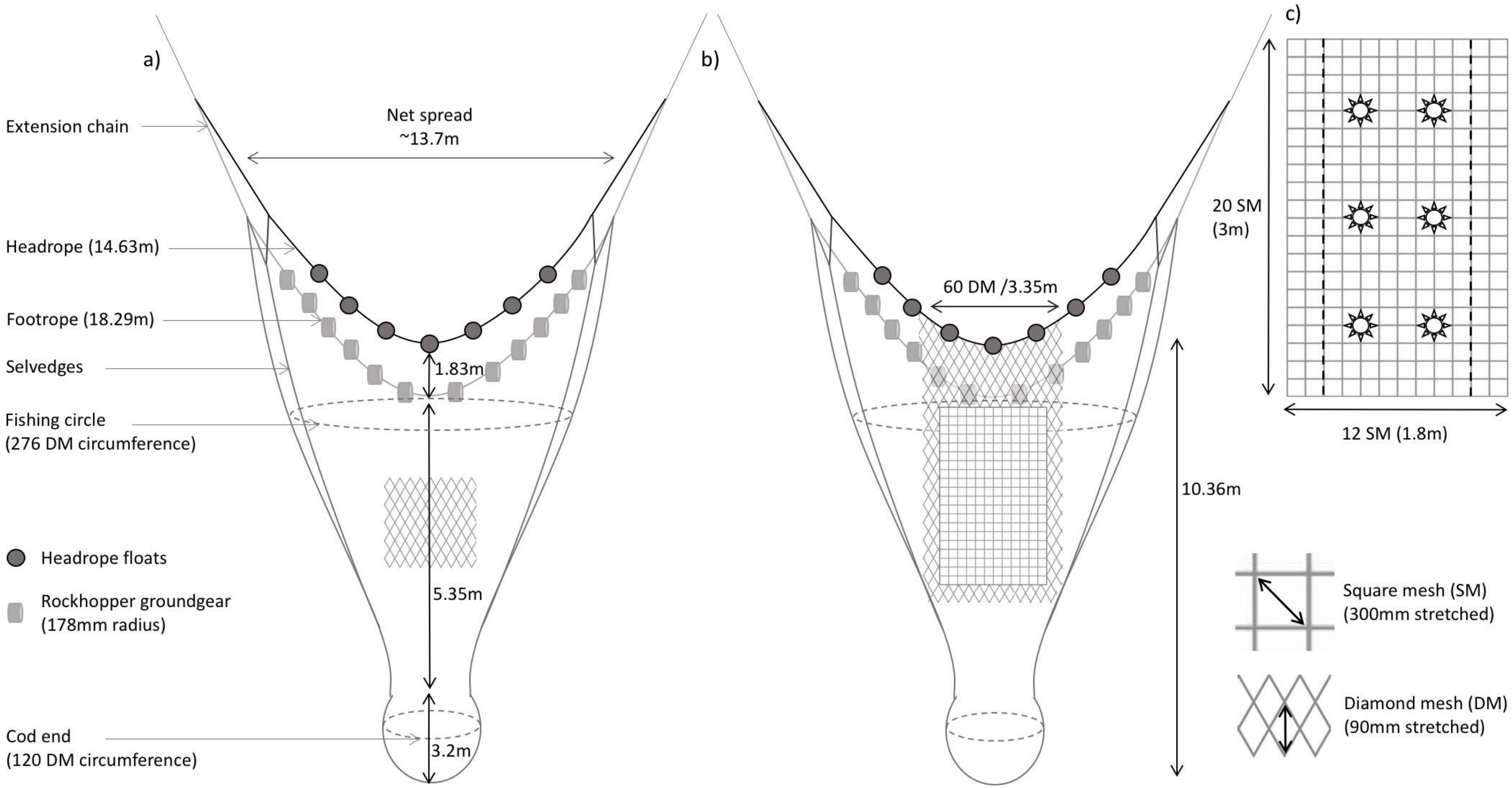


Figure 3 Diagrams of the nets used within the bycatch trial in the IoM QSC fishery 2017, illustrating the dimensions and configuration of a) the control net, a conventional all diamond mesh IoM QSC otter trawl net; b) the treatment net, which has identical dimensions and configurations to the control net, with the addition of the square mesh panel (SMP: 20x12M), inserted aft of the fishing circle (dashed circle near the mouth of the net) and; c) a schematic of the square mesh panel and the placement of the 6 LED lights (SMP+L). The dashed vertical lines indicate the perimeter of the modified SMP (20x8M) with 4 strips of square mesh were removed from the panel (two on either side) to alleviate damage incurred to the nets.SM =Square mesh. DM= Diamond mesh.

2.3 Gear and vessels

The commercial trials were conducted using two fishing vessels that actively participate in the IoM QSC fishery (Figure 4). Two vessels of similar size and power (enabling direct comparisons of the catch and BRD effectiveness) were selected for the trial. “Two Girls” (TG) has an overall length of 13.88m, with 216.24 kW engine power and “Our Sarah Jane” (OSJ) is 13.98m in overall length with a 187 kW engine. The use of the commercial vessels provided a more realistic representation of the conventional commercial fishing practices within the IoM QSC industry throughout the experiment. The vessels participating in the trial also had the incentive that the BRDs may be adopted by the fishery if they proved effective in reducing bycatch thus the modifications needed to comply with the current gear configurations of the commercial vessels.

Figure 4 *The two Queen scallop rock hopper stern trawlers utilized for the bycatch reduction trials, “Two Girls” (top), “Our Sarah Jane” (bottom). Both vessel are local IoM fishing vessels and were*

selected for the comparative trial as the two most identical commercial Queen scallop vessels in the IoM.

The nets used were two replicate conventional rock hopper otter trawls, unique to the IoM QSC fishery. The nets were identical to one another excluding the BRD modifications and it is therefore assumed that the two nets would have the same fishing ability and configuration when towing. The initial design produced by a local Manx net maker is illustrated in (Figure 3a.), with the fishtail set 'square' so that the end of the headrope and the footrope sit directly above one another (Figure 5). Members of the fishing industry and the skippers of the vessels were involved in the design and rigging of the nets. Any modifications made during the trial were replicated for both nets and vessels.

The nets comprised of diamond mesh (90mm stretched + 16mm knot) (Appendix 2), with a total length of 80.5 meshes from the footrope to the codend (~8.5m). The footrope is longer than the headrope, resulting in the headrope sitting 1.8m further forward of the footrope when towing, thus the top section of net (above the selvedges) is longer than the lower section (headrope to the codend ~10.3m). The fishing circle is immediately anterior of the SMP and is 276 mesh in circumference (bottom section 132 meshes + top section 144 meshes), while the codend circumference is 120 meshes (top 60 meshes + bottom 60 meshes). The rockhoppers used were ~14 inches in diameter, therefore the gear is towed ~7 inches above the seabed (Figure 5). The headrope height is estimated to be 3-4ft when towing (top section 40 meshes high + bottom section 35 meshes). Also note that the IoM QSC net differs to conventional fish or prawn bottom trawls, as the diamond mesh near to the mouth of the net are held open due to the wider spaced meshes (fewer mesh inserted across a certain area ie. 60 mesh into 3.34m) (Figure 3b.). This style of rigging is adopted to reduce drag and increase waterflow through the area, enabling easier more efficient towing (pers comms MFPO; Campbell *et al.* 2010). The twine material used in the top section of the net was 3mm thick compact polyethelene twine and 4mm thick compact double (two ropes tied together) polyethelene twine in the bottom section (Appendix 2). The use of double twine is needed in the lower section to strengthen the net, as this area is most prone to chafing and snagging. The selvedges join the lower and upper halves of the net together, an area which takes a lot of the strain and tension from the load of the catch, so they are reinforced through lacing meshes together with twine (8 meshes total) (Figure 3a). Both nets were spread using otter boards made from steel, Dunbar V doors (5-6ft)

(Appendix 3) and the headrope was kept buoyant with standard Nokalon trawline floats (Appendix 4). A tickler chain was not fitted to the mouth of the net.

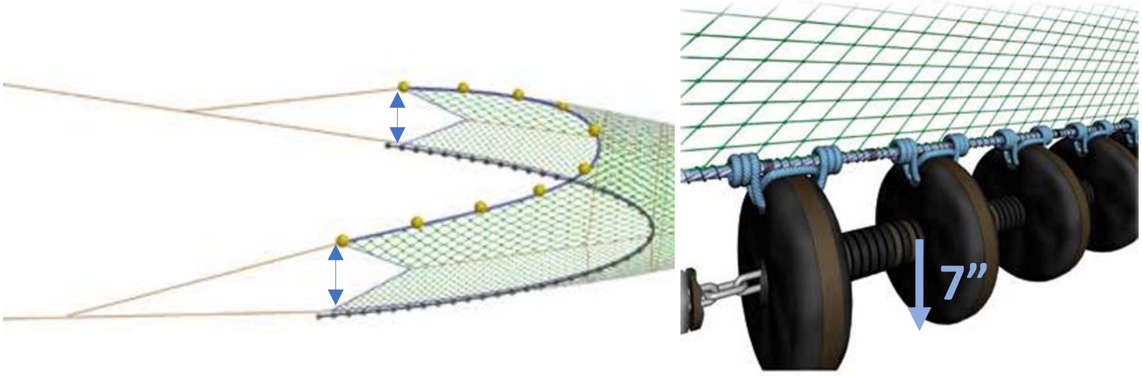


Figure 5 *Illustration of a ‘square set’ fish tail, with the headrope and footrope set directly above one another (Left) and; the rock hopper footrope, illustrating the height in which the footrope gear is towed above the seabed (Right) (Adapted from, Seafish 2015).*

2.4 Experimental design

The effects and selectivity of the two treatments; 1) inserting a SMP into a conventional all diamond mesh net and; 2) the effect of incorporating 6 constant white LED lights into the SMP, on both bycatch species and target species (QSC) catchability were evaluated in comparison to the conventional all diamond mesh net, across three fishing grounds during the commercial trial in the IoM.

The experiment consisted of a paired tow design, whereby the two vessels towed identical trawls simultaneously, one vessel fishing with the control net (conventional all diamond mesh net) and the other the treatment net (all diamond mesh with the SMP / SMP and lights inserted). The tows were conducted randomly and were decided at the discretion of the skippers to ensure normal fishing practices and safe commercial operations were achieved. The catches of the control and treatment paired tows were compared to evaluate the relative difference in catch of the two treatment trawls compared to the control, assessing bycatch species along with marketable and undersized QSC catch.

Each vessel towed the nets on the same bearing throughout the tows (generally into the tide when feasible) and the warp released was standardised at three times the depth. The vessels towed as close as possible to one another, while maintaining a safe operating distance, ensuring both independent but comparative sampling. The distance between the vessels was determined by the skipper on the day, depending on the sea state at the time of towing. The benefit of towing the two vessels simultaneously enabled a reliable assessment of the BRD performance as the variance in catches would be much smaller than tows conducted on the same vessel at different times and over different grounds, meaning spatial and temporal influences were reduced.

Trials were carried out over a total of 11 days, from June the 19th to August the 10th, during daylight hours which was typical for the fishery. Sampling occurred both before and after the commercial QSC season started and spanned across all tidal stages, with spring tides in mid to late June, neap tides in early July and low springs in August.

Commercial tow duration ranges from 1.5-2hrs, however tows were shortened to 60 minutes throughout Targets and Chickens, due to limited time to trial the BRDs with enough replication for a robust study. Tow duration in Ramsey was restricted to 30 minutes due to high densities of brittle star and kelp beds. Towing speeds were maintained at ~2.2 knots for all tows across the commercial trials.

To control for potential differences in catch efficiency between the two vessels and nets, the treatment (SMP net) and control (all diamond mesh net) were interchanged after every second day of the experiment. To achieve this in the most practically feasible and time efficient manner, both nets were fitted with a SMP of the same configuration and an interchangeable diamond mesh panel was sewn over the top of the SMP, with the latter configuration representing the control net. The vessel also switched from port to starboard periodically after every tow, to account for any effect of relative position of the boats, ie. if tidal currents were blocked by one vessel in the lee of the other.

To account for any environmental variation throughout the day affecting catch efficiency or composition, the two treatments (SMP/ SMP+L) were also changed sequentially, through removing the LED lights after every second tow (Table 1). This was not achieved on the 9th and 10th of August in Chickens, as the large sea state proved difficult to attach and detach the lights, resulting in an entire day of trialling the SMP alone on the 9th and SMP+L on the 10th minus the last tow of the day. Additionally, only the SMP treatment was investigated in

Ramsey, as preliminary analyses conducted in Targets indicated that in shallower water (with high ambient light levels), the SMP+L treatment was less effective. Therefore, to increase the replication of the SMP treatment, the SMP+L treatment was dropped in this site.

Table 1 *An example schematic of the sampling routine with the treatments changed periodically after every second tow from, square mesh panel (SMP) to square mesh panel+lights (SMP+L) on the treatment vessel, while the control vessel remained constant throughout sampling. The vessels posed as both the treatment boat and the control boat at different times throughout the survey (TG= Two Girls, OSJ= Our Sarah Jane.*

	Day 1.						**Day 2.**					
Tow	1	2	3	4	5	6	1	2	3	4	5	6
OSJ	SMP	SMP	SMP +L	SMP +L	SMP	SMP	SMP +L	SMP +L	SMP	SMP	SMP +L	SMP +L
TG	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl	cntrl

2.5 Sampling design

During the commercial trials, sampling of the catch and bycatch was undertaken on board the vessels and fish samples were also retained for laboratory analysis. Catch data was collected for each tow once the net had been hauled and emptied on to the deck or into the hopper.

Fish bycatch

Firstly, the bycatch was separated from the target catch and sorted roughly into baskets, grouped into *quota roundfish*, *rays and skates*, *flatfish* and *non quota species*. Individuals were then identified to species level, while all other catch such as invertebrates and debris were discarded. For Targets and Ramsey, abundance data were collected through counts of all bycatch species. While, size data were taken through recording total lengths of quota species (species assigned a TAC within EU waters (Appendix 5.), measured to the nearest 0.1mm using measuring boards. However, abundance and size data were recorded for all quota and non-quota bycatch during the trial in Chickens, due to extended time intervals between tows due to the greater depth and spatial extent of the survey site. Elasmobranch species such as rays, skates and sharks were the first group to be measured, identified and returned to the water. Flatfish were second due to high survivability rates attributed to these species relative to other bycatch species such as gadoids (Van Beek and Rijnsdorp 1989; Revill *et al.* 2005; Enever *et al.* 2009). A subsample of >50 individuals per quota species were retained for further laboratory analysis on the length~weight relationship for these species, so that length measurements made on board could be converted to weight per species caught.

Queen scallop catch

For length distribution analysis a subsample of 100 QSC per tow were measured at random using the first individuals encountered from a basket of the unriddled catch, with each individual measured to the nearest 0.1mm using electronic measuring boards (Zebra-Tech™), to determine the proportion of undersized QSC in the catch. The QSC were then sorted using the on board mechanical riddle, which eliminates undersized QSC and discards them automatically back into the water. The riddle consists of a rotating cylindrical barrel made up of steel bars and rings of a specific width and diameter, through which the small QSC fall once the riddle is rotating, forcing them down a plastic shoot overboard. Once the target catch had been processed, QSC were bagged and the number of bags of marketable QSC per tow were recorded (Appendix 7). The weight of these bags was further estimated using the average bag weight per day data provided by IoM fish processors, to use for analyses of the catch efficiency of marketable QSC.

Spatial records

Spatial data were recorded using GPS Route Logger Dongle, Geographical Positioning System loggers polling at 1 minute intervals, recording the position (co-ordinates, lat/long), speed (knots) and time (UTC), to determine the exact locations of the tows for further spatial analysis, such as swept area and depth. The position of the start and end location and time of each tow was also recorded on board the vessels by the skippers.

Environmental variables

In situ environmental observations that may have influenced the catch rates were recorded. Variables recorded per tow included sea state, as this may have affected the catch efficiency of the net, with measurements based on the Beaufort scale and cloud cover (%) as varying light levels above water may have affected visibility in the water column, and consequentially affect the escapement of bycatch species. Ambient light levels (lux) in the net, which may have been influenced by variation in depth were recorded with HOBO UA-002-64 64K Pendant Temp/Light Loggers (Tempcon Ltd.). The loggers were attached facing upright in the same position on both nets (30cm anterior of the square mesh panel), this position remained constant throughout the experiment. To ensure the loggers were robust enough for the deeper limits of the survey sites, the light logger chips were removed from their casings and were inserted into the housings used for the LED lights (Appendix 8). Therefore, the light loggers were calibrated prior to the experiment (see Figure 6) to allow for the adjusted sensitivity of the sensors due to the thick plastic housings. The calibration process comprised of an integration sphere, set to 6 different light intensities which were measured using a calibration light meter, to ascertain the true lux readings at the 6 intensities, to which the light logger readings were then compared to when inside the different housings.

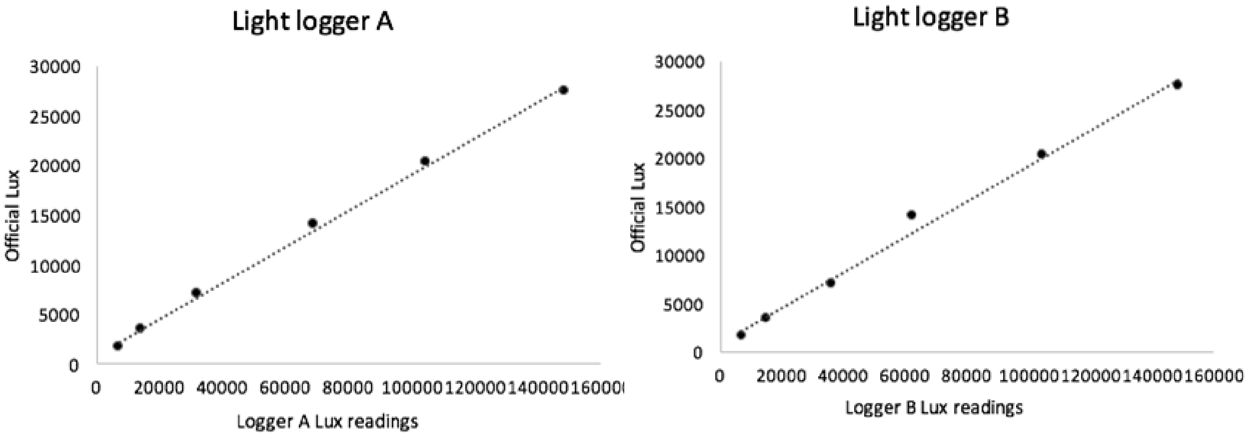


Figure 6 *Calibration coefficient for both HOBO loggers used in the survey (logger A and B), with the official lux readings recorded using a calibration light meter, correlated against the readings recorded by the loggers.*

Turbidity (m) was also measured using a Secchi disk, which was lowered into the water over the side of the vessel at the end of every tow, and the depth (m) recorded was the depth at which the disk was no longer visible when submerged vertically (photograph in Appendix 9).

General observations of the catch compositions were also noted and photographed, e.g. if large numbers of brittle stars were encountered, as this may have affected the catch efficiency of the trawl. Data on the tidal coefficient were also retrieved to analyse any affect the tidal state had on the catch rate throughout the survey, a mean daily coefficient was used for each day (data sourced from tides4fishing.com).

Video footage

The use of underwater video was also explored within the trial, to ascertain the behavioural responses and presence/absence of species encountering the net and associated BRDs. Two GoPro Hero 4 cameras were attached to a resilient plastic housing, 35cm anterior to the central part of the SMP. One camera was attached to the outside of the net and one on the inside, to capture the behaviour of species caught inside and species escaping or responding to the net from the outside. The number of tows recorded ranged from 2-3 a day, ensuring both treatments (SMP & SMP+L) were recorded. Due to the shallow depths and greater levels of ambient light in Targets and Ramsey, the cameras could be deployed without the need for any extra light sources to illuminate the net. However, as Chickens is substantially deeper, video could not be utilized at this site, as the visibility was extremely low, even when filming with the LED lights attached to the SMP. The use of extra light may have confounded behavioural reactions of the fish species to the BRDs therefore; video footage was not attained from this site.

2.6 Lab analysis

Length/weight relationship

Due to the fact TAC is measured by weight of landed catch, the length/weight of bycatch species of commercial interest were modelled to quantify the effectiveness of the BRDs to reduce bycatch by weight. Subsamples of bycatch fish species of commercial interest (species analysed are listed in Appendix 5) were returned to shore (~50 individuals per species, ranging in size). The length/weight relationships for these species were determined using linear regressions on log-transformed weight data. The weight of all quota bycatch species caught in each tow could then be estimated using the length data recorded on board the vessels. The total length (TL (0.1mm) of all individuals were recorded using measuring boards in the manner minimum landing size (MLS) are measured for teleost fish (tail to nose) (Appendix 10). The wet-weight of the individuals subsampled was measured on a laboratory balance (W, 0.1g).

2.7 Video analysis

Analysis of the video footage was used as an observational tool to assess the geometry and rigging of the net (how well the net is fishing), which enabled the fishers to modify the nets if needed. The footage was used as a tool to visually assess the variation in ambient light intensity at the depth of the nets. Anecdotal evidence through observations of species inside the net were used to indicate which species were encountering the nets and their subsequent escape responses to the BRDs.

2.8 Data processing

Spatial

In order to standardise catch and bycatch data to catch per unit area (CPUA), the swept area per tow was calculated using the GPS points recorded on board the two vessels. Using the tow start and end times recorded by the skippers, the GPS points were assigned to either ‘fishing’ or ‘not fishing’ and each individual tow could be defined by a *towcode* (vessel, date and tow no.). GPS points were then imported into ArcGIS (ESRI,v10.3) and converted into lines using the individual towcodes. The buffer geoprocessing tool was then implemented to convert towlines into areas, with the width of the buffer corresponding to the net spread ratio (0.75; the lateral spread as a percentage of headrope length) The net spread is the lateral distance the headrope spans when the gear is being towed (Sterling 2005).

Secondly, depth (m) data were also extracted from GIS raster bathymetry data (*EMODnet.EU)* using the *zonal statistics as table* summary tool, and the average depths across the whole of the individual tows were calculated. The depth across the tows conducted by the treatment vessel were imported into R (Version 1.0.153) as the explanatory variable to incorporate into further univariate analysis. Particle size data were also extracted from GIS raster layer in the same way to distinguish differences in environmental context between sites (White 2011).

Data manipulation

The raw dataframe (incorporating the bycatch, target catch and environmental variables) was imported into R. A dataframe was created to facilitate analysis that requires a single observation for each paired tow, such as generalised linear models (GLMs). The summed total weights (kg) per tow were estimated for those species for which a length/weight relationship was modelled.

The summed species data for each individual tow was then standardised by the swept area, so that the data represented the CPUA. Similarly, the weight-per-unit-area (WPUA) was also calculated in the same way, dividing the summed weight by the swept area. Unit area was displayed in hectares (ha). The calculations made are represented in equation below.

$$WPUA\ (kg\ ha^{-1}) = \frac{Estimated\ weight\ (kg)}{Swept\ Area\ (ha)}$$

$$CPUA(n\ ha^{-1}) = \frac{Count\ of\ individuals\ (n)}{Swept\ Area\ (ha)}$$

A dataframe was created that summarised the above by each paired tow, thereby presenting the control and treatment CPUA and WPUA within a single observation, so that the paired tows would remain paired in analysis conducted.

The data was calculated further to create a ‘response ratio’ (RR), where the treatment value is divided by the control value (CPUA or WPUA). Note that all WPUA and CPUA was transformed (+1) to account for zero values. The response ratio was then transformed by a natural logarithm (ln) to lessen the effect of outliers, referred to as the ‘log response ratio’ (LogRR), shown in the following equation.

$$LogRR_{Count} = Ln(\frac{CPUA_{Treatment} + 1}{CPUA_{Control} + 1})$$

$$LogRR_{Weight} = Ln(\frac{WPUA_{Treatment} + 1}{WPUA_{Control} + 1})$$

As a single value, the LogRR, then represents and quantifies the proportional change in catch rate due to the modifications to the net, within each treatment tow relative to the ‘paired’ controlled tow (Lajeunesse 2011; Sciberras *et al.* 2013) A logRR was preferred instead of an untransformed RR, as the transformation linearises the metric, ensuring changes to the denominator and numerator are treated equally (Hedges *et al.* 1999).

Environmental explanatory variables

Note that because the LogRR values correspond to two environmental observations (one per vessel) there are also two unique observations for each paired tow. In most instances, the observer for each environmental variable were kept constant to alleviate bias in assessing sea state and cloud cover. Exceptions included turbidity where the maximum Secchi value was selected from the two vessels. This was because the motion of the vessel or time restraints may have reduced the observers’ ability in recording the true visible measurements. Lux and depth were selected from the treatment vessel only. The depth recorded on the treatment vessel were chosen instead of the average depth between the control and the treatment paired vessels, as the effect depth has on the BRDs in the treatment vessel is deemed to be of greater importance.

Depth will have a greater influence on the effectiveness of the BRDs, in the treatment net due to the rate at which light dissipates vertically, whereas varying light levels in the control net will have had less of an effect on the escapement of species, due to the lack of escape routes. The difference in the depth at which the nets are towed between paired tows (Control – Treatment Av. depth) due to variations in bathymetry (referred to as depth difference), was also calculated to test whether the difference in depth between them had a significant effect on the observed catch rates of QSC and bycatch species. Only one light-logger was utilized during the majority of the trial due to equipment failure in Targets and the sensitivity of the working logger was found to be incapable of detecting low natural ambient light levels. Therefore, the working logger was deployed on the treatment net to account for the differences in light illumination caused by the use of the LEDs.

Analysis were only performed on tows where the species being investigated were present. Therefore, data were removed if the CPUA for both treatment and control nets were recorded as 0. The process was repeated for different subsets species encountered, so that the LogRR values could be investigated within several analyses.

Marketable Queen scallop catch

Utilizing data collected from Chickens and Ramsey, the catch rate of marketable QSC were analysed. These sites were selected for target catch analyses as in these areas the catch were consistently riddled (under normal fishing operations the skipper would have discarded the catch due to a high proportion of undersized individuals). To estimate the amount of commercial-size QSC retained, the total number of filled standard commercial bags were multiplied by the weight of an estimated average QSC bag of ~35kg each (MFPO *pers comms*). The number of bags per tow were converted into WPUA/ha (see *Data manipulation* above). The raw WPUA values were then grouped into SMP, SMP+L or control and converted into logRRs in the same manner that the fish bycatch data were converted.

Undersized Queen scallop catch

The proportion of undersized QSC per tow were estimated via the randomly selected subsample of unriddled catch measured on board the vessels (100 individuals/tow). The length/weight relationship was applied to the height of each of the individual QSC measured on board the vessels. Historically, the data collected for QSC has been the height of the carapace, however the MLS for these species refers to the width of the individual, therefore to assess the proportion of the catch of undersized QSC height was converted to width. The height measurements were converted using a width/height conversion formula previously calculated in 2011 on QSC catch from IoM waters (the predicted widths using the measured heights are on average within 1 mm of the actual measurement) (Figure 7). The individuals were then categorised into undersized (55mm and <55mm width) and oversize (>55m width) based on the estimated widths. The estimated weight(g) of QSC <MLS and >MLS were calculated for each subsample per tow, which was converted into a proportion (%).

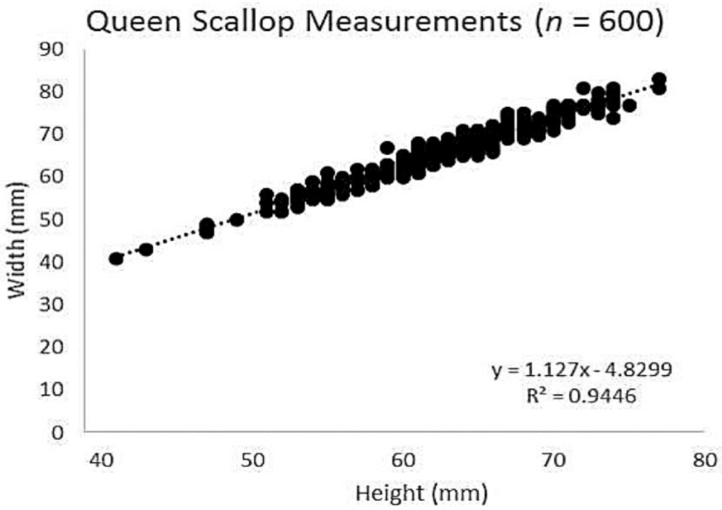


Figure 7 Total shell height/width (mm) relationship for queen scallop (*Aequipecten opercularis*) modelled on data collected in 2011 in the waters around the IoM (graph supplied by DEFA).

2.9 Statistical Analysis

Site community assemblage and environmental context analysis

Community structure for each fishing ground as assessed from the control tows at each of the three sites fished throughout the trial. The count data of all species caught in the control tows across all sites were combined into the abundance dataset (total count of each species/tow) and were uploaded into the ecological software package PRIMER v.7 (Clarke and Warwick 1994).

The abundance data were square root transformed to appropriately weight the influence of common and rare species and to down-weight the effect of outliers. The transformed abundance data were converted into a Bray-Curtis index of similarity matrix, from which CLUSTER analysis was applied, through the creation of multi-dimensional scaling (MDS) ordination plots. MDS scatter and 2-dimensional bubble plots were used to visually interpret the differences and similarities in community assemblages, both among and within each individual trialled site. An analysis of similarities (ANOSIM) was implemented on the abundance resemblance matrix, to test whether site significantly affected the percentage similarity of the community assemblages (999 permutations). Pairwise tests were applied to detect which sites were significantly different from one another. To lower the risk of type I error, in all tests the threshold α=0.05 for significance was used. Significant differences in community assemblage of bycatch between sites were further investigated using Similarity of Percentages (SIMPER) analysis. SIMPER ranks species in order of dominance within sites, revealing which species contribute to the most similarity within the tows for each site, and in turn indicates the species that characterise each site. Further, SIMPER calculates the dissimilarity between aggregated site community data and presents the relative percentage contributions for each species driving the dissimilarity between each site. MDS plots were used in conjunction with the SIMPER output to detect patterns within the abundance data to inform further analysis. Species that contributed most to the dissimilarity between the sites were overlaid on to the abundance MDS scatter plot, using the 2-dimensional bubble feature to assess at which sites species were encountered most and to determine which fishing grounds should be used in intra-site analyses.

Data from several species were aggregated to increase sample size and statistical power, where it was appropriate to do so. For instance, poor cod *(Trisopterus minutus)* and pouting *(Trisopterus luscus)* were aggregated and analysed independently as *Non-quota gadoids.* Data were aggregated to assess the effectiveness of the BRDs on these selected species as they are considered the most likely to escape due to their physiology and behavioural responses. *Rays and skates, flatfish, gurnard species and shark* species, were aggregated and analysed on an intra-site basis, as the composition of each aggregated group may differ across grounds, which would invalidate inter-site analysis. These species were also aggregated as they share similar physiologies and would therefore be expected to respond in a similar manner to the BRDs. At present, rays and skates are aggregated by fisheries managers and considered under a single TAC-quota, which further justifies aggregating the data in this way.

Species of highest concern with regards to the landings obligation, such as *quota gadoids* (cod, haddock and whiting) were further assessed using the sites in which they were encountered in the highest abundances, regardless of whether they were reported as species with high similarity in the SIMPER results, due to the need to assess the effectiveness of the BRDs on these species.

Univariate analysis

Univariate statistical analyses were run in 'R' (Version 1.0.153). The data used to conduct all statistical models and analyses (such as GLMs and ANOVAs) were tested to check the appropriate assumptions were met. Models were inspected for normality of residuals using the Kolmogorov –Smirnov test and inspected visually using a Q-Q plot. Cook's distance plot was used to check for outliers, while heteroscedasticity was tested using the Levene's test and scatter plots of the standardized residuals, fitted values and all covariates were assessed. In the case of GLMs the diagnostics of the averaged model was plotted after the best AICc models were selected, using the statistical packages "arm" and "MuMIn" in R.

Length/weight relationships

The equation and power function $W = aL^b$ (King, 2007), was fitted to the natural log(ln) transformed weight(g) and length (total length (0.1mm)) data, where *W* is the weight (g), *L* is the TL (mm), and *a* and *b* are constants. Linear regression determined both the slope of the regression lines and the coefficient values (*a* and *b*) and generated the R^2 goodness of fit values for fish bycatch species. The same equation was fitted to a subsample of 400 QSC which were retained from the unriddled catch on board the vessels, to estimate total weight of target catch caught, however in this case ***L*** (TL) refers to total shell height.

Vessel effect analysis

To ensure there was no effect of vessel or observer influencing the catch rates in either the control, SMP or SMP+L treatments, analyses were conducted on the control tows in which species were encountered on both vessels TG and OSJ. To ensure there was no variation in the catchability of bycatch species in either vessels, the three main quota gadoids of concern were grouped (haddock, cod and whiting). TG and OSJ fished as the control boat in both Targets and Chickens, therefore vessel effect analysis utilized tows that encountered either of the three gadoids in these sites. The average CPUA/ha of the gadoids caught in unique tows by TG were compared to OSJ in a two-way ANOVA incorporating both factors site and vessel. The same process was implemented on *all bycatch species* in Targets.

The same approach was used to assess whether the catchability of marketable QSC differed between vessels, using data collected from Chickens where consistent riddling occurred and both boats fished as the control. The QSC size data were analysed to ensure no vessel or observer biases were influencing the size comparisons of QSC in each treatment. Analyses were employed on the control tows for both OSJ and TG and were separated by site. The mean of the grouped QSC size averages per tow were then compared between vessels using a one-way ANOVA and tukey HSD *post hoc* testing was used to investigate where (if any) differences lay.

Queen scallop catch

Intercept only linear regression models were conducted on the logRR of the retained bags of QSC (WPUA) to test whether the catch rate of marketable QSC caught in both treatments nets differed from the control (ie. 0). Generalised linear modelling assessed whether any environmental parameters influenced the catch of QSC in the SMP and in the SMP+L treatments. The global GLM that was fitted to the logRR (WPUA) caught within the paired SMP tows in both Ramsey and Chickens was:

glm(logRRWPUA ~ tidal strength + depth + sea state + site)

Multi-model interference techniques were used to extract the best set of models that could explain the response (logRR) with the explanatory (environmental) variables. This method of predicting an averaged model across a selection of the most appropriate models used to explain the data was preferred over a stepwise multiple regression approach, as stepwise approaches increase the chance of biases in parameter estimations, incur inconsistencies within model selection algorithms and rely on the inappropriate need to select a single top model. Whereas multi-model averaging techniques include the inference of numerous models that could describe the data equally well (Whittingham *et al.* 2006).

Initially a global model was created, incorporating all environmental variables that may have affected the catch of QSC (depth(m), sea state(bft), tidal co-efficient and site). The models were then ranked using the AICc, which compared all combinations of the explanatory variables in the global model and selected the top ranked model and all models within 2 AICc values of that model. These sets of models were then averaged, so that all the best models were considered in the reported model, with a Gaussian distribution.

Size analysis was conducted using the data collected on board the vessels. The mean average height of the ~100 individual QSC measured on board the vessels from each tow were calculated by control, SMP and SMP+L. The control tows were paired with their corresponding treatment tows and T tests were conducted on the pairs, using the paired t-test to test for significant differences in the size-structure of the target-species.

Species sharing similar physiology

The following grouped species: *Non-quota gadoids, rays and skates, flatfishs, Gurnard spp., Other shark spp.* and Lesser spotted catshark (*Scyliorhinus caniculata)* were analysed using linear models to investigate whether each group differed in response to the SMP and SMP+L treatments. Initially, ANOVAs in the form of a lm(logRR~ treatment) were conducted on the logRR of the CPUA of both levels (SMP & SMP+L). This determined whether the relative response values (logRR) significantly differed between treatments, indicating whether the grouped species have significantly different responses depending on which treatment they encountered. Secondly, intercept only linear models were carried out on the subsets of SMP logRR values and SMP+L logRR values, to distinguish whether the CPUA in each treatment significantly differed from 0 (i.e no difference between control and treatment).

***Choke* gadoid bycatch species**

The three quota gadoids of highest concern (haddock, cod and whiting) were analysed through the same process. Initially, differences in LogRR of both the CPUA and WPUA were visualised graphically for each species within each site, to assess any relative effects the BRDs had on the catch rates of the bycatch species.

ANOVAs were used to test whether the intercept of two independent distributions (logRRs of CPUA/WPUA in either the SMP or SMP+L treatment) were significantly different from 0, explained by the function lm(logRR~treatment). The ANOVAs were implemented to assess whether the average relative CPUA/ WPUA for the paired tows conducted in either treatment (SMP +SMP+L) differed significantly from the intercept (ie. 0 or the control net). The analyses were conducted on an intra site level at the sites in which the species under investigation were encountered most frequently.

The logRRs were plotted against the environmental variables, to visually assess whether any correlations were present. If correlative relationships were present, linear regressions were fitted to the data and the slopes and coefficients of the lines were analysed and compared accordingly. ANOVAs were used to compare the slopes of any regressions present, once the assumptions of homogeneity and normality were checked.

Furthermore, GLMs were fitted using the same multi-model inference approach (with Gaussian family distribution), which was implemented on the QSC catch data. However these models incorporated all the environmental variables.

The initial global models created and conducted on both treatments and bycatch species subsets were:

glm(logRR CPUA~ cloud cover + depth + depth difference + tidal strength + ambient light level + turbidity + sea state)

Factors site and vessel were not included in the global model, as both site and depth were considered to be confounding variables, as depth differed distinctly between each site. The models were fitted to subsets for each treatment (SMP and SMP+L) so that the analysis could be conducted independently of one another.

3.Results

3.1 Lab analysis

Length/weight relationships of Queen scallop and bycatch species

A total of 668 individual bycatch fish species and 400 individual QSC were analysed in the lab to determine the length/weight relationships, of which all species presented were retained in sufficient numbers for analysis (Figure 8, Table 2).

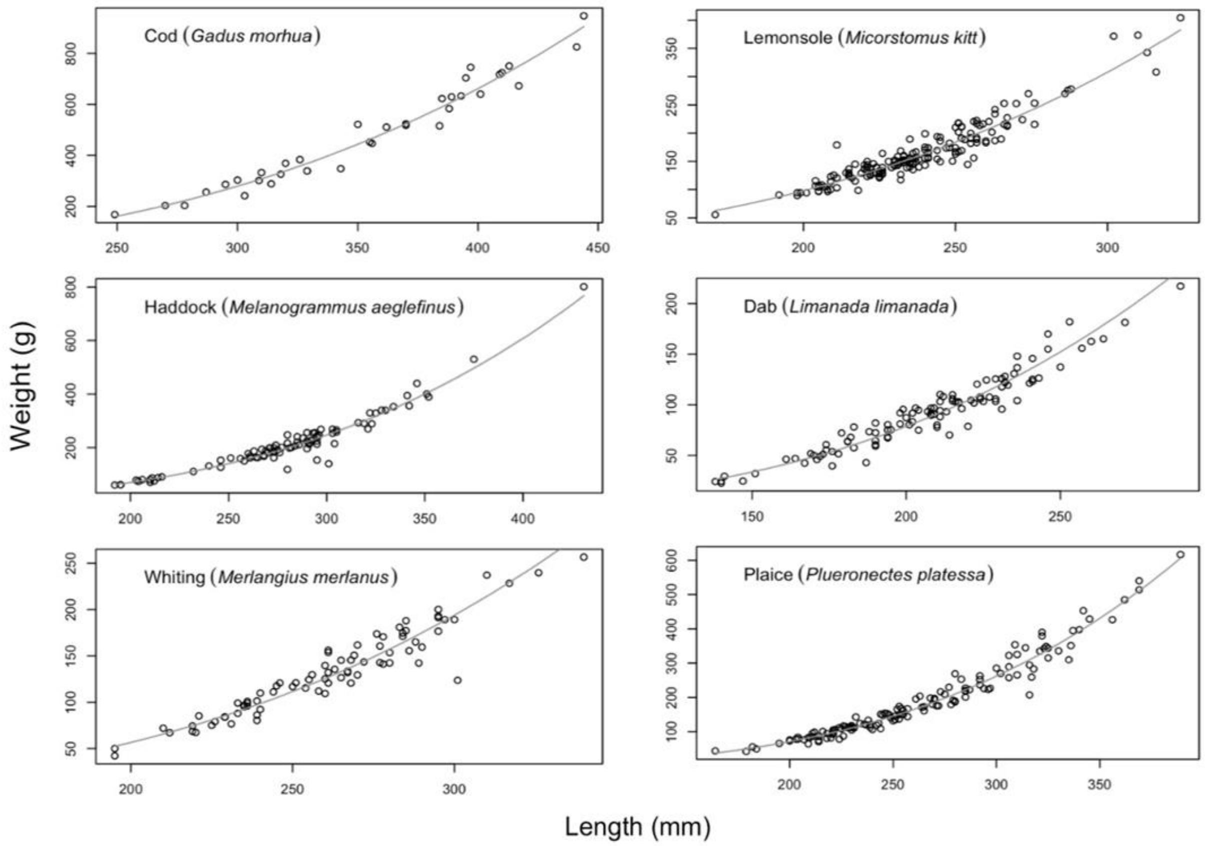


Figure 8 *The total length (mm)/weight (g) relationship of bycatch species caught and retained from in the IoM QSC fishery (2017) including; haddock, cod, whiting, lemon sole, dab and plaice.*

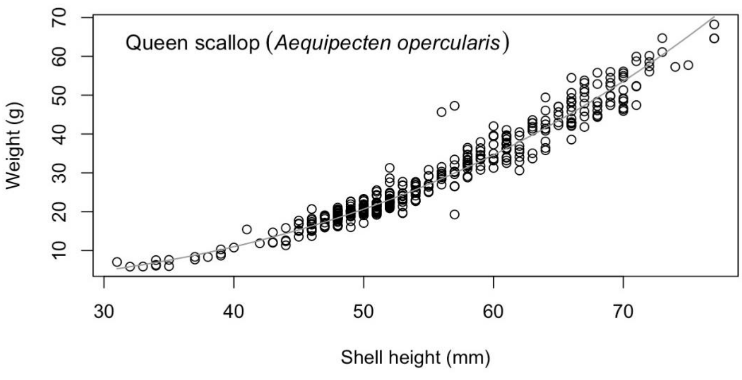


Figure 9 *The length (total shell height) (mm)/weight (g) relationship of queen scallop caught and retained from in the IoM QSC fishery (2017).*

Table 2 ***Length weight Factors (a and b) used in the length weight equation for fish bycatch species and Queen scallop, R^2 goodness of fit values for each subsample of fish species, number of individuals per subsample of bycatch species (n) and the transformation used in the linear equation which determined the factor values***

Species	**Factor**				
	a	**b**	**R^2**	**n**	**Transformation**
Lemon sole *(Micorstomus kitt)*	-10.407373	2.829204	0.8936	172	ln
Dab *(Limanda limanda)*	-11.303324	2.957324	0.9298	107	ln
Plaice *(Plueronectes platessa)*	-12.824653	3.224888	0.9652	138	ln
Whiting *(Merlangius merlanus)*	-12.038805	3.034202	0.9176	79	ln
Haddock *(Melanogrammus aeglefinus)*	-12.32826	3.12748	0.9407	89	ln
Cod *(Gadus morhua)*	-11.487862	3.001368	0.9671	35	ln
Queenscallop *(Aequipecten opercularis)*	-8.08176	2.831494	0.9599	400	ln

3.2 Overall trial results and sampling effort

Across the 11 days trialling between the 19^{th} of June and 10^{th} August, a total of 141 out of 142 individual tows were valid. The excluded tow was the first tow in Ramsey where OSJ caught an excessive number of brittle stars, resulting in the catch being discarded before hauling, as it was unsafe to haul and empty the catch on board, due to heavy listing. Therefore, there was a remaining 70 successful paired tows in total (70 tows from both OSJ & TG) (Table 3).

Table 4 gives an overview of the towing criteria attributed for the paired tows and treatments across each site. Overall a total of 10,234 bycatch individuals were caught across the three sites, with 939 (9.18%) individuals caught in Ramsey, 4441 (43.4%) in Targets, and 4853 (47.42%) in Chickens. All species encountered during the trials are listed in Appendix 5, with the quota status for each species. The catch of commercial sized QSC were considerably low compared to catches experienced during standard commercial operations in the IoM QSC fishery. Subsequently, the influence that large catches of target species have on the composition and quantities of bycatch species could not be used as a factor to explain the variation in catch rates of bycatch species (Table 4).

The sampling effort of the trial spanned across a variation in tidal strength, the majority took place around spring tides (for Targets and Chickens), with the exception of the first two days in Targets occurring on neap tides as well as the two days sampling in Ramsey Bay (Figure 10). Tidal strength is a known factor that influences fish catchability, therefore the variation in tidal co-efficient is worth noting (Michalsen *et al.* 1996).

Table 3 *Details of the successful paired tows conducted in each site across the IoM for both treatments, square mesh panel (SMP) and square mesh panel with lights (SMP+L) (See Appendix 11 for full details per tow).*

Survey site	Dates	No. of paired tows	
		SMP~ control	SMP+L~ control
Targets	19th -22nd, 26th & 27th June	19	21
Ramsey	3rd & 4th July	12	0
Chickens	8th – 10th August	9	9

Table 4 *Tow characteristics described for each paired tow across all three sites, indicating the treatment (square mesh panel or square mesh panel + lights), the total no. of tows, mean warp(fa), mean tow duration(min), and mean speed per site(km^{-1}). Environmental parameters are displayed as total/mean swept area(ha^{1}), mean depth(m), for the grouped control and treatment tows for each treatment per site. Catch data on the total no. of bycatch species and total and mean no. of QSC bags caught in the control and treatment groups per treatment in each site are also reported.*

Site	**TAR**		**RAM**	**CHI**	
Treatment	SMP	SMP+L	SMP	SMP	SMP+L
No. of tows	19	21	12	9	9
Tow duration (min)	60.35		29.75	62.83	
Mean speed (knots)	2.35		2.85	2.33	
Warp (m)	130		40	75	
Mean swept area (km)	C= 61167.35	C=63519.74	C=28661.77	C=64565.48	C=68142.52
	T=60854.56	T=63117.69	T=29833.65	T=64310.50	T=68843.82
Total swept area (km)	C=1162179.63	C=1333914.52	C=343941.26	C=581089.30	C=613282.70
	T=1156236.69	T=1325471.54	T=358003.81	T=578794.51	T=619594.41
Mean water depth (m)	T=-34.25	T=-33.46	T= -15.89	T= -65.64	T= -64.6
	C=-34.23	C=-33.54	C=-15.88	C= -66	C= -63.65
Total no. of bycatch species	C=1169	C=1297	C=527	C=1121	C=1373
	T= 913	T=1062	T=414	T=1450	T=909
Av. No. of QSC bags per tow	C=1.18 T=1.14	C=0.9 T=0.83	C=3.42 T=3.5	C=1.06 T=0.77	C=3.66 T=1.17
Total no. of QSC bags	C=22.5 T=21.75	C=19 T=18.75	C=41 T=42	C=9.5 T=6.9	C=16 T=10.5

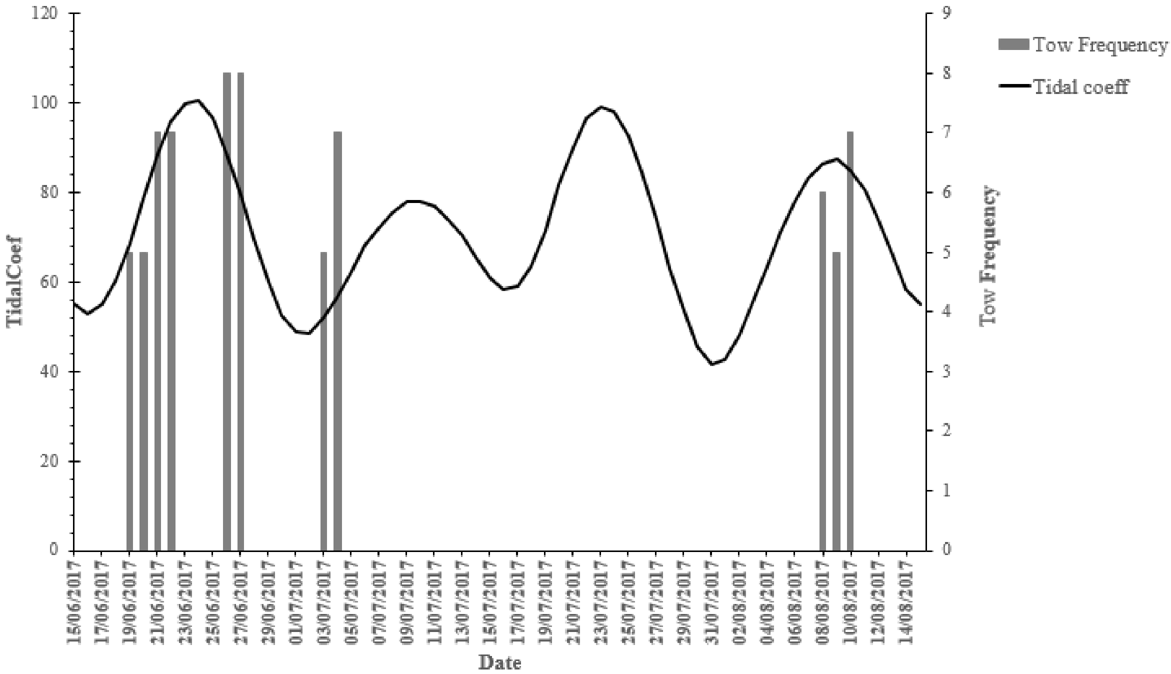


Figure 10. *The sampling effort across the summer of 2017 at different stats of the tidal co-efficient. The solid line shows the tidal cycle throughout the sampling period and the bars indicate the number of sample tows conducted each day (Tides4fishing.com). (See Appendix 1 for the tidal stream strengths.)*

3.3 Community assemblages and Environmental contexts per site

Species composition

The MDS plot based upon community structure of bycatch (species count) caught in the control nets alone, indicated that the species assemblages differ between sites (Figure 11) ANOSIM pairwise testing conducted on the species abundance data (count/tow), showed that all sites differed significantly from one another in species assemblage (Table 5). The MDS ordination plots for the three main choke species of concern in the IoM (haddock, cod, whiting) display the distributions of the species overlayed on the clustered community composition (Figure 12). These plots show that the distribution of cod is concentrated within Targets. While haddock were widely distributed and frequently encountered, with the largest catches recorded in Chickens, fewer in Targets, and lowest in Ramsey. Whiting, too have a wide spread distribution, however the catch rates of whiting were much lower than haddock.

Table 5. *ANOSIM pairwise test results showing the similarity of community assemblage (average species) between sites (TAR = Targets; RAM = Ramsey; CHI = Chickens). * indicates statistical significance (p < 0.05). Global R = 0.596, sample statistic p-value = 0.001.*

Bycatch species composition (abundance)		
Sites	**R statistic**	***p*-value**
TAR-RAM	0.55	0.001*
TAR-CHI	0.56	0.001*
RAM-CHI	0.82	0.001*

Although, ANOSIM revealed that all three sites differed significantly from one another when considering the entire community assemblage, there were several species that were commonly caught within all three sites, namely lesser spotted catshark, dab and plaice. This result reveals that these species are present across all three fishing grounds. Lemon sole and haddock were only encountered in low numbers in Ramsey, although they were consistently caught in Targets and Chickens, while red gurnard was encountered in Ramsey and Chickens.

Species that were found to contribute to the similarity within a single site, for instance, species found most consistently in Targets alone were grey gurnard, whiting, squid, spurdog and thornback ray. In Ramsey, species frequently encountered included tub gurnard and john dory, whilst Chickens was characterised by bull huss and poor cod. Species that were found to contribute most to dissimilarity between sites were plotted in MDS bubble plots and visually assessed to locate where these species were encountered the most (Appendix 12). Pouting were found to be encountered principally in Targets in low numbers, with few caught in Chickens and zero caught in Ramsey. Similarly, monk fish and cod were encountered most frequently in abundance at Targets, with low, less frequent catches in the other areas. Thornback ray, spotted ray and cuckoo rays data were encountered in low frequencies across the control tows in the trial, with the highest densities encountered in Targets. While carachiniforme species other than bull huss and lesser spotted catshark were encountered infrequently, starry smoothhound, smoothhound and tope were encountered in the highest densities in Chickens.

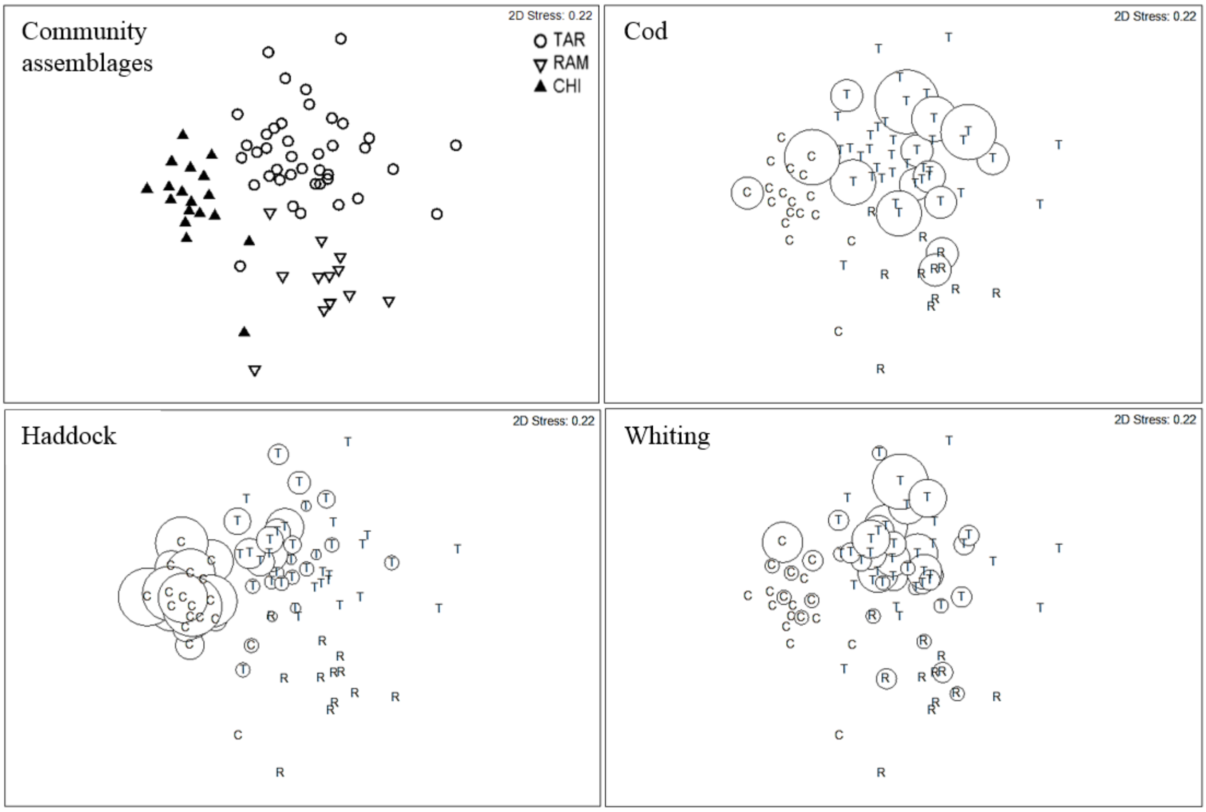


Figure 11. *MDS plots constructed on the square root abundance (count of all bycatch species) caught across the 70 control tows conducted in Targets, Ramsey and Chickens in Summer 2017, illustrating in the; Top left - the clustering of species composition within each site, note the distinct clustering for each group according to site; Top right – the species assemblage plot with the abundance of haddock (Melanogrammus aeglefinus) overlayed as bubble plots; Bottom left – whiting (Merlangius merlanus) and; Bottom right cod (Gadus morhua) overlayed in the same way. The larger the bubble the higher the no. of individuals caught in the tow.*

Table 6*. The community composition of each sampled fishing ground (Targets, Ramsey, Chickens) as indicated by the output of the SIMPER analysis, which highlights species characterising each fishing ground. Species most typical for each site are displayed highest in the table, with the largest contribution of similarity within a site (% Contribution). Species that are found to have a consistently large presence within catches are species with a high ratio of similarity to their standard deviation (Sim/SD). Species are also described by their species order (CAR= Carcharhiniformes, PLEUR= Pleuronectiformes, TEUT= Teuthida, SCOR= Scorpaeniformes, GAD= Gadiformes, RAJ= Rajiformes, ZEI= Zeiformes).*

Species	**Sp. Order**	**Av. Abund**	**% Contribution**	**Sim/SD**
Targets Average similarity: 54.61				
Lesser spotted catshark *(Scyliorhinus caniculata)*	CAR	21.34	30	2.4
Lemon sole *(Micorstomus kitt)*	PLEUR	4.80	14.83	2.18
Dab *(Limanda limanda)*	PLEUR	3.10	9.62	1.59
Plaice *(Plueronectes platessa)*	PLEUR	2.99	8.42	1.08
Grey Gurnard *(Eutrigla Gurnadus)*	SCOR	1.39	5.47	1
Whiting *(Merlangius merlanus)*	GAD	1.74	5.46	0.89
Squid *(Lolligo. Sp)*	TEUT	1.54	5.1	0.87
Spur dog *(Squalus acanthias)*	CAR	2.13	5.04	0.76
Haddock *(Melanogrammus aeglefinus)*	GAD	1.35	4.2	0.73
Thornback ray *(Raja clavata)*	RAJ	0.59	2.91	0.64
Ramsey Average similarity: 58.65				**Sim/SD**
Lesser spotted catshark *(Scyliorhinus caniculata)*	CAR	18.58	33.7	2.03
Dab *(Limanda limanda)*	PLEUR	6.35	25.66	3.38
Plaice *(Plueronectes platessa)*	PLEUR	3.84	19.74	3.1
Red gurnard *(Chelidonichthys cuculus)*	SCOR	0.98	5.82	0.8
Tub gurnard (*Trigla lucerna)*	SCOR	0.38	3.95	0.65
John Dory *(Zeus faber)*	ZEI	0.48	3.01	0.51
Chickens Average similarity: 60.42				
Lesser spotted catshark *(Scyliorhinus caniculata)*	CAR	31.25	22.67	2.84
Plaice *(Plueronectes platessa)*	PLEUR	35.64	21.63	2.19
Haddock *(Melanogrammus aeglefinus)*	GAD	13.84	13.63	1.91
Lemon sole *(Micorstomus kitt)*	PLEUR	9.06	11.61	2.06
Red gurnard *(Chelidonichthys cuculus)*	SCOR	10.18	11.14	1.77
Nursehound/bull huss *(Scyliorhinus stellaris)*	CAR	1.74	4.61	1.02
Dab *(Limanda limanda)*	PLEUR	2.28	3.81	0.81

Environmental context

Along with species community composition, it is also apparent that the environmental parameters such as depth differ distinctly between each site, which is evident in the MDS plot constructed on community composition (count) data with depth levels clustered per site (Figure 12). Table 7 describes the depths encountered across the swept area at each site, depths ranged from ~15m in Ramsey to ~95m in Chickens. The particle size values indicate that the area swept in Targets was comprised of the smallest particles and Ramsey the largest. The average ambient light levels were also found to differ by site, with Ramsey consisting of the highest light levels and Chickens the lowest. Although these readings have been calibrated, the readings are still not accurate as the sensor could not pick up low light levels, however these values indicate that light levels relate to the water depth at each site. The total biomass of target catch from 2015 until 2017 indicate the densities of QSC, with the largest catches recorded in Targets for both 2015 and 2016 while, in 2017 East Douglas experienced the highest fishing pressure.

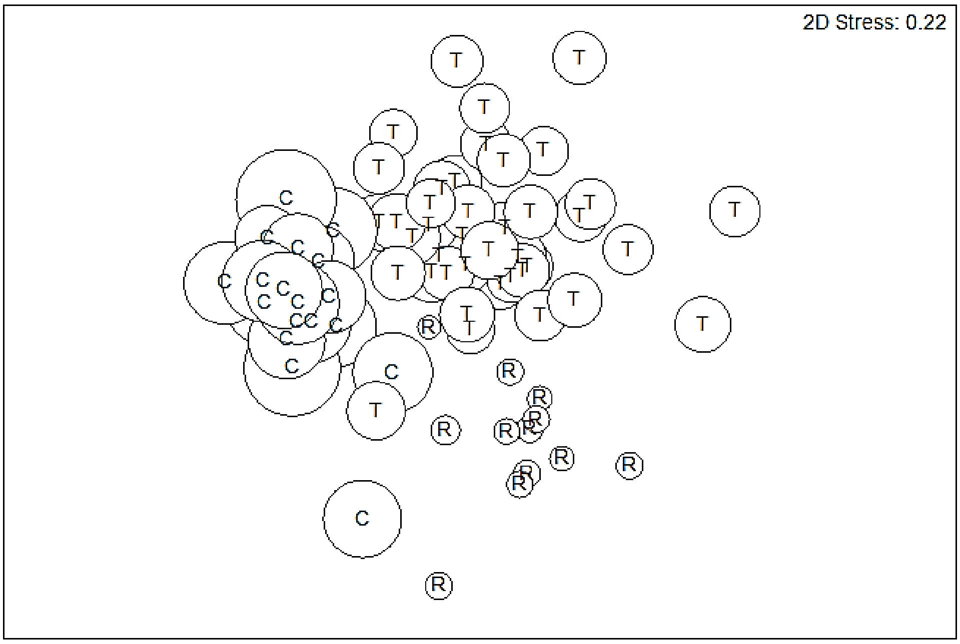


Figure 12 *MDS plots constructed on the square-root abundance (count of all bycatch species) caught across the 70 control tows, conducted over the summer of 2017, with the mean depth (EMODnet.EU) attributed to each tow overlaid as bubbles. The larger the bubble the deeper the water depth per tow, note the clustering of bubbles of similar sizes for each site, TAR= Targets, RAM = Ramsey and CHI= Chickens.*

Table 7 *The mean maximum and minimum depth (m) spatially analysed per tow using bathymetry (EMODnet.EU) and particle size data (White 2011). Average ambient light levels calibrated from data collected by the HOBO light-loggers (+- standard deviation). As well as the total biomass of QSC removed by the net fishery in recent years from 2015-2017 (pers comms DEFA) for all fishing grounds (RAM = Ramsey, TAR= Targets, CHI = Chickens, EDG= East Douglas).*

Site	**Depth(m)**			**Substrate**	**Ambient light levels**	**Total biomass of QSC removed (tonnes)**		
	Mean	**Max**	**Min**	**Mean particle size (mm)**	**Av. lux**	**2015**	**2016**	**2017**
RAM	-15.91	-17.29	-14.47	0.82	978.03 (+-107.49)	15	0	26
TAR	-33.85	-40.28	-29.24	0.59	906.14 (+-23.69)	790	623	95
CHI	-64.98	-95.38	-45.56	0.64	897.25 (+-0)	180	180	138
EDG	NA	NA	NA	NA	NA	NA	NA	491

Vessel and observer effect

There was no effect of vessel detected between the two vessels TG and OSJ on the catchability of *all bycatch species, quota gadoids* and *marketable QSC* caught in the control tows (Table 8). Therefore, there was no effect of observer or vessel influencing the catch data collected or the size comparison analysis.

Table 8. *A table summarising the results of one-way analysis of variance (ANOVA) comparing the abundance (count) of species caught in either vessel Two Girls and Our Sarah Jane, including: all bycatch species within all sites; quota gadoids (haddock, cod and whiting) caught within Targets and Chickens; the biomass (kg) of marketable QSC caught in Ramsey and Chickens in the control tows and; size data on QSC height (mm) measured in all sites and tows.*

Species group	**Df**	***f-value***	***p-value***
All bycatch species	65	0.20	0.66
Quota gadoids	56	0.09	0.76
Marketable QSC	10	0.39	0.55
QSC height	90	0.24	0.27

3.4 Response to the BRDs

3.4.1 Target Catch Queen Scallop (*Aequipecten opercularis*)

The total catch of QSC throughout the trial was 213 bags (~7455 kg), with each bag weighing approximately 35kg. The total catch in Targets was 82, Ramsey 88 and Chickens 43 bags. Analysis on the target catch incorporated the data collected in Chickens and Ramsey (where the catch was consistently riddled). Through initial observation of the catch of QSC (WPUA/ha kg) the treatment nets caught less marketable QSC than the control, although, the reductions by weight are small, with a maximum loss on average of 13.24kg per hectare in the SMP+L treatment in Chickens (Table 9, Figure 13).

Table 9. *The average weight and standard deviation of the raw catch of QSC per hectare (kg) caught in each treatment (control, square mesh panel (SMP) and square mesh panel and light (SMP+L)) in Chickens (CHI) and Ramsey (RAM).*

Area	Treatment	Av. WPUA/ha (kg)	SD	% change
CHI	Control	6.51	7.67	-30.88
	SMP	4.50	4.68	
CHI	Control	19.78	15.38	-66.49
	SMP+L	6.54	8.40	
RAM	Control	41.86	13.50	-1.48
	SMP	41.24	12.18	

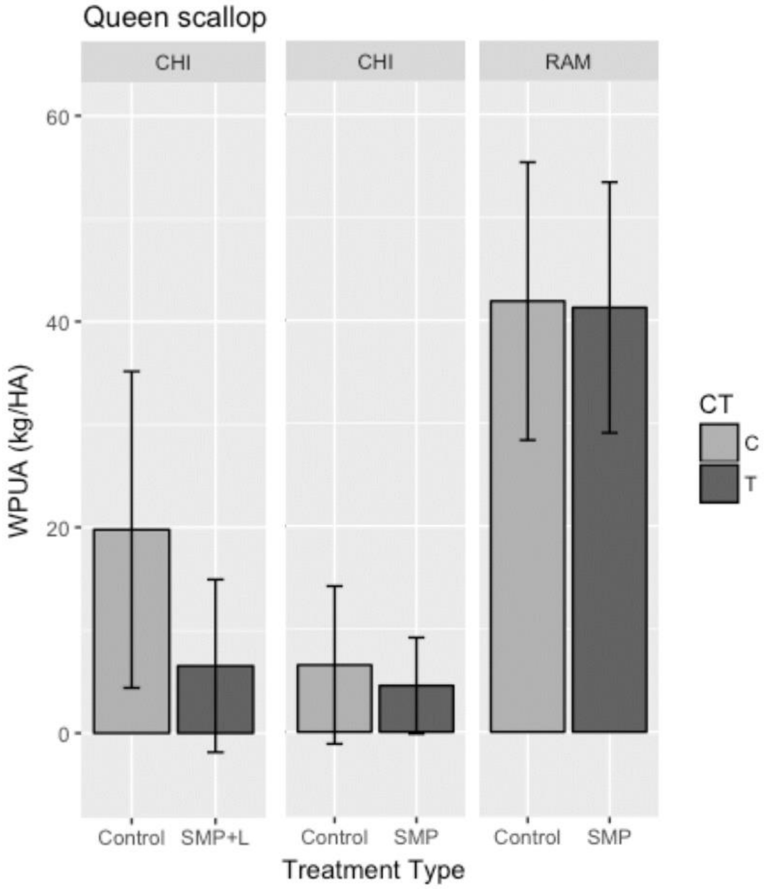


Figure 13 *The raw average WPUA/hectare of Queen scallop (Aequipecten opercularis) caught across the grouped tows in the control nets (C) compared to their corresponding paired treatment tows (SMP = square mesh panel and SMP+L= square mesh panel & lights). The catch is presented in both sites where the catch were consistently riddled (CHI = Chickens, RAM = Ramsey) with the standard deviation indicated in the error bars. Light grey indicates the control (C) tows and dark grey indicates the treatment tows (T). No data (ND) were collected for SMP+L in Ramsey therefore a catch comparison could not be made between the grouped SMP+L tows and their grouped paired control tows in this site.*

Using intercept only linear regressions it was shown that the catch in the SMP tows in Ramsey did not significantly differ from their paired control tows, as the average logRR of QSC caught in the SMP tows did not significantly differ from 0 (Table 10., P=0.92). Similarly, in Chickens linear regressions found that there was no significant reduction in catch of QSC caught in both treatment nets compared to their paired control tows. The average logRR of QSC caught in both the SMP and SMP+L treatments did not differ significantly from 0 (Table 10., SMP: P=0.61; SMP+L: P=0.22) An ANOVA also showed that the relative WPUA (logRR) caught in the SMP did not differ significantly to the SMP+L paired tows (Table 10., P=0.89).

Table 10 *Outputs from the ANOVAs incorporating both treatments (Lm(logRR ~treatment) and intercept only linear models (Lm(logRR ~ control)) to detect whether each treatment independently differed from '0' or the control. Models were conducted on the relative catch (LogRR) for the weight(kg) (WPUA/ha) of Queen scallop (Aequipecten opecularis). The factors for each model are displayed, with both treatments being analysed at each site separately, the estimate (+- standard error, SE) is the mean logRR response for that treatment and it indicates whether the catch has increased or decreased relative to the control (+= increase, - = decrease),* ***t*** *value and p values are noted, with bold indicating significant values and *=significant (P=<0.05), **=very significant (P=<0.005). The factors and treatments are: SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in sites CHI = Chickens, RAM = Ramsey.*

	Lm(logRR ~treatment) (ANOVA)						Lm(logRR ~ control) (intercept only linear regression)					
Site	**Factor**	**Estimate**	**S.E**	***t*-value**	**P**	**d.f**	**Factor**	**Estimate**	**S.E**	***t*-value**	**P**	**d.f**
RAM	Intercept (SMP)	NA					SMP	-0.01	+-0.11	-0.097	0.93	11
	SMP+L						NA					
CHI	Intercept (SMP)	-0.15	+-0.25	-0.59	0.57	10	SMP	-0.22	+-0.13	-1.75	0.22	2
	SMP+L	-0.07	+-0.50	-0.15	0.89		SMP+L	-0.15	+-0.28	-0.53	0.61	8

The preferred averaged model used to explain the variation in logRR for WPUA of QSC revealed that neither depth(m) or site had a significant influence on QSC catchability (Table 11, Av. d.f ranged from 2-4 across the selected models). The model fit and assumptions of homogeneity and normality were considered acceptable on visual inspection of the plots (diagnostic plots in Appendix 13).

Table 11 *The estimated parameters, z values and p values for the preferred averaged generalised linear model describing the relationship between the relative weight(kg) caught per hectare (logRR of WPUA) of Queen scallop (Aequipecten opecularis) and the environmental variables recorded or calculated post hoc for each paired tow.*

Parameters	Estimate	z value	P
(Intercept)	-0.07	0.50	0.61
Site	-2.86	1.87	0.06
depth	2.06	1.11	0.27

With Ramsey conducting only SMP paired tows compounded by QSC analysis being restricted to Chickens and Ramsey, a GLM could not be implemented on the SMP+L treatment as the number of tows was insufficient and model assumptions could not be met.

The mean proportion of juvenile catch caught in both the SMP and SMP+L tows did not significantly differ from their paired control tows in any of the three sites (two way ANOVA:

SMP:$F_{1,74}$=0.36, P=0.70; SMP+L: $F_{1.51}$=0.54,P= 0.47). This indicates that the treatments themselves did not result in a change to the proportion of undersize bycatch and subsequently there were no losses to the proportion of marketable QSC caught (Table 12).

Table 12 *The mean(+-standard devation) proportion(%) undersized (<55mm shell width) QSC per site for each treatment SMP and SMP+L compared to the mean proportion of undersized QSC caught in their associated paired control tows.*

	Average proportion undersized (%)			
	Control	**SMP**	**Control**	**SMP+L**
CHI	0.00(+-0.00)	0.87(+-2.30)	2.35(+-4.45)	1.89(+-4.44)
RAM	15.41(+-7.54)	22.05(+-5.44)	NA	NA
TAR	8.76(+-11.75)	14.41(+-19.10)	10.40(+-13.42)	15.32(+-16.64)

Size analysis of the target catch were conducted through paired T-tests, which showed the average size of QSC caught in the control tows were significantly greater than their paired SMP tow by 1.88mm (t=3.1, df=39, P=0.004*). In contrast, the size of individuals caught in the SMP+L tows were not found to significantly differ in comparison to their paired control tows. The mean height of QSC measured on board the control boat were 0.38mm greater than the SMP+L boat, however the difference in size between the control and treatment were not significant (t = 0.73, df = 27, p-value = 0.47). Although, the size of individuals caught in the SMP net were significantly smaller than the control net, the reduction in size in both the SMP and SMP+L nets was low, with only a consistent difference of <2mm (Figure 14).

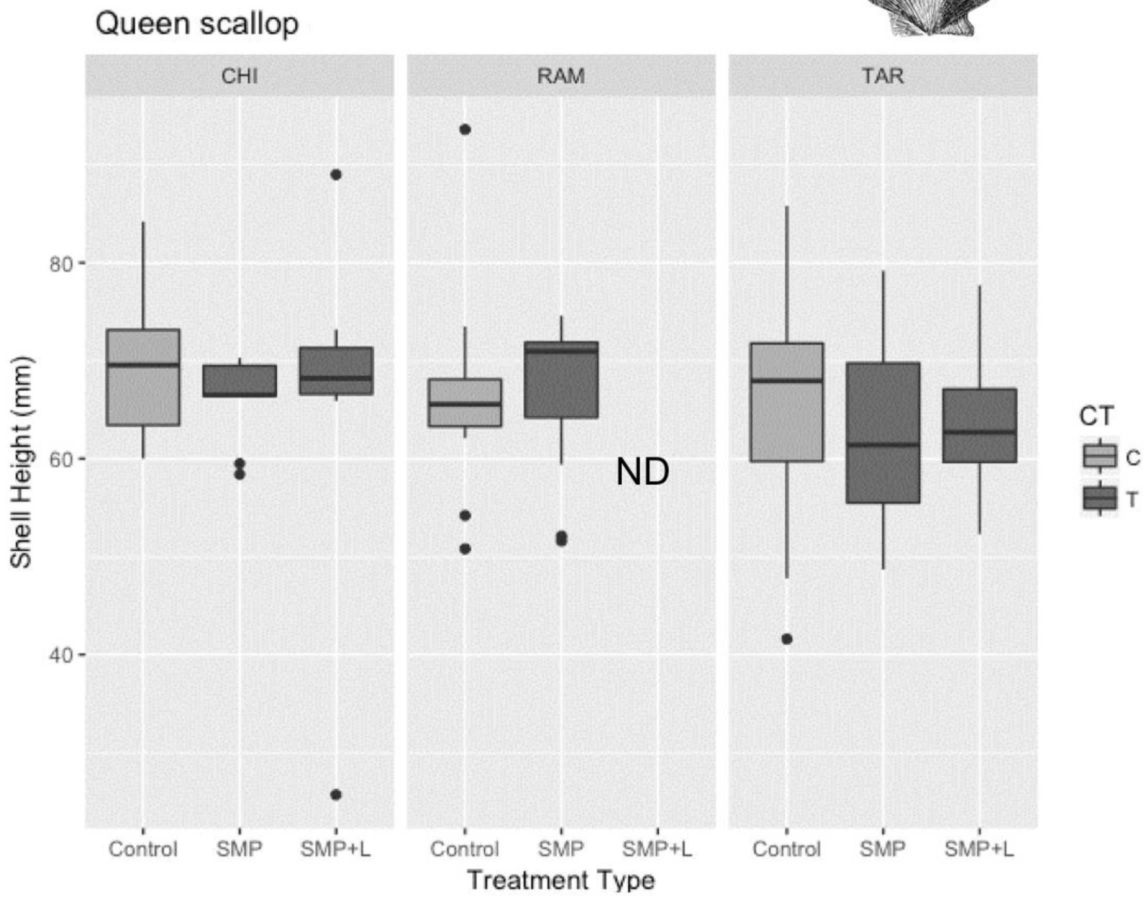


Figure 14. *Boxplots displaying the grouped mean average shell heights (mm) per tow of Queen scallop (Aequipecten opercularis) measured on board the control boat (C) compared to their paired treatment boats (SMP = square mesh panel and SMP+L= square mesh panel & lights). The measurements are illustrated within all three sites (CHI = Chickens, RAM = Ramsey, TAR = Targets) with the median mean average sizes per grouped treatment indicated by the horizontal line and the vertical lines indicate the 95% confidence intervals, while the dots represent outliers. Light grey indicates the control (C) tows and dark grey indicates the treatment tows (T). No data () were collected for SMP+L in Ramsey therefore a size comparison could not be made between the grouped SMP+L tows and their grouped paired control tows in this site.*

3.4.2 Responses of species with similar physiology to the BRDs

Non-quota gadoids consisting of pouting (87 individuals caught in total) and poor cod (346 individuals), the CPUA in the SMP+L treatment was slightly lower than the SMP net, for both Chickens and Targets (Table 13, Figure 15). Although the catches did not differ significantly between treatments, nor did the CPUA differ compared to the paired control tows (Table 14).

The *gurnard species* analysed were grey gurnard (254 individuals), red gurnard (573 individuals) and tub gurnard (87 individuals), for which neither of the treatments significantly differed from the control (linear regression Table 14). The treatments were found to have opposite effects and differ significantly from one another in Chickens, with a lower CPUA caught in the SMP+L net compared to the SMP (ANOVA Table 14 & Figure 15).

Rays and skates consisted of cuckoo ray (34 individuals), spotted ray (52 individuals) and thornback ray (103 individuals). Although, the model coefficient estimates for the linear regressions were found to be negative indicating a very slight reduction in catch (Table 13, Table 14). The treatments did not differ from one another, nor did they significantly reduce the catch relative to their paired control tows, suggesting the BRDs used have no influence in reducing rays and skate species (Figure 15, Table 14).

Lesser spotted catshark were analysed separately to the *other shark species* encountered, due to high catches. The *other shark species* grouped for analysis were nursehound/bull huss (141 individuals), smoothhound (31 individuals), starry smooth hound (54 individuals), and spur dog (354 individuals). Even though the catch appears to have increased with the treatment nets in Targets (Table 13, Figure 15), there was no significant effect of the BRDs on the CPUA of the grouped shark species (linear regressions Table 14), nor did the catch differ significantly between treatments (ANOVA Table 14).

The lesser spotted catsharks (3450 individuals) response in CPUA to the BRDs were found to vary depending on the area, with significantly different responses found in the two treatments in Chickens and Targets (Table 13, Figure 15). In Targets the SMP nets were found to significantly reduce the catch in comparison to the control, while the SMP+L did not differ in catch rates compared to the control. The opposite effect was found in Chickens with the SMP+L reducing the catch significantly, while the SMP had no influence in reducing the catch rate relative to the paired control net (linear regression Table 14). However, in Ramsey the SMP did not significantly influence the catch rate of lesser spotted catsharks (Table 14).

Flatfish including brill (6 individuals), dab (610 individuals), common sole (5 individuals), lemon sole (750 individuals) and plaice (1915 individuals) were found not to significantly differ in response to the SMP treatment in any of the three sites (Figure 16, Table 14). However, in Chickens the SMP+L were found to reduce the CPUA significantly relative to the paired control nets (linear regression Table 14).

Table 13 *The mean CPUA/ha +- standard deviation (SD), of grouped species that are of the same order or share similar physiology within each site Targets = TAR, Ramsey = RAM, Chickens =CHI for each treatment control, square mesh panel (SMP) & square mesh panel + lights (SMP+L). Species groups are as follows: Non-quota gadoids = Pouting (Trisopterus luscus), Poor cod (Trisopterus minutus); Gurnand species = Tub gurnard (Trigla lucerna), Red gurnard (Chelidonichthys cuculus), Grey gurnard (Eutrigla gurnadus); Rays and skates = Cuckoo ray (Leucoraja naevus), Thornback ray (Raja clavata), Blonde ray (Raja brachyuran), Spotted ray (Raja montagui); Other shark species =Starry smooth hound (Mustelus asterias), Smooth hound (Mustelus mustelus), Spur dog (Squalus acanthias), Bull huss (Scyliorhinus stellaris), Tope (Galeorhinus galeus); Lesser spotted catshark (Scyliorhinus caniculata); Flatfish = Brill (Scophthalmus rhombus), Dab (Limanda limanda), Dover/ Common sole (Solea solea), Lemon sole (micorstomus kitt), Plaice (Plueronectes platessa).*

Species	Site	Control	SMP	% change	Control	SMP+L	% change
Non-quota gadoids	TAR	0.03(+-0.07)	0.03(+-0.09)	0	0.35(+-1.22)	0.09(+-0.39)	-74.29
	RAM	0.00	0.00	NA	ND	ND	ND
	CHI	0.33(+-0.74)	1.36(+-2.95)	+312.12	0.27(+-0.63)	0.44(+-1.01)	+62.96
Gurnard spp.	TAR	0.20(+-0.34)	0.13(+-0.21)	-35	0.15(+-0.25)	0.12(+-0.19)	-20
	RAM	0.35(+-0.42)	0.37(+-0.37)	+5.71	ND	ND	ND
	CHI	0.82(+-1.51)	1.08(+-1.52)	+31.71	0.96(+-1.41)	0.58(+-0.87)	-39.58
Rays and skates	TAR	0.08(+- 0.16)	0.10(+-0.38)	+25%	0.07(+-0.12)	0.05(+-0.13)	-28.57
	RAM	0.05(+-0.16)	0.04(+-0.13)	-20	ND	ND	ND
	CHI	0.04(+-0.08)	0.02(+-0.06)	-50	0.05(+-0.10)	0.29(+-0.07)	+480
Other shark spp.	TAR	0.21(+-0.57)	0.20(+-0.59)	-4.76	0.14(+-0.77)	0.16(+-0.86)	+14.29
	RAM	0.05(+-0.18)	0.09(+-0.19)	+80	ND	ND	ND
	CHI	0.12(+-0.20)	0.10(+-0.22)	-16.67	0.11(+-0.25)	0.11(+-0.29)	0
Lesser spotted catsharks (*Scyliorhinus caniculata)*	TAR	4.34(+-1.93)	2.85(+-2.38)	-34.33	3.43(+-2.16)	3.34(+-1.90)	-2.62
	RAM	8.89(+-11.78)	5.91(+-5.66)	-33.52	ND	ND	ND
	CHI	5.04(+-4.25)	6.17(+-2.25)	+22.42	5.83(+-3.29)	3.01(+-1.53)	-48.37
Flatfish	TAR	0.42(+-0.56)	0.47(+-0.63)	+11.90	0.48(+-0.58)	0.41(+-0.52)	-14.58
	RAM	0.78(+- 1.21)	0.69(+-1.08)	-11.54	ND	ND	ND
	CHI	1.85(+- 3.63)	1.83(+-3.53)	-1.08	1.70(+-3.29)	1.25(+-2.55)	-26.47

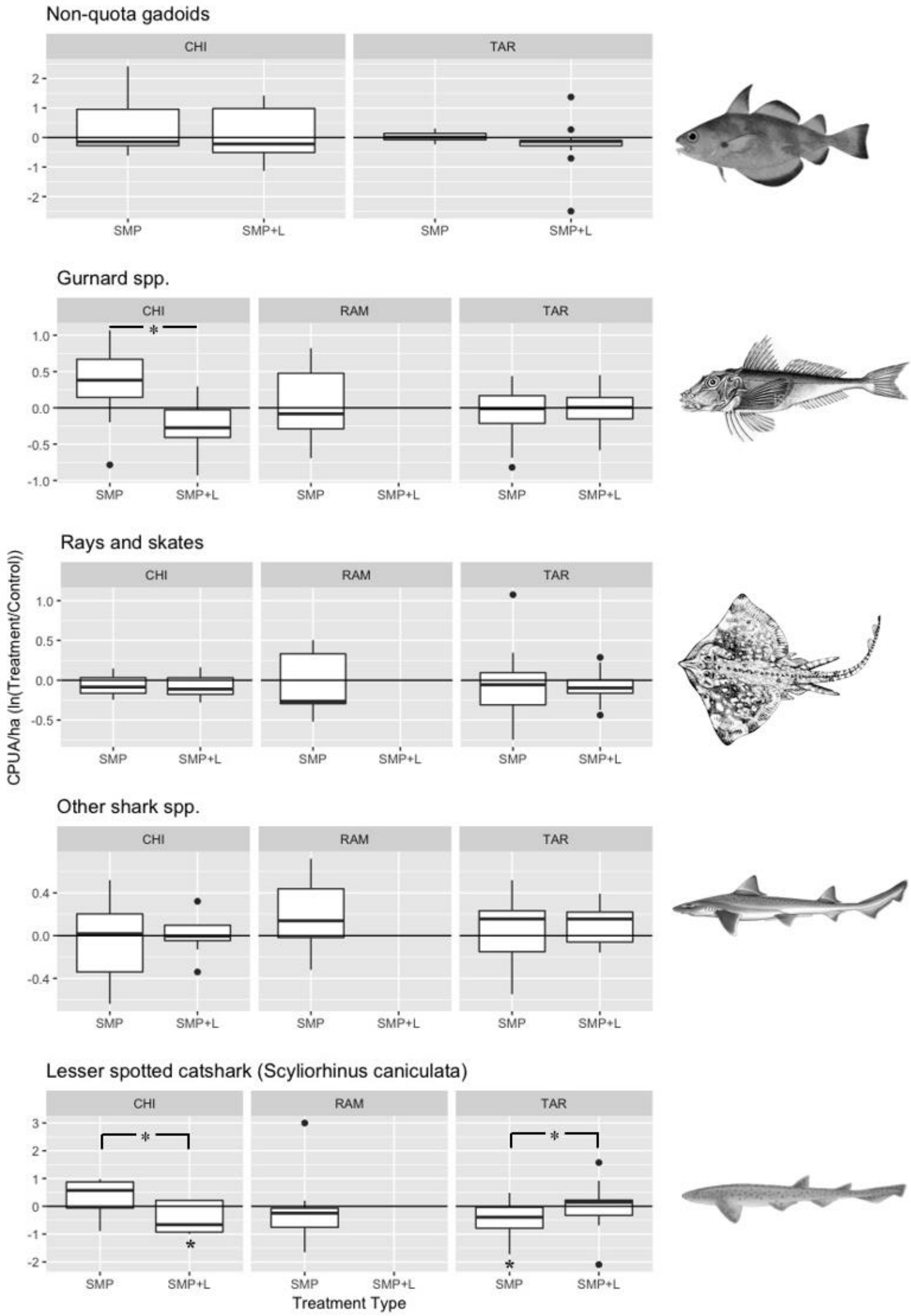

Non-quota gadoids
CHI
TAR
Gurnard spp.
CHI
RAM
TAR
Rays and skates
CHI
RAM
TAR
Other shark spp.
CHI
RAM
TAR
Lesser spotted catshark (Scyliorhinus caniculata)
CHI
RAM
TAR
SMP
SMP+L
CPUA/ha (ln(Treatment/Control))
Treatment Type

Figure 15. *The relative catch (LogRR) for the abundance (CPUA/ha) per hectare of species groups: Other gadoids = Pouting (Trisopterus luscus), Poor cod (Trisopterus minutus); Gurnand spp.= Tub gurnard (Trigla lucerna), Red gurnard (Chelidonichthys cuculus), Grey gurnard (Eutrigla gurnadus); Rays and skates = Cuckoo ray (Leucoraja naevus), Thornback ray (Raja clavata), Blonde ray (Raja brachyuran), Spotted ray (Raja montagui); Other shark species=Starry smooth hound (Mustelus asterias), Smooth hound (Mustelus mustelus), Spur dog (Squalus acanthias), Bull huss (Scyliorhinus stellaris), Tope (Galeorhinus galeus); Lesser spotted catshark (Scyliorhinus caniculata); Flatfish = Brill (Scophthalmus rhombus), Dab (Limanda limanda), Dover/ Common sole (Solea solea), Lemon sole (micorstomus kitt), Plaice (Plueronectes platessa), caught in both treatments SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in sites CHI = Chickens, RAM = Ramsey, TAR = Targets. The median is indicated by the horizontal line and the error bars indicate the 95% confidence intervals and the dots represent outliers.* ***** *above the boxes* **=** *indicate a significant difference (P<0.005) in catches between the two treatments. * below the boxes = a significant difference between the logRR(CPUA) in a single treatment compared to the control.*

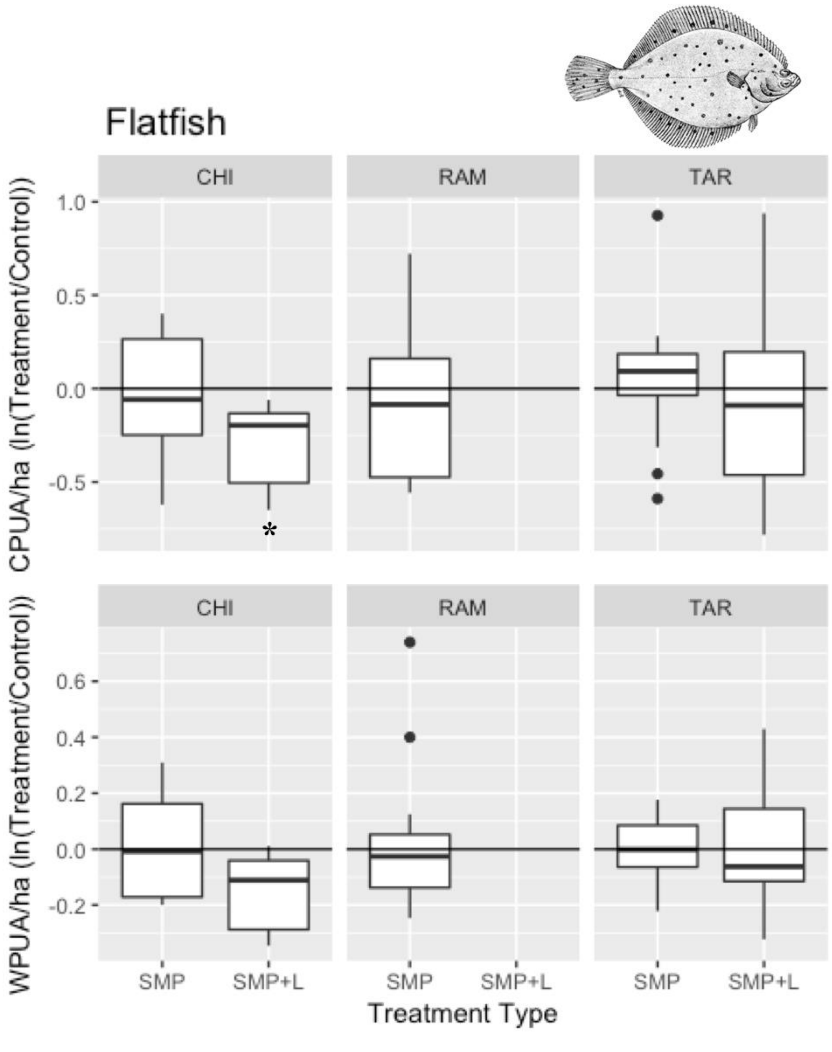


Figure 16.*. The relative catch (LogRR) for both the abundance (CPUA, top) and biomass (WPUA, bottom) per hectare of flatfish: brill (Scophthalmus rhombus), dab (Limanda limanda), Dover sole (Solea solea), lemon sole (micorstomus kitt), plaice (Pleuronectes platessa), caught in both treatments SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in all sites CHI = Chickens, RAM = Ramsey, TAR = Targets. The median is indicated by the horizontal line and the error bars indicate the 95% confidence intervals and the dots represent outliers. * above the boxes = indicate a significant difference (P<0.005) in catches between the two treatments. * below the boxes = a significant difference between the logRR in a single treatment compared to the control.*

Table 14 *Outputs from the linear models incorporating both treatments, using ANOVAs (Lm(logRR ~treatment) and intercept only linear models (Lm(logRR ~ control)) to detect whether each treatment independently differed from '0' or the control. Models were conducted on the relative catch (LogRR) for the abundance (CPUA/ha) of species grouped by family or similar physiology. The factors for each model are displayed, with both treatments being analysed separately, the estimate (+- standard error, SE) (the mean logRR response for that factor variable) indicates whether the catch has increased or decreased relative to the control (+= increase, - = decrease),* ***t*** *value and p values are noted, with bold indicating significant values, with *=significant (P=<0.05), **=very significant (P=<0.005). The factors and treatments are: SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in sites CHI = Chickens, RAM = Ramsey, TAR = Targets The species groups are defined above.*

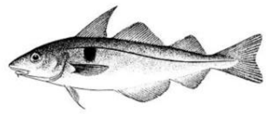
		Lm(logRR ~treatment) (ANOVA)						**Lm(logRR ~ control) (Intercept only linear regression)**					
Species	**Site**	**Factor**	**Estimate**	**S.E**	***t*-value**	**p value**	**d.f**	**Factor**	**Estimate**	**S.E**	***t*-value**	**p value**	**d.f**
Non-quota gadiformes	TAR	Intercept (SMP)	0.03	+-0.25	0.12	0.91	19	SMP	0.03	+-0.07	0.42	0.69	6
		SMP+L	-0.27	+-0.31	-0.87	0.40	19	SMP+L	-0.24	+-0.21	-1.12	0.28	13
	CHI	Intercept (SMP)	0.48	+-0.36	1.34	0.20	13	SMP	0.48	+-0.36	1.32	0.22	8
		SMP+L	-0.38	+-0.57	-0.67	0.52	13	SMP+L	0.11	+-0.43	0.25	0.82	5
Gurnard spp.	TAR	Intercept (SMP)	-0.09	+-0.07	-1.23	0.23	38	SMP	-0.09	+-0.08	-1.13	0.27	18
		SMP+L	0.05	+-0.10	0.49	0.63	38	SMP+L	-0.04	+-0.06	-0.64	0.53	20
	RAM	NA	NA	NA	NA	NA	NA	SMP	0.05	+-0.15	0.36	0.73	11
	CHI	Intercept (SMP)	0.32	+-0.16	1.97	0.07	16	SMP	0.32	+-0.19	1.69	0.13	8
		SMP+L	-0.61	0.23	-2.64	**0.02***	16	SMP+L	-0.29	+-0.13	-2.21	0.06	8
Rays and skates	TAR	Intercept (SMP)	-0.04	+-0.09	-0.49	0.63	29	SMP	-0.04	+-0.12	-0.37	0.72	13
		SMP+L	-0.04	+-0.12	-0.36	0.72	29	SMP+L	-0.08	+-0.05	-1.79	0.09	16
	RAM	NA	NA	NA	NA	NA	NA	SMP	-0.05	+-0.14	-0.32	0.76	7
	CHI	Intercept (SMP)	-0.06	+-0.06	-1.11	0.29	14	SMP	-0.06	+-0.05	-1.22	0.26	7
		SMP+L	-0.02	+-0.08	-0.21	0.84	14	SMP+L	-0.08	+-0.06	-1.29	0.24	7
Other shark spp.	TAR	Intercept (SMP)	0.04	+-0.08	0.55	0.59	23	SMP	0.04	+-0.09	0.46	0.65	13
		SMP+L	0.07	+-0.11	0.63	0.54	23	SMP+L	0.11	+-0.06	1.91	0.08	10
	RAM	NA	NA	NA	NA	NA	NA	SMP	0.17	+-0.11	1.51	0.17	9

	CHI	Intercept (SMP)	-0.05	+-0.10	-0.56	0.58	15	SMP	-0.05	+-0.12	-0.46	0.66	8
		SMP+L	0.06	+-0.14	0.41	0.69	15	SMP+L	0.003	+-0.07	0.04	0.97	7
Lesser spotted catsharks (*Scyliorhinus caniculata)*	TAR	Intercept (SMP)	-0.44	+-0.15	-2.95	**0.005****	38	SMP	-0.44	+-0.13	-3.31	**0.004****	18
		SMP+L	0.44	+-0.20	2.16	**0.04***	38	SMP+L	0.01	+-0.15	0.03	0.98	20
	RAM	NA	NA	NA	NA	NA	NA	SMP	-0.23	+-0.33	-0.69	0.51	11
	CHI	Intercept (SMP)	0.33	+-0.20	1.68	0.11	16	SMP	0.33	+-0.21	1.56	0.16	8
		SMP+L	-0.78	+-0.28	-2.78	**0.01***	16	SMP+L	-0.44	+-0.18	-2.47	**0.04***	8
Pleuronectiformes	TAR	Intercept (SMP)	0.06	+-0.09	0.68	0.5	38	SMP	0.06	+-0.07	0.84	0.41	18
		SMP+L	-0.12	+-0.12	-0.96	0.35	38	SMP+L	-0.06	+-0.10	-0.58	0.57	20
	RAM	NA	NA	NA	NA	NA	NA	SMP	-0.09	+-0.11	-0.8	0.44	11
	CHI	Intercept (SMP)	-0.02	0.10	-0.21	0.84	16	SMP	-0.02	+-0.12	-0.17	0.87	8
		SMP+L	-0.30	0.14	-2.17	0.06	16	SMP+L	-0.32	+-0.10	-4.38	**0.002****	8

3.4.3 Quota gadoid responses to the BRDs

Haddock *(Melanogrammus aeglefinus)*

Haddock were most frequently encountered in both the control and treatment tows conducted in Chickens with 551 individuals caught. Targets had the second highest encounter with 144 individuals, while tows conducted in Ramsey caught only two individuals in total. These findings resulted in the responses of haddock being analysed in Chickens and Targets.



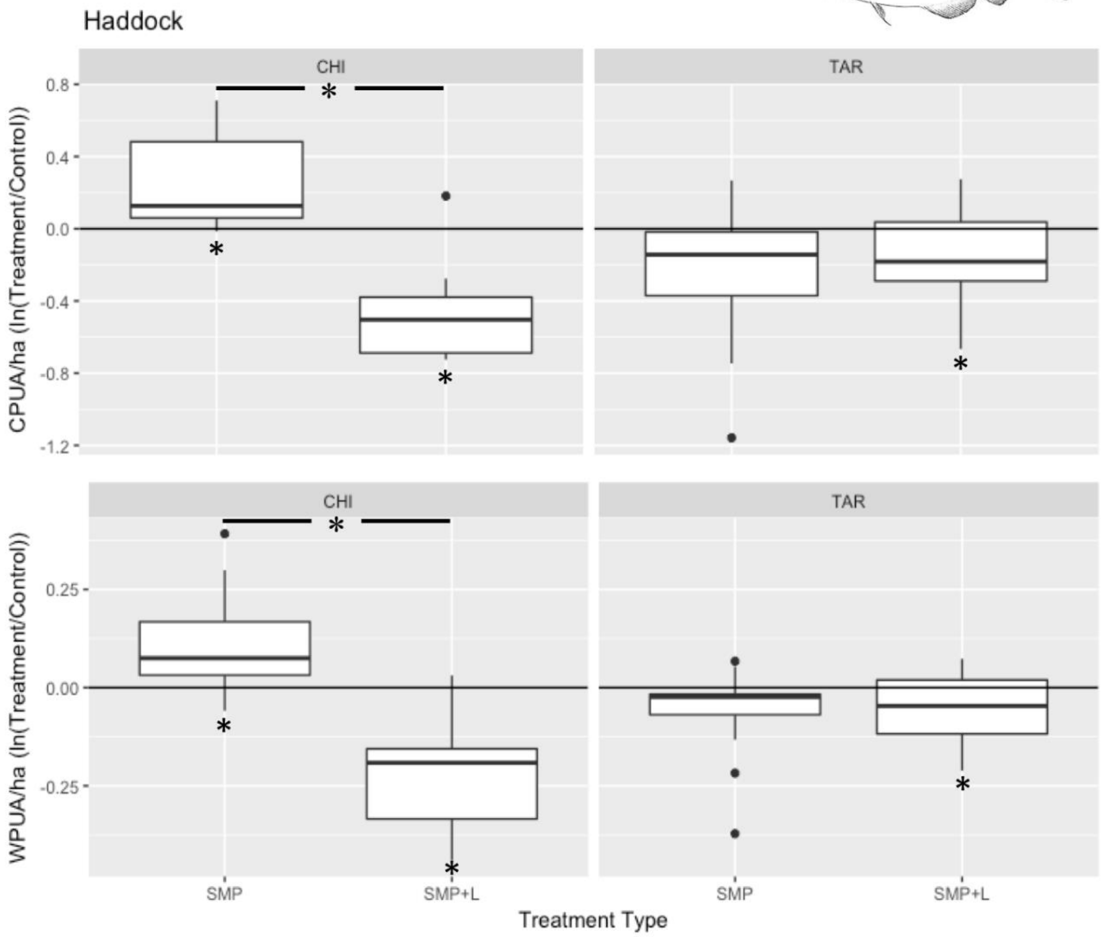


Figure 17**. The relative catch (LogRR) for both the abundance (CPUA, top) and biomass (WPUA, bottom) per hectare of haddock (Melanogrammus aeglefinus) caught in both treatments SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in both sites CHI = Chickens and TAR = Targets. The median is indicated by the horizontal line and the error bars indicate the 95% confidence intervals and the dots represent outliers.* ** *above the boxes* **=** *indicate a significant difference (P<0.005) in catches between the two treatments. * below the boxes = a significant difference between the logRR in a single treatment compared to the control.*

When analysing the treatments individually in Targets, the average CPUA/WPUA caught in the SMP+L tows did not significantly differ from the SMP tows (Table 15). The intercept only linear regression indicated that the average logRR (CPUA/WPUA) of haddock in the SMP did not differ significantly from the control (Table 16, P=0.06). However, haddock caught by the SMP+L paired tows in Targets, were significantly reduced in CPUA/WPUA relative to the control (Table 16). This indicates that although the responses in catch rate to the treatments did not differ significantly from one another, the SMP+L net had a significant influence in reducing haddock catch in Targets, whereas the SMP net did not.

Interestingly, in Chickens alone, the response of CPUA/WPUA of haddock in the SMP nets were considerably different to the catch in the SMP+L nets (Table 16). The SMP and SMP+L treatments significantly differed in catches of haddock compared to their paired control net (Table 16). However, the estimate (logRR of CPUA) was found to be above the 0 intercept, indicating the SMP increased the catch of haddock. Whereas, the SMP+L exhibited a negative estimate value, (Table 16) demonstrating that the catch of haddock was significantly reduced with the addition of lights in Chickens.

Table 15 *The average and standard deviation (S.D) of the abundance per hectare (CPUA/ha) of haddock (Melanogrammus aeglefinus) measured on board the vessels in Chickens (CHI) and Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Area	Treatment	Av. CPUA/ha	S.D	% change
CHI	Control	1.72	1.58	+ 46.51
	SMP	2.52	2.34	
CHI	Control	3.33	1.51	- 43.54
	SMP+L	1.88	1.60	
TAR	Control	0.41	0.57	-63.41
	SMP	0.15	0.23	
TAR	Control	0.42	0.58	-54.75
	SMP+L	0.19	0.24	

***Table 16** Outputs from the linear models incorporating both treatments, using ANOVAs (Lm(logRR ~treatment) and intercept only linear models (Lm(logRR ~ control)) to detect whether each treatment independently differed from '0' or the control. Models were conducted on the relative catch (LogRR) for the weight(kg) (WPUA/ha) and abundance (count) (CPUA/ha) of Haddock (Melanogrammus aeglefinus). The factors for each model are displayed, with both treatments being analysed at each site separately, the estimate (+- standard error, SE) is the mean logRR response for that treatment and it indicates whether the catch has increased or decreased relative to the control (+= increase, - = decrease), **t** value and p values are noted, with bold indicating significant values and *=significant (P=<0.05), **=very significant (P=<0.005). The factors and treatments are: SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in sites CHI = Chickens, TAR = Targets.*

	Lm(logRR ~treatment) (ANOVA)					Lm(logRR ~ control) (Intercept only linear regression)				
Site	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**
TAR CPUA	Intercept (SMP)	-0.22 (+-0.09)	-2.44	0.02*	28	SMP	-0.22 (+-0.10)	-2.08	0.06	13
	SMP+L	0.04 (+-0.12)	0.36	0.72		SMP+L	-0.17 (+-0.07)	-2.55	0.02*	15
CHI CPUA	Intercept (SMP)	0.25 (+-0.10)	2.55	0.02*	15	SMP	0.25 (+-0.10)	2.60	0.04*	7
	SMP+L	-0.72 (+-0.14)	-5.23	0.0001***		SMP+L	-0.46 (+-0.09)	-4.84	0.001**	8
TAR WPUA	Intercept (SMP)	-0.06 (+-0.03)	-2.3	0.03*	28	SMP	-0.06 (+-0.03)	-2.02	0.06	13
	SMP+L	0.007 (+-0.04)	-0.21	0.84		SMP+L	-0.05 (+-0.02)	-2.57	0.02*	15
CHI WPUA	Intercept (SMP)	0.12 (+-0.05)	2.19	0.05*	28	SMP	0.25 (+-0.10)	2.60	0.04*	7
	SMP+L	-0.36 (+-0.08)	-4.73	0.0003***		SMP+L	-0.46 (+-0.10)	-4.84	0.001**	8

Linear regressions were fitted to the depth of the net towed by the treatment vessel and the logRR (CPUA) of haddock caught in both the treatments in Targets and Chickens (Figure 18). When analysing the SMP paired tows and their relative catch compared to the control (LogRR), there was a significant positive effect of depth, with the catch of haddock increasing in deeper water (t value = -3.34, P = 0.003, adjusted R^2 = 0.33). Interestingly, there was also a significant but negative linear relationship of depth against the SMP+L paired tows, with the catch of haddock decreasing as the net fishes deeper (t value = 3.1, P = 0.005**, adjusted R^2 = 0.27). The linear relationships between depth and the logRR of haddock caught in the SMP and the SMP+L treatments were found to be significantly different from one another (ANOVA $F_{1,23}$ = 9.65, P=0.005). However, the effect of depth only explains ~30% of the variation in the catch of haddock, therefore a GLM was fitted incorporating the other recorded explanatory variables to distinguish whether they could further explain the remaining 70% variation in the catch.

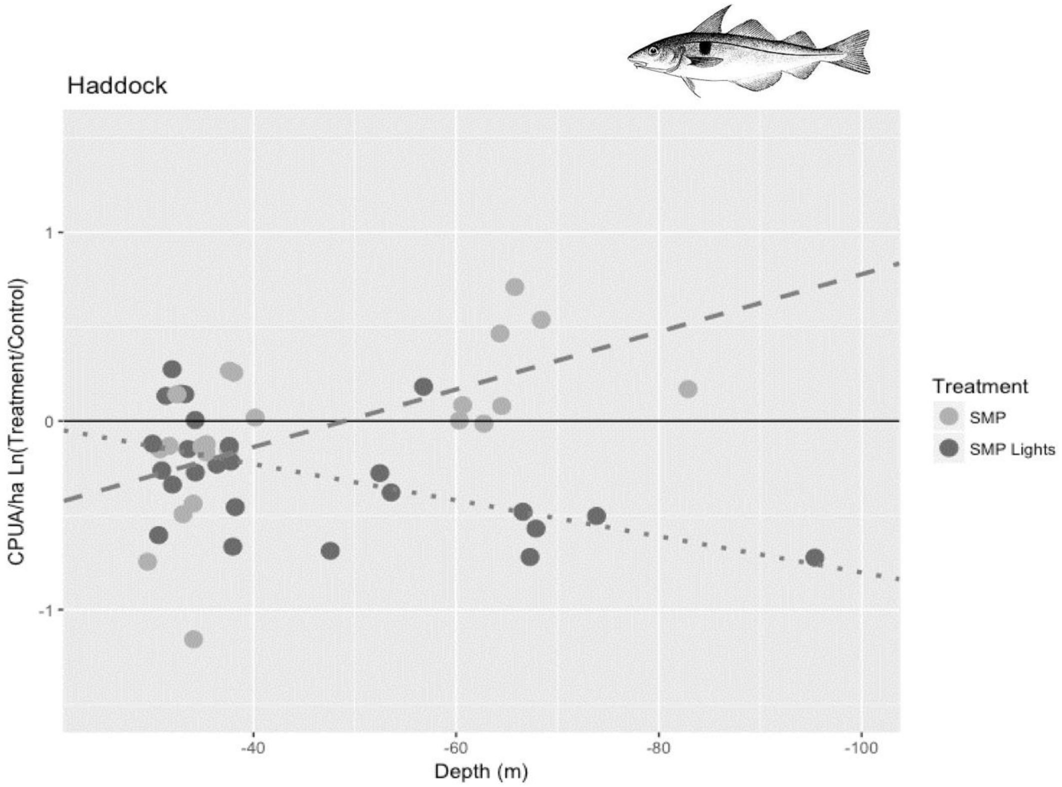


Figure 18. *The modelled linear relationship between the depth (m) and the relative CPUA per hectare (LogRR) of Haddock (Melanogrammus aeglefinus) caught in both treatments SMP (dashed line: LogRR= 0.02 depth - 0.75) = square mesh panel paired tows. SMP+ Lights (dotted line: LogRR= -0.01 depth + 0.15) = square mesh panel and lights paired tows, caught within sites Targets and Chickens.*

GLMs conducted on the logRR of haddock caught across Chickens and Targets confirmed that there was a significant influence of environmental parameters affecting the relative catch rates influencing the differences in CPUA between Chickens and Targets.

When analysing the SMP+L subset across the two sites, the averaged model chosen to explain the variation in the response of CPUA, concluded that the factor depth (P= 0.004) had a significant effect on the distribution of the logRR (relative CPUA) (Table 17) (averaged across the 7 top set of models, ranging from 3-6 d.f, Gaussian dispersion, diagnostic plots reported in Appendix 14).The positive estimate output for depth (0.32 +- 0.1) indicates that as depth increases (becomes more negative), the logRR becomes more negative, therefore the effectiveness of the SMP+L increases with depth.

Table 17 *The estimated parameters, z values and p values for the preferred averaged generalised linear model describing the relationship between the relative abundance (count of individuals) caught per hectare in the SMP+L paired tows (logRR of CPUA) of Haddock (Melanogrammus aeglefinus) and the environmental variables recorded or calculated post hoc for each paired tow.*

Parameters	Estimate	z value	P
(Intercept)	-0.28	5.14	<0.00001***
Depth	0.32	2.85	0.004**
Ambient light level	0.17	1.50	0.13
Turbidity	0.18	1.56	0.12
Tidal coefficient	0.13	1.22	0.23

The average model used to explain the relationship between haddock caught in the SMP nets and environmental variables also found that, depth had a significant effect on the logRR of the SMP paired tows (P=0.002**) (Table 18) (Gaussian dispersion, with d.f ranging from 3-5, across the 4 models selected, diagnostic plots in Appendix 15). However, the relationship between depth and the distribution of the logRR of haddock is negative, with the logRR increasing as depth becomes more negative (deeper) (estimate -0.58 +- 0.17) (Table 18). This reveals that as depth increases the control net catches relatively more haddock than the SMP net ie. the effectiveness of the SMP is reduced with depth.

Table 18 *The estimated parameters, z values and p values for the preferred averaged generalised linear model describing the relationship between the relative abundance (count of individuals) caught per hectare in the SMP paired tows (logRR of CPUA) of Haddock (Melanogrammus aeglefinus) and the environmental variables recorded or calculated post hoc for each paired tow.*

Parameters	Estimate	z value	P
(Intercept)	-0.04	0.60	0.55
Depth	-0.58	3.14	0.002**
Cloud cover	0.26	1.52	0.13
Depth difference between vessels	0.25	1.47	0.14

This result suggests that, the SMP alone becomes less affective with depth, to the extent that the logRR becomes positive (ie. the treatment net caught more haddock than the control in deep water). However, with the addition of lights, the effect is reversed and the treatment net reduces haddock catches, with significantly lower CPUA than the control.

The other variables recorded were found to have no significant effect on the distributions of haddock CPUA in either the SMP or SMP+L treatments.

Analysis on the average total length of haddock caught per tow revealed that there was no significant difference between the control tows and their paired treatment tows (SMP and SMP +L) in both Chickens and Targets (Two way ANOVA: $F_{2,71}$=1.2, P= 0.32). However, visual interpretation of the data (Figure 19) suggests that in Targets, the SMP tows caught slightly larger individuals, with on average ~20mm larger individuals in the SMP net compared to the control net (Table 19).

Table 19 *The average and standard deviation (S.D) of the total length (TL) of haddock (Melanogrammus aeglefinus) measured on board the vessels in Chickens (CHI) and Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Area	**Treatment**	**Av.TL (mm)**	**S.D**
CHI	Control	294.38	23.77
	SMP	294.25	7.74
CHI	Control	296.44	18.43
	SMP+L	295.13	27.93
TAR	Control	286.69	34.06
	SMP	306.50	38.01
TAR	Control	280.50	28.15
	SMP+L	286.00	22.93

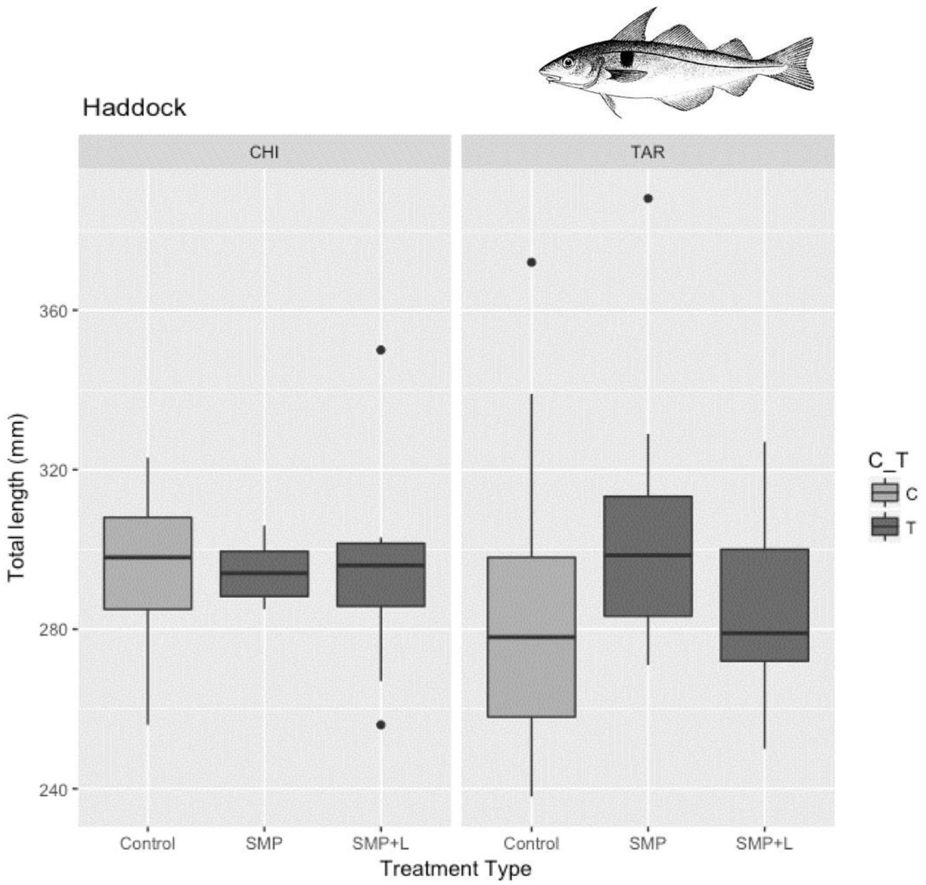


Figure 19. *The distribution of the mean total lengths (mm) per tow of Haddock (Melanogrammus aeglefinus) measured on board the control boat (C) compared to their paired treatment boats (SMP = square mesh panel and SMP+L= square mesh panel & lights). The measurements are displayed within all three sites (CHI = Chickens, RAM = Ramsey, TAR = Targets) with the median of the mean sizes per treatment indicated by the horizontal line and the error bars represent the 95% confidence intervals, while the dots represent outliers. Light grey indicates the control (C) tows and dark grey indicates the treatment tows (T).*

Whiting *(Merlangius merlangus)*

The distribution of whiting caught in both treatment and control tows was not as frequent or as wide spread as haddock, with the lowest abundances in Ramsey (8 individuals), higher abundances in Chickens (33 individuals) and the greatest abundances in Targets (139 individuals). Therefore all analyses conducted on whiting responses to the BRDs were conducted in Targets. Within Targets overall, the catch rates of whiting were reduced in both the treatment nets (SMP and SMP+L) relative to their paired control nets. The response to the BRDs for whiting can be observed by the raw CPUA data (Table 20) and through visual interpretation of the grouped tows for each treatment relative to their paired control (logRR) (Figure 20).

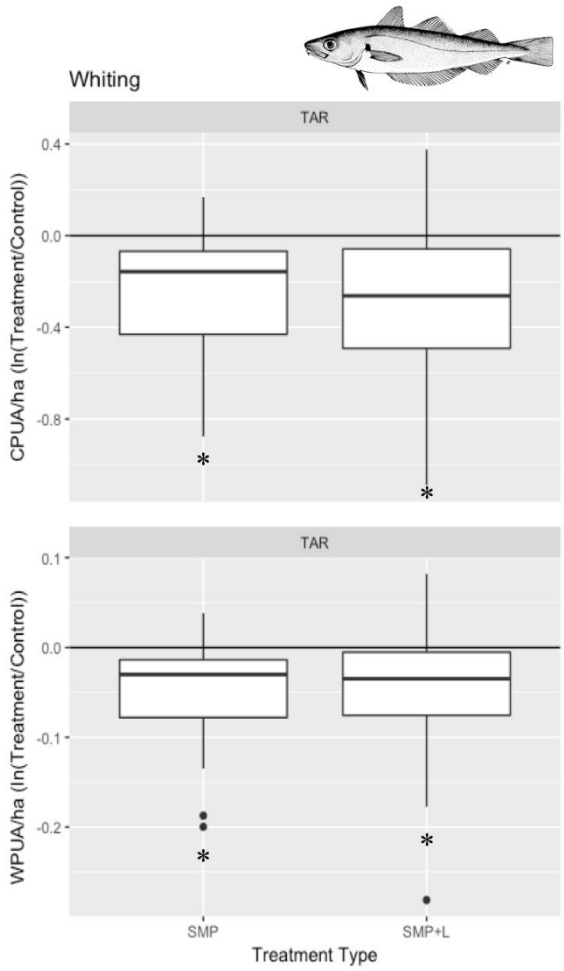


***Figure 20.** The relative catch (LogRR) for both the abundance (CPUA, top) and biomass (WPUA, bottom) per hectare of whiting (Merlangius merlangus), caught in both treatments SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, caught in Targets (TAR). The median is indicated by the horizontal line and the error bars indicate the 95% confidence intervals and the dots represent outliers. * above the boxes = indicate a significant difference (P<0.005) in catches between the two treatments. * below the boxes = a significant difference between the logRR in a single treatment compared to the control.*

Table 20 *The average and standard deviation (S.D) of the abundance per hectare (CPUA/ha) of whiting (Merlangius merlangus) recorded on board the vessels in Chickens (CHI) and Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Site	Treatment	Av. CPUA/ha	S.D	% difference
TAR	Control	0.38	0.47	-81.58
	SMP	0.07	0.11	
TAR	Control	0.53	0.61	-77.36
	SMP+L	0.12	0.16	

The CPUA/WPUA in the SMP+L treatment were found not to significantly differ from the catch in the SMP treatment (Table 21). Intercept only linear modelling showed there was a significant reduction in whiting in the SMP treatment relative to the control, with the average logRR CPUA of whiting caught in the SMP -0.27 (+-0.09 S.E) less than the control (Table 21.). While, the SMP+L net also significantly differed from their paired control tows, with the CPUA reduced on average by -0.29 (+- 0.12 S.E) relative to the control (Table 21.).

Table 21 *Outputs from the linear models incorporating both treatments, ANOVAs (Lm(logRR ~treatment) and intercept only linear models (Lm(logRR ~ control)) testing whether the treatment catches differed from the control. Models were conducted on the relative catch (LogRR) for the weight(kg) (WPUA) and count(CPUA) of whiting (Merlangius merlangus). The factors for each model are displayed, with both treatments analysed separately, the estimate (+- standard error, SE) is the mean logRR response for that treatment and it indicates whether the catch has increased or decreased relative to the control (+= increase, - = decrease),* ***t*** *value and p values are noted, with bold indicating significant values and *=significant (P=<0.05), **=very significant (P=<0.005). The factors and treatments are: SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in TAR = Targets.*

	Lm(logRR ~treatment) (ANOVA)					**Lm(logRR ~ control) (Intercept only linear regressions)**				
Site	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**
TAR CPUA	Intercept (SMP)	-0.27 (+-0.09)	-2.88	0.007**	32	SMP	-0.27 (+-0.09)	-3.07	0.008**	14
	SMP+L	-0.02 (+-0.12)	-0.18	0.86		SMP+L	-0.29 (+-0.09)	-3.36	0.003**	18
TAR WPUA	Intercept (SMP)	-0.05 (+-0.02)	-2.6	0.01*	32	SMP	-0.05 (+-0.02)	-2.78	0.015*	14
	SMP+L	-0.0008 (+-0.03)	-0.03	0.98		SMP+L	-0.05 (+-0.02)	-2.83	0.01*	18

None of the variables in the averaged GLM were considered to significantly affect the catch rate of whiting in the SMP+L compared to the control net (Table 22) (the selected models ranged from 2-5 d.f). Assumptions and model fit were deemed acceptable (diagnostic plots in Appendix 16). As the other environmental variables were absent from the selected model (cloud cover (%), depth(m), ambient light (lux)), it can be assumed that they too were not responsible for the change in catch rate of whiting compared to the control vessel in Targets.

Table 22 *The estimated parameters, z values and p values for the preferred averaged generalised linear model describing the relationship between the relative abundance (count of individuals) caught per hectare in the SMP paired tows (logRR of CPUA) of whiting (Merlangius merlangus) and the environmental variables recorded or calculated post hoc for each paired tow.*

Parameters	Estimate	z value	P
(Intercept)	-0.29	3.25	0.001**
Tidal coefficient	0.32	1.73	0.08
Turbidity	0.26	1.33	0.18
Seastate	0.22	1.20	0.23

When analysing the effect of the environmental parameters on the variability of the relative catch of whiting in the SMP treatment compared to the control, no environmental variables were reproduced in the averaged GLM. Therefore, none of the environmental variables recorded can be considered to explain the variation in response of catch rates of whiting caught in the SMP compared to their control in Targets.

The average total length of whiting caught per tow did not differ significantly in size between the control, SMP and the SMP+L nets in Targets (ANOVA: $F_{2,42}$= 0.34, P= 0.72) (Table 23, Figure 21) .

Table 23 *The average and standard deviation (S.D) of the total length (TL) of whiting (Merlangius merlangus), measured on board the vessels in Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Area	Treatment	Av.TL (mm)	S.D
TAR	Control	267.50	26.87
	SMP	260.17	39.50
TAR	Control	262.10	16.06
	SMP+L	270.45	31.03

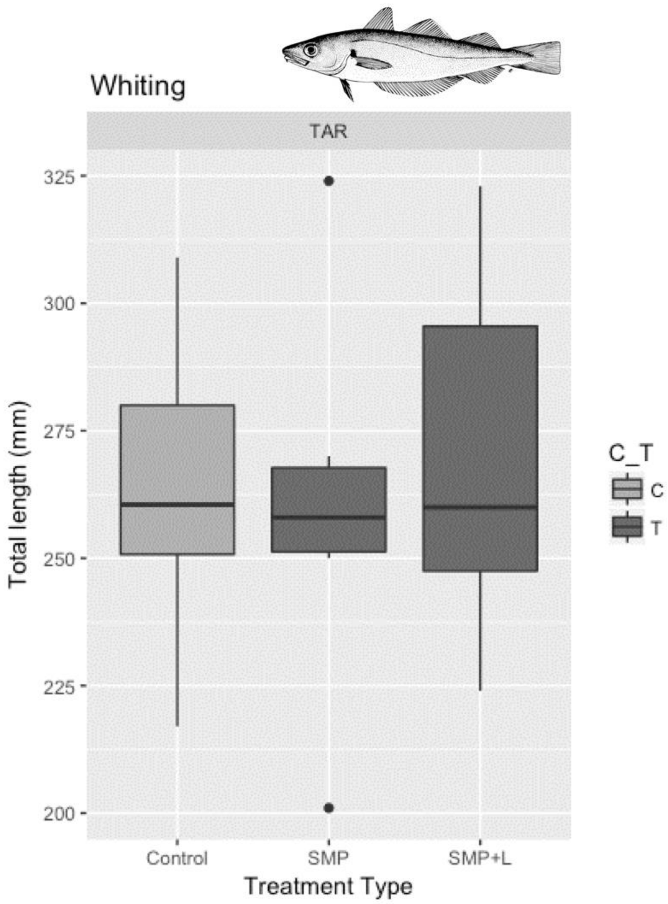


Figure 21. *The distribution of the mean total lengths (mm) per tow of Whiting (Merlangius merlangus) measured on board both vessels in Targets (TAR), with the control net compared to their paired treatment nets (SMP = square mesh panel and SMP+L= square mesh panel & lights). The median of the mean sizes per treatment is indicated by the horizontal line and the error bars represent the 95% confidence intervals, while the dots represent outliers. Light grey indicates the control (C) tows and dark grey indicates the treatment tows (T).*

Cod *(Gadus morhua)*

Out of the three main choke species of concern in the IoM QSC fishery, cod were caught in the lowest abundances throughout the trial, with a total of 57 individuals caught across all three sites in all treatments (CHI = 4, RAM = 4, TAR= 49). Cod analysis was conducted for Targets as the highest abundances of Cod were caught there. Across Targets, the raw average CPUA of cod in the treatment nets varied only slightly compared to the average CPUA in the paired control tows (Table 24). However, the catch rate increased overall in both the SMP and SMP+L, with the SMP+L treatment encountering the highest CPUA of cod compared to both the SMP treatment and the control (Figure 22).

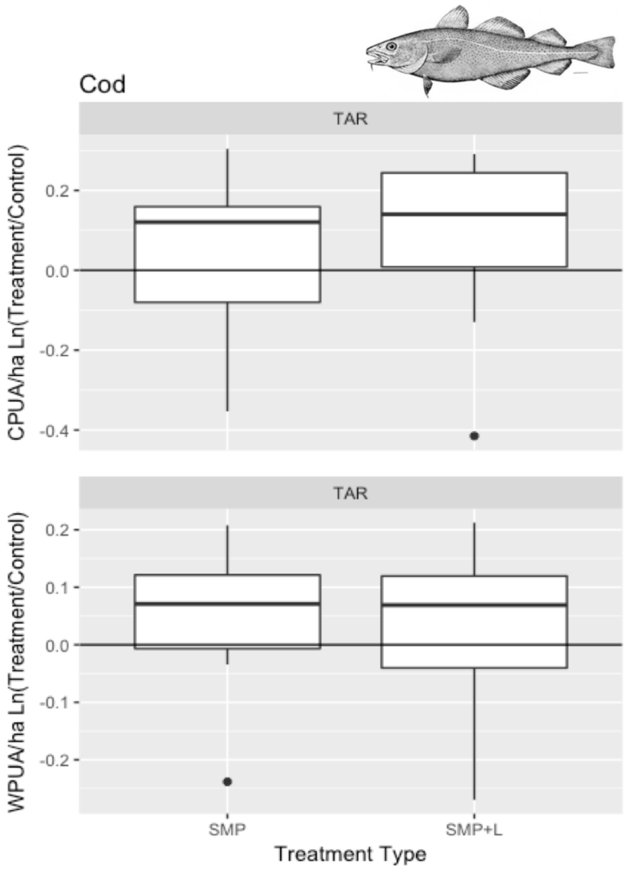


Figure 22. *The relative catch (LogRR) for both the abundance (CPUA, top) and biomass (WPUA, bottom) per hectare of cod (Gadus morhua), caught in both treatments SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, caught in Targets (TAR). The median is indicated by the horizontal line and the error bars indicate the 95% confidence intervals and the dots represent outliers.*

Table 24 *The average and standard deviation (S.D) of the abundance per hectare (CPUA/ha) of cod (Gadus morhua) recorded on board the vessels in Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Site	Treatment	Av. CPUA/ha	S.D	% difference
TAR	Control	0.09	0.17	+44.44
	SMP	0.13	0.17	
TAR	Control	0.07	0.14	+57.14
	SMP+L	0.11	0.18	

Although, these difference were not significant with only a small relative increase in average CPUA/WPUA logRR for cod in the SMP compared to the paired control tows and again only a small non significant increase in the SMP+L treatment relative to the control (linear regressions Table 25). The result of the ANOVA also discloses that the response and catch rate of cod in the SMP net did not differ significantly from the SMP+L nets, however no reductions in these species were achieved (Table 25).

Table 25 *Outputs from the linear models incorporating both treatments, using ANOVAs (Lm(logRR ~treatment) and intercept only linear models (Lm(logRR ~ control)) to detect whether each treatment independently differed from '0' or the control. Models were conducted on the relative catch (LogRR) for the weight(kg) (WPUA/ha) of cod (Gadus morhua). The factors for each model are displayed, with both treatments analysed separately, the estimate (+- standard error, SE) is the mean logRR response for that treatment and it indicates whether the catch has increased or decreased relative to the control (+= increase, - = decrease),* ***t*** *value and p values are noted, with bold indicating significant values and *=significant (P=<0.05), **=very significant (P=<0.005). The factors and treatments are: SMP = square mesh panel paired tows and SMP+L = square mesh panel + lights paired tows, in TAR = Targets.*

	Lm(logRR ~treatment) (ANOVA)					**Lm(logRR ~ control) (Intercept only linear regression)**				
Site	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**	**Factor**	**Estimate**	***t*-value**	**P**	**d.f**
TAR CPUA	Intercept (SMP)	0.06 (+-0.07)	0.88	0.39	17	SMP	0.06 (+-0.07)	0.92	0.38	9
	SMP+L	0.006 (+-0.10)	0.06	0.96		SMP+L	0.07 (+-0.08)	0.87	0.41	8
TAR WPUA	Intercept (SMP)	0.05 (+-0.04)	1.24	0.23	17	SMP	0.05 (+-0.04)	1.29	0.23	9
	SMP+L	-0.02 (+-0.06)	-0.30	0.77		SMP+L	0.03 (+-0.05)	0.73	0.49	8

As a result of the low catch rates and subsequent low replication of tows encountering cod across the trials, analyses in the form of GLMs could not be conducted to determine the influence of the environmental variables on the variation in relative CPUA of cod (logRR) for both the SMP and SMP+L treatments.

Cod caught in both the SMP and SMP+L treatment tows did not significantly differ in size in comparison to the paired control nets (ANOVA $F_{2,46}$=2.73, P= 0.08). However similarly to haddock, visual interpretation of the grouped average measurements per tow (Figure 23), suggest that the SMP tows caught slightly larger individuals than the control net and the SMP+L net, with an average of a ~26mm increase in size in the SMP treatment (Table 26).

Table 26 *The average and standard deviation (S.D) of the total length (TL) of cod (Gadus morhua), measured on board the vessels in Targets (TAR) for both treatments, square mesh panel (SMP) and square mesh panel & lights (SMP+L).*

Area	**Treatment**	**Av.TL (mm)**	**S.D**
TAR	Control	346.20	50.48
	SMP	372.73	31.55
TAR	Control	337.70	46.40
	SMP+L	341.79	43.96

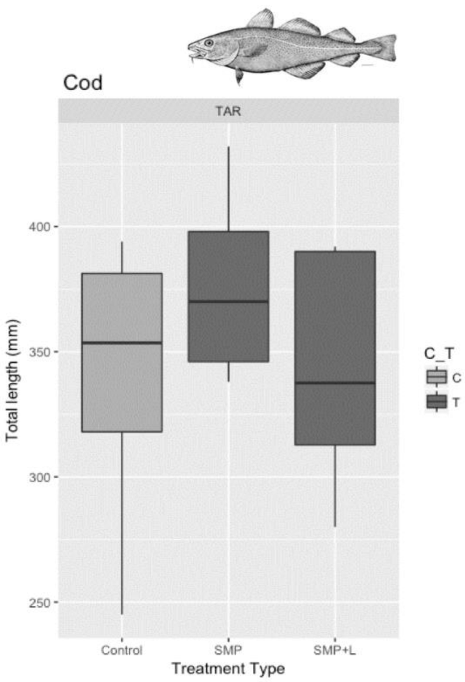


Figure 23. *The distribution of the mean total lengths (mm) per tow of cod (Gadus morhua), measured on board both vessels in Targets (TAR), with the control net compared to their paired treatment nets (SMP = square mesh panel and SMP+L= square mesh panel & lights). The median of the mean sizes per treatment is indicated by the horizontal line and the error bars represent the 95% confidence intervals, while the dots represent outliers. Light grey indicates the control (C) tows and dark grey indicates the treatment tows (T).*

4. Discussion

Across the trial, fewer bycatch species were encountered in the modified nets compared to the traditional control nets, with an average of 0.33(+-1.41) bycatch species per hectare caught with the control, compared to 0.31(+-1.24) in the SMP and 0.24 (+-0.87) in the SMP+L treatment nets. However, the response to the BRDs and change in bycatch CPUA and WPUA differed between sites and species and interestingly, in the case of some species, depth had either a positive or negative influence on the effectiveness of the BRD.

Species were found to have distinctly different responses to the two treatments, with these responses varying across sites. Figure 24 illustrates the quantified change in catch rate of species groups caught in both treatment nets relative to the control nets, indicating how these changes varied across sites. The species that were found to be most sensitive to the differences in the two treatments (ie. whether lights were present or not) were haddock and gurnard species when caught in Chickens and lesser spotted catshark in both Chickens and Targets (Figure 15 & 17). There was a mixed response detected when certain species encountered the SMP with both statistically significant increases and decreases observed in bycatch rates. Significant reductions in bycatch were detected for lesser spotted catshark, haddock and whiting in the SMP treatment (Figures 15, 17 & 20). However, significant increases in the catch rate of haddock were observed in the SMP in Chickens, with depth modelled as a significant factor affecting the CPUA (Table 17, 18 & Figure 18). With the addition of lights (SMP+L), significant reductions were seen in lesser spotted catshark, flatfish species, haddock and whiting (Figure 15, 16, 17 & 20). Importantly, these reductions in bycatch rates were achieved without affecting catch efficiency of queen scallop, as no significantly significant reductions in target species were detected within either treatment (Table 10).

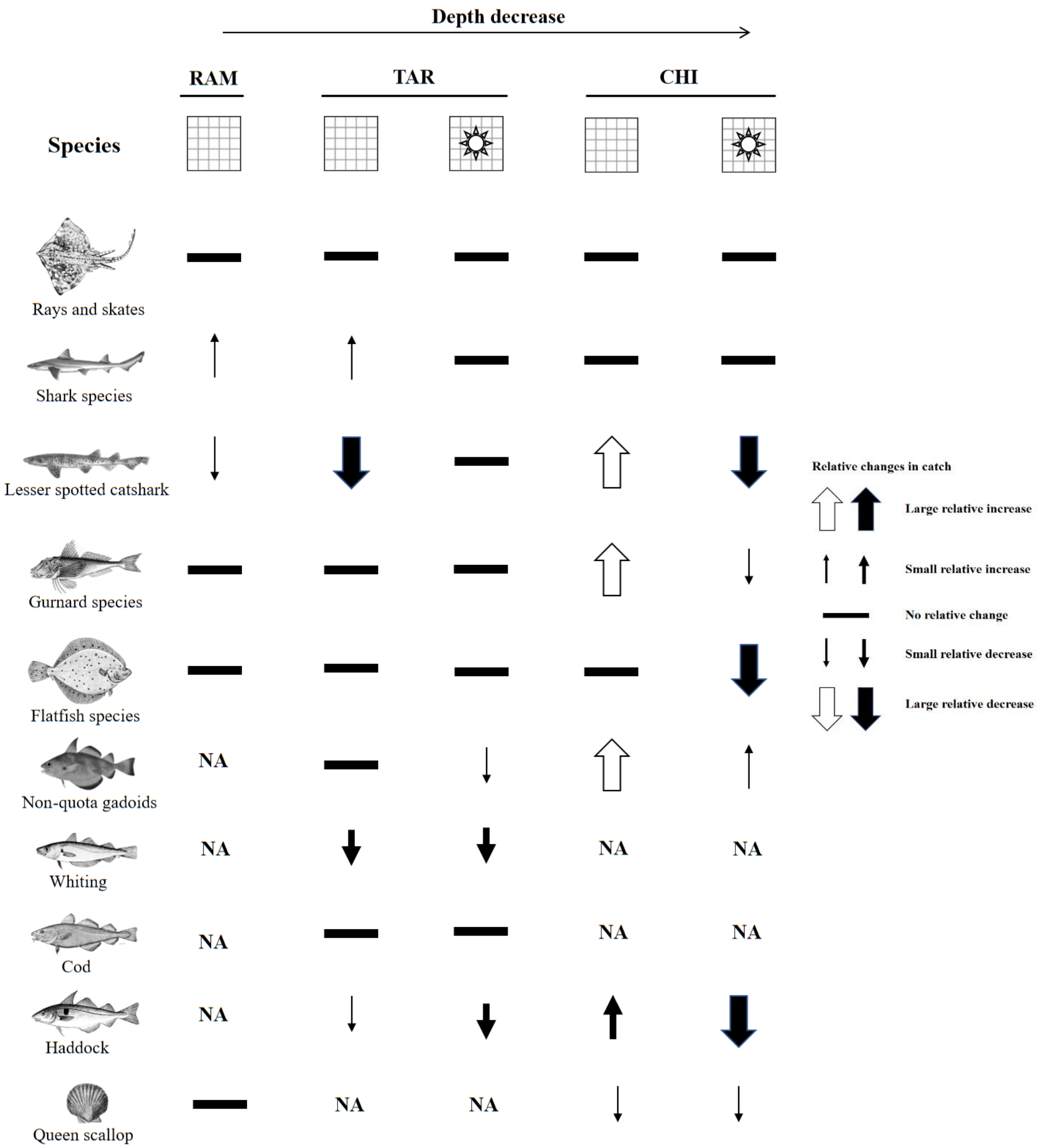


Figure 24 *The relative change of bycatch and target species groups CPUA (the groups are described in statistical methods section) as a response to the two treatments, SMP (indicated by the square grid) and the SMP and lights (indicated by the square grid and light symbol), caught in each site (RAM = Ramsey, TAR= Targets, CHI= Chickens). The change refers to either an increase or decrease in the relative CPUA (logRR) and utilizes the co-efficient estimate from the model lm(logRR~0), where a positive value means the catch in the control>treatment, while negative means treatment<control. The size of the change is categorised where by a value of: <0.10 = no relative change; 0.1 - 0.3 = a small relative change and; >0.3 = a large relative change in catch, which applies to both increases (+) and decreases (-). The bold arrows identify significant changes in catch, whereas the hollow or thin arrows represent non-significant changes.*

4.1 Community structure and environmental variation between grounds

Despite a degree of similarity in species assemblage between sites, the composition of bycatch species caught with the control net were found to differ significantly between sites (Table 5), which indicates that the three sites vary environmentally and were correctly identified as being an important factor within the study. Lesser spotted catshark contributed most to the similarity between sites (Table 6) and also characterised the largest portion of bycatch (CPUA) in both Ramsey (58.54%) and Targets (39.15%). Contrastingly, plaice dominated the bycatch in Chickens (31.21%). However, the assemblage of other bycatch species varied significantly between sites and drove the dissimilarity between sites. For instance, the quota gadoids were not encountered uniformly, with haddock representing the highest percentage of bycatch in Chickens (12%), whilst whiting contributed most to total bycatch in Targets (4.66%). The site in which cod generated the largest proportion of overall bycatch was Targets (0.82%), however cod was caught infrequently across all sites.

The environmental parameters attributed to the grounds were also found to differ, primarily by depth with distinct depth ranges for each site (Table 7 & Figure 12). The average particle sizes encountered across the swept area for each site were in contrast to what is reported elsewhere in the literature, for example Chickens is typically known to be characterised by rocky substrate and Targets is comprised of sandy/gravelly substrate, while Ramsey has finer muddy substrate (Hinz et al. 2010). The same study highlighted that the habitats and biotopes also differed between the same grounds (Hinz *et al.* 2010). This reinforces that the response of bycatch species to the BRDs could only be assessed on a site by site bases, as variations in the combinations of community structure and environmental parameters at different fishing grounds can influence the effectiveness of BRDs.

As a result of varying species physiology (with regards to strength, swimming ability, agility and vision) fish have certain species-specific behavioural characteristics and escape responses which differ when they encounter approaching nets fitted with BRDs (Wardle 1983; Watson 1989). For example, a study conducted in the north Queensland tiger prawn fishery found that in shallower waters, the reduction in bycatch was greater and it was suggested that this was because the fish caught were larger and therefore stronger swimmers, therefore more capable of escape (Courtney *et al.* 2000). It is important to understand how certain species respond to the modifications, as some individuals are of higher conservation status, or economic importance than others. This study focused on species-specific responses to the BRDs, or grouped animals that share physiological characteristics and could therefore expect to exhibit similar escape responses.

Specifically, the catchability of cod and haddock are known to be affected by environmental parameters, for instance tidal currents affect the vertical distribution of fish dictating the likeliness of them being caught by a bottom trawl (Michalsen *et al.* 1996). Ambient light intensity is also a factor that affects catch rates and species ability to detect and subsequently avoid capture by a trawl, as the level of light fish can adapt to varies with species. This is evident in the habitat depth preferences of species, which have evolved photoreceptor cells responsible for detection of light and colour within their ecological envelope (Glass and Wardle 1989; Gordon *et al.* 2002). Ambient light levels decrease with depth, therefore the fish caught in Chickens in the IoM study encountered the nets in much lower light and subsequently, visual ability will have been reduced compared to the fish captured in Targets and Ramsey. This is evident in the underwater video stills taken of the nets on each day of the survey (Appendix 15), as there is a decrease in light levels in footage from Chickens in depths ranging from -45 to -95 m. Light levels recorded by the light sensors mirrored this observation, with data showing the lowest light in the deeper sites (Table 7).

4.2 QSC catch by weight and size

There was a slight decrease found in target catch when comparing the WPUA of QSC caught in the modified nets with the all diamond mesh control, however the reduction was non-significant for both treatments (Figure13, Table 10). The size of the individuals caught were found to have a slight but significant decrease in the SMP treatment (Figure 14). Yet, further investigation is required as to whether the modifications do in fact change the selectivity of QSC trawls for target species, as the SMP+L tows were not found to significantly change the size selectivity of QSC and there is no evidence that suggests that the addition of lights would have an impact on the catchability of larger QSC. Interestingly, a study investigating the Atlantic sea scallop *(Placopecten magellanicus)* found that a higher proportion of individuals responded to artificial light by remaining still and swam more freely in darkness (Siemann *et al.* 2015). However, this does not explain why the SMP+L caught larger individuals, unless there is a distinct change in the behavioural response to light that changes with size in the species. Importantly, the proportion of undersized individuals was found not to differ between treatments (Table 12). This result also proved to be encouraging as not only did the treatment nets maintain the weight of target catch, they also did not increase the proportion of undersized queen scallop, subsequently maintaining the proportion of marketable sized catch.

4.3 Species responses in abundance and weight to the BRDs

4.3.1 Grouped species with similar physiology

Rays

As expected, species caught in the treatment nets that lacked the required size and shape to escape through the SMP did not differ in catch rate compared to those caught in the control nets. For instance, ray species bycatch were reduced very slightly in CPUA in both the SMP and SMP+L treatments but this difference was non-significant and the introduction of light had no effect on the catch (Figure 15). Although ray species are capable of both pelagic and benthic swimming, they tend to use pectoral fin locomotion to propel themselves through the water or along the seabed and likely lack the speed needed for escape (Carrier *et al.* 2012; Rosenberger 2001).

Shark species

Shark species (excluding lesser spotted catshark), were among the largest individuals caught in the nets and as a result these species saw no significant difference in CPUA in either treatment nets compared to the control, and like rays the addition of lights had no influence on the catch rates (Figure 15). However there was a slight increase in catch in Ramsey and Targets (Table 13), this increase is surprising as shark species are strong swimmers and anecdotal evidence captured on the video footage confirms that the shark species are capable of escaping through the square meshes (Carrier *et al*. 2012) (Figure 25).

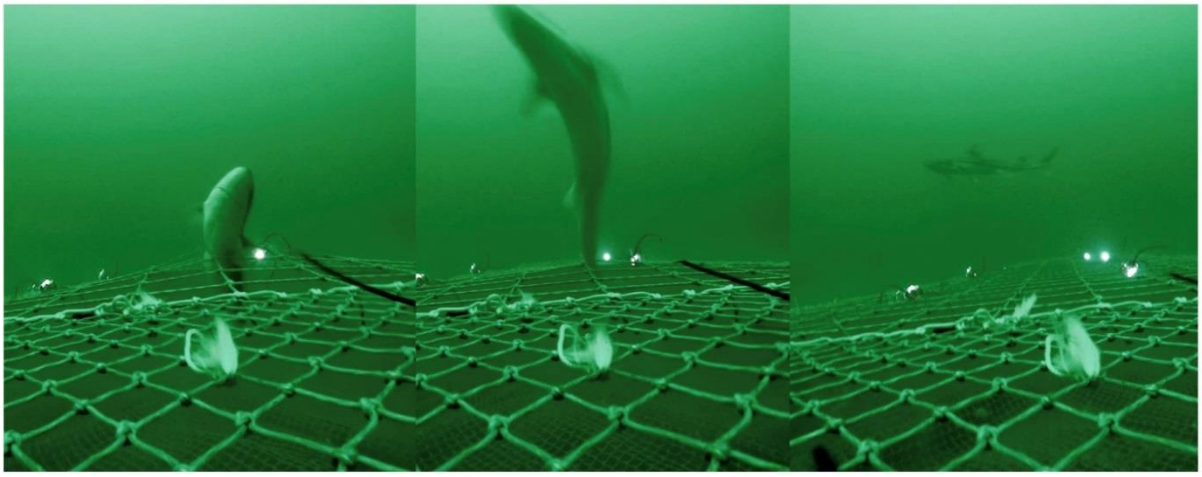


Figure 25 *Stills from the GoPro video footage of a shark species escaping through the large meshes in the square mesh panel implemented into the queen scallop otter trawl, in the IoM. The image is taken from the top of the net anterior to the square mesh panel on the outside of the net looking towards the aft end of the net.*

The flexibility of the mesh also allows these larger animals to force their way out, which was witnessed on video and found to be the case for other large animals in trials using SMPs (Broadhurst *et al.* 2002). Interestingly, an individual shark species was also seen escaping via the mouth of the net, ensuring it did not fall back into the codend where water pressure is highest (Broadhurst and Kennelly 1996). If this is their usual escape strategy, this could explain the slight increase in CPUA, as drag is known to be reduced with larger meshes like that of the SMP (Campbell *et al.* 2010). The increase in flow generated by the water rushing out of the SMP may have made the mouth a more difficult escape route in comparison to the control net with smaller meshes causing higher pressure and therefore slower water flow through the mouth and central column of the net.

Non-quota gadoids

The SMP relative to the control net saw no change in the CPUA of *non-quota gadoids* (poor cod and pouting) (Figure 15 & Table 14). Furthermore, the addition of artificial lights to the panel failed to stimulate an escape response of these species, although they may lack the strength to swim against the flow and escape through the meshes due to their small size. This result is a little discouraging as the incorporation of square meshes are known to reduce gadoid bycatch, including small fish (Robertson 1983; Kim *et al.* 2008). Other methods to reduce such species may need to be sought, should these species become commercially important in the

Irish Sea, as SMPs have previously been found to have little or no effect on the reduction of demersal species such as pouting and poor cod in comparison to pelagic round fish (Fonseca *et al.* 2005; Özbilgin *et al.* 2005).

Gurnard species

A similar response was true for gurnard spp., as their catch rate did not change significantly when encountering either treatments (Figure 15 & Table 14). Their physiology is suited to that of a benthic fish, which tends to glide over the seabed and may therefore lack the escape responses needed to direct itself out of the codend and up towards the SMP (Norman & Greenwood, 1963;Davenport, 1999). However, a study investigating the effect of SMPs in the prawn fishery in New South Wales successfully reduced gurnard spp. bycatch. These reductions were attributed to the displacement of water flow and hydrodynamic pressure away from the back of the net as a result of the SMP anterior to the codend, enabling smaller fish such as gurnards (which had fallen back and gathered in the codend) to maintain their position and encourage them to escape out of the SMP. However, the effectiveness of this method is sensitive to the size and position of the SMP and in the case of the IoM otter trawls, which were fitted with a large SMP relative to the overall size of the net, the SMP may have generated an overall increase in water flow through the square mesh, resulting in an environment that did not stimulate the necessary escape responses and failed to encourage the fish to swim out of the large SMP. This theory will be discussed in more detail later in the discussion (Broadhurst and Kennelly 1996; Broadhurst *et al.* 1999; Broadhurst *et al.* 2002). In Chickens, where the light levels were exceptionally low, gurnard spp. catch increased (though non-significantly). The failed escapement of this group in Chickens could be a combination of the aforementioned increased water flow, reducing the gurnards ability to escape compounded with the poor vision attributed to the species in low light levels (Hunt *et al.* 2015). This theory is also reinforced through the opposite reaction to the SMP incorporating artificial light in Chickens, which saw a decrease in CPUA and this response was significantly different to that of the response observed in the net incorporating the SMP alone (Figure 15 & Table 14). This indicates that although neither treatment significantly differed from that of the control, the introduction of lights in water depths below 45m induces a significantly different escape response in *gurnard species*, with more fish locating and escaping through the SMP with the aid of the lights.

Flatfish

The number of flatfish caught in the SMP net did not significantly differ from that caught by the paired controls (Table 14 & Figure 16). Much like rays, gurnards and some gadoids, flatfish are demersal species and when encountering a trawl they tend to remain low and gather into the lower sections of the net (Main and Sangster 1982). However albeit a small reduction, encouragingly flatfish were found to be reduced in the SMP+L net (Table 14 & Figure 16). The theory explained previously for gurnards may also be true for flatfish, as they exhibited a similar pattern in Chickens with increased catch in the SMP and a significant decrease when lights were added. Flatfish species have previously been found to avoid capture with green lights attached to the footrope of a prawn trawl in Oregon, promoting the idea that artificial light can reduce the catch of flatfish (Hannah *et al.* 2015).

The survivability of *Flatfish* and *rays and skates* is increased with smaller overall catch, as lower levels of abrasion from other captured animals in the cod end of the net are found to reduce mortality rates (Kaiser and Spencer 1995;Enever *et al.* 2009). Therefore, the reductions observed in lesser spotted catshark, flatfish, haddock and whiting bycatch may increase the probability that skates and rays would survive post discarding.

4.3.2 Individual species responses

Lesser spotted catshark

In contrast to the other shark species encountered, lesser spotted catshark were found to be reduced albeit non-significantly in the SMP net in Ramsey and significantly in Targets by ~34%, (Table 13, Table 14 & Figure 15). This reduction is encouraging as the use of the SMP in these areas could reduce overall bycatch, as these species generated the largest proportion of bycatch in both Ramsey and Targets, 58.54% and 39.15% respectively. Although, previous studies have found that these species remain low both when approached by and once inside a trawl (Main and Sangster 1982), they imply that these sharks are agile swimmers with physiological and behavioural characteristics required for escapement.

Observations from the video footage indicated that they have a more *erratic* response described by Kim and Wardle (2003) when inside the net, this response works in their favour as it seems to have increased their chance in locating the SMP compared to the more controlled response seen in the *other shark species*. However, this reduction was reversed when lesser spotted catshark encountered the net with the SMP alone in the deeper, darker waters in Chickens (Table 14 & Figure 15). The previously mentioned theory predicting that a change in hydrodynamic flow caused by the open square meshes in the panel, may have created a more difficult environment for the lesser spotted catsharks to escape, which then compounded with the lack of ambient light may have caused the observed (non-significant) increase in numbers of the species caught in the SMP net in Chickens (Table 14 & Figure 15). With the introduction of lights in Chickens, a significant decrease of -48.37% compared to the control net was observed (Table 13 & Table 14). This finding implies that, like gurnards, these shark are positively influenced by the aid of artificial light as they are more likely to locate the SMP when the LED lights are attached in dark water in depths >45m. Interestingly, but rather discouragingly in Targets in depths from ~29 to 40m, the SMP+L net contradicted the results in Chickens and although both treatments reduced the catch, the SMP+L net caught relatively more lesser spotted catshark than the SMP net (Table 14 & Figure 15). This mixed response implies the species have a strong reaction to artificial light, which may be enhanced or weakened with ambient light levels. This theory has been explored by Kim and Wardle (1998) who point out objects begin to lose definition and colour in depths >20-30m as the light becomes monochromatic. Therefore the addition of light at these depths will have increased the contrast and definition of the netted SMP and this contrast will have intensified in deeper water, which could explain why in Chickens the escape response was much greater than in shallower waters in Targets. The change in contrast between the LED lights, the deeper/darker water and the SMP netting is demonstrated in the video stills in Appendix 15-20. Ryer *et al.* (2009) also found more active species swam away from light sources, as an avoidance behavioural strategy, which could explain the reactions seen in Targets as species avoided the panel rather than swimming towards it, yet this does not explain why this behaviour was not seen in Chickens and requires further investigation.

Haddock, cod and whiting

The effect of BRDs on the catchability of the gadoid species of highest concern in the IoM also had a mixed effect between treatments and sites. In Targets both haddock and whiting were significantly reduced in both the treatment nets (Figure 17 & 20). Haddock saw similar reductions when fished with the SMP and SMP+L nets compared to the control, with an average reduction of 0.26 (63.41%) and 0.23 (54.75%) CPUA per hectare respectively (Table 15). Whiting also saw similar reductions in the SMP and SMP+L nets, although the reductions were greater than haddock with average reductions of 0.31 (81.58%) and 0.41(77.36%) CPUA per hectare, respectively (Table 20). However, the numbers of cod caught in the SMP or SMP+L nets did not differ from the catch fished by the all diamond mesh net (Figure 22 & Table 25). These responses have been observed in previous studies, as whiting and haddock both share the desired escape responses needed to successfully utilise the SMP. They have a vertical swimming preference and lift into the upper part of the panel through exhaustion and during herding in the net they swim in fast *erratic* dashes followed by escape through the square mesh. Contrastingly, cod tend to enter the trawl low and remain in the bottom panel of the trawl and *drift* passed the escape panel (Main and Sangster 1982; Ferro *et al.* 2007; Kim *et al.* 2008; Krag *et al.* 2009; Herrmann *et al.* 2015). Briggs (1992) noted that during video observations of whiting encountering a SMP, the species actively escape through the meshes once in the vicinity of the panel, whereas when caught in a diamond mesh net, they simply *nose* the diamond mesh attempting to escape through the closed meshes. Cod were also caught in very low numbers with an average of 0.13 CPUA caught with the SMP net in Targets (Table 24). It is possible that low levels of bycatch may have inhibited cod to initiate an escape response, as previous studies have found that larger densities of fish crowding in the codend can evoke escape responses urging fish to swim out of the escape panel (Watson 1989; Broadhurst and Kennelly 1996; Broadhurst *et al.* 2002).

It is likely that the escapement of haddock and whiting increased with greater ambient light levels in the shallower water at Targets. When facing the nets in deeper water (> 45m) with lower ambient light levels in Chickens, haddock shared a similar response to the treatment nets as gurnards and lesser spotted catshark with a significant average increase of 0.8 in CPUA in the SMP but a drop in CPUA when the LED lights were attached to the SMP by an average of 1.45 individuals per hectare, compared to the control net. Studies investigating gadoids reactions to trawls found that in very low light levels, fish are incapable of swimming at a control pace in an ordered pattern in front of the net, which is observed in higher light levels (Glass and Wardle 1989). It has been suggested that vision is the primary sense that fish use to detect oncoming nets in daylight or shallower waters. When confronted with nets in the dark, they are incapable of locating the gear to avoid collisions, which in turn explains why with the absence of the aid of lights in Chickens there was no reduction in haddock as they were unable to locate the SMP and escape through the panel. In darkness a larger proportion of haddock have also been found to remain low in the net compared to individuals encountered in daylight and gadoids in general are found to enter nets at greater heights in higher light levels (Main and Sangster 1982; Ferro *et al.* 2007). However, these findings alone do not explain why there was an increase in catch compared to the control. This unexpected pattern in the data was also identified, albeit to a lesser extent, in *gurnards*, *flatfish* and lesser spotted catshark, and may be due to the previously mentioned theory that the insertion of an SMP in a IoM QSC otter trawl changes the hydrodynamics of the water flow in the main body of the net (Broadhurst *et al.* 2002).

4.4 The influence of the geometry of the net, the size and placement of the SMP and recommendations for future trials

Changes in water flow have suggested to be the reason for changes in gadoid behaviour observed in previous gear trials (Thomsen 1993; Broadhurst *et al.* 2002; Marlen 2003; Campbell *et al.* 2010). For instance, Thomsen found that cod rose up in a beam trawl that had large mesh openings in the forward top section of the trawl, indicating the inflow of water changed the hydrodynamics in the net exerting more force on the fish lifting them up from the lower sections of the net. In the case of the IoM QSC otter trawls, the large SMP, covering a third of the net length, may have exerted an increase in flow on the fish pushing them back and upwards in the net, which worked in their favour in high ambient light as they were able to see the panel to escape. Whereas in darkness fish capture may have increased as the ability of the animals to locate the open meshes is reduced, combined with an increase of inflow of water in the mouth of the net compared to the control net.

The damage to the net was also thought to be a result of the larger SMP (20x12M) changing the geometry and flow within the net, resulting in less pressure being exerted on the top section of the net from within, causing the net to lose the shape that traditionally the all diamond mesh net maintained, allowing the net to drop down directly below the SMP and subsequently the sides of the net sagged and chafed on the seabed (MFPO *pers comms* 2017). The skippers reported that the smaller SMP (20x8M) greatly improved the performance and durability of the net once it replaced the larger SMP, which indicates the change to the dimensions of the SMP alleviated the net sag and re-established the water pressure and net geometry required.

Alterations to the size and position of the SMP have been tested in commercial gear trials elsewhere to reduce gadoid bycatch. Herrmann (2015) found that the change to the size of the SMP of 50% did not affect the escapement efficiency of gadoids, if the panel is close to the codend. Placement was limited in the IoM QSC trawls due to the net being much smaller than other trawls (ie. Nephrops trawls). The SMP was positioned ~0.5m from the forward meshes of the cod end and ~3.5m from the codline. However, if the SMP was reduced in size and placed as close as possible to the codline without the risk of losing QSC, both water flow and distance from the SMP would be reduced increasing the chance of bycatch species swimming forward to escape through the panel. The majority of studies found that the escapement increased as the distance between the SMP and the codline decreased, thus reducing gadoid catch including cod as well as haddock and whiting (Graham *et al.* 2003; Broadhurst *et al.* 2002; Herrmann *et al.* 2015). These reductions are induced through strategically placing the panel so that it is situated in the position at the rear end of the net, where water pressure is greatest (the codend). The displacement effect that the position of the SMP has on the water-flow through the net stimulates an escape response in fish, in turn forcing them to swim out through the panel (Broadhurst *et al.* 2002; Herrmann *et al.* 2015). However, in this study, there is some evidence that insertion of an SMP may result in the loss of target catch, which is evident in fisheries elsewhere that have trialled an SMP overlapping the codend. Therefore, SMP placement further forward of the codend would be most suitable for the IoM QSC trawls. Escape efficiency of haddock and whiting can be maintained in SMPs placed away from the codend. However, cod are found to drift passed the panel and into the codend unless additional devices are utilized such as *float ropes* that guide the fish up and out of the panel (Herrmann *et al.* 2015) (Figure 25). *Blacktunnels* are also found to enchance escape efficiency of haddock and whiting in nets with the SMP placed ~5-7m away from the codline, as the fish are found to be reluctant to swim through the dark tunnel situated directly behind the SMP, turning to swim out of the SMP instead (Glass and Wardle 1995). Although catch rates of both haddock and whiting have been significantly reduced in this trial, these devices could prove useful in further reducing haddock and whiting, as well as cod bycatch in waters with higher ambient light levels.

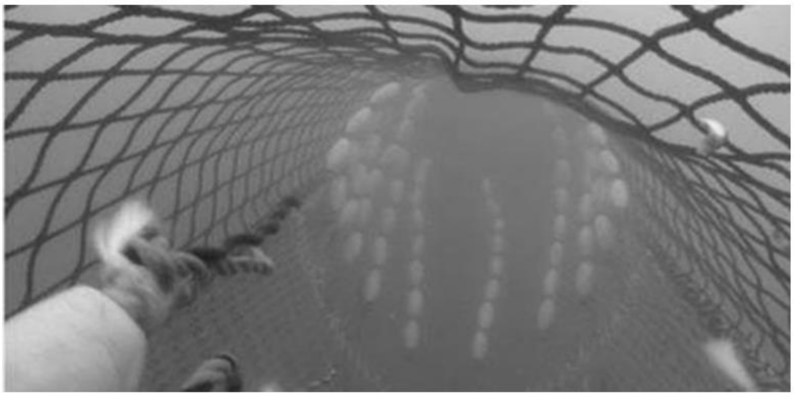


Figure 26 *Image of the float ropes used to guide fish, such as cod to swim up towards the SMP rather than remaining low in the net. This photo is taken during towing at a speed of three knots. The image is taken at the front part of the codend looking towards the aft end. (Herrmann et al. 2015)*

The addition of artificial light in this trial has been shown to have increased escape responses in numerous species of various shapes and sizes including haddock, lesser spotted catshark, gurnard species, and flatfish. Therefore, trialling artificial light at the mouth of the net, with the aim of detering species from entering, or enable species to detect the approaching net, could potentially reduce the capture of species that are unlikely to escape through the SMP (Hannah *et al.* 2015). However, the majority of fishing pressure over the past few years has been concentrated in shallower grounds, therefore the use of light may not be as effective in the IoM territorial sea (Table 7). A combination of devices may prove most effective in reducing cod, haddock, whiting and potentially other bycatch species, including *float ropes* situated below the SMP, with the addition of lights either attached to the headrope and/or the SMP.

4.5 Size selectivity of quota gadoids in the BRDs

The size of the three quota gadoids (haddock, cod and whiting) were not found to differ as a response to either treatment compared to the control net (Figure 19, 20 & 23). However, the raw data suggest there was a slight increase in average size of haddock and cod caught in the SMP net in Targets compared to the control with increases of ~10mm and ~26mm, respectively (Table 19 & 23). This implies the SMP allowed smaller individuals to escape, which has been observed previously, with SMPs used as a tool to reduce juvenile bycatch (Briggs 1992; O'Neill *et al.* 2006). Although, as the IoM fishery aim to reduce both adult and juvenile gadoid bycatch, there is no need to increase size-selectivity of these species and the results are encouraging as they imply both large and small indivduals are capable of escape.

4.6 Teleost bycatch stomach content analysis and scavenging behaviour

A study in 2012 found that within IoM waters scavenging species such as dab feed on discarded QSC, this feeding behaviour may be encouraged as a result of the consequential fatigue of QSC on the seabed after being discarded (Boyle and Thompson 2012). Therefore, several bycatch species caught throughout the trial were retained to investigate further whether QSC had been preyed upon during the survey using stomach content analysis.

The species and number of individuals dissected were 51 dab; 45 plaice; 69 lemon sole; 21 whiting; 12 cod and; 19 haddock. However, preliminary analysis found that most of the stomachs removed were empty and the few with partially full stomachs were opened and the content did not contain QSC, with the exception of 2 Cod individuals. However, the individuals were partially digested and identification could not be certain, crab and small mollusc species were found most commonly in the full stomachs. We hypothesized that due to the different technique in fishing practices, compared to the previous study, such as the random nature in which the nets were towed, there was little chance that the fish preying upon the recently discarded QSC would be caught in the nets, as the same direct ground was very rarely towed over repeatedly (Boyle and Thompson 2012). Therefore, no further investigation was pursued into stomach content analysis during this trial, as the fishing methods may have varied in comparison to previous studies which made these findings incomparable. Although, these findings may prove useful when designing the tow structure for future discards surveys focusing on scavenging behaviour.

5. Conclusion

The Isle of Man fishery requires the evidence or tools necessary to conform to the *landings obligation* which will enforce a ban on discarding all EU quota species by 2019. Therefore, the current study investigated the potential to reduce bycatch through inserting: 1) a square mesh panel alone and; 2) a square mesh panel incorporating six artificial white lights into a commercial queen scallop otter trawl in the Isle of Man fishery.

The trial confirmed that the Isle of Man queen scallop fishing grounds differ in both community assemblages and environmental parameters, therefore the effectiveness of the bycatch reduction devices differed between grounds. Water depth was found to be a significant factor influencing bycatch rates. It is also assumed that ambient light had an influence on the escapement of the bycatch species in question, as light decreases with depth.

In Ramsey Bay, the shallow ground, no significant change in catch was observed in any of the species fished with the modified net. Whereas in Targets (with medium depths), the square mesh panel net was found to reduce whiting bycatch by 82% and lesser spotted catshark by 34% less than the control net per hectare. The efficiency in reducing bycatch in the net incorporating both the square mesh panel and lights did not differ compared to the net with the panel alone in medium depths. Yet relative reductions were seen in haddock by 55% and whiting by 77%. Whilst in Chickens, which was the deepest ground, a reoccurring pattern was observed whereby species groups increased in catch when fished with the square mesh panel net (in low ambient light levels) which were then reduced substantially when the lights were attached illuminating the escape panel. This pattern was observed in non-commercial species, gurnards and lesser spotted catsharks. Haddock was also highly influenced by the addition of lights in depth >45m with significant increases fished the panel alone of 46% and decreases of 44% in catch when fishing with the lights. Unexpectedly, the catch of flatfish species was also reduced when fished with the square mesh panel and lights net in deep water by 26%. Importantly, the catch rate of these bycatch species was reduced whilst maintaining target catch rates of queen scallop.

Although reductions were observed in the key *choke* species whiting and haddock, no change in catch rates were observed in either treatment net for cod. All three gadoids were caught infrequently in all sites, with cod caught the least of the three species. However, the need to reduce the quota species bycatch is crucial as stocks are recovering for both haddock and cod in the Irish Sea. Although the total allowable catch for the area will increase, it may also mean fishers will suffer an increase in bycatch (ICES 2017b; ICES 2017a). Despite the use of technical modifications to nets, total discards estimates remain high for whiting in the Irish Sea, therefore ICES advise that the catch remain at zero until at least 2020 (ICES 2017c).

There is potential to trial further alterations to the nets to increase reductions in cod as well as whiting and haddock bycatch. Light alone could also be used as a tool to reduce bycatch of species of varying shapes and sizes, there was a strong reaction to artificial light. However, the context in which the lights are implemented is key to reducing bycatch, as further investigation is required to determine whether these species are attracted to the lights and subsequently swim towards them and through the mesh openings, or whether the light simply illuminates the panel enabling the species to locate it and direct themselves out of the net. If the latter is true then lights attached to the mouth of the net could prove most useful, as artificial light could illuminate the net and prompt the species to avoid it, rather than attracting them towards it and consequently increasing bycatch.

References

Alverson, D.L. (1994). *A Global Assessment of Fisheries Bycatch and Discards*. Food & Agriculture Org.

B. Isaksen and J.W Valdemarsen (1986). Selectivity experiments with sqaure mesh codends in bottom trawl. *International Council for the Exploration of the Sea*:18.

Van Beek, F.A. and Rijnsdorp, P.I. van L.A.D. (1989). On the survival of plaice and sole discards in the otter trawl and beam trawl fisheries in the North Sea. *Netherlands Journal of Sea Research* **1989/G:46**:18.

Bellido, J.M., Santos, M.B., Pennino, M.G., Valeiras, X. and Pierce, G.J. (2011). Fishery discards and bycatch: Solutions for an ecosystem approach to fisheries management? *Hydrobiologia* **670**:317–333.

Ben-Yami, M. (1988). Attracting fish with light. :72.

Ben-Yami, M. (1976). Fishing with light. *Food and Agriculture Organization of the United Nations, Fishing News Books* :131.

Boyle, K., Kaiser, M.J., Thompson, S., Murray, L.G., Duncan, P.F., Pe, N. and Kingdom, U. (2016). SPATIAL VARIATION IN FISH AND INVERTEBRATE BYCATCHES IN A SCALLOP TRAWL FISHERY. *Journal of Shellfish Research* **35**:1–9.

Boyle, K. and Thompson, S. (2012). Bycatch Survey – Isle of Man Queen Scallop Otter Trawl Fishery Summer 2012.

Brčić, J., Herrmann, B. and Sala, A. (2016). Can a square-mesh panel inserted in front of the codend improve the exploitation pattern in Mediterranean bottom trawl fisheries? *Fisheries Research* [Online] **183**:13–18. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0165783616301448.

Briggs, R.P. (1992). An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea Nephrops fishery. *Fisheries Research* **13**:133–152.

Broadhurst, M.K. (2000). Modifications to reduce bycatch in prawn trawls: A review and framework for development. *Reviews in Fish Biology and Fisheries* **10**:27–60.

Broadhurst, M.K. and Kennelly, S. (1996). Effects of the circumference of codends and a new design of square-mesh panel in reducing unwanted by-catch in the New South Wales oceanic prawn-trawl fishery, Australia. *Fisheries Research* **27**:203–214.

Broadhurst, M.K., Kennelly, S.J. and Eayrs, S. (1999). Flow-related effects in prawn-trawl codends: Potential for increasing the escape of unwanted fish through square-mesh panels. *Fishery Bulletin* **97**:1–8.

Broadhurst, M.K., Kennelly, S.J. and Gray, C.A. (2002). Optimal positioning and design of behavioural-type by-catch reduction devices involving square-mesh panels in penaeid prawn-trawl codends. *Marine and Freshwater Research* **53**:813–823.

Campbell, R., Harcus, T., Weirman, D., Fryer, R.J., Kynoch, R.J. and Neill, F.G.O. (2010). The reduction of cod discards by inserting 300 mm diamond mesh netting in the forward sections of a trawl gear. *Fisheries Research* **102**:221–226.

Carrier, J.C., Musick, J.A. and Heithaus, M.R. (2012). *Biology of Sharks and Their Relatives, Second Edition*. CRC Press. Available at: https://books.google.co.uk/books?id=7qXMBQAAQBAJ.

Catchpole, T.L., Frid, C.L.J. and Gray, T.S. (2005a). Discarding in the English north-east coast Nephrops norvegicus fishery: The role of social and environmental factors. *Fisheries Research* **72**:45–54.

Catchpole, T.L., Frid, C.L.J. and Gray, T.S. (2005b). Discards in North Sea fisheries: Causes, consequences and solutions. *Marine Policy* **29**:421–430.

Catchpole, T.L. and Gray, T.S. (2010). Reducing discards of fish at sea : a review of European pilot projects. *Journal of Environmental Management* [Online] **91**:717–723. Available at: http://dx.doi.org/10.1016/j.jenvman.2009.09.035.

Clarke, K.R. and Warwick, R.M. (1994). An approach to statistical analysis and interpretation. *Change in marine communities* **2**.

Clucas, I. (1997). A study of the options for utilization of bycatch and discards from marine capture fisheries. *FAO fisheries circular* **928**:1–59.

Condie, H.M., Grant, A. and Catchpole, T.L. (2014). Incentivising selective fi shing under a policy to ban discards ; lessons from European and global fi sheries. *Marine Policy* [Online] **45**:287–292. Available at: http://dx.doi.org/10.1016/j.marpol.2013.09.001.

Courtney, A.J., Campbell, M.J., Roy, D.P., Tonks, M.L., Chilcott, K.E. and Kyne, P.M. (2008). Round scallops and square meshes: A comparison of four codend types on the catch rates of target species and by-catch in the Queensland (Australia) saucer scallop (Amusium balloti) trawl fishery. *Marine and Freshwater Research* **59**:849–864.

Courtney, A.J., Haddy, J.A., Campbell, M.J., Roy, D.P., Tonks, M.L., Gaddes, S.W., Chilcott, K.E., *et al.* (2000). *Bycatch Weight, Composition and Preliminary Estimates of the Impact of Bycatch Reduction Devices in Queensland's Trawl Fishery*.

Crowder, L.B. and Murawski, S. a. (1998). Fisheries Bycatch: Implications for Management. *Fisheries* **23**:8–17.

Davenport, J. (1999). Swimbladder volume and body density in an armoured benthic fish, the streaked gurnard. *Journal of Fish Biology* **55**:527–534.

Davies, R.W.D., Cripps, S.J., Nickson, A. and Porter, G. (2009). Defining and estimating global marine fisheries bycatch. *Marine Policy* **33**:661–672.

EC (2013). REGULATION (EU) No 1380/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC. *Official Journal of the European Union* **L354**:40.

Elliott, S. and Catchpole, T. (2015). *Trawl Light. A Scoping Study*.

Enever, R., Catchpole, T.L., Ellis, J.R. and Grant, A. (2009). The survival of skates (Rajidae) caught by demersal trawlers fishing in UK waters. **97**:72–76.

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J. and Buckett, B. (2007). Separating species using a horizontal panel in the Scottish North Sea whitefish trawl fishery.

Fonseca, P., Campos, A., Mendes, B. and Larsen, R.B. (2005). Potential use of a Nordmøre grid for by-catch reduction in a Portuguese bottom-trawl multispecies fishery. *Fisheries Research* **73**:49–66.

Garcia, S.M. (2003). *The Ecosystem Approach to Fisheries: Issues, Terminology, Principles, Institutional Foundations, Implementation and Outlook*. Food & Agriculture Org.

Gilman, E., Passfield, K. and Nakamura, K. (2014). Performance of regional fisheries management organizations: ecosystem-based governance of bycatch and discards. *Fish and Fisheries* [Online] **15**:327–351. Available at: http://doi.wiley.com/10.1111/faf.12021.

Glass, C.W. and Wardle, C.S. (1989). Comparison of the Reactions of Fish to a Trawl Gear, at High and Low Light Intensities. *Fisheries Research* **7**:249–266.

Glass, C.W. and Wardle, C.S. (1995). Studies on the use of visual stimuli to control fish escape from codends. II. The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends. *Fisheries Research* **23**:165–174.

Gordon, J.D.M.D.M., Bergstad, O.A.A. and Pascoe, P.L.L. (2002). The influence of artificial light on the capture of deep-water demersal fish by bottom trawling. *Journal of the Marine Biological Association of the UK* [Online] **82**:339–344. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0036553763&partnerID=tZOtx3y1%5Cnhttp://www.scopus.com/inward/record.url?eid=2-s2.0-0036553763&partnerID=40&md5=23f8021d6a3e4808f24a23a016708db7.

Graham, N., Ferro, R.S.T., Karp, W.A. and Macmullen, P. (2007). Fishing practice , gear design , and the ecosystem approach — three case studies demonstrating the effect of management strategy on gear selectivity and discards. :744–750.

Graham, N., Kynoch, R.J. and Fryer, R.J. (2003). Square mesh panels in demersal trawls: Further data relating haddock and whiting selectivity to panel position. *Fisheries Research* **62**:361–375.

Grazia Pennino, M., Muñoz, F., Conesa, D., López-Quílez, A. and Bellido, J.M. (2014). Bayesian spatio-temporal discard model in a demersal trawl fishery. *Journal of Sea Research* [Online] **90**:44–53. Available at: http://dx.doi.org/10.1016/j.seares.2014.03.001.

Hall, S.J. and Mainprize, B.M. (2005). Managing by catch and discards: how much progress are we making and how can we do better? *Fish and Fisheries* **6**:134–155.

Hannah, R.W. and Jones, S.A. (2012). Evaluating the behavioral impairment of escaping fish can help measure the effectiveness of bycatch reduction devices. *Fisheries Research* [Online] **131**–**133**:39–44. Available at: http://dx.doi.org/10.1016/j.fishres.2012.07.010.

Hannah, R.W., Lomeli, M.J.M. and Jones, S.A. (2015). Tests of artificial light for bycatch reduction in an ocean shrimp (Pandalus jordani) trawl: Strong but opposite effects at the footrope and near the bycatch reduction device. *Fisheries Research* [Online] **170**:60–67. Available at: http://dx.doi.org/10.1016/j.fishres.2015.05.010.

Hedges, L. V., Gurevitch, J. and Curtis, P.S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology* **80**:1150–1156.

Herrmann, B., Wienbeck, H., Karlsen, J.D., Stepputtis, D., Dahmn, E. and Moderhak, W. (2015). Understanding the release efficiency of Atlantic cod (Gadus morhua) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. *ICES Journal of Marine Science* **72**:686–696.

Hinz, H., Murray, L.G., Gell, F., Hanley, L., Horton, N., Whiteley, H. and Kaiser, M.J. (2010). Seabed habitats around the Isle of Man. *Fisheries & Conservation report No. 12, Bangor University*:1–29.

Hunt, D.E., Rawlinson, N.J.F., Thomas, G.A. and Cobcroft, J.M. (2015). Investigating photoreceptor densities, potential visual acuity, and cone mosaics of shallow water, temperate fish species. *Vision Research* [Online] **111**:13–21. Available at:

http://dx.doi.org/10.1016/j.visres.2015.03.017.

ICES (2017a). *Cod (Gadus Morhua) in Division 7 . a (Irish Sea).*

ICES (2017b). *Haddock (Melanogrammus Aeglefinus) in Division 7 . a (Irish Sea).*

ICES (2017c). *Whiting (Merlangius Merlangus) in Subarea 4 and Division 7 . D (North Sea and Eastern English Channel).*

Karlsen, L. and Larsen, R. (1989). Progress in the selective shrimp trawl development in Norway. In: *Proc. World Symp. Fishing Gear and Fishing Vessel Design. Marine Institute. St. John*. p. 1989.

Kelleher, K. (2005). *Discards in the World'S Marine Fisheries. An Update.*

Kim, Y.H. and Wardle, C.S. (1998). Measuring the brightness contrast of fishing gear, the visual stimulus for fish capture. *Fisheries Research* **34**:151–164.

Kim, Y.H. and Wardle, C.S. (2003). Optomotor response and erratic response: Quantitative analysis of fish reaction to towed fishing gears. *Fisheries Research* **60**:455–470.

Kim, Y.H., Wardle, C.S. and An, Y.S. (2008). Herding and escaping responses of juvenile roundfish to square mesh window in a trawl cod end. *Fisheries Science* **74**:1–7.

Krag, L.A., Holst, R. and Madsen, N. (2009). The vertical separation of fish in the aft end of a demersal trawl. *ICES Journal of Marine Science* **66**:772–777.

Lajeunesse, M.J. (2011). On the meta-analysis of response ratios for studies with correlated and multi-group designs. *Ecological Society of America* **92**:2049–2055.

Lomeli, M.J.M. and Wakefield, W.W. (2014). Examining the Potential Use of Artificial Illumination to Enhance Chinook Salmon Escapement Out a Bycatch Reduction Device in a Pacific Hake Midwater Trawl. :61–66.

Lythgoe, J.N. (1979). *Ecology of Vision*. Clarendon Press.

Main, J. and Sangster, G.I. (1982). A Study of a Multi-Level Bottom Trawl for Species Separation Using Direct Observation Techniques. *Scottish Fisheries Research Report* **26**:17.

Marchesan, M., Spoto, M., Verginella, L. and Ferrero, E.A. (2005). Behavioural effects of artificial light on fish species of commercial interest. *Fisheries Research* **73**:171–185.

Marlen, B. Van (2003). Improving the selectivity of beam trawls in The Netherlands The effect of large mesh top panels on the catch rates of sole , plaice , cod and whiting. **63**:155–168.

Maynard, D. and Gaston, T.F. (2010). *At-Sea Testing of a Submerged Light BRD Onboard the FV Ocean Thief for Approval in Australia's Northern Prawn Fishery*. University of Tasmania.

Michalsen, K., Godo, O.R. and Ferno, a (1996). Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. *Ices Journal of Marine Science* **53**:389–395.

Net Positive Fishing (2016). *Disruptive Seafood Harvesting Workshop Executive Summary Organisers The Workshop Participants The Design Challenge The Design Process A Vision For Disruption Next Steps*.

Norman, J.R. and Greenwood, P.. (1963). Physiological factors causing variations in acoustic target strength of fish. *Journal of the Marine Biological Association of the United Kingdom*

70:107–127.

O’Neill, F.G., Kynoch, R.J. and Fryer, R.J. (2006). Square mesh panels in North Sea demersal trawls: Separate estimates of panel and cod-end selectivity. *Fisheries Research* **78**:333–341.

Özbilgin, H., Tosunoğlu, Z., Aydin, C., Kaykaç, H. and Tokaç, A. (2005). Selectivity of standard, narrow and square mesh panel trawl codends for hake (Merluccius merluccius) and poor cod (Trisopterus minutus capelanus). *Turkish Journal of Veterinary and Animal Sciences* **29**:967–973.

Pennino, M.G., Vilela, R., Valeiras, J. and Bellido, J.M. (2017). Discard management : A spatial multi-criteria approach. *Marine Policy* [Online] **77**:144–151. Available at: http://dx.doi.org/10.1016/j.marpol.2016.12.022.

Revill, A.S., Dulvy, N.K. and Holst, R. (2005). The survival of discarded lesser-spotted dogfish (Scyliorhinus canicula) in the Western English Channel beam trawl fishery. *Fisheries Research* **71**:121–124.

Robertson, J.H.B. (1983). Square mesh nets help young fish escape. *Fish. News* **3652**:10–11.

Robertson, J.H.B. and Stewart, P.A.M. (1988). A comparison of size selection of haddock and whiting by square and diamond mesh codends. *ICES Journal of Marine Science* **44**:148–161.

Robertson, J.H.B. and Stewart, P.A.M. (1986). An Analysis of Length Selection Data from Comparitive Fishing Experiments on Haddock and Whiting with Square and Diamond Mesh Codends. *Working Paper* [Online] **June**:32. Available at: http://www.scotland.gov.uk/Uploads/Documents/SFWP986.pdf.

Rosenberger, L.J. (2001). Pectoral fin locomotion in batoid fishes: undulation versus oscillation. *The Journal of experimental biology* **204**:379–394.

Ryer, C.H., Stoner, A.W., Iseri, P.J. and Spencer, M.L. (2009). Effects of simulated underwater vehicle lighting on fish behavior. *Marine Ecology Progress Series* **391**:97–106.

Schill, F., Zimmer, U.R. and Trumpf, J. (2004). Visible Spectrum Optical Communication and Distance Sensing for Underwater Applications. *Australasian Conference on Robotics and Automation*:1–8.

Sciberras, M., Jenkins, S.R., Mant, R., Kaiser, M.J., Hawkins, S.J. and Pullin, A.S. (2013). Evaluating the relative conservation value of fully and partially protected marine areas. *Fish and Fisheries* **16**:58–77.

Siemann, L.A., Parkins, C.J. and Smolowitz, R.J. (2015). Scallops caught in the headlights: swimming escape behaviour of the Atlantic sea scallop (Placopecten magellanicus) reduced by artificial light. *ICES Journal of Marine Science: Journal du Conseil* [Online] **72**:2700–2706. Available at: https://academic.oup.com/icesjms/article-lookup/doi/10.1093/icesjms/fst034.

Sigurðardóttir, S., Kemp, E., Condie, H., Margeirsson, S., Catchpole, T.L., Bellido, J.M., Qvist, S., *et al.* (2015). How can discards in European fi sheries be mitigated ? Strengths , weaknesses , opportunities and threats of potential mitigation methods. *Marine Policy* [Online] **51**:366–374. Available at: http://dx.doi.org/10.1016/j.marpol.2014.09.018.

Sterling, D.J. (2005). *Modelling the Physics of Prawn Trawling For Fisheries Management*. Curtin University of Technology.

THE COUNCIL OF THE EUROPEAN UNION (2017). *COUNCIL REGULATION (EU) 2017/127 of 20 January 2017 Fixing for 2017 the Fishing Opportunities for Certain Fish Stocks and Groups of Fish Stocks, Applicable in Union Waters And, for Union Fishing Vessels, in Certain Non-Union Waters*.

Thomsen, B. (1993). Selective flatfish trawling. **196**:161–164.

Walsh, S.J., Millar, R.B., Cooper, C.G. and Hickey, W.M. (1992). Codend selection in American plaice : diamond versus square mesh. *Fisheries Research* **13**:235–254.

Wardle, C.S. (1983). Fish reactions to towed fishing gears. *Experimental biology at sea*:167–195.

Watson, J.W. (1989). Fish behaviour and trawl design: potential for selective trawl development. In: *Proceedings of the World Symposium on Fishing Gear and Fishing Vessels'.(Ed. CM Campbell.) Pp*. pp. 25–29.

White, S. (2011). An investigation of biotope distribution and susceptibility to fishing pressure in Manx territorial waters for the development of management recommendations for conservation. :242.

Whittingham, M.J., Stephens, P.A., Bradbury, R.B. and Freckleton, R.P. (2006). Why do we still use stepwise modelling in ecology and behaviour? *Journal of Animal Ecology* **75**:1182–1189.

Image credits

Does your catch measure up? 2017 Available from: https://www.gov.im/media/1354964/defa-full-sign-bass-edit-2017.pdf [**Accessed 08 September 2017]**

Whiting *(Merlangius merlangus)* illustration. Available from : http://www.fao.org/fishery/species/3022/en [**Accessed 08 September 2017]**

Cod*(Gadus morhua)* illustration. Available from: http://www.fao.org/fishery/culturedspecies/Gadus_morhua/en **[Accessed 08 September 2017]**

Haddock *(Melanogrammus aeaglefinus)* illustration: http://www.fao.org/fishery/species/2228/en **[Accessed 08 September 2017]**

Thornback ray *(Raja clavata)* illustration. Available from: http://www.charterboats-uk.co.uk/fish/thornbackray/ **[Accessed 08 September 2017]**

Tub gurnard *(Chelidonichthys lucerna)*
Illustration. Available from: https://www.istockphoto.com/gb/vector/tub-gurnard-gm536778435-57224654 **[Accessed 08 September 2017]**

Starry smoothhound *(Mustelus asterias)* illustration. Available from: http://www.anglingaddicts.co.uk/wp-content/uploads/2011/03/smoothhound.jpg **[Accessed 08 September 2017]**

Lesser spotted catshark (*Scyliorhinus canicula). Available from:* http://www.gettyimages.co.uk/detail/illustration/illustrated-side-view-of-small-spotted-royalty-free-illustration/72196719 **[Accessed 08 September 2017]**

Pouting illustration (*Trisopterus luscus*). Available from: http://skaphandrus.com/en/marine-animals/species/Trisopterus-luscus **[Accessed 08 September 2017]**

Queen scallop *(Aequipecten opercularis). Available from:* https://www.istockphoto.com/gb/vector/antique-illustration-of-queen-scallop-gm508347203-46014264 **[Accessed 08 September 2017]**

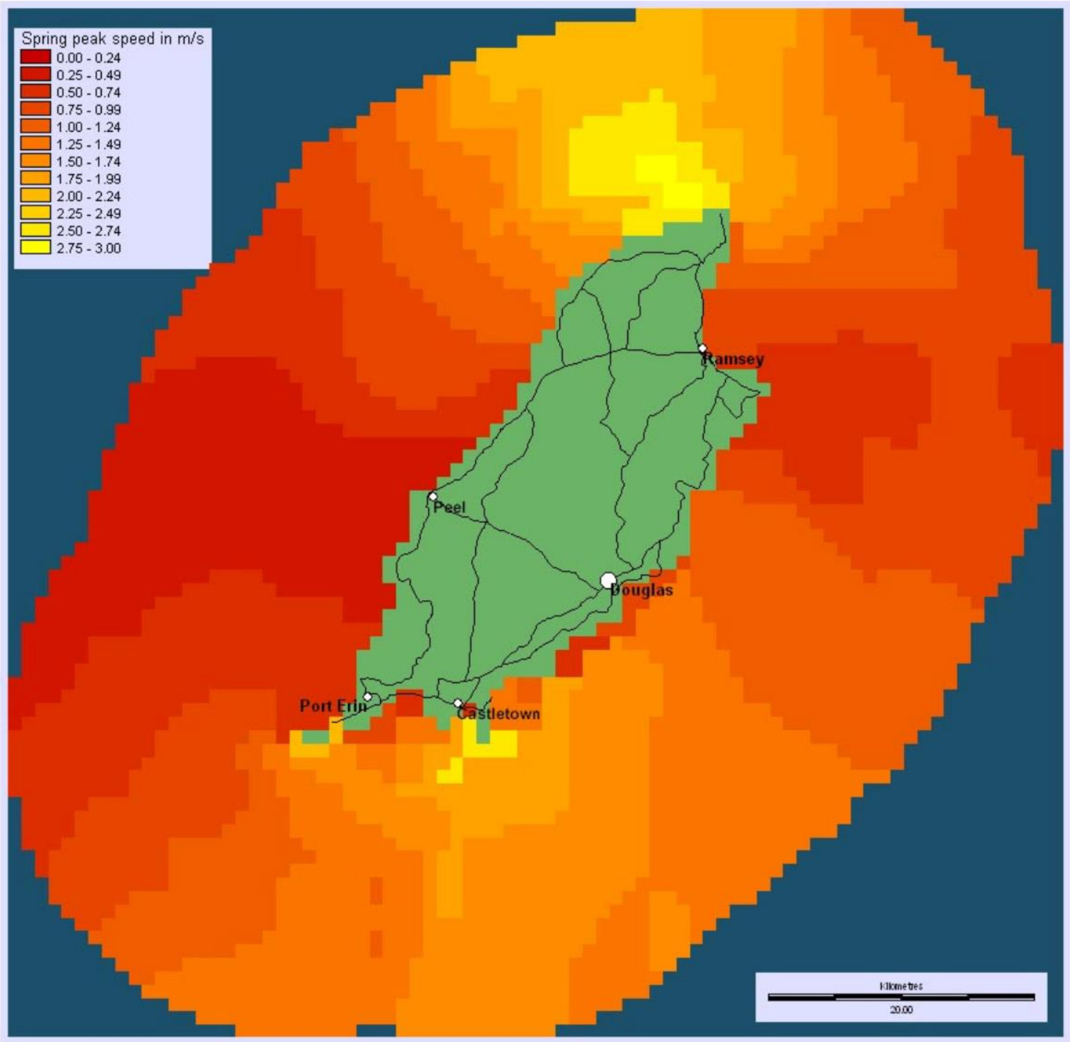
Trawl gear images. Available from: SEAFISH (2015). Basic Fishing Methods. A Comprehensive Guide to Commercial Fishing Methods. **[Accessed 08 September 2017]**

Floatrope video still: Herrmann, B., Wienbeck, H., Karlsen, J.D., Stepputtis, D., Dahmn, E. and Moderhak, W. (2015). Understanding the release efficiency of Atlantic cod (Gadus morhua) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. *ICES Journal of Marine Science* **72**:686–696. [**Accessed 08 September 2017]**

HOBO Pendant Temp/light logger. Available from: http://www.onsetcomp.com/products/data-loggers/ua-002-64 **[Accessed 08 September 2017]**

Weblinks
Bathymetry data sourced from EMODNET (2017). Available from http://emodnet.eu/ **[Accessed 08 September 2017]**
Tidal co-efficient sourced from Tides4Fishing (2017): http://www.tides4fishing.com/uk/wales [**Accessed 08 September 2017]**

Appendix



Appendix 1. *The spring peak tidal stream speeds (m/s) in Manx waters, with areas of slowest flow rate indicated in red and fastest in yellow (Aquatera 2006).*

Appendix 2. *Photograph of the diamond mesh measured from knot to knot: top photo – single twine meshes used in the top section of the net; bottom photo – double twine used in the bottom section of the net.*

Appendix 3. *Otter board doors. Left – illustration of a typical Steel V door (Seafish, 2015); Right – a photograph of one of the Dunbar V doors used on the vessels Two Girls and Our Sarah Jane in the commercial gear trials.*

Appendix 4. *Images of the trawl floats used on the headline of the nets towed by the vessels Two Girls and Our Sarah Jane in the commercial gear trials.*

Appendix 5 *Species that were caught during the QSC otter trawl bycatch trails in IoM waters 2017, the total individuals caught across the trial in all ground Targets, Chickens and Ramsey and the species order they belong to are noted. The species that are regulate under EU total allowable catch limits (EU TAC) and species tht are subject to TAC within VIIa (EU TAC Incl. VIIa) are also noted and highlighted in bold*(THE COUNCIL OF THE EUROPEAN UNION 2017) ***(LW)****= species of which a length/weight relationship was obtained.*

Species	**Total caught**	**Species order**
Ballan wrasse (Labrus bergylta)	2	Perciformes
Blonde ray (Raja brachyura) TAC EU incl. VIIa	2	Rajiformes
Brill (Scophthalmus rhombus) TAC EU	6	Pleuronectiformes
Capelin (Mallotus villosus)	7	Osmeriformes
Cod (Gadus morhua) TAC EU incl.VIIa (LW)	57	Gadiformes
Common Dragonet (Callionymus lyra)	29	Perciformes
Common Topknot (Zeugopterus punctatus)	1	Pleuronectiformes
Cuckoo ray (Leucoraja naevus) TAC EU incl. VIIa	34	Rajiformes
Cuckoo wrasse (Labrus mixtus)	2	Perciformes
Dab (Limanda limanda) EU TAC (LW)	610	Pleuronectiformes
Dover/ Common sole (Solea solea) EU TAC incl. VIIa	5	Pleuronectiformes
Edible crab (Cancer pagurus)	7	Decapoda
European lobster (Homarus gammarus)	9	Decapoda
Grey Gurnard (Eutrigla Gurnadus)	254	Scorpaeniformes
Haddock (Melanogrammus aeglefinus) EU TAC incl. VIIa (LW)	697	Gadiformes
Hake (Merluccius merluccius) EU TAC	2	Gadiformes
John Dory (Zeus faber)	38	Zeiformes
Lemon sole (micorstomus kitt) EU TAC (LW)	750	Pleuronectiformes
Lesser spotted catshark (*Scyliorhinus caniculata)*	3450	Carcharhiniformes
Ling (Molva molva) EU TAC incl. VIIa	8	Gadiformes
Mackerel (Scomber scombrus) TAC EU incl. VIIa	1	Perciformes
Monk/ Anglerfish (Lophius piscatorius) TAC EU Incl. VIIa	80	Lophiiformes
Nursehound/bull huss (Scyliorhinus stellaris)	141	Carcharhiniformes
Octopus (E. Cirrhosa)	19	Octopoda
Plaice (Pleuronectes platessa) EU TAC Incl. VIIa (LW)	1915	Pleuronectiformes
Poor cod (Trisopterus minutus)	346	Gadiformes
Pouting (Trisopterus luscus)	87	Gadiformes
Red gurnard (Chelidonichthys cuculus)	573	Scorpaeniformes
Reticulated dragonet (Callionymus reticulatus)	3	Perciformes
Smoothhound (Mustelus mustelus)	31	Carcharhiniformes
Spotted dragonet (Callionymus maculatus)	5	Perciformes
Spotted ray (Raja montagui) EU TAC Incl.VIIa	52	Rajiformes
Spur dog (Squalus acanthias)	354	Squaliformes

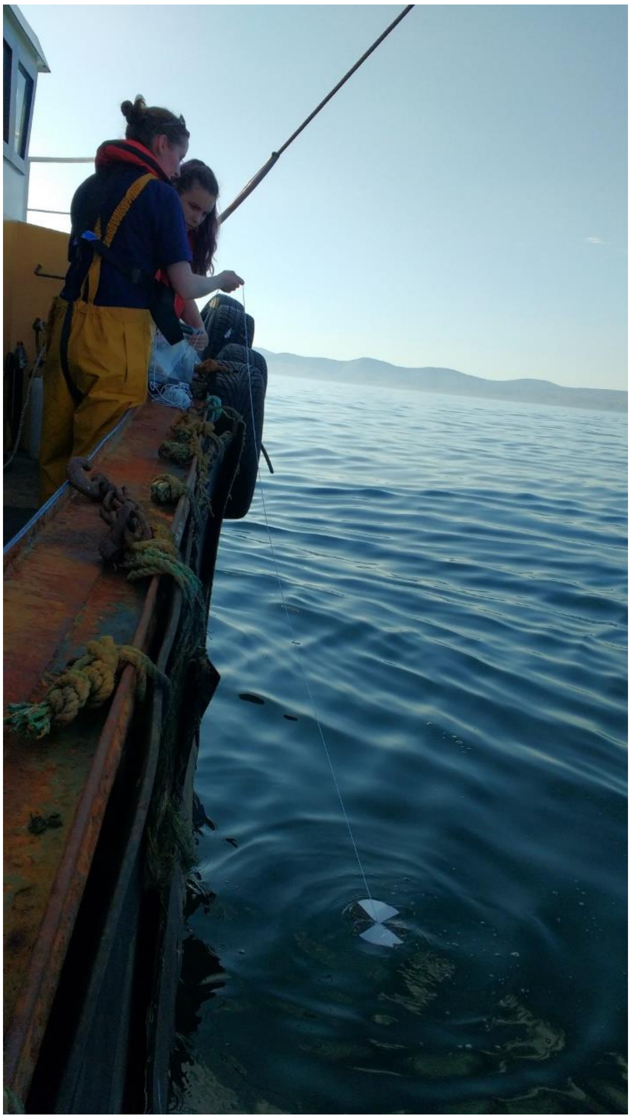
Squid (Lolligo. Sp)	198	Teuthida
Starry smooth hound (Mustelus asterias)	54	Carcharhiniformes
Streaked Gurnard (Trigloporus lastoviza)	26	Scorpaeniformes
Thornback ray (Raja clavata) EU TAC Incl. VIIa	103	Rajiformes
Tompot blenny (Parablennius gattorugine)	1	Perciformes
Tope (Galeorhinus galeus)	6	Carcharhiniformes
Tub gurnard (Trigla lucerna)	87	Scorpaeniformes
Weever spp.	2	Perciformes
Whiting (Merlangius merlangus) EU TAC Incl. VIIa (LW)	180	Gadiformes
Total individuals caught	10234	NA

Appendix 6 *Species or groups of species that include species caught in the IoM QSC otter trawl bycatch reduction trials, that are subject to EU TACs which include the Irish sea (VIIa); the annual allowed quota for the UK; the TAC for the member states combined and; the region (ICES areas) the TAC and quota apply to are noted. [1]Exclusively for by-catches. No directed fisheries are permitted under this quota. [2] Picked dogfish shall not be targeted in the areas covered by this TAC. When accidentally caught in fisheries where picked dogfish is not subject to the landing obligation, specimens shall not be harmed and shall be released immediately* (THE COUNCIL OF THE EUROPEAN UNION 2017)

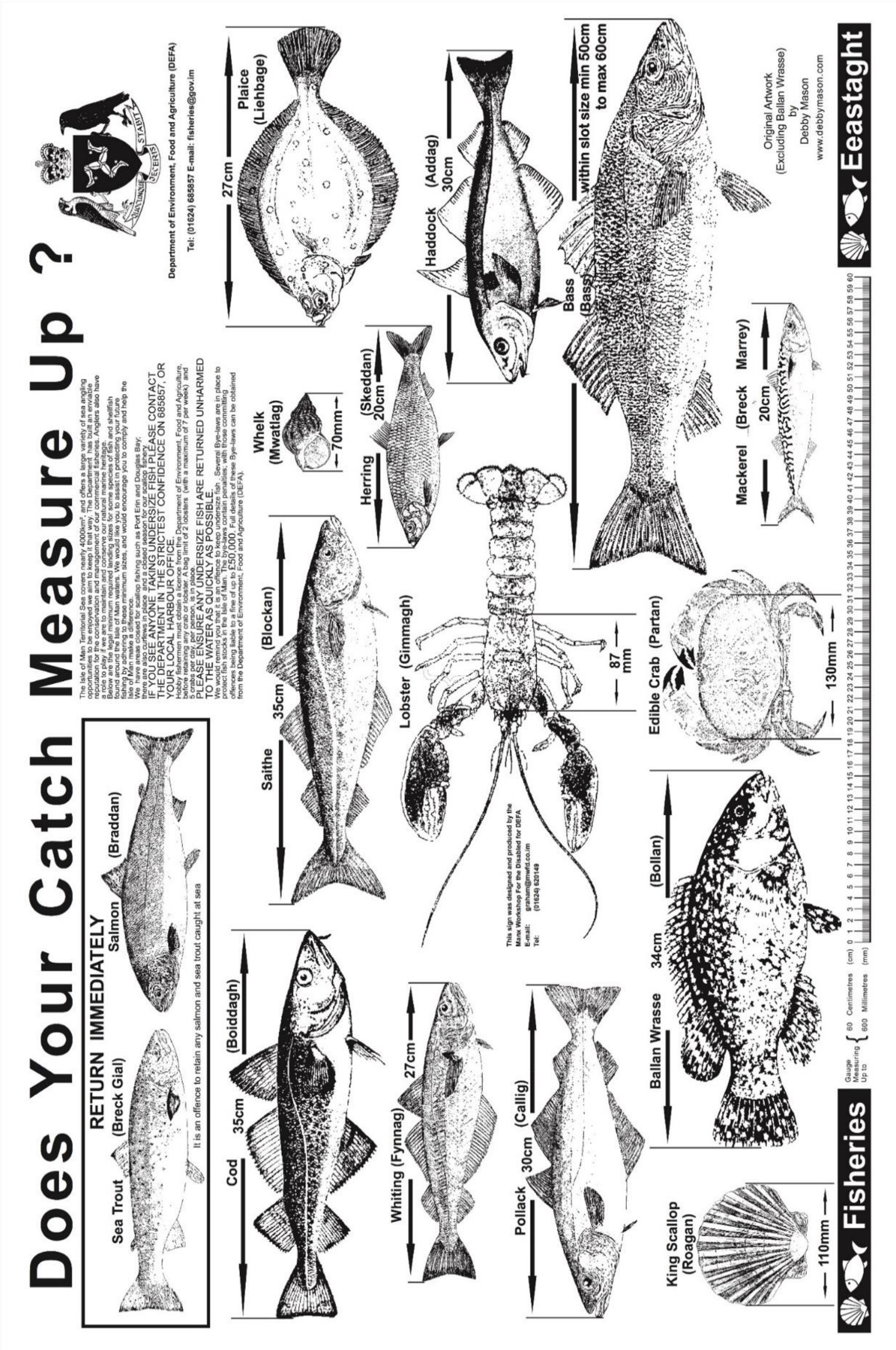
Species	**UK Quota tonnes**	**TAC tonnes**	**ICES areas**
Skates and Rays: cuckoo ray (Leucoraja naevus), thornback ray (Raja clavata), blonde ray (Raja brachyura), spotted ray (Raja montagui), sandy ray (Raja circularis) and shagreen ray (Raja fullonica).	2 180	8 434	Union waters of VIa, VIb, VIIa-c and VIIe-k
Cod *(Gadus morhua)*	42	146	VIIa
Whiting *(Merlangius merlanus)*	31	80	VIIa
Haddock (Melanogrammus aeglefinus)	993	2074	VIIa
Plaice (Pleuronectes platessa)	281	1 098	VIIa
Dover/ Common sole (Solea solea)	10	40	VIIa
Ling (Molva molva)[1]	4 634	20 396	Union and international waters of VI, VII, VIII, IX, X, XII and XIV
Mackerel (Scomber scombrus)	237 677	1 020 996	VI, VII, VIIIa, VIIIb, VIIId and VIIIe; Union and international waters of Vb; international waters of IIa, XII and XIV
Anglerfish Lophiidae *spp.*	6 027	33 516	VII
Spur dog / Picked dogfish *(Squalus acanthias)*[2]	100	270	Union and international waters of I, V, VI, VII, VIII, XII and XIV

Appendix 7 *Queen scallop catch being poured into the mechanical riddle, to mechanically sort the undersized (<55mm) individuals from the oversized marketable catch which is subsequently retained in commercial sacks ready to be landed (photograph taken on board Two girls during the bycatch trials 2017).*

Appendix 8 *HOBO UA-002-64 64K Pendant Temp/Light Loggers (Tempcon Ltd) (left) and the HOBO loggers inserted into the SafetyNet Technologies Ltd. housings made originally for LED lights, as they can withstand higher pressure in comparison to the original HOBO casings (Right).*



Appendix 9 *A photograph demonstrating the procedure used to measure water turbidity, using a Secchi disk which was lowered into the water column until it was no longer visible and then the number of notches (1 every metre) were counted as it was hoisted back on board the vessel, during the bycatch trials in IoM waters.*



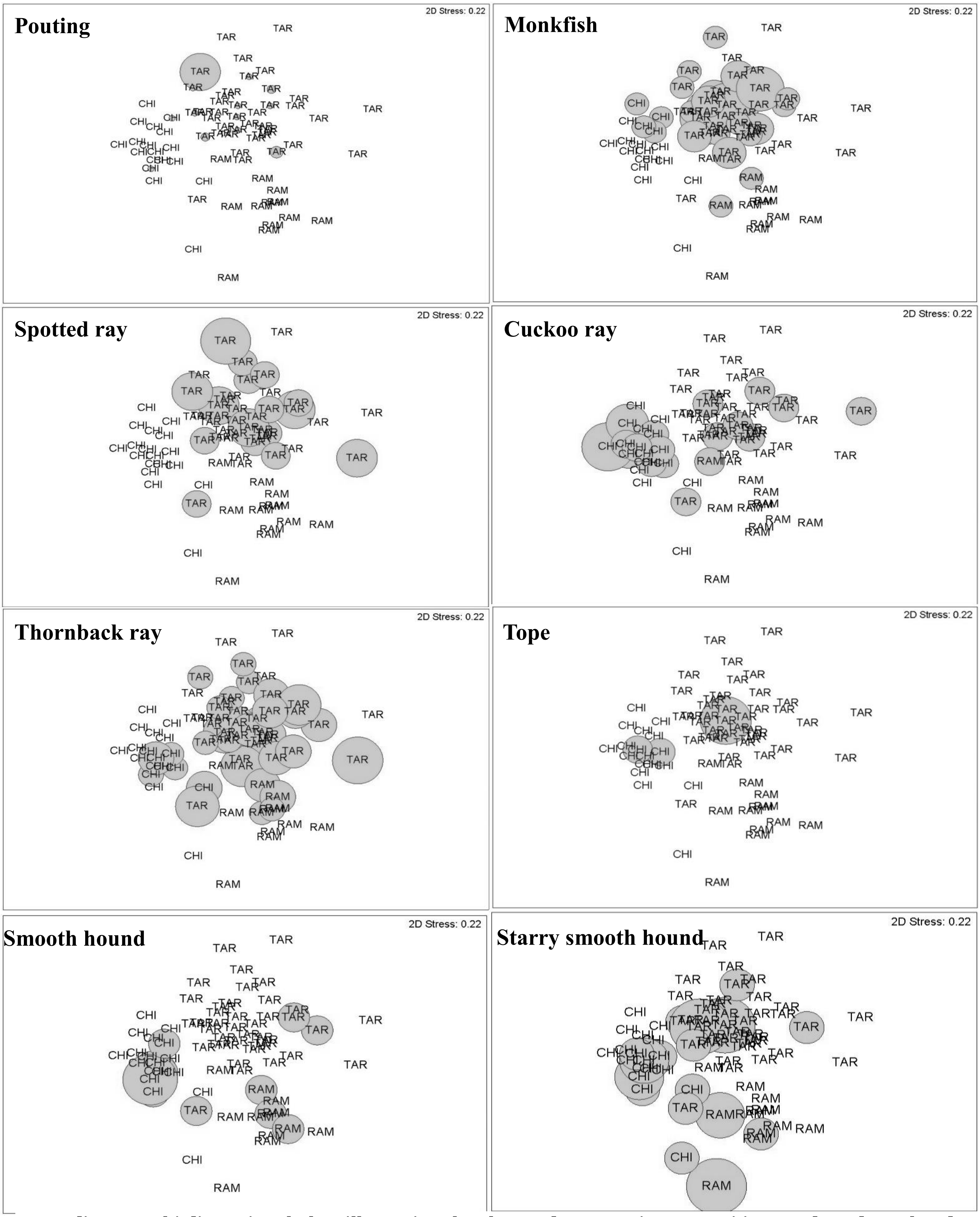
__Appendix 10__ A poster illustrating the legal minimum required landing sizes and how to measure some species of fish and shellfish found in the Isle of Man territorial waters. (Department of Environment, Food and Agriculture (DEFA), Isle of Man)

Appendix 11 *Details of each paired tow conducted with all three sites (TAR=Targets, CHI=Chickens, RAM=Ramsey) the treatment implemented on the experimental boat for each paired tow is noted, along with the duration of the tow (min), any observations, the length of warp payed out from the vessels per tow (m), total number of bags of marketable QSC caught per tow (data from Ramsey and Chickens were used for analysis), and the mean water depth (m)*

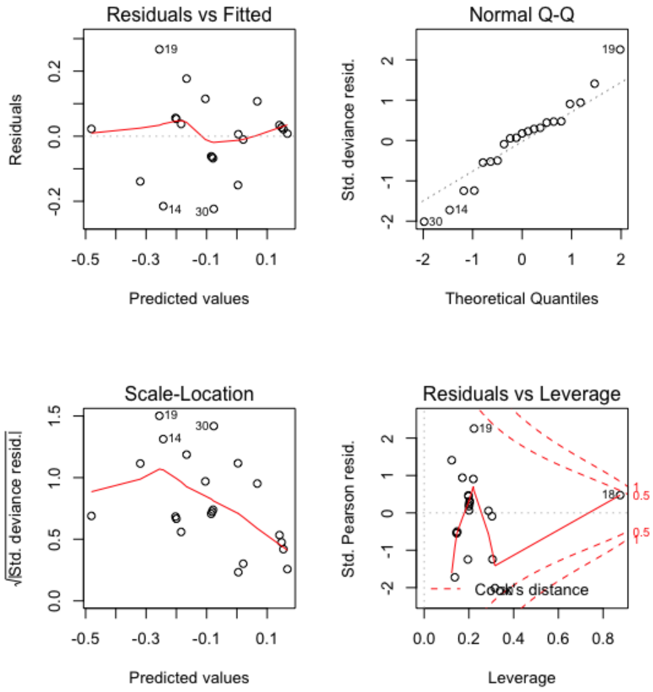
Haul no.	**Site**	**Treatment**	**Duration (min)**	**Observations**	**Warp length (m)**	**Target catch (no. 35kg bags)**		**Mean water depth**	
						Treatment	Control	Treatment	Control
1	TAR	SMP+L	60		70	NA	NA	-33.54	-34.05
2	TAR	SMP+L	60		70	NA	NA	-33.34	-32.98
3	TAR	SMP	60		70	NA	NA	-31.56	-31.68
4	TAR	SMP	60		60	NA	NA	-29.25	-29.43
5	TAR	SMP+L	60		60	NA	NA	-29.24	-29.36
6	TAR	SMP+L	70	OSJ Snagged- 10 minutes added	80	NA	NA	-36.39	-36.09
7	TAR	SMP	60		80	NA	NA	-40.16	-40.27
8	TAR	SMP	60		75	NA	NA	-37.55	-37.09
9	TAR	SMP+L	60		75	NA	NA	-33.33	-33.39
10	TAR	SMP+L	60		75	NA	NA	-31.95	-31.85
11	TAR	SMP	60		75	NA	NA	-30.78	-30.75
12	TAR	SMP+L	60		80	NA	NA	-32.82	-32.72
13	TAR	SMP+L	59		80	NA	NA	-31.67	-31.64
14	TAR	SMP	61		80	NA	NA	-37.63	-37.72
15	TAR	SMP	72	TG snagged	80	NA	NA	-34.08	-34.20
16	TAR	SMP+L	60		80	NA	NA	-33.23	-33.71
17	TAR	SMP+L	65	TG snagged	80	NA	NA	-31.97	-31.73
18	TAR	SMP	60		80	NA	NA	-38.06	-38.37
19	TAR	SMP	60		80	NA	NA	-36.36	-36.18
20	TAR	SMP+L	61		80	NA	NA	-31.37	-31.90
21	TAR	SMP+L	60		80	NA	NA	-37.61	-38.06
22	TAR	SMP	60		80	NA	NA	-35.29	-35.59
23	TAR	SMP	60		80	NA	NA	-34.78	-34.77
24	TAR	SMP+L	60		75	NA	NA	-34.26	-34.22
25	TAR	SMP+L	60		60	NA	NA	-30.95	-31.04

26	TAR	SMP	60		60	NA	NA	-31.69	-31.73
27	TAR	SMP	60		80	NA	NA	-34.09	-34.08
28	TAR	SMP+L	60		80	NA	NA	-37.75	-37.61
29	TAR	SMP+L	60		80	NA	NA	-37.96	-37.89
30	TAR	SMP	60		80	NA	NA	-34.91	-34.64
31	TAR	SMP	60		80	NA	NA	-34.05	-34.07
32	TAR	SMP+L	60		80	NA	NA	-34.25	-34.57
33	TAR	SMP+L	60		80	NA	NA	-38.20	-38.00
34	TAR	SMP	60		80	NA	NA	-35.34	-34.96
35	TAR	SMP	60		75	NA	NA	-32.44	-32.40
36	TAR	SMP+L	60		60	NA	NA	-30.65	-30.88
37	TAR	SMP+L	45		60	NA	NA	-30.05	-30.42
38	TAR	SMP	60		60	NA	NA	-29.56	-30.02
39	TAR	SMP	60		75	NA	NA	-33.04	-32.42
40	TAR	SMP+L	60		75	NA	NA	-32.01	-32.08
41	RAM	SMP	30		40	3	2.5	-16.57	-14.54
42	RAM	SMP	30		40	4	4	-15.40	-16.31
43	RAM	SMP	30		40	3	3.5	-16.99	-15.98
44	RAM	SMP	30		40	5	2	-16.20	-17.294
45	RAM	SMP	30		40	4	3	-15.67	-16.09
46	RAM	SMP	30		40	2	2	-14.47	-15.62
47	RAM	SMP	30		40	2	4	-15.87	-15.21
48	RAM	SMP	30		40	3	4	-16.06	-16.17
49	RAM	SMP	30		40	5	4	-16.24	-16.04
50	RAM	SMP	30		40	4	3	-16.20	-16.05
51	RAM	SMP	27		40	4	3	-6.02	-16.00
52	RAM	SMP	30		40	3		-15.05	-15.22
53	CHI	SMP	60		140	0.5	0.5	-65.78	-65.49
54	CHI	SMP	60		140	0	0.5	-68.39	-67.51
55	CHI	SMP+L	60		140	0.5	0.5	-67.28	-67.17
56	CHI	SMP+L	60		140	3	4.5	-73.84	-72.95
57	CHI	SMP+L	83	Snagged	140	4	6	-95.38	-95.11
58	CHI	SMP	60		140	1	3	-82.87	-88.50

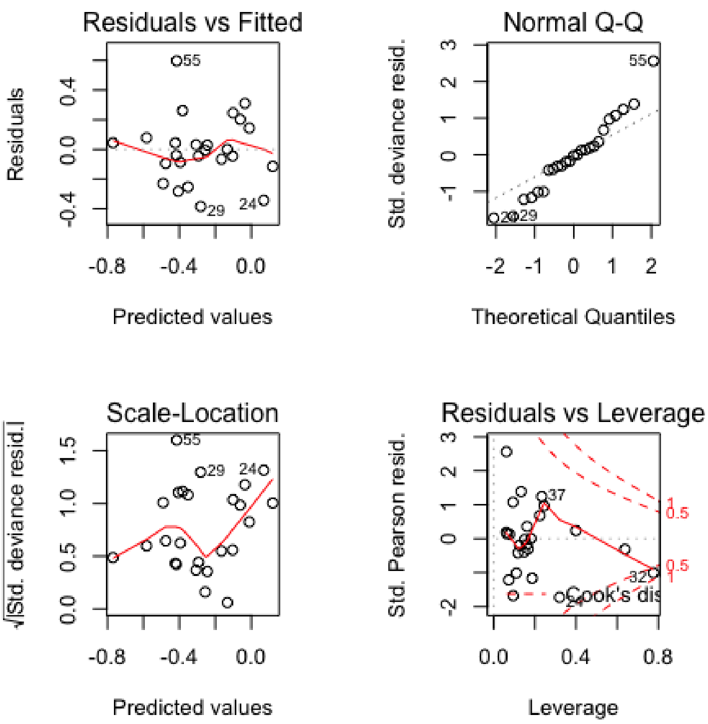
59	CHI	SMP	60		120	1.9	1.5	-62.72	-62.90
60	CHI	SMP	60		120	2.1	2.5	-64.48	-64.54
61	CHI	SMP	60		120	0.3	0	-64.32	-63.87
62	CHI	SMP	60		120	0.3	0	-61.30	-60.90
63	CHI	SMP	88	Longer tow due to tide and weather deteriorating	120	0.3	1	-60.31	-60.57
64	CHI	SMP+L	60		120	0	NA	-47.58	-45.56
65	CHI	SMP+L	60		120	0.5	NA	-53.57	-53.80
66	CHI	SMP+L	60		120	1	NA	-52.46	-52.15
67	CHI	SMP+L	60		120	1	NA	-56.78	-54.26
68	CHI	SMP+L	60		120	0	NA	-67.87	-65.27
69	CHI	SMP+L	60		120	0.5	NA	-66.58	-66.58
70	CHI	SMP	60		120	0.5	0.5	-60.63	-59.77



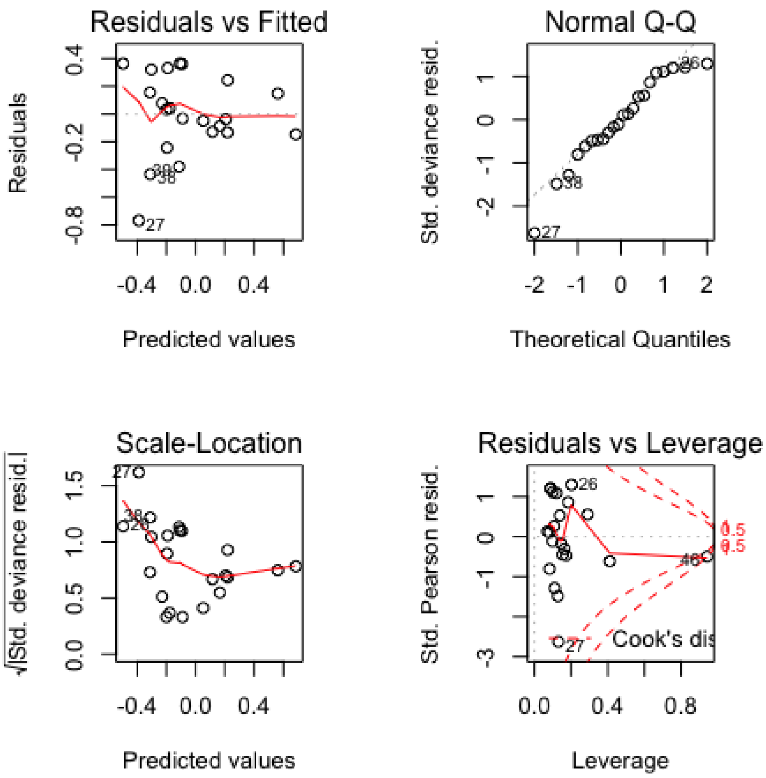
Appendix 22 Multi dimensional plots illustrating the clustered community composition conducted on abundance data (counts) of species caught with the three grounds TAR = Targets, CHI= Chickens, RAM= Ramsey, with the distribution of species considered to indicate dissimilarity between sites overlayed as bubbles (the larger the bubble the higher the abundance of species encountered, each bubble indicates a single control tow).



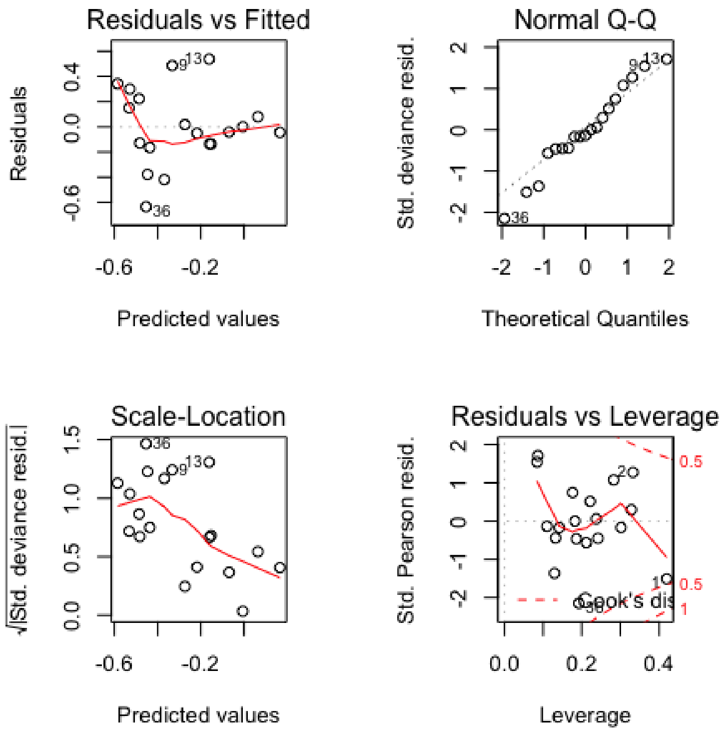
Appendix 13. *Diagnostics of the GLM conducted on the relative catch (logRR) of QSC catch caught per paired tow in Ramsey and Chickens, incorporating the variables in the model: glm(logRR~Site + seastate +Tidal coefficient + Depth , data = SMPlogRR(QSCbags)*



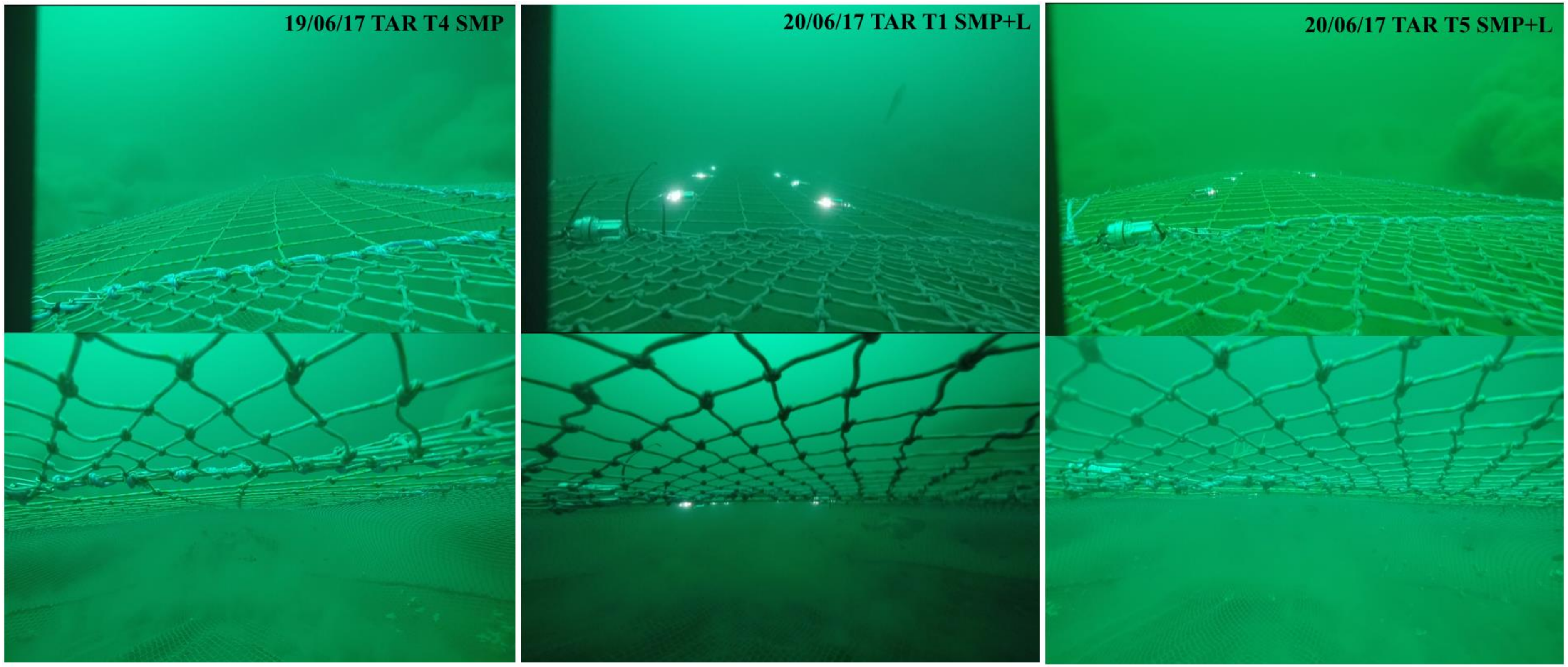
Appendix 14. *Diagnostics of the GLM conducted on the relative catch (logRR) of haddock catch caught per paired SMP+L tow within Targets and Ramsey, including the variables in the following model: glm(logRR~ difference in depth between the two nets + Depth of the treatment vessel + cloud cover , data = SMP+L logRR of Haddock CPUA)*



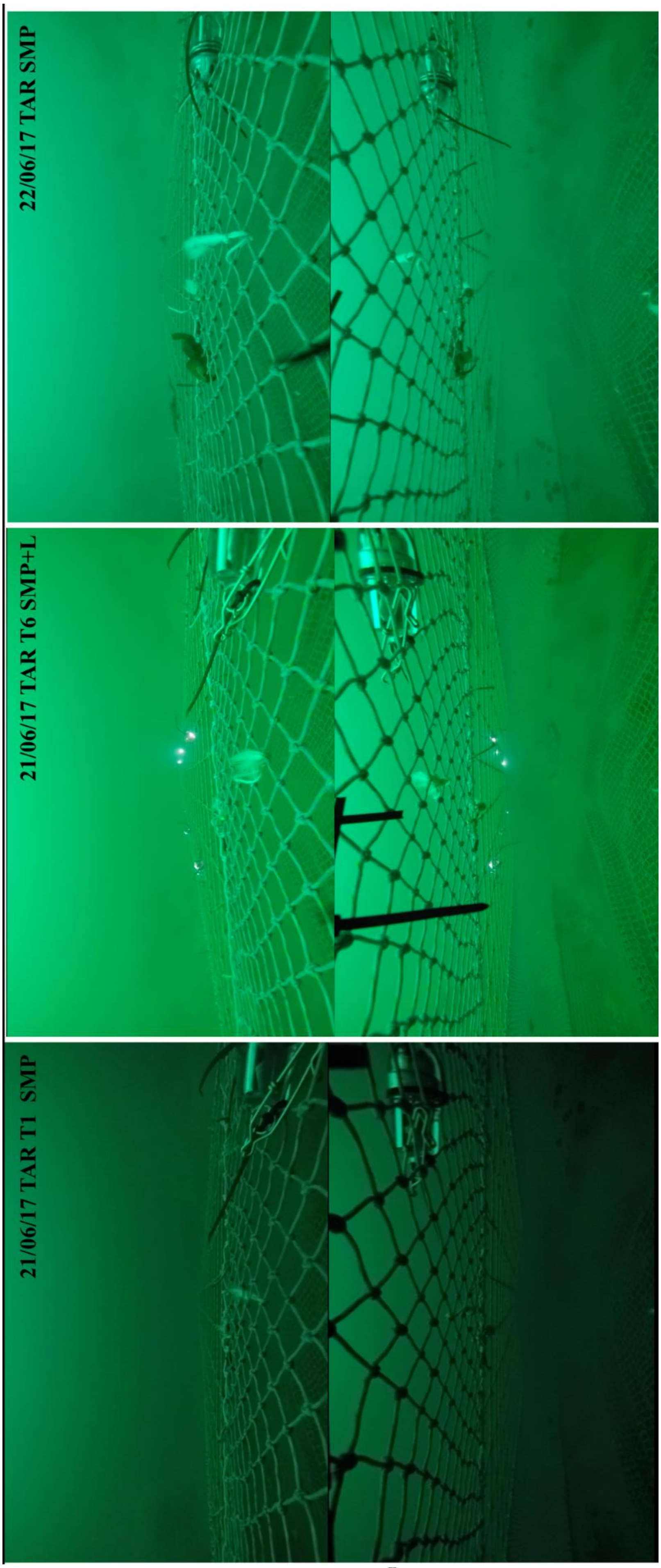
Appendix 15. *Diagnostics of the GLM conducted on the relative catch (logRR) of haddock catch caught per SMP paired tow, within sites Targets and Ramsey including the variables in the following model: glm(logRR~ difference in depth between the two nets + Depth of the treatment vessel + cloud cover , data = SMPlogRR of Haddock CPUA)*



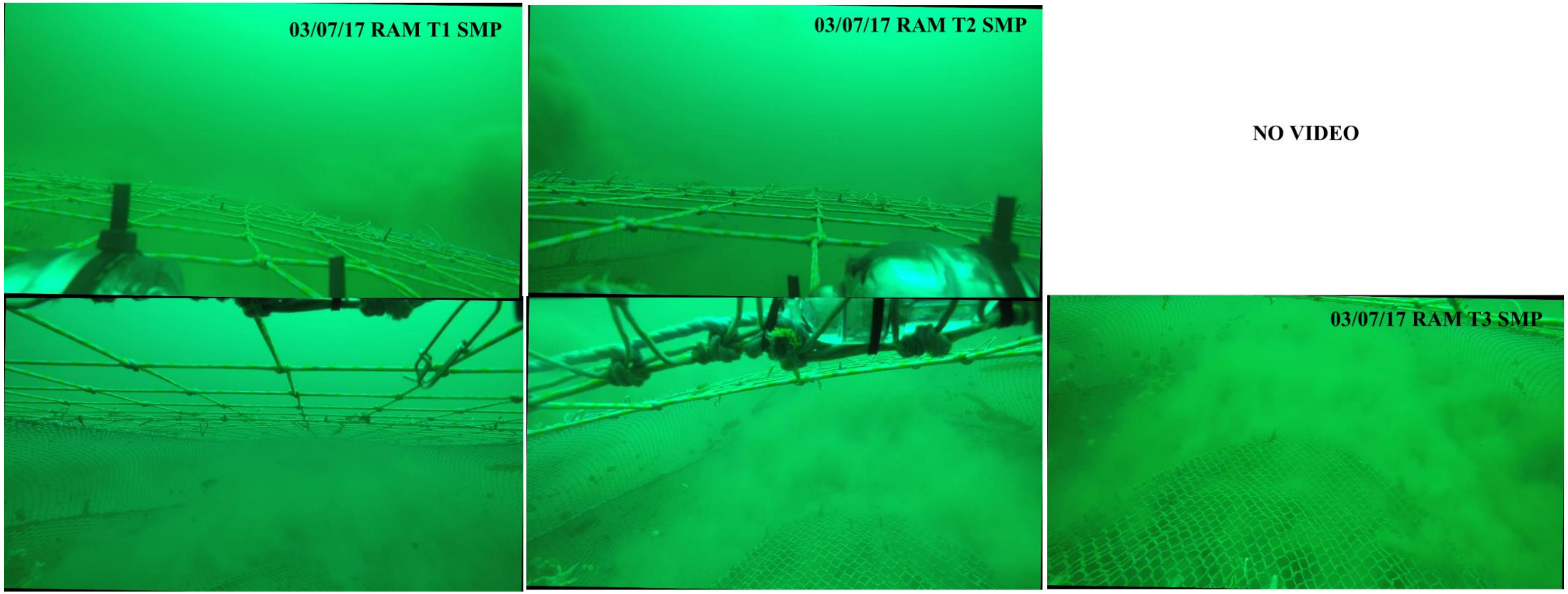
Appendix 14. *Diagnostics of the GLM conducted on the relative catch (logRR) of whiting catch caught per paired SMP+L tow within Targets, including the variables in the following model: glm(logRR~ difference in depth between the two nets + Depth of the treatment vessel + cloud cover , data = SMP+L logRR of whiting CPUA) Averaged across a combinaton of the set of top mdels selected using multi-model interference techniques based on the following global model glm(logRR~Cloudcover+Depth difference +Tidalcoef+Ambinet light levels +Depth +Turbidity+Seastate, data= logRR of whiting CPUA SMP+L)*



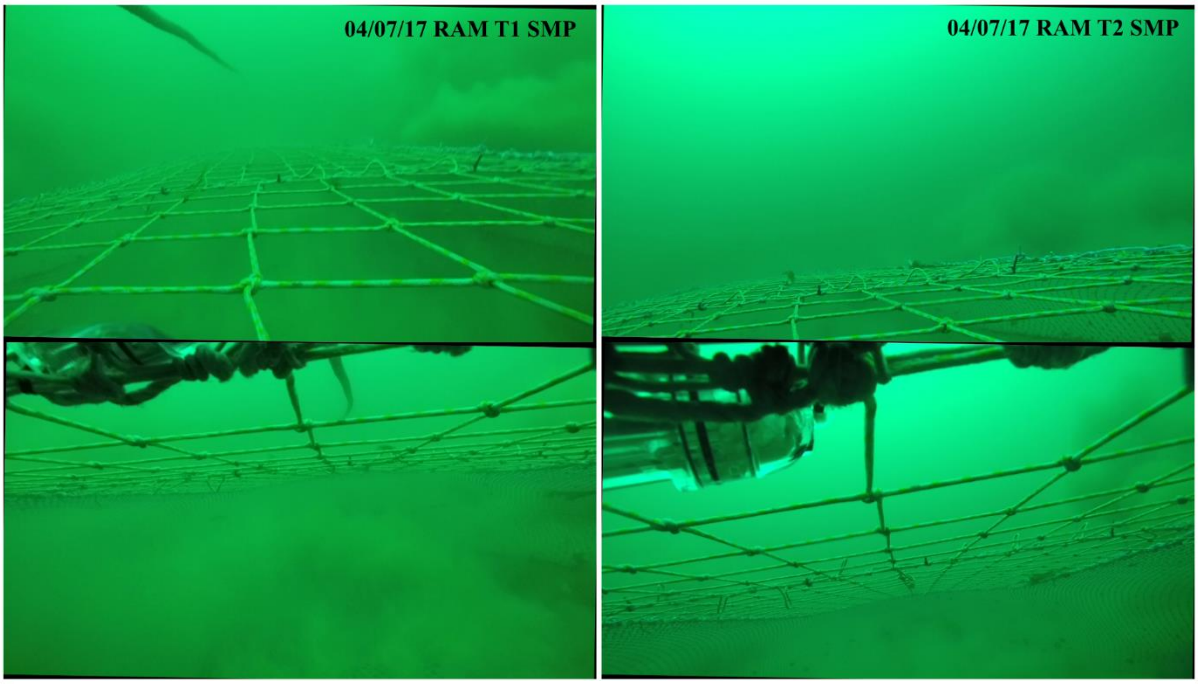
Appendix 15. *Stills taken from the GoPro footage recorded on the treatment vessel, with the camera situated just anterior to the SMP facing back towards the codend. The images demonstrate the light intensity at each site, which varies with depth levels, as the light dissipates in deeper waters lessening the cameras ability to capture the detail of the net and fish encountering the BRD, the date, site (TAR = Targets, RAM= Ramsey, CHI= Chickens), tow number (T2,T2,etc.) and treatment are presented. Note how the intensity of the artificial LED lights is less in lighter ambient light levels, with less contrast to already lit surrounding waters and also note how the light levels increase with tow number, as the morning turn to midday.*



Appendix 16. *See caption for appendix 15.*



Appendix 17. *See caption for appendix 15.*



Appendix 18. *See caption for appendix 15.*

Appendix 19. *See caption for appendix 15.*

Appendix 20. *See caption for appendix 15.*