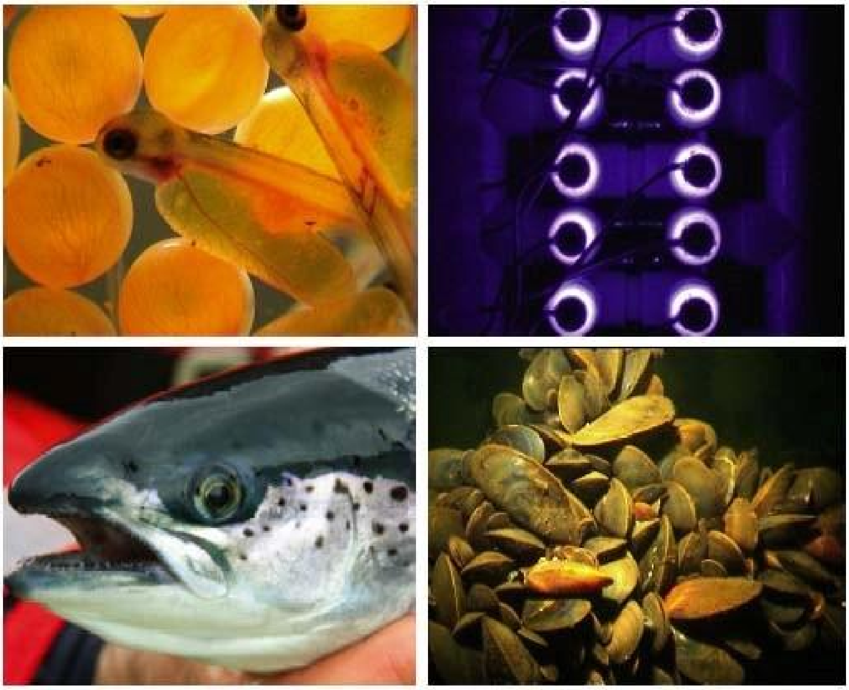
SARF097 - Plugging the Gaps - Improving Our Knowledge of How Predators Impact Salmon Farms



A REPORT COMMISSIONED BY SARF
AND PREPARED BY

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Executive Summary

The recent development of a Technical Standard for Scottish Finfish Aquaculture has focused attention on the lack of information on seal depredation and its role in enabling caged salmon to escape. The present project aimed to address several knowledge gaps identified in a previous SARF Report (SARF073) on issues relating to containment of salmon in marine fish farms. Four overall objectives were: to use underwater video systems to observe how seals attack salmon pens; to investigate net deformation in tidal currents using motion data loggers; to review existing literature and other sources to better understand predator attacks; and to use trained captive seals to better understand the forces they are able to generate underwater to push against nets, and their behaviour associated with taking fish from net enclosures.

- Our underwater camera system was deployed at four sites over 96 days in total, however seal depredation rates were low at all sites, and no seal depredation event was recorded. Nevertheless, we used the opportunity to refine the system and deployment methods.
- We were unable to gain agreement to deploy motion sensors on any aquaculture pens, though we did develop suitable attachment methods and software tools for visualisation and analysis of data should a site be made available in future.
- We trained three grey and three harbour seals of a range of sizes to push against a stretched piece of nylon salmon cage netting to establish how much force they would be able or willing to exert against such netting for a food reward.
- Results suggest a tight relationship between seal size (mass) and maximum force, and extrapolations suggest a large 300 kg grey seal might be able to exert a force of over 800 newtons.
- We quantified the amount of net deformation for samples of nylon cage netting under load, and used these results to calculate the maximal deformation of a typical bottom net panel from a 100 m diameter circular pen. An incursion of at least 30 cm would be expected from even a medium sized seal.
- We note that newer netting materials such as High Density Polyethylene (HDPE) currently being trialled at farm sites in Scotland, have a lower extensibility than nylon and may therefore make seal incursions more difficult. Controlled tests of HDPE netting in the context of seal predation would be useful.
- All seals tested found it very difficult to feed on salmon presented to them in a model of a salmon pen. When seals had access to fish over long periods, they recreated the damage characteristics typically seen at fish farms by chewing much of the flesh from the carcass, but leaving the spine, head and tail intact.
- The stereotyped gashes and abdominal bite-marks sometimes seen in large numbers at fish farms were not recreated, and are probably therefore indicative of fish being live at the point of attack. Only dead fish could be fed as part of our experiments.

Further work is needed to explore seal behaviour and net configurations in the real world. This will need the active participation of fish farming companies. Pool and laboratory based results need to be compared and followed up with observations and tests made in the wild and on fish farm sites.

Plugging the Gaps: Improving Our Knowledge of How Predators Impact Salmon Farms

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Contents

1 Introduction

1.1 Project background

Farming of Atlantic salmon has become one of Scotland's most important industries, growing from <40,000 T in 1990 to 179,000 T in 2014. The industry is an important source of employment, both on-shore and at-sea, and is particularly important in rural and coastal communities where wild capture fisheries were traditionally more prevalent. Marine Scotland estimates a contribution of at least £550 million per annum through direct production, and up to £1.8 billion in turnover across the UK when including the catalytic effect. It contributes at least 2,800 jobs directly in Scotland, and up to 8,800 across the UK including the supply processing chain (Marine Scotland, 2014).

Scotland's National Marine Plan (2015a) aims for production of marine finfish to increase to 210,000 tonnes by 2020, potentially increasing the annual UK stimulated economic growth to £2.5 billion, and over 11,000 jobs (full and part-time). The need for high standards of environmental protection in the planning, operation and regulation of fish farms is highlighted in order to ensure environmental sustainability. The Scottish Government's renewed strategic framework for Scottish aquaculture, 'A Fresh Start' (Marine Scotland, 2009), also highlights the need for growth of the aquaculture industry to be sustainable, within the carrying capacity of the environment and balanced against the needs of other stakeholders in the marine environment. Predator management has been listed as a potential environmental impact within the National Marine Plan.

Depredation is defined here as an act of predation where the prey is already held captive, either by being caught in wild capture fisheries equipment or as part of an aquaculture system. Seal depredation in Scottish aquaculture was first reviewed scientifically by Hawkins (1985) who found depredation by seals at 65% of farms, and then by Ross (1988) who found depredation at 96% of farms. More recent studies have suggested the proportion of sites at which seal damage was considered problematic remained high at around 72% (Northridge et al., 2010). The economic loss to the industry is difficult to reliably quantify, but Coram et al. (2014) estimated a figure of £25,000 per site per annum based on 87 Scottish sites over a 129-month monitoring period. The problem is also known to occur internationally, with studies documenting depredation by pinnipeds (otariid and phocid seals) in several other countries including New Zealand, Canada, Turkey, the USA, Australia and Chile.

A licensing scheme was brought in as part of the Marine (Scotland) Act 2010, and has been in place since 2011, allowing fish farms to apply for permission to shoot a specified number of each seal species to protect farmed salmon. The act makes it an offence to kill or injure a seal except under licence (or on grounds of animal welfare), effectively removing the unregulated removal of seals which was previously permitted. Licences are only issued for use by nominated marksmen who hold an appropriate qualification in seal management and who are capable of hitting a four-inch circle three times at 100 m range. The licencing scheme makes clear that seal licences are issued only where non-lethal alternatives have been shown to be unsuccessful or have been precluded for other reasons.

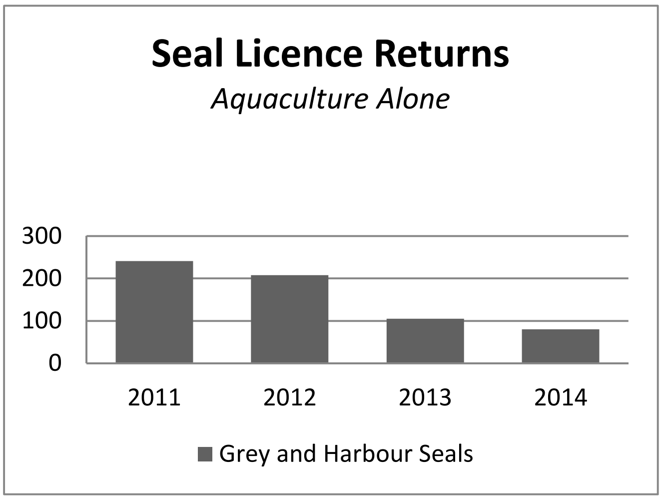

Figure 1 – Lethal removal of seals under licence (Aquaculture)

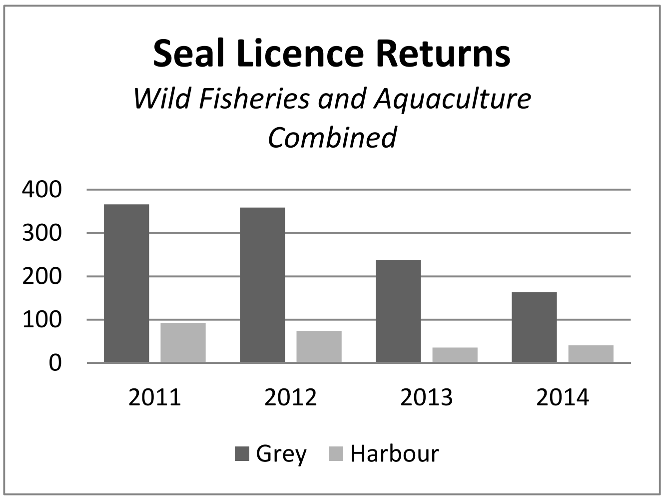

Figure 2 – Lethal removal of seals under licence (wild fisheries and aquaculture)

To accompany the new legislation in 2011, Marine Scotland introduced a code of good practice (CoGP) for seal management. Under the CoGP, '*a seal should only be shot where, in the opinion of a nominated marksman or licence holder, it is necessary to prevent serious damage to a fishery or fish farm or to protect the health and welfare of a farmed fish*'.

Seals must only be shot from a stable platform, in daylight, and '*ideally'* in the absence of people (general public) and when there is a good chance of recovering the carcass. The maximum range permitted is 150 m and expanding bullets must be used. The marksman or licensee must take all reasonable steps to recover the carcass so that scientific data can be collected, and the details must be reported within ten days of the end of each three-month reporting period.

The introduction of this licencing scheme has coincided with, or triggered, a period of steep reduction in the number of seals being shot. Data covering the period prior to the licencing system is not available, because records were not required during this time, but it seems likely that this reduction in seal shooting (Figure 1 & Figure 2) comes at least in part as a result of increased regulatory pressure. In addition to government involvement, there has been an apparent increase in media coverage, with several high profile articles about seal shooting from major news organisations.

In 2010 a group that includes animal welfare organisations, industry and retail representatives, government departments and academics was established to help find and further develop alternatives to shooting in order to limit seal damage at farm sites. The Salmon Aquaculture and Seals Working Group (www.saswg.org.uk) is a forum for exploring such methods and lobbies for improvements in methods to limit seal damage so that any need to shoot seals can be eliminated.

A new technical standard was introduced in 2015 (Marine Scotland, 2015b) which sets out the general requirements for equipment and procedures which must be met by all finfish aquaculture producers in Scotland by 2020. This standard emphasises the importance of rigorous containment procedures in the prevention of stock escapes, but also specifies the use of 'sufficient tension' in the down-ropes to deter potential predators. Exactly what constitutes sufficient tension is likely to vary depending on range of factors some of which we aim to investigate here.

1.2 Aims and scope of the present study

During the development of the recently agreed Technical Standard for Scottish Finfish Aquaculture (Marine Scotland, 2015b) consideration was given to measures necessary to ensure reliable fish containment in aquaculture pens. A SARF Report (Thistle Environmental Partnership, 2012) made proposals for technical standards for containment, while also identifying several knowledge gaps. Predators, mainly seals, play a significant role in enabling finfish escapes from marine aquaculture cages, and SARF073 suggested further research was needed in four areas related to depredation: to provide a better understanding on how predators attack nets, on how best to protect nets from predators, on how to optimise net tensioning to reduce escapes due to depredation, and on how best to use anti-predator nets.

The present study was initiated to address these knowledge gaps, but builds on previous work conducted at the University of St Andrews during which an underwater video system was developed, and in which some initial considerations have been given to net design and construction (Northridge et al., 2013).

The objectives of the project were initially fourfold.

1) Record observations of seals taking salmon from fish cages using underwater video monitoring system: describe tactics used to remove fish.
2) Examine net deformations in high tidal current sites to better understand net structure and fish behaviour under current induced cage deformation: determine nature and extent of bagging.
3) Train captive seals to take fish through the meshes of a net in order to:
    a. Quantify forces that seals may exert for a reward
    b. Describe behaviour associated with extracting fish through grower mesh and other mesh types
4) Review existing literature and collate further industry information and anecdotes on:
    a. modes of predator attack (including mink and otters)
    b. net holes and depredation events in relation to net and site characteristics

From the outset we were clear that Objective 1 was ambitious, and would likely only succeed if we had access to farm sites with ongoing serious levels of mortality. As it happened, no such site could be found, and although we made some progress in improving out monitoring system, we were unable to describe depredatory behaviour in the wild.

Similarly, with regard to Objective 2, although we made progress in theoretical understanding and in software development, we were unable to find a site willing to risk putting motion sensors on their nets.

Much of what follows therefore addresses elements of Objective 3, under which we went further than we had originally proposed, by testing the capability of six individual seals in generating forces, in exploring how naïve seals are able or unable to manipulate salmon through the meshes of a net, and in exploring net deformation under laboratory conditions and subject to the level of force we predict large grey seals ought to be able to generate.

On the advice of our steering group, we did not spend a great deal of time on the fourth objective, and confined our efforts in this respect to discussions with colleagues in other countries about the use of anti-predator nets and other means of minimising seal damage.

Finally, we have synthesised what we have learned under the current project and have outlined areas that we believe would best be addressed in further studies to try to elucidate the four relevant knowledge gaps: on how predators attack nets, on how best to protect nets from predators, on how to optimise net tensioning and on how best to use anti-predator nets.

To improve readability, we have altered the order in which each of these objectives is reported on below.

Six seals took part in the captive part of this study, three harbour seals (*Phoca* vitulina) (referred to here individually as T, U and V) and three grey seals (*Halichoerus grypus*) (W, Z and C). Details of the test subjects are described in Table 3. Animals were temporarily held in captivity and released at the original capture site after completion of experimental work. All work was carried out after approval by the University Animal Welfare and Ethics Committee under home office project licence number 70/7806.

The captive facility includes a pool 40 m in length by 2.5 m deep with fresh seawater supply. Approximately 10 m of this pool was partitioned for the purpose of this study, and all experiments were conducted here with one animal at a time.

2 The use of underwater video systems to describe seal tactics in removing salmon at farm sites

2.1 Introduction

One of the most crucial and yet unexplained aspects relating to seal depredation is simply, ‘how do seals attack, kill and eat live, healthy fish from the opposite side of the physical barrier of a fish farm net?’. Typically, these nets have a square mesh size of 15 – 25 mm and are constructed from tough, though pliable, knotless nylon with a twine diameter in the region of 2 to 3 mm. High density polyethylene (HDPE) twine is also being used more recently. Net panels are heavily weighted, either by connection of down-ropes to individual steel/concrete weights, or by attachment to heavy weighted rings (sinker tubes). Circular nets are generally made with the diameter of the base slightly smaller than that at the surface, allowing the net to taper toward the base. Theoretically, this allows tension to be delivered from the weighting system, through the down-ropes, to be applied evenly to the netting itself.

If a netting section is adequately and evenly tensioned, it is difficult to imagine how a seal might be able to push the netting far enough to reach a swimming fish, quickly enough to overcome the fishes' flight response, and then be able to bite the fish in such a way as to either kill it outright or prevent its escape. In order to be able to successfully attack fish through a net, it seems likely that some behavioural tactics may have been developed by some seals, exploiting either fish behaviour or some weaknesses in net design or implementation, whereby nets do not behave in the expected manner, or both.

The simplest way of addressing the uncertainty over the methods employed by depredating seals is by direct observation of their behaviour, and we have spent significant effort pursuing this aim.

An important secondary aspect of the video monitoring work was to look for evidence of fish behaviour which may be contributing to the possibility of depredation by seals. Certain behaviours might be seen to encourage depredation by making the fish an easier target, and we hypothesised that these behaviours could be observed using our recording system.

The types of injury commonly associated with seal depredation (deep abdominal gouges on both flanks, ventrally centred) suggest that many attacks occur through the base panels of the nets. This agrees with anecdotal information from fish farm managers that most attacks happen at the base or bottom corners. Our primary hypothesis was therefore that fish may swim very close to the base panels, or even rest on them, making themselves highly vulnerable to attack. We also aimed to investigate an alternative hypothesis; that seals are only able to take fish that are already moribund or already dead. These fish are thought to sink to the net base where they would be highly accessible to seals. During video analysis, we therefore made observations of fish behaviour and noted the closest distance the fish regularly came to the netting material.

Prior to the commencement of this project, we had developed and tested a series of devices for recording multi-channel underwater video (Northridge et al., 2013). Although results were limited, we have improved the design and deployment methods for the system as described below.

2.2 Methods

Throughout the course of the project we have also continued to develop our system, and the protocol for its use, to improve the results we are able to obtain. These improvements have fallen into three main areas:

2.2.1 Integration of an upgraded recording unit

Our original recording unit was designed for continuous monitoring and recording on up to four channels of CCTV (Northridge et al., 2013). This offered vast improvements over standard 'handheld' video recorders in terms of battery life, hard drive size, and reliability, but this system in itself was far from perfect. We faced significant challenges transferring and backing up the video data due to the limitations of the proprietary software associated with the hard drive recording system, and the quality of the footage itself was sometimes unsatisfactory. In early 2015 an upgraded recording unit became available and preliminary tests showed that its software allowed much more flexibility than the original system.

In collaboration with a local marine technology firm (Prove Systems), we integrated the new recorder into the existing system, allowing continuous four-channel recording for up to a month.

Figure 3 - Old software was very basic and did not allow backup of video files

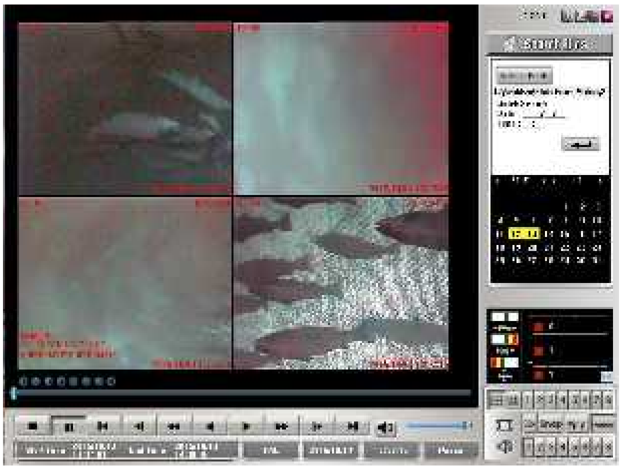

Figure 4 - New playback software has more functionality and better playback controls

2.2.2 Cameras attachments to nets

One of the most challenging aspects of continuous underwater video monitoring is the attachment and positioning of the cameras. Marine biofouling, moving nets, fish and currents as well as wind and wave action combine to make the environment highly dynamic. Despite setting the camera with a perfect view of the corner of a fish farm net, changes in current speed and direction can mean the camera itself or the net may have moved to an entirely new position. In our early efforts, we had relied, in the main, on collecting enough hours of video to expect with reasonable certainty to collect a useful amount of usable video. In order to increase the likelihood of detection of a depredation event, it was important to increase the proportion of time that the cameras were positioned appropriately. Earlier work (Northridge et al., 2013) has suggested that the most useful camera angles are positioned near the base of the net, looking either toward the net corners (if the net is square), or along the base, where the majority of depredation events are apparently expected. Attaching cameras directly to the netting could potentially cause abrasion and damage to the net, and the camera would be too close to the net, reducing the area of net visible within the frame of view.

Under the present project we therefore experimented with several different designs for mounting the cameras onto the fish farm netting, and constructed a simple mounting attachment with a soft rubber backing which could easily be attached. The rubber backing was soft enough to reduce the risk of net abrasion, and was perforated (see Figure 5) allowing water to flow freely through the netting. A stainless steel rod, bent in two and attached securely to the rubber pad, allowed the camera to stand at a distance from the netting, and allowed the camera to retain its orientation with respect to the net, despite changing currents.

Figure 5 - Underwater camera attached to mounting frame

2.2.3 Camera positioning

In previous camera deployments, we had always positioned cameras remotely (from the surface), using combinations of rope and weighting to move and orient the camera, whilst watching the live output feed to find a suitable camera angle. While this technique was often effective, it proved very difficult to maintain suitable positions for any length of time, particularly at sites with a high tidal flow.

The new camera attachment frames could hold the cameras in a stable position, but could not be installed remotely. Instead, we were able to utilise commercial divers on routine site visits. Installation of all four cameras took no more than thirty minutes, so did not add greatly to the workload. Using divers in this way proved to be very effective, as they could use their knowledge of the nets and the underwater environment to advise on the best way to position the cameras.

Figure 6 - Deployments of recorder on steel walkway and plastic circles

2.3 Results

We aimed to deploy our video system in as many farm sites as we could, especially at sites with ongoing seal depredation problems to maximise the probability of being able to observe the seal behaviour associated with such events. Clearly any operationally realistic video system can only monitor a relatively small area or volume of the net cages and their immediate vicinity, so the higher the rate of depredation at a site, the higher the probability of being able to capture such events on video and thereby understand the process involved. We were in contact with three salmon farming companies, each of which afforded us one or more opportunities to deploy our camera system, though none had a particularly severe depredation problem at the times of deployment.

Table 1 shows the number and extent of deployments we have been able to conduct overall so far, including four deployments in a previous study. Several different aquaculture companies are represented here, and we are grateful for the assistance they have provided.

2.3.1 Seal depredation

Through the course of this project, we have had cameras in the water for almost 3 months (96 days), with video data being collected from 54 days in total. Deployments under the present project are highlighted in Table 1. Analysis of this large volume of data presented a significant challenge, so we took a targeted approach to selecting video which would be most likely to contain footage of an attack. Mortality records attributed to seals were used to select days when a seal attack could have been captured and these days were watched in full. The likelihood of having missed a successful attack is considered to be very low. Throughout the length of deployments, mortality numbers (as regularly assessed by uplift and dive teams) remained very low, and no seal depredation was observed on camera. This is perhaps not too surprising, particularly as we were not able to deploy a system at a site with any serious seal depredation problem.

Table 1 – Underwater camera system deployments

recorder no.	start date	end date	channels (at start)	site name	company
1	27/09/2011	27/09/2011	4	Port na Cro	Meridian/Lakeland (now Cooke)
1	08/11/2012	21/11/2012	4	Loch Leven	Marine Harvest

1	21/11/2012	18/12/2012	3	Strome, Lochcarron	Scottish Salmon Company
1	18/12/2012	13/02/2013	3	Strome, Lochcarron	Scottish Salmon Company
1	**19/03/2014**	**18/04/2014**	**1**	**South Tarbert, Loch Fyne**	**Scottish Salmon Company**
2	**30/06/2015**	**23/07/2015**	**3**	**Fara, Orkney**	**Cooke Aquaculture**
2	**23/07/2015**	**22/08/2015**	**2**	**Fara, Orkney**	**Cooke Aquaculture**
2	**13/10/2015**	**26/10/2015**	**4**	**Sconser, Skye**	**Marine Harvest**

2.3.2 Observations of fish behaviour

No moribund fish were observed during the video deployment periods, so we were unable to conclude whether these fish are the primary source of depredation mortalities. However, mortality counts carried out at the same time as installation of the video system revealed a number of superficially healthy fish with bite wounds, including one which was still twitching, so had clearly been attacked very recently (see supplementary video 1). This piece of evidence disproves the hypothesis that *only* moribund or previously deceased fish are ever attacked.

Salmon were regularly seen swimming very close to the net – both side walls and the base. Under normal behaviour (i.e. non-startled) salmon swim relatively slowly and frequently come within 2 cm of the nets. While no evidence was found for fish resting on the base panel, this slow swimming behaviour, so close to the net, is likely to make the fish much more vulnerable to attack.

2.4 Conclusion

The most effective way of positioning monitoring cameras on aquaculture nets is by utilising the existing dive teams who regularly visit the sites. These teams have a detailed knowledge of the site and will be likely to understand the pertinent issues relating to camera positioning. They will also be likely to know which nets are most susceptible to depredation damage, and to have a current knowledge of any ongoing problems. Most sites are visited regularly by divers conducting net checks, and attachment of cameras is not prohibitively onerous or time consuming to interrupt their normal activities.

The new camera mounting system (Figure 5) is a substantial improvement over previous ways of positioning cameras. Cameras can be attached quickly by divers and the system is flexible enough to be used in a variety of positions, allowing a variety of different camera angles, increasing the likelihood of capturing seal depredation behaviour.

We have found that some farm managers appear reluctant to participate in experiments involving underwater video of seal behaviour. There may be a perception that results may be used in a negative context to undermine the industry’s efforts to reduce depredation. This is unfortunate because it severely hampers our ability to collect behavioural data which could potentially inform new mitigation measures to help reduce depredation.

The hypothesis held by some outside of the industry, that seals are only able to take moribund fish, or chew on carcasses that have already died, is false. Our results confirm that live and apparently healthy fish are taken by seals. This conclusion will come as no surprise to those experienced in management of seal depredation, but we feel it is an important point to highlight in the context of a report available to the general public.

Video of salmon behaviour has shown that fish often swim close to the sides and base of nets. This behaviour makes fish more susceptible to seal depredation. If this behaviour could be altered to keep fish further from the base of the net in some way, then stocked salmon nets might be less vulnerable to depredating seals. We found no evidence for salmon resting on the base of nets, but our observations were not made during times of high depredation.

3 Captive seal behaviour in relation to salmon depredation

3.1 Introduction

Under this Objective (3b) we aimed to describe behaviours exhibited by seals extracting fish through typical salmon cage netting in controlled conditions. This work was planned to supplement the observations made under section two.

Discussions with farmers and divers throughout the course of this project have revealed a variety of anecdotes, describing depredatory behaviours attributed to seals. Often these anecdotes are vague or second-hand, but certain strategies seem to be particularly commonly accepted.

One of the more widely accepted opinions is that seals are able to build up speed by swimming toward the net, and use that speed to 'ram' or push into the netting and capture a fish. An alternative opinion is that seals attach themselves to the nets with their fore-flippers and use their teeth and muzzle to push and twist at the netting. This second strategy would explain holes or areas of abrasion occasionally observed and attributed to seals, but does not explain how a seal could capture a healthy free-swimming fish inside a net.

While attempts to understand behavioural mechanisms at farm sites were unsuccessful, we made use of the captive seal facility at the Sea Mammal Research Unit to explore the capabilities of naïve captive seals when confronted with whole salmon as a prey item. The captive seal facility is unique in Europe, having access to both wild grey and harbour seals. We aimed to explore how captive seals might be able to manipulate whole fish through a net barrier similar to what might be expected at a fish farm site.

3.2 Methods

A large three sided 'mock fish farm' was constructed (see Figure 7) from aluminium and nylon netting. Netting was supplied by Marine Harvest, and polysteel rope (polypropylene) was used for the downlines and net corners. To attach the netting to the poolside in a realistic manner, an aluminium frame was built to which the net could be tied. This frame was bolted securely onto attachment points built into the side of the pool and could be raised up and down in order to present fish in different positions. A large weight was suspended from the outer corner, delivering tension through the corner down-rope onto a crane above. Tension across different parts of the net could be adjusted by varying the amount of weight suspended from the outer corner.

A section of net was constructed in order to mimic the corner of a typical square fish farm net (Figure 7). Two such net corners were constructed, one using 15 mm, and one using 25 mm knotless nylon, each using three sections of 3 m^2 netting sewn into polysteel ropes which formed the down-ropes and bottom edges. The netting was typical of untreated netting used on salmon farms.

The netting was at first left with almost no tension during a training period, in order to make it easier for the animals to take fish. Once animals were more comfortable with the experimental setup, net tension was increased. As seals became more adept at manipulating the fish through the net, the tension was increased by moving the attachment point on the crane (on the outside corner) away from the net, and by increasing the size of the weight on the outer corner (Figure 8).

Two different camera types were used to record the behaviour of the animals. The four channel recording system developed for this project was used to record continuously while fish were available to the seals. These cameras were positioned to cover as much of the net as possible. Underwater visibility in the captive facility was limited at certain times due to algal growth, so another camera (GoPro 3+ Black) was mounted onto a pole to capture higher resolution video of seal behaviour at close quarters.

Fish were presented in three different manners, with increased handling difficulty for the seal at each stage. At the outset of experiments, when each seal was unfamiliar with netting, fish were thrown whole into the pool, encouraging them to become familiar with eating whole salmon and in order to see how they would deal with a whole salmon without any netting restrictions. Later, seals were familiarised with netting and fed small pieces of fish or small fish which could be sucked or chewed through netting.

Study animals were initially fed with their preferred fish type, sprat, through the netting. They would not eat whole salmon through the net until they had become familiar with taking smaller fish. Several days of familiarisation were required for each individual seal before realistic observations could be made. Salmon for feeding of seals were kindly supplied by Scottish Sea Farms and ranged in size from 3 - 6 kg.

Once animals were comfortable with eating smaller fish, large salmon were presented in a variety of positions within the net. Fish ranged from 3 – 6kg and were either deposited on or next to the netting or were held in position some distance from the net in different locations. In this way we aimed to observe the way in which seals consumed fish through the side netting, through the base, and near corners.

To simulate a live, healthy fish swimming inside the net, spaced some distance away from the inside netting, we secured the whole fish to a 'T-shaped' bar which was held loosely inside the netting section about 20 cm from the net wall. To access this fish, the seals had to push against the netting, and take whatever they could from the carcass through the side wall of the net.

Seals were therefore observed feeding on salmon under three conditions: 1) With free access to fish; 2) fish loose inside the net; 3) fish held in place inside the net. Records and photographs were taken of all interesting or relevant damage to the fish carcass and observations of how seals manipulated the fish in all three circumstances were described.

Figure 7 - Model aquaculture net for behavioural experiments

Figure 8 - The base of the netting as installed without tension. Some small fish available on the base for the seal to eat.

3.3 Results

3.3.1 Free access feeding

When seals were given free access to whole salmon, the fish were often taken below the water surface where, due to limited visibility and/or limited numbers of underwater cameras, we were unable to record the behaviour during handling. When fish were consumed at the surface, observations and video recordings were made.

When consuming salmon at the surface, seals used their teeth and fore-flippers in opposition to tear chunks of flesh from the carcass. Usually the fish was held in the mouth, while one or both of the fore-flippers were used to rip or peel the remaining fish away. The 'nail' of the first digit was often used to tear off pieces of skin, which were usually discarded. One animal in particular developed a technique where the fish was held in the mouth and spun at high speed by rotating the seal's head. This would cause the fish to break apart into smaller pieces that could then be more easily consumed (see supplementary video 2).

3.3.2 Fish placed loose inside the net

When fish were presented inside the net, but loose and unattached to anything else, seals used a variety of methods to grab and rip the fish. Usually they would lunge at the food source, extending their neck rapidly to grab the fish between teeth. They would also use fore-flippers in a similar way to when the fish was loose on the surface, holding the fish in the mouth and ripping and tearing off chunks with the first digit of the flipper. The resulting damage to the fish carcass (shown in Table 2, row 1) was typical of damage we have previously seen on farm sites, where it was classified as seal damage (Category 1 injury, figure 22 in Northridge et al. 2013 report).

Seals usually took hold of the fish securely in their jaws while using their claws to rip off smaller sections which were then sucked through the netting. Alternatively, they hold the fish in their jaws through the meshes twist and shake the fish to break it into smaller chunks and to peel the fleshy sections away from the head and skeleton, which was usually discarded. See supplementary video 3 for an example of this behaviour. For a seal to be able to rip chunks from the fish carcass in this way, a certain amount of slack netting must be required. It is very difficult to envisage this behaviour being feasible through an optimally tensioned net.

Occasionally, seals would also make apparent attempts to break the net – taking a piece of netting between their teeth and chewing and twisting it. At some points this resulted in the seal becoming temporarily entangled in the netting. At no point were any of the seals able to make holes in the netting and at no point were any of the seals in danger.

3.3.3 Fish held in place inside the net

Seals found it very difficult to reach the fish when presented in this manner, with only one seal (V) achieving any success. This was a harbour seal and was the most aggressive subject tested. He could easily push the net as far back as the salmon (around 20 cm) but then would struggle to get any purchase on the carcass. Instead of being able to hold the fish in the fore-flippers, the seal could only chew and twist using the mouth, and this proved to be a much less effective method of feeding. Supplementary video 4 shows the behaviour he employed to try and break small pieces of flesh from the fish. He would often become frustrated and devote attention to apparently trying to break the net, using teeth and fore-flippers to pull and twist on the netting adjacent to the fish. Even he, however, only managed to break the carcass in a few places and consume a small amount before becoming distracted and ending the task (Table 2, row 3).

Table 2 – Categories of damage to seal carcasses seen after experiments

Free access feeding		
Fish placed loose inside the net		
Fish held in place inside the net		

3.4 Conclusion

In general, only a small amount of the available flesh on each fish was consumed. Some seals would not eat whole salmon at all, even after training them by feeding gradually larger chunks of fish, and even when they were given free access to the fish. Reducing the amount fed to each seal had some effect on motivation, but we could not substantially restrict feeding to the point that might be expected in natural conditions.

The preferred method of feeding on small items of food was suction feeding, where the animals swim up to the food item until it is at their lips. By rapidly increasing the volume of the mouth, they can then suck the fish in through the meshes of the net and swallow it whole. This is often accompanied by a rapid jerk of the head, characteristic of this feeding style.

When given whole fish, certain stereotypical behaviours were observed which tended to result in specific, identifiable types of injuries to the fish carcass. These behaviours were dependent on how easily the seals were able to access the fish. Whenever possible, a combination of the teeth and fore-flippers were used to rip whole fish into smaller pieces.

Our results suggest that seals preferentially use teeth and claws to break fish apart into smaller pieces that can more easily be consumed. At least some slack netting is required for this behaviour. When seals have access to the fish for extended periods of time, the resulting damage closely replicates the 'cartoon fish' typically seen at farm sites. When access to the fish is made more difficult, the prospect becomes significantly less attractive, to the point where whole carcasses were often left almost untouched.

It is noteworthy that we never saw the stereotyped gashes and abdominal bite-marks (Category 4 damage in Northridge et al. 2013) that are often seen in large numbers at fish farms.

4 Forces generated by captive seals

4.1 Introduction

The question of how are seals able to kill and eat farmed salmon through the mesh of the containing net is fundamental to mitigating the problem of seal depredation. Without an understanding of the mechanism behind these attacks, development of measures to prevent them is unlikely to proceed efficiently. One possibility is that seals are able to identify flaws in net design, such as areas of loose netting.

In some cases, however, fish farmers report that even when nets are tensioned optimally, using modern weighting systems (such as sinker tubes), seals are still able to attack and kill fish. One response to these reports is to consider that even if nets are weighted 'correctly' (i.e. according to manufacturer's designs) and evenly, the fact that seals are able to reach the fish makes it evident that the intrinsic net tension is inadequate, *ipso facto*.

Our aim under this objective was to quantify the maximum forces that seals may exert for a reward, both to provide input to the continued development of the Technical Standards and with a view to determining how much displacement of a well tensioned net they might be able to effect.

Seals are only able to apply a finite amount of force. By measuring this force, and comparing it with the characteristics of typical aquaculture net materials, we aim to predict the maximum deflection that a seal is likely to achieve from the normal plane of an optimally tensioned net. This is considered further from a theoretical perspective in the subsequent section on net deformation.

Table 3 - Details of seals used in this study

Seal	Mass (kg)	Species	Gender	Age
T	60.8	*P. vitulina*	M	Sub-Adult
U	86	*P. vitulina*	M	Adult
V	90	*P. vitulina*	M	Adult
W	35	*H. grypus*	M	Juvenile
Z	42.3	*H. grypus*	M	Juvenile
C	225	*H. grypus*	M	Adult

4.2 Theoretical context

The most simplistic way of considering the maximum force a seal can put onto a fish farm net is to consider the maximum force a seal can generate, and assume that all of this force could theoretically be transferred to the net.

Force is a product of mass and acceleration

$$F = ma$$

Acceleration is change in speed over time, so force can be expressed as

$$F = \frac{m\Delta v}{\Delta t}$$

Force can also be expressed as change in momentum over an interval of time

$$F = \frac{\Delta p}{\Delta t}$$

Momentum (p) is the product of mass and velocity, measured in kg m/sec

$$p = mv$$

Our largest seal had a mass of 225 kg, assuming a maximum swim speed of 3 m/s (Thompson and Fedak, 1993), it has momentum of 675 kg m/sec.

High resolution measurements of force transferred onto the netting show that it generally takes between 0.5 and 1 second for the seal to decelerate completely (Figure 13). This would therefore produce a force of 675 - 1350 N.

Alternatively, considering force as a function of the distance travelled during the impact (s) in metres, the kinetic energy of the seal travelling is converted to work through the equation:

$$F\,s = \frac{1}{2}\,m\,v^2$$

or expressed as a function of the slow down distance:

$$F = \frac{1}{2} m\, v^2/s$$

With a seal of mass 225 kg and distance travelled of 0.5 m this equates to a force of 2025 N, assuming net elasticity is independent of force already applied.

Another approach would be to use established values from the scientific literature. Significant effort was put into estimation of the drag experienced by marine mammals (particularly dolphins) which led to the coining of Gray's paradox (Gray, 1936), the (since disproved) assertion of a mismatch between the high speed at which dolphins are able to swim, and the high drag that early models calculated they should experience. Drag is the force exerted on an object by the medium which it is moving through. To overcome this force and accelerate, an animal must exert a greater force in the opposite direction. Gray estimated a swimming dolphin's maximum force output by assessment of muscle mass and suggested it was insufficient to overcome the drag generated. His assumption that drag experienced by a swimming animal at a particular speed will be equal to the force the animal is generating, meaning that force will be equal to drag assuming a constant velocity, has since been disproved for undulating swimmers (Bale et al., 2014).

Williams and Kooyman (1985) measured the drag force on a harbour seal directly by towing live animals around a tank at speeds between 0.7 and 3.5 m/s. They found a relationship between drag (*D*) in units of newtons, and velocity (*v*) in metres per second, of

$$D = 6.49\, v^{1.79}$$

For our largest animal, this produces a value of 46.4 N, far less than previous estimates. This could be due to the increase in drag experienced by actively swimming animals (Fish et al., 1988). This wide variety of possible values highlights the uncertainty of making estimates based solely on theoretical models.

4.3 Methods

In order to measure the force that a seal is able (and willing) to exert on to a piece of fish farm netting, a pressure test rig was constructed. This consisted of an aluminium frame attached via a pivot to a calibrated load cell (Omni-Instruments CBES-200), which indirectly measured the force applied horizontally on to the netting (see Figure 9 below). The load cell was connected via a USB digitiser (Measurement Computing PMD 1208LS) sampling at 5 Hz, to a custom-written VBA script which allowed measurements to be recorded directly into Microsoft Excel. High frequency measurements were also taken using a National Instruments USB 6351 DAQ (sample rate 500 kHz) board to describe the nature of the force in more detail. As the distance from the centre of the net to the pivot point of the frame was greater than the distance from the pivot point to the load cell, measurements were adjusted by a ratio of 1:1.4 (Figure 9). The range of voltages measured could be adjusted as necessary, allowing for an expected increase in force output throughout the experiment. Results were recorded from inside a hut positioned above the net panel, reducing distraction for the animal while maintaining separation of the observer form the subject.

A square panel of netting, one metre in width, was threaded on to four steel bars, the length of which could be adjusted via bottle-screws in order to vary the tension on the netting. The steel bars were bolted at the corners into four diagonal slots on an outer frame, allowing the inner frame to increase in size as tension was increased (

).

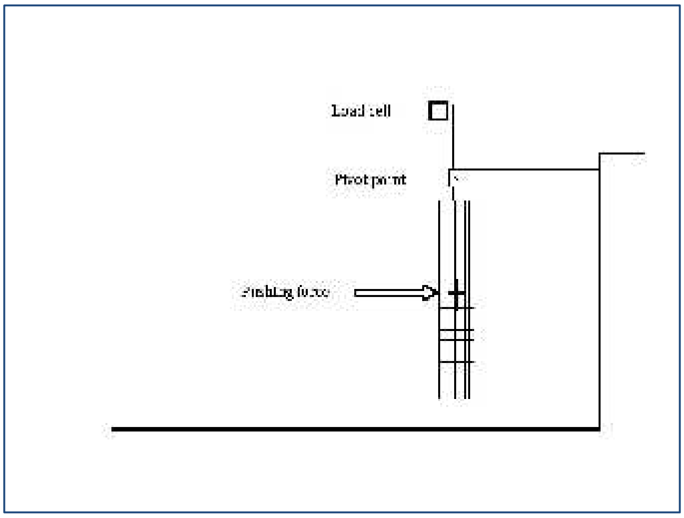

Figure 9 - Mechanism of force measurement plate. Seals were trained to push against the centre of netting.

Before the equipment was installed, a series of calibrations was conducted using known weights. A pulley was installed behind the centre of the net panel and weights were attached so that force was delivered directly on to the centre of the net. From this the voltage output of the load cell was calibrated to the actual force measured in newtons, and the relationship between the two was found to be linear.

Six captive seals were trained to push against the centre of the netting in order to receive a food reward. Seals received regular a feeding regime, but feeding was sometimes delayed or restricted (in accordance with the home office licence conditions) in order to slightly increase motivation state. Training of seals was a gradual process which took several days of work with each individual. Animals were initially familiarised with the equipment by being fed from a small plastic tube (feeding tube) on the end of a pole. This pole was gradually positioned next to, and then behind the net panel, allowing the seal to easily take the fish through the meshes. The distance from the feeding tube to the pivot point needed to be fixed (in order to maintain the 1:1.4 ratio) so the feeding tube was located into a slot behind the netting panel. Once animals were comfortable touching the net panel, the distance between the panel and the food reward was incrementally increased until the seal needed to exert significant force onto the panel to reach the fish. Once animals were able to take fish even at the greatest distance, the tension on the net panel was increased, making it more difficult for the seals to deflect the net.

Eventually, seals were pushing so hard on the netting that they were able to push the netting all the way to the panel behind, even when the netting was stretched as tightly as possible. This meant that we could no longer increase the distance between the net and the target. Instead, we reduced the area of netting which was available to stretch by weaving steel rods through the meshes, and using the rods to put additional tension on the netting (see

). Additionally, seals were pushing hard enough that they were unable to manipulate the food reward out of the feeding tube. To maintain the behavioural reinforcement of a food reward, the feeding tube was replaced with a target, which seals were trained to touch. This target was placed behind the netting so that seals had to push through the netting in the same way as with the feeding tube, but the food reward was instead thrown into the water beside the apparatus.

Individual animals were found to be highly variable in their amenability to training. The youngest animal in particular was most comfortable taking food from behind the net. Older animals, in general, required more time familiarising with the system before usable measurements of maximum force could be made. For each animal, at least two full days of familiarisation were required before force readings could be made, but for certain individuals this period was significantly longer.

Initial familiarisation was incremental, with learning required on the part of both the animal subject and the researcher carrying out the experiments. On several occasions we came across limitations either with the equipment or the techniques we were using and these challenges were addressed one by one until a consistent training protocol was established. The largest seal we tested, an adult male grey seal, was the largest seal ever held in the SMRU facility and this presented unique challenges as this individual proved particularly destructive. This experience was typical of developing novel experimentation techniques on untrained animals.

A digital recording of force output was made for each experimental session and a seal was deemed to have reached its maximum force output when a series of sessions was conducted with no increase in maximum force reading. Early experiments were occasionally limited by restrictions of the equipment, rather than the seal's effort, and this could be easily recognised by observing the seals underwater behaviour. Once restrictions were addressed, the gradual increase in force output continued until an asymptote was reached. As the project progressed the training techniques were improved which meant that later seals in the series (W, Z, C) became familiar with the task more quickly and reached an asymptotic force sooner than the first three seals (T, U and V).

Aside from the force plate measurement, we also observed and described the behaviour of the seals as they pushed against the net to obtain a reward.

Figure 10 - Body and neck extended

Figure 11 - Body and neck retracted

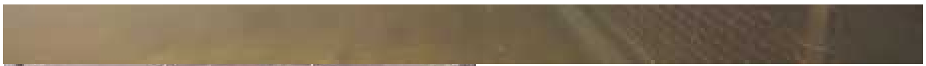

Figure 12 - Square netting panel that seals were trained to push against

4.4 Results

The most common method by which seals pushed on the net is shown in Figure 10 and Figure 11. Seals would swim down to the netting and stop with their muzzle close to, or resting on the centre of the netting. The rear flippers were then used in a regular swimming pattern, alternating from one to the other to keep the animal in position in front of the net and stop it from being pushed backwards. The neck is retracted to allow the chest and body as close to the netting as possible, and the neck is then extended in short, sharp pulses, rapidly forcing the net back into contact with the target. Supplementary videos 5 and 6 show this mechanism from two different perspectives. This behaviour was described by Fjalling (2006). Detection of this behaviour on animal-borne sensors has also been used to indicate prey engulfment in harbour seals (Ydesen et al., 2014).

In between the main bursts of force, seals would sometimes spin about their longitudinal axis. This appeared to be an indication of frustration, when the target was held slightly beyond reach. This behaviour was sometimes combined with using their teeth to pull or twist the netting, which was also seen when the seal could not quite reach the target. This behaviour was similar to that discussed above (in section three) where the subject appeared to be trying to break the netting. No breaks were made in the netting as part of either experiment, but if this behaviour had continued for prolonged periods (hours), then the net would have been broken. This chewing and twisting behaviour was only observed at times when the feeding target was presented behind the netting.

Only one seal was observed using a different technique for part of the training. This seal would occasionally forego the short pause before initiating its first neck extension, instead using the momentum it already had from swimming toward the netting. This seal would swim noticeably faster than the others toward the net in order to build up momentum. This technique did not produce noticeably higher force outputs, and would usually transition into the normal technique where the body was held stationary.

The force delivery over time, as measured by a high sample-rate data acquisition system is shown in Figure 13, and was seen from all of the seals tested. The force was very impulsive in nature, with rapid onset of force over 0.5 – 1 second. If the seal did not quite reach its target, a series of subsequent quick bursts usually followed, increasing in amplitude until the target was reached or the seal gives up. Sometimes a small amount of force was maintained on the panel in between the main bursts, as the seal held station with its muzzle pushing relatively gently on the netting.

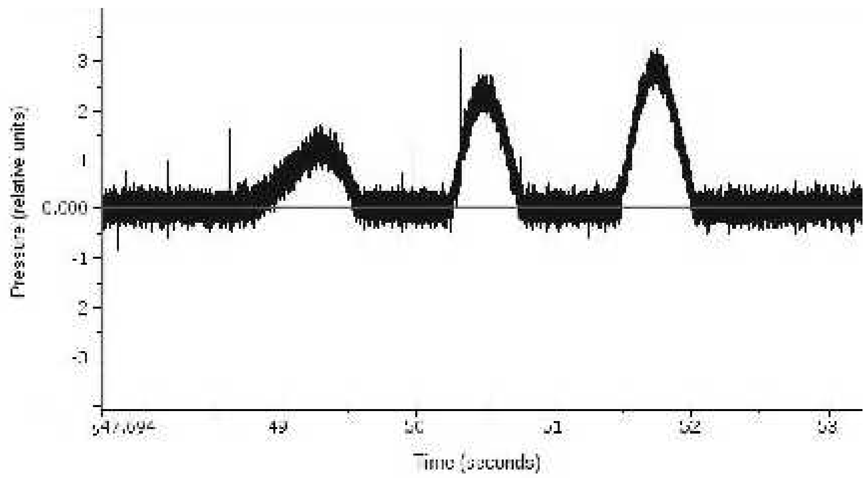

Figure 13 - High frequency force measurements, showing the impulsive nature of the seal attacks. Amplitude increases until the seal is able to reach the target and receive the reward.

Seals gradually became more confident pushing into the netting, initially being reluctant to even touch it. Once they were familiarised with the technique required, animals slowly started to push harder and harder. Figure 14 shows how the maximum force output changed for each seal over the course of the experiments.

A clear logarithmic relationship was found between animal weight and maximum force (Figure 15), showing that larger (heavier) animals are able to produce more force than smaller, lighter animals, but that this increase becomes proportionally smaller as mass increases. This relationship appears to hold for both grey and harbour seals, which both fit onto the same curve.

The maximum force observed in experimental trials was 717 N. This was produced by the largest seal (C), an adult male grey seal.

We fitted a logarithmic regression through the six maximum force measurements with respect to seal body mass in Figure 15. The relationship between body mass (M) and force (F) was best described by the equation $F = 223.69 \times \ln(M) - 463.37$ with a goodness of fit statistic of $R^2 = 0.94$

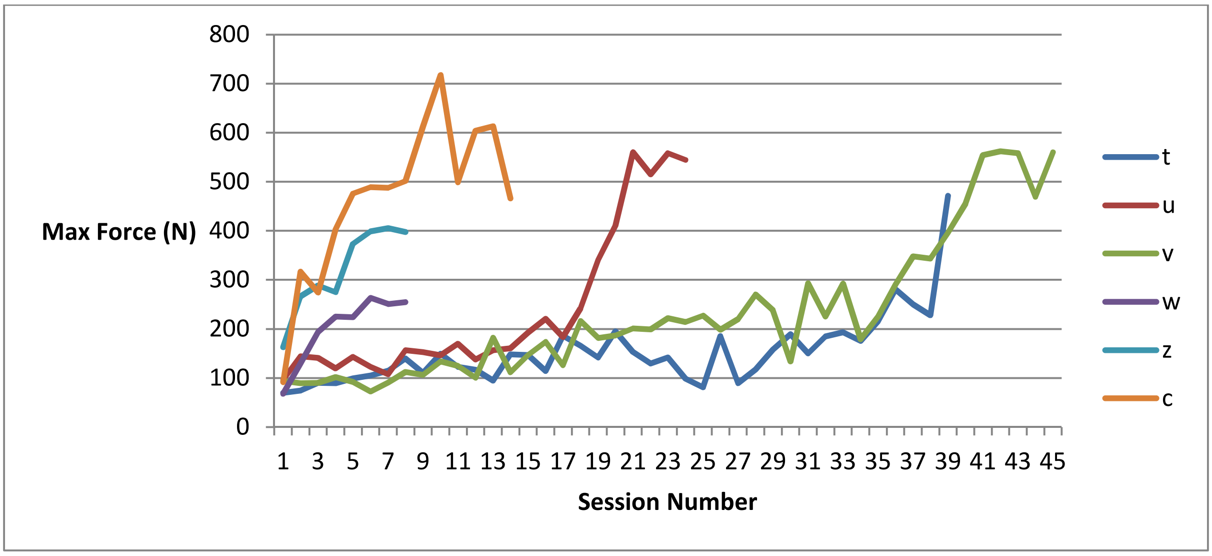

Figure 14 - Maximum force per session, showing a gradual increase until an asymptote

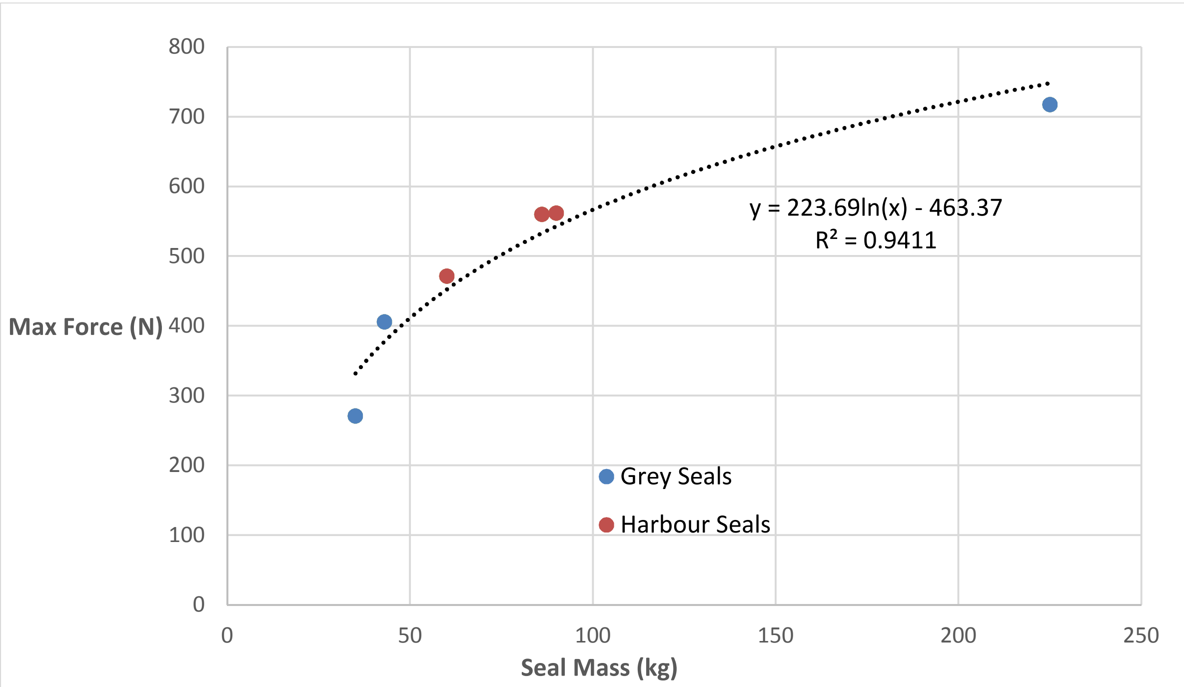

Figure 15 - Seal mass vs maximum force output

4.5 Conclusion

The limit to the amount of force a seal is willing or able to exert may be physiological i.e. surface area of the hind flippers, may relate to the physics of the net, or may be caused by physical discomfort of repeatedly pushing onto the net.

A basic force modelling approach using maximum swim speed is probably inappropriate for several reasons. Using the distance travelled during the impact created the highest estimate of maximum force (2025 N), but this relies heavily on the distance travelled and assumes that the whole seal was in motion at 3 m/s before the impact.

Motivation is clearly highly important in the development of these depredatory behaviours. Seals do not seem to be naturally predisposed to come into contact with nets.

Nets were not broken, but could have been if seals had been allowed to gnaw for extended periods. The fact that seals only showed this behaviour at times when the feeding target was present behind the netting suggests that seals are not innately predisposed to chewing on nets, but rather do so out of 'frustration' when a food source is almost within reach.

As with the previous experiment, all animals found it difficult to eat through the stretched netting.

It seems clear that motivation (and experience) are also key features in determining the force that seals are able to generate in pushing nets. Although we have seen a general increase in force through time, it is clear that on a day to day basis animals were also more or less motivated – we assume to some extent at least by how hungry they were. Patience was therefore needed to discover the maximum force they are each capable of generating. Even then, our maximum reading may still have been limited to some extent by the constraints of the experimental set up.

It is also evident that some animals are able to make the link between pushing on the net and obtaining a reward more quickly than others. There are clearly individual differences in learning speed.

Theoretically we might expect that for two seals of the same species, sex and maturity, the amplitude of the maximum potential force output will depend on body mass. This is based on the assumption that the musculature is similar and in the same proportion to body weight in all of the animals being tested. Based on our present data, we can estimate that maximum force in kilograms is roughly one third of body weight. If this holds true, then a large bull grey seal of 300 kg might be expected to generate a force of 1000 N (equivalent to 100 kg). If we use the equation derived from Figure 15, and extrapolate beyond the range of body masses in the experiment, a figure of 812 N is derived for a 300 kg seal. Further experiments should help refine our underestimating of this relationship and whether grey seals are able to exert proportionally more force per unit weight than harbour seals. As an interim measure, these figures may help in determining weights needed to counteract the effects of seals pushing against cage walls.

When manipulating netting in attempts to reach food, seals can be incredibly determined and vigorous, even to the extent of becoming temporarily entangled in the netting. This behaviour is potentially dangerous in the wild, where larger sheets of loosely tensioned netting could easily entangle a seal more permanently.

5 Net deformation

5.1 Introduction

In order to maintain a healthy growing environment for farmed salmon, fish farms are usually sited in highly dynamic marine environments, typically in sites with relatively high tidal flow. This allows a good supply of dissolved oxygen, as well as helping to remove and disperse waste. One consequence of this is that cages must be designed to withstand high tidal flow and the associated drag forces. Drag will be heightened by any biofouling of nets, and will be strongest when nets with small mesh (more surface area) are used.

It is easy to imagine fish farm netting as a continuous, homogenous, well tensioned and evenly distributed sheet of material designed to withstand tidal forces at all stages of the tide. However, our experience in monitoring fish farms using underwater video, as well our discussions with net manufacturers, has shown that this idealised picture is never fully achieved. There are many interdependent factors which govern the way a net panel hangs in the water, and in reality nets are subject to forces and strains that are likely to produce uneven netting surfaces, creases, bags and billows, any or all of which might be exploited by seals to attack fish.

While the forces generated by tidal currents are likely to be very large, in contrast, seals might seem unlikely to be able to distort nets to anything like the same extent. Even relatively small forces however, if applied in the right places, may enable a seal to take a fish from the other side of a net panel, especially if seals are able to exploit existing deformations caused by water movement. Vilata et al. (2010) found the number of sightings of South American sea lions was higher around salmon farms in Southern Chile was higher around times of peak tidal flow, highlighting the potential for learnt behaviours which exploit weaknesses caused by strong currents.

There seems to be a widely held assumption within the industry that the lack of adequate tension in nets makes cages more susceptible to seal depredation, although this has yet to be demonstrated scientifically, and of course the respective roles of tidal flow and of the seals themselves in this context has yet to be addressed.

The questions that we begin to try to explore here are, firstly, how much displacement occurs in nets that are rigged as designed (optimally tensioned according to the present design criteria) when subject to tidal forces and how does this displacement affect net shape? Secondly how much displacement of such a net can a seal achieve - so that we can then ask, how might this affect its ability to catch a fish, and how might the effects of tidally driven net deformation assist the seal in so doing?

We began this project with the aim of recording data about the movement of nets *in situ,* using sensors to log the net movement, either in part or whole, relative to the speed and direction of the tidal current.

Appropriate sensors were found which would log depth and accelerometer information at a high enough frequency, and which would run long enough to measure the effect over several tidal cycles (OpenTags by Loggerhead Instruments). We developed mounting attachments and software tools to ensure that the 3-axis movements of a net panel surface could be monitored and described.

The lack of any opportunity to deploy these tags or collect field measurements on net panel movements encouraged us to modify our initial objective and to explore the above questions from a more theoretical perspective. We were able to use the results obtained from the pool experiments to try to explore how the maximum forces that seals are predicted to be able to generate might translate into displacement of typical well tensioned netting. Using the relationship that we previously uncovered between seal body mass and maximum force, we can begin to explore how seals might be able to displace nets in order to take fish from the other side of the net. By using theoretical or measured parameters we can deduce the maximum degree of deflection for a given panel of netting subject to maximum forces that seals might be able to produce.

In order to gain representative measurements to apply to fish-farms, we have taken measurements from small scale physical models and also used mathematical modelling of the movements and forces involved, and then scaled up to a more realistic size, representative of the real-world situation. Comparing this maximum deflection with information on fish behaviour (such as minimum approach distance to net panels, flight speed in response to an attack, etc.) would return a general idea about the effectiveness of optimal net tensioning.

5.2 Methods

We have explored the degree of displacement that might occur for a single net panel subject to a seal exerting maximum force at the centre of the panel. A review by the Scandinavian Foundation for Scientific and Industrial Research (SINTEF) of techniques for assessing various relevant metrics from materials used in aquaculture demonstrates the use of finite element methods in modelling material movements (Casanova and Dwikartika, 2013). Finite element techniques break the description of natural phenomena into a discrete number of elements in order to model certain properties, such as strain and stretch. In order to create an accurate finite element model (FEM), the physical qualities of individual elements must be known. The key metrics in this context are elasticity and plasticity (more colloquially known as net 'sheer'), which describe the 'stretchiness' and pliability of a particular netting material. Unfortunately, values for net sheer of the commonly used fish farm netting materials do not appear to be publically available, so a method was developed to make empirical measurements from netting.

We have used two different steps to measure the net displacement or incursion against applied force in a small-scale model of a net panel with a variable size frame extending up to 105 cm x 105 cm and used measurements from the physical model to estimate the maximal incursion a seal might achieve on a full-sized net base panel.

In a first step, we measured the normal deformation of the net under repeated application of a variable force for two frame sizes (104 x 84 cm and 46 x 30 cm). This allowed us to examine the hysteresis effect of repeatedly stretching the net. The displacement was measured from the initial net position (a flat plane) to its new position when pulled by a variable weight. The experiment was repeated six times for the larger net size and three times for the smaller net size. Figure 19 shows the side-view of the setup used and Figure 16**Error! Reference source not found.** shows the top view of the deformation achieved.

In a second step we measured the relationship between maximal deformation and net size. We used a model net consisting of a metal frame with fixed width of 84 cm and variable length between 15 and 105 cm. A constant weight of 6 kg was used to produce the maximum potential deformation. As the net was subject to this weight, we varied the length of one of the sides of the rectangular frame and measured the overall deflection of the net as a function of this length.

We next extrapolated these results with a theoretical model to estimate the maximal deformation of a net panel of realistic dimensions. When scaling up to a typical net panel in a fish farm, based on discussions and diagrams provided by a net manufacturer, we used measurements of a 'circular' net with a 100 m circumference at the base, where the base consists of 10 triangular net panels, each panel or segment being 1024 cm along the outer edge and having a radial length of 1623 cm from centre of the cage bottom to the outer edge. Each such panel is supported by ropes at the outer edges and also a support rope connected along the radius or centre of the panel. The resultant segment between support ropes is therefore a right angle triangle with catheti of 1623 cm and 512 cm and a hypotenuse of 1702 cm (see Figure 17 c). The edges of the panel, representing the supporting ropes, were assumed to be rigid structures, unaffected by the force applied in the centre of the panel and the netting was assumed to be optimally tensioned.

5.3 Results

Regarding our work on motion sensing tags to measure real world net deformations, we designed and manufactured attachments so that the loggers could be attached underwater by divers to the netting. The attachments were designed based on our experience with mounting cameras onto netting underwater, and were made in such a way that they could easily be attached and retrieved by divers.

Tools for visualisation and analysis of data were also progressed using MathWorks MATLAB ©. We intended to use these tools to develop metrics by which individual sites and cages within sites could be compared, but full development of the software tools could not be completed without real data to support them.

Unfortunately, no sites were found to be both suitable and willing to allow installation of the accelerometry tags, so this objective could not be fully met.

We were able to progress work on theoretical modelling of net displacement somewhat further. **Error! Reference source not found.** (a) shows the model net deformation as a function of the force applied for two different frame sizes. The upper six curves are the measures for a large frame size (104 cm x 84 cm) and the lower three curves are for the smaller frame size (46 cm x 30 cm). Each curve corresponds to a successive series where the force was increased from 0.5 – 6 kg and deformation in the direction of the pull force was measured. Observations showed that multiple applications of force on the net deliver different relationships between force and deformation (hysteresis). This behaviour can be understood as the interplay between a fast elastic behaviour and a slow plastic behaviour. In effect, the elasticity of the net changes after successive deformations such that the net shows a larger deformation for small forces after multiple applications. We further observed that, in the absence of any force applied, the net recovers to its initial position after twenty minutes. Regardless of the magnitude of the force applied and the number of times the force has been increased and decreased, the *maximal* deformation remains constant. This corresponds to the limit of stretch within the fibres of the nylon netting.

By combining the experimentally derived level of elasticity (as a function of net size and force applied) with our empirical measurements of seal force output, and applying this to a realistic-sized net panel (Figure 17 c) we can calculate the maximal deformation. Figure 18 shows a conservative logarithmic extrapolation of the maximal deformation and a linear fit to the same data. The predicted deformation for the realistic net panel based on these extrapolations is therefore between 24 and 37 cm.

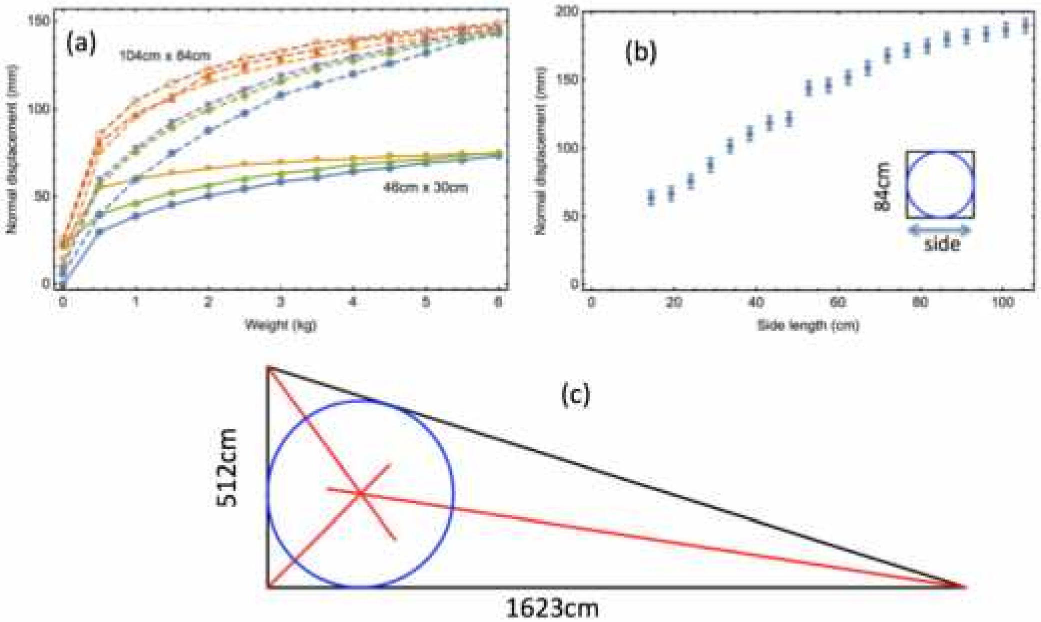

Figure 17 - (a) Measured net displacement vs weight for two frame sizes, (b) Net deflection vs length of panel side, (c) Geometry used to calculate the point of maximal deflection

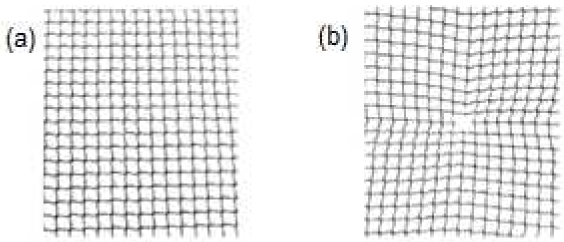

Figure 16 - (a) & (b) Top-down view of net without and with loading

Figure 19 - Side-view of net stretch experimental configuration

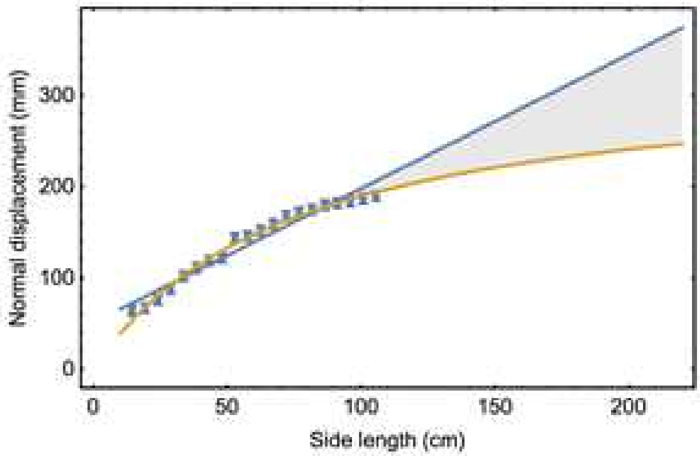

Figure 18 - Linear and logarithmic extrapolations of net deformation vs net size

5.4 Conclusion

The measurements and extrapolations developed indicate that even a medium sized seal of around 100 kg should be able to deform a standard net panel at the base of net to a maximal elastic deformation of around 30 cm. In practice, this figure is likely to be an underestimate, given the assumption that the panel edges are fixed, rigid structures.

Of course measurements made in an artificial experimental set-up are not necessarily directly transferrable to the real-world environment, where net panels may behave in ways that are not obvious. Multiple factors, such as the age of the net, its behaviour in water and the exact hanging geometry, will influence the precise value of this maximal deformation. The constraints of the experimental scenario limited the scale of the netting sheet which could be presented to the seals. To deliver a better understanding of the net's behaviour it would be necessary to validate the elasticity model *in situ* with a measured net deformation in a realistic underwater scenario and also against the deformation of a single knot under strain. These two cases correspond to a macroscopic and a microscopic study of the net and should deliver improved net design and improved net tensioning rules.

The methods employed here could easily be developed further for the assessment and comparison of different types of netting materials e.g. HDPE. Using a photogrammetric approach (such as Figure 16) alongside simple image recognition software, it would be possible to rapidly compute the level of deformation and create more sophisticated models of net elasticity.

Nevertheless, what is clear is that the use of nylon netting, with its inherently ‘stretchy’ properties, may assist seals in being able to displace the netting even under what might be considered optimally tensioned conditions. Of course, displacing the netting by 30 cm is not the same as being able to take a fish that is 30 cm inside the netting. Fish are likely to react and retreat, depending on how fast the net can be displaced by seal. Perhaps more importantly, however, is that fact that under the conditions of full exertion against a piece of netting, our pool observations suggest that it is still extremely difficult for a seal to take a fish in its mouth (which is simultaneously involved in the mechanics of net displacement) and handle the fish in a way that actually results in a mouthful of food. We may presume there is some trade-off between physical exertion to displace the net and the ability of the seal to manipulate the fish with its jaws.

Much therefore remains to be discovered about how seals are able to displace nets in such a way as to guarantee catching and eating a fish, and yet more remains to be done to explore how the additional tidal forces may help or hinder seal depredation and how changes to net shapes under tidal flows may provide feeding opportunities for depredatory seals.

Finally, it is worth noting that one of the most significant changes the industry is currently undergoing is the development and uptake of novel netting materials. The principal component of many new net types is HDPE, which has several key benefits over ‘traditional’ nylon nets, including greater strength and rigidity.

In the context of our work, these new materials provide an opportunity for studies that would compare their extensibility with that of nylon netting. We have been given access to samples of several different types of polyethylene based net materials, and notice a distinct reduction in elasticity compared with nylon. This factor is potentially important in helping to prevent seal depredation, and further work could easily be undertaken to make some measured comparisons.

6 International Perspective

6.1 Introduction

Salmon aquaculture is a global industry, and difficulties with depredation and net damage will undoubtedly be faced by most, if not all international partners. The largest companies operating in Scotland are also multinational operators, and should therefore be assimilating knowledge and experience from their operations overseas. Ireland, Canada, the USA, Chile, Norway, South Africa, and Australia are all producers of Atlantic salmon, and we have made efforts to contact researchers in these places to find out how seal depredation is dealt with. Measures include lethal removal, anti-predator nets and acoustic deterrent devices (ADDs). Nowhere has the effectiveness of these measures been assessed rigorously.

6.2 Ireland

Aquaculture operators in Ireland are reported to use both ADDs and anti-predator nets to limit seal damage. Shooting of seals in Ireland is illegal unless licenced under Section 42 of the Wildlife Acts (1976-2012), and we understand that very few such licences are granted. Evidence of damage to pens needs to be provided for a licence to be granted.

6.3 Chile

Anti-predator nets and ADDs are widely used in Chile, and fibreglass models of killer whales were also tried, but were not deemed efficient (Sepulveda and Oliva, 2005).

Sea lions in Chile are officially protected from hunting, but derogations exist allowing hunting or live capture under certain conditions, such as if the population in a certain area is shown to be excessive. The Chilean national Fisheries Service issues permits to kill sea lions that are known to cause problems (Kemper et al., 2003). While we lack recent information, Claude and Oporto (2000 - not seen – cited in Kemper et al. 2003) estimated that 5000 - 6000 South American sea lions were shot annually in the 1980s and 1990s, largely illegally.

6.4 Norway

Colleagues in Norway have suggested that seal depredation is not considered a significant problem facing the industry. Seal populations are relatively low and highly dispersed, with a Norwegian population of only around 6000 grey seals (Nilssen and Haug, 2007) compared with more than 100,000 in Scotland, and the populations are probably artificially suppressed to some extent by ongoing hunting (a much more commonly accepted cultural practice).

Similar to Scotland's licencing laws for lethal removal of seals, Norway employs a regionally administrated licencing system for seal hunting. Licences are available to those who already possess a 'huntsman's' licence. Each area council has a total maximum limit, which is dictated by the Fisheries Directorate and based on advice from experts at the Institute of Marine Research. Certain time and area closures are applied, depending on the reproductive cycles of the relevant species.

We understand that both ADDs and anti-predator nets are used to some extent, but reliable figures are not available.

6.5 Canada

Since 2010, Canadian aquaculture site licences include a provision authorising the humane destruction of 'nuisance seals' under certain conditions (Fisheries and Oceans Canada, 2015). These provisions under the Pacific Aquaculture Regulations replace the previous 'nuisance seal licences' and describe the conditions under which a seal may be shot, including the presence of, and compliance with, a Predator Management Plan. 'All reasonable methods' must be used to deter seals and sea lions from coming into conflict with the facility. Regular site audits by biologists from the Department of Fisheries and Oceans Canada are used to ensure compliance with licence conditions and the Predator Management Plan.

The number of harbour seals recorded as being removed fell consistently from a peak of 577 in 1995 to 556 in 2010. A similar pattern occurred for the California sea lion with a lower peak of 243 animals removed in 2000, down to <10 per year from 2004 – 2008. There was, however, a more recent increase up to 170 animals in 2010.

The most common netting systems in Canada include anti-predator netting (Fisheries and Oceans Canada, 2015). Figures available on the DFO website show that between 1 and 13 harbour seals have become entangled per year since 2011. One incident was reported in 2007 of 51 sea lions drowned in anti-predator nets at one site in Tofino, British Columbia (CanWest News Service, 2007).

Nylon netting is now being phased out of use, in favour of HDPE based nets due to perceived benefits reducing depredation (Knox Nets, pers. comm., 2015).

6.6 USA

Nelson et al. (2006) report that salmon farms in the Gulf of Maine routinely use anti-predator nets and ADDs to deter seal depredation. Killing any marine mammal in the USA is illegal under the Marine Mammal Protection Act. Under Section 120 of the Act "A State may apply to the Secretary to authorize the intentional lethal taking of individually identifiable pinnipeds which are having a significant negative impact on the decline or recovery of" salmonid stocks that may be deemed threatened. Shooting at aquaculture sites is therefore not an option.

6.7 Australia

Depredation by otariids at Australian finfish sites has been a significant problem, accounting for the loss of c. 2% of stock in 1997/1998, valued at AUD$ 1.5 (Schotte and Pemberton, 2002). All seals species are protected by the 1999 Environment Protection and Biodiversity Conservation Act. Governmental permits can be issued for their removal, but these do not appear to be granted for the protection of aquaculture sites. A 2007 report acknowledged a problem with illegal shooting, but numbers were not known (Anon, 2007).

A 2002 study (Schotte and Pemberton, 2002) assessed the use of flexible oceanic pens and recommended maximising of weight hung on the predator netting (minimum 2.4 T for a 120 m circumference circle). They also recommended the use of 'separation sticks' to maintain the distance between the growth and predator nets. In 2013 a Tasmanian company began using Dyneema® netting hoping to reduce seal predation (ABC News, 2013), and their website states that no escapes occurred in the last three years, though no further details have been reported.

7 Discussion

Since the introduction of licencing in 2011, the number of seals shot annually has dropped dramatically, suggesting that the act has already led to some improvements in management measures to limit seal damage. The new technical standard also provides a platform for continued focus on aspects of containment relevant to seal depredation.

This project began with four defined objectives, some of which were ambitious and relied explicitly on collaborative assistance with other parties, as well as a degree of good fortune. Unsurprisingly, we were unable to fulfil all of the objectives as we had initially hoped, but we instead focused in greater detail on the aspects of the project which were proving fruitful. In particular, objective one (to record underwater observations of seals attacking salmon at farm sites) was ultimately missed despite significant effort and almost three months of underwater camera deployment time. Despite the frustration at not being able to attain our primary ambition, we feel that progress has been made toward this end with the development of a new attachment technique using divers and the integration of an upgraded recording unit.

Deploying this equipment at a site with an active depredation problem would provide a unique opportunity to record and describe the mechanisms of attack.

While not providing any new information on seal predatory behaviour, the improved underwater recording system has allowed us to learn more about the behaviour of salmon. Observations of salmon regularly swimming slowly within 2 cm of the side and base panels of the net show us that fish behaviour may exacerbate the problem of seal depredation. Further work on fish behaviour may provide more pertinent information, particularly if further evidence of behaviour likely to increase vulnerability can be found, or if ways of preventing such behaviour can be identified.

Much of our effort throughout this project was focused on understanding the predatory behaviour of seals using the SMRU captive facility. Several modifications to the original experimental design were required in order to create useful readings of maximum force. This is typical of experiments with untrained captive animals, which rarely behave as expected. In addition, the practical logistics of using the captive facility required practice before a smooth training regime was established. For example, moving animals between pools took much longer than anticipated and significant periods of time were lost due to algal blooms and/or filter failures causing reduced visibility, which made training underwater behaviour very difficult or sometimes impossible.

It was very notable that certain animals were more amenable to training than others and this impacted strongly on the amount of time it took to reach their maximum force output. Motivation for food seemed to be an important factor, with greater ‘leaps of progress’ occurring when seals had recently been fed less. Toward the end of training sessions, when animals were nearing satiation, they quickly became frustrated if they were unable to reach the target, and were more likely to give up.

The fact that seals took significant time and persuasion before they would interact with netting suggests that they are not inherently predisposed to try to take salmon by attacking fish farm nets. This indicates that if the initial stimulus for interaction can be removed or reduced, it may be possible to prevent the positive reinforcement of predatory behaviour.

There was a clear preference for seals to use teeth and fore-flippers in combination to manipulate fish whenever possible. As access to the fish was made increasingly difficult, the effectiveness of this feeding behaviour was substantially reduced. In cases where the fish were placed some distance away from the netting, it proved difficult or impossible for seals to simultaneously manipulate fish with their teeth and flippers. Feeding was far less effective when seals were only able to use their teeth. The fact that increasing the difficulty of accessing the fish led to seals rapidly losing interest in the task indicates that improved containment measures are likely to be an effective solution.

We have been able to highlight certain depredatory behavioural mechanisms, but the deep gashes and abdominal gouges (“belly bites”) typically seen during investigations on fish farms were not replicated. Combining this with observations from site visits of recently retrieved still live fish exhibiting these same wounds provides a strong indication that these injuries occur only when the fish are alive. This leaves open the question of the exact mechanism of this type of attack given the difficulty seals had in manipulating or even reaching fish behind a flat net panel. It would seem that this apparent conundrum can only be addressed by *in situ* underwater recording of seal depredation. Conversely, the damage seen when seals had access to fish carcasses over extended periods of time was identical to Category 1 damage, described in Northridge et al. (2013). This suggests that this category may be more indicative of scavenging, rather than predation on live fish. Quantification of the number of fish taken by seals relies heavily on accurate discrimination between predation and scavenging, and this is very challenging since there is no objective method of determining whether dead fish classified as seal morts were predated or scavenged.

During the project we became aware that some Scottish fish farm sites are now starting to use HDPE netting of various types, and we believe that it would be useful to compare the abilities of seals to manipulate fish through these different netting materials.

A clear logarithmic relationship was found between seal mass and maximum force output. This suggests that some factor, other than body mass alone, limits the pushing ability of a seal. Likely potential factors are the surface area of flippers, which can be expected not to increase linearly with body mass, and the physical discomfort of pushing onto a net panel. If the latter is indeed an important factor, it may open avenues for the use of rougher, more tactile netting materials, which could increase discomfort.

The very large force that seals have been shown to be capable of exerting onto netting, combined with the degree of nylon net deformation that we have shown to be caused by this level of force and our observations of fish swimming in very close proximity to the netting, indicate that it will be very difficult to exclude seals totally from being able to access salmon. Nylon netting has been shown to be relatively stretchy and pliable compared to HDPE-based netting materials, which may offer increased protection from predators. Some aquaculture companies have begun trialling HDPE netting, and the results from these trials will be important in showing any benefits of these materials in regards to limiting predator damage. Continued development of the methods described here for testing net elasticity would be an important step in allowing comparison of the merits of different netting materials. Likewise, *in situ* validation of these tests in a real-world environment would allow a broader understanding of the issues associated with net deformation.

Discussions with net manufacturers has shown that production of ‘perfectly fitting’ nets is a complicated undertaking. Designing equipment to function adequately in the typical range of conditions experienced at sea is challenging and requires experience as well as selection of appropriate materials. The net material itself can provide different degrees of protection from seal predation, depending on the construction material, construction method, mesh size, degree of biofouling and any additional treatments such as anti-foulant or hot wax as well as other factors.

Even when nets are theoretically well tensioned, according to the specification of the manufacturer, nets are still highly dynamic. Areas of low tension or bagging are very hard to prevent, and this will be particularly true in sites with high tidal flow. It is increasingly apparent that a more detailed understanding of these factors is crucial in addressing the fundamental questions relating to predation. Despite a lack of progress on this front under the present project, we still believe this is a very important area for further research if we are to fully understand how seals are able to depredate healthy fish inside an aquaculture pen.

Our investigations into interactions between seals and aquaculture in industries abroad has shown that anti-predator nets are commonly used elsewhere. The potential for entanglement appears to remain high wherever they are used, with Canadian aquaculture reporting up to thirteen harbour seals drowned per year since 2011. With the exception of some work in Australia, little detailed assessment of the design and deployment methods for anti-predator nets has been published. Schott and Pemberton (2002) recommended the use of separation sticks in between fish nets and anti-predator nets, which to our knowledge has not been tried in Scotland.

Future Research:

- Deploying camera system at a site with an ongoing depredation problem
- Further study of fish behaviour in pens to identify possible vulnerabilities
- Captive seal trials of fish manipulation through a range of other netting materials
- Captive seal trials of willingness and ability to deform stiffer and rougher netting types
- Continued development of methods for evaluating and comparing net elasticity
- *In situ* validation of net elasticity evaluation methods.
- *In situ* assessment of net deformation and how this may aid seal depredation

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SARF - Member Organisations

Industry

SEAFISH
Association of Scottish Shellfish Growers
Scottish Salmon SSPO
British Trout Association

Government and Regulators

Scottish Natural Heritage
SEPA Scottish Environment Protection Agency
marinescotland
The Scottish Government
HIE Highlands and Islands Enterprise Iomairt na Gaidhealtachd 's nan Eilean

Non-Governmental Organisations

The Crown Estate
Scottish Environment LINK
Rivers & Fisheries Trusts of Scotland Safeguarding Scotland's Rivers & Lochs
ASFB The Association of Salmon Fishery Boards