

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

P R I F Y S G O L
BANGOR
U N I V E R S I T Y



**Trialling innovative disruptive technology for fish bycatch
reduction in the Isle of Man queen scallop (*Aequipecten
opercularis*) fishery, using square mesh panels and artificial light**

Supervisors: Professor Michel Kaiser, Dr Isobel Bloor and Jack Emmerson

By Frances Clare Ratcliffe
BSc Marine and Freshwater Biology
(Aberystwyth University, 2015)

School of Ocean Sciences
Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK

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: Frances Ratcliffe



Date: 14/09/2017

Statement 1: This dissertation is being submitted in partial fulfilment of the requirements for the degree of Master of Science, Marine Environmental Protection

Candidate: Frances Ratcliffe



Date: 14/09/2017

Statement 2: This dissertation is the result of my own independent work/investigation except where otherwise stated.

Candidate: Frances Ratcliffe



Date: 14/09/2017

Statement 3: I hereby give consent for my dissertation, 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: Frances Ratcliffe



Date: 14/09/2017

Abstract

Discarding is currently one of the greatest challenges of fisheries management. Although rates of discarding are declining globally, the introduction of the 'landing obligation' by the European Commission has led to an urgent need to reduce discards by changing the way fishing is conducted. This has become increasingly crucial to prevent early closures occurring in fisheries that have insufficient quota for bycatch species. Trawl fisheries, in particular, generate the greatest quantity of discards globally and while many trawl bycatch reduction devices have been already trialled, their efficacy is species-specific and varies between location and gear specification. Gear modifications such as square mesh panels are an effective, although species-specific, measure to reduce bycatch, however they rely on fish being able to orientate themselves for escape, and therefore, their efficacy may be greatly improved by the use of visual cues. This study trialed the use of a square mesh panel (2.9x1.8m, 300mm stretched mesh) inserted into a Queen Scallop otter trawl net, with and without the addition of LED light. The trial took place at two fishing grounds within the Isle of Man Territorial Sea, with the specific aim of reducing gadiform bycatch. Importantly, whiting (*Merlangius merlanus*) bycatch was reduced by both net modifications and at both grounds by a mean reduction of 73% by weight, and an increase in percentage of whiting over minimum landing size was also observed, when using the modified net. In contrast, haddock (*Melanogrammus aeglefinus*) catch per unit area was reduced only when light was added to the panel. Overall, however, the addition of lights did not significantly decrease gadiform bycatch when compared with the square mesh panel alone. The greatest reaction to the presence of light was exhibited by the lesser spotted catshark (*Scyliorhinus canicula*), the bycatch of which was reduced by 35% when using the square mesh panel, however when light was added no reduction was observed. No reductions in marketable size queen scallop catch were observed when using the panel. This study provides a basis to recommend the use of a square mesh panel for whiting bycatch reduction in this fishery. Furthermore, it provides a basis for developing additional mechanisms for bycatch reduction for a range of quota bycatch species within the Isle of Man queen scallop fishery.

Acknowledgements

Firstly, I would like to express my gratitude to the funders of this research: The Isle of Man Government (Department of Environment, Fisheries and Agriculture), the Manx Fish Producers Organisation, SafetyNet Technologies and Young's Seafood. I would also like to thank Professor Michel Kaiser for giving me the opportunity to work on this project and for providing a wealth of knowledge and experience, as well as encouragement, throughout the completion of this thesis. Special thanks are given to Lucy Southworth, for working alongside me throughout this project as my partner-in-crime. I would also like to thank the Bangor team at DEFA, Dr Isobel Bloor, Jack Emmerson and Claire Lambden (aka beautiful assistant) for their assistance during the fieldwork and their help with *R*. Without the support of my partner Dr Tom Blanchard this thesis would have been infinitely more stressful, so thank you, you computer-wizard. Lastly, I would like to thank my mother for her undying enthusiasm for proof reading and my friends for making me laugh.

Table of Contents

Trialling innovative disruptive technology for fish bycatch reduction in the Isle of Man queen scallop (<i>Aequipecten opercularis</i>) fishery, using square mesh panels and artificial light	1
Abstract	3
Acknowledgements	4
Table of Contents	5
List of figures	7
List of tables	8
Abbreviations	9
1. Introduction	10
1.1 Bycatch: a global issue	10
1.2 Bycatch reduction in Trawl Fisheries	11
1.3 Bycatch in the Isle of Man queen scallop (<i>Aequipecten opercularis</i>) fishery	13
1.4 Aims and Hypotheses	15
2. Methodology	16
2.1 Sample Area	16
2.2 Net design and net modifications	17
2.3 Experimental design	19
2.4 Sampling	20
2.4.1 Fish sampling	21
2.4.2 QSC sampling	21
2.4.3 Environmental variables	21
2.4.3 Video sampling	22
2.5 Data treatment	22
2.5.1 Fish weight	22
2.5.2 Fish abundance and weight by area swept	22
2.5.3 Fish groupings for analysis	23
2.5.3 Queen scallop total weight and percentage undersize calculations	24
2.6 Statistical analysis	24
2.6.1 Differences in fish community assemblages between grounds and treatments	24
2.6.2 Fish abundances and weights by area swept	25
2.6.3 Gadiform size analysis	25
2.6.4 QSC analysis	26
2.6.4 Fishery choke time calculations	26
3. Results	26
3.1 Fish community composition between grounds and the influence of environmental variables on gadiform bycatch	26
3.2 Differences in fish abundances when using modified nets	27
3.2.1 Gross community metrics	27
3.2.1 Differences in individual species abundances when using modified nets	31
3.3 Differences in fish by weight and length between treatment	34
3.4 Differences in queen scallop catches between treatment and vessel	38
3.5 Choke timings for the QSC otter trawl fishery, a focus on whiting	39
4. Discussion	40
4.1 Differences in community structure between fishing grounds and the influence of environmental variables	40

4.2 Fish abundance and weight.....	41
4.2.3 Gadiform responses.....	41
4.2.4 Placement of SMP.....	43
4.2.5 Differences in response to the SMP and SMP+L.....	43
4.3 Fish length	44
4.4 Queen Scallop catches	45
4.5 Choke timings for the QSC otter trawl fishery, and recommendations for future trials.....	46
4.6 Conclusion	47
References.....	48
Grey literature.....	52
Illustration credits:.....	52
Photo credits:	52
Appendix.....	53

List of figures

Figure 1. The Isle of Man territorial sea with the two sample areas where the trial took place.	16
Figure 2. Net plan showing a) the control net, a standard QSC otter trawl net as used by the Isle of Man QSC fishery; b) the treatment net.....	18
Figure 3. a) LED light used in the trials (SafetyNet Technologies); b) The headrope of the net.....	19
Figure 4. a) The QSC otter trawl vessel, Two Girls; b) an example of the unsorted catch from a tow; c) a cod being measured during the trial; d) an example of the fish bycatch from one tow during the trial at Targets.	20
Figure 5. Mean (LnRR+1) of the abundance per hectare (CPUA) for the following bycatch components: a) total fish bycatch; b) quota species; c) gadiformes; d) pleuronectiformes; e) rajiformes and f) carcharhiniformes.	29
Figure 6. The mean (LnRR+1) of the abundance per hectare for the following bycatch species: a) haddock; b) whiting; c) lesser spotted catshark.	33
Figure 7. Mean (LnRR+1) of the weight per hectare (WPUA) for the following bycatch species: a) quota species; b) gadiform species; c) haddock; d) whiting.	36
Figure 8. Total length (mm) frequency histograms for a) all gadiformes; b) Haddock; and c) whiting, caught during the gear trials	37
Figure 9. Shell height of QSC caught in a) control tows and two treatments; b) the two vessels; c) The mean Log Response Ratio change in QSC landed catch, by weight per unit area.....	38
Figure 10. Cumulative % of whiting bycatch on a month by month basis throughout the Isle of Man QSC otter trawl season.....	39

List of tables

Table 1. Summary of ‘choke’ species in Manx waters based on actual landings using data from 2015 and 2016.....	14
Table 2. Experimental design for the trials carried out at Targets fishing ground (TAR) and Ramsey Bay (RAM).	19
Table 3. Sample Size for Estimation analysis (Minitab v17).....	19
Table 4. List of all fish bycatch species encountered during the survey and their taxonomic species order.....	23
Table 5. ANOSIM pairwise comparisons between treatment and ground.....	27
Table 6. SIMPER analysis showing mean abundances (log(X+1) transformed) per hectare and contribution (%) of gadiform bycatch species that drove dissimilarity between fishing grounds and control and SMP treatment.....	27
Table 7. Independent samples t-test results for comparisons between the two treatments.....	28
Table 8. Results of one-sample t-test/one-sample permutation t-test (Perm test) results performed on CPUA LnRR performed for gross community metrics.....	30
Table 9. Results of one-sample t-test/one-sample permutation t- test results (Perm test) performed on CPUA LnRR performed for 3 species, haddock, whiting and lesser spotted catshark..	32
Table 10. Results of Chi-square tests performed on the % frequencies of total length distributions for all gadiform species, haddock and whiting..	34
Table 11. Results of one-sample t-test/one-sample permutation t-test (Perm test) performed on WPUA LnRR for a) quota species; b) gadiforme speices; c) haddock and d) whiting	36

Abbreviations

ANOVA	Analysis of variance
CFP	Common Fisheries Policy
CPUA	Catch per unit area
DEFA	Department of Environment, Fisheries and Agriculture (Isle of Man)
FAO	Food and Agriculture Organization of the United Nations
LnRR	Log response ratio
LED	Light emitting diode
MFPO	Manx Fish Producers Organisation
OSJ	Fishing vessel ‘Our Sarah Jane’
QSC	Queen scallop (<i>Aequipecten opercularis</i>)
RAM	Ramsey Bay fishing ground
TAR	Targets fishing ground
TG	Fishing vessel ‘Two Girls’
WPUA	Weight per unit area

1. Introduction

1.1 Bycatch: a global issue

Over the past 30 years, the quantity of bycatch and discards generated by global fisheries has become a source of increasing concern, both in terms of the ecological impact of the practice on the marine environment, as well as on commercial fish stocks (Kelleher, 2005; Zeller *et al.*, 2017). Due to the multispecies nature of the marine environment (Little *et al.*, 2015) and unselective fishing gears (Guanais *et al.*, 2015; Boyle *et al.*, 2016), targeting one species or group of organisms alone remains challenging (Boyle *et al.*, 2016) and therefore leads to the incidental catch of non-target species (Kelleher, 2005), which may be separated into the following components (definitions after Alverson *et al.*, 1994; Kelleher, 2005; Jennings *et al.*, 2001):

Target catch: one or a selection of species of value (commercial or energetic) that the fisher aims to catch.

Incidental catch: non-target species that the fisher is not aiming to catch, but are caught as a result of occurring in association with the target species. Some may hold commercial value and may be retained.

Discards/discarded catch: the residual catch (once target species and valuable bycatch has been removed), which is dumped at sea, for whatever reason. These may include undersize or damaged individuals of the target species.

Bycatch: comprises of the sum of the incidental catch and discarded catch.

Although discards are in decline, most recent estimates place the global figure to be just under 10% of total yearly target catches, equating to slightly below 10 million tons per annum (Zeller *et al.*, 2017). A partial explanation for this trend is the greater utilisation of incidental catch, that would previously have been discarded, in the fishmeal industry (Zeller and Pauly, 2005). However, while the decline in discards may be seen as a positive step, it reflects a pattern of declining global catches, thereby raising concern that the reduction is not due to an improvement of fishing practices, but rather a by-product of declining fish stocks (Zeller *et al.*, 2017).

Discards often comprise of fish suitable for human consumption, and therefore the practice is seen as a waste of potential resources that could contribute to world food security (Borges, 2015; Zeller *et al.*, 2017). International resolutions, such as UN 49/118 (1994) and 50/25 (1995) have addressed the issue, and the UN FAO International Code of Conduct for Responsible Fisheries (1995) requires that discards should be minimized. In addition, the reforms to the EU

Common Fisheries Policy, (CFP, Regulation (EU) No 1380/2013 of the European Parliament and of the Council), introduced the ‘Landing Obligation’ which will prohibit the discarding of quota species by the end of 2019. Although some exemptions will be permitted (Article 15, CFP), there is an increasing need to improve the selectivity of fishing methods to reduce discards at source (Condie *et al.*, 2014; Veiga *et al.*, 2016).

1.2 Bycatch reduction in Trawl Fisheries

Globally, bottom trawl fisheries account for the highest proportion of discards of any fishing gear (Zeller *et al.*, 2017), although they vary in selectivity (Broadhurst and Kennelly, 1996; Courtney *et al.*, 2007, 2008), with shrimp trawls accounting for up to 62% of global discards, while pelagic midwater trawls account for 3.4% (Kelleher, 2005). In the Northeast Atlantic, discards are dominated by gadiform and redfish (Sebastidae) species, including quota species such as haddock (*Melanogrammus aeglefinus*) cod (*Gadus morhua*) and hake (*Merluccius merluccius*) which account for 19%, 11% and 6% respectively of fish bycatch in this area (Zeller *et al.*, 2017).

While many bycatch reduction devices to reduce bycatch in trawl fisheries have been trialled (Grimaldo *et al.*, no date; Herrmann *et al.*, 2014; Brinkhof *et al.*, 2017), either separating the catch mechanically by size or by behaviour (Broadhurst, 2000), the introduction of the landings obligation will require larger decreases in bycatch than was previously required (Catchpole and Gray, 2010; Salomon *et al.*, 2014). Therefore, there is a need to trial new bycatch reduction devices (BRDs) and improve those already in existence (Veiga *et al.*, 2016), with the aim of finding methods that are possible to use under commercial fishing conditions, as well as being economically viable for a fishery to adopt.

One such BRD consists of the use of square mesh panels (SMPs), which may provide a simple but effective modification to reduce bycatch in trawl nets (Broadhurst *et al.*, 2002; Herrmann *et al.*, 2014; Brčić *et al.*, 2016). The use of SMPs alone has, in some cases, yielded positive results, with notable decreases in gadiform bycatch observed (Briggs, 1992; Herrmann *et al.*, 2014). For instance, in Iceland, the use of SMPs is mandatory due to their success in reducing bycatch of small herring, whiting and haddock (Thorsteinsson, 1992). It should be noted, however, that in some fisheries, SMPs have little impact on bycatch reduction, because, once in the trawl, fish tend to avoid contact with the netting and rarely change swimming direction (Grimaldo *et al.*, 2017), and therefore fishes may drift past the escape panels and into the codend, thereby rendering an SMP ineffective (Herrmann and Sala, 2016; Krag *et al.*, 2017).

In addition, gadoid species such as cod (*Gadus morhua*) tend to enter the trawl near the footrope and remain low in the trawl until they reach the codend, thereby lessening their contact with escape panels placed in the upper portion of the net (Grimaldo *et al.*, 2017). One strategy to increase the efficacy of an SMP is to ensure that the SMP is placed close to the codend of the net, where the catch accumulates (Herrmann *et al.*, 2014). However, net design and loss of target catches may render this solution impractical, and therefore alternative methods for enhancing their efficacy may need to be employed (Broadhurst, 2000).

One such approach is to utilise species specific behavioural traits in order to separate bycatch species of concern from target catches (Broadhurst, 2000). These devices make use of stimuli that either attract or repel fishes, thereby changing their path within the trawl, either deterring them from entering the codend, or encouraging them towards escape gaps (Glass and Wardle, 1995; Hannah *et al.*, 2015). They may take the form of mechanical or visual stimuli such as fluttering ropes and floats placed anterior to the codend and below an SMP (Grimaldo *et al.*, 2017; Krag *et al.*, 2017), fluttering net panels (Kim and Whang, 2010) or black tunnels that are designed to ‘scare’ the fish to deter them from entering the codend (Glass and Wardle, 1995). While this approach may be used to increase the probability of contact between the fish and the escape panel, there is an underlying assumption that they are effective mainly through visual detection (Ryer and Olla, 2000). This therefore limits their efficacy in low light or turbid conditions (Kim and Whang, 2010; Ryer and Olla, 2000). In addition, it is important that BRDs be practical to deploy, and do not disrupt the fishing performance of the gear to which they are attached.

A solution, that may overcome both of the aforementioned drawbacks, is the use of artificial light, which is easily attachable to a trawl (Hannah *et al.*, 2015), and may remain effective in turbid conditions or at depths where there is low light penetration (Kim and Whang, 2010; Ryer and Olla, 2000), and thereby successfully enhance the performance of a BRD under a variety of conditions (Clarke *et al.*, 1986; Hannah *et al.*, 2015, Hunt, 2015). In addition, the use of LED light may provide a low-cost visual stimulus and has been adopted on a fishery-wide scale in the Oregon Shrimp Fishery (Hannah *et al.*, 2015). Interestingly, however, the placement of the lights was crucial for the success of the method in this fishery, with trials showing that green light illuminating the escape gaps led to large increases in bycatch, whereas, when the same light was placed on the footrope, significant decreases were observed (Hannah *et al.*, 2015). However, some trials indicate that illuminating escape gaps can be effective, for instance in the Pacific hake (*Merluccius productus*) midwater trawl fishery, chinook salmon (*Oncorhynchus tshawytsch*) were shown to preferentially escape through illuminated escape

gaps in contrast to gaps that were not illuminated (Lomeli and Wakefield, 2014). In addition, preliminary trials in the North Sea *Nephrops* trawl fishery indicated that illuminated escape gaps could lead to a reduction in whiting and dab bycatch (Elliot and Catchpole, 2015). Other trials have yielded mixed results, Grimaldo *et al.*, (2017) observed that, when LED lights were added to a SMP, there was a size dependent reduction in bycatch of haddock (*M. aeglefinus*), however the measure was less effective for cod (*G. morhua*), and the use of light in this trial was less effective than mandatory sorting grid already used by the fishery (Grimaldo *et al.*, 2017).

When considering the design of a light BRD, it is important to note that there is considerable variation in species' responses to light (Ben-Yami, 1979, Marchesan *et al.*, 2005), which may change based on the intensity, colour (wavelength), and whether the light source is moving or stationary (Marchesan *et al.*, 2005). Nevertheless, responses to light BRDs may be predicted to some extent, based on visual acuity and swimming speed (Hunt, 2015), as well as species specific feeding ecology (Ben-Yami, 1979). In addition, fish have been noted to be attracted to white light (Ben-Yami, 1979), and repelled by blue and green lights (Marchesan *et al.*, 2005). Therefore, given the variables of trawl design, SMP placement, light design and species-specific responses to light, it is important that gear trials occur on a fishery-by-fishery basis and, in addition, the impact of any trawl modifications on the weight of target catch retained should be considered.

1.3 Bycatch in the Isle of Man queen scallop (*Aequipecten opercularis*) fishery

The Isle of Man otter trawl queen scallop (QSC, *Aequipecten opercularis*) fishery is the most important QSC fishery in the UK. Although overall bycatch within the fishery is low $7.42\% \pm 0.52$ and varies between different fishing grounds (Boyle *et al.*, 2016), with the introduction of the 'landing obligation' there is a potential for early closures of the fishing season (July-October) to occur due to 'choke' species (MFPO 2017, pers.comm. 26 April). While *de minimus* exemptions to the landing obligation may be granted (Article 15, CFP), fisheries must provide evidence that they have trialed methods to reduce bycatch, as well as evidence that the total bycatch is below 5% by weight of the target catch (MFPO 2017, pers.comm. 26 April). Critically, gadiform bycatch, specifically whiting (*M. merlangus*) and cod (*G. morhua*) and, to a lesser extent haddock (*M. aeglefinus*), are among the species most likely to choke the fishery and prevent seasonal target catch quotas from being landed (MFPO 2017, pers.comm. 26 April, Table 1).

Table 1. Summary of 'choke' species in Manx waters based on actual landings using data from 2015 and 2016. Details of the catches of each species in the QSC net fishery, the total Manx catch for all fisheries combined, quota allocated to Manx fisheries and the balance (the difference between the quota and actual landings) and the minimum quota uplift that would be required, if no exemptions are granted are detailed (MFPO 2017, pers.comm. 26 April). The increase in quota for 2018 is also given.

Species	Cod (<i>G. morhua</i>)	Whiting (<i>M. merlangus</i>)	Haddock (<i>M. aeglefinus</i>)	Plaice (<i>P. platessa</i>)	Dover Sole (<i>S. solea</i>)	Cuckoo Ray (<i>R. naevus</i>)	Spotted Ray (<i>R. montagui</i>)	Thornback Ray (<i>R. clavata</i>)
Total Queenie Net Manx Waters 2015 (kg)	502	395	1319	484	79	194	123	83
Total Manx fisheries 2015 (kg)	1175	1014	3679	7152	666	3395	2222	494
Available Quota 2015 (kg)	300	300	5100	4099	200	0	0	0
Balance 2016 (kg)	-875	-714	1421	-3053	-466	-3395	-2222	-494
Minimum Quota Uplift Required 2015 (kg)	1000	1000		3000	500	Combined skates and rays 6500		
Total Queenie Net Manx Waters 2016 (kg)	1311	967	2469	2299	141	194	863	828
Total Manx fisheries 2016 (kg)	4348	1495	5573	8781	689	4939	7420	2672
Available Quota 2016 (kg)	300	400	5600	4100	100	0	0	0
Balance 2016 (kg)	-4048	-1095	27	-4681	-589	-4939	-7420	-2672
Minimum Quota Uplift Required 2016 (kg)	4000	1250		4000	600	Combined skates and rays 15100		
Available quota 2018	1100	400	6600	8100	100	No quota available		

For these species of most concern, the use of SMPs has resulted in decreases in bycatch (Grimaldo *et al.*, no date; Briggs, 1992; Revill, Catchpole and Dunlin, 2007; Herrmann *et al.*, 2014), and while literature on gadiform reactions to artificial light is sparse, studies indicate that all three species may exhibit a reaction to artificial light: cod has been experimentally caught using green light (Corresp *et al.*, 2016), whiting is known to be attracted to light (Ben-yami, 1979) and haddock has been known to be caught using light (Ben-yami, 1979), as well as exhibit a panic response to green light which results in higher escape rates through an SMP (Grimaldo *et al.*, 2017).

1.4 Aims and Hypotheses

This study aims to test whether the insertion of a SMP and the addition of LED light are a commercially viable method for bycatch reduction in the QSC otter trawl fishery and to provide evidence that gear modifications have been trialed (Article 15, CFP). The following hypotheses will be tested:

H₁ The use of square mesh panels and artificial light will change the community composition of fish species caught in the queen scallop otter trawl.

H₂ The use of square mesh panels will reduce the bycatch of gadiform species. There will be a greater reduction in gadiform bycatch with the addition of light to square mesh panels in comparison to reduction observed when using square mesh panels alone.

H₃ There will be a reduction in catches of gadiformes below legal landing size when using a modified net. There will be a difference between gadiformes of fish between the control and treatments

H₄ There will be a reduction in undersize queenies when using SMPs. There will be no reduction (weight) in legal size queenies when using SMPs with or without light.

H₅ The use of the modified net will reduce the likelihood of an early termination of fishing due to lack of choke species quota.

2. Methodology

2.1 Sample Area

Sampling took place at two of the four main fishing grounds within the Isle of Man Territorial Sea: Targets (TAR) and Ramsey Bay (RAM) in the Manx Territorial Sea (Figure 1). TAR is frequently fished with otter trawls for queen scallops, while RAM lies within Ramsey Bay Marine Nature Reserve, designated in 2009, and is currently closed to QSC otter trawl fishing (Isle of Man Government, 2017) although it is possible that QSC fishing will be permitted at this ground in the future (DEFA 2017, pers.comm. 22 July). Tow locations were geolocated using a handheld differential Global Positioning System with the start and end points of the tows recorded by hand using the vessel's chart plotter. Mean depth of tows conducted at TAR was 33.85m and 15.9m at RAM.

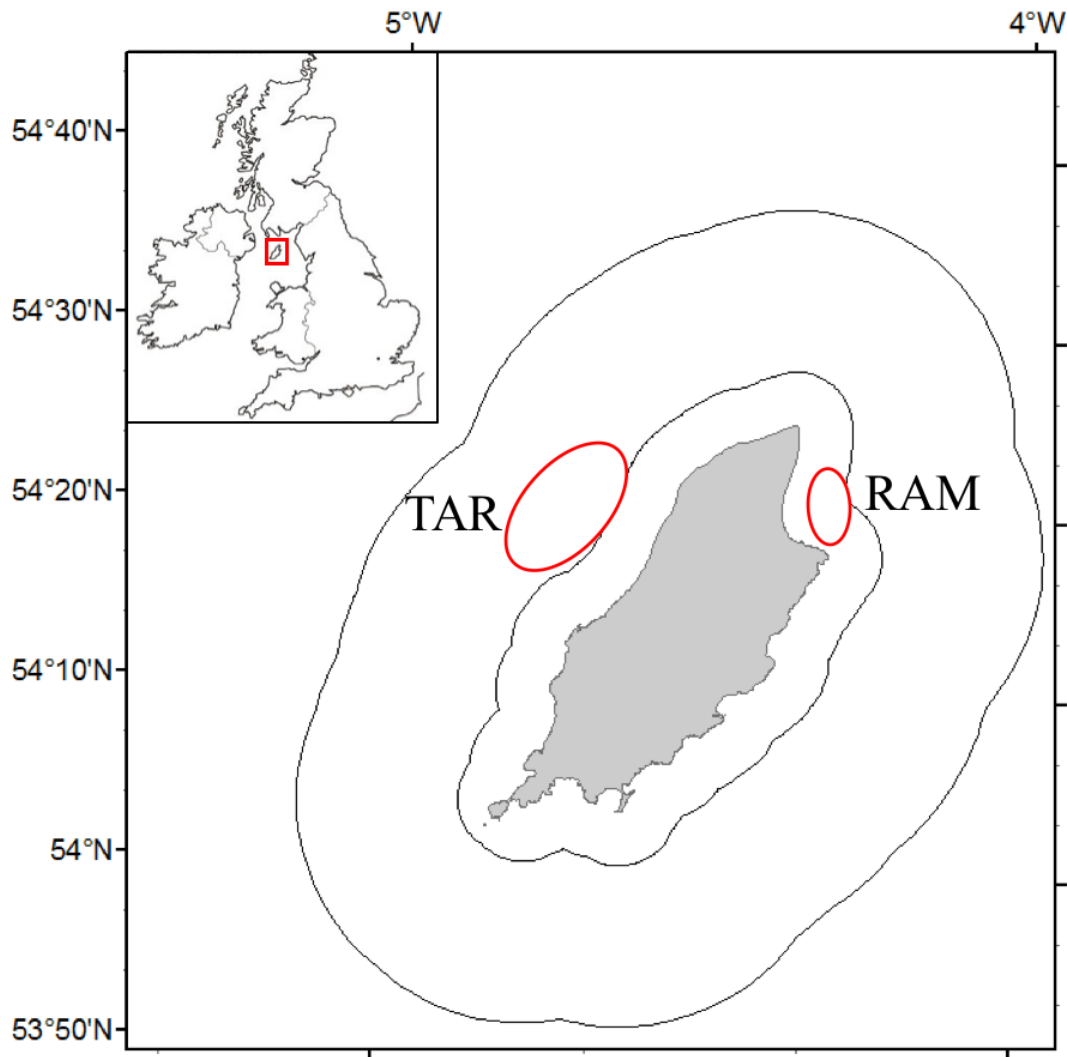


Figure 1. The Isle of Man territorial sea with the two sample areas where the trial took place. TAR= Targets fishing ground. RAM= Ramsey Bay Marine Nature Reserve. Inset indicates the position of the Isle of Man in relation to the British Isles. The 3 and 12 nautical mile limits are also represented.

2.2 Net design and net modifications

Both nets used in the trial were standard Manx QSC otter trawl net constructed using polyethylene twine (3mm thickness for the head and 4mm double stranded for the belly) (MFPO 2017, pers.comm. 19 August), and measuring 8.53m from the centre of the headrope to the codend (Figure 2). Dunbar V door (5/6ft) otter boards were used and attached to the net using extension chains (MFPO 2017, pers.comm. 19 August), and, during towing, the headrope floated 1.83m anterior to the footrope. A square mesh panel (Atlantic Weave Ltd) 20 x 12 mesh, measuring 2.9m x 1.80m, was inserted 1.83m posterior to the headrope and directly above the footrope (Figure 2) of both nets, and the SMP ended 51cm anterior to the first row of codend meshes. The panel was inserted by cutting away 40 diamond meshes across the width of the headline of the net (Figure 2) and sewing the SMP in their place. Because the process of switching nets between vessels was too time-consuming for a trial of this scale, in order to alternate between control and SMP, the diamond mesh was then reattached below the SMP using cable ties to be used as the control net, and removed to reveal the SMP for use as the treatment net. This was carried out after every 2 days at sea at TAR, in order to switch the control and treatment vessels and thereby minimise vessel effects. Unfortunately, at RAM this was not possible, due to only 2 days of trials taking place at that site. For the SMP+L treatment, 6 white, constant Lindgren-Pitman Electrolume lights (supplied and modified by SafetyNet) were attached directly to the mesh of the square mesh panel (Figure 2, Figure 3). Each light was set to constant illumination on contact with water. SMP and SMP+L treatments were switched every 2 tows throughout the survey day to account for differing light levels and changing environmental parameters.

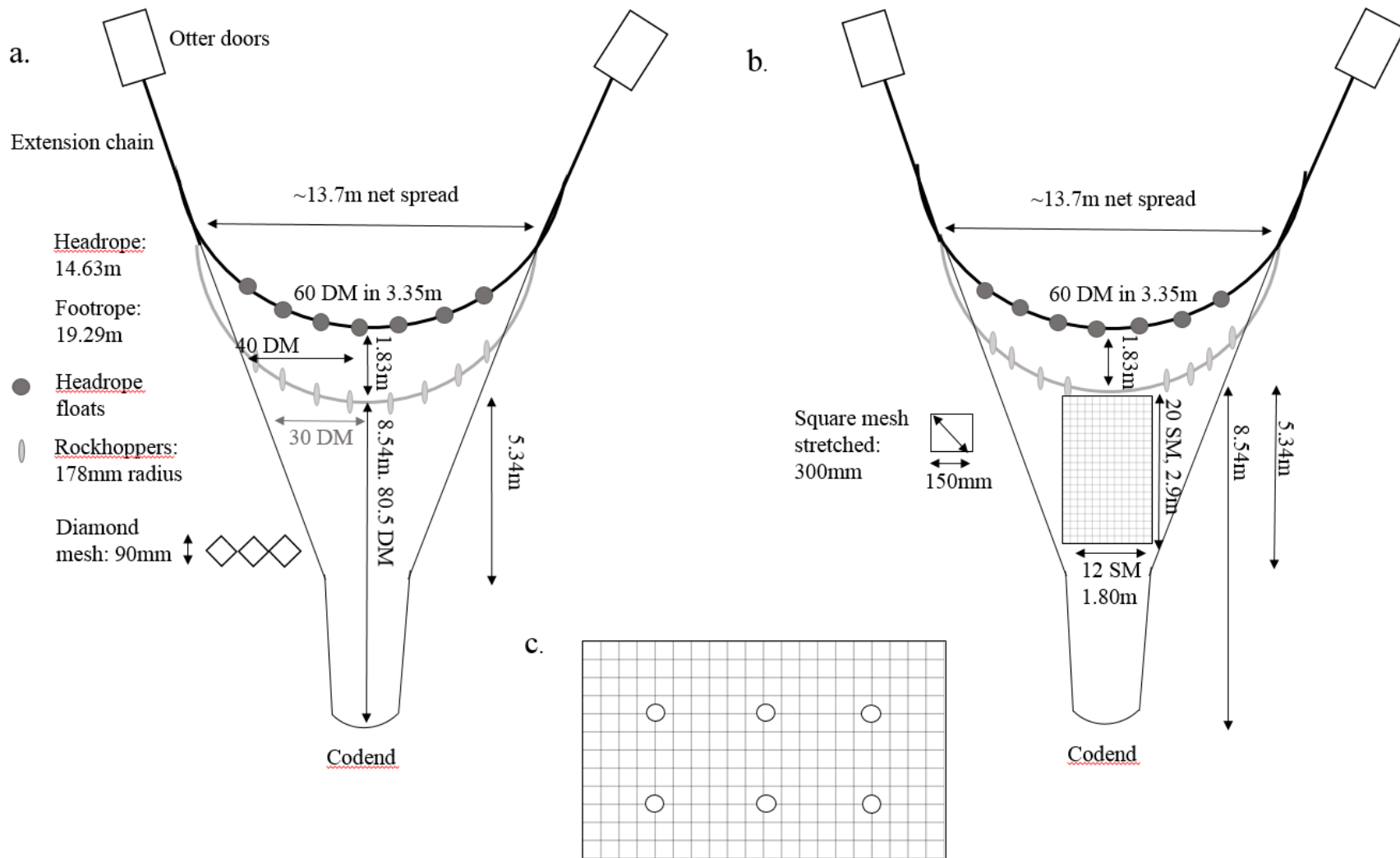


Figure 2. Net plan showing a) the control net, a standard QSC otter trawl net as used by the Isle of Man QSC fishery. The net has rockhoppers, which consist of rubber rollers attached to the footrope and floats attached to the headrope. b) the treatment net was identical to the control net, however a SMP was inserted into the head of the net; c) a schematic of the SMP showing the positioning of LED lights indicated by circles. Light grey indicates measurements in the belly of the net, while black indicates measurements in the head panel of the net. Interestingly, the diamond mesh of a QSC otter trawl is held open by the headrope because mesh spacings are relatively wide (60 diamond meshes are attached to 3.35m of headrope)



Figure 3. a) LED light used in the trials, (SafetyNet Technologies). This same casing was used for the light logger. b) The headrope of the net showing the light logger attached to the margin of the SMP and the robust plastic GoPro housing with floats attached to the net.

2.3 Experimental design

The experiment was designed with two factors: ‘fishing ground’ of which there were two levels, TAR and RAM and ‘net-type’ of which there were two treatments: the SMP, and SMP + L. Each treatment tow was paired with a control tow.

Table 2. Experimental design for the trials carried out at Targets fishing ground (TAR) and Ramsey Bay (RAM). SMP= square mesh panel. SMP+L = square mesh panel with the addition of 6 LED fishing lights. All tows were paired with a control tow, however

Targets	Replicates	Ramsey Bay	Replicates	Data type
SMP vs Ctrl	19	SMP vs Ctrl	12	Paired
SMP+L vs Ctrl	21	-	-	Paired
SMP vs SMP+L	19/21	-	-	Random

To ascertain the appropriate number of replicates needed at each site, the standard error in bycatch abundance observed by Boyle *et al.*, (2016) at TAR and RAM was used to calculate the minimum number of replicates needed to ascertain an accurate mean at each size, using Sample Size for Estimation (Minitab v17,) analysis (Table 3). This indicated that the minimum number of replicates would be 17 tows at TAR and 16 at RAM.

Table 3. Sample Size for Estimation analysis (Minitab v17). SE= standard error, SD= standard deviation.

Fishing	SE	SD	Margins of Error	(n)	Tows	(n) Boyle <i>et al.</i> , 2016
Chickens	0.54	2.02	1.06	17	14	
Ramsey	0.96	3.46	1.88	16	13	

A total of 40 paired tows were completed at TAR, 19 with SMP and Ctrl nets and 21 tows with SMP+L (Table 2). At Ramsey, only the SMP with respective control tows were trialled, due to

preliminary data analysis indicating no difference between the SMP treatments and the SMP+L treatments at TAR; and due to vessel time constraints only 12 tows were conducted at this site. In addition, due to limits of vessel time, it was not possible to conduct paired tows to test both treatments against each other, therefore differences between the treatments were tested using a random design.

2.4 Sampling



Figure 4. a) The QSC otter trawl vessel, Two Girls; b) an example of the unsorted catch from a tow; c) a cod being measured during the trial; d) an example of the fish bycatch from one tow during the trial at Targets.

Sampling was carried out on board two commercial fishing vessels, ‘Our Sarah Jane’ (OSJ) and ‘Two Girls’ (TG), (TG: registered Length = 11.86m, overall Length = 13.88 m, engine power = 216.24 kW. OSJ: Registered Length = 11.97m, overall length = 13.98m, engine power = 187 kW, Figure 4) and took place between the 19th of June and 4th of July, 2017. The location of the tows was chosen by the skippers of the vessels, and vessels switched port to starboard after every tow in order to account for cross current effects, which may have resulted in differential dispersion of sediment plumes, thereby impacting turbidity and light levels. Vessels conducted tows into the direction of the current, and were asked to maintain an equal distance between each other for the duration of the tow. Tows were 1 hour in duration at TAR and 30mins at RAM, due to the permit for running the trial inside the closed area limiting the footprint of the survey. When nets were snagged and the gear was therefore hauled, the sister

vessel also hauled the net and the tow was then lengthened by the amount of time this process took.

2.4.1 Fish sampling

For each tow, all fish species were separated from the Queen Scallop (QSC) catch, and all individuals counted. At TAR, all quota species (Table 4) in FAO Division VIIA, ((EU) No 1221/2014 of 10 November 2014) were measured (Figure 4c) and a subsample retained to be weighed on shore to ascertain a weight/length relationship which was then used calculate the weight of quota species in the catch. Dab (*Limanda limanda*), which is not a quota species in FAO Division VIIA was also measured and a subsample weighed, due to this species relevance to other fisheries to which the landing obligation applies. At RAM, all fish, including non-quota species, were measured, with the exception of Lesser Spotted Catsharks (*S. canicula*) of which a subsample of 10 from each tow were measured.

2.4.2 QSC sampling

For each tow, a subsample of 100 QSC were measured per vessel, using digital measuring boards (Zebra-Tech Ltd) with an accuracy of +/- 1mm, to ascertain the proportion of undersize QSC in the catch. A subsample of 400 QSC were kept for laboratory analysis. The QSC catch was then passed through a mechanical riddle, that operates using fixed diameter steel rings to allow undersize QSC (< 55m, DEFA 2017, pers.comm. 27 June) to pass through, whilst retaining target catch (Boyle *et al.*, 2016). Although the riddle was used for all tows in RAM, due to very low QSC catch rates, some of the QSC catch was separated by hand at TAR. At both sites the number of bags of landed catch were counted and undersize QSC discarded. Each bag was assumed to weigh 35kg, as this is the mean weight recorded during commercial fishing by both vessels (DEFA 2017, pers.comm. 27 June).

2.4.3 Environmental variables

Environmental variables were recorded on board during each tow: cloud cover (%), sea state (Beaufort) and Secchi depth (m). Light loggers were attached 30cm anterior to the SMP. These consisted of HOBO UA-002-64 64K Pendant Temp/Light Loggers (Tempcon Ltd), which were removed from their original casings and placed inside a Lindgren-Pitman light case (Figure 3) and recorded light levels (lux) once per minute for the duration of each tow. Light loggers were calibrated (Appendix 8) using an integration sphere in which light intensity could be controlled

and measured using a calibration unit. Both light loggers exhibited similar responses during calibration, therefore, a single equation was derived to convert both loggers readings to lux:

$$Lux = 0.1822x + 910.03$$

The mean of these readings during each tow was then calculated for use in analysis. Tidal coefficient data was obtained from <http://www.tides4fishing.com/tides/tidal-coefficient>, and a mean of the coefficient supplied for 12am and that supplied for 12pm was used to obtain one value for each day of the survey.

2.4.3 Video sampling

Two GoPro Hero 4 silver cameras were attached 35cm anterior of the SMP using a robust plastic housing (Figure 3), which allowed one camera to film the inside of the SMP and the other the outside. Video was recorded at 1080p (progressive scan) and at 60 frames per second. A minimum of one tow per treatment (SMP, SMP+L) was filmed each day. No additional lighting was used for video recordings so as not to confound behavioural reactions to the net modifications by adding an additional light source. This was possible because the depth of tows did not exceed 41m and therefore ambient light in the trawl was sufficient to obtain behavioural footage for future analysis, although this is beyond the scope of the current study.

2.5 Data treatment

2.5.1 Fish weight

A subsample of quota species caught at TAR were kept, and weighed and measured in the laboratory. A weight-length relationship was then calculated for each species with sufficient numbers (Appendix 1) using the power function:

$$W = aL^b \text{ (King, 2007)}$$

where W denotes weight (g), L denotes TL (cm), and a and b are constants. These equations were then used to calculate an estimated weight for the lengths of each quota species individual in each tow.

2.5.2 Fish abundance and weight by area swept

GPS trackers, recording positioning every minute, were on board each vessel throughout the survey (where GPS trackers failed, 15 minute VMS data were used) to ascertain tow tracks for each vessel. These GPS tracks were then used to calculate area swept for each tow (control and treatment) using zonal statistics (ArcMap 10.4.1) and the following equation:

$$\text{Area swept} = \frac{F \times NSF \times D}{10,000}$$

in which F represents the footrope length (meters) (Figure 2), NSF represents the net spread factor [0.75 (Sterling 2005)], and D represents the distance covered during the tow (meters) (Boyle *et al.*, 2016). The counts/weights of individuals for each species in each tow were then divided by the area swept to obtain catch per unit area (CPUA) or weight per unit area (WPUA) values.

2.5.3 Fish groupings for analysis

While analysis on a species-by-species basis would have been preferable, individuals of some species were present in numbers too low for meaningful analysis, and therefore species were grouped by species order for analysis (Table 4).

Table 4. List of all fish bycatch species encountered during the survey and their taxonomic species order. Quota species in FAO division VIIa (Fishing TACs and quotas, 2015) are indicated by “Q” and non-quota species indicated by “NQ”. *although dab is not a quota species in division VIIa, this species was measured and subsample weighed.

Species	Order	Quota
Ballan wrasse (<i>Labrus bergylta</i>)	Perciformes	NQ
Brill (<i>Scophthalmus rhombus</i>)	Pleuronectiformes	NQ
Cod (<i>Gadus morhua</i>)	Gadiformes	Q
Common Dragonet (<i>Callionymus lyra</i>)	Perciformes	NQ
Common Topknot (<i>Zeugopterus punctatus</i>)	Pleuronectiformes	Q
Cuckoo ray (<i>Leucoraja naevus</i>)	Rajiformes	NQ
Cuckoo wrasse (<i>Labrus mixtus</i>)	Perciformes	Q
Dab (<i>Limanda limanda</i>)	Pleuronectiformes	NQ*
Dover/ Common sole (<i>Solea solea</i>)	Pleuronectiformes	Q
Edible crab (<i>Cancer pagurus</i>)	Decapoda	NQ
European lobster (<i>Homarus gammarus</i>)	Decapoda	NQ
Grey Gurnard (<i>Eutrigla Gurnadus</i>)	Scorpaeniformes	NQ
Haddock (<i>Melanogrammus aeglefinus</i>)	Gadiformes	Q
Hake (<i>Merluccius merluccius</i>)	Gadiformes	Q
John Dory (<i>Zeus faber</i>)	Zeiformes	Q
Lemon sole (<i>micorstomus kitt</i>)	Pleuronectiformes	Q
Lesser spotted catshark (<i>Scyliorhinus caniculata</i>)	Carcharhiniformes	NQ
Ling (<i>Molva molva</i>)	Gadiformes	NQ
Mackerel (<i>Scomber scombrus</i>)	Perciformes	Q
Monk/ Anglerfish (<i>Lophius piscatorius</i>)	Lophiiformes	Q
Norweigan topknot (<i>Phrynorhombus norvegicus</i>)	Pleuronectiformes	NQ
Nursehound/bull huss (<i>Scyliorhinus stellaris</i>)	Carcharhiniformes	NQ
Octopus (<i>Eledone cirrhosa</i>)	Octopoda	NQ
Plaice (<i>Plueronectes platessa</i>)	Pleuronectiformes	Q
Pogge (<i>Agonus cataphractus</i>)	Scorpaeniformes	NQ
Poor cod (<i>Trisopterus minutus</i>)	Gadiformes	NQ

Pouting (<i>Trisopterus luscus</i>)	Gadiformes	NQ
Red gurnard (<i>Chelidonichthys cuculus</i>)	Scorpaeniformes	NQ
Reticulated dragonet (<i>Callionymus reticulatus</i>)	Perciformes	NQ
Sand sole (<i>Pegusa lascaris</i>)	Pleuronectiformes	NQ
Smoothhound (<i>Mustelus mustelus</i>)	Carcharhiniformes	NQ
Spotted dragonet (<i>Callionymus maculatus</i>)	Perciformes	NQ
Spotted ray (<i>Raja montagui</i>)	Rajiformes	Q
Spur dog (<i>Squalus acanthias</i>)	Squaliformes	NQ
Squid (<i>Lolligo spp.</i>)	Teuthida	NQ
Starry smooth hound (<i>Mustelus asterias</i>)	Carcharhiniformes	NQ
Streaked Gurnard (<i>Trigloporus lastoviza</i>)	Scorpaeniformes	NQ
Thornback ray (<i>Raja clavata</i>)	Rajiformes	Q
Tompot blenny (<i>Parablennius gattorugine</i>)	Perciformes	NQ
Tope (<i>Galeorhinus galeus</i>)	Carcharhiniformes	NQ
Tub gurnard (<i>Trigla lucerna</i>)	Scorpaeniformes	NQ
Turbot (<i>Scophthalmus maximus</i>)	Pleuronectiformes	Q
Whiting (<i>Merlangius merlanus</i>)	Gadiformes	Q

2.5.3 Queen scallop total weight and percentage undersize calculations

A subsample of 400 QSC were measured and weighed in the laboratory to ascertain the weight length relationship (method as per 2.5.1 Fish weight). The percentage undersize was calculated from 100 scallops measured scallops per tow, ascertaining the percentage of QSC below 55mm in shell height (DEFA 2017, pers.comm. 7 September). Total bag weight was calculated by from the mean weight (35kg) multiplied by the number of bags of retained catch per tow.

2.6 Statistical analysis

2.6.1 Differences in fish community assemblages between grounds and treatments

All multivariate analysis was conducted using PRIMER v.6 (Clarke and Gorley, 2006). CPUA of fish species data (all species in the survey, and gadiformes only) were $\log(X+1)$ transformed, and a Bray-Curtis similarity matrix was then calculated. Subsequently, a 2-way crossed ANOSIM with replicates and fixed factors of ground and treatment was used investigate changes in species composition. SIMPER analysis (similarity of percentages) was used to ascertain which species accounted for the patterns in community composition observed. The BEST analysis routine was then used to determine which environmental variables correlate best with the patterns observed. Where light logger (lux) data was missing, the missing value tool in PRIMER was used to generate small numbers of missing values at random under strict model assumptions (Clarke and Gorley, 2006), to enable the analysis to proceed.

2.6.2 Fish abundances and weights by area swept

All univariate analysis was carried out in R (Version 1.0.136). The sum CPUA/WPUA of catch component under investigation (all bycatch species, species order, species) was calculated for each control and treatment tow. Log response ratios (LnRR) were chosen to calculate the proportional change in the sum of the control and treatment tows for each pair (Lajeunesse, 2011), and thereby quantify the change resulting from the modifications to the net (Sciberras *et al.*, 2015). The following equation was used:

$$\text{LnRR} = \text{Log}_{10} \frac{\text{trt} + 1}{\text{ctrl} + 1}$$

where “trt” is the sum of the catch component in the control tow, and “ctrl” is the sum of the catch in control tow. While meta-analysis methods calculate LnRR based on means (Hedges *et al.*, 1999; Lajeunesse, 2011; Sciberras *et al.*, 2015), in this case as each tow was a replicate, the sum of CPUA/WPUA for each tow was used. LnRR was chosen in place of a response ratio calculated on untransformed CPUA values, because this method linearizes the metric, leading to changes in the denominator and numerator being treated equally (Hedges *et al.* 1999).

LnRRs were then tested for normality using Shapiro-Wilk test in R (Version 1.0.136). Where data was normally distributed, the one-sample t-test was used in order to test if the mean of the LnRR in question was different to a mean of zero. Where assumptions of normality of variance were violated, the one-sample Permutation t-test (Good, 2000) was used in conjunction with the one sample t-test to provide further evidence of a change in mean being present/absent, because it does not require assumptions of normal distribution to be met (Nichols and Holmes, 2001). Mean LnRR decrease for each treatment at each site was then back transformed to mean percent decrease to aid interpretation (Kroeker *et al.*, 2013; Hiddink *et al.*, 2017), using the following formula:

$$P = (1 - 10^{-L}) \times 100$$

Where P = percentage decrease and where L is mean decrease in LnRR. Upper and lower confidence intervals were calculated based on the t-test distribution and were separately back-calculated to percentages, using the method above, thus taking into account the logarithmic scale, which results in the upper bound percentage being greater than that of the lower.

2.6.3 Gadiform size analysis

Due to low numbers of gadiform species captured by the modified net (SMP and SMP+L), for this analysis both treatments were combined to augment the sample size. Total length data for

catch components (species order, species) was divided into 20mm categories, and length frequencies were calculated as a percentage of the total number of individuals of that species/species order. Percentage frequencies of fish in the treatment nets were then compared against individuals caught in the control net using a chi-square test (R Studio v. 1.0.136), and percentages below/above minimum landing size were calculated.

2.6.4 QSC analysis

LnRR were calculated for the weight of target catch retained per tow (method as per 2.6.2 Fish abundances and weights by area swept), and compared against a mean of 0 using a one-sample t-test. A two-way ANOVA and Tukey HSD (honest significant difference) post hoc analysis was used to compare QSC size between treatments and vessels and to identify interactions between treatments and vessels.

2.6.4 Fishery choke time calculations

The mean and lower and upper confidence interval % decreases in whiting WPUA (kg) bycatches were obtained using LnRR, and back-calculating mean and upper and lower confidence interval % decreases when using the SMP at RAM. This provided a conservative estimate of the reduction as this site had the smallest decrease in whiting weight. These decreases were then applied to estimated monthly bycatch rates (kg) in the QSC otter trawl fishery in Manx territorial waters, obtained during the 2014-2015 and 2015-2016 seasons (provided by the MFPO). While this provides a crude estimate, it results in a conservative estimate of what might be achieved if all vessels in the QSC fishery adopted an SMP.

3. Results

3.1 Fish community composition between grounds and the influence of environmental variables on gadiform bycatch.

There was a significant difference in community structure for the metrics total fish bycatch (all fish caught during the trial), quota species bycatch and gadiform bycatch (Table 5, Appendix 2,3) between the two grounds surveyed, Targets and Ramsey Bay. For this reason, it was decided to investigate the performance of the net modifications separately for the different grounds, as well as for the treatments overall for both grounds combined. SIMPER analysis

indicated that the differences in gadiform bycatch were driven by higher abundances of haddock, whiting and cod at TAR, and the absence of poor cod and pouting at RAM (Table 6). Environmental variables that best explained patterns in gadoid community assemblage were tidal coefficient, mean depth (m), (BEST ρ 0.25), and depth and mean light intensity within the trawl (lux) (BEST ρ 0.25).

Table 5. ANOSIM pairwise comparisons between treatment and ground calculated from a Bray-Curtis similarity matrix from CPUA($\log(X+1)$ transformed) data for 3 bycatch components (Total fish, Quota species, Gadiform species). For each comparison, the R statistic and P value are specified. P=p-value (* $p < 0.05$, ** < 0.01)

Byatch component	Grounds		Control/SMP		Control/SMP+L		SMP/SMP+L	
	R	P	R	P	R	P	R	P
Total fish	0.45	0.001**	0.14	0.014*	0.017	0.35	0.01	0.31
Quota species	0.44	0.001**	0.092	0.057	0.022	0.3	-0.02	0.76
Gadiformes	0.26	0.001**	0.15	0.03*	0.078	0.57	-0.005	0.49

Table 6. SIMPER analysis showing mean abundances ($\log(X+1)$ transformed) per hectare and contribution (%) of gadiform bycatch species to the dissimilarity between fishing grounds and between the control and SMP treatment. TAR=Targets, RAM=Ramsey Bay, CTRL= control, SMP=square mesh panel.

Species	TAR		RAM		Contribution %	Cumulative %
	Mean Abundance		Mean Abundance	Mean Dissimilarity		
Haddock (<i>Melanogrammus aeglefinus</i>)	0.21		0.03	26.83	31.36	31.36
Whiting (<i>Merlangius merlanus</i>)	0.2		0.09	26.13	30.54	61.9
Cod (<i>Gadus morhua</i>)	0.08		0.05	16.64	19.45	81.35
Poor cod (<i>Trisopterus minutus</i>)	0.07		0	6.8	7.95	89.3
Pouting (<i>Trisopterus luscus</i>)	0.07		0	4.86	5.68	94.98

Species	CTRL		SMP		Contribution %	Cumulative %
	Mean Abundance		Mean Abundance	Mean Dissimilarity		
Whiting (<i>Merlangius merlanus</i>)	0.29		0.05	26.85	33.24	33.24
Haddock (<i>Melanogrammus aeglefinus</i>)	0.23		0.1	22.41	27.73	60.97
Cod (<i>Gadus morhua</i>)	0.06		0.09	14.73	18.23	79.2
Poor cod (<i>Trisopterus minutus</i>)	0.07		0.02	6.63	8.2	87.41
Pouting (<i>Trisopterus luscus</i>)	0.08		0.01	5.44	6.73	94.14

3.2 Differences in fish abundances when using modified nets

3.2.1 Gross community metrics

Total fish bycatch assemblages differed significantly (Table 5) between the control and the square mesh panel treatment across both grounds, however R values were low (Table 5), indicating that the effect sizes were small. SIMPER analysis indicated that these differences

were driven by lower abundances of haddock and whiting within the SMP treatment net (Table 6). There were no differences in community structure between the control and SMP+L or between the SMP and SMP+L treatments (Table 5). Quota species did not show a significant pattern in community structure between the treatments (Table 5), however univariate analysis demonstrated that mean abundances per hectare for quota species decreased significantly between control and SMP+L at Targets, equating to a 19.59% decrease (Table 8) in CPUA at this site. However, 95% confidence intervals were large, with the upper bound lying at a 3.66% reduction, and the lower bound equating to 32.89% and therefore this variance should be taken into account.

For the species of most concern to the Isle of Man Queen Scallop Fishery, namely gadiform species, significant decreases were observed at TAR for both treatments, where the order was encountered at higher abundances (Table 6); when using both the SMP and the SMP+L treatments, however, at RAM, no decrease was observed (Table 8, Figure 5). The addition of lights to the SMP at Targets increased this difference from 23.71% with the SMP alone to 32.03%; however, paired t-tests conducted on the LnRRs of the two modifications at TAR indicated that no significant differences between the two treatments was observed during the trials (Table 7).

No differences in abundance were found for the species orders of pleuronectiformes or rajiformes for either net modification at either site (Table 8, Figure 5). When using only an SMP, carcharhiniforme bycatch abundance was decreased by 33.5% at Targets alone and 29% when both sites were combined (Table 8). Interestingly, however, when lights were added to the SMP, there was no difference between the control and modified net (Table 8, Figure 5), indicating that the lights reversed the benefits of the presence of the SMP in terms of reducing bycatch for this order.

Table 7. Independent samples t-test results for comparisons between the two treatments: square mesh panel and square mesh panel with lights. This analysis was only carried out with data from Targets as the square mesh panel and lights treatment was not tested at Ramsey Bay. P=p-value.

Catch component	Levene's (P)	DF	T	t-test (P)
All species combined	0.474	38	-0.974	0.336
Quota spp (count)	0.669	38	-0.840	0.406
Quota spp (weight)	0.735	38	-0.434	0.663
Gadoids (count)	0.226	38	-0.664	0.511
Gadoids (weight)	0.072	38	-0.896	0.380

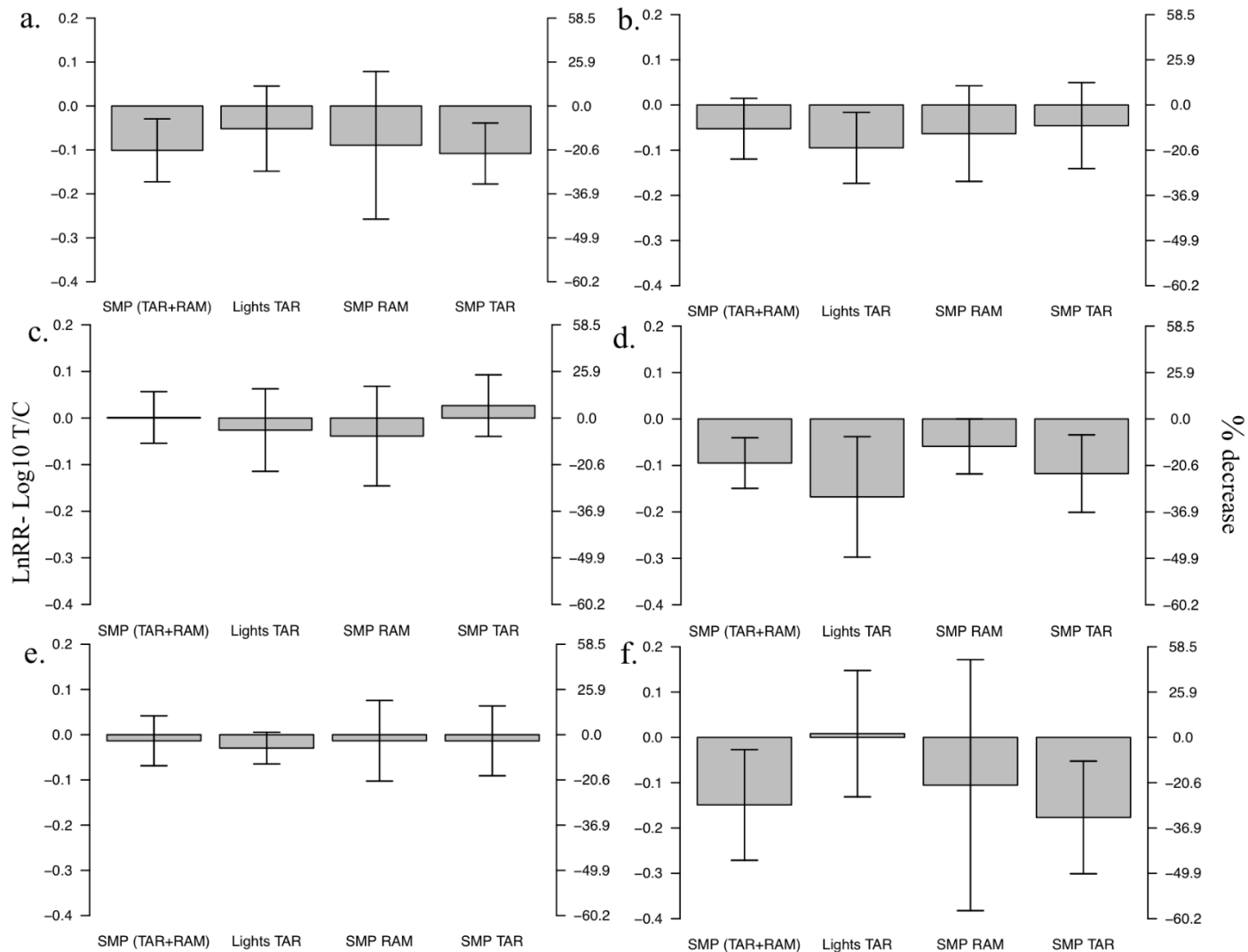


Figure 5. Mean ($\text{LnRR}+1$) of the abundance per hectare (CPUA) for the following bycatch components: a) total fish bycatch; b) quota species; c) gadiformes; d) pleuronectiformes; e) rajiformes and f) carcharhiniformes for the following treatments: SMP (TAR+RAM)=square mesh panel paired tows at Targets and Ramesy Bay, Lights TAR= square mesh panel with 6 LED lights attached. SMP TAR=square mesh panel at Targets SMP RAM=square mesh panel at Ramsey Bay. % reductions are back calculated from LnRR . Error bars represent 95% confidence intervals.

Table 8. Results of one-sample t-test/one-sample permutation t-test (Perm test) results performed on CPUA LnRR to assess if mean LnRR were different to a mean of 0, performed for gross community metrics (all species and quota species) as well as species orders. Where data was not normally distributed (as calculated using the Shapiro-Wilk test, Shapiro (p)), results for both t and permutation tests are presented SMP= square mesh panel, SMP+L=square mesh panel with the edition of artificial light. TAR= Targets fishing ground, RAM=Ramsey fishing ground. P=p-value (*p<0.05, **<0.01, *** p<0.001).

Catch component	Treatment	Site	Shapiro	DF	T	t-test (P)	Perm test (P)	% Reduction	%CI upper	%CI lower
All species	SMP	TAR+RAM	0.710	30	-2.878	0.007**		20.74	6.53	32.79
	SMP	TAR	0.555	18	-3.280	0.004**		22.06	8.57	33.55
	SMP	RAM	0.836	11	-1.171	0.266		NA		
	SMP+L	TAR	0.160	20	-1.112	0.279		NA		
Quota species	SMP	TAR+RAM	0.026*	30	-1.592	0.122	0.126	NA		
	SMP	TAR	0.051	18	-1.007	0.328		NA		
	SMP	RAM	0.038*	11	-1.316	0.215	0.216	NA		
	SMP+L	TAR	0.093	20	-2.516	0.021*		19.59	3.66	32.89
Gadiformes	SMP	TAR+RAM	0.005***	30	-3.561	0.001**	<0.001***	19.63	8.90	29.09
	SMP	TAR	0.097	18	-2.960	0.008**		23.71	7.55	37.04
	SMP	RAM	0.232	11	-2.193	0.051		NA		
	SMP+L	TAR	0.177	20	-2.697	0.014*		32.03	8.38	49.58
Pleuronectiforme	SMP	TAR+RAM	0.022*	30	0.047	0.963	0.966	NA		
	SMP	TAR	0.022*	18	0.844	0.410	0.435	NA		
	SMP	RAM	0.218	11	-0.079	0.442		NA		
	SMP+L	TAR	0.650	20	-0.609	0.549		NA		
Rajiformes	SMP	TAR+RAM	0.020*	30	-0.501	0.620	0.628	NA		
	SMP	TAR	0.016*	18	-0.371	0.715	0.732	NA		
	SMP	RAM	0.256	11	-0.330	0.748		NA		
	SMP+L	TAR	0.361	20	-1.767	0.092		NA		
Carcharhiniforme	SMP	TAR+RAM	0.010*	30	-2.492	0.018*	0.018*	29.04	6.01	46.43
	SMP	TAR	0.937	18	-2.986	0.008**		33.42	11.37	49.98
	SMP	RAM	0.035*	11	-0.84	0.837	0.421	NA		
	SMP+L	TAR	0.037*	20	0.124	0.903	0.908	NA		

3.2.1 Differences in individual species abundances when using modified nets

While numbers of cod (*G. morhua*) were too low within the survey to assess statistically, haddock and whiting were present in sufficient numbers to proceed with analysis. At TAR when using the SMP alone, 95% confidence intervals (and hence the one sample t-test approach), indicated that this treatment had no effect on haddock abundance (Table 9), although it should be noted that, with a t-test *P* value of 0.06 and a one sample permutation test *P* value of 0.046, the non-normal distribution of this data may have masked an effect. Interestingly however, when lights were added to the SMP, there was a significant decrease in haddock abundance, equating to 12.27% reduction. At RAM, haddock numbers were insufficient for meaningful analysis. Whiting, however, responded to both treatments at TAR, and interestingly, although CPUA was low at RAM, a significant decrease was also observed at this site (Table 9). The maximum mean decrease between treatment and control (22.9%) was observed with the addition of lights (Table 9), however no difference was detected between the SMP and SMP+L treatments (Figure 6). The analysis of lesser spotted catsharks indicated that the pattern of decrease followed that of their species order, with the addition of an SMP resulting in a mean decrease in abundance of 35% at TAR; but when light was added, no decrease was observed (Table 9, Figure 6). At RAM, no difference was observed in abundance of this species when using the SMP (Table 9).

Table 9 Results of one-sample t-test/one-sample permutation t- test results (Perm test) performed on CPUA LnRR to assess if mean LnRR were different to a mean of 0, performed for 3 species, haddock, whiting and lesser spotted catshark. Where data was not normally distributed (as calculated using the Shapiro-Wilk test, Shapiro (p)), results for both t and permutation t-tests are presented. SMP= square mesh panel, SMP+L=square mesh panel with the edition of artificial light. TAR= Targets fishing ground, RAM=Ramsey fishing ground. P=p-value (*p<0.05, **<0.01, *** p<0.001). Where confidence intervals are negative, this indicates that the upper bound is positive, and therefore greater than 0.

Catch component	Treatment	Site	Shapiro (P)	DF	T	t-test (P)	Perm test (P)	% Reduction	%CI upper	%CI lower
Haddock	SMP	TAR+RAM	<0.001***	30	-1.952	0.060	0.046*	9.29	-0.45	18.09
	SMP	TAR	0.005**	18	-2.012	0.059	0.046*	14.7	-0.71	27.75
	SMP	RAM	<0.001***	11	-1	0.389	1	NA		
	SMP+L	TAR	0.316	20	-2.445	0.024*		12.27	1.90	21.54
Whiting	SMP	TAR+RAM	0.002**	30	-3.759	<0.001***	<0.001***	16.75	8.03	24.64
	SMP	TAR	0.033*	18	-2.893	0.010**	0.007**	18.92	5.58	30.37
	SMP	RAM	0.003**	11	-2.640	0.023*	0.055	13.19	2.32	22.85
	SMP+L	TAR	0.489	20	-3.272	0.004**		22.89	8.99	34.67
Catshark	SMP	TAR+RAM	<0.001***	30	-2.373	0.025*	0.020*	30.02	4.85	48.53
	SMP	TAR	0.899	18	-3.302	0.004**	0.004**	35.43	14.71	51.12
	SMP	RAM	0.007**	11	-0.687	0.506		NA		
	SMP+L	TAR	0.034*	20	0.029	0.977	0.980	NA		

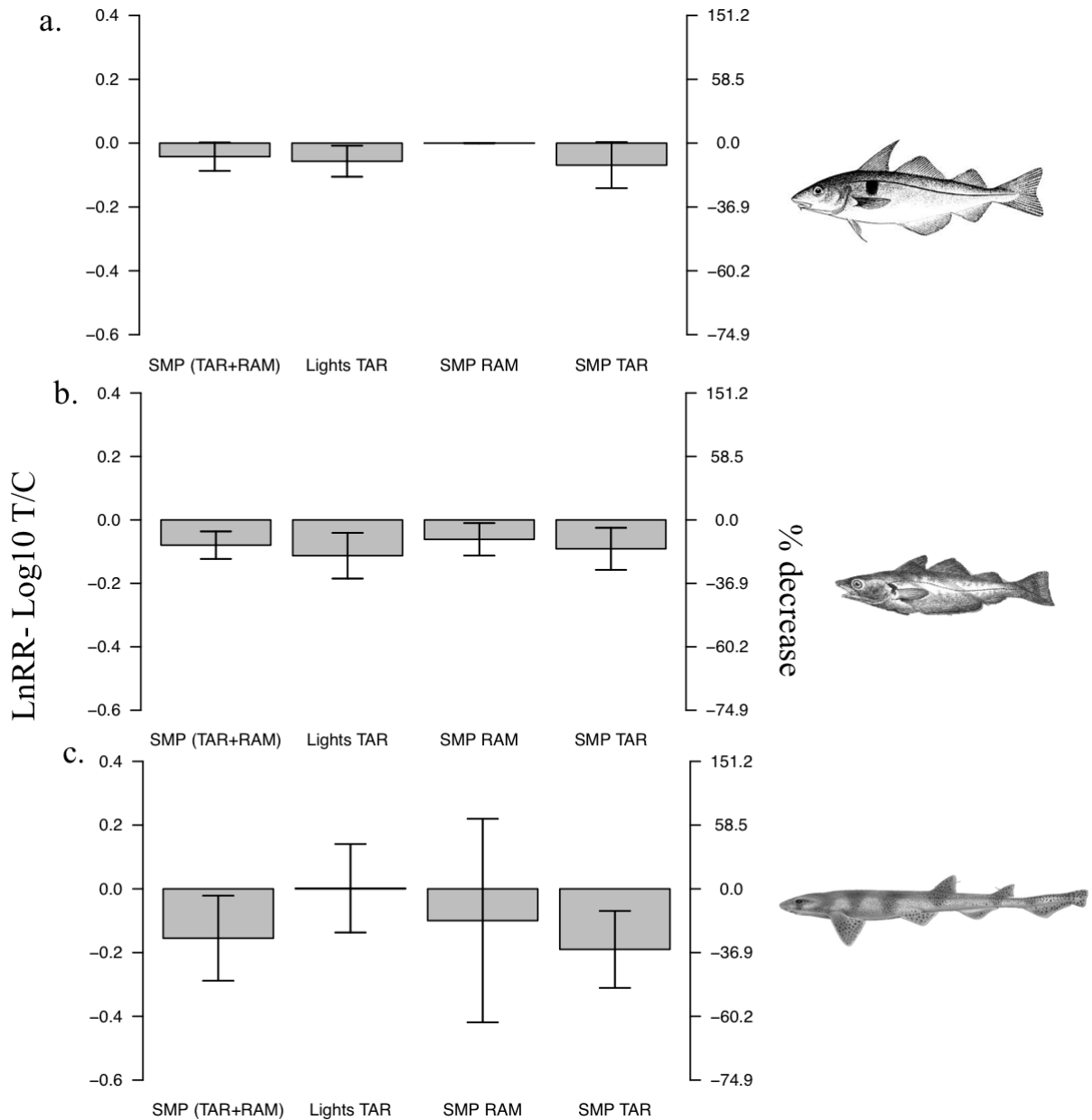


Figure 6 The mean ($\text{LnRR}+1$) of the abundance per hectare for the following bycatch species: a) haddock; b) whiting; c) lesser spotted catshark and for the treatments: SMP (TAR+RAM)=square mesh panel paired tows at Targets and Ramesy Bay, Lights TAR= square mesh panel with 6 LED lights attached. SMP TAR=square mesh panel at Targets SMP RAM=square mesh panel at Ramsey Bay. % reductions are back calculated from LnRR. Error bars represent 95% confidence intervals.

3.3 Differences in fish by weight and length between treatment

There were no differences in quota species weight between the treatments at either ground. The most commonly encountered quota species order was pleuronectiforme, which did not respond to the modified net (Table 8), thereby driving the ineffectiveness of the SMP for reducing quota species overall. There was, however, a 67% decrease in gadiform quota species WPUA when the SMP was employed at TAR (Table 11). In contrast, no decrease was observed with the addition of light, or at RAM. Interestingly, analysis of WPUA for haddock exhibited an opposite pattern to that observed when using CPUA, with significant decreases in weight occurring when using the SMP at TAR, but no differences being observed with the addition of light. This highlights the additional variance observed due to differential weights of individual fish. The greatest decreases observed for any single gadiform species were exhibited by whiting (Figure 7), with mean decreases in WPUA ranging between 73 and 79% observed at both sites and for both treatments (Table 11).

Size frequency distributions (Figure 8) indicate that there was no difference in the size distribution of quota gadiform species or haddock retained between control and treatment nets (Table 10), however the size distribution of whiting retained as bycatch differed significantly between the control and treatment nets. Only 32.2% of haddock caught during the survey were over the minimum landing size of 300mm (MMO, 2017) while 44% of whiting in the control net, and 48% in the treatment nets were above the minimum landing size of 270mm (MMO, 2017).

*Table 10 Results of Chi-square tests performed on the % frequencies of total length distributions for all gadiform species, haddock and whiting. Minimum landing size refers to Minimum Conservation Reference Sizes (MCRS) in UK waters (MMO, 2017) P=p-value (*p<0.05, **<0.01, *** p<0.001). DF=Degrees of freedom.*

	χ^2	DF	P	Minimum landing size
All gadiform species	104.530	84	0.064	NA
Haddock	70.095	54	0.069	30cm
Whiting	64.000	3	<0.001***	27cm

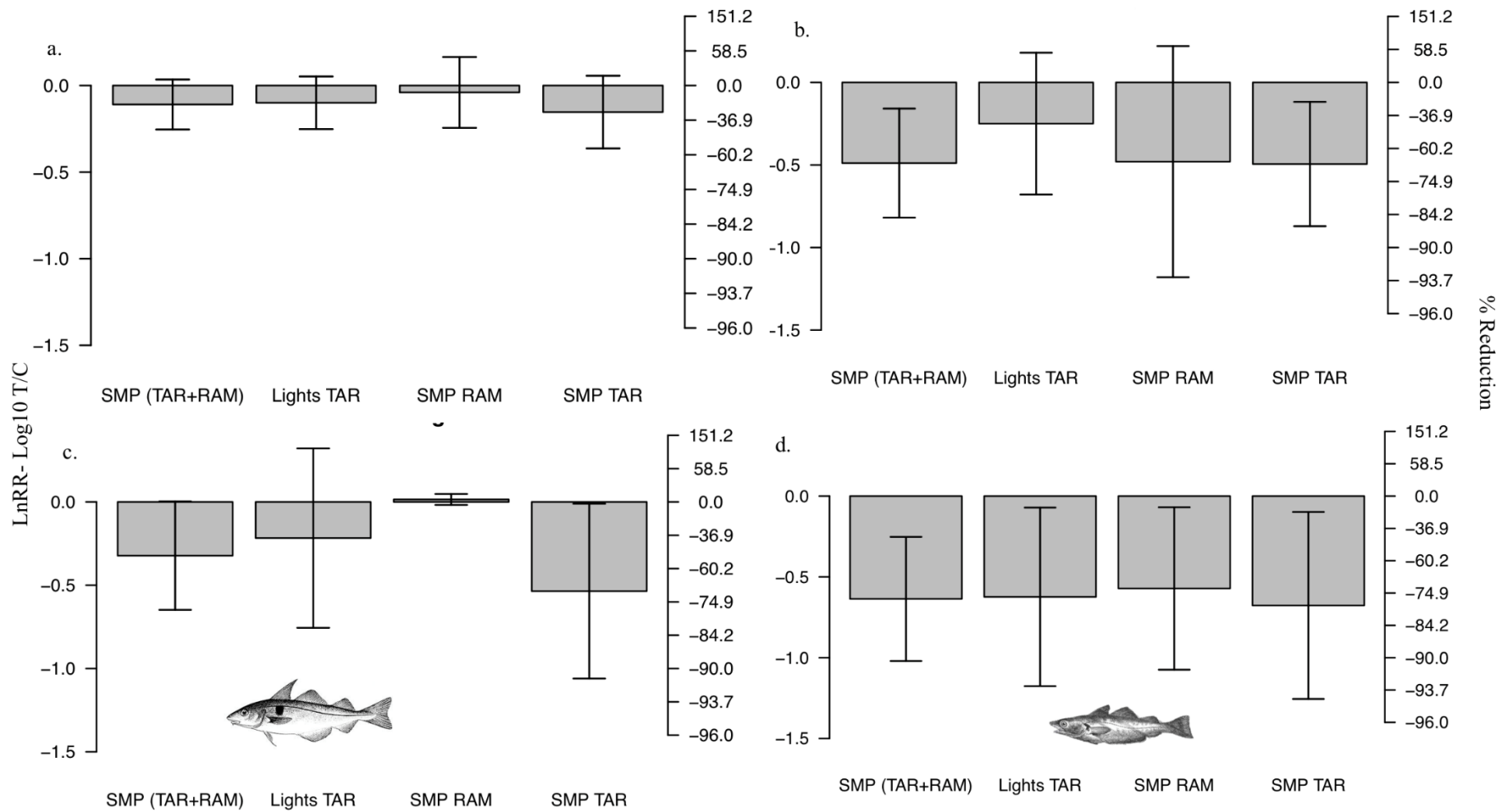


Figure 7 Mean ($\text{LnRR}+1$) of the weight per hectare (WPUA) for the following bycatch species: a) quota species; b) gadiform species; c) haddock and d) whiting for the treatments: SMP (TAR+RAM)=square mesh panel paired tows at Targets and Ramesy Bay, Lights TAR= square mesh panel with 6 LED lights attached. SMP TAR=square mesh panel at Targets SMP RAM=square mesh panel at Ramsey Bay. % reductions are back calculated from LnRR. Error bars represent 95% confidence intervals.

Table 11 Results of one-sample t-test/one-sample permutation t-test (Perm test) results performed on WPUA LnRR for quota species; gadiform speices; haddock and whiting to assess if mean LnRR were different to a mean of 0. WPUA data was estimated using length/weight relationships. Where data was not normally distributed (as calculated using the Shapiro-Wilk test, Shapiro (p)), results for the one Sample permutation t-test are presented. SMP= square mesh panel, SMP+L=square mesh panel with the edition of artificial light. TAR= Targets fishing ground, RAM=Ramsey fishing ground. P=p-value (*p<0.05, **<0.01, *** p<0.001)

Catch component	Treatment	Site	Shapiro (P)	DF	T	t-test (P)	Perm-test (P)	% Reduction	%CI upper	%CI lower
Quota spp.	SMP	TAR+RAM	<0.001***	30	-1.549	0.132	0.126	NA		
	SMP	TAR	<0.001***	18	-1.537	0.142	0.139	NA		
	SMP	RAM	<0.001***	11	-0.428	0.677	0.688	NA		
	SMP+L	TAR	0.058	20	-1.369	0.186		NA		
Gadiformes	SMP	TAR+RAM	<0.001***	30	-3.021	0.005**	<0.001***	67.55	30.54	84.84
	SMP	TAR	0.002**	18	-2.757	0.013*	0.003**	67.96	23.73	86.54
	SMP	RAM	0.045*	11	-1.509	0.160	0.053	NA		
	SMP+L	TAR	0.499	20	-1.212	0.240		NA		
Whiting	SMP	TAR+RAM	<0.014*	30	-3.385	0.002**	0.003*	76.90	44.07	90.46
	SMP	TAR	0.0193*	18	-2.460	0.024*	0.022*	76.22	20.35	90.46
	SMP	RAM	<0.001***	11	-2.509	0.029*	0.067	73.20	14.76	91.58
	SMP+L	TAR	0.119	20	-2.354	0.029*		78.96	15.07	93.34
Haddock	SMP	TAR+RAM	<0.001***	30	-2.024	0.052	0.060			
	SMP	TAR	0.019*	18	-2.143	0.046*	0.048*			
	SMP	RAM	<0.001***	11	1	0.339	1			
	SMP+L	TAR	0.052	20	0.841	0.411				

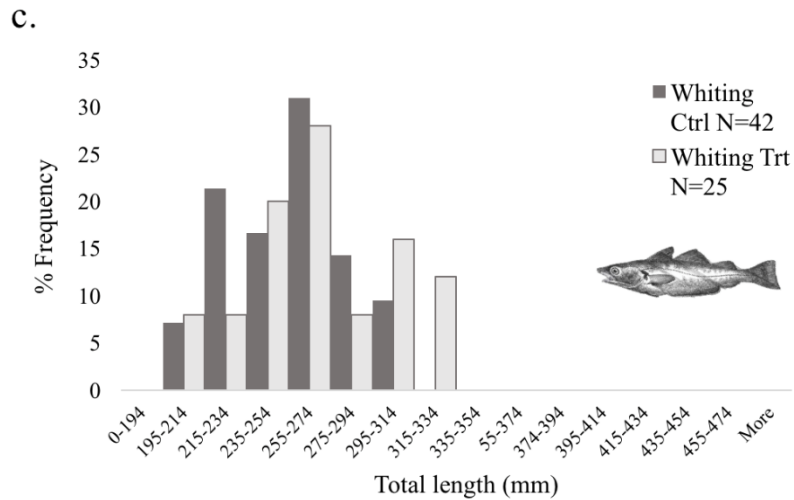
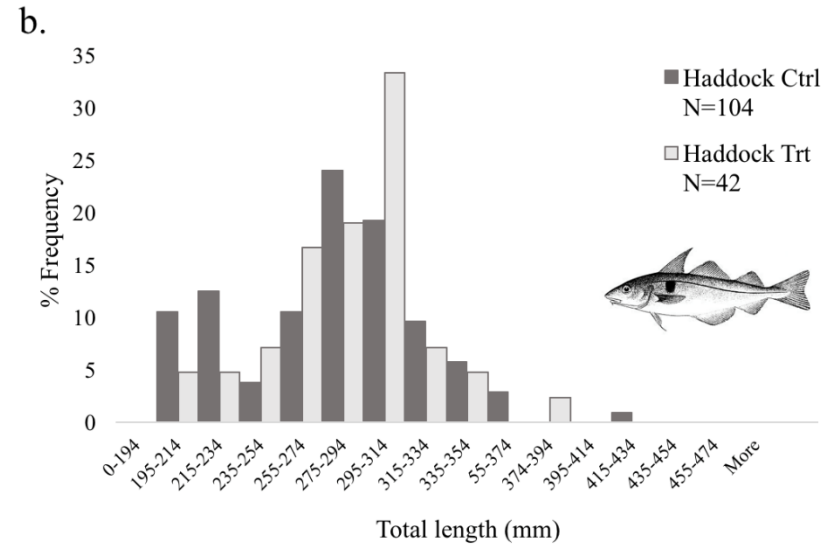
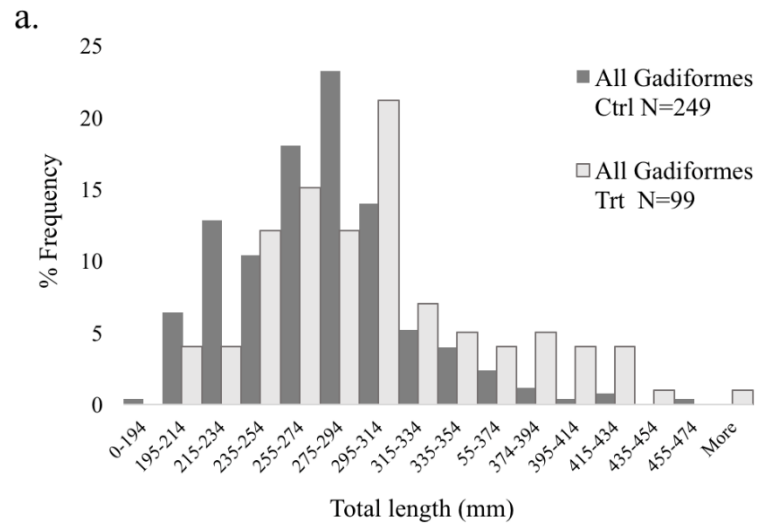


Figure 8 Total length (mm) frequency histograms for a. all gadiformes, b. Haddock and c. whiting caught during the gear trials. The number of fish in each part of the analysis is represented (N) on each graph.

3.4 Differences in queen scallop catches between treatment and vessel.

Landed QSC catches remained low throughout the survey (mean weight per tow at TAR: 35kg, mean weight per tow at RAM: 121kg); however they remained unaffected by the net modifications (Figure 9). Interestingly, however, there was a significant decrease in QSC size when using the modified nets (ANOVA, $F_{1, 11149} = 83.85$, $P < 0.001$, Figure 9). Further investigation showed that there was also a significant interaction between treatment and vessel on QSC shell height (two-way ANOVA, $F_{2, 11150} = 42.41$, $P < 0.001$) and mean shell height measured on TG was significantly lower than that measured on OSJ (ANOVA, $F_{1, 11149} = 345.8$, $P < 0.001$, Figure 9). Due to technical limitations, the control and treatment nets were not swapped between vessels at Ramsey, and Two Girls conducted all SMP tows at this site. Over the entire survey, OSJ conducted 7 SMP tows and 7 SMP+L tows in contrast to TG, which conducted 25 SMP tows and 14 SMP+L tows. Therefore, vessel effect was viewed as a confounding factor to the observed treatment effect.

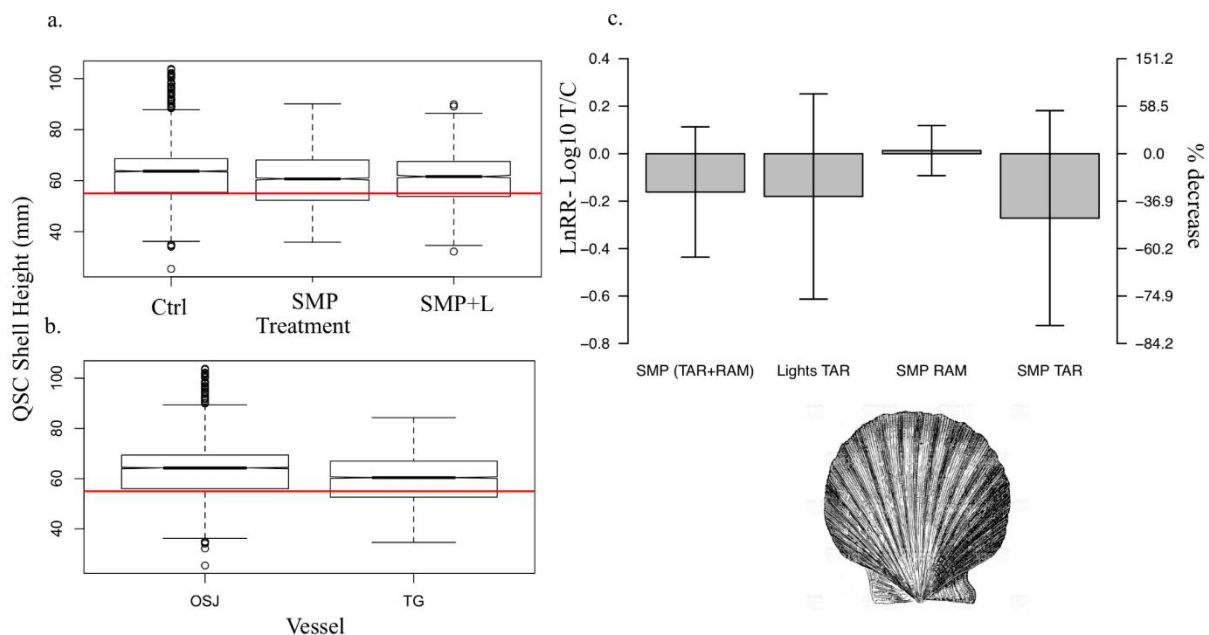


Figure 9. Shell height of QSC caught in a), control tows and two treatments (Ctrl=control, SMP=square mesh panel, SMP+L= square mesh panel and lights); b) the two vessels (OSJ= Our Sarah Jane, TG= Two Girls). Mean legal landing size, 55mm shell height is represented by red lines. The median is represented by the horizontal line within each box. Where notches do not overlap, this indicates that the medians of the groups analysed differ at the 5% significance level. c. The mean Log Response Ratio change in QSC landed catch, by weight per unit area. Error bars represent 95% confidence intervals.

3.5 Choke timings for the QSC otter trawl fishery, a focus on whiting

The only gadiform species for which there were consistent decreases across both sites and both treatments was whiting. Mean and 95% confidence intervals (Figure 10) indicate that, the cumulative bycatch of whiting could be reduced by the introduction of an SMP. The percentage by which this could occur is, however, this is variable as indicated by the confidence interval bands. If mean percentage decreases were to be achieved, this would enable the otter trawl fishery to not exceed the allocated quota of 400kg per year, however this analysis does not include whiting catch for other Isle of Man fisheries, which also share this quota.

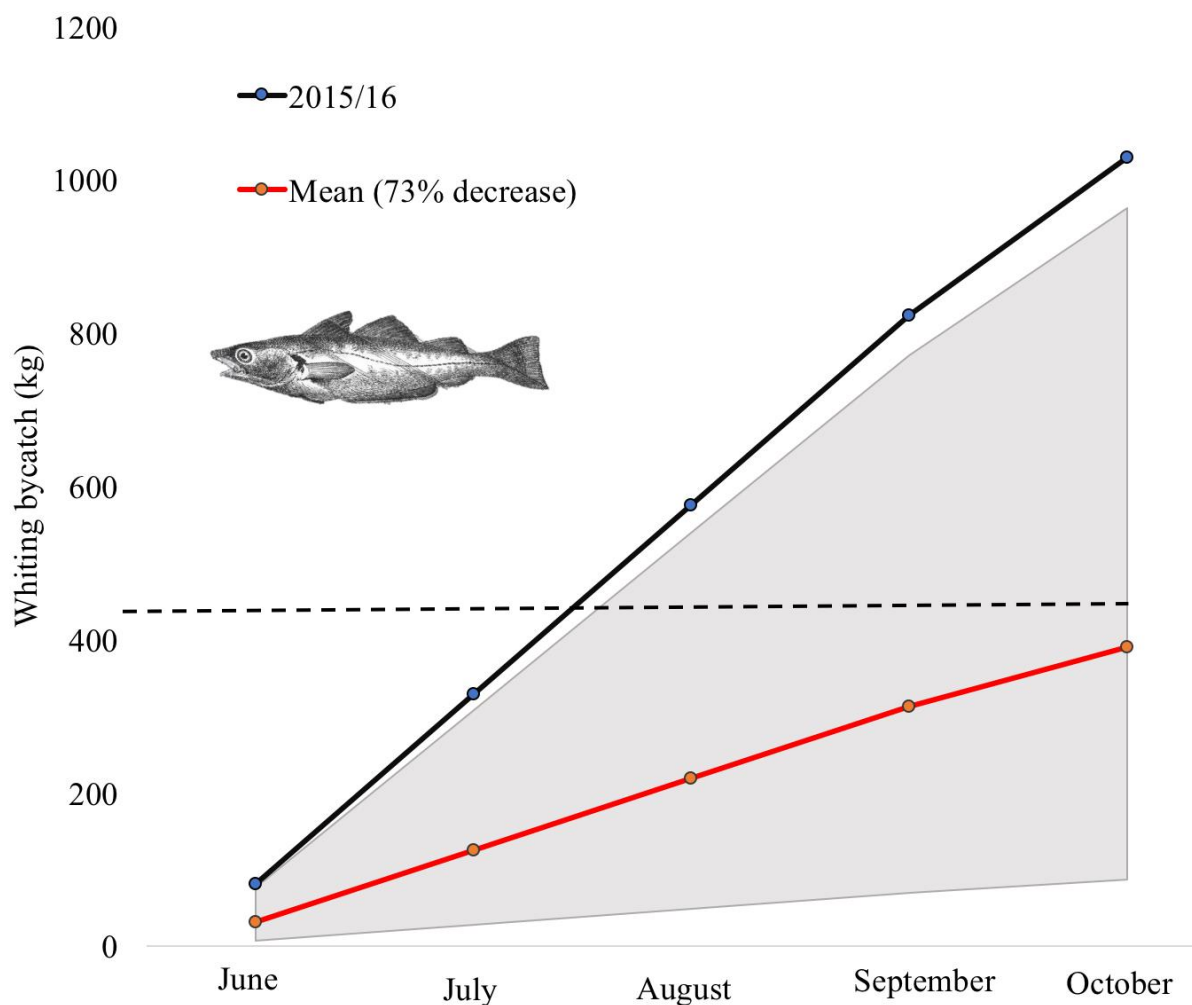


Figure 10. Cumulative % of whiting bycatch on a month by month basis throughout the Isle of Man QSC otter trawl season. The (kg) 2014-2016 data was based on unadjusted catch rates per month (kg) during 2014-15 and 2015-16 QSC season. The % reduction was calculated from the LnRR mean reduction from the trial data RAM, because this was the smallest reduction observed over the trial. The grey shaded area represents 95% confidence intervals: upper 14.7%, lower 91.58%. Current quota (2018) is represented by the dashed line.

4. Discussion

This study investigated the performance of two modifications, a square mesh panel and square mesh panel with the addition of light, to a QSC otter trawl net, using a paired tow design on board commercial fishing vessels, in order to assess if these net modifications would reduce the likelihood of an early termination of fishing due to lack of choke species quota. Results indicate that the adoption of a square mesh panel would result in a reduction of whiting, and the addition of lights may result in a reduction of haddock bycatch, and provide a basis for further trials.

4.1 Differences in community structure between fishing grounds and the influence of environmental variables.

Previous studies (Boyle *et al.*, 2016) have established that bycatch differs significantly between fishing grounds within the Isle of Man Territorial Sea, and therefore the difference in community composition between TAR and RAM was anticipated, and highlights the need to trial the net modifications at different grounds if the intervention is to be adopted for the fishery as a whole. Importantly, Ramsey Bay had a lower density of gadiformes overall, and as a result, sample sizes were too small to detect changes in abundance between the control and the modified net. This highlights the possibility for the different fishing grounds to be treated differently in terms of bycatch reduction strategy (Boyle *et al.*, 2016), and would suggest that an element of spatial management could be of benefit when developing a bycatch reduction strategy for the Isle of Man territorial sea.

Environmental factors that had the highest correlation with the observed patterns in gadiform abundances were tidal coefficient, mean depth and mean light intensity within the trawl. Tidal states (neaps/springs) are known to influence fish abundance (Arnold and Cook, 1984), and this phenomenon may account for the higher fish abundance observed at TAR during spring tides. Depth has previously been shown to drive differences in community assemblages at these sites (Boyle *et al.*, 2016), and this study supports that finding.

Behavioural responses of finfishes may change with fluctuating ambient light levels: when light is scarce ($< 10^{-6}$ lux), fish exhibit a startle response when they strike the sides of the net (Glass and Wardle, 1989), and this results in an increasingly disordered response as light levels decrease (Walsh and Hickey, 1993). For the SMP treatment, fish were dependent on vision, and hence light levels, to orientate themselves for escape, and therefore this may explain the influence of ambient light within the trawl on fish assemblage structure throughout the study.

In addition, the efficacy of SMPs as a BRD have been shown to be reduced in turbid conditions where visibility is reduced (Rulifson *et al.*, 1992), further supporting the importance of conditions that enable fish to see the net to orientate themselves for escape.

4.2 Fish abundance and weight

While total bycatch (all fish counted in the trial) differed significantly between control and SMP nets, both in terms of community composition and species abundance as calculated from LnRR, there was no difference between SMP and SMP+L or between control and SMP+L. Due to species specific differences in terms of reactions to behavioural BRDs (Clarke *et al.*, 1986; Briggs, 1992; Grimaldo *et al.*, 2017), it was not expected that the intervention would be successful for all species. For instance, an SMP which relies on fish finding their way to the top of the net is unlikely to be successful for flatfish species, as they tend to keep low within a trawl (Thomsen, 1993; Krag *et al.*, 2009). The most abundant species in the survey was the lesser spotted catshark (*S. canicula*), which was reduced by the SMP; however, this effect was negated with the addition of lights. Although it is not a quota species, this marked reaction to the presence of LED light may provide a useful insight into the potential use of this BRD. Elasmobranch species such as *S. canicula* have evolved to have high visual acuity (Jordan *et al.*, 2013), possessing duplex retinas and both rod and cone photoreceptors (Hueter *et al.*, 2004) and, in contrast to teleost species, *S. canicula* possess oblique slit pupils that are particularly adapted to low light conditions (Hueter *et al.*, 2004). Therefore, the possibility that this species' response to light were driven by increased visual capabilities as well as feeding ecology may warrant further investigation.

4.2.3 Gadiform responses

The reduction of quota gadiform bycatch was the main rationale behind this trial, and while, for the order as a whole, statistical differences were observed for both treatments and both grounds, CPUA was low throughout the study, and, in some cases, did not allow for species level analysis. This was of particular concern for cod, which is a potential choke species in this fishery (MFPO 2017, pers.comm. 25 August). For those species (haddock and whiting) where analysis was possible, responses varied. Haddock CPUA was not reduced by the square mesh panel alone but when lights were added, CPUA decreased. Video analysis (Grimaldo *et al.*, 2017) revealed that green LED lights (of the same specification as the white lights in the current study) induced a panic reaction, which resulted in rapid swimming movements, and a higher

escape rate through an SMP. Although quota in the QSC fishery is sufficient for current haddock bycatch, if haddock abundance and therefore bycatch in the Irish Sea were to increase, artificial light BRDs may be beneficial in the future. However, there was an opposite pattern observed for haddock WPUA with the only reduction being observed when the SMP alone was used, although a P value of 0.046 indicates that this was on the margins of significance. It is therefore suggested that further trials be carried out to ascertain which approach is most effective for this species.

While haddock bycatch presents a less pressing concern to the fishery, no extra quota for whiting is may be purchased in Division VIIa (MFPO 2017, pers.comm. 19 August), and therefore whiting bycatch poses a serious challenge. With only 400kg of quota available, there is a strong likelihood that this species could choke the QSC otter trawl fishery. Encouragingly, however, whiting bycatch reduced when using both treatments at both grounds, which equated to a mean decrease in weight (73%) when using the SMP. This would be sufficient to prevent a choke occurring over the course fishing season, with mean values indicating that cumulatively, a mean 391kg would be caught by the end of the season, which lies below the quota of 400kg. However, CPUA data indicated smaller reductions, of as little as 22% (at RAM), therefore the encouraging decreases in WPUA should be viewed with some caution and it should also be noted that if whiting stocks, and therefore whiting bycatch, were to increase, greater reductions would be necessary. However, SMPs have been successfully used to reduce whiting (*Merlangius merlangus*) bycatch in the Irish Sea nephrops fishery, under both commercial and experimental conditions (Briggs, 1992), providing further support for their use.

The species-specific differences in reaction of these gadiformes highlights that the order, as a whole, cannot be expected to have the same response to the modified nets. Similar studies would suggest that cod may not respond in the same manner as haddock. Grimaldo *et al.*, (2017) observed that, while haddock attempted escape through an SMP both with and without LED light stimulation, cod showed no significant increase in escape in response, and were shown to glide below the SMP and into the codend. In addition, while whiting bycatch in the Irish Sea *Nephrops* fishery was reduced with an SMP, the same measure was ineffective for reduction of cod (Briggs, 1992). Therefore, the current study cannot draw any conclusions as to the responses cod and other gadiform species that were not present sufficient numbers for analysis.

4.2.4 Placement of SMP

While large decreases in bycatch were observed during the study, the configuration of SMPs is known to play an important role in their efficacy (Herrmann *et al.*, 2014). For an SMP to be most effective in terms of bycatch reduction, it is recommended that, especially for species such as cod that stay low in the net (Grimaldo *et al.*, 2017), the SMP be positioned to overlap with the area of the codend where the fish bycatch accumulates (Herrmann *et al.*, 2014), such as in the BACOMA codend design used by Baltic Sea cod fisheries (Herrmann *et al.*, 2014). Because the placement of an SMP so near the codend often leads to concerns about loss of target species catch, a compromise can be sought between minimising target catch loss and maximising bycatch reduction (Broadhurst *et al.*, 2002). In the present trial, although there was a gap of only 50cm between the SMP and the codend (which itself measured 311cm), catches in this study were lower than under commercial fishing conditions. When fish enter the trawl; they tend to swim away from the net and lines, and are herded into the mouth of the net, where they swim at a similar speed to the moving trawl, however, once they tire, they are either swept upwards within the net or swept into the codend (Broadhurst, 2000). Therefore, it is reasonable to suggest that, when the net is full of scallops, the “catch accumulation zone” may overlap further with the SMP, and this may augment bycatch escape because exhausted/tired fish will accumulate directly below the SMP, rather than at the rear of the codend.

4.2.5 Differences in response to the SMP and SMP+L

Interestingly, while the addition of LED lights did not negate the decreases observed when using the SMP alone in this study, the use of light on the SMP did not significantly augment (or in the case of carcharhiniformes, decrease) bycatch reduction in comparison to the SMP alone. One explanation for this could be that light levels within the net were sufficient to enable fish to orientate themselves without the assistance of the light (Appendix 5) and therefore may have rendered the function of the lights obsolete; however, the strong response exhibited by *S. canicula* would indicate that, for species that respond strongly to the stimulus, light levels did not reduce the response.

Studies using LED lights as a means of bycatch reduction have yielded mixed results (Hannah *et al.*, 2015; Hunt, 2015). In the Oregon shrimp fishery, placing lights next to escape gaps led to increases in eulachon (*Thaleichthys pacificus*) bycatch, whereas placing light along the footrope of the trawl led to 91% reductions in bycatch (Hannah *et al.*, 2015), indicating that, for species that are strongly attracted or repelled by a certain wavelength of light, placement

is key. It would appear that in the current study, in daylight at relatively shallow depths, the influence of white LED light on gadiform species was not marked. While explanations such as the colour of the lights used may provide some insight (Marchesan *et al.*, 2005), it should also be noted that using LED light as a means of bycatch reduction has often been carried out at night (Clarke *et al.*, 1986; Hannah *et al.*, 2015; Hunt, 2015). Therefore, there is potential that the lights would be more useful as a guiding mechanism for escape when other visual cues are absent, such as at deeper depths or at night. Consequently, it is recommended that this BRD be trialed either at deeper depths or during night fishing before conclusions are drawn about the placing, intensity and colour of the lights. In the Isle of Man territorial sea however, TAR is the second deepest of the fishing grounds (mean depth 35.7) and while fishing also takes place at Chickens (mean depth 56.8m), the majority of tows take place in depths shallower than 41m. Therefore, if ambient light levels are the deciding factor in the efficacy of this BRD, it may need to be adopted on a ground by ground basis.

4.3 Fish length

The size (total length) frequency of all gadiformes did not differ significantly between the control and treatment nets; however, there was a significant difference in the size distribution of whiting between the treatment and control nets. While mesh size may have an influence on size selectivity of whiting (Vogel *et al.*, 2017), in this study the square meshes of the net used were relatively large, at 300mm stretched mesh, therefore they were unlikely to be limiting the size of fish that could pass through them. Therefore, further investigation may be required to ascertain why this SMP resulted in differential size selection. In contrast, there was no significant difference in haddock size distribution between the control and treatments, although *P* values of 0.06 indicate that the potential for a difference may exist. Grimaldo *et al.*, (2017) observed that, when using an SMP with an average mesh size of 141mm, the release efficiency of haddock through the panel was size dependent, and larger fish, although physically able to pass through the panel, were less likely to do so, unless a stimulation device, such as LED light was used. In the present study, sample sizes in the SMP and SMP+L treatments were small, and therefore further trials may be beneficial to ascertain if there is a difference in the size of fish retained when LED light is used. In addition, the use of a codend cover (i.e. as Grimaldo *et al.*, 2017), would be useful in ascertaining the size of fish that were escaping from the codend.

While the aim of introducing a BRD into this fishery is to minimise bycatch of choke species, there is potential that some of the fish above minimum landing size (MLS) could be sold for human consumption and therefore a small amount of profit could be generated. Therefore, if an SMP were to increase the percentage of fish bycatch of marketable size, this could provide some secondary benefit. However, in the case of whiting, while a small increase of marketable fish was observed with an SMP, the benefit/profit would be immaterial if the species was likely to choke the fishery, preventing further profits being generated from the target catch. In addition, there is concern that if a market for fish that would otherwise be discarded is found, the focus may be shifted to commercial utilisation rather than reducing bycatch at source (Catchpole *et al.*, 2005).

4.4 Queen Scallop catches

Landed QSC catches were low (below commercially viable quantities, mean per tow at TAR: 35kg, RAM: 121kg) throughout the survey, therefore impact of the modifications on the target catch is difficult to quantify. In addition, the entire catch was only riddled for every tow at RAM, whereas at TAR some tows were sorted by hand and the riddle sizes were not identical on the two vessels. No significant differences were found between the treatments, although variance was very large as demonstrated by 95% confidence intervals. Because the SMP was located in the forward portion of the net and did not overlap with the codend where the target catch accumulates, it is unlikely that, with such low catch rates, QSC were lost through the SMP. It should be noted that the SMP in its current configuration was not fit for commercial fishing purposes due to extensive snagging (Appendix 7); therefore, modifications to the SMP, as well as further trials, would be needed to ascertain if QSC catches could be lost through an SMP.

The decrease in QSC in the treatment net is likely to be confounded by the vessel effect as the number of replicates was unbalanced between the two vessels. This may be down to observer error, considering that QSC were selected from a basket by eye and measured by hand. On OSJ, the fishermen themselves measured the catch, while on board TG, the catch was measured by scientists. Therefore, it is difficult to draw conclusions as to the influence of the SMP and SMP+L treatments on the size of QSC within the catch. Crucially, the decrease observed in the treatments and aboard TG equated to a decrease in marketable size QSC, highlighting the need for further trials.

4.5 Reductions in likelihood of an early termination of fishing due to lack of choke species quota, and recommendations for future trials

The decrease in whiting bycatch observed during these trials, when applied to data from the 2015-16 season, has the potential to decrease the likelihood of a choke due to whiting. While encouraging decreases in whiting bycatch were observed when using both the SMP and SMP+L, it may be possible to augment these decreases further. Due to the dimensions of the QSC otter trawl net, changing the placement of the SMP may be challenging. However, research on SMP configurations, indicate that the greatest decreases in undersize whiting are achieved using a square mesh cylinder, which consists of square mesh sections in both the head and belly of the net (Vogel *et al.*, 2017) and reductions increase when cylinders are situated closer to the codend (Vogel *et al.*, 2017). Interestingly, mesh sizes in many trials (Marlen, 2003; Catchpole and Revill, 2008; Vogel *et al.*, 2017) were smaller than in the current study, therefore potentially a compromise could be sought by reducing the size of the mesh (and thereby alleviating some concerns over loss of QSC catch) and positioning either a SMP even closer to the codend of the net.

While this study cannot draw any conclusions of the efficacy of an SMP in reducing cod bycatch, it is expected that, in 2018, an extra 800kg of cod quota will be allocated to the Isle of Man fisheries (MFPO 2017, pers.comm. 19 August). This decrease, although does not eliminate, the threat of cod choking this fishery. The responses of haddock and carcharhiniformes indicate that LED lights may have a role to play in bycatch reduction in this fishery. Of note too are marginally non-significant decreases in rajiforme bycatch observed only with the use of lights. Large rajiformes were unable to escape through the SMP in this study, however this result may indicate that, if escape were possible, lights may influence the rates at which this occurs. In addition, the strong response to light demonstrated by carcharhiniformes indicates that, if lights were placed along the headrope or footrope of the net (e.g. Hannah *et al.*, 2015, Hunt, 2015), they may be discouraged from entering a net. These findings further support the use of light in trials to reduce elasmobranch bycatch, and provide an encouraging basis for future trials. The possibility that larger carcharhiniforme species such as spur dog (*Squalus acanthius*), that were too large to escape through an SMP, may also exhibit a repulsion response to light along the headrope/footrope is worthy of investigation. Potential trials that experiment with green light (Grimaldo *et al.*, 2017) or with the use light along the headrope and/or footrope may be beneficial in this case.

4.6 Conclusion

This current study provides a basis on which to recommend the use of an SMP for the reduction of whiting bycatch in the Isle of Man QSC otter trawl fishery. Mean reductions in WPUA of 73% were observed for this species, and therefore this measure would assist in reducing the risk of potential early closures of the fishery due to whiting bycatch. While no conclusions can be reached for the reduction of cod bycatch, haddock CPUA was reduced by use of lights, and WPUA by the use of an SMP, therefore the net modifications trialled may prove useful for this species. Although lesser spotted catshark bycatch was reduced by an SMP, this species exhibited an avoidance response to the addition of LED light, and did not escape when using LED light. There was an indication that the net modifications resulted in a small increase in marketable sized fish, and therefore there is potential that the modifications may result in a small increase in profitability of gadiform bycatch, although this would only be beneficial if the risk of choke was also reduced. Due to confounding effects, it was not possible to quantify the impact of the SMP on all aspects of the QSC catch, although importantly, no reduction in the weight of legal size, landed catch was observed. In conclusion, this study provides a basis for the adoption of an SMP and the continuation of gear trials to reduce a wider range of quota species bycatch in the QSC otter trawl fishery.

References

- Arnold, G. P., & Cook, P. H. (1984). 'Fish migration by selective tidal stream transport: first results with a computer simulation model for the European continental shelf'. *Mechanisms of migration in fishes* (pp. 227-261).
- Ben-yami, M. (1976). 'Fishing with light'. FAO fishing manuals. In: FAO of the United Nations. Fishing News Books, Oxford.
- Borges, L. (2015) 'The evolution of a discard policy in Europe', *Fish and Fisheries*, pp. 534–540.
- Boyle, K., Kaiser, M. J., Thompson, S., Murray, L. G. and Duncan, P. F. (2016) 'Spatial Variation in Fish and Invertebrate Bycatches in a Scallop Trawl Fishery', *Journal of Shellfish Research*, 35(1), pp. 7–15.
- 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*, 183(May), pp. 13–18.
- 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
- Brinkhof, J., Larsen, R. B., Herrmann, B. and Grimaldo, E. (2017) 'Improving catch efficiency by changing ground gear design : Case study of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea bottom trawl fishery', *Fisheries Research*. 186, pp. 269–282.
- Broadhurst, M. K. (2000) 'Modifications to reduce bycatch in prawn trawls: A review and framework for development', *Reviews in Fish Biology and Fisheries*, 10(1), pp. 27–60.
- Broadhurst, M. K. and Kennelly, S. J. (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(4), pp. 203–214.
- 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(4), pp. 813–823.
- Catchpole, T. L., Frid, C. L. J. and Gray, T. S. (2005) 'Discards in North Sea fisheries: Causes, consequences and solutions', *Marine Policy*, 29(5), pp. 421–430.
- Catchpole, T. L., & Gray, T. S. (2010). 'Reducing discards of fish at sea: a review of European pilot projects. *Journal of Environmental Management*', 91(3), pp. 717-723.
- Catchpole, T. L. and Revill, A. S. (2008) 'Gear technology in Nephrops trawl fisheries', *Reviews in Fish Biology and Fisheries*, 18(1), pp. 17–31.
- Clarke, M. R., Pascoe, P. L. and Maddock, L. (1986) 'Influence of 70 Watt Electric Lights on the Capture of Fish By Otter Trawl Off Plymouth', *Journal of the Marine Biological Association of the United Kingdom*. Prifysgol Bangor University, 66(3), p. 711.

Clarke, K.R., Gorley, R.N., (2006). PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth, 192pp.

Courtney, A.J., Haddy, J.A., Campbell, M.J., Roy, D.P., Tonks, M.L., Gaddes, S.W., Chilcott, K.E., O'Neill, M.F., Brown, I.W., McLennan, M. and Jebreen, J.E., 2007. 'Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery', *Report to the Fisheries Research Development Corporation*, (2000/170).

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(3), pp. 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(1–2), pp. 165–174.

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R. B., Brinkhof, J. and Tatone, I. (2017) 'Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behaviour', *Canadian Journal of Fisheries and Aquatic Sciences*, p. cjfas-2017-0002.

Good, P. 2000. Permutation Tests. Springer, New York.

Guanais, J. H. G., Medeiros, R. P. and McConney, P. A. (2015) 'Designing a framework for addressing bycatch problems in Brazilian small-scale trawl fisheries', *Marine Policy*. 51, pp. 111–118.

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*. 170, pp. 60–67.

Hedges, L.V., Gurevitch, J. and Curtis, P.S., 1999. 'The meta-analysis of response ratios in experimental ecology'. *Ecology*, 80(4), pp.1150-1156.

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*, 183, pp.13-18.

Elliot, S., Catchpole, T., 2015. 'Trawlright: a scoping study' *CEFAS report: C6557*. pp. 31

Herrmann, B., Wienbeck, H., Karlsen, J. D., Stepputtis, D., Dahm, E. and Moderhak, W. (2014) '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(2), pp. 686–696.

Hiddink, J. G., Jennings, S., Sciberras, M., Szostek, C. L., Hughes, K. M., Ellis, N., Rijnsdorp, A. D., McConnaughey, R. A., Mazon, T., Hilborn, R., Collie, J. S., Pitcher, R., Amoroso, R. O., Parma, A. M., Suuronen, P. and Kaiser, M. J. (2017) 'Depletion and recovery of seabed biota following bottom trawling disturbance', *Proceedings of the National*

Academy of Sciences, 114(31), pp. 1–67.

Hueter, R.E., Mann, D.A., Maruska, K.P., Sisneros, J.A. and Demski, L.S., 2004. 'Sensory biology of elasmobranchs'. *Biology of sharks and their relatives*, pp.325-368.

Hunt, D. E. (2016). The effect of visual capacity and swimming ability of fish on the performance of light-based bycatch reduction devices in prawn trawls (Doctoral dissertation, University of Tasmania).

Jordan, L. K., Mandelman, J. W., McComb, D. M., Fordham, S. V., Carlson, J. K. and Werner, T. B. (2013) 'Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: A review with new directions for research', *Conservation Physiology*, 1(1), pp. 1–20.

Kelleher, K. (2005). Discards in the world's marine fisheries: an update (No. 470). Food & Agriculture Organisation.

Kim, Y. H. and Whang, D. S. (2010) 'An actively stimulating net panel and rope array inside a model cod-end to increase juvenile red seabream escapement', *Fisheries Research* 106(1), pp. 71–75.

King, M., 2007: Fisheries Biology, Assessment and Management. 2nd Edition. Oxford, Blackwell Publishing, 382 pp.

Krag, L. A., Herrmann, B., Feekings, J., Lund, H. S. and Karlsen, J. D. (2017) 'Improving escape panel selectivity in *Nephrops*-directed fisheries by actively stimulating fish behavior', 493(August 2016), pp. 486–493.

Krag, L. A., Madsen, N. and Karlsen, J. D. (2009) 'A study of fish behaviour in the extension of a demersal trawl using a multi-compartment separator frame and SIT camera system', *Fisheries Research*, 98(1–3), pp. 62–66.

Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M. and Gattuso, J. P. (2013) 'Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming', *Global Change Biology*, 19(6), pp. 1884–1896.

Lajeunesse, M. J. (2011) 'On the meta-analysis of response ratios for studies with correlated and multi-group designs', *Ecology*, 92(11), pp. 2049–2055.

Little, A. S., Needle, C. L., Hilborn, R., Holland, D. S. and Marshall, C. T. (2015) 'Real-time spatial management approaches to reduce bycatch and discards: Experiences from Europe and the United States', *Fish and Fisheries*, 16(4), pp. 576–602.

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', *NMFS Northwest Fisheries Science Center Report*. (April), pp. 61–66.

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(1–2), pp. 171–185.

Van Marlen, B., 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'. *Fisheries Research*, 63(2), pp.155-168.

Meintzer, P., Walsh, P., & Favaro, B. (2017). Will you swim into my parlour? In situ observations of Atlantic cod (*Gadus morhua*) interactions with baited pots, with implications for gear design. *PeerJ*, 5, e2953.

Nichols, T. E. and Holmes, A. P. (2001) 'Nonparametric Permutation Tests for {PET} functional Neuroimaging Experiments: A Primer with examples', *Human Brain Mapping*, 15(1), pp. 1–25.

Revoll, A. S., Catchpole, T. L. and Dunlin, G. (2007) 'Recent work to improve the efficacy of square-mesh panels used in a North Sea *Nephrops norvegicus* directed fishery', *Fisheries Research*, 85(3), pp. 335–341.

Rulifson, R. A., Murray, J. D. and Bahen, J. J. (1992) 'Finfish Catch Reduction in South Atlantic Shrimp Trawls Using Three Designs of By-catch Reduction Devices', *Fisheries*, 17(1), pp. 9–20.

Salomon, M., Markus, T. and Dross, M. (2014) 'Masterstroke or paper tiger - The reform of the EU's Common Fisheries Policy', *Marine Policy* 47(January 2016), pp. 76–84.

Sciberras, M., Jenkins, S. R., Mant, R., Kaiser, M. J., Hawkins, S. J. and Pullin, A. S. (2015) 'Evaluating the relative conservation value of fully and partially protected marine areas', *Fish and Fisheries*, 16(1), pp. 58–77.

Sterling, D.J., 2005. 'Modelling the physics of prawn trawling for fisheries management' (Doctoral dissertation, Curtin University).

Thomsen, B., 1993. 'Selective flatfish trawling'. *ICES Marine Science Symposia* 196, pp. 161-164).

Thorsteinsson, G. 1992. 'The use of square mesh codends in the Icelandic shrimp (*Pandalus borealis*) fishery'. *Fisheries Research* 13 pp. 255–266.

Veiga, P., Pita, C., Rangel, M., Gonçalves, J.M., Campos, A., Fernandes, P.G., Sala, A., Virgili, M., Lucchetti, A., Brčić, J. and Villasante, S., 2016. 'The EU landing obligation and European small-scale fisheries: What are the odds for success?'. *Marine Policy*, 64, pp.64-71.

Vogel, C., Kopp, D. and Méhault, S. (2017) 'From discard ban to exemption: How can gear technology help reduce catches of undersized *Nephrops* and hake in the Bay of Biscay trawling fleet?', *Journal of Environmental Management*, 186, pp. 96–107.

Vogel, C., Kopp, D., Morandeau, F., Morfin, M. and Méhault, S. (2017) 'Improving gear selectivity of whiting (*Merlangius merlangus*) on board French demersal trawlers in the English Channel and North Sea', *Fisheries Research*, 193(April), pp. 207–216.

Walsh, S.J., Hickey, W. M. (1993) 'Behavioural reactions of demersal fish to bottom trawls at various light conditions', *ICES mar. Sci. Symp.*, 196, pp. 68–76.

Zeller, D., Cashion, T., Palomares, M. and Pauly, D. (2017) 'Global marine fisheries discards: A synthesis of reconstructed data', *Fish and Fisheries* (February), pp. 1–10.

Zeller, D. and Pauly, D. (2005) 'Good news, bad news: global fisheries discards are declining, but so are total catches', *Fish and Fisheries*, 6(6), p. 156.

Grey literature

Common Fisheries Policy, 2013. Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:354:0022:0061:EN:PDF>. Last accessed 12 Sep. 17

DEFA, Isle of Man Government, 2017. Available at: <https://www.gov.im/about-the-government/departments/environment-food-and-agriculture/>. Last accessed 12 Sep. 17

Fishing TACs and quotas, 2015. Available at https://ec.europa.eu/fisheries/sites/fisheries/files/docs/body/poster_tac2015_en.pdf. Last accessed 12 Sep. 17.

Marine Management Organisation, 2017. Minimum landing sizes. Available at: <https://www.gov.uk/government/publications/minimum-conservation-reference-sizes-mcrs/minimum-conservation-reference-sizes-mcrs-in-uk-waters>. Last accessed 12 Sep. 17

Tides for fishing, 2017. Available at: <http://www.tides4fishing.com/tides/tidal-coefficient>
Last accessed 12 Sep. 17

Illustration credits:

Haddock. Available at: <http://www.fishecology.org/soniferous/image112.gif>. Last accessed 12 Sept 17.

Whiting. Available at: <http://www.alamy.com/stock-photo-haddock-melanogrammus-aeglefinus-merlangius-merlangus-whiting-merling-107982703.html> and edited by the author. Last accessed 12 Sept 17.

Catshark. Available at: <http://www.gettyimages.co.uk/detail/illustration/illustrated-side-view-of-small-spotted-royalty-free-illustration/72196719> and edited by the author. Last accessed 12 Sept 17.

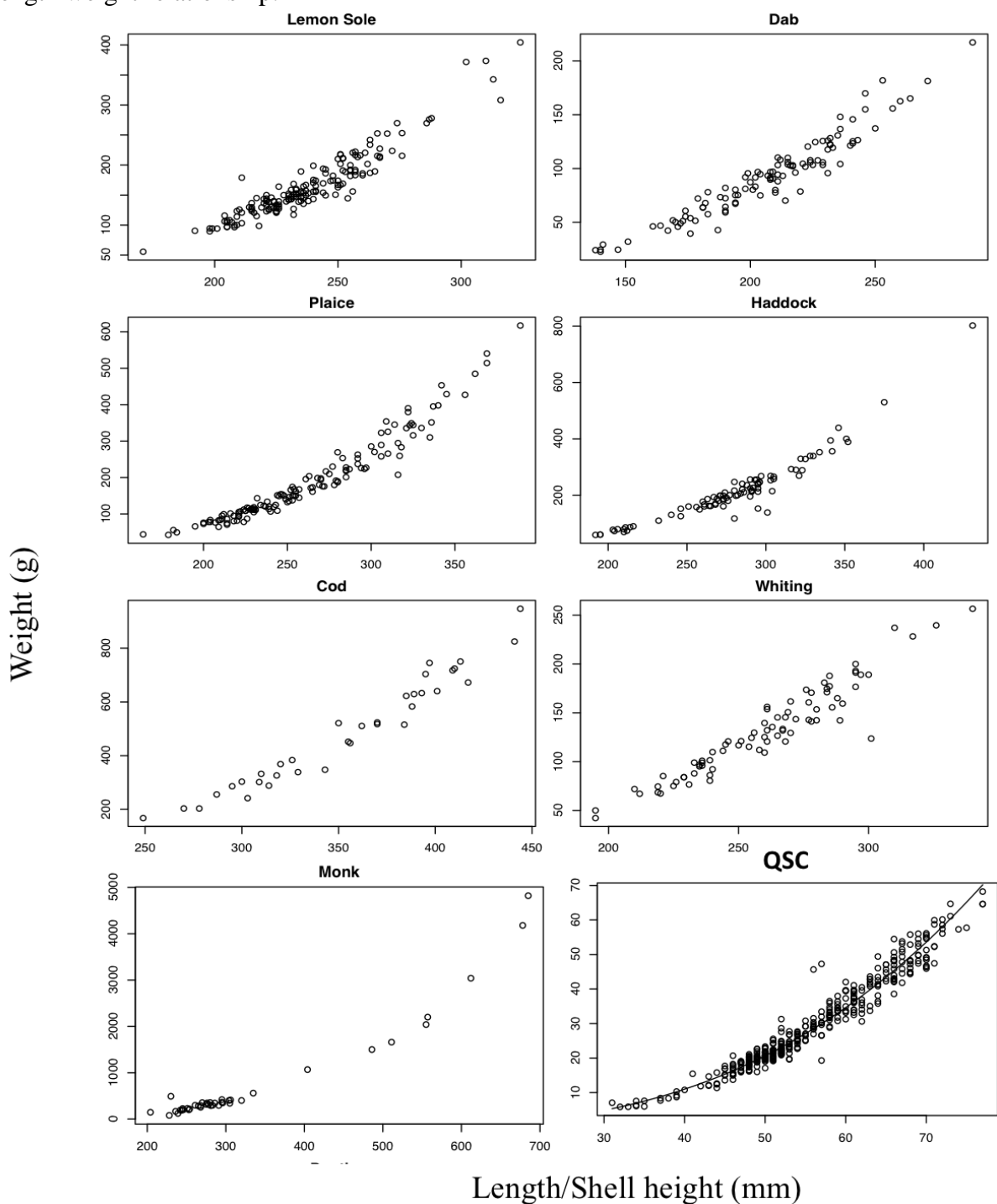
Queen scallop. Available at: <http://www.istockphoto.com/gb/vector/antique-illustration-of-queen-scallop-gm508347203-46014264>. Last accessed 12 Sept 17.

Photo credits:

All photos in this thesis were taken during the gear trials by Lucy Southworth, Jack Emmerson, Isobel Bloor, Frances Ratcliffe and Claire Lambden.

Appendix

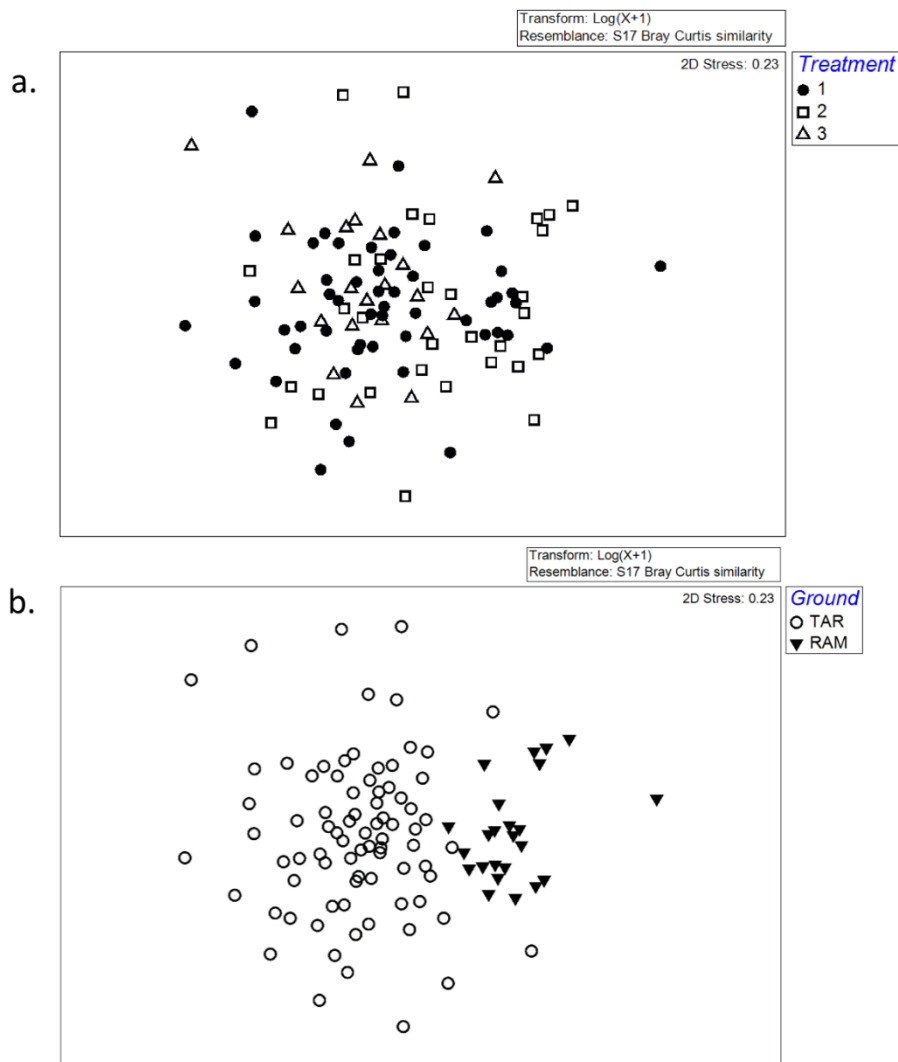
Appendix 1. Weight length relationship plots and “a” and “b” values for use in the equation: $W = aL^b$ (King, 2007) where W denotes weight (g), L denotes TL (cm), and a and b are constants for quota species which were present in the study sufficient numbers to ascertain a length weight relationship.



Appendix 1. cont'd

Species	a	b
Lemon sole (<i>micorstomus kitt</i>)	-10.407373	2.829204
Whiting (<i>Merlangius merlanus</i>)	-12.038805	3.034202
Cod (<i>Gadus morhua</i>)	-11.487862	3.001368
Haddock (<i>Melanogrammus aeglefinus</i>)	-12.32826	3.12748
Monk/ Anglerfish (<i>Lophius piscatorius</i>)	-10.700586	2.917665
Plaice (<i>Plueronectes platessa</i>)	-12.824653	3.224888
Dab (<i>Limnada limnada</i>)	-11.303324	2.957324
Queen scallop (<i>Aequipecten opercularis</i>)	-8.048176	2.831494

Appendix 2. MDS ordination plots showing the represent similarity and dissimilarity of species CPUA data within replicate tows between a. treatments (1= control, 2= square mesh panel, 3= square mesh panel and light) and b., between the two different fishing grounds (TAR=Targets, RAM=Ramsey Bay).



Appendix 3. Output from the SIMPER routine, used to identify which species (when looking at both quota and non-quota fish caught during the trials) contributed most to the differences observed between the fishing grounds. TAR=Targets, RAM=Ramsey Bay.

All fish bycatch species caught during the trials SIMPER analysis

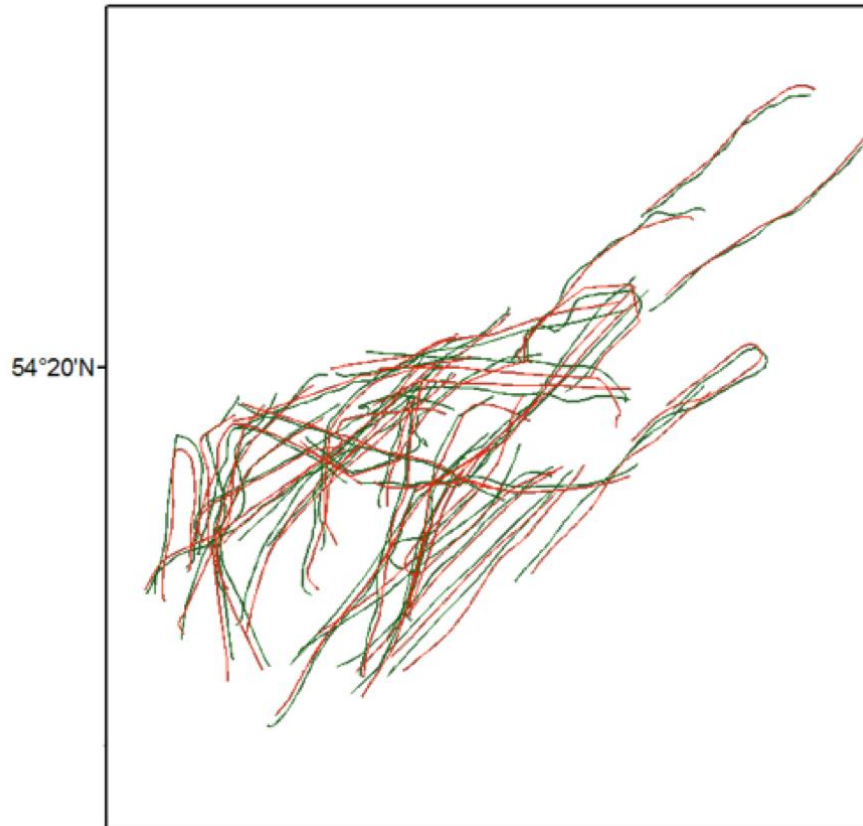
Groups TAR & RAM

Average dissimilarity = 56.18

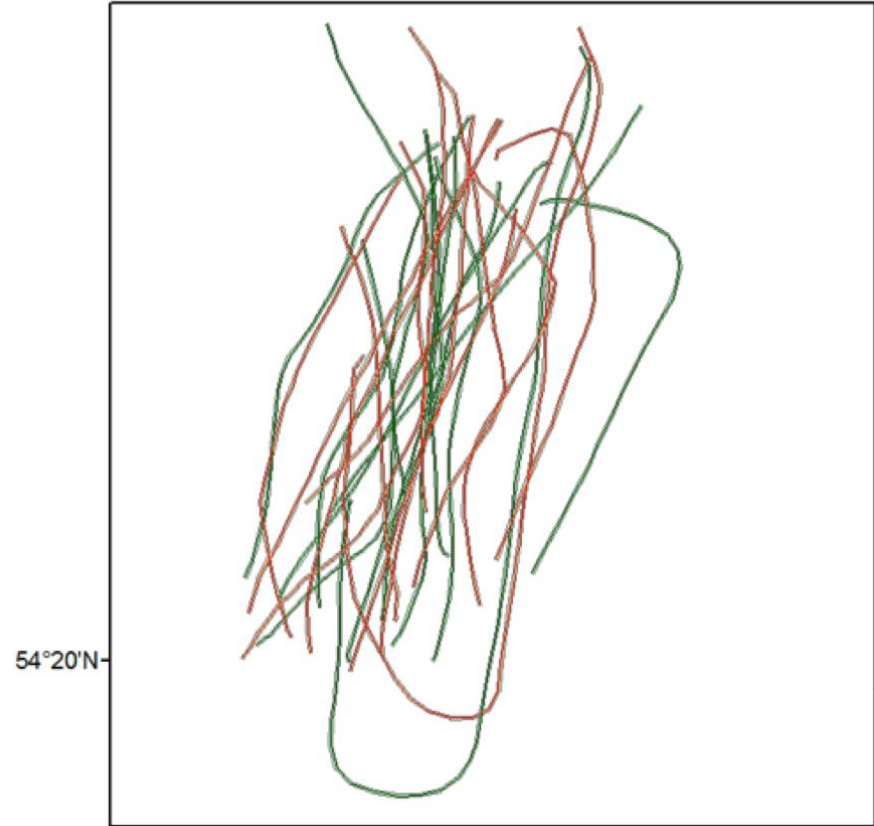
Species	Group TAR	Group RAM	Av.Diss	Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund				
Lesser spotted catshark (<i>Scyliorhinus canicula</i>)	1.38	1.74	7.78	1.28	13.86	13.86
Dab (<i>Limnanda limnada</i>)	0.45	1.08	6.64	1.53	11.82	25.67
Lemon sole (<i>micorstomus kitt</i>)	0.53	0.07	4.78	1.60	8.51	34.19
Plaice (<i>Plueronectes platessa</i>)	0.49	0.81	4.59	1.37	8.18	42.37
Spur dog (<i>Squalus acanthias</i>)	0.37	0.00	3.56	0.84	6.33	48.70
Red gurnard (<i>Chelidonichthys cuculus</i>)	0.09	0.38	3.20	1.22	5.70	54.39
Tub gurnard (<i>Trigla lucerna</i>)	0.03	0.29	2.51	1.06	4.47	58.87
Squid (<i>Lolligo Spp</i>)	0.27	0.00	2.35	0.79	4.18	63.05
Grey Gurnard (<i>Eutrigla Gurnadus</i>)	0.24	0.14	2.24	1.15	3.99	67.05
Haddock (<i>Melanogrammus aeglefinus</i>)	0.21	0.03	2.12	0.85	3.77	70.82
John Dory (<i>Zeus faber</i>)	0.02	0.21	2.09	0.87	3.71	74.53
Whiting (<i>Merlangius merlanus</i>)	0.20	0.09	2.07	0.93	3.69	78.22
Thornback ray (<i>Raja clavata</i>)	0.14	0.10	1.71	0.89	3.04	81.27
Starry smooth hound (<i>Mustelus asterias</i>)	0.05	0.14	1.42	0.73	2.52	83.79
Monk/ Anglerfish (<i>Lophius piscatorius</i>)	0.11	0.06	1.26	1.01	2.25	86.04
Streaked Gurnard (<i>Trigloporus lastoviza</i>)	0.03	0.07	1.08	0.57	1.92	87.96
Cod (<i>Gadus morhua</i>)						

Appendix 4. The tracks of paired tows conducted during the trials at a., Targets and b., Ramsey Bay.

a.



b.



Appendix 5. Still taken from video footage of a fish escaping through the square mesh panel, whilst lights were attached to the net during the trial at Targets. This illustrates the light levels whilst towing at the deepest site in the survey.



Appendix 6. a. Stretched diamond mesh (90mm) (single stranded) used for the head of the QSC nets. b., The net seen from the stern of the vessel, showing the positioning of the floats along the headline and the square mesh panel. Note the position of the choke, which overlaps with the square mesh panel.

a.



b.

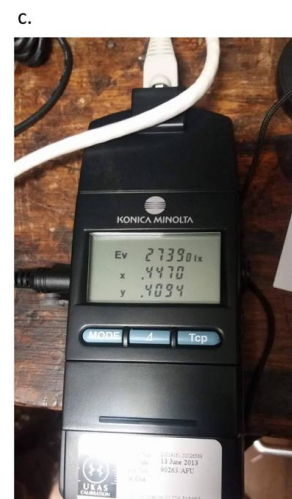
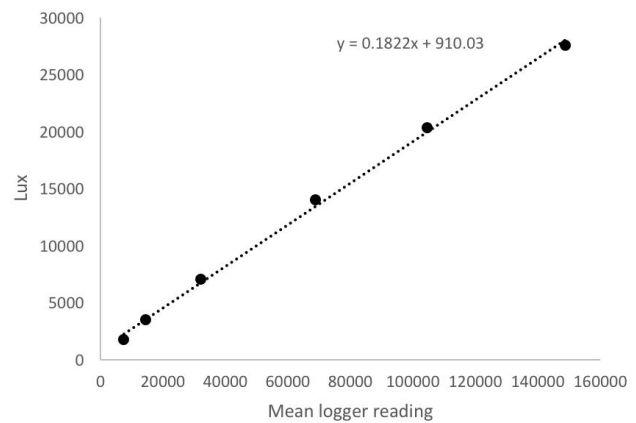


Appendix 7. Net adjustment made to the SMP after the current trial

During the trials conducted, QSC catches were low and there was no difficulty in using the modified nets, however, under normal fishing conditions where catches were greater, substantial snagging occurred on the sides of the belly panel of the net. The net was then adjusted by slackening the headrope, which resulted in more tension being transferred to the salvages of the net, and caused the sides of the net to be lifted, thus avoiding snagging. In addition, the size of the SMP was reduced from 20 x 12 square meshes to 20 x 8 meshes

Appendix 8. Table and scatter plot showing values obtained during the calibration of the light loggers. a., the integration sphere used for calibration. b., the light logger used the study consisting of a HOBO UA-002-64 64K Pendant Temp/Light Loggers (Tempcon Ltd), inside a Lindgren-Pitman electrolume light case. c., Konica Minolta calibration unit.

Mean logger reading	Calibration unit (lux)
148801	27520
104712	20320
68889	14010
32148	7021
14467	3476
7406	1706



Appendix 9: Whiting bycatch (kg) for the QSC otter trawl fishery by month. Kg 2015/16= estimated whiting bycatch for the 2015 and 2016 seasons. Mean kg=the predicted mean weight of whiting bycatch when using an SMP (73% decrease). Upper and lower CI= confidence intervals back calculated to percentage.

Month	kg 2015/16	Mean kg (73%)	Lower CI kg	Upper CI kg (14.76%)
June	82	31.16	6.9044	69.8968
July	329	125.02	27.7018	280.4396
August	576	218.88	48.4992	490.9824
Sept	823	312.74	69.2966	701.5252
Oct	1029	391.02	86.6418	877.1196