Environmental Impact of Scallop Innovation Gear (EASIG) project

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Environmental Impact of Scallop Innovation Gear (EASIG) project

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Executive summary

The scallop sector is one of the UK's valuable fisheries, supporting a network of catching and processing businesses. However, traditional dredging methods that use spring-loaded Newhaven scallop dredges to fish for king scallop (*Pecten maximus*) pose significant environmental challenges threatening the sustainability of the environment and the industry. Efforts are being made by the fishery to move towards a more sustainable fishing practice and towards net zero. The Environmental Assessment of Scallop Innovation Gear (EASIG) project is an industry and science led collaboration project that undertook rigorous testing of several modified scallop dredge gear with the aim of maintaining catch efficiency while reducing the environmental impact of the king scallop dredging activity. The modifications include using the N-virodredge instead of the traditional Newhaven dredge, which replaces the fixed metal teeth with individually sprung tines, and using a skid belly bag instead of the conventional belly bag to elevate belly bags off the ground thereby reducing drag and seabed contact. In total, three modified gear (N-virodredge with conventional belly bag (N-virodredge), N-virodredge with skid belly bag (Nviro-skid), Newhaven dredge with skid belly bag (Newhaven-skid)) were compared against the industry standard (Newhaven dredge with conventional belly bag). The innovation supports the UK's move towards sustainable fisheries and responds to the industry's ever-increasing need for sustainably sourced seafood.

The EASIG project has been separated into four work packages that follow these objectives:

1. ***Work package 1*** – Catch yield and selectivity of the modified scallop gears in comparison to the industry standard. Comparisons of the biomass and size of the *P. maximus* retained, the abundance and species composition of the bycatch, and the weight of stone and debris retained were carried out.
2. ***Work package 2*** – Comparison of the catch and bycatch quality and survivability between the different gear types to assess the damage inflicted on retained species and likelihood of survivability after capture.
3. ***Work package 3*** – Comparison of fuel usage (litres per hour of fishing) and CO_2 emissions among the modified dredges and standard dredge.
4. ***Work package 4*** – Comparison of seabed impacts, in terms of epifauna depletion and seabed topographical changes, of the modified dredges to the standard dredge in different habitat types.

Work Package 1: Scallop Dredge Catchabilty and Selectivity

KEY FINDINGS:

- The use of skid belly bags improved catch performance for both the Newhaven and N-virodredge, increasing market-sized scallop yields by 14–19% compared to conventional belly bags. The N-virodredge did not improve the catch of market-size scallops relative to the Newhaven dredge,

- N-virodredges significantly reduced the catch of undersized scallops by an average of 42% compared to Newhaven dredges, and this pattern was consistent across sandy and stoney grounds. The addition of skids to N-virodredges led to a reduction in the catch of undersized scallops, whereas the opposite was observed when skid belly bags were used in combination with the Newhaven dredge,

- Catch selectivity varied among the modified gear; Newhaven-skid caught significantly more individuals within the size class of 110 to 120mm relative to the industry standard, whereas N-virodredge and N-virodredge-skids caught significantly less individuals below the minimum landing size (105 mm in Scotland),

- N-virodredges reduced the catch of stones by three-fold compared to Newhaven dredges, irrespective of which belly bag type was used. In contrast Newhaven-skid bellies increased the catch of stones significantly,

- None of the modified gears decreased the catch of bycatch species (e.g. starfish, sea urchins, crabs) relative to the industry standard.

Work Package 2: Catch and bycatch damage and Survivability

KEY FINDINGS:

- Fauna damage was species-specific. Bycatch fauna including starfish, crabs and sea urchins experienced greater impact than king scallops. Whereas the proportion of dead bycatch and fauna with major injuries was 25% and 18%, respectively, the proportion of dead and king scallops with major injuries were only 1.3% and 1.1%, respectively,

- No association between dredge type and bycatch damage was found, and no relationship between the quantity of stone in belly bag and species damage was detected,

- Survival probability was highest for organisms that did not incur any physical damage, however probaility of survival dropped to 78% and 48% for organisms with minor and major injuries, respectively.

Work Package 3: Fuel Consumption and CO_2 emissions

KEY FINDINGS:

- The N-virodredge resulted in 30% lower fuel consumption during typical fishing operations, representing a significant reduction in CO_2 emissions relative to Newhaven dredges,

- The addition of skids to the belly bag did not affect fuel consumption when these were used in combination with either the Newhaven dredges or the N-virodredges,

- Fuel consumption increased significantly with sea state for all gear types, but there was no significant effect of surface tidal current or water depth,

- A 30% reduction in fuel consumption would generate signficant fuel savings for fishers and significant reductions in CO_2 emissins. The amount of avoided CO_2 emissions and cost savings are shown for a typical UK scallop dredger which is over and under 15 m in length.

	Newhaven conventional dredge used		**N-virodredge used and assuming a 30% reduction in fuel consumption**	
	over 15 m scallop vessel	**under 15 m vessel**	**over 15 m scallop vessel**	**under 15 m vessel**
Average daily fuel consumption (ltrs / day)	1114 ltrs /day[1] (estimate includes fishing & steaming)	519 ltrs / day[1] (estimate includes fishing & steaming)	779 ltrs / day	363 ltrs / day
Annual CO_2 emissions ($kgCO_2$-e) per vessel assuming 86[1] and 177[1] working days in a year for under and over 15 m vessel, respectively and	547,261 $kgCO_2$-e / yr	123,880 $kgCO_2$-e / yr	382,690 $kgCO_2$-e / yr	86,645 $kgCO_2$-e / yr

2.77547 kgCO$_2$-e from marine gas oil fuel[2]				
Fuel Cost per year (£ / yr) per vessel assuming 86[1] and 177[1] fishing days in a year for under and over 15 m vessel, respectively, and assuming price of fuel equals to £0.78 per ltr	£153,799 / yr	£34,815 / yr	£107,549 / yr	£24,350 / yr
	over 15 m scallop vessel		**under 15 m vessel**	
Tonnes of avoided CO$_2$ emissions on a yearly basis per vessel by using N-virodredge instead of Newhaven dredge	164,571 kgCO$_2$-e / yr		37,235 kgCO$_2$-e / yr	
£ saved on a yearly basis per vessel by using N-virodredge instead of Newhaven dredge	£46,250 / yr		£10,465 / yr	

[1] https://www.seafish.org/document/?id=1c3071b9-23e4-4073-a9af-da5ea0547215

[2] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

Work Package 4: Seabed Disturbance

KEY FINDINGS:

- Fauna depletion was lowest for N-virodredge with skid belly bags, and no significant differences in fauna abundance was observed inside and outside the dredge tracks. In contrast, both the Newhaven and N-virodredge designs with standard belly bags led to an average 20% reduction in fauna abundance inside the dredge lanes relative to outside,

- Gear designs with standard belly bags created significantly larger furrows than gears with skid belly bags, which reduced the gear footprint on the seabed by 55% on average,

- In general, seabed fauna depletion and gear footprint were lower for skid bellies.

Summary table: ***Performance of 3 modified scallop dredge gear relative to the Newhaven dredge (industry standard)***

***GREEN** – achieves goal*
***YELLOW** - Variable*
***RED** – does not achieve goal*

Example of how to interpret results in summary table
Goal: Does the modified gear significantly reduces fuel consumption relative to the Newhaven dredge (industry standard)?
GREEN = indicates that goal is achieved, therefore significant reduction in fuel consumption for the modified gear relative to the Newhaven dredge was observed.
YELLOW = indicates no clear significant differences between the modified and conventional dredge. This is due to variability in the observations, while some observations indicate that fuel consumption is reduced, others indicate that fuel consumption is increased, leading to an overall non-significant difference in fuel consumption between the modified and standard gear.
RED = indicates that the goal of reducing fuel consumption is not achieved. Fuel consumption of the modified gear could have been the same as that of the Newhaven dredge or more. For more details of the result, the reader is encouraged to read the full scientific report below.

GOALS (comparisons relative to Newhaven dredge with standard belly)	**Maintain or increase catch of market-size scallops**	**Reduce catch of undersized scallops**	**Reduce catch of stones**	**Reduce by-catch**	**Lower seabed fauna depletion between inside & outside dredge tracks**	**Reduce gear footprint**	**Reduce fuel consumption**
Newhaven dredge + skid belly	🟩 Increases	🟥	🟥	🟥	🟨	🟩	🟥
N-virodredge + standard belly	🟨	🟩	🟩	🟨	🟨	🟥	🟩
N-virodredge + skid belly	🟩 Maintains	🟩	🟩	🟥	🟩	🟩	🟩

In conclusion, the EASIG project has shown that gear modifications—particularly the use of N-virodredges with skid belly bags—offer a practical way to reduce the environmental impact of scallop dredging in UK waters. This configuration led to significant reductions in fuel consumption, carbon emissions, seabed disturbance, and the catch of undersized scallops and stones.

However, from both ecological and economic standpoints, it is essential that new gear does not compromise profitability or inadvertently increase environmental harm. Certain configurations, such as adding skids to traditional Newhaven dredges, illustrate potential trade-offs. While this setup improved the catch of market-sized *Pecten maximus*, it did not reduce fuel use, bycatch, juvenile scallop retention, or debris collection. In contrast, N-virodredges were more effective in reducing juvenile catch and seabed disruption, though they only improved the harvest of marketable scallops when skids were also included.

These examples highlight the importance of evaluating gear performance holistically. The feasibility of adoption also hinges on economic considerations: if modifications are too costly relative to the benefits, uptake within the industry will likely be limited. Nevertheless, the combination of N-virodredges and skid belly bags represents a promising step toward more sustainable scallop fishing, delivering tangible environmental benefits without sacrificing catch efficiency.

Ultimately, the success of gear innovations depends on their integration within a broader, adaptive fisheries management framework. Given the sedentary nature of *P. maximus*—which makes it especially vulnerable to overfishing—additional measures such as effort controls, co-management models, and rights-based systems like Territorial Use Rights for Fisheries (TURFs) should be explored. While technical modifications are valuable tools, their full potential can only be realized when aligned with comprehensive strategies that safeguard both the sustainability of the resource and the livelihoods it supports.

1 General introduction

The scallop fishery is a vital part of the economies of many UK coastal communities where they support the fishing fleet and the wider seafood supply chain. In 2021, the king scallop fishery (*Pecten maximus*) provided around £44.5 million to the UK economy equating to a value of 24,700 tonnes of live weight (FMP REPORT DEFRA, 2023). However, scallop dredging has also been associated with negative environmental impacts due to the removal and loss of benthic fauna and epifauna, reduction in benthic production, emissions of CO_2, and alteration of trophic structures (Hiddink et al., 2011; Lambert et al., 2011; Hinz et al., 2012; Cortés et al., 2022). With ongoing media focus on fishing methods that do not meet required environmental standard, there is a clear need for the sector to move towards more sustainable fishing practices, or risk loss of markets as demand for sustainably caught seafood increases.

Currently, the UK king scallop fishery is managed through gear design regulations, minimum landing size, spatial and temporal closures primarily aimed at protecting spawning and recruitment of the species, but is not subject to any quota management such as total allowable catch (TACs). An example of a temporal closure was the closure of the ICES area 7d and 7e for UK and EU vessels between May and September 2024, to promote the spawning and recruitment of *P. maximus* juveniles (MMO, 2024). Technical gear modifications are one of several management measures and industry actions that can be taken to reduce impacts on target stocks and the environment. Typically, king scallops are fished using the Newhaven (spring-toothed) dredge, of which 95% of the *P. maximus* caught is using this dredge design (DEFRA, 2023). The Newhaven dredge relies on the direct contact of the dredge teeth with the seabed to collect king scallops that lie buried in the sediment. The retaining belly bag acts as a second point of contact with the seabed, creating furrows where sediment is displaced and fauna is impacted. Impact varies with fishing frequency, ground type and duration of tow length; longer hauls equate to greater collection of target species, bycatch, rock and other detritus that increase the weight and abrasion of the gear on the seabed (Sciberras et al., 2022; Lart, 2023). During the LISIG (Low Impact Scallop Innovation Gear) project a modified retaining belly bag was developed with the aim of increasing catch selectivity and reducing environmental impact (Sciberras et al,. 2022). Specifically, the modification involved the addition of ‘skids’ to the bottom of the belly bag that lifted the bag off the ground by about 10 cm, thereby reducing the contact of the collecting bag with the seabed. Evidence of the environmental and economic benefits of the LISIG skid belly bag collected during scientific gear trials and commercial practice with fishermen showed significantly higher catch (+5%) of market-size scallops per unit area fished and significantly lower gear contact area on the seabed when using the modified dredge relative to the standard dredge, maintaining catch and lowering gear wear (Fenton et al., 2024). However, the modified dredge with skid belly bag also retained significantly higher bycatch (+11%) and undersized scallops (+16%) (Fenton et al., 2024), and showed similar fuel consumption to the Newhaven dredge (Sciberras et al., 2022). To fully realize the environmental benefits of improved catchability with the LISIG skid belly bag, additional gear modifications are therefore necessary to reduce the catch of undersized scallops, bycatch and fuel consumption. These changes would enhance stock health and lower the operational costs, benefiting both the marine ecosystem and the industry. Catching undersized scallops stresses the organisms, reducing growth and gonad mass of scallops by 19 – 24% (Kaiser et al., 2007). Therefore, increasing catch selectivity to prevent repeated captures of undersized scallops is essential for maintaining stock health. Between 2020 and 2021, operational costs in the scallop dredging sector rose by 10% for vessels under 15 meters and 27% for vessels over 15 meters, driven by rising fuel prices and the increasing cost of materials like steel for gear manufacturing (Quintana & Wilkie, 2022). Reducing fuel consumption not only lowers industry expenses but also decreases CO_2 emissions, providing environmental benefits alongside economic gains. The N-Virodredge™, developed by Deeside Marine Ltd, Kirkcudbright, replaces the fixed metal teeth with individually sprung tines, and places the dredge frame on skids. Preliminary trials in French and Canadian waters indicated a 50% reduction in stone catches (Filippi, 2013; Chevarie & Chevarie, 2020) and a 12 – 30% decrease in fuel consumption (Filippi, 2013). The reduction in sorting time and minimized secondary damage to the catch on deck could lead to more efficient fishing operations and lower environmental footprint.

The Environmental Assessment of Scallop Innovation Gear (EASIG) project is a science and industry collaboration project that undertook rigorous testing of three modified scallop dredge designs to examine modifications to both the teeth at the mouth of the scallop dredge and the retaining belly bag. The modified scallop dredges were: (i) N-virodredge with conventional belly bag, (ii) N-virodredge with skid belly bag, (iii) Newhaven dredge with skid belly bag. Gear performance and environmental impact were compared to the Newhaven dredge with conventional belly bag (industry standard). Each modification is described in more detail in section 2. Gear trials were conducted to assess performace of the modified scallop dredges relative to the industry standard in terms of; the scallop gear catchability and size selectivity of *P. maximus* (work package 1, WP1), bycatch damage and survivability (WP2), fuel consumption and CO_2 emissions (WP3), and seabed disturbance and impacts (WP4).

2 Gear description

The EASIG project is based around four designs of scallop dredge gear, which will be termed Newhaven, Newhaven-skid, N-virodredge, and Nviro-skid for this report. A scallop dredge is composed of the dredge with dredge teeth at the front and a collector bag (aka belly bag) at the rear (Figure 2.1a). The dredge teeth form the first major penetrative contact with the seabed, and it is the interaction between the teeth and the scallops, which enables the capture of the scallops. The belly bag section is made up of interlocking metal rings (internal diameter 75 - 85 mm) on the bottom and a top section made up of nylon netting (diamond stretched mesh aperture 100mm) and metal rings (aka half-backs). Both dredge mouth and belly bag sections have been modified and tested during the EASIG project (Figure 2.1b), and a full description of these modifications are provided in the follwoing sub-sections. The dimensions of the sections and modifications of the scallop gear is presented in Table 2.1.

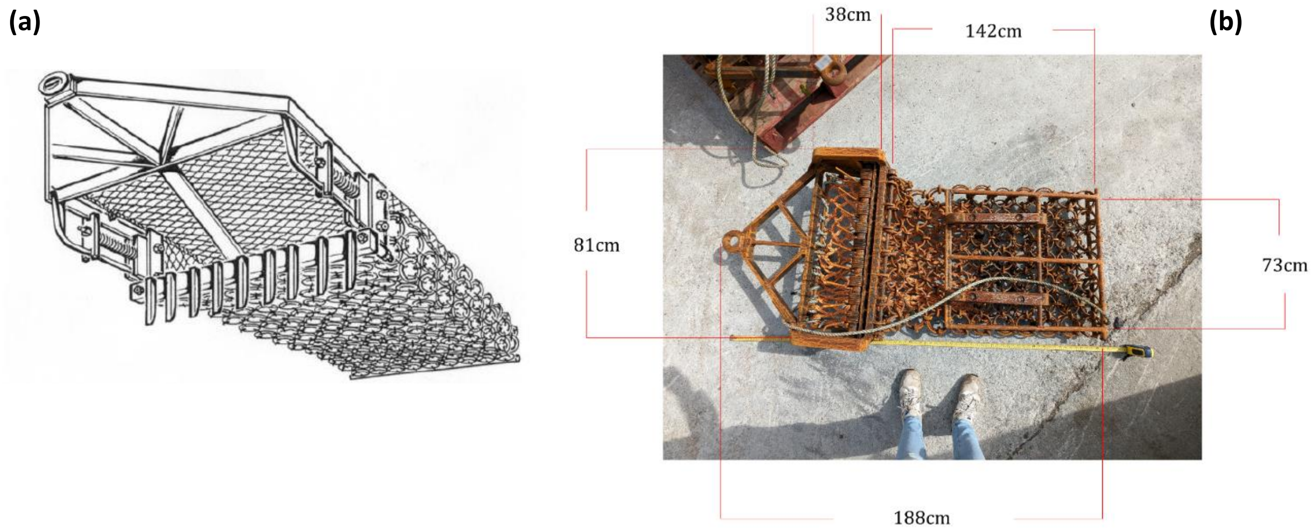


Figure 2.1: (a) Spring-toothed Newhaven dredge used to catch king scallop, *Pecten maximus*, in the UK (Image taken from Lart et al. 2003). (b) Modified scallop dredge that includes the N-virodredge mouth with associated tines, and the skid frame attached to the retaining belly bag. This image was taken after 30 fishing hauls across two separate seabed types (stone and gravel/sand). (Image credit: Blair Easton).

Table 2.1: Dimensions of the separate components of the scallop dredge gear utilised in the EASIG project.

	Length (cm)	Width (cm)	Height (cm)	Weight (kg)
Newhaven dredge including dredge teeth	46	76	33	56
N-virodredge including tines	46	81	33	51.5

Conventional Belly Bag including catcher patch	142	73	-	53
Modified skid belly bag including catcher patch				57
Skid sole (removable)	40	4	2 - 3	
Skid Frame	73	72	8	

2.1 The Dredge Mouth

The industry standard, termed a Newhaven dredge (Newhaven), utilises a fixed spring-loaded tooth bar to retrieve buried scallops into the retaining belly bag as it is dragged along the seabed (Figure 2.2). The teeth or 'swords' of the Newhaven dredge are typically 115mm in length and usually there are between 8 – 9 teeth per tooth bar (Figure 2.2). The N-virodredge^{TM} is a modification of the dredge frame and teeth designed and patented by Deeside Marine Ltd (Kirkcudbright). The sprung tooth bar in the Newhaven dredge is replaced by individually sprung tines around 17 cm long and 8 mm wide. The tines are threaded on to a rod spaced so that there are 8 tines per dredge mouth (Filippi, 2013). Skids on each end of the tine bar support the weight of the bar, with the intention to move the weight of the dredge from the teeth on to the side of the dredge frame, hence reducing the pressure at the teeth and reducing drag during the fishing activity (Figure 2.3).

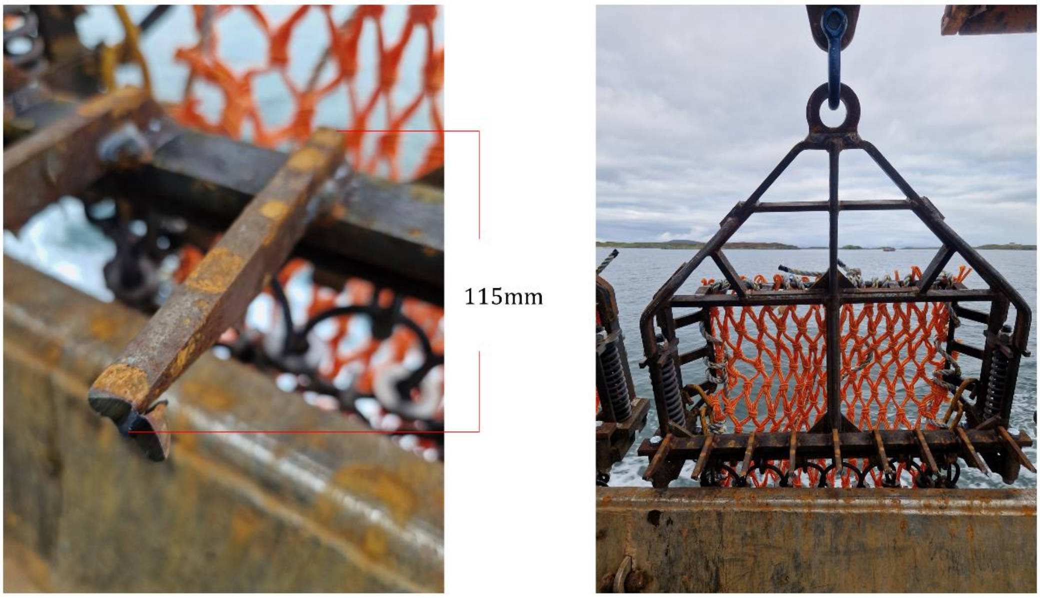


Figure 2.2: The conventional Newhaven dredge mouth. The dredge teeth of length 115mm are shown attached to the spring-loaded bar. (Images credit: Blair Easton).

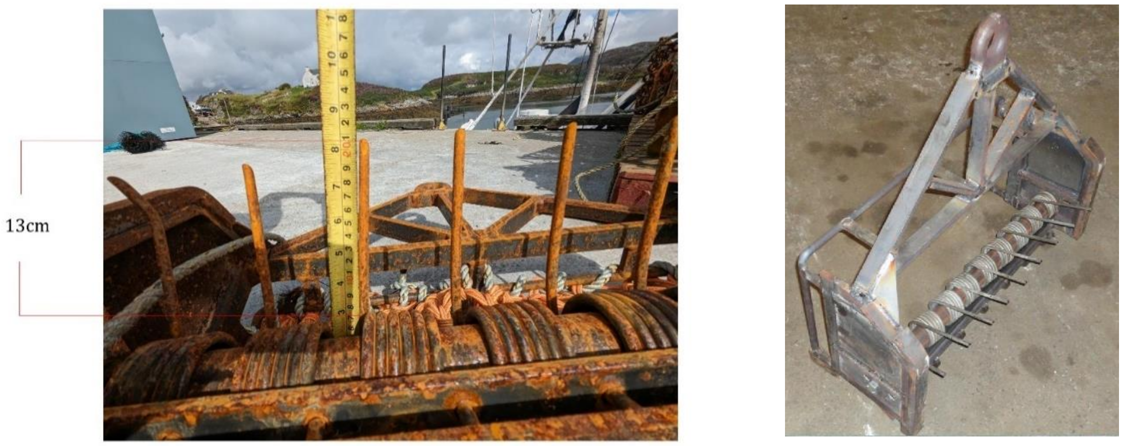


Figure 2.3: The N-virodredge mouth composed of the individual tines wrapped around the tine bar to act as a spring. The N-virodredge mouth also has skids built into its frame on either side of the mouth. (Image credit: left - Blair Easton, right – Filippi, 2013).

2.2 The Retaining Belly Bag

The conventional retaining belly bag typically used by the industry consists of a belly section made up of interlocking metal rings (internal diameter 75 - 85 mm depending on national jurisdiction) and a heavy netting top and rear section (diamond stretched mesh aperture 100mm) (Figure 2.4.a). A typical belly bag is 7 rings across and 9 rings deep with either 5 or 7 row backs dependant on the fishers' preferences and is about 97cm long by 77cm wide and weighs 53 kg (excluding the weight of the nylon netting that is used on the top side of the bag) (Table 2.1).The modified retaining belly bag has two skids attached on a steel frame, therefore lifting the bag off the seabed by a height of 13.5cm (Figure 2.4.b). The skid frame is made from EN 1025 mild steel and the skids are made from EN 16T and case hardened. The steel frame is 73cm long by 72cm wide and is welded to the underside of the chain mail belly bag. It bears two brackets of 44cm length that allow the skids to be bolted on allowing ease of replacement once worn. A brand-new skid is 40mm in width, 40.1cm in length, and around 20mm in height (Figure 2.4.C). The weight of the skid belly bag is 57kg (excluding the weight of the nylon netting that is used on the top side of the bag).

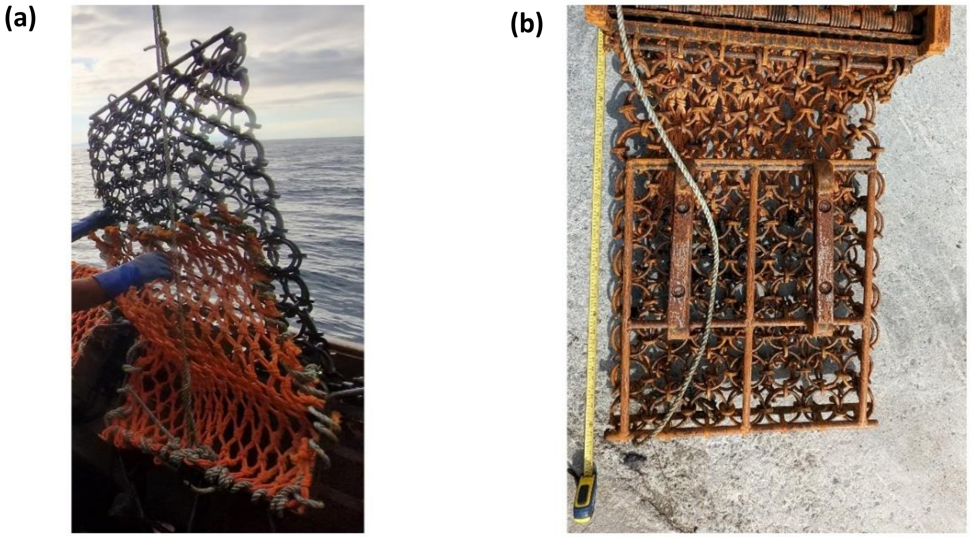


Figure 2.4: (a) A conventional retaining belly bag with interlocking metal rings; (b) modified retaining belly bag with skid frame attached, shown is a brand-new (grey in colour) skid central of the frame and on either side a worn skid after 30 hauls.

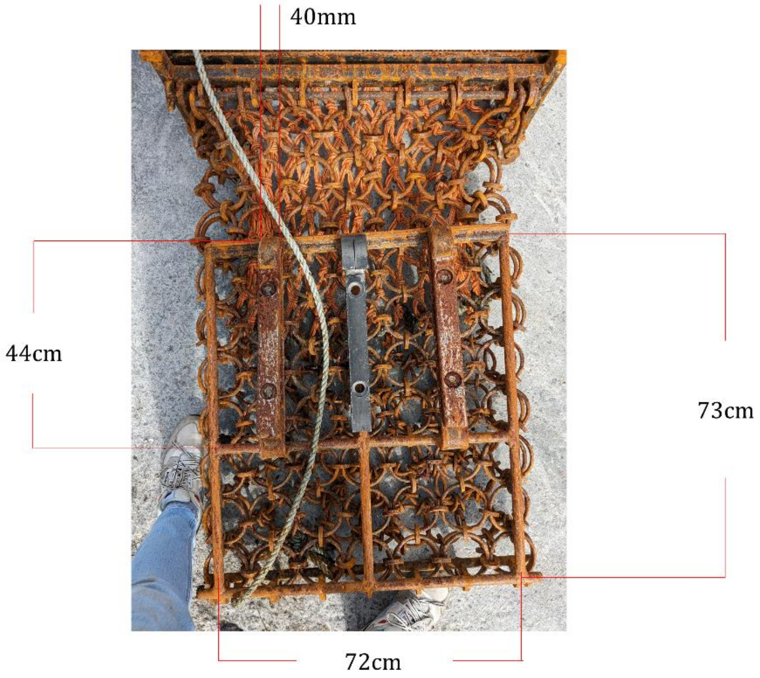


Figure 2.4.(c) Skid frame attached to the retaining belly bag. Included is the comparison of a brand new skid to two used skids. Dimensions of the skid frame and skids are included.

3 WP1 – Comparison of catch

3.1 Objective

WP1 delivers knowledge on the economic viability and the ecological benefits of the modified gear by collecting data on catch of market-size scallops and undersized scallops, catch of bycatch and stones for the three scallop dredge innovation technologies relative to the conventional Newhaven dredge.

3.2 Methods

3.2.1 Survey location and vessel characteristics

Over the course of August (2nd to 27th) 2023, field trials were conducted in the Outer Hebrides on the West coast of Scotland (Figure 3.1.a). Permission to carry out scientific gear trials using modified scallop dredge gear in Scottish waters was obtained from Marine Scotland prior to the start of the surveys. Surveys took place across a variety of sediment types on the East coast of the archipelago, ranging from a mixture of sand and finer sediment (Figure 3.1.b) to a mixture of coarse sand, cobbles and boulders (Figure 3.1.c & Figure A3(appendix)). Sampling took place between Loch Maddy and Stuley Island which is closed to scallop dredging between the 1st of March to the 30th of April and between the 25th of August and 31st of October. Hence, the sampling period concluded before the closed season. All sampling took place on MFV Valaura, which is a 6-aside scallop dredger and based at Kallin harbour, North Uist (57°28'52.6"N 7°12'18.7"W).

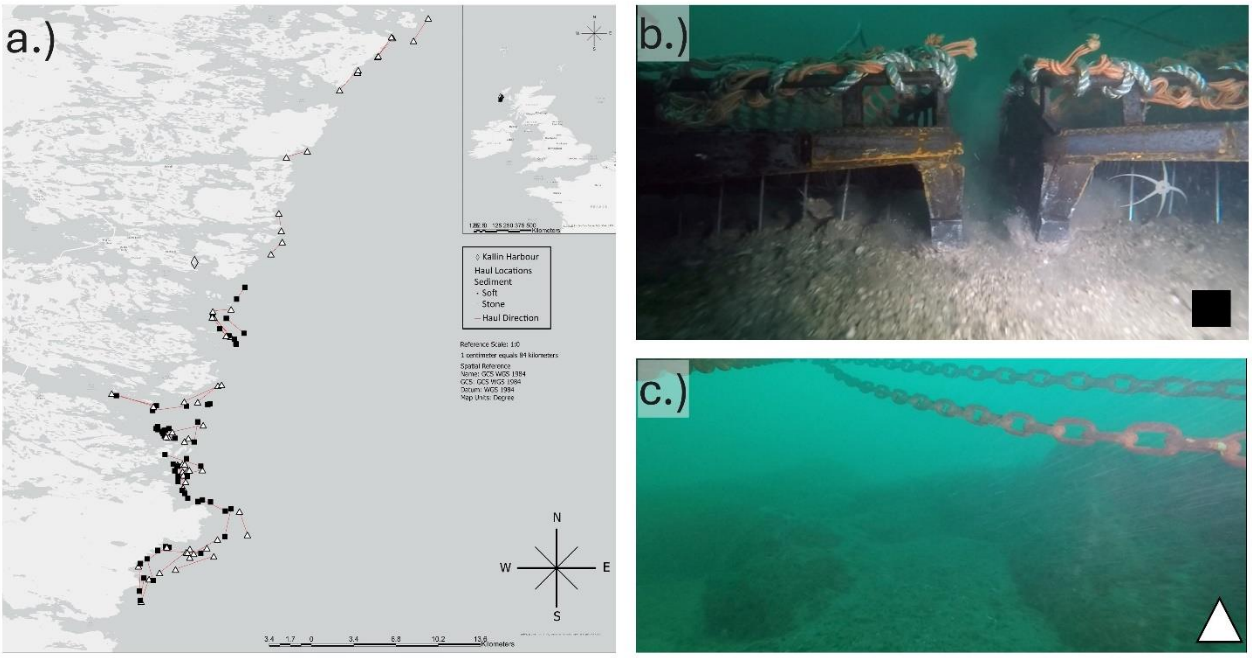


Figure 3.1 (a) Map of all the locations fished during the August field trials. An example of seabed made up of a mixture of sand and finer sediment is shown in (b) and its location is indicated by a black square in (a). An example of seabed made up of a mixture of coarse sand, cobbles and boulders is shown in (c) and is indicated by white triangles in (a).

3.2.2 Experimental design

In total, 61 thirty-minute hauls were carried out; 30 hauls using the N-virodredges and the other 31 using the Newhaven dredges. For each haul, a paired-tow experimental design was adopted whereby the dredge with the 'standard belly bag' was towed on the starboard side of the vessel and the modified 'skid belly bag' was towed on the portside of the vessel (Figure 3.2). This paired gear design was adopted to avoid introducing confounding effects in the data due to variation in sea-state and tidal conditions, towing speed and warp length between different tows and different survey days. There are key operational difference between the Newhaven dredge and the N-virodredge, therefore replicate hauls were first conducted with the N-virodredge gear, before swapping to the Newhaven dredge gear. To prevent gear entanglement during towing, the skipper paid out more cable (5 – 10 m) on one side than the other. To minimize bias and potential errors in catch data related to warp length, the side with the extra cable was alternated between successive hauls. GPS co-ordinates and time were recorded at the start (when the gear hit the seabed) and end (when gear left the seabed) of each tow. Depth, sea state, and the warp length of the dredge cables were also recorded (Table 3.1).

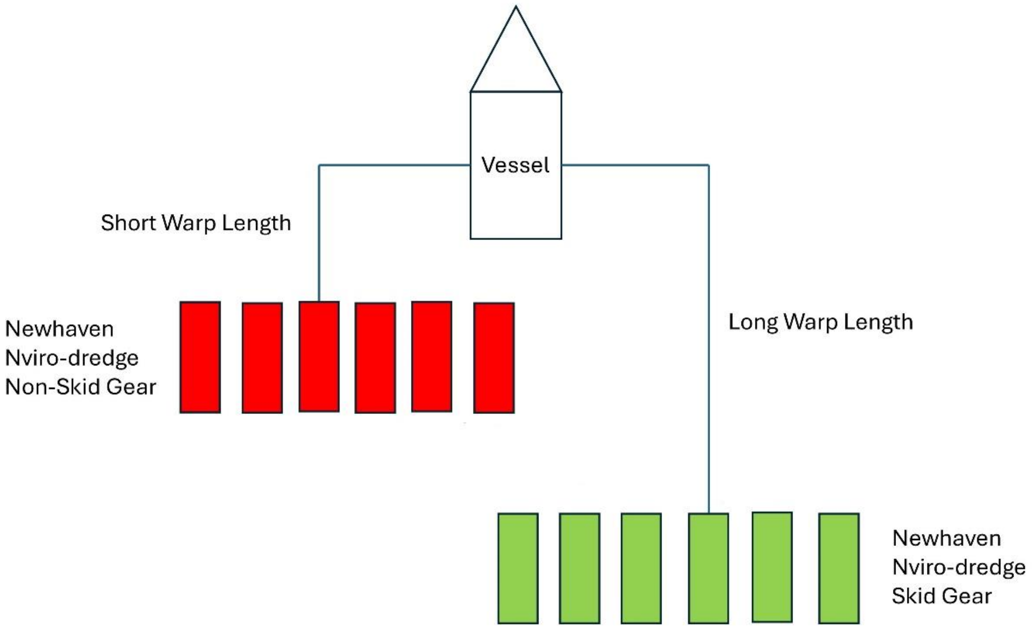


Figure 3.2 Paired-tow experimental design to compare catch of market-sized scallops, undersized scallops, by-catch and stones among the four scallop dredge variations. Warp length was alternated between port and starboard side with each fishing haul. Operational differences between the Newhaven and N-virodredge prevented an experimental design in which both gears were used at the same time.

Table 3.1 Operational and environmental characteristics of the fishing activity for the scallop dredge designs used. Skid variations have been grouped by the dredge mouth used. Mean ± SE values are provided for towing speed, water depth and sea state data.

Gear Type	No. of Hauls	Towing speed (knots)	Depth (m)	Sea state
Newhaven	31	2.14 ± 0.02	36.4 ± 1.29	2.26 ± 0.22
Nviro	30	1.98 ± 0.01	31.8 ± 0.96	2.13 ± 0.21

After each haul, the dredges were pulled on to the side of the vessel and contents were emptied onto the deck of the vessel. In the appendix, Table A1 to A5 relate to the recording sheets used to the collect data described. The catch was sorted into *Pecten maximus*, bycatch, and stone/debris. The scallops were sorted further into those below the minimum landing size of 105mm (undersized scallops) and those above (market-size scallops). A standard fish measuring board and calipers were used to measure scallop length (mm). For hauls that caught a large volume of *P. maximus* individuals, a subset of 90 individuals was randomly selected for length measurements. The biomass of undersized scallops (<MLS) and market-size scallops (>MLS) was weighed separately to give a total biomass value per gear type. All bycatch species were identified to the lowest possible taxonomic level (Appendix; Table A6, Figure A1, and Figure A2) and morphometric measurements, length (mm) and weight (g) were recorded. Furthermore, each individual was assigned a damage score as described in Table 3.2 to determine the level of injury sustained during the fishing operation. Once the measurements were recorded, the bycatch species and undersized scallops were released back to sea. Scallops above the minimum landing size were retained by the fishermen. The weight of stones and debris were also recorded for each gear type to provide the total weight value (kg) per haul. The total weight of scallops and stones was recorded using a hand weighing scale (Meilen Fish Scale (110lb/50kg)), whereas total weight of bycatch was recorded using Marel M1100 15-30 kg (5-10 g) weighing scale.

Table 3.2 Description of damage score assigned to each bycatch individual retained across the sampling period. Damage scores for *P. maximus* individuals were those described for bivalves. (Adapted from Jenkins et al. 2001).

	Damage Score 1	Damage Score 2	Damage Score 3	Damage Score 4
Crabs	No damage	Pereiopods missing/small carapace cracks	Major carapace cracks	Crushed/dead
Starfish	No damage	Arms missing	Minor disc damage/ arm damage/worn	Major disc damage/ dead
Urchins	No damage	<50% spine loss	>50% spine loss/minor cracks	Crushed/dead
Whelks	No damage	Edge of shell chipped	Shell cracked or punctured	Crushed/dead
Bivalves	No damage	Edge of shell chipped	Hinge broken/large cracks	Crushed/dead

3.2.3 Data analyses

Comparison of scallop, bycatch and stone catches

Catch of scallop, bycatch (any live organisms other than scallops) and stones was compared for the four dredge types. *P. maximus* data was separated into two size classes (undersized and marketable) which relate to the individuals below the minimum landing size (105mm) and above (>105mm). Raw biomass (kg) values taken from the onboard observations were standardised by haul duration (minutes). Two metrics were used to compare catches using a two-tiered approach; (i) the Standardized biomass, to compare catches between Newhaven dredge and N-virodredge variations, irrespective of belly bag type, and (ii) ln-transformed response ratio (lnRR), to compare catches between skid belly bags and standard belly bags for each dredge type (Newhaven and N-virodredge). LnRR was calculated by dividing biomass collected using skid belly bags by biomass collected using standard belly bags, and transformed using the natural log to provide a relative response ratio (lnRR). Positive lnRR values indicate a higher biomass in skid belly bags relative to standard belly bags, whereas a negative lnRR value indicate lower biomass in dredges with skid belly bags.

$$lnRR = ln\left(\frac{Biomass\ of\ Skid}{Biomass\ of\ Standard}\right)$$

LnRR uses the paired-tow data, thereby minimizing the risk of bias due to variation in sea-state and tidal conditions, operation conditions and patchiness in scallop abundance on the ground. It would have been inappropriate to compare the Standardized biomass (kg per haul) across all 4 dredge variations (Newhaven, Newhaven-skid, N-virodredge, Nviro-skid) in one statistical model as data for N-virodredge and Nviro-skid, and for Newhaven and Newhaven-skid are not independent replicate hauls due to the paired-tow design.

Generalised linear models (GLMs) were used to assess environmental and operational parameters that could influence catches. Two models were tested:

Model 1

Standardized biomass (kg per haul) = Gear type x Stone

where

- *Gear Type*: compared Newhaven dredge and N-virodredge variations
- *Stone: Normalised standardised Stone Weight*. The amount (kg) of stone hauled was used as an indicator of the ground type at each haul location. For each haul, the standardised weight of stone was calculated based on the tow duration, and normalized between 0 and 1 using (X-X_{min} / X_{max} – X_{min}) to compensate for the fact that Newhaven dredges caught substantially more stones than N-virodredges

Model 2

LnRR = Gear type x Stone + WL

where

- *Gear Type*: compared catch differences between skid and standard belly bags for Newhaven dredge and N-virodredge variations
- *Stone: Normalised standardised Stone Weight (as above)*
- *WL* is *Warp length (short or long).* This factor was included in the model to determine whether scallop catch was influenced by the amount of cable paid out for the scallop dredges.

A significant interaction term suggests that catch differences between gears varied notably based on ground type. Interaction terms in the models were examined, and any terms with a variance inflation factor (VIF) greater than 3 were removed. All combinations of the explanatory variables were tested and ranked by the Akaike Information Criterion (AIC). The best ranked model, and all models within two AICc values, were selected using the R packages 'arm' and 'MuMIn'. All models were inspected for normality of residuals using the Kolmogorov–Smirnov test and a Q-Q plot. Cook's distance identified influential outliers, while heteroscedasticity was tested using the Levene's test and scatter plots of the standardized residuals, fitted values and all covariates were assessed. Overdispersion was checked before applying Poisson models; if overdispersed (n >1), a negative binomial model was used instead. All statistical analysis was conducted using 'RStudio' (version 0.06.2023 Build 421). A significance value of $p = 0.05$ was used to indicate any significant difference from the null hypothesis.

Comparison of scallop size selectivity

To determine if the dredges caught significantly more or less scallops of any given length class a catch comparison analysis was undertaken using the 'selfisher' package in R (Brooks and Melli, 2022). The scallop length data was grouped into 10mm categories to increase the numbers within each size class at the extreme ends of the size-class spectra examined. The number of scallops of each length class was calculated.

The catch comparison analysis modelled the relative retention as a 4th-order polynomial, plus a spline with 5 degrees of freedom using the 'splines' package. Model selection was performed using AIC (Akaike Information Criterion) values to determine the best fit. Response ratios were predicted, with bootstrapped confidence intervals using the 'predict' and 'bootSel' functions from 'selfisher' (Brooks and Melli, 2022).

3.3 Results

3.3.1 Scallop catch yield

Market-size scallops (>MLS)

Catches of market-size scallops were variable, but on average catches were higher for Newhaven dredge (35.5 ± 2.9 kg / haul) than for N-virodredges (26.9 ± 1.9 kg / haul), and catches increased significantly on stonier grounds for both dredge types (Figure 3.3 a, Table 3.3a). The use of skid belly bags improved catch performance for both dredges relative to the conventional belly bag; with an average increase of 19% when a skid belly bag was used with N-virodredge (lnRR = 0.18 ± 0.06), and 14% increase when a skid belly bag is used with Newhaven dredge (lnRR = 0.13 ± 0.05) (Figure 3.3b, Table 3.4a).

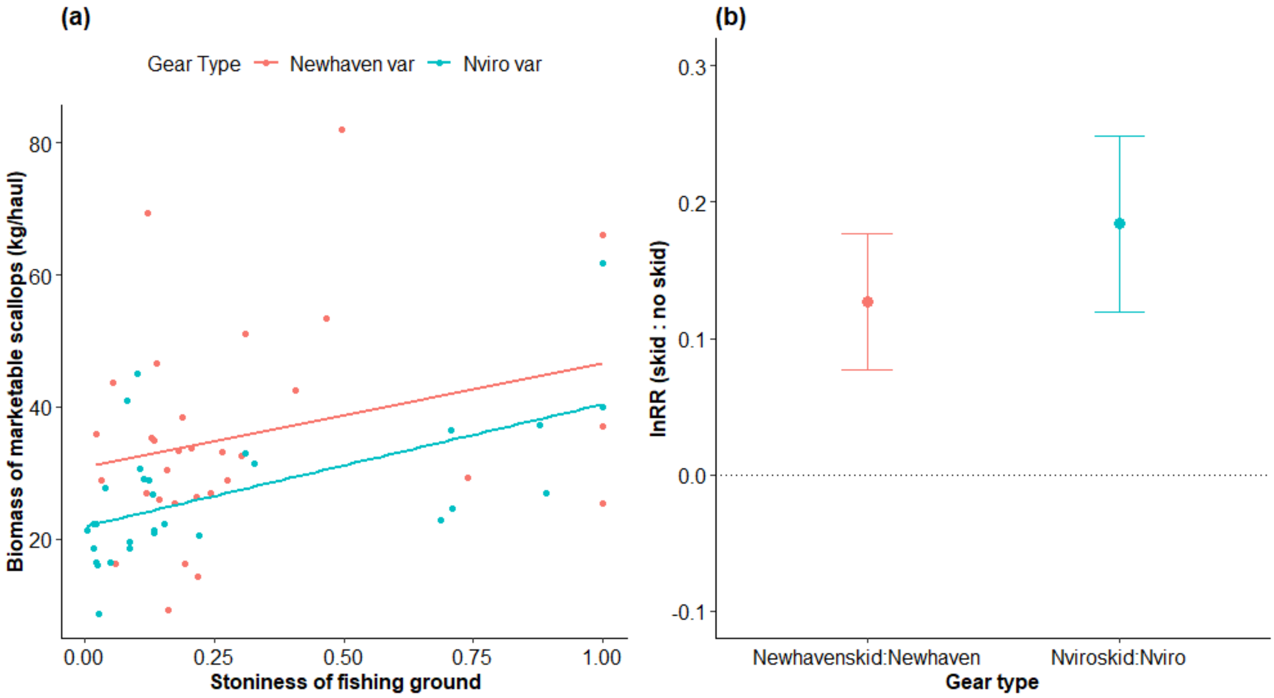


Figure 3.3 (a) Standardised biomass (kg/haul) of market-size *P. maximus* (>105mm, MLS) separated for Newhaven (orange) and N-virodredges (green) in different ground types, (b) The relative catch (lnRR) of market-size scallops comparing skid belly bags vs. standard belly bags for Newhaven (orange) and N-virodredge (green). The horizontal dashed line in (b) represents equal catches of *P. maximus* (skid vs. non-skid). Positive lnRR represents larger catches of *P. maximus* in scallop dredge designs with skids compared to non-skid designs. Confidence intervals (95%) that do not overlap the lnRR = 0 line represent significant differences.

Undersized scallops (<MLS)

Catches of undersized scallops were significantly lower for N-virodredges (3.5 ± 0.5 kg / haul) than for Newhaven dredges (6.1 ± 0.8 kg / haul) across all ground types (Figure 3.4a, Table 3.3b). On stonier ground, the N-virodredges with skid belly bags caught significantly lower catches of undersized scallops than those with conventional belly bags, but significantly higher catches of undersized if fishing with Newhaven dredge skid bellies (Figure 3.4b, Table 3.4b).

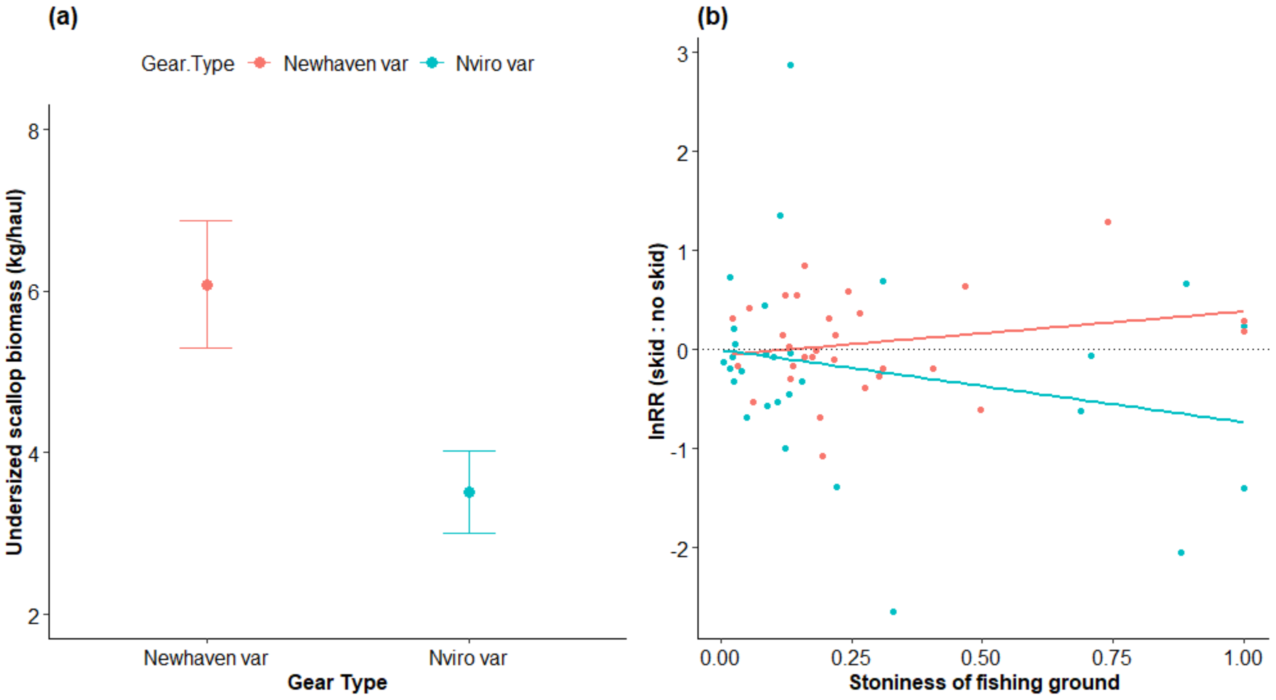


Figure 3.4 (a) Standardised biomass (kg/haul) of undersized *P. maximus* (<105mm, MLS) separated for Newhaven and N-virodredges in different ground types, (b) The relative catch (lnRR) of undersized scallops comparing skid belly bags vs. standard belly bags for Newhaven and N-virodredge. The horizontal dashed line in (b) represents equal catches of *P. maximus* (skid vs. non-skid). Positive lnRR represents larger catches of *P. maximus* in scallop dredge designs with skids compared to non-skid designs. Negative lnRR represents lower catches of *P .maximus* in dredge designs with skids. Confidence intervals (95%) that do not overlap the lnRR = 0 line represent significant differences.

3.3.2 Stones catch

Newhaven dredges (59.4 ± 14.9 kg/haul) caught significantly more stones than N-virodredges (19.5 ± 4.9 kg/haul) - on average three times more (Figure 3.5a, Table 3.3c). Dredges with skid belly bags collected significantly more stones than standard belly bag for Newhaven dredge, but not for N-virodredge (Figure 3.5b, Table 3.4c).

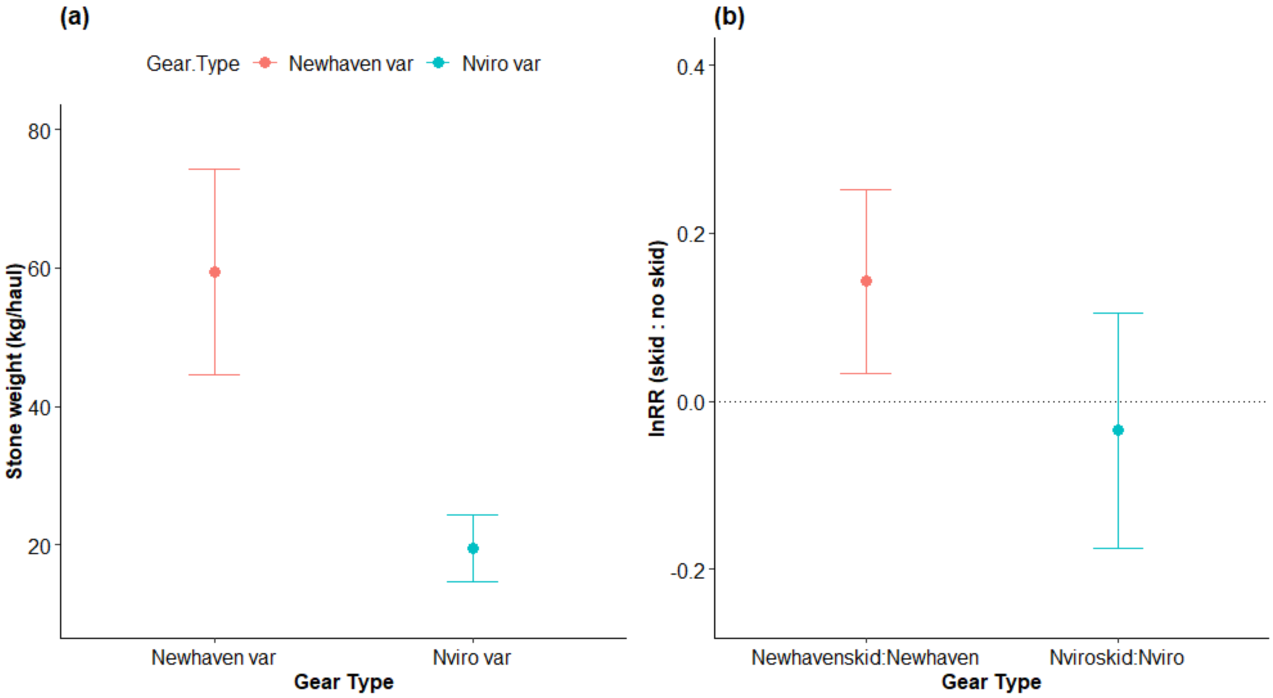


Figure 3.5 (a) Standardised weight (kg/haul) of stones separated for Newhaven and N-virodredges in different ground types, (b) The relative catch (lnRR) of stones comparing skid belly bags vs. standard belly bags for Newhaven and N-virodredge. The horizontal dashed line in (b) represents equal catches of *P. maximus* (skid vs. non-skid). Positive lnRR represents larger catches of *stones* in scallop dredge designs with skids compared to non-skid designs. Negative lnRR represents lower catches of *stones* in dredge designs with skids. Confidence intervals (95%) that do not overlap the lnRR = 0 line represent significant differences.

3.3.3 Bycatch fauna

The bycatch composition across all scallop dredge designs primarily comprised *Luidia ciliaris* (22.2%), *Cancer pagurus* (22.9%), *Marathasterias glacialis* (13.6%), *Echinus esculentus* (10.3%) and *Asterias rubens* (9.9%) equating to 81.9% of the overall bycatch species retained. Biomass of by-catch was higher for stonier grounds irrespective of whether a Newhaven dredge or N-virodredge was used (Figure 3.6a, Table 3.3d). Skid belly bags caught more by-catch than standard belly bags, and this difference was more pronounced for N-virodredge (lnRR = 0.54 ± 0.13, 72% higher in skid bellies) than Newhaven dredge (lnRR = 0.25 ± 0.09, 28% in skid bellies) (Figure 3.6b, Table 3.4d).

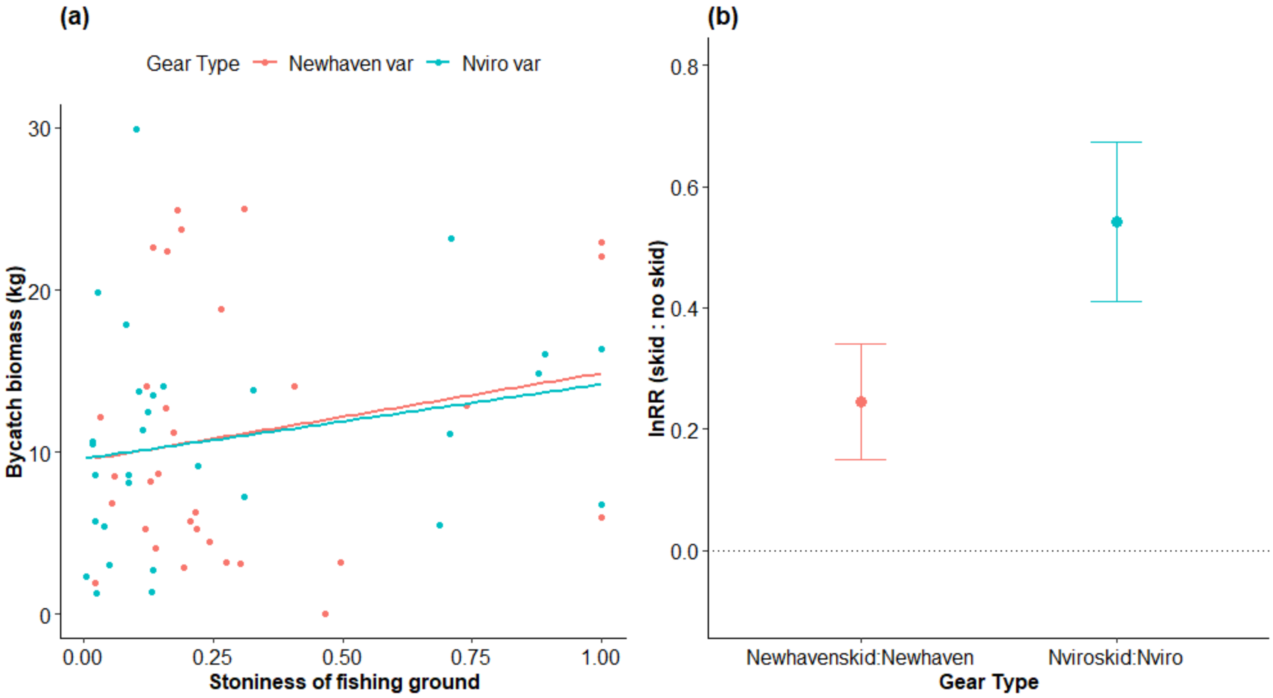


Figure 3.5 (a) Standardised biomass (kg/haul) of by-catch separated for Newhaven and N-virodredges in different ground types, (b) The relative catch (lnRR) of by-catch comparing skid belly bags vs. standard belly bags for Newhaven and N-virodredge. The horizontal dashed line represents equal catches (skid vs. non-skid). Positive lnRR represents larger catches of *by-catch* in scallop dredge designs with skids compared to non-skid designs. Confidence intervals (95%) that do not overlap the lnRR = 0 line represent significant differences.

Table 3.3 The estimated parameters, standard error, t-value and p-values for the best fitted generalised linear model comparing the standardised weight (kg/haul) of scallop catch, by-catch and stones between the Newhaven and N-virodredges.

Standardized Weight (kg/haul)	Parameters	Estimate	Std.Error	t.value	P.value
(a) Market-size scallops (> MLS)	(Intercept)	30.33	2.77	10.94	<0.001
	Gear (N-virodredge var)	-8.17	3.24	-2.52	0.015
	Stone	17.40	5.39	3.23	0.002
(b) Undersized scallops (< MLS)	(Intercept)	6.08	0.66	9.19	<0.001
	Gear (N-virodredge var)	-2.57	0.94	-2.73	0.008
(c) Stones	(Intercept)	59.40	11.12	5.34	<0.0001
	Gear (N-virodredge var)	-39.85	15.86	-2.51	0.015
(d) Bycatch	(Intercept)	9.54	1.27	7.54	<0.001
	Stone	4.94	3.06	1.62	0.11

Table 3.4 The estimated parameters, standard error, t-value, and p-values for the best fitted generalised linear model comparing the lnRR (relative catch) of scallop catch and by-catch for the Newhaven and N-virodrege.

LnRR	Parameters	Estimate	Std.Error	t.value	P.value
(a) Market-size scallops (> MLS)	(Intercept)	0.16	0.04	3.84	<0.001

(b) Undersized scallops (< MLS)	(Intercept)	-0.06	0.21	-0.27	0.79
	Gear (Nviro)	0.05	0.28	0.19	0.85
	Stone	0.44	0.58	0.75	0.46
	Gear:Stone	-1.17	0.74	-1.58	0.12
(c) Stones	(Intercept)	0.06	0.09	0.71	0.48
(d) Bycatch	(Intercept)	0.25	0.11	2.14	0.04
	Gear (Nviro)	0.29	0.16	1.83	0.07

3.3.4 Scallop size selectivity

The size of the *P. maximus* individuals collected ranged from 61 – 162mm (Newhaven), 63 – 185mm (Newhaven-skid), 54 – 196mm (N-virodredge), and 51 – 204mm (Nviro-skid), respectively (Table 3.5). As the scallop population size composition might differ among fishing grounds due to varying natural recruitment patterns, we discourage direct comparison of number of scallops in different size classes among the four dredges. However, size frequency distribution shown in Figure 3.7 indicates that undersized scallops are more frequent in the catch of Newhaven dredge and Newhaven-skid dredge than for N-virodredge and Nviro-skid.

Catch comparison modelling was used to test the difference between the modified and Newhaven dredges using all *P. maximus* individuals caught (Figure 3.8). Newhaven dredges with skids caught significantly more individuals within the size class of 110 to 120mm compared to Newhaven dredges, whereas N-Virodredges caught significantly less individuals in the 95 to 120mm size class, and N-Virodredges with skids caught significantly less individuals in the 100 to 115mm size class, all represented by the confidence intervals sitting above and below 1 (Figure 3.8). There is low confidence in the modelled catch ratio at either end of the size spectrum due to the low numbers of very small and very large scallops that were caught, hence catch ratio values at the extreme ends of the size spectrum should be interpreted with caution.

Table 3.5 Range of *P. maximus* individuals by size (mm) for all four scallop dredge designs. Data has also been presented as mean ± SE.

	Total		
	Min (mm)	Max (mm)	Mean ± SE
Newhaven	61	162	116.33 ± 0.25
Newhaven-skid	63	185	116.88 ± 0.23
N-viro	54	196	118.40 ± 0.32
Nviro-skid	51	204	119.45 ± 0.29

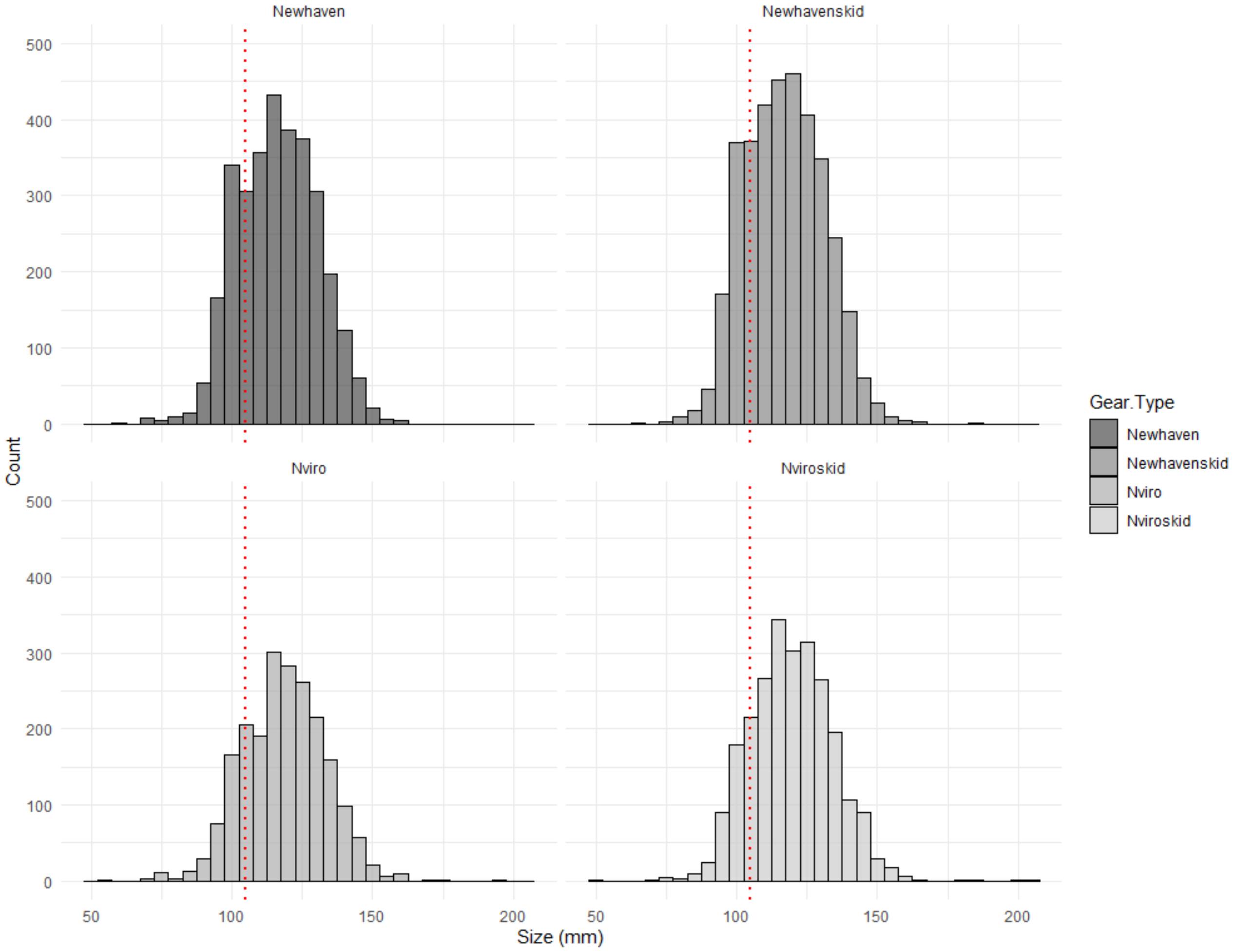


Figure 3.7 Size frequency distribution of *P. maximus* caught across by the four gear types. The red dashed vertical line represents the minimum landing size of *P. maximus* in Scotland (105mm).

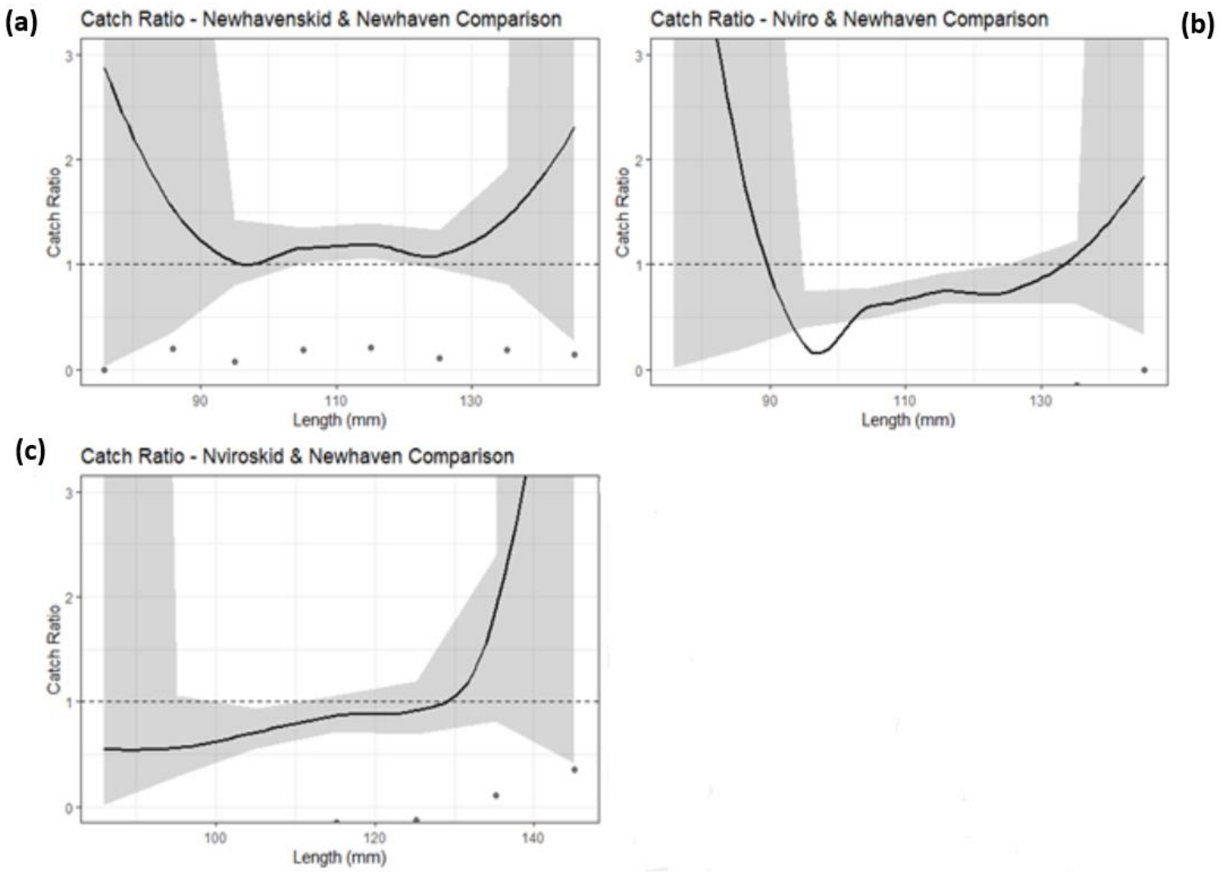


Figure 3.8 The modelled catch ratio showing difference between the modified dredges and standard dredge across different scallop size classes for *P.maximus*. (a) Comparison of Newhaven-skid vs Newhaven dredge, (b) Comparison of N-virodredge vs Newhaven dredge, (c) Comparison of Nviro-skid dredge vs Newhaven dredge. The catch ratio is calculated as the ratio of catches between the modified and standard gear. The horizontal dotted line, located at catch ratio = 1, indicates equal catches for modified gear and Newhaven dredges. The grey band indicates the 95% confidence intervals, significant differences between modified gear and Newhaven dredges occur when the grey band does not overlap the horizontal dotted line (equal catches across dredge designs).

4 WP2 – Bycatch damage and survivability

4.1 Objective

To assess physical damage and evaluate the survival rate of undersized scallops and other bycatch species (e.g. starfish, crabs, urchins) among the four dredge types. It is expected that injury and survivability will be species-specific and correlated to the quantity of stone and detritus collected in belly bags. Larger quantities of stone inside the bellies are expected to cause higher species damage. The survival of species with varying vulnerability to trawling (e.g., soft- vs. hard-shelled organisms) and differing regeneration capacities (e.g., starfish) will be assessed over a seven-day period at an on-land processing facility.

4.2 Methods

WP2 evaluated the damage and survival rate of undersized scallops and invertebrates (e.g. starfish, crabs, urchins) caught during fishing operation using two assessment methods:

- **(a) Injury assessment** – assesses damage and injury level incurred bycatch during the fishing and on-board handling practice,

(b) Survival experiment - assesses the survival capacity of bycatch animals that have sustained different levels of injury and damage (as determined by the Injury assessment).

4.2.1 Data collection for fauna injury assessment

Fauna was collected as described in section 3.2.2. Injury to individual organisms was visually assessed based on a 4-point damage scoring system reported in Jenkins et al. 2001, where 1 denotes no injuries, 2 and 3 denotes some level of injury and 4 denotes a dead organism (Table 4.1, Figure 4.1). In the appendix, Tables 2A to 2D pertain to the recording sheets used to collect data for WKP2, as described in this section.

Table 4.1 Description of damage score assigned to each bycatch individual retained across the sampling period. Damage scores for *P. maximus* individuals were those described for bivalves. (Adapted from Jenkins et al. 2001).

	Damage Score 1	Damage Score 2	Damage Score 3	Damage Score 4
Crabs	No damage	Pereiopods missing/small carapace cracks	Major carapace cracks	Crushed/dead
Starfish	No damage	Arms missing	Minor disc damage/ arm damage/worn	Major disc damage/ dead
Urchins	No damage	<50% spine loss	>50% spine loss/minor cracks	Crushed/dead
Whelks	No damage	Edge of shell chipped	Shell cracked or punctured	Crushed/dead
Bivalves	No damage	Edge of shell chipped	Hinge broken/large cracks	Crushed/dead

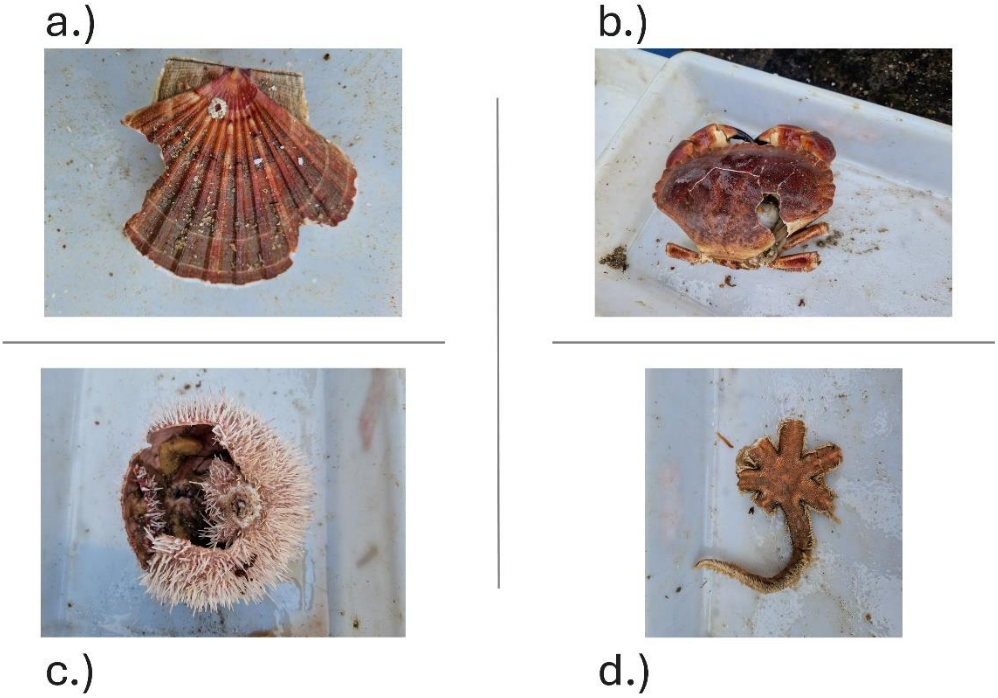


Figure 4.1 Representation of damage indices 3 – 4 for bivalves, crabs, sea urchins and starfish. Shown is a *P. maximus* (a) individual with a damage score of 3, *Cancer pagurus* (b) individual with a damage score of 3,

Echinus esculentus (c) individual with a damage score of 4, and a *Luidia ciliaris* (d) individual with a damage score of 3.

4.2.2 Data collection for survival experiment

The Outer Hebrides

Over the course of May (13th to 18th) 2024, fieldwork was conducted in the Outer Hebrides on the West coast of Scotland. Specifically, surveys took place across the East coast of Uist (Figure 4.2). The seabed varied greatly, with a mixture of sand and finer sediment to rock and harder material. All sampling took place on MFV Valaura based at Kallin harbour, North Uist (57°28'52.6"N 7°12'18.7"W).

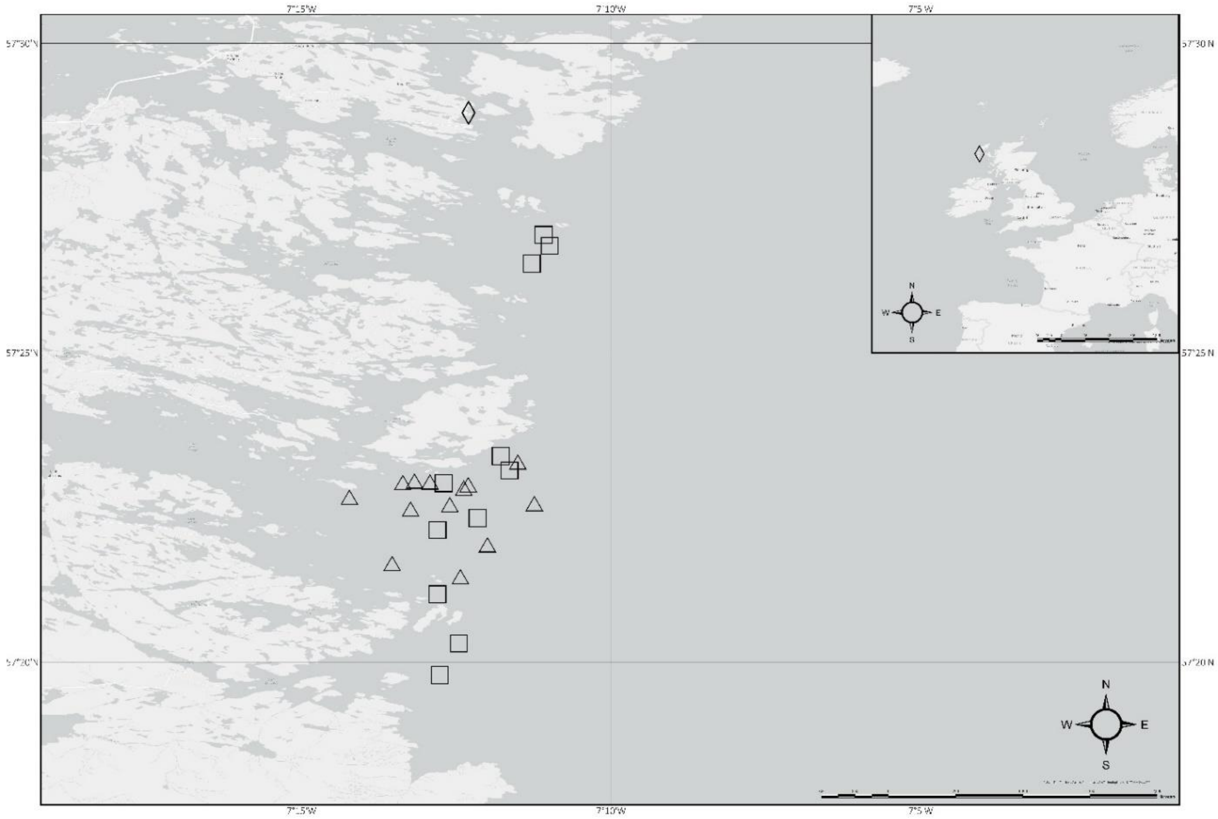


Figure 4.2 Map of all the locations fished during the May 2024 fieldwork. The data points are separated by the gear type used - Newhaven gear hauls are represented by the triangles and N-virodredge gear are represented by the squares.

Experimental Design

Catch survival was compared between Newhaven dredges and N-virodredges. In total, 25 hauls of ~60 minutes duration (Nviro; 67mins, Newhaven; 59:55mins) were completed across similar habitat types (soft and hard). Of these hauls, 12 were conducted using the N-virodredges and the other 13 were fished with the Newhaven dredge. Start and end time and position as well as depth, sea state and warp length were recorded for each haul.

Onboard Sampling

After each haul, dredges were pulled alongside the vessel, and contents emptied onto the deck. Biota were sorted into scallops (*Pecten maximus*), bycatch, and stone/debris. Scallops were further classified by size using a standardized gauge; those above the 105mm minimum landing size were retained by fishers. Stones and debris were weighed, and biomass recorded by gear type. Bycatch and undersized *P. maximus* were assigned species-specific damage scores described in Table 4.1. The bycatch species included in this study were *Asterias rubens, Cancer pagurus, Marthasterias glacialis, Luidia ciliaris*, and *Echinus esculentus*, as these composed approximately 90% of the total catch in the study area.

For the survival study, 25 individuals from each damage category (1 to 3) were selected for each of the six study species. In the appendix, Figures 2E to 2J display examples of species with different damage level. During sorting, animals were placed in a deck holding tank with ambient seawater to minimize air exposure. Handling time (sorting duration) and air exposure time (from gear retrieval to tank placement) were recorded (Table 4.2). Individuals were kept at 5°C, which was similar to the bottom seawater temperature, 4.92 ± 0.23°C, at the time of study. Individuals belonging to different species and damage category were kept in separate aerated tanks topped with fresh seawater (Figure 4.2a). Water parameters (temperature and oxygen) were monitored at setup and after the final haul during transit to Kallin Harbour (Table 4.3). Any decline in water quality was addressed, including one case requiring a fresh seawater input due to detritus buildup.

Individuals were tagged with coloured cable ties to indicate gear type and damage index (Figure 4.2b). *Cancer pagurus* were tagged on the last pleopod, starfish around the central disk, and *Echinus esculentus* with a polystyrene ball attached to a spine. Undersized *P. maximus* were placed in labeled baskets in the aquaria facility. Tags were applied to minimize physical stress.

Table 4.2 Bycatch handling time and air exposure time (minutes:seconds) by dredge type. Handling time ended when the last bycatch individual entered the holding tanks in the vessel cold store. Air exposure time was recorded from gear retrieval to the final individual's placement in the deck holding tank. Data is presented as mean ± SE.

	Handling Time	Air Exposure Time
Newhaven	45:37 ± 0.13	34:27 ± 0.08
Nviro-dredge	34:59 ± 0.16	33:17 ± 0.09

Table 4.3 Water parameters (dissolved oxygen (DO), pH, general and carbonate hardness (GH + KH), nitrite (NO2-), nitrate (NO3-) taken from the holding tanks onboard the fishing vessel MFV Valaura. The data is presented as mean ± SE encompassing all recordings during the offshore data collection.

	Dissolved Oxygen (mg/L)	pH	Carbonate Hardness	General Hardness	Nitrite	Nitrate	Ammonia
Tank Parameters	8 ± 1.89	6.4 ± 0	100 ± 0	225 ± 70.16	0.1 ± 0.1	1 ± 1	0.25 ± 0.14

Figure 4.2 (a) The holding tank set-up within the cold store of the fishing vessel, designated for a specific species and damage index. Each holding tank was created from a 42L storage box with a battery-operated airline attached to the lid which provided continuous aeration to the ambient seawater.

Figure 4.2 (b) Identification tagging for damage index and gear type for the bycatch species. The tag was secured across the central disc of *Asterias rubens* to prevent loss from autotomy, while for *Cancer pagurus*, the tag was attached to the last pleopod to reduce visual stimulus and prevent removal from other appendages.

Aquaria – Survivability assessment

At the end of the fishing day, the retained bycatch was transported to Kallin harbour and animals were transferred to the land-based facility, which housed tanks (2.62 x 2.04 x 0.48m, L x W x H) equipped with a flow through seawater system. The seawater supply to the facility was pumped from the sea outside in Kallin harbour, and fresh seawater was cycled through the facility every 2hrs. Air-stones ensured that seawater remained oxygenated at all times. The fully enclosed facility, with no daylight, mimicked the light conditions of the bycatch's natural depth (>40m). Animals caught by Newhaven dredges were kept in separate tanks to those caught by N-virodredges and individuals from different species were also kept separate to reduce the potential for intra-species competition leading to increased stress that may influence the survival rate. Animals were not fed during the 7-day assessment period.

Initially, water parameters were recorded every 12 hours, but after four days, sampling was reduced to once daily as values remained stable (Table 4.4). Measurements were taken using 'Tetra Test 6-in-1 Strips' for pH, general and carbonate hardness (GH + KH), nitrite (NO_2^-), nitrate (NO_3^-), and chlorine (Cl_2). Dissolved oxygen (DO) was intended to be measured with a YSI probe but was instead recorded using 'Tetra Test O_2' due to logistical issues. Tanks were checked for mortalities every 12 hours over the 7-day assessment period.

At each 12-hour interval, dead animals were removed, weighed (kg), and measured (mm) using calipers and rulers. Weights were recorded with a standardized scale (equipment details here). Day and time of death, species, and damage index were also documented. After the 7-day assessment, surviving individuals underwent the same process, with tags removed before release back into the sea.

Table 4.4 Water parameters taken across the survivability assessment periods in the aquaria facility. Data is separated by the dredge gear and presented as mean ± SE.

	Temp (°C)	DO (mg/L)	pH	Ammonia	Nitrite	Carbonate Hardness	General Hardness
Newhaven	8.63 ± 0.06	9.00 ± 0.76	6.62 ± 0.09	0.09 ± 0.07	0.06 ± 0	153.1 ± 43.4	184.4 ± 39.8
N-Virodredge	9.19 ± 0.04	9.29 ± 0.21	6.69 ± 0.09	0.21 ± 0.07	0.06 ± 0	410.7 ± 23.1	89.3 ± 7.4

4.2.3 Data analysis

Injury assessment: Comparison of scallop and bycatch damage

The degree of physical damage that might reduce the commercial value of the market-size scallops and the survivability of undersized scallops and by-catch was examined by calculating the proportion of individuals within each damage score category for each tow. Chi-squared analysis was conducted to assess whether the species-damage level was associated to dredge type.

Furthermore, it was hypothesized that the damage of bycatch was influenced by the quantity of retained stone in the collector bag. Therefore, the relationship between stones and the proportion of animals in each of the four damage categories was examined using the model:

$$\mathrm{Pr}\,oportion = Species * Damage\ Index + Damage\ Index *\ Stone\ (Log10)$$

Where

- *Damage Index:* Damage index was separated into four levels based on severity; 1 = no damage, 2 = minor cracks/damage, 3 = loss of limbs/major cracks, 4 = crushed/dead,
- *Stone(Log10):* $\log_{10}$-transformed standardized stone weight,
- *Species:* referes to different taxonomic groups.

A significant positive Stone * Damage Index interaction term suggests that fauna damage becomes higher as volume of stones inside the belly bag increases. A significant Species * Damage interaction term suggests that fauna damage is species-specific. Interaction terms in the models were examined, and any terms with a variance inflation factor (VIF) greater than 3 were removed. All combinations of the explanatory variables were tested and ranked by the Akaike Information Criterion (AIC). The best ranked model, and all models within two AICc values, were selected using the R packages 'arm' and 'MuMIn'. All models were inspected for normality of residuals using the Kolmogorov–Smirnov test and a Q-Q plot. Cook's distance identified influential outliers, while heteroscedasticity was tested using the Levene's test and scatter plots of the standardized residuals, fitted values and all covariates were assessed. Overdispersion was checked before applying Poisson models; if overdispersed (n >1), a negative binomial model was used instead. All statistical analysis was conducted using 'RStudio' (version 0.06.2023 Build 421). A significance value of $p = 0.05$ was used to indicate any significant difference from the null hypothesis.

Survivability experiment: Comparison of species survival rates

Data was organised to create a data table that included the morphometric measurements, species classification, gear type, damage index of each individual and the time of death. Every individual was assigned a status value: 0 for survivors and 1 for mortalities.

Chi-Square tests were used to assess the association between damage and the categorical factors gear type (Newhaven vs N-virodredge) and size of the individuals (mm). The tests determined whether greater damage was associated with a particular gear type and whether size influenced the extent of damage sustained during the fishing operation. Individuals were categorized into 'small' and 'big' based on the median size for each species, with those below the median classified as 'small' and those above classified as 'big'.

Kaplan Meier survival curves are a non-parametric test that are used to assess the survival function over time for descriptive survival analysis, in this case for groups based on species and gear type. The status value (also known as censoring) assigned to each individual was incorporated to account for individuals that died after the assessment period. The test calculates survival probability at specific time points and examines how survival probability varies based on gear type, damage index, and species. Differences between survival curves were assessed using a post hoc log-rank test. Cox proportional hazard models are semi-parametric regression models that estimate the effect of multiple variables on survival time. These models assess the risk of death based on a hazard ratio (HR) which show how different factors (e.g., species, gear type, damage level) influence the risk of mortality. A HR>1 indicates an increased risk of mortality whilst HR<1 indicates a reduced risk of mortality.

4.3 Results

4.3.1 Injury assessment: Fauna damage

The majority of scallops experienced minor injuries (damage index = 2). A strong association between the scallop damage and the scallop dredge gear designs was found (Chi square test, $\chi^2 = 247.98$, $p < 0.05$), with the Nivro-skid design associated with higher numbers of individuals with lower levels of damage (D1 = 21.74%) and Newhaven dredge with relatively less individuals with no damage (D1 = 8.8%) (Table 4.5).

Table 4.5 Chi-square test statistics for *P. maximus* in each damage index score (D1 – D4) separated by gear type. Shown are the observed, expected and chi-square contribution values. Proportion of catch (%) - The proportion of scallops (in %) with low (scores 1 and 2) and high (3 and 4) damage caught by the four dredge types (Newhaven, Newhaven-skid, N-viro, Nviro-skid).

Damage Score	Dredge type	Observed Count	Expected Count	χ^2 contribution, (% contribution)	Proportion of catch (%)
D1	N-viro	373	300.5	4.2, (7.1)	17.6
	Nviro-skid	537	350.6	9.9, (39.9)	21.7
	Newhaven	277	449.5	-8.1, (26.7)	8.8
	Newhaven-skid	421	507.4	-3.8, (5.9)	11.8
D2	N-viro	1694	1768.9	-1.8, (1.3)	80.0

Damage Score	Dredge type	Observed Count	Expected Count	χ^2 contribution, (% contribution)	Proportion of catch (%)
	Nviro-skid	1906	2063.8	-3.5, (4.9)	77.1
	Newhaven	2812	2646.2	3.2, (4.2)	88.8
	Newhaven-skid	3054	2987.1	1.2, (0.6)	85.4
D3	N-viro	28	22.4	1.2, (0.6)	1.3
	Nviro-skid	14	26.2	-2.4, (2.3)	0.6
	Newhaven	32	33.6	-0.3, (0.03)	1.0
	Newhaven-skid	46	37.9	1.3, (0.7)	1.3
D4	N-viro	22	25.2	-0.6, (0.2)	1.0
	Nviro-skid	13	29.4	-3.0, (3.7)	0.5
	Newhaven	46	37.74	1.3, (0.7)	1.5
	Newhaven-skid	54	42.60	1.7, (1.2)	1.5

Bycatch fauna experienced greater impact than scallops, as on average the proportion of dead bycatch (Damage score = 4) and fauna with major damage (Damage score = 3) was 25% and 18%, respectively. Conversely, the proportion of scallops in damage scores 4 and 3 were only 1.3% and 1.1%, respectively (Tables 4.5, 4.6). No association between dredge type and bycatch damage was found (Chi-square test, $\chi^2(9) = 7.65$, $p = 0.57$) (Table 4.6). However, the damage inflicted on the retained bycatch varied by ground type. For example, in soft sediment, N-virodredge and Nviro-skid resulted in a higher proportion fauna with lower damage (~45%) than Newhaven dredge and Newhaven-skid (~25%) (Figure 4.3).

Table 4.6 Chi-square test statistics for *bycatch* in each damage index score (D1 – D4) separated by gear type. Shown are the observed, expected and chi-square contribution values. Proportion of catch (%) - The proportion of fauna (in %) with low (scores 1 and 2) and high (3 and 4) damage caught by the four dredge types (Newhaven, Newhaven-skid, N-viro, Nviro-skid).

Damage Score	Dredge type	Observed Count	Expected Count	χ^2 contribution, (% contribution)	Proportion of catch (%)
D1	N-viro	72	73.6	-0.2, (0.5)	29.5
	Nviro-skid	85	90.8	-0.6, (4.9)	28.2
	Newhaven	77	82.7	-0.6, (5.1)	28.1
	Newhaven-skid	101	87.8	1.4, (25.8)	34.7
D2	N-viro	73	64.9	1.0, (13.4)	29.9
	Nviro-skid	84	80.0	0.4, (2.6)	27.9
	Newhaven	67	72.8	-0.7, (6.1)	24.5
	Newhaven-skid	71	77.3	-0.7, (6.8)	24.4
D3	N-viro	42	44.8	-0.4, (2.4)	17.2
	Nviro-skid	55	55.3	-0.04, (0.02)	18.3
	Newhaven	59	50.4	1.2, (19.4)	21.5
	Newhaven-skid	48	53.5	-0.7, (7.3)	16.5
D4	N-viro	57	60.7	-0.5, (2.9)	23.4
	Nviro-skid	77	74.8	0.2, (0.8)	25.6

Damage Score	Dredge type	Observed Count	Expected Count	χ^2 contribution, (% contribution)	Proportion of catch (%)
	Newhaven	71	68.1	0.3, (1.6)	25.9
	Newhaven-skid	71	72.4	-0.2, (0.3)	24.4

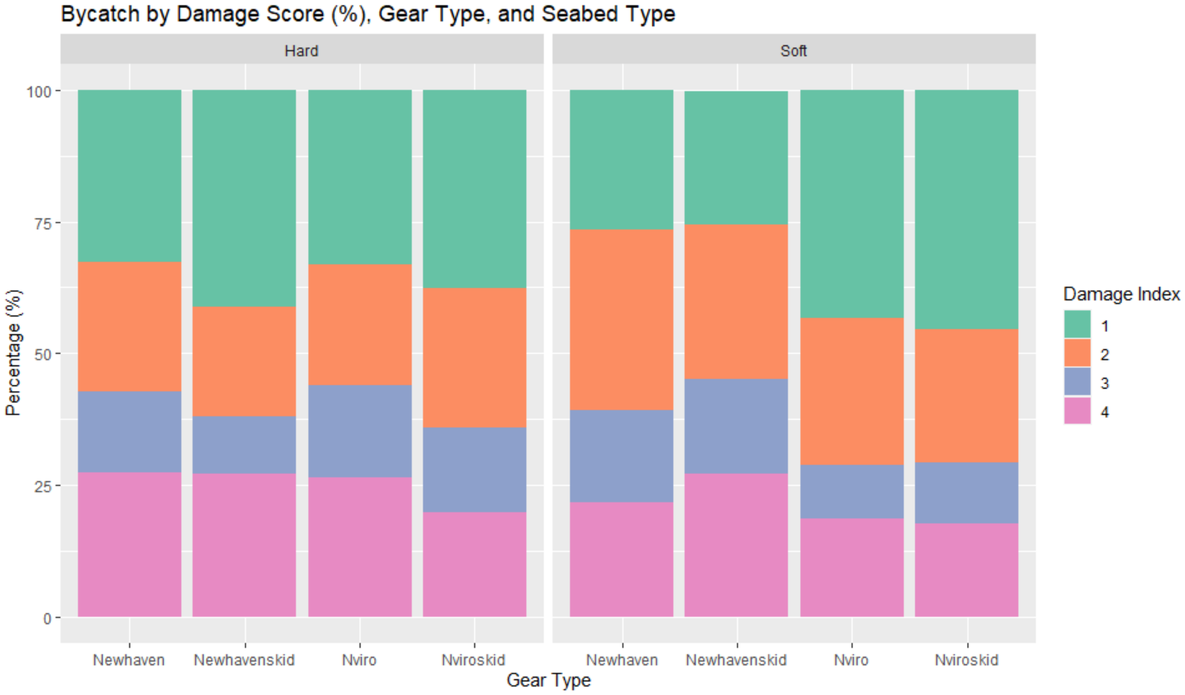


Figure 4.3 The proportion of bycatch fauna (in %) with low (scores 1 and 2) and high (3 and 4) damage caught by the four dredge types (Newhaven, Newhaven-skid, N-viro, Nviro-skid) in hard ground (left) and soft ground (right).

Impact of stone retention on bycatch damage index across dredge types

Newhaven dredges retained more stone (57.55 ± 7.76 kg/haul) than the N-virodredges (18.07 ± 7.18 kg/haul). We did not find a relationship between the quantity of stone in belly bag and species damage (i.e. non-significant Stone * Damage Index interaction term). However, we found a significant Species * Damage interaction term suggesting that fauna damage is species-specific (best model in Table 4.7). *Asterias rubens* experienced the least damage as it had the highest proportion of individuals with no damage (D = 1) and lowest proportion of damaged organisms in D2 & D3 (Table 4.7). This indicates that *A. rubens* is the least vulnerable to dredging impact from among the bycatch species examined. Conversely, *Marthasterias*, *Echinus*, *Cancer* and *Luidia* all experienced significantly more damage as they had higher proportion of organisms in D2 & D3 than *Asterias* (Table 4.7). *Luidia* was the most vulnerable to damage by dredging.

Table 4.7 The estimated parameters, standard error, t-value, and p-values for the best fitted generalised linear model comparing the proportion of bycatch across scallop gear types by their damage index score and the weight of stone retained (Log10).

	AIC	Estimate	Std.error	*t*-value	*p*-value
Full model: Prop ~ Species*Damage Index + Damage Index*Logstone	-21				
Best model: Prop ~ Species + Damage Index + Species: Damage Index	-25.64				

Intercept	0.83	0.04	21.97	<2e-16
Cancer pagurus	-0.43	0.05	-8.63	<2e-16
Echinus esculentus	-0.30	0.06	-5.29	1.69e-07
Luidia ciliaris	-0.71	0.07	-10.88	<2e-16
Marthasterias glacialis	-0.29	0.05	-5.45	7.47e-08
Damage Index 2	-0.25	0.06	-4.43	1.10e-05
Damage Index 3	-0.64	0.12	-5.25	2.08e-07
Cancer pagurus : Damage Index 2	0.17	0.07	2.40	0.02
Echinus esculentus : Damage Index 2	-0.00	0.10	-0.01	0.98
Luidia ciliaris : Damage Index 2	0.51	0.08	6.04	2.63e-09
Marthasterias glacialis : Damage Index 2	0.23	0.08	3.07	0.00
Cancer pagurus : Damage Index 3	0.4	0.13	3.00	0.00
Echinus esculentus : Damage Index 3	0.42	0.14	3.00	0.00
Luidia ciliaris : Damage Index 3	0.9	0.14	6.54	1.32e-10
Marthasterias glacialis : Damage Index 3	0.42	0.14	3.04	0.00

4.3.2 Survival experiment

A total of 732 individuals were collected (Newhaven; n = 387; Nviro; n = 345). The low number of *Cancer pagurus* collected is likely due to the early season, as many individuals are migrating shoreward for mating. However, the number across the gear types were comparable for analysis. The retained bycatch fell within a similar size range across both gear types to limit any bias in the mortality rate (Table 4.8).

Table 4.8 Size ranges (in mm) of the bycatch species retained during offshore sampling. Data is separated by damage index score and the scallop dredge gear. Data is presented as mean ± SE.

	Damage Index 1		Damage Index 2		Damage Index 3	
	N-viro	Newhaven	N-viro	Newhaven	N-viro	Newhaven
Asterias rubens	137.9 ± 4.5	141.7 ± 3.4	150.5 ± 9.0	144.9 ± 7.5	143.1 ± 13.8	152.5 ± 8.3
Cancer pagurus	165.1 ± 10.2	137.9 ± 7.1	166.6 ± 10.9	147.3 ± 4.9	138 ± 10.1	148 ± 7.4
Echinus esculentus	102.1 ± 2.0	102.2 ± 1.4	104.2 ± 3.5	100.4 ± 2.4	110.5 ± 4.4	103.7 ± 1.7
Luidia ciliaris	159.5 ± 3.7	154.7 ± 9.1	174.4 ± 5.2	147.0 ± 9.9	140.3 ± 7.6	107.9 ± 7.0
Marthasterias glacialis	176 ± 5.9	176.4 ± 6.1	187.3 ± 7.8	171.6 ± 5.7	193.2 ± 6.7	195.7 ± 9.5
Pecten maximus	99.6 ± 0.95	98.4 ± 0.6	98.0 ± 0.95	99.4 ± 1.0	97.2 ± 1.49	99.8 ± 1.1

4.3.2.1 Survival and Cumulative Incidence Curves

Organisms that had experienced lowest damage (damage score index of 1) from the fishing operation exhibited the highest survival probability, starting at 99.6% (95% CI: 98.7–100%) at day 1 and gradually decreasing to 93.8% (95% CI: 90.8–97.0%) at day 7 (Figure 4.4). The survival probability for individuals with a damage index of 2 decreased from 98.7% (95% CI: 97.3–100%) at day 1 to 77.7% (95% CI: 72.5–83.2%) at day 7. Survival for individuals with major damage (damage index 3) had declined to 87.1% (95% CI: 83.0%–91.5%) by day 3, and dropped further to 48.1% (95% CI: 42.2–54.9%) by day 7, indicating that over half of the organisms with major damage died by the end of the study period (Figure 4.4).

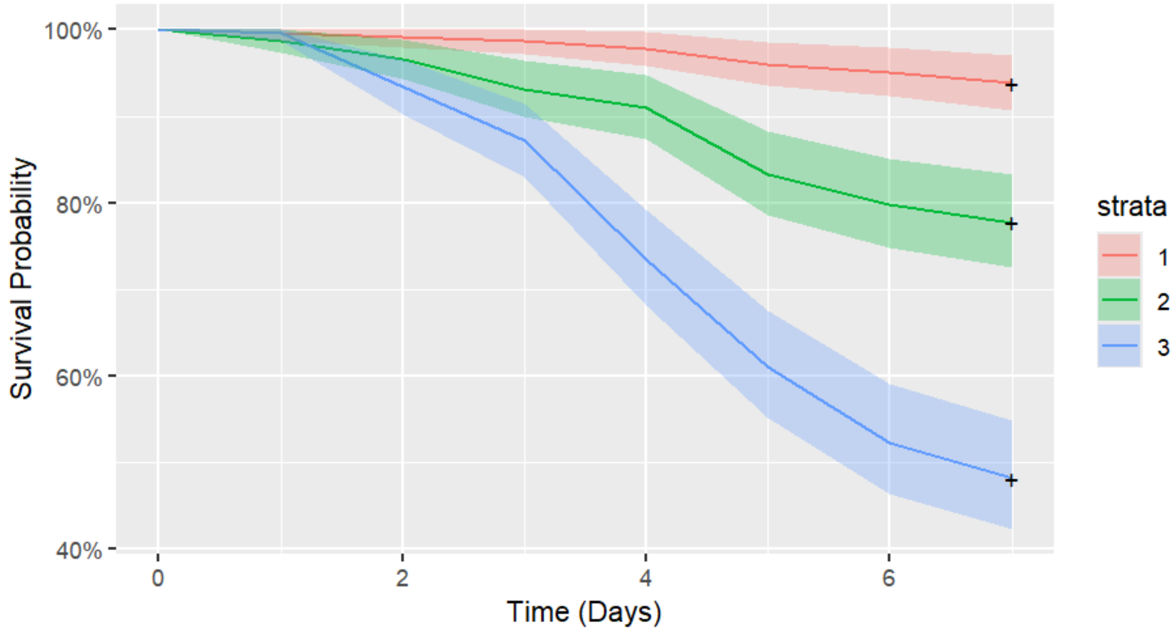


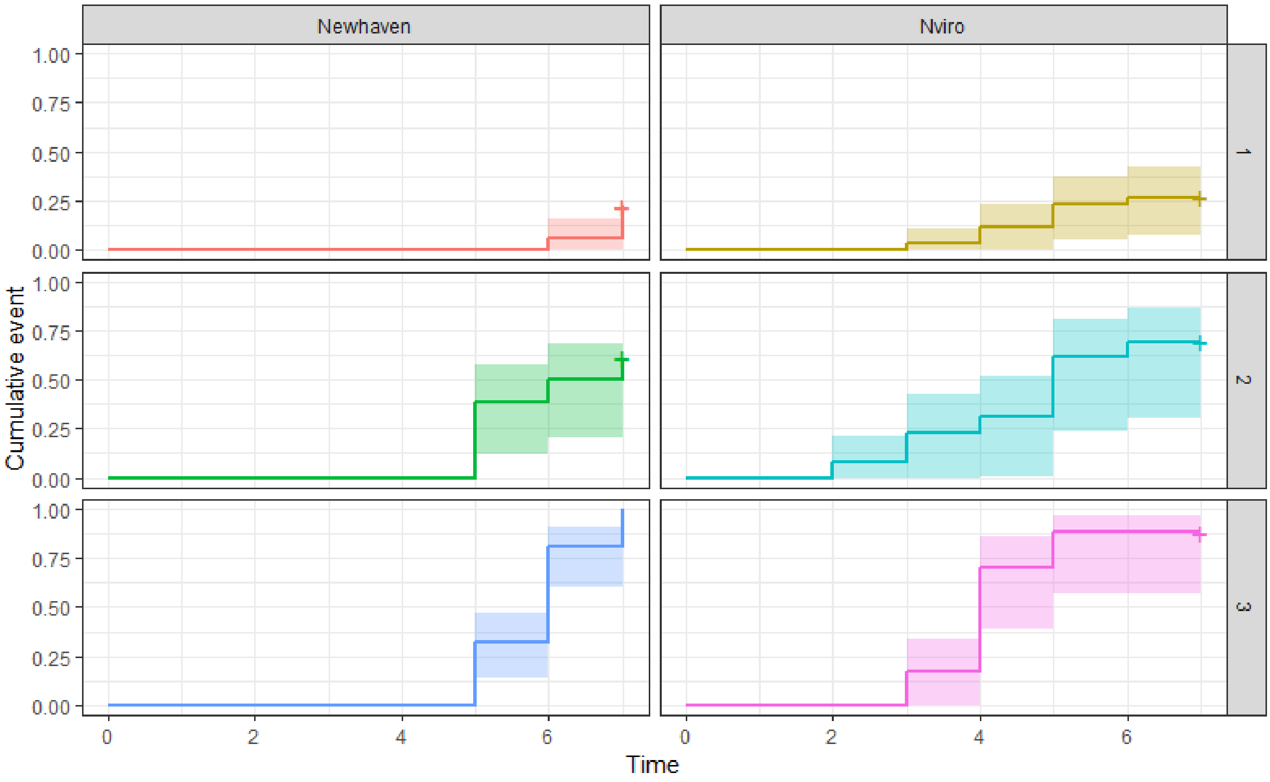
Figure 4.4 Survival probability curves of the total bycatch grouped by the assigned damage index scores.

Survival varied between species (Table 4.9), with *Echinus esculentus* in damage index 3 showing the lowest percentage of survivors (Nviro = 11.8%, Newhaven = 0%). Whereas, there was no significant difference in survival rates between the gear types ($\chi^2 = 0.1$, df = 1, p = 0.8), survival varied between species (Table 4.9) ($\chi^2 = 110$, df = 5, p = p <0.05). *Echinus esculentus* exhibited the greatest decline to 84.6% by day 4 and decreased further to 37.4% by day 7 (Figure 4.5a). *Marthasterias glacialis* showed the greatest survival across the 7-day monitoring period, 95.8% by day 5 (Figure 4.5b). All other species showed lower deviations between observed and expected mortalities, with intermediate survivability ranging between 67.5% to 79.3% by day 7. Survival curves for *Asterias rubens* (Figure 2K), *Cancer pagurus* (Figure 2L), *Luidia ciliaris* (Figure 2M), and *Pecten maximus* (Figure 2N) are provided in the appendix of this report.

Table 4.9 The percentage of surviving individuals across various damage categories for each of the six studied species at the end of the 7-day monitoring period. The initial number of individuals per treatment is provided in brackets. Data is shown for the two scallop dredge gears tested: the Newhaven dredge and the N-virodredge.

	Survivors Damage index 1		Survivors Damage index 2		Survivors Damage index 3	
	Nviro	**Newhaven**	**Nviro**	**Newhaven**	**Nviro**	**Newhaven**
Asterias rubens	100% (20)	95.8% (24)	63.6% (11)	77.8% (9)	37.5% (8)	50% (10)
Cancer pagurus	100% (7)	92.3% (14)	77.8% (9)	73.1% (26)	33.3% (3)	55.6% (9)
Echinus esculentus	100% (26)	77.8% (18)	18.2% (11)	38.9% (18)	11.8% (17)	0% (28)
Luidia ciliaris	100% (11)	100% (7)	68.2% (22)	66.7% (12)	58.8% (34)	58.8% (34)
Marthasterias glacialis	100% (20)	100% (24)	100% (23)	100% (29)	83.3% (24)	91.3% (23)
Pecten maximus	100% (28)	100% (26)	89.3% (28)	90.9% (33)	31.8% (22)	44% (25)

(a) ***Echinus esculentus***



(b) ***Marthasterias glacialis***

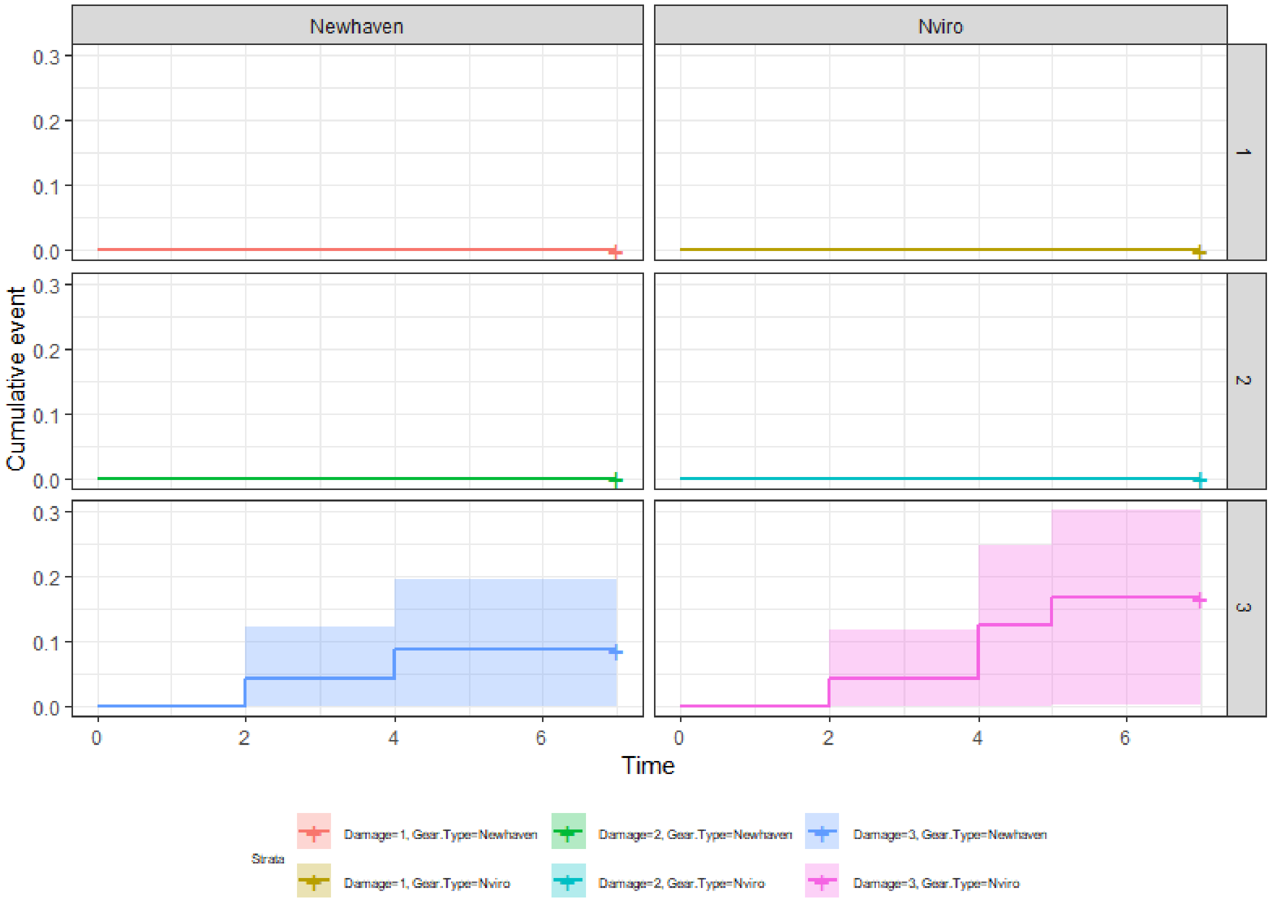


Figure 4.5 Survival curves of (a) *Echinus esculentus* (lowest survival) and (b) *Marthasterias glacialis* (highest survival) across both scallop dredge gear and damage index score. Data presented as the percentage increase in mortality across the 7-day monitoring period. Survival curves for *Asterias rubens* (Figure 2K), *Cancer pagurus* (Figure 2L), *Luidia ciliaris* (Figure 2M), and *Pecten maximus* (Figure 2N) are provided in the appendix of this report.

4.3.2.2 Cox Porportional Hazard

The Cox proportional hazard method, examined the influence of various predictor variables, including gear type, species, and damage level, on the risk of mortality. The model included 698 observations, with 189 events recorded and three observations excluded due to missing values. The overall model was statistically significant (Likelihood ratio test: $\chi^2(9) = 261.9$, $p < 0.001$), suggesting a strong relationship between the predictor variables and risk of mortality. The concordance index was 0.82 (SE = 0.01), indicating good predictive ability. Risk of mortality (HR values) differed by species, *Echinus esculentus* present a greater risk of death (HR = 2.37, 95% CI: 1.39–4.04, $p < 0.001$), whilst *Marthasterias glacialis* presents a lower risk of death (HR = 0.1, 95% CI: 0.04–0.26, $p < 0.001$) (Figure 4.6). Individuals assigned a damage index of 2 or 3 were at greater risk of death. Those with damage index 2 (HR = 5.16, 95% CI: 2.84–9.37, $p < 0.001$) were five times more likely to die, while those with damage index 3 (HR = 14.64, 95% CI: 8.31–25.80, $p < 0.00$) were fifteen times more likely to die (Figure 4.6).

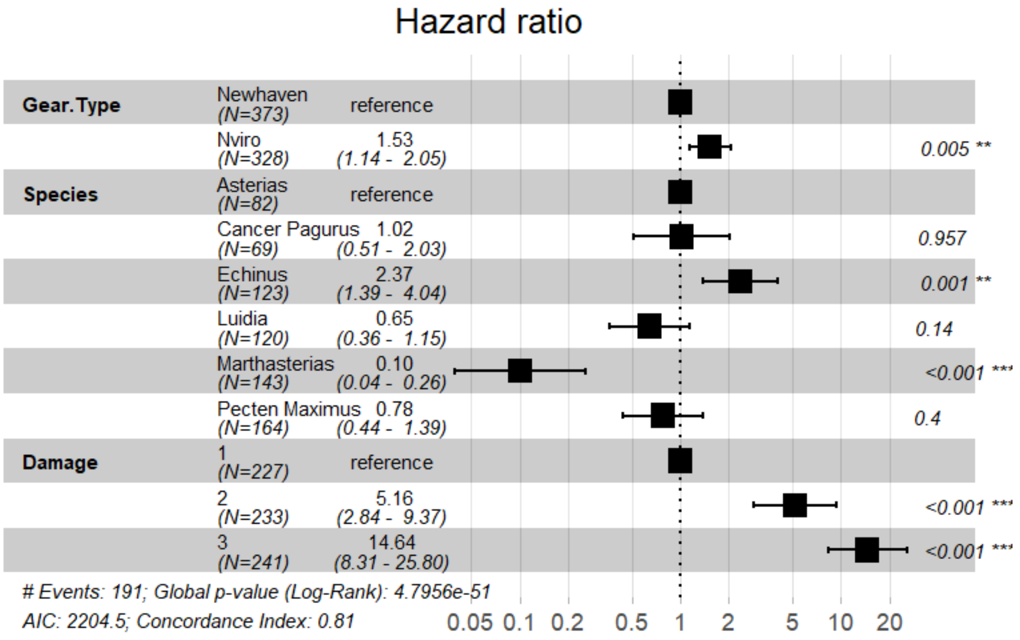


Figure 4.6 Hazard ratio plot for the cox proportional hazard model (survivability ~ gear type + species + damage index). Shown is the risk of death (HR – hazard ratio) with confidence intervals by the model covariates. Significant differences were considered when $p < 0.05$.

5 WP3 – Fuel consumption

5.1 Objective

Assessment of the fuel consumption and CO_2 emissions of the modified scallop dredges gear relative to the standard Newhaven dredge.

5.2 Methods

5.2.1 Description of 3 vessels and study locations

Data collection on fuel consumption was industry-led and was collected by three fishing vessels during standard commercial practice in different fishing grounds in Welsh (MFV Harmoni), Scottish (MFV Valaura) and English waters (MFV Lass O Doune) (Figure 5.1 map of areas of operation). Fuel consumption is expected to vary depending on factors such as vessel size and engine power and number of dredges towed, therefore we have sought fishing vessels that cover a range of these factors to increase the generalizability of the data collected (Table 5.1). The MFV Lass O Doune fished with the conventional Newhaven dredge and with the Newhaven dredge equipped with the skid belly bag, the MFV Valaura fished with the N-virodredge equipped with conventional belly bag and the MFV Harmoni fished with all four types of dredges.

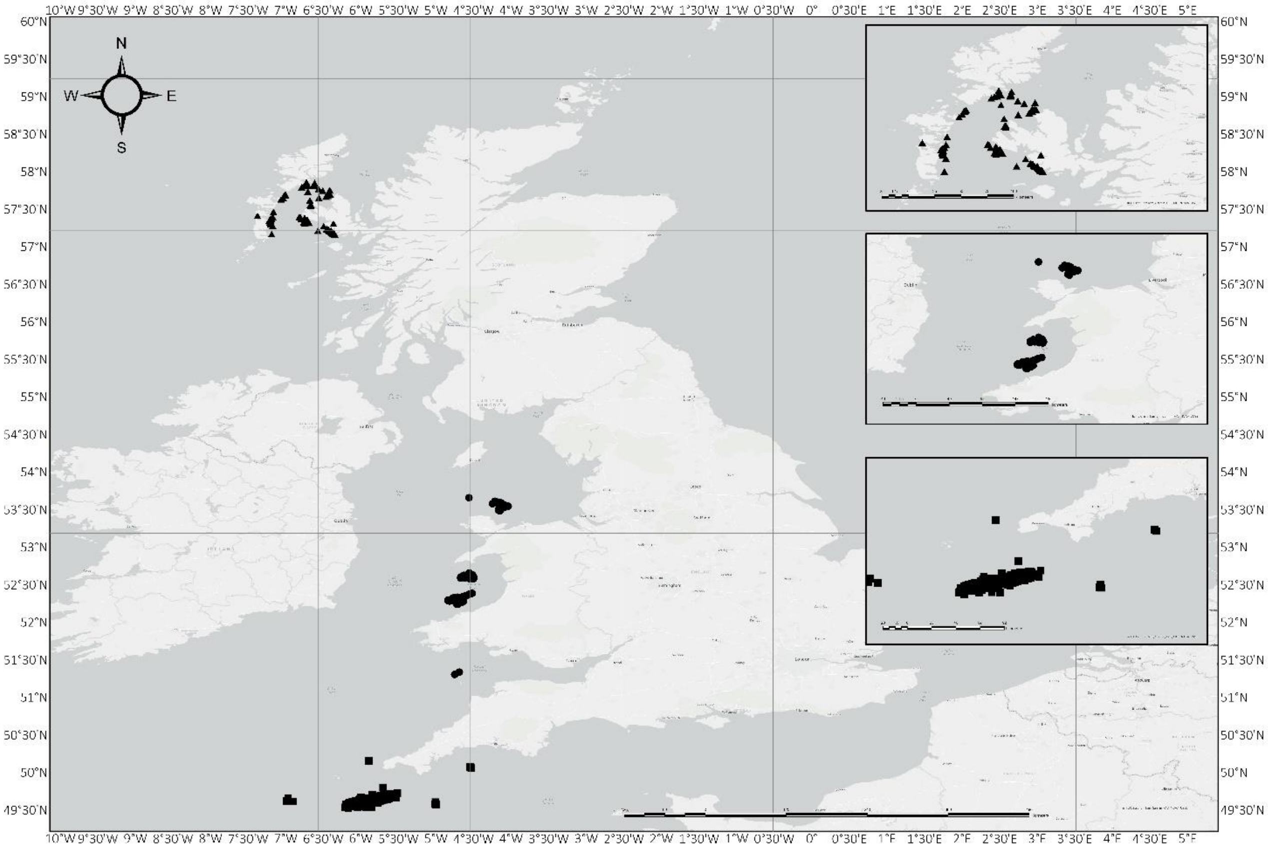


Figure 5.1 Locations of fuel data collection in the Outer Hebrides, Scotland (Triangle – MFV Valaura); Anglesey, North Wales (Circle – MFV Harmoni); English Channel, England (Square – MFV Lass O Doune).

Table 5.1 Scallop dredge vessel and fishing operation characteristics.

	MFV Harmoni	**MFV Valaura**	**MFV Lass O Doune**
Length of vessel (m)	14.9	13.4	23.9
Gross registered tonnage	120 GRT, 59.84 GT	32.39 GT	150 GRT
Engine power (kW)	214	239	221
Number of dredges per side	7	6	10
Standard belly rings (internal diameter, mm)	85	75	75
Gears operated during project	Newhaven Newhaven-skid N-virodredge Nviro-skid	N-Virodredge	Newhaven Newhaven-skid
Typical areas of operation	Welsh waters, Isle of Man waters	Western Isles (Outer Hebrides, Skye)	ICES division 7d and 7E

5.2.2 Data collection

Fuel usage was recorded using a fuel flowmeter (AIC 908 flowmeter with BC3034 display) installed on each of the vessels, over a period of at least 3 weeks for each gear type. During each fishing trip the same gear type was used on the port and starboard side of the vessel to avoid creating an unbalanced drag which might affect gear performance and fuel consumption. Throughout the trip the skipper recorded fuel usage during fishing for each haul, that is from the moment the dredges hit the seabed to when they left the seabed. The skipper recorded the following parameters for each haul:

- positional data (Latitude and longitude),
- time at start and end of haul (hr:min),
- distance dredged (nm),
- vessel speed during fishing (towing speed in knots),
- sea state (using Beaufort scale). Sea state was recorded on the Beaufort scale, and where a range was given for a haul, this was converted to a numerical value for data analysis (e.g. 4-5 = 4.5),
- tidal current (vessel drift at surface in knots),
- water depth (metres),
- gear type,
- Fuel at start and end of haul (litres).

The data recording sheet used by skipper is provided in the appendix (Table 3A).

5.2.3 Data analysis

5.2.3.1 Fuel consumption

Fuel consumption in litres per hour [FLH] was calculated as:

$$\text{Fuel used per haul} = \text{Fuel}_{\text{END}} - \text{Fuel}_{\text{START}}$$

$$\text{Duration of haul} = \text{Time}_{\text{END}} - \text{Time}_{\text{START}}$$

$$\text{FLH (ltrs/hr)} = \text{Fuel used per haul (ltrs)} / \text{Duration of haul (hrs)}$$

Linear mixed-effect models were used to test for the influence of gear type and different environmental variables on fuel consumption [FLH] while accounting for the hierarchical structure of the data.

MFV Valaura

The MFV Valaura carried out single-day fishing trips using the N-virodredge standard belly bag (N-viro), collecting fuel data across various fishing conditions, including different seabed types, towing speeds, sea states, and tidal conditions. The following model was tested:

FLH = seastate + tidal current + water depth + tow speed + location, random=~1|Trip ID

The factor 'Trip ID' was used as a random effect to account for correlation between hauls from the same fishing trip for the Valaura. Towing speed was more variable for the Valaura but not for the other vessels, therefore the influence of towing speed on FLH was examined for the Valaura. The Valaura collected fuel data from six different locations in the Outer Hebrides and Skye, therefore differences in fuel consumption among locations were also tested.

MFV Lass O Doune

The MFV Lass O Doune carried out multiple-day trips to test the fuel performance between the Newhaven dredge with standard belly bag (Newhaven) and Newhaven dedge with skid belly bag (Newhaven-skid). Data was collected from the same study location but different sea states and tidal conditions. The following model was tested:

FLH = Gear*sea state + Gear*tidal current + water depth, random=~1|Trip ID/Date

MFV Harmoni

The MFV Harmoni carried out multiple-day trips to test the fuel performance between the Newhaven dredge with standard belly bag (Newhaven), Newhaven dedge with skid belly bag (Newhaven-skid), N-virodredge with standard belly bag (N-viro), and N-virodredge with skid belly bag (Nviro-skid). Data was collected from the same study location but different sea states and tidal conditions. The following model was tested:

FLH = Gear*sea state + Gear*tidal current + water depth, random=~1|Trip ID/Date

A random intercept model for individual days (Date) nested within each fishing trip (Trip ID) was applied to data collected by the Lass O Doune and Harmoni to account for correlation between hauls from within the same day and fishing trip. Fuel data was not considered comparable among the three vessels due to differences in vessel characteristics, including engine power, vessel length, and the number of towed dredges, and was thus analyzed and presented separately.

Whilst a significant main term such as 'sea state', would imply that fuel consumption is influenced by sea state condition, a significant interaction term such as 'Gear*sea state' indicates that the influence of sea state on fuel consumption is gear specific. It was not possible to examine the interaction term Gear*depth for the Harmoni as the spread of data was not the same across all gears; the skewness in the data would have introduced bias in the analysis.

All models were inspected for normality of residuals using the Kolmogorov–Smirnov test and a Q-Q plot. Cook's distance plot was used to check for outliers. Heteroscedasticity was tested using the Levene's test and scatter plots of the standardized residuals, fitted values and all covariates were assessed. Model residuals were checked for equal distribution. All combinations of the explanatory variables were tested and ranked by the Akaike Information Criterion (AIC). A backwards selection process was used, and the least significant interactions and model terms were removed using a stepwise selection process. All model combinations of variables were examined using the log-likelihood method.

5.2.3.2 Predicted reductions in CO_2 emission and fuel savings

Fuel consumption data collected by the MFV Harmoni comparing all four dredge types, showed that on average, the N-virodredge resulted in a 30% reduction in fuel consumption compared to the Newhaven dredge. There was no significant difference in fuel consumption between gear with conventional and skid belly bag. This 30% percentage reduction in fuel consumption was used to calculate the predicted avoided atmospheric CO_2 emission and the fuel savings for over 15 m and under 15 m scallop dredge vessels in the UK fleet.

Two sets of daily fuel consumption (ltrs / day) values were used: (i) one from actual fuel data recorded by the Lass O Doune (vessel length 23.9 m) and Harmoni (vessel length 14.9 m), (ii) the other from average daily fuel consumption values for a typical scallop dredger above and below 15 m in 2023 as provided in the Seafish economics report (Wright, 2024). The key difference between these values is that the average daily fuel consumption (liters/day) for (ii) includes activities such as steaming and towing gear on the seabed for fishing, whereas for (i), it only accounts for fuel consumption while towing gear on the seabed for fishing.

The average daily fuel consumption values were converted to kg carbon dioxide-equivalent emissions (CO_2-e) per annum, based on the emission conversion factor of 2.77547 kg CO_2-e for marine gas oil as reported in (Greenhouse gas reporting: conversion factors 2023 - GOV.UK), and based on a year with 86 fishing days for a vessel under 15 m and 177 fishing days for a vessel over 15 m (Wright, 2024).

To calculate fuel costs, the price of fuel was assumed to be at £0.78 per litre.

5.3 Results for each vessel

5.3.1 Comparison of fuel consumption between gear during fishing operation

MFV Harmoni

A total of 287 hauls were conducted by the Harmoni; 106 hauls from 4 trips with the Newhaven dredge, 42 hauls from 2 trips with the Newhaven-skid, 60 hauls from 2 trips with the N-virodredge, and 79 hauls from 2 trips with Nviro-skid. On average haul duration was 1.74 ± 0.16 hrs. Towing speeds differed between the Newhaven dredge variants (2.91 ± 0.03 knots) and the N-virodredge variants (2.20 ± 0.22 knots) as the N-virodredge performs best at lower towing speeds. Fishing occurred over mixed bottom composed of gravel, sand and stone at water depth ranging between 25 – 50 m (mean±SD = 35.23 ± 6.18 m).

Fuel consumption was significantly reduced when fishing with the N-virodredges; on average these reduced fuel consumption by 30% relative to the conventional Newhaven dredge (Figure 5.2a). The addition of skids to the belly bag did not affect fuel consumption when these were used in combination with either the Newhaven dredges or the N-virodredges (Figure 5.2a). On average, the fuel consumption for N-virodredges with skid bellies was 24.43 ± 4.15 litres per hour of fishing, whereas that for the standard bellies was 22.91 ± 2.46 litres per hour of fishing. Conversely, the fuel consumption for Newhaven dredges with skid bellies was 32.89 ± 2.55 litres per hour of fishing, whereas that for the standard bellies was 33.03 ± 3.68 litres per hour of fishing.

Fuel consumption increased significantly with sea state (Figure 5.2b) for all gear types, but there was no significant effect of surface tidal current or water depth (Figure 5.2 c, d respectively). The fitted model for fuel consumption and sea state indicates that for each unit increase in sea state, fuel consumption increases by approximately 0.93 ± 0.13 ltrs/hr (Table 5.2).

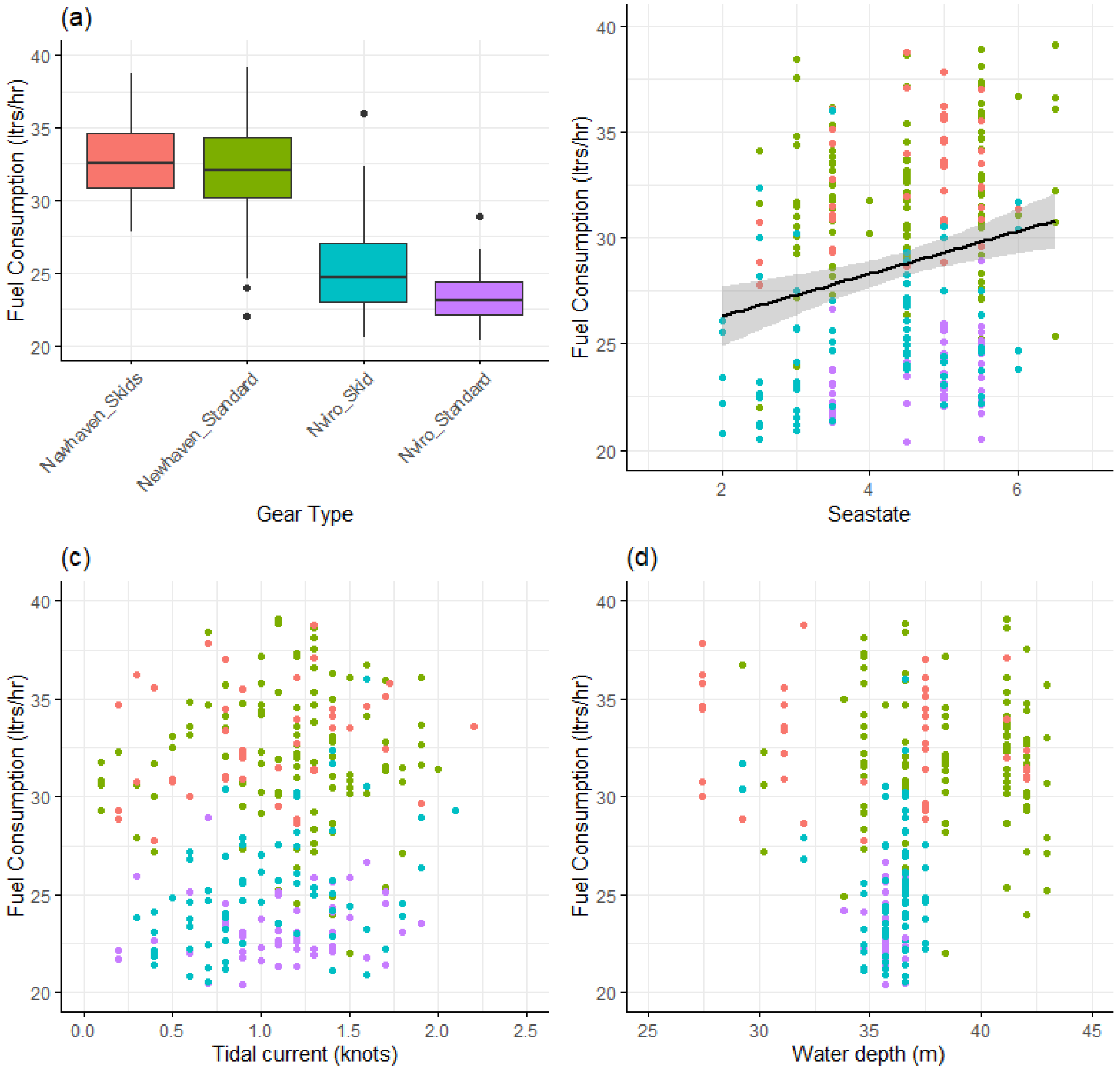


Figure 5.2 Fuel consumption (litres used per hour of fishing, ltrs/hr) when fishing with the conventional Newhaven dredge (Newhaven_Standard, green), Newhaven dredge with skid belly (Newhaven_Skids, orange), N-virodredge with skid belly (Nviro_Skid, blue) and N-virodredge with conventional belly (Nviro_Standard, purple). The influence of sea state (b), surface tidal current (c), and water depth (d) on fuel consumption for each gear type is shown. Coloured dots represent fuel consumption data for each fishing haul. A significant linear relationship was found only between fuel consumption and sea state and the fitted model is shown by a solid line in plot (b).

Table 5.2 Output for the linear mixed-effects model with significant terms, showing a significant influence of sea state and gear type on fuel consumption (ltrs per hour of fishing).

Fuel consumption (litres per hour)				
	Value	**Std.Error**	**t-value**	**p-value**
(Intercept)	32.32	0.77	41.66	<0.001
sea state	0.93	0.19	4.74	<0.001
Gear (Newhaven_Stand)	-0.41	0.93	0.43	0.68

Gear (Nviro_Skid)	-7.61	1.03	7.41	<0.001
Gear (Nviro_Stan)	-9.61	1.04	9.25	<0.001

MFV Lass O Doune

A total of 428 hauls were conducted by the Lass O Doune; 227 hauls from 3 trips with the conventional Newhaven dredge and 201 hauls from 3 trips with the Newhaven dredge - skid belly bag. On average haul duration was 1.5 ± 0.08 hrs and towing speed was 3.49 ± 0.07 for both dredge types. Fishing occurred over mixed bottom primarily composed of gravel at water depth ranging between 88 – 104 m (mean±SD = 98.46 ± 3.31).

Fuel consumption did not differ significantly between the Newhaven dredge with skid and standard belly bags (Figure 5.3a) or with sea state (Figure 5.3b), tidal current (Figure 5.3c) or water depth (Figure 5.3d). On average, the fuel consumption for dredges with skid bellies was 62.1 ± 7.2 litres per hour of fishing, whereas that for the standard dredges was 59.4 ± 7.4 litres per hour of fishing.

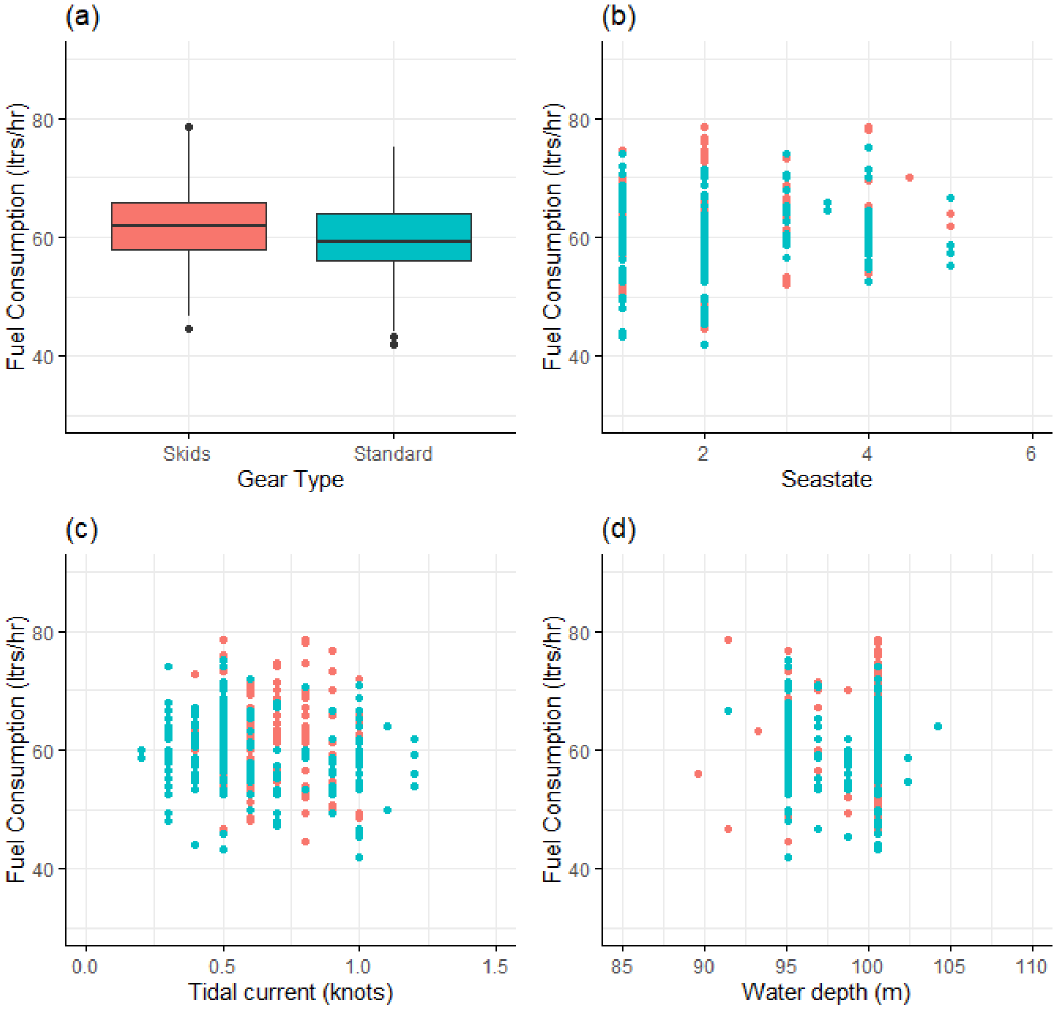


Figure 5.3 (a) Fuel consumption (litres used per hour of fishing, ltrs/hr) for MFV Lass O Doune when fishing with the conventional Newhaven dredge (Standard, green) and Newhaven dredge - skid belly (Skids, orange). Coloured dots represent fuel consumption data for each fishing haul and gear type. No significant influence of sea state (b), surface tidal current (c) and water depth (d) on fuel consumption was found.

MFV Valaura

A total of 157 hauls were conducted by the Valaura from 21-day trips fishing with the N-virodredge – conventional belly. On average haul duration was 1.15 ± 0.18 hrs and towing speed was 1.9 ± 0.1 and ranged from 1.7 to 2.4 knots. Fishing occurred over several grounds with the following MSFD Broadscale habitat type (i) Circalittoral coarse sediment, (ii) Circalittoral sand, (iii) Circalittoral mixed sediment, and (iv) Circalittoral rock and biogenic reef. Water depth ranged between 25 – 95 m (mean±SD = 47.4 ± 16.3 m).

On average, the fuel consumption for N-virodredge was 24.9 ± 3.2 litres per hour of fishing. There was slight variation in fuel consumption among the seven study sites; fuel usage was on average higher at North Skye, NW Skye and Off Harris than at the other sites, however these differences were not significant (F-value = 0.67, p=0.64) (Table 5.3). Fuel consumption did not differ significantly with tow speed (F = 0.13, p = 0.72), sea state (F = 2.39, p = 0.13), tidal current (F = 0.15, p = 0.69) or water depth (F = 0.39, p =0.54) (Figure 5.4).

Table 5.3 Mean ± SD values for fuel consumptions and different environmental descriptors at the the 7 surveyed sites.

Location	**Fuel consumption (ltrs/hr)**	**Tow speed (knots)**	**Sea state**	**Surface tidal current (knots)**	**Depth (m)**	**Number of hauls**
North Skye	25.9 ± 1.7	1.9 ± 0.1	2.9 ± 1.5	0.6 ± 0.5	53.3 ± 21.1	13
NW Skye	26.9 ± 2.7	1.9 ± 0.1	2.7 ± 0.9	0.6 ± 0.4	48.6 ± 16.9	9
Off Harris	27.5 ± 2.5	1.8 ± 0.1	2.5 ± 0.9	1.7 ± 0.9	na	14
Sound of Harris	24.2 ± 2.5	2.1 ± 0.1	3.6 ± 0.5	na	na	10
South Uist	24.9 ± 2.8	1.9 ± 0.1	3.3 ± 1.9	0.7 ± 0.5	49.9 ± 16.7	24
SW Skye	24.5 ± 2.1	1.9 ± 0.1	3.0 ± 1.3	0.7 ± 0.2	43.9 ± 11.4	27
West Skye	24.7 ± 2.9	1.9 ± 0.1	3.2 ± 1.8	0.6 ± 0.5	50.2 ± 16.8	31

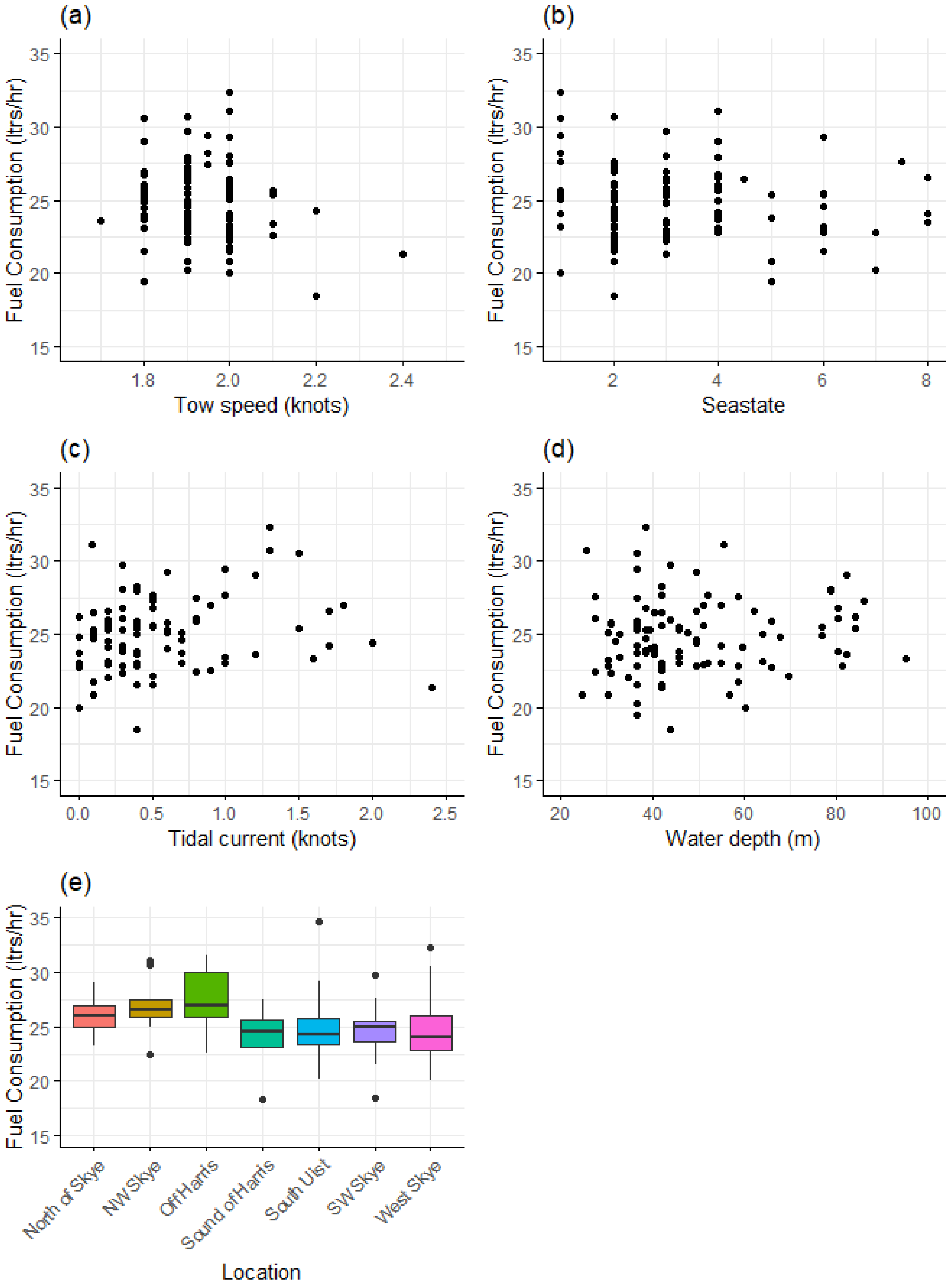


Figure 5.4 (a) Fuel consumption (litres used per hour of fishing, ltrs/hr) for MFV Valaura when fishing with the N-virodredge – conventional belly bag. Black dots represent fuel consumption data for each fishing haul. No significant influence of sea state (a) tow speed, (b), surface tidal current (c), water depth (d) and location (e) on fuel consumption was found.

5.3.2. Comparison of CO_2 emissions and fuel savings among gear types

Tables 5.4 and 5.5 provide estimates of fuel emissions and cost savings associated with using N-virodredge relative to the conventional Newhaven dredge. For over 15 m vessels, average daily fuel use is estimated to drop from 1114 to 779 litres, resulting in a potential reduction in annual CO_2 emissions equivalent to 164,571 $kgCO_2$-e and saving £46,250 per year. For under 15 m vessels, average daily fuel consumption is estimated to decrease from 519 to 363 liters, resulting in 37,235 $kgCO_2$-e fewer emissions annually and a cost saving of £10,465 (Table 5.4).

Results for the Lass O Doune and Harmoni suggest an annual fuel saving of £45,698 and £13,751, respectively when N-virodredges are used. This also results in a substantial amount of avoided CO_2 emission in the atmosphere, 162,533 $kgCO_2$-e for the Lass O Doune, and 48,932 $kgCO_2$-e for the Harmoni.

Table 5.4 Fuel consumption, CO_2 emissions, and fuel cost estimates for over and under 15 m scallop vessels using the Newhaven conventional dredge compared to the N-virodredge (assuming a 30% reduction in fuel consumption). The table includes daily fuel consumption (liters/day), annual CO2 emissions (kgCO2-e/year), and annual fuel costs (£/year) based on estimated fishing and steaming activities.

	Newhaven conventional dredge used		**N-virodredge used and assuming a 30% reduction in fuel consumption**	
	over 15 m scallop vessel	**under 15 m vessel**	**over 15 m scallop vessel**	**under 15 m vessel**
Average daily fuel consumption (ltrs / day)	1114 ltrs /day[1] (estimate includes fishing & steaming)	519 ltrs / day[1] (estimate includes fishing & steaming)	779 ltrs / day	363 ltrs / day
Annual CO2 emissions ($kgCO_2$-e) per vessel assuming 86[1] and 177[1] working days in a year for under and over 15 m vessel, respectively and 2.77547 $kgCO_2$-e from marine gas oil fuel[2]	547,261 $kgCO_2$-e / yr	123,880 $kgCO_2$-e / yr	382,690 $kgCO_2$-e / yr	86,645 $kgCO_2$-e / yr
Fuel Cost per year (£ / yr) per vessel assuming 86[1] and 177[1] fishing days in a year for under and over 15 m vessel, respectively, and assuming current price of fuel £0.78 per ltr	£153,799 / yr	£34,815 / yr	£107,549 / yr	£24,350 / yr
	over 15 m scallop vessel		**under 15 m vessel**	
Tonnes of avoided CO_2 emissions on a yearly basis per vessel by using N-virodredge instead of Newhaven	164,571 $kgCO_2$-e / yr		37,235 $kgCO_2$-e / yr	
£ saved on a yearly basis per vessel by using N-virodredge instead of Newhaven	£46,250 / yr		£10,465 / yr	

[1] https://www.seafish.org/document/?id=1c3071b9-23e4-4073-a9af-da5ea0547215

[2] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

Table 5.5 Fuel consumption, CO_2 emissions, and fuel cost estimates for Lass O Doune and Harmoni using the Newhaven conventional dredge compared to the N-virodredge (assuming a 30% reduction in fuel consumption). The table includes daily fuel consumption (liters/day), annual CO2 emissions (kgCO2-e/year), and annual fuel costs (£/year) based on estimated fishing activities only.

	Newhaven conventional dredge used		**N-virodredge used and assuming a 30% reduction in fuel consumption**	
	Lass O Doune (over 15 m scallop vessel)	**Harmoni (under 15 m vessel)**	**Lass O Doune (over 15 m scallop vessel)**	**Harmoni (under 15 m vessel)**
Average daily fuel consumption (ltrs / day)	1103 ltrs /day (based on 18 hours of actual fishing)	715 ltrs / day (based on 22 hours of actual fishing)	772 ltrs / day	510 ltrs / day
Annual CO2 emissions (kgCO_2-e) per vessel, assuming 86[1] and 177[1] working days in a year for under and over 15 m vessel, respectively, 2.77547 kgCO_2-e from marine gas oil fuel[2]	541,784 kgCO_2-e / yr	170,664 kgCO_2-e / yr	379,251 kgCO_2-e / yr	121,732 kgCO_2-e / yr
Annual Fuel Cost (£ / yr) per vessel, assuming 86[1] and 177[1] working days in a year for under and over 15 m vessel, respectively, and assuming current price of fuel £0.78 per ltr	£152,280 / yr	£47,962 / yr	£106,582 / yr	£34,211 / yr
	Lass O Doune (over 15 m scallop vessel)		**Harmoni (under 15 m vessel)**	
Tonnes of avoided CO_2 emissions on a yearly basis per vessel by using N-virodredge instead of Newhaven	162,533 kgCO_2-e / yr		48,932 kgCO_2-e / yr	
£ saved on a yearly basis per vessel by using N-virodredge instead of Newhaven	£45,698 / yr		£13,751 / yr	

[1] https://www.seafish.org/document/?id=1c3071b9-23e4-4073-a9af-da5ea0547215

[2] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

6 WP 4 – Seabed impact

6.1 Objective

The gear's physical interaction with the seabed leads to the removal of organisms living on or near the seafloor (e.g., crabs, sea urchins, starfish, scallops), resulting in a biological impact. Additionally, it alters the seabed through substrate penetration, sediment displacement, and pressure transmission through the sediment, collectively termed the geotechnical impact. Alteration to the sediment surface may range from superficial scouring to a trench with well-defined edges, possibly berms either side, and backfilling of sediment which settles at a characteristic angle. We expect that the *biological* and *geotechnical* impact will depend on sediment types as this influences both the species composition of the biological community and the mechanical properties of the sediment. WP4 quantifies seabed impact of the three modified scallop dredge gear relative to the standard Newhaven scallop dredge in two sediment types (stoney vs sand & gravel) typically targeted by the industry.

6.2 Methods

6.2.1 Experimental design

Gear trials were conducted NorthEast of Anglesey, Wales, UK, across two habitat types, stone & pebble, and sand & gravel (Figure 6.1). This increases the generalizability of our results as gear impacts are expected to differ depending on sediment type (Sciberras et al. 2018; Hiddink et al. 2017). Side Scan Sonar (SSS) and benthic camera surveys were conducted aboard the research vessel Prince Madog to estimate the depletion of macrofaunal individuals inside relative to outside the dredge tracks (*biological* impact) and to evaluate changes in seabed topography (*geotechnical* impact) before and after dredging with each of the four gears.

Dredging disturbance plots were created by MFV Harmoni at water depths between 20 – 40 m in two sediment types. Two 1.5 nm long by 50 m wide dredge lanes were created by the fishing vessel for each dredge gear and sediment type, resulting in a total of 16 dredge lanes across the two sediment types. The fishing vessel's track was recorded in Open CPN software using AIS data, and positioning data was relayed to the research vessel in real-time. Both the SSS and benthic camera sled were equipped with a USBL (Applied Acoustics Easytrack Nexus Lite, 1319A Micro Beacons), which ensured accurate surveying of the dredge tracks.

SSS data was collected with an Edgetech 4125 Sidescan Sonar System before fishing took place and within 2 hours of the fishing disturbance event to observe changes in seabed topography due to dredges. The Edgetech 4125i dual-frequency SSS system was set up in accordance with instructions provided by the manufacturer (EdgeTech 2020, 2023), and was operated using a standalone laptop computer, and connected to the vessel's GPS system for accurate positioning. SSS output frequencies were between 400 - 900 kHz and data was recorded using EdgeTech Discover software. The towfish's altitude above the seabed was kept constant around 3 - 5 m off the seabed.

For the assessment of the biological impact, each dredge lane was split into two 500 m long by 50 m wide survey rectangles, resulting in a total of 32 rectangles that were surveyed by underwater cameras. A benthic sled fitted with SubC Rayfin camera system - including a camera, parallel lasers (Mantaray), an LED strobe (Aquorea Mk3) and a forward-facing 'CatchCam' video camera angled at 45° - was deployed 4-8 hours after the fishing disturbance to assess seabed fauna inside and outside the dredge lanes for each dredge type. Digital stills were collected every 10 seconds.

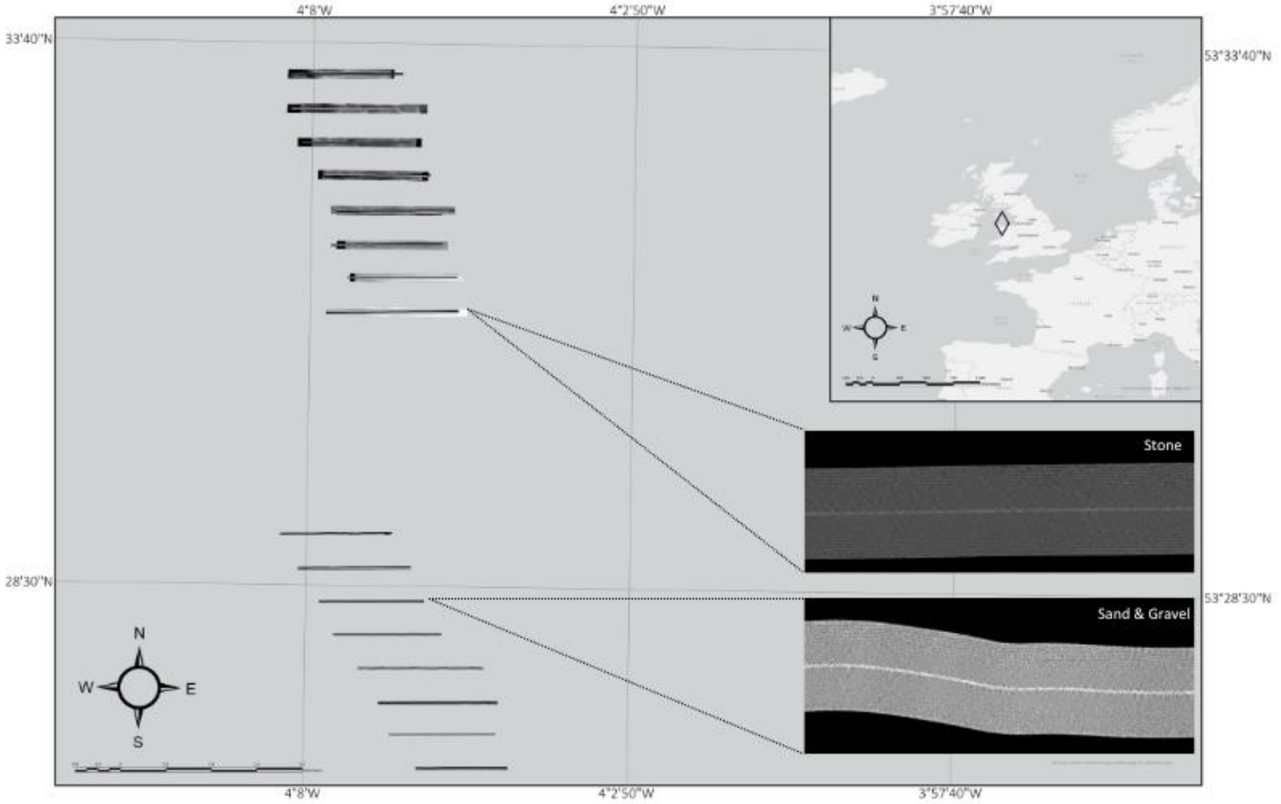


Figure 6.1: Map of the fishing disturbance lanes for the four scallop dredge designs created in the Irish Sea, North Wales. The two fished areas were located off the coast of Anglesey (diamond symbol), with northern lanes on a stoney seabed and southern lanes on sand and gravel seabed. High frequency side scan images illustrate seabed topographical changes and the dredge lanes. Track maps used by the fishing and research vessels can be seen in the appendix (Figure 4A & 4B).

6.2.2 Quantification of seabed fauna impact using HD digital stills

Digital stills were screened for quality and any poor-quality images (e.g. heavily blurred due to movement of the sled, low light, or covered by marine snow) were removed from the analysis. The USBL GPS co-ordinates of the benthic sled were mapped onto the geo-referenced side scan images to verify alignment with the dredge tracks. Images were sub-divided into those from 'within the dredge track' (Figure 6.2) and those 'outside the dredge track' (Figure 6.3). Supplementary still images of the dredge track and off-track disturbance for the scallop dredge designs can be found in the appendix (Figure 4D & 4F). The number of images varied across replicates, and a random sample of 50 images per replicate was selected for the analysis. In total, 2642 images were analysed, 1560 from within dredge tracks and 1082 from outside the dredged areas.

Images were processed using Biigle (Langenkämper et al., 2017), which enabled the annotation of benthic species based on the WORMS database (Horton et al., 2017). Count data was collected during the image analysis. The number of individuals were standardised to the spatial area of each image ($0.453m^2$). The total area was calculated using the formula:

$$Total\ Area = n \times 0.453$$

where n is the number of images per replicate survey transect. The number of individuals was standardized to an area of $10m^2$.

$$Number\ of\ Individuals = \frac{(No.of\ individuals\ \times 10)}{Total\ Area}$$

The proportional change (lnRR) between dredge tracks and off track areas was calculated for each gear type to assess differences. The lnRR is calculated using the following equation:

$$lnRR = ln\left(\frac{Number\ of\ Individuals - Dredge}{Number\ of\ Individuals - Off\ Track}\right)$$

Positive lnRR values indicate higher number of benthic fauna inside dredged tracks relative to outside, whereas and a negative lnRR value indicates lower fauna counts inside dredged tracks. *Ophiothrix fragilis* abundance was extremely high for some images (in excess of 1000 individuals per 10m^2). Therefore, before analysis took place, the value of *Ophiothrix* was removed from the lnRR totals for each replicate to reduce skewed results.

Figure 6.2: A camera still image taken from within the dredge track of an Nviro-dredge gear with skid belly bags within the stone & gravel study area, in the Northern sampling box.

Figure 6.3: A camera still image taken from outside the dredged track for N-virodredge with skid belly bag within the stone & gravel study area.

6.2.3 Assessment of topographic changes using Side Scan Sonar data

Side scan mosaics were created from high and low frequencies data using SonarWIZ v7. Side scan sonar data was processed by Envision Ltd. In brief, slant range corrections were applied to remove the 'blind zone', and the geographic position was corrected using the layback correction method to calculate the position of the towfish in relation to the research vessel. The length of the cable that was deployed with the towfish was used to offset the data position to represent the real geographic location. Signal intensity corrections were made using beam angle correction (BAC), automatic gain control (AGC), and time variant gain. Individual sonar swathes were then stitched into a mosaic, and exported as GeoTIFF files. The high-frequency data was exported at 2cm resolution, while the low-frequency data at 5cm. An example of the final mosaic is shown in Figure 6.4.

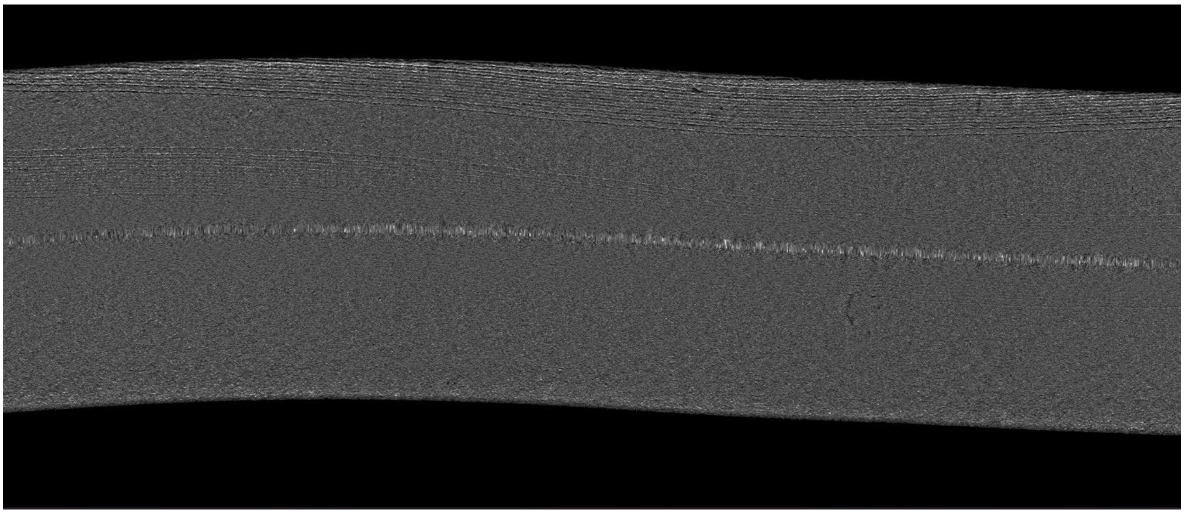


Figure 6.4 The final mosaic image produced following processing corrections. The image was created by Envision (18/12/2024).

Side Scan Sonar mosaics were analyzed in ArcGIS to measure width of furrows (dredge scars) left behind in each dredge track (Figure 6.4). As the dredge lanes were created to be 1.5nm, six randomly generated distances along each individual transect were calculated (represented by the boxes in Figure 6.5). For each randomly generated distance (white box, Figure 6.5), six random furrow width measurements were recorded using the ArcGIS measurement tool. In total, this equated to 570 furrow width measurements, 72 measurements per dredge design per habitat type. The furrow width measurements were taken as per Figure 6.5, whereby the width was taken from the first shadow to the second, repeated along the dredge lane six times.

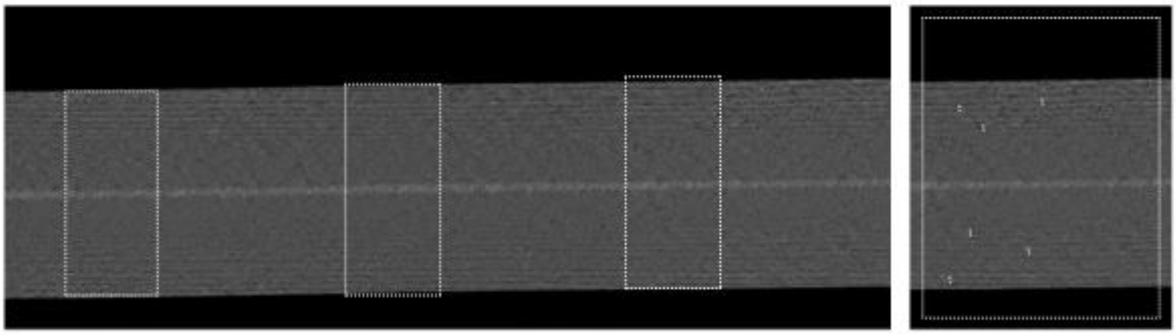


Figure 6.5: A high frequency side scan sonar image showing the furrow measurement sampling for the seabed disturbance analysis. Six areas along each scallop dredge lane (1.5nm) were randomly selected and within each area, six random furrow measurements were taken. The furrow measurements can be seen by the white lines in the right image. Mosaic images for both N-Viro (Figure 4C) and Newhaven dredges (Figure 4E) can be found in the appendix of this report.

6.2.4 Data analysis

General linear models (GLM) were used to test the lnRR and furrow width measurements in relation to gear and habitat types. The initial models used Poisson distributions and included all relevant explanatory parameters. The structure of the model was as follows:

$$lnRR \sim Gear\ Type * Habitat\ Type$$

$$Furrow\ Width \sim Gear\ Type * Habitat\ Type$$

Interaction terms in the models were examined, and any terms with a variance inflation factor (VIF) greater than 3 were removed. Only interaction terms (vif < 3) were retained. All combinations of the explanatory variables were tested and ranked by the Akaike Information Criterion (AIC). The best ranked model, and all models within two AICc values, were selected. Using the R packages 'arm' and 'MuMIn', each set of models were averaged. All models were inspected for normality of residuals using the Kolmogorov–Smirnov test and a Q-Q plot. Cook's distance identified influential outliers, while heteroscedasticity was tested using the Levene's test and scatter plots of the standardized residuals, fitted values and all covariates were assessed. Overdispersion was checked before applying Poisson models; if overdispersed (n >1), a negative binomial model was used instead.

6.3 Results

6.3.1 Epibenthic fauna depletion inside dredge tracks

Across all 2642 images, the three dominant species occurring across both habitat types were; *Ophiothrix fragilis* (n = 14,069 (61.69% of total abundance)), *Alcyonium digitatum* (n = 6,132 (26.89% of total abundance)), and *Asteroynx loveni* (n = 1,526 (6.69% of total abundance)).

Fauna depletion (lnRR) was lowest for N-virodredge with skid belly bags (G4) (Figure 6.6). Both the Newhaven and N-virodredge designs with standard belly bags (G1 & G3) led to an average 20% reduction in fauna abundance inside the dredge lanes relative to outside (Figure 6.6). Overall, the effects on epifauna were comparable across the two habitat types examined, except for the Newhaven dredge with skid belly bag (G2), which caused greater fauna depletion in stoney ground than in soft sediment composed of sand and gravel (Figure 6.6). Despite these observed trends, fauna depletion did not differ significantly between gear types and habitat types (Table 6.1). We note that sample size, defined by the number of replicate transects for each gear and habitat type combination, was relatively small (ranging from 3 to 4 replicates). Therefore, results should be interpreted with caution, and a future survey with a larger number of replicates is necessary to confirm the observed trends.

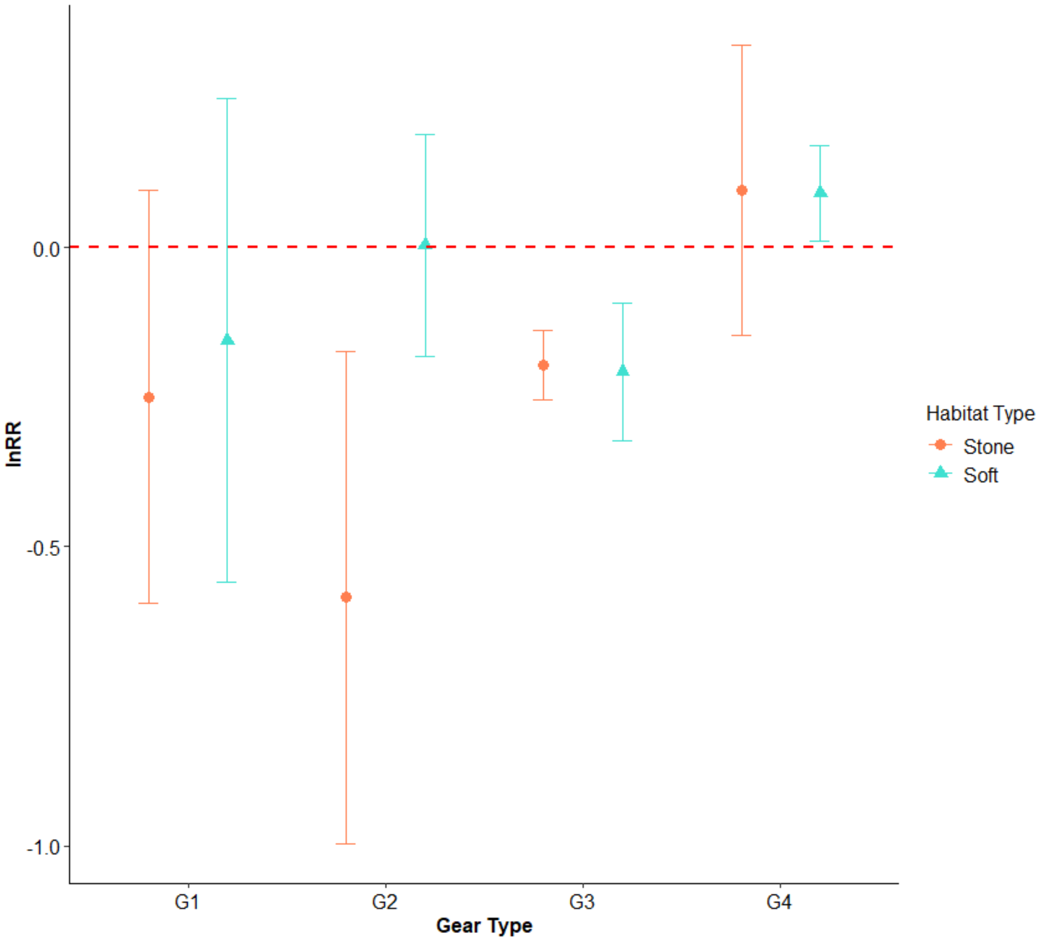


Figure 6.6 Response ratio (lnRR) of abundance (mean ± sem) of benthic marine fauna caught in dredge and non-dredge lanes for all scallop dredge designs and seabed types. The dashed horizontal line (0) represents equal catches between dredge lanes and non-dredge lanes. Positive lnRR values indicates higher abundance per m^2 in dredge lanes compared to non-dredge lanes, negative lnRR values indicates lower abundance per m^2 in dredge lanes. A significant difference occurs when the 95% CI does not overlap lnRR = 0. The x-axis labels are as follows; G1 – Newhaven Standard Belly, G2 – Newhaven Skid Belly, G3 – Nviro-Dredge Standard Belly, and G4 – Nviro-Dredge Skid Belly.

Table 6.1: Estimated regression parameters, standard errors, *t*-values and *p*-values of the relationship between lnRR of bycatch abundance, the scallop dredge design, and the seabed type fished. The outputs shown are created following a GLM analysis with a Poisson distribution with values rounded up.

	Estimate	Std.error	*t*-value	*p*-value
Intercept	-0.279	0.216	-1.293	0.210

G2 - Newhaven Skid Belly	-0.132	0.280	-0.471	0.642
G3 - Nviro Standard Belly	-0.028	0.283	-0.098	0.923
G4 - Nviro Skid Belly	0.312	0.290	1.075	0.294
Soft	0.182	0.203	0.896	0.381

6.3.2 Gear footprint from side scan sonar data

Gear designs with standard belly bags (G1 and G3) created significantly larger furrows than gears with skid belly bags, which reduced the gear footprint on the seabed by 55% (Table 6.2, Table 6.3). Furrow width were similar across the two habitat types examined, except for the Newhaven dredge with skid belly bags, which created significantly larger furrows in softer seabed types than in stoney ground (Table 6.2, 6.3).

Table 6.2: Furrow width measurements across both sampled habitat types and the four scallop dredge designs. Data is presented as mean ± SE.

Gear Type	Furrow Width (m)	
	Stone	Soft
G1 - Newhaven Standard Belly	0.85 ± 0.01	0.86 ± 0.01
G2 - Newhaven Skid Belly	0.38 ± 0.01	0.45 ± 0.01
G3 - Nviro Standard Belly	0.89 ± 0.01	0.89 ± 0.01
G4 - Nviro Skid Belly	0.35 ± 0.01	0.37 ± 0.01

Table 6.3: Estimated regression parameters, standard errors, *t*-values and *p*-values of the relationship between furrow width measurements, the scallop dredge design, and the seabed type fished. Best fitting model, furrow ~ gear type * habitat (AIC = -1116.86). The outputs shown are created following a GLM analysis with a poisson distribution with values rounded to the nearest two decimal points. Asterisks (*) indicate a significant relationship.

	Estimate	Std.error	*t*-value	*p*-value
Intercept	0.85	0.01	80.46	<2e-16 *
Newhaven Skid Belly	-0.48	0.02	-31.78	<2e-16 *
Nvirodredge Standard Belly	0.04	0.02	2.59	0.01 *
Nvirodredge Skid Belly	-0.50	0.02	-33.35	<2e-16 *
Habitat - Soft	0.00	0.02	0.29	0.78
N-Virodredge : Soft	-0.01	0.02	-0.43	0.67
N-Viroskid : Soft	0.01	0.02	0.45	0.65
Newhaven Skid Belly : Soft	0.07	0.02	3.27	0.00 *

7 Discussion

7.1 Catch yield of market-size scallops

The retention of *Pecten maximus* varied by gear type and seabed composition, consistent with findings from Sciberras et al. (2022). While skid belly bags improved catch performance for both dredges, increasing market-sized scallop yields by 14–19% compared to conventional belly bags, the N-virodredge did not improve the catch of market-size scallops relative to the Newhaven dredge. The higher catches with skid belly bags are likely due to their added weight that may stabilize the dredge and increase the contact of the dredge teeth with the seabed, thereby improving catch efficiency (Fenton et al., 2014; Miller et al., 2019). The reason for lower catches with the N-Virodredge remain uncertain. Throughout the survey, efforts were made to sample similar areas for Newhaven and N-virodredges under consistent weather conditions, therefore the observed reduction in catch of market-sized scallops between Newhaven and N-virodredges is unlikely to be due to sampling bias. Rather, this may be related to differences in how its dredge teeth interact with the seabed. Catches for both the Newhaven and N-Virodredges were influenced by ground type, with higher market-sized scallop yields on stoney seabeds. While gear performance may have benefited from increased ground roughness, variations in scallop abundance and distribution could also explain differences between stoney and softer grounds. Scallop population abundance are known to be influenced by factors such as seabed roughness, cobbles, stones, water currents, and food availability (Beukers-Stewart et al., 2003; Orensanz et al., 2016). Additionally, since the survey was conducted in existing scallop fishing grounds, fishers may avoid stonier grounds to prevent their nets from filling with stones, potentially influencing observed scallop abundances. Further research may help to better understand the interaction between dredge design, seabed characteristics and seabed composition to optimize catch efficiency.

7.2 Improved catch selectivity (undersized scallops and stones)

One of the main barriers to uptake of fishing gear innovation is the potential for loss of catch and income unless this is offset by improved catch quality and/or reductions in operational costs such as fuel usage and gear maintenance. Our results show that the lower biomass of market-sized scallops caught by the N-virodredges, would be partially offset by the signficantly lower catches of undersized scallops (- 42%) and stones (- 67%), and partially by the lower fuel consumption (- 30%) of N-virodredges compared to Newhaven dredges. These reductions were consistent with previous studies. Gear trials in the Bay de Seine comparing N-Virodredges to spring-tooth dredges over three months across four vessels found significant reductions in retained stones and fuel savings of 12.2% – 31.4% (Filippi, 2013). Similar benefits were reported when the N-virodredge was compared to other scallop dredge types. Trials off the Îles-de-la-Madeleine in the Gulf of St Lawrence found that the N-Virodredge reduced stone capture by 50%, undersized scallop biomass, and fuel consumption by 20% relative to the Digby dredge (Chevarie & Chevarie, 2020). When compared to the New Bedford dredge, the N-Virodredge demonstrated improved fuel efficiency, reduced habitat impacts, and a 50% decrease in bycatch for most species (Bethony et al., 2023).

The increased selectivity of the N-Virodredge benefits the fishery in the long term by reducing bycatch of undersized scallops, which can experience negative physiological effects from repeated capture and release. Cumulative stress events, such as repeated dredging, can lower reproductive output as energy is diverted toward recovery (Kaiser et al., 2007). Maguire et al. (2002) found that dredged scallops exhibited slower righting and re-burial speeds, making them more vulnerable to predation. Additionally, captured undersized scallops have been shown to demonstrate reduced swimming efficiency (Jenkins & Brand, 2001), and exposure to air has been reported to impair their escape response (Jenkins & Brand, 2001), further increasing predation risk. Any increase in juvenile scallop mortality or decline in reproductive success could negatively impact the fishery, highlighting the need for selective gear like the N-Virodredge as part of a sustainable management strategy.

The lower proportion of stones in catches potentially allows for a more efficient and profitable practice, as less time would be required by vessel crew to sort the catches. Additionally, fewer retained stones mean reduced seabed disturbance, which is particularly important for maintaining habitat complexity and biodiversity. Emergent epifauna colonizing hard substrates, such as hydroids and bryozoans, serve as crucial settlement habitats for juvenile scallops (*Pecten maximus* and *Aequipecten opercularis*) (Bradshaw et al., 2003). These species are among the first species to be removed by fishing disturbance as repeated dredging and the subsequent return of stones to the seabed contribute to the selective removal of fragile species (Veale et al., 2000). Since small-scale habitat complexity plays a key role in structuring benthic communities, minimizing the retention and displacement of stones through modified dredging practices could help preserve essential biological structures, ultimately benefiting both the ecosystem and the long-term viability of the scallop fishery.

7.3 Reduced fuel consumption and CO_2 emissions

As climate change concerns continue to increase, fuel consumption and the associated carbon emissions by the fisheries sector are under scrutiny. For the *P.maximus* fishery, fuel use is estimated at 0.541 litres of fuel per kg of scallop meat, translating to around 8.6 to 13.61 CO2e kg− 1 scallop meat (Bloor et al., 2021; Walsh, 2010). This sector has been identified as a high emissions and low yield meat, with the intensity of its fuel use outweighing the return in product (Cortés et al., 2022). In view of this and of increasing fuel prices, the drive to create a sustainable fishery with lower CO_2 emissions and economical operation is critical.

Although fuel consumption did not differ between gears with and without skid belly bags, the N-virodredge resulted in significantly lower fuel consumption relative to the Newhaven dredge. This reduction is likely due to a number of factors, primarily due to the lower optimal towing speed of the N-virodredge (approximately 2 knots) compared to the Newhaven dredge (around 3 knots), and the indivudally sprung tines and skids on dredge frame that are likely to result in lower drag on the seabed. Towing at a lower vessel speed is a fuel-saving strategy that enhances economic viability while simultaneously reducing the environmental footprint of fishing operations. Ultimately, the optimal towing speed fishermen adopt will depend on the catch efficiency – towing speed relationship, which will be influenced by wave action and wind acting on the vessel, design of the propulsion system, drag of the gear in the water and ground type (Walsh, 2010; Suuronen et al., 2012; Poos et al., 2013). In keeping with our results, other bottom fishing gear have witnessed 23 to 43% reductions in fuel consumption following gear modifications (Herrera-González et al., 2021; Suuronen et al., 2012). While no empirical estimates of the effect of vessel speed on fuel consumption are available for scallop dredgers, Prat et al. (2008) modeled otter trawl gear drag as scaling with the square of speed. Future research should measure fuel use in scallop dredgers, similar to studies on semi-pelagic trawlers in the Adriatic (Sala et al., 2011), and examine catch efficiency as a function of towing speed.

7.4 The retained bycatch

Improving the survival rates of discarded catch is increasingly recognized as a critical factor in enhancing the long-term sustainability of fisheries (Roberts et al., 2024). By minimizing post-capture mortality, particularly for undersized or non-target species, fisheries can help maintain healthy stock levels and support ecosystem balance. Our results showed that injury severity and survivability of bycatch species was species-specific, and survival rates were closely linked to the extent of damage sustained. Species with robust shells, such as scallops, predominantly suffered minor damage, such as shell chippings, and exhibited low mortality, with only 2 – 3% of the catch sustaining major or fatal injuries (D3 & D4). In contrast, more fragile species, such as echinoids, and those with limited regenerative capacity, such as decapods, were significantly more vulnerable to dredging. For these species, severe injuries (D3–D4) exceeded 40%, with over half of affected individuals succumbing within seven days. Starfish are known for their regenerative abilities, often shedding limbs, a process called autonomy, in response to injury or threat (Bergmann, 2001). Bergmann (2001) suggested that *Asterias rubens*, another species observed in this study, could recover from fishing stress relatively quickly. However, individuals that experienced induced autonomy saw a 10% increase in mortality. Aside from physical damage, factors such as handling time and time spent on deck play a significant role in the survival of discarded species. Although these factors were not directly assessed in this study, existing literature indicates their importance (Breen & Catchpole, 2021). In our study, handling time and air exposure were monitored regularly and kept similar among hauls to avoid handling bias.

None of the modified dredge gear examined in this study succesfully reduced bycatch rates or improved bycatch survivability compared to the Newhaven dredge. The use of skid belly bags resulted in higher bycatch catches consistent with findings from Sciberras et al. (2022). While the N-Virodredge effectively reduced stone retention, this benefit did not extend to bycatch fauna. Although its tines generate less resistance than the fixed tooth bar of the Newhaven dredge, they probably still exert enough force to dislodge fauna from the seabed. One potential strategy to reduce bycatch could involve increasing the spacing between dredge teeth; however, this may come at the cost of scallop catch efficiency. Alternative gear designs, such as the Hydrodredge—which replaces dredge teeth with hydrocups that create a downward jet to lift scallops from the seabed—have demonstrated reductions in both dead scallops and bycatch compared to the Newhaven dredge (Shephard et al., 2009). However, the Hydrodredge was 10–40% less efficient at catching king scallops, rendering it commercially unviable despite its bycatch benefits (Shephard et al., 2009). Although we did not find a significant relationship between the amount of stone in the catch and fauna damage, other studies indicate that shorter tow durations, which result in lower stone retention and reduced abrasion time, could help minimize bycatch injury (Bradshaw et al., 2001; Howarth & Stewart, 2014).

7.5 Seabed impact

Scallop dredge gear fitted with skids caused the least disturbance to the seabed, producing a smaller benthic footprint due to the narrower furrows they created compared to standard belly bags. However, differences emerged within gear types: for example, Newhaven dredges with skid bellies formed significantly larger furrows in sandy habitats than in stony ones. This is likely due to the retaining bag becoming heavier as it fills with catch, bycatch, stones, and other debris, causing it to sink deeper into softer sediments (Sciberras et al., 2022). In contrast, this effect was not observed in stoney habitats, where the gear's weight is supported by bedrock and other stable substrates, resulting in shallower furrows (Howarth and Stewart, 2014). While standard belly bags distribute weight more evenly over a broader surface area, skids concentrate pressure over a smaller area, which is likely to influence gear penetration depth. It was not possible to measure gear penetration depth accurately in this study. Future research directly comparing the penetration depth of skid versus standard belly bags across different sediment types would enhance our understanding of gear-seabed interactions.

Results demonstrated that fauna depletion was lowest for N-virodredge with skid belly bags, and was considerably less than the depletion by dredges with standard belly bags that led to an average 20% reduction in fauna abundance inside the dredge lanes relative to outside. The disturbance of standard scallop dredges on marine benthic habitats is well documented (Boulcott et al., 2014; Bradshaw et al., 2001; Howarth and Stewart, 2014; Kaiser et al., 2006; Roberts et al., 2024; Smith et al., 2025). The combination of the N-virodredge with a skid belly bag presents a promising solution, offering gear selectivity and reduced seabed impact. However, while this modification mitigates some environmental damage, it does not eliminate it entirely.

7.6 Conclusion

The EASIG project has shown that gear modifications—particularly the use of N-viro dredges with skid belly bags—offer a practical way to reduce the environmental impact of scallop dredging in UK waters. This configuration led to significant reductions in fuel consumption, carbon emissions, seabed disturbance, and the catch of undersized scallops and stones.

However, from both ecological and economic standpoints, it is essential that new gear does not compromise profitability or inadvertently increase environmental harm. Certain configurations, such as adding skids to traditional Newhaven dredges, illustrate potential trade-offs. While this setup improved the catch of market-sized *Pecten maximus*, it did not reduce fuel use, bycatch, juvenile scallop retention, or debris collection. In contrast, N-viro dredges were more effective in reducing juvenile catch and seabed disruption, though they only improved the harvest of marketable scallops when skids were also included.

These examples highlight the importance of evaluating gear performance holistically. The feasibility of adoption also hinges on economic considerations: if modifications are too costly relative to the benefits, uptake within the industry will likely be limited. Nevertheless, the combination of N-viro dredges and skid belly bags represents a promising step toward more sustainable scallop fishing, delivering tangible environmental benefits without sacrificing catch efficiency.

Ultimately, the success of gear innovations depends on their integration within a broader, adaptive fisheries management framework. Given the sedentary nature of *P. maximus*—which makes it especially vulnerable to overfishing—additional measures such as effort controls, co-management models, and rights-based systems like Territorial Use Rights for Fisheries (TURFs) should be explored. While technical modifications are valuable tools, their full potential can only be realized when aligned with comprehensive strategies that safeguard both the sustainability of the resource and the livelihoods it supports.

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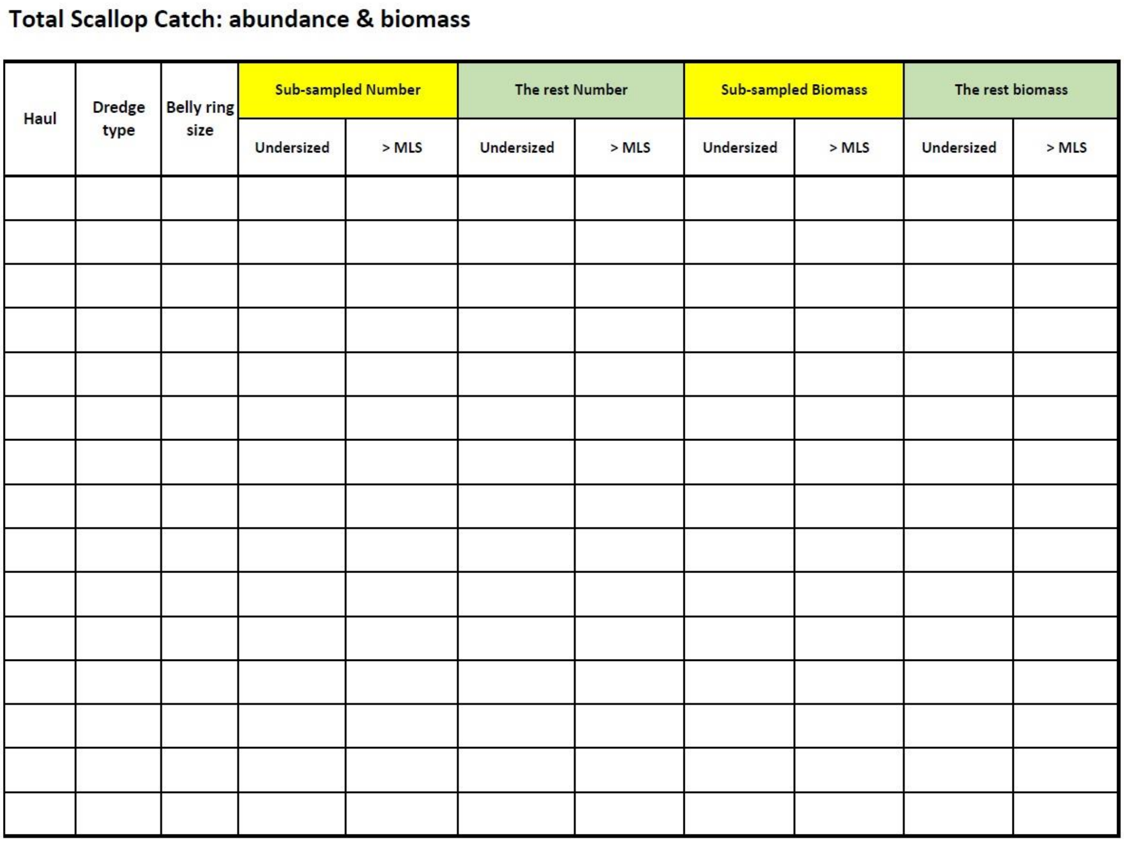
Supplementary material

Appendices below are separated by the respective work packages. Included in this section are recording sheets used during fieldwork for each work package and supplementary images and tables that showcase the disturbance and impacts of the modified scallop dredges.

Appendix A: Work Package 1 – Gear Catchability

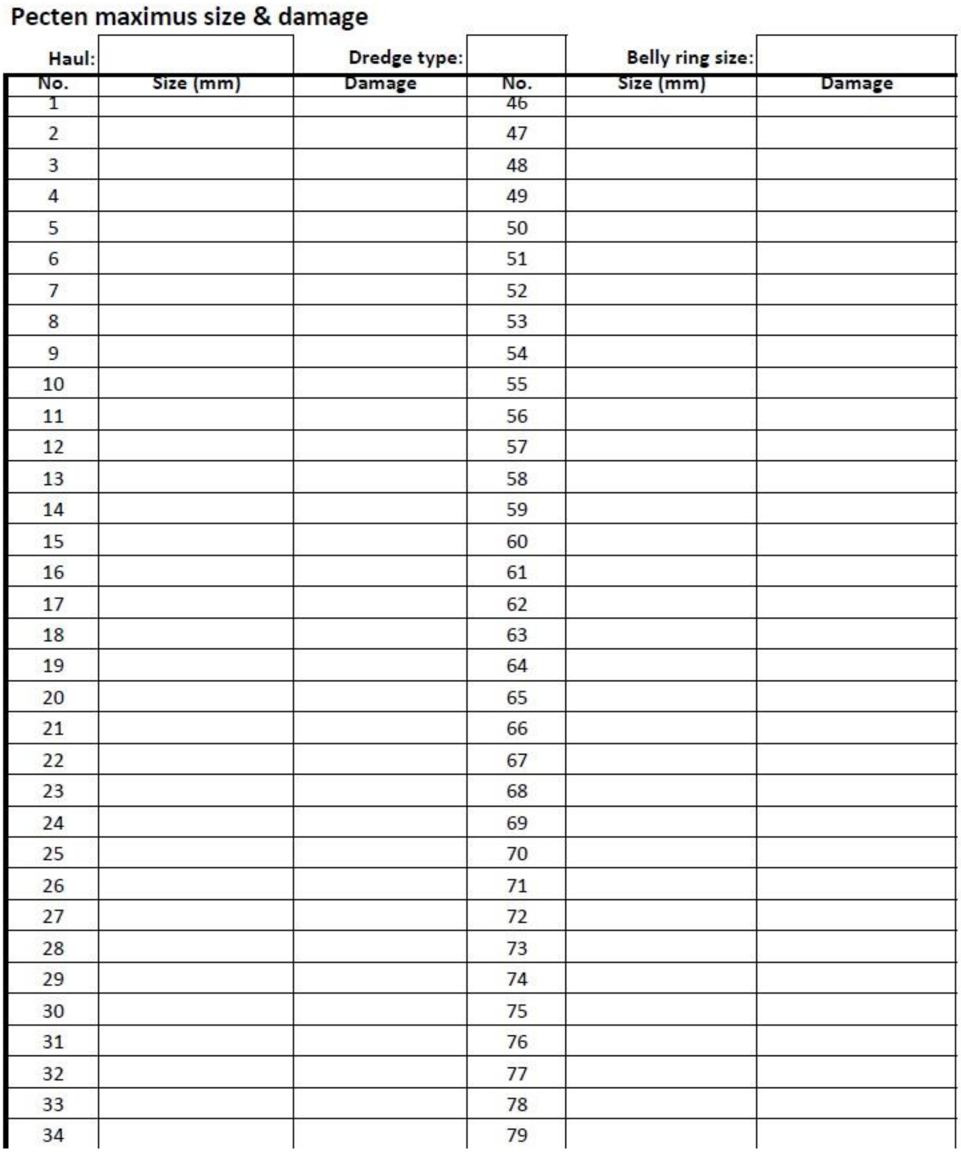
Table A1: WKP1 recording sheet used to collect the abundance and biomass of *P.maximus* for all modified scallop dredges assessed.



Total Scallop Catch: abundance & biomass

Haul	Dredge type	Belly ring size	Sub-sampled Number		The rest Number		Sub-sampled Biomass		The rest biomass	
			Undersized	> MLS	Undersized	> MLS	Undersized	> MLS	Undersized	> MLS

Table A2: WKP1 recording sheet for P.maximus size and damage scores collected for each modified scallop dredge. Sheets were separated by the dredge type and the size of belly ring used. Damage scores were based on the table presented in appendix ?.



Pecten maximus size & damage

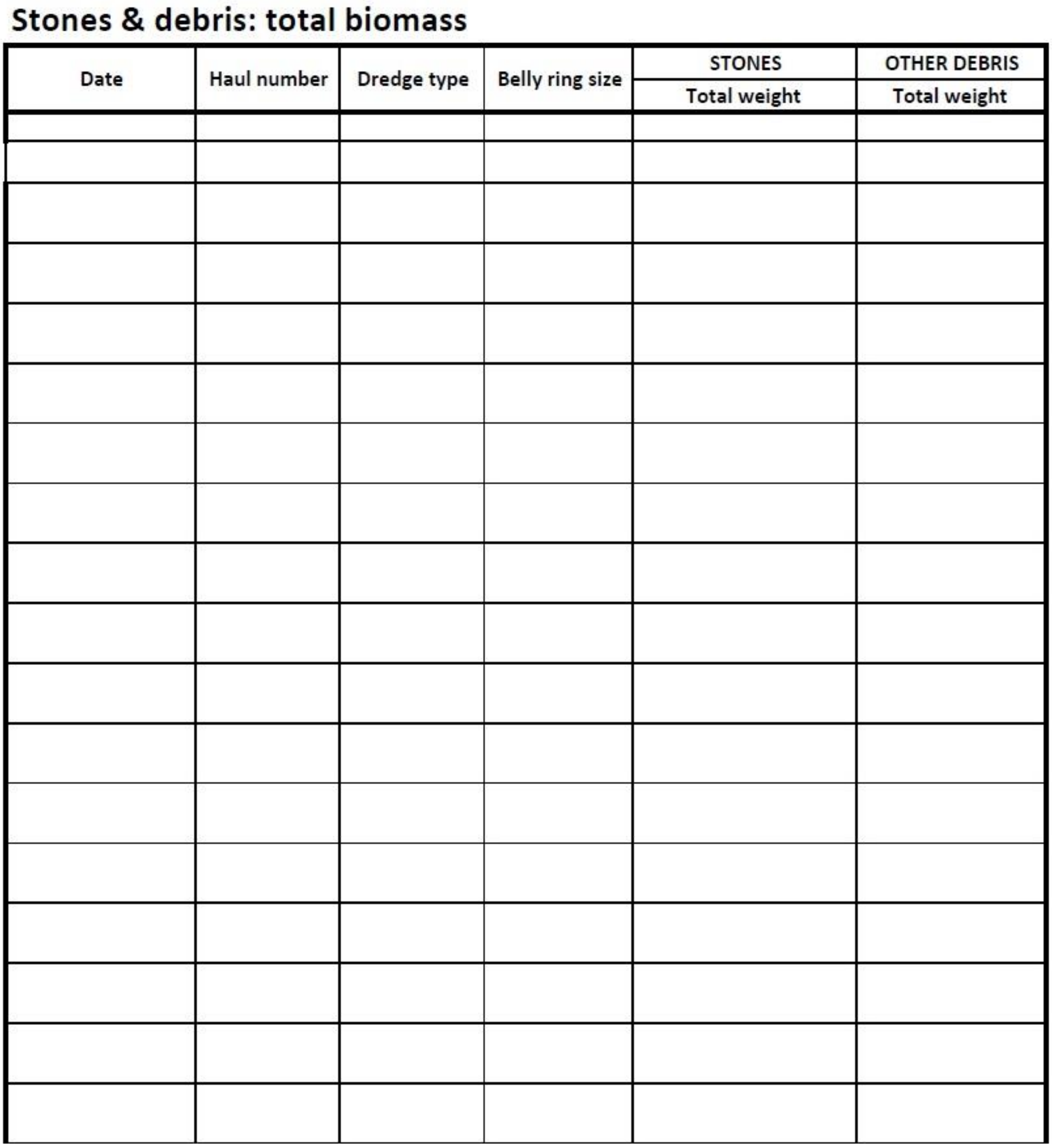
Haul:

Dredge type:

Belly ring size:

No.	Size (mm)	Damage	No.	Size (mm)	Damage
1			46		
2			47		
3			48		
4			49		
5			50		
6			51		
7			52		
8			53		
9			54		
10			55		
11			56		
12			57		
13			58		
14			59		
15			60		
16			61		
17			62		
18			63		
19			64		
20			65		
21			66		
22			67		
23			68		
24			69		
25			70		
26			71		
27			72		
28			73		
29			74		
30			75		
31			76		
32			77		
33			78		
34			79		

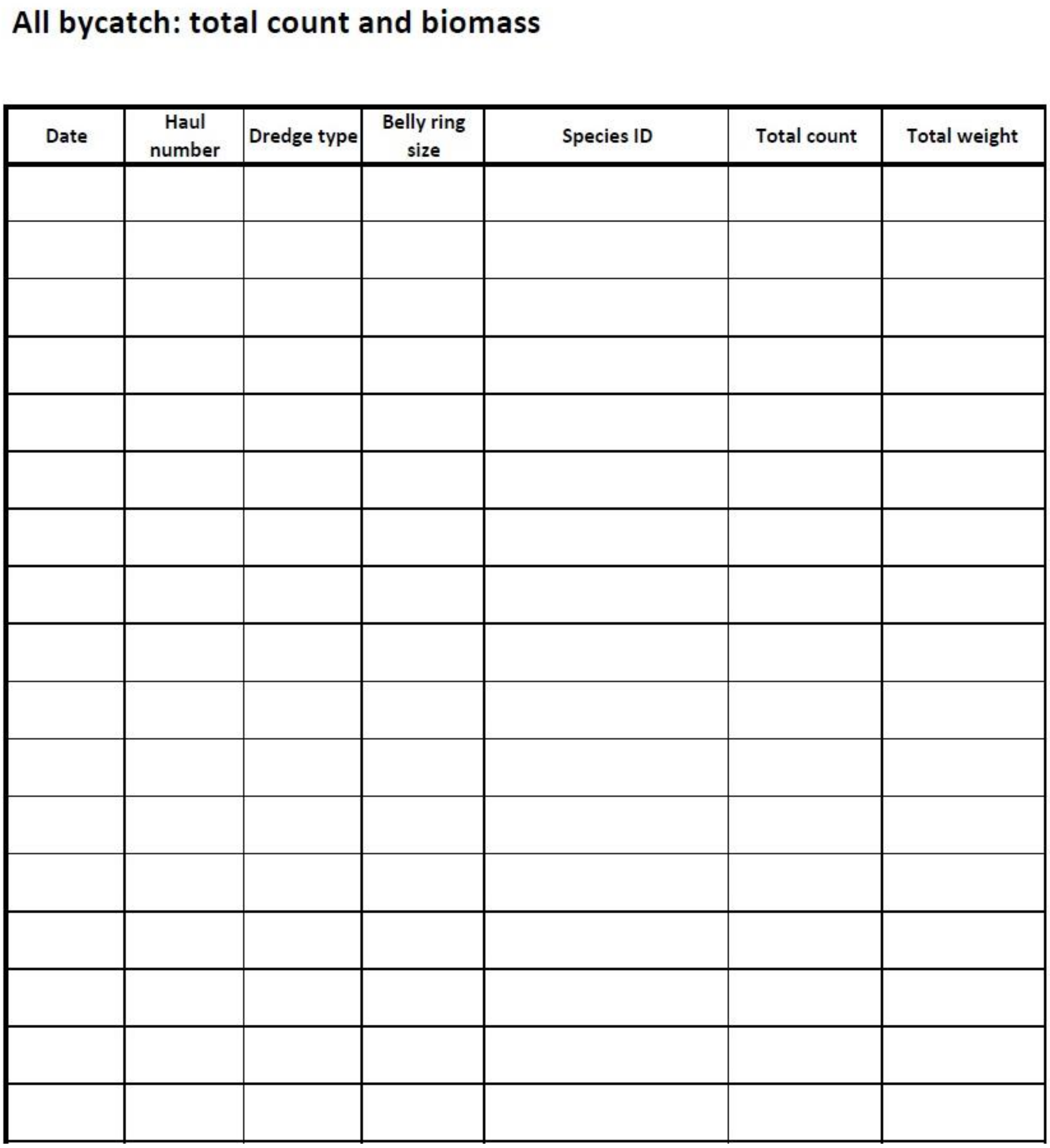
Table A3: WKP1 recording sheet for the weight of stone and debris collected for all modified scallop dredges assessed. The weight of stone and debris were separated before measurement. Recordings were separated by the dredge type and the belly ring size used.



Stones & debris: total biomass

Date	Haul number	Dredge type	Belly ring size	STONES	OTHER DEBRIS
				Total weight	Total weight

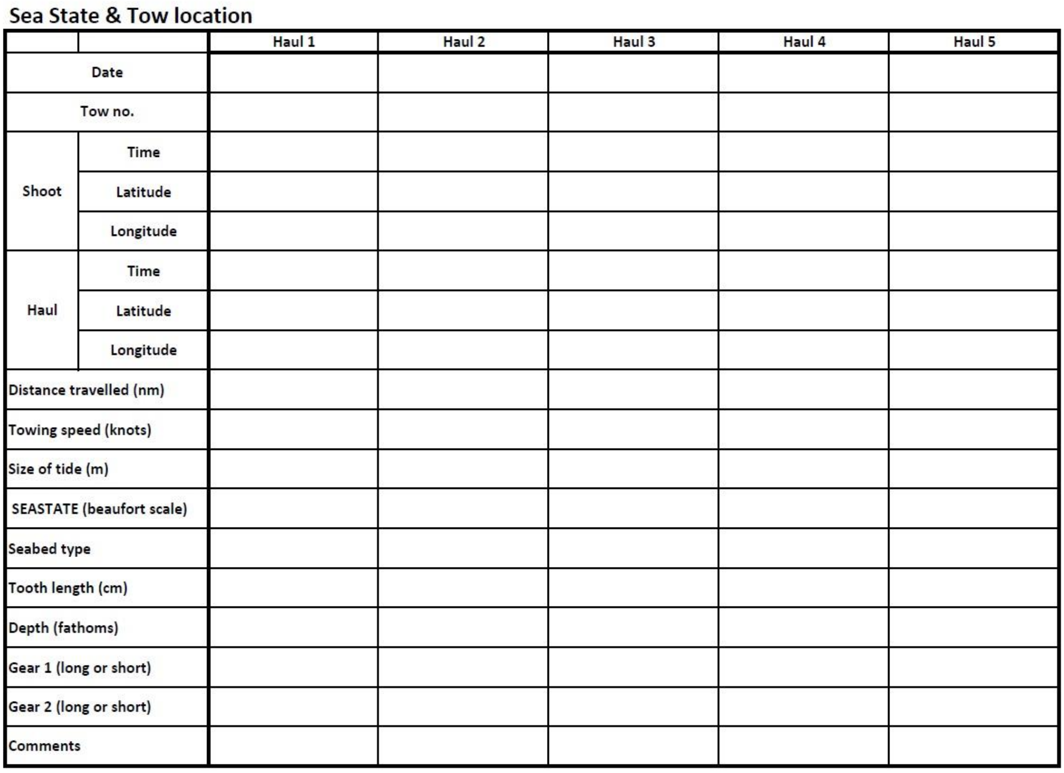
Table A4: WKP1 recording sheet for the bycatch species collected by each modified scallop dredge. The abundance of each species collected, and the biomass is recorded, separated by the dredge type and belly ring size used.



All bycatch: total count and biomass

Date	Haul number	Dredge type	Belly ring size	Species ID	Total count	Total weight

Table A5: Recording sheet for the sea state and other environmental parameters during the WKP1 fieldwork. This recording sheet was also used in WKP2 to collect the same data.



Sea State & Tow location

		Haul 1	Haul 2	Haul 3	Haul 4	Haul 5
Date						
Tow no.						
Shoot	Time					
	Latitude					
	Longitude					
Haul	Time					
	Latitude					
	Longitude					
Distance travelled (nm)						
Towing speed (knots)						
Size of tide (m)						
SEASTATE (beaufort scale)						
Seabed type						
Tooth length (cm)						
Depth (fathoms)						
Gear 1 (long or short)						
Gear 2 (long or short)						
Comments						

Table A6: Species list for bycatch species caught across all scallop dredge designs in the Outer Hebrides, Scotland.

Species name	Class
Luidia ciliaris	Asteroidea
Asterias rubens	Asteroidea
Marthasterias glacialis	Asteroidea
Porania pulvillus	Asteroidea
Anseropoda placenta	Asteroidea
Stichastrella rosea	Asteroidea
Astropecten irregularis	Asteroidea
Crossaster papposus	Asteroidea
Henricia oculata	Asteroidea
Henricia sanguinolenta	Asteroidea
Glycymeris Glycymeris	Bivalvia
Arctica islandica	Bivalvia
Octopus vulgaris	Cephalopoda
Loligo vulgaris	Cephalopoda
Antedon petasus	Crinoidea
Echinus esculentus	Echinoidea
Psammechinus miliaris	Echinoidea
Raja Clavata	Elasmobranchii
Dipturus nidarosiensis	Elasmobranchii
Leucoraja naevus	Elasmobranchii
Raja montagui	Elasmobranchii
Buccinum Undatum	Gastropoda
Nudibranch	Gastropoda
Cancer pagurus	Malacostraca
Munida rugosa	Malacostraca
Necora puber	Malacostraca
Pagurus prideaux	Malacostraca
Liocarcinus depurator	Malacostraca
Box Crab	Malacostraca
Inachus sp.	Malacostraca
Carcinus maenas	Malacostraca
Alcyonium digitatum	Octocorallia
Ophiura Ophiura	Ophiuroidea
Aphrodita aculeata	Polychaeta
Limanda limanda	Teleostei
Plueronectes platessa	Teleostei
Lepidorhombus whiffiagonis	Teleostei
Chelidonichthys cuculus	Teleostei
Lophius piscatorius	Teleostei

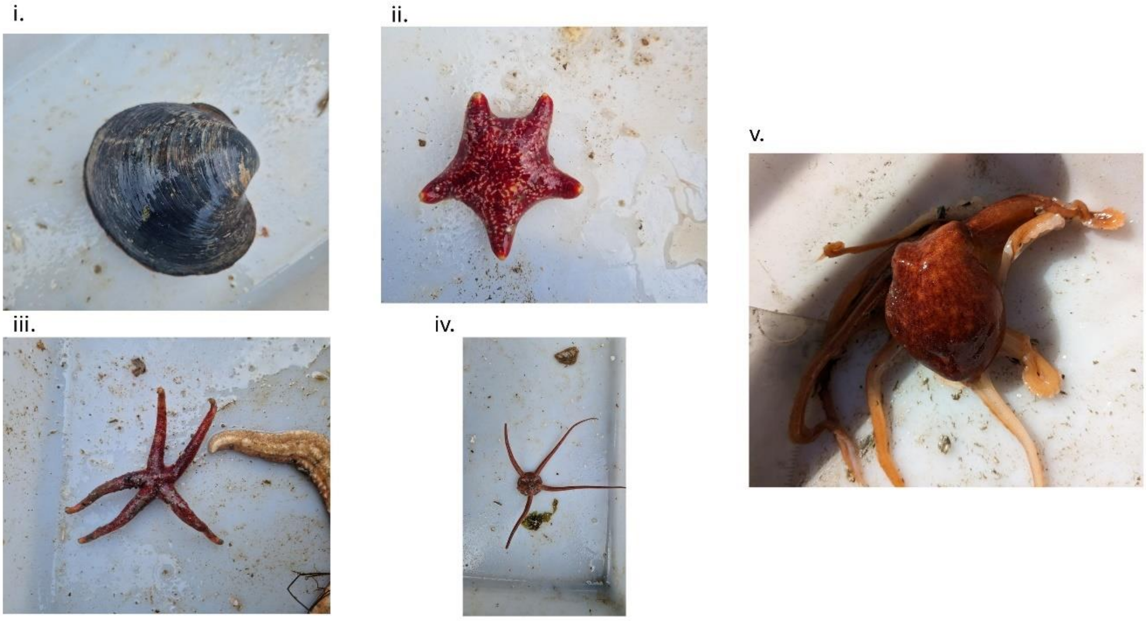


Figure A1: Bycatch species caught across all scallop dredge designs during the survey campaigns in the Outer Hebrides, Scotland. (i) *Arctica islandica*, (ii) *Porania pulvillus*, (iii) *Henricia oculata*, (iv) *Ophiura Ophiura*, (v) *Octopus vulgaris.*

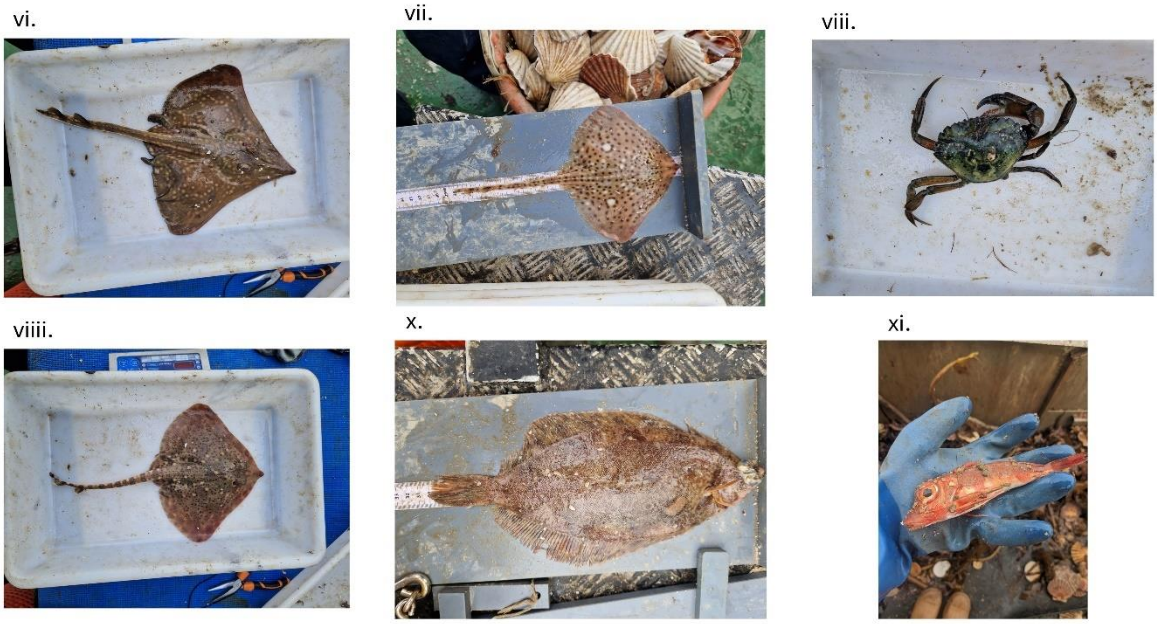
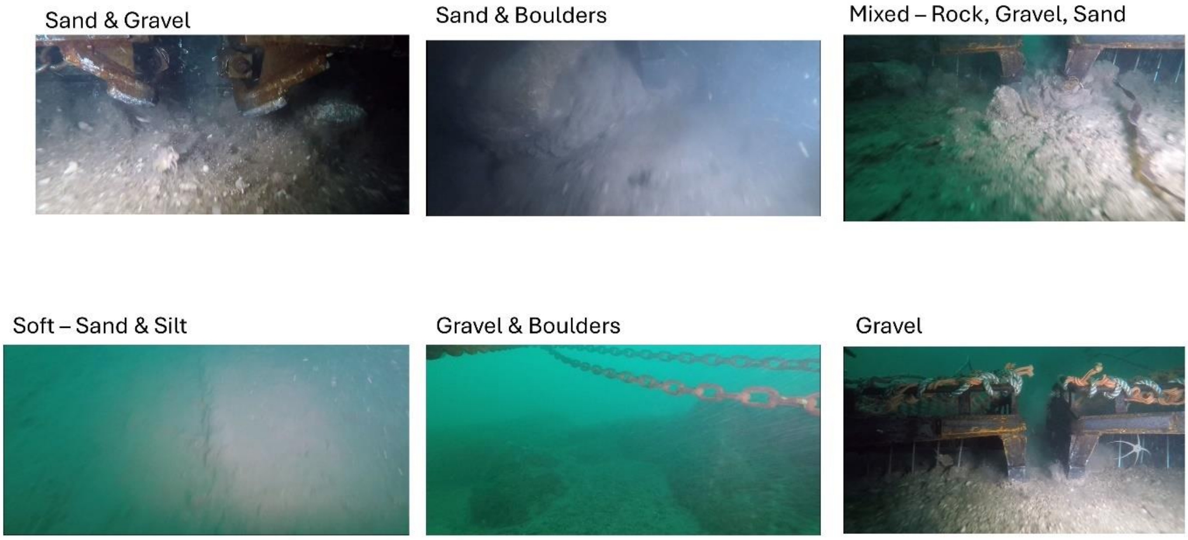


Figure A2: Bycatch species caught across all scallop dredge designs during the survey campaigns in the Outer Hebrides, Scotland; (vi) *Dipturus nidarosiensis*, (vii) *Raja montagui*, (viii) *Carcinus maenas*, (viiii) *Raja Clavata*, (x) *Limanda limanda*, (xi) *Chelidonichthys cuculus.*



Sand & Gravel

Sand & Boulders

Mixed – Rock, Gravel, Sand

Soft – Sand & Silt

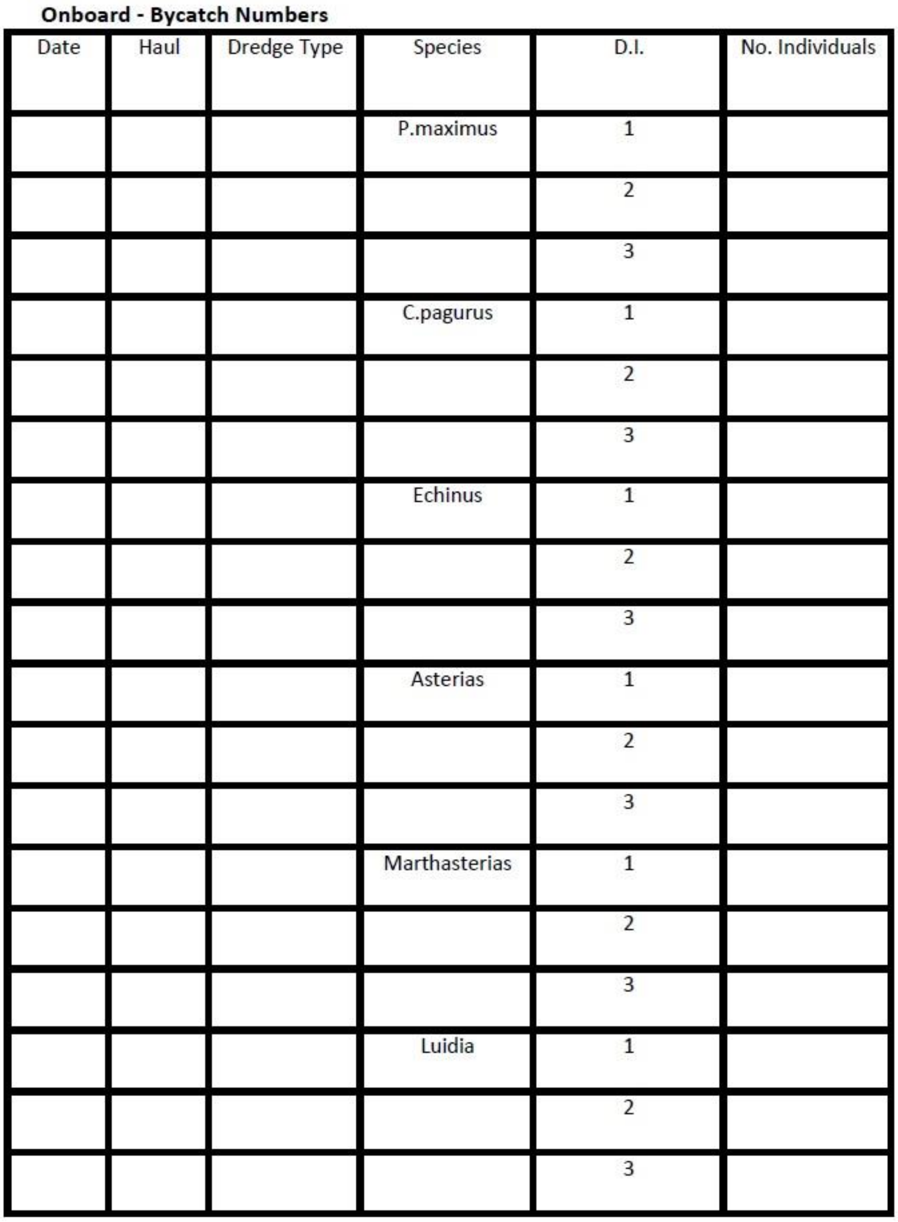
Gravel & Boulders

Gravel

Figure A3: Still images of the varying seabed types in the Outer Hebrides, Scotland. As presented in Figure 3.1, these seabed types were grouped into two separate categories, one representing the rock-based seabed types and the other representing the finer, soft sediment.

Work Package 2 – Bycatch Survivability

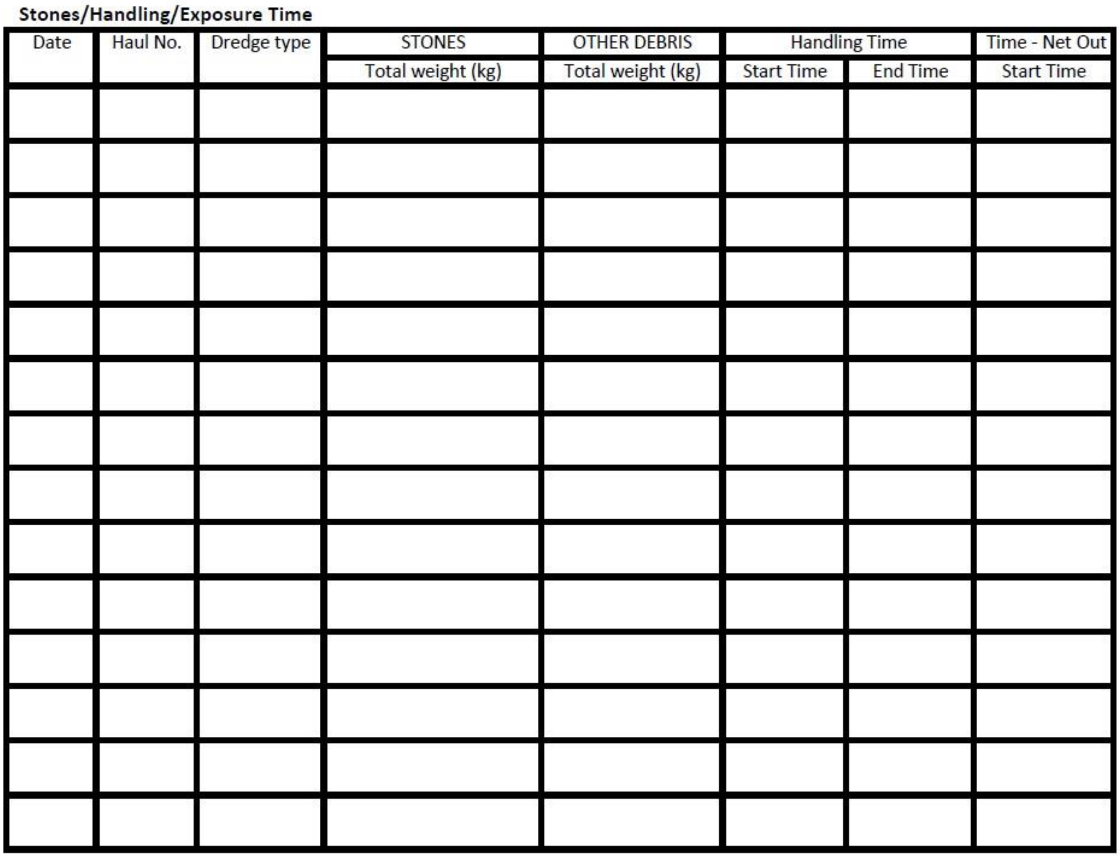
Table 2A: Recording sheet for the number of individuals caught during each haul for WKP2 separated by each damage score. Data sheets were separated by the gear type also to prevent any mixing of data.



Onboard - Bycatch Numbers

Date	Haul	Dredge Type	Species	D.I.	No. Individuals
			P.maximus	1	
				2	
				3	
			C.pagurus	1	
				2	
				3	
			Echinus	1	
				2	
				3	
			Asterias	1	
				2	
				3	
			Marthasterias	1	
				2	
				3	
			Luidia	1	
				2	
				3	

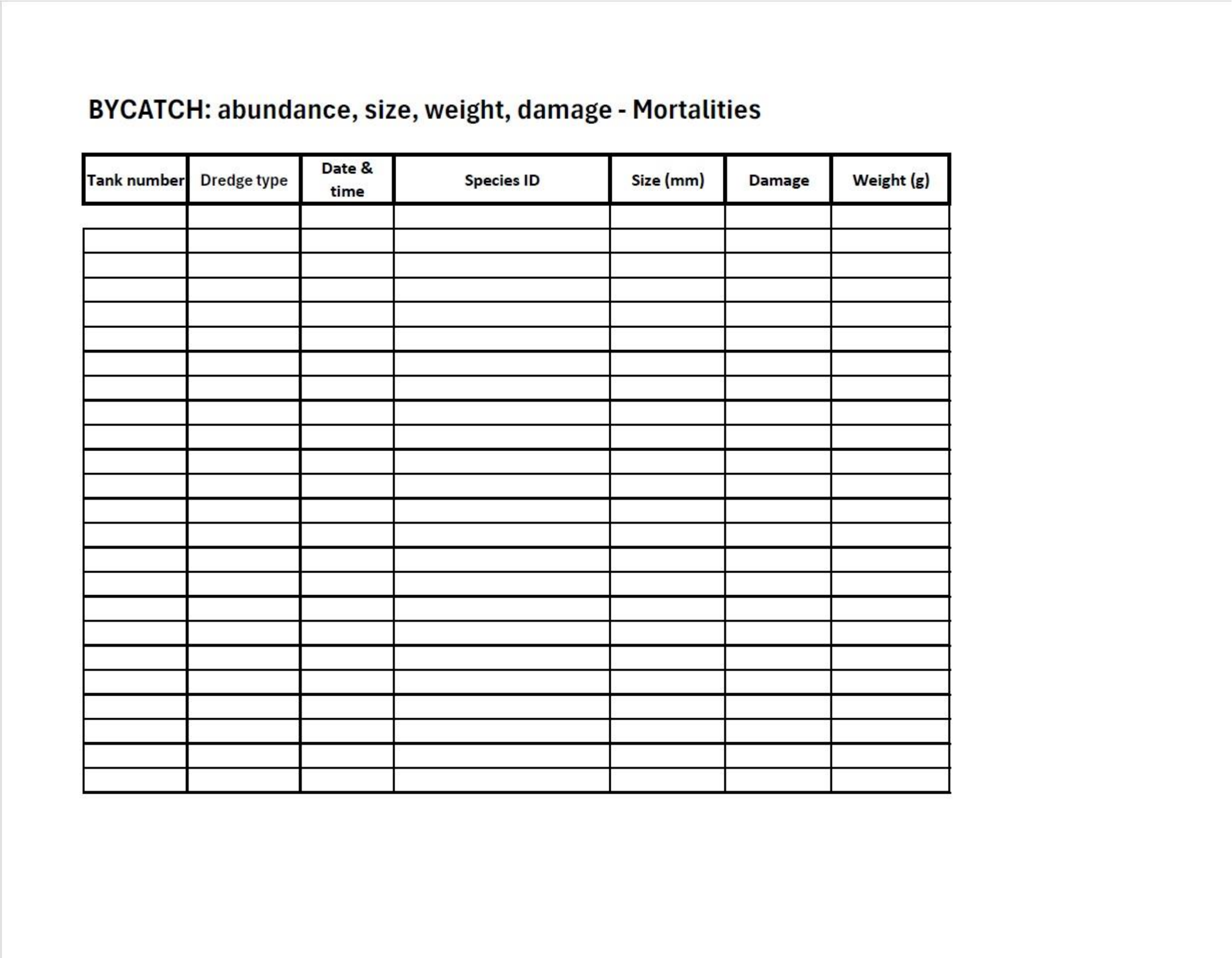
Table 2B: Recording sheet for the stone and debris collected during the bycatch survivability hauls. Included in the recording sheet is a section for the handling time and air exposure time. Both handling time and air exposure end times corresponded with the last individual entering the on deck holding tank.



Stones/Handling/Exposure Time

Date	Haul No.	Dredge type	STONES	OTHER DEBRIS	Handling Time		Time - Net Out
			Total weight (kg)	Total weight (kg)	Start Time	End Time	Start Time

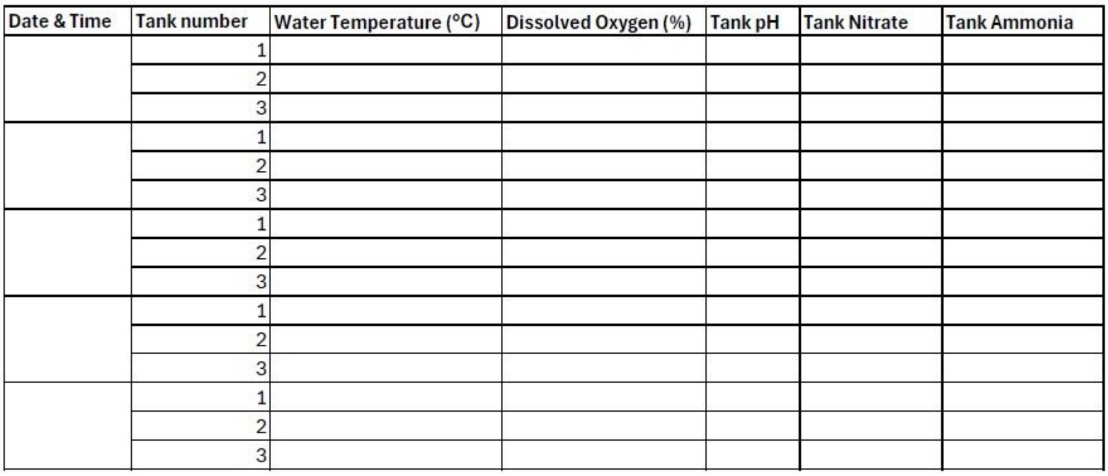
Table 2C: Recording sheet for mortalities and survivors following bycatch survivability monitoring (mortality sheet shown). Separate sheets were created for the survivors and mortalities per gear type.



BYCATCH: abundance, size, weight, damage - Mortalities

Tank number	Dredge type	Date & time	Species ID	Size (mm)	Damage	Weight (g)

Table 2D: Recording sheet for the sea water parameters monitored over the bycatch survivability period. Sheets were separated by the gear type to prevent any mixing of data.



Date & Time	Tank number	Water Temperature (°C)	Dissolved Oxygen (%)	Tank pH	Tank Nitrate	Tank Ammonia
	1					
	2					
	3					
	1					
	2					
	3					
	1					
	2					
	3					
	1					
	2					
	3					
	1					
	2					
	3					

Figure 2E: Still images of the damage specific to each damage index score for *P.maximus*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.

Damage Index 1

Damage Index 2

Damage Index 3

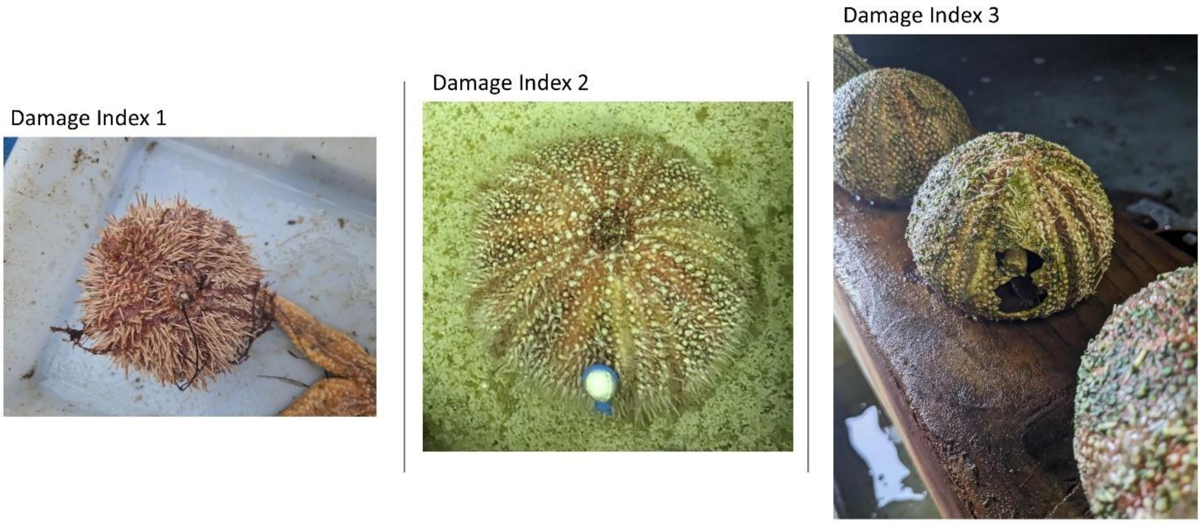
Figure 2F: Still images of the damage specific to each damage index score for *Cancer pagurus*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.

Damage Index 1

Damage Index 2

Damage Index 3

Figure 2G: Still images of the damage specific to each damage index score for *Luidia ciliaris*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.

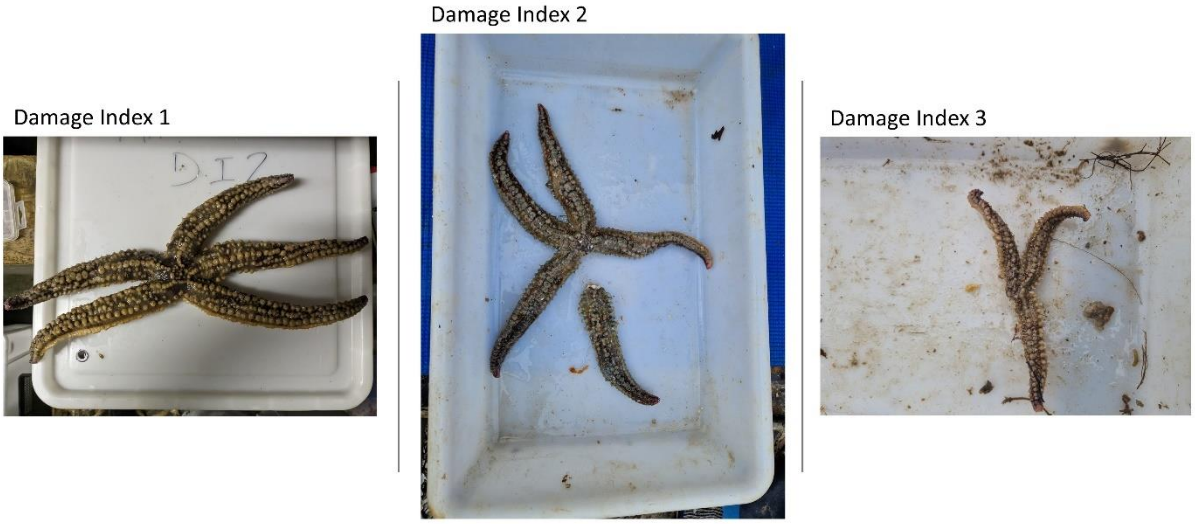


Damage Index 1

Damage Index 2

Damage Index 3

Figure 2H: Still images of the damage specific to each damage index score for *Echinus esculentus*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.



Damage Index 1

Damage Index 2

Damage Index 3

Appendix 2I: Still images of the damage specific to each damage index score for *Marthasterias glacialis*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.


Damage Index 1

Damage Index 2

Damage Index 3

Figure 2J: Still images of the damage specific to each damage index score for *Asterias rubens*. Such still images were used during WKP1 and WKP2 to assess the damage of the individuals caught by the various dredge designs.

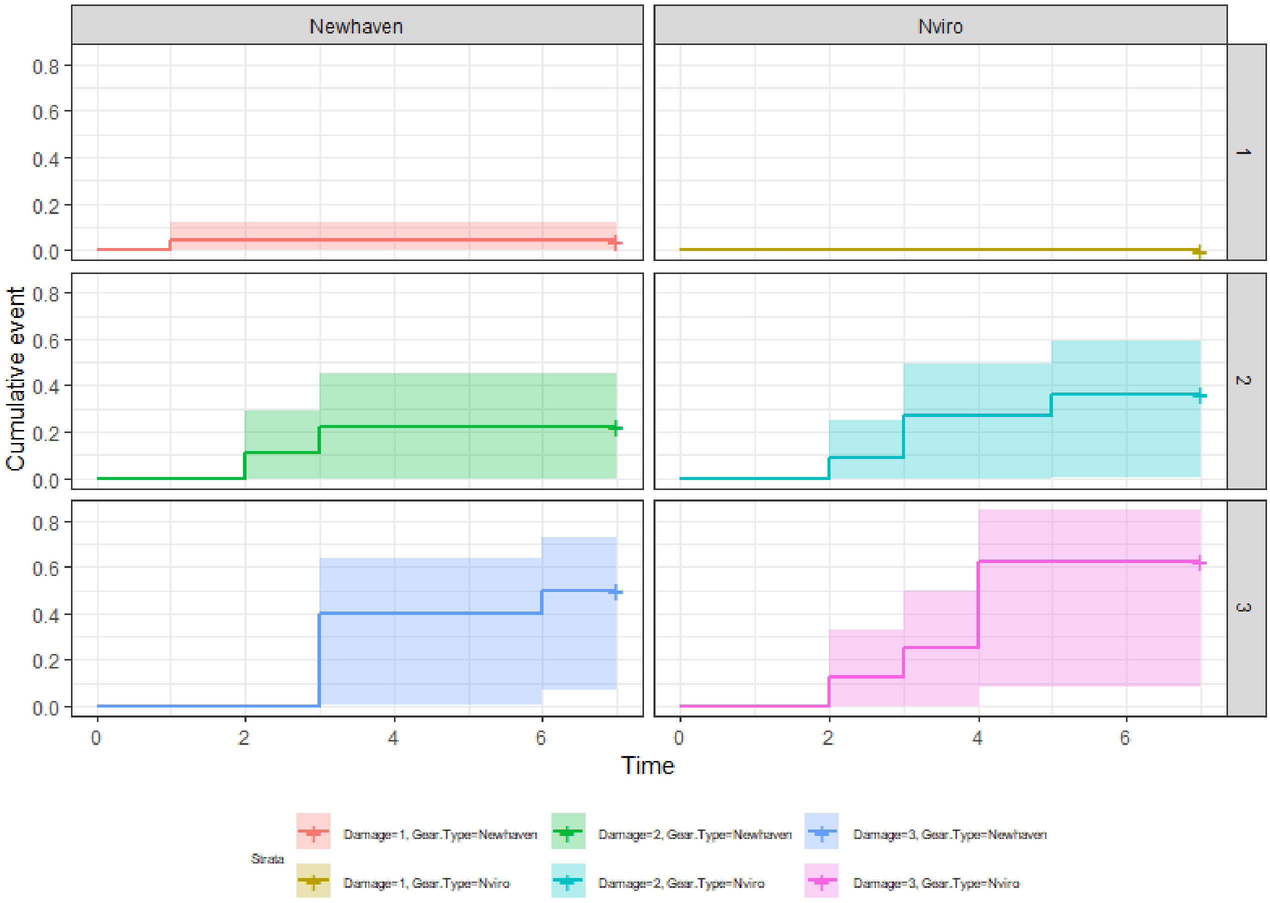


Figure 2K: Survival curves of *Asterias rubens* across both scallop dredge gear and all damage index score. Data presented as the percentage increase in mortality across the 7-day monitoring period.

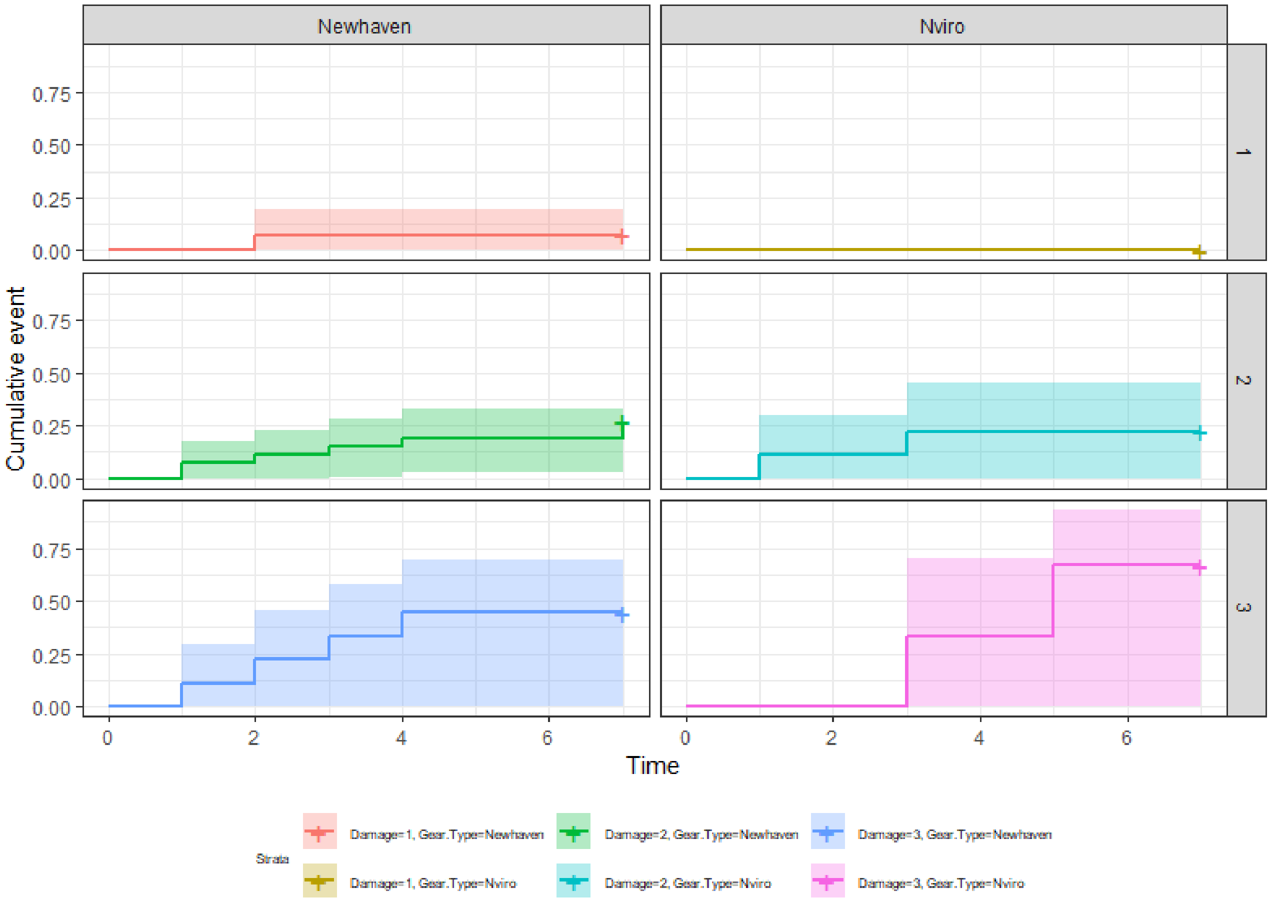


Figure 2L: Survival curves of *Cancer pagurus* across both scallop dredge gear and all damage index score. Data presented as the percentage increase in mortality across the 7-day monitoring period.

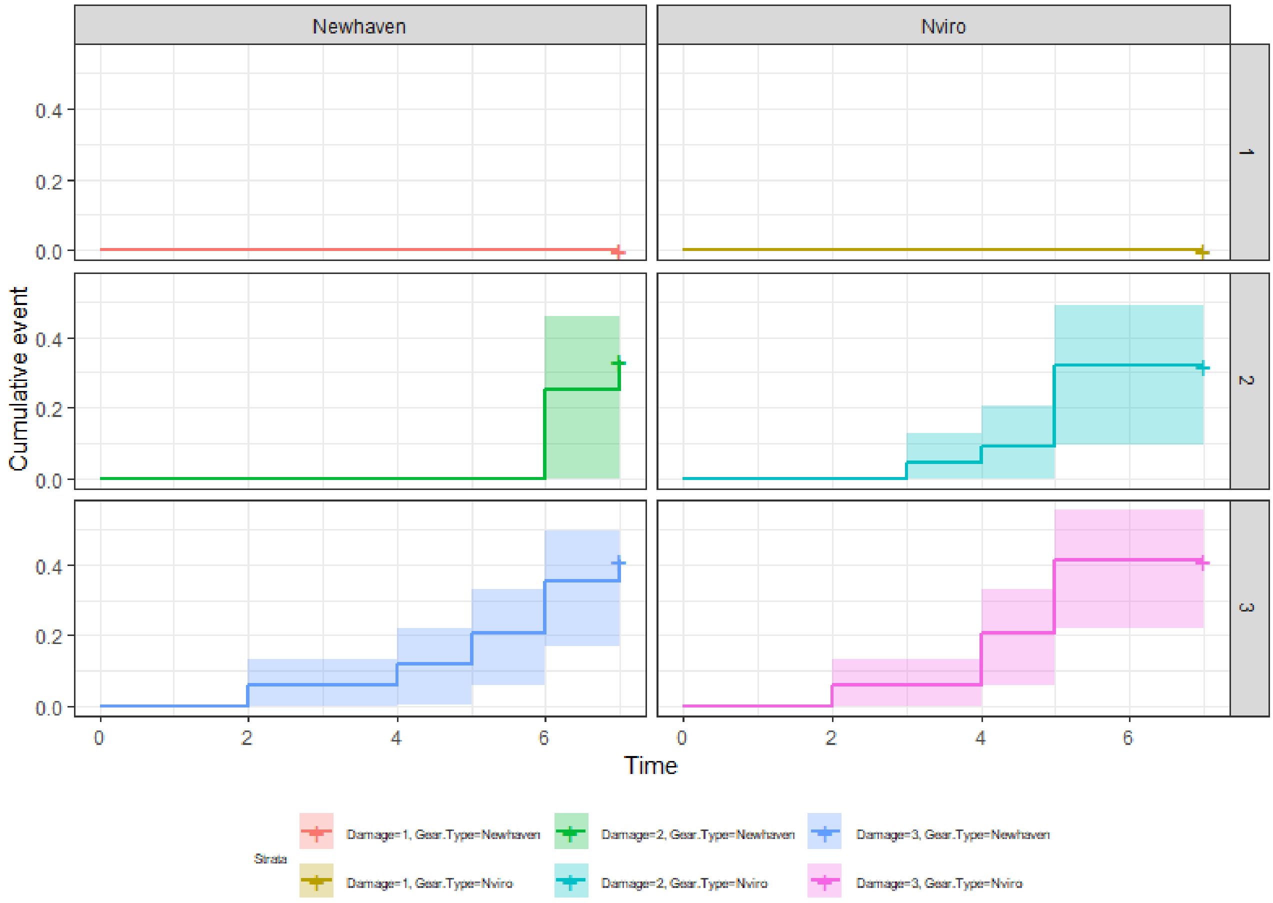
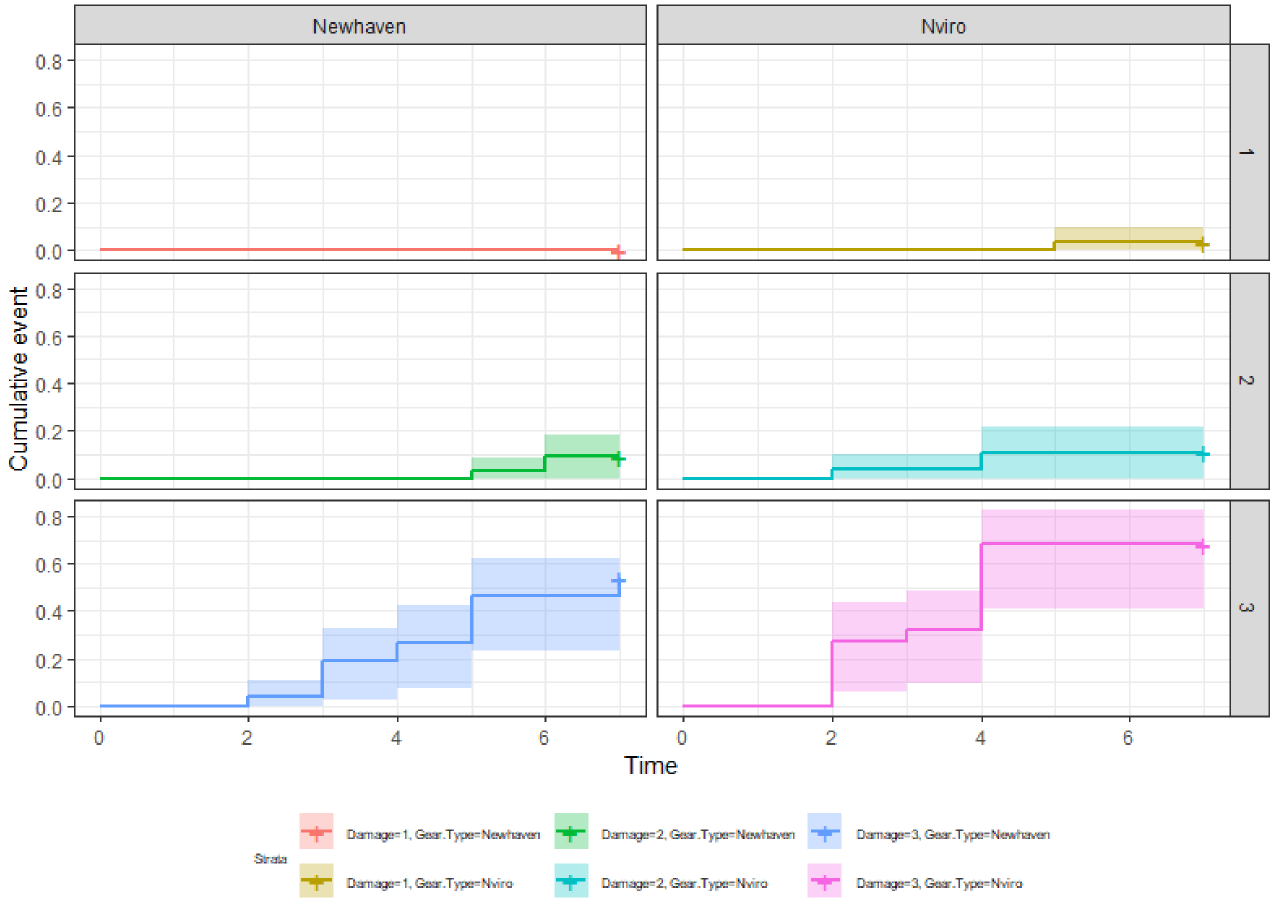


Figure 2M: Survival curves of *Luidia ciliaris* across both scallop dredge gear and all damage index score. Data presented as the percentage increase in mortality across the 7-day monitoring period.



Appendix 2N: Survival curves of *Pecten maximus* across both scallop dredge gear and all damage index score. Data presented as the percentage increase in mortality across the 7-day monitoring period.

Work Package 3 – Fuel Efficiency

Table 3A: Fuel consumption recording sheet. Sheets were sent via PDF or by post to the skippers of each fishing vessel. Sheets were returned by email or post, and values were extracted into an excel sheet prior to statistical analysis. Vessels were encouraged to indicate if the dredges in use were using the standard retaining belly bags or those with skids.

Fuel Consumption per HAUL (in litres) **Vessel name:** Standard ☐ Skids ☐

Date	Time	Fuel (litres)	GPS location	Vessel speed (knots)	Depth (fathoms)	Tidal current (m/s)	Seabed type	Curnt direction on dredges	Distance travelled (nm)	SEASTATE (beaufort scale)
							sft/med/hard	*Agnst/acrs/wth*		
	START	START	LAT							
	END	END	LONG							
	START	START	LAT							
	END	END	LONG							
	START	START	LAT							
	END	END	LONG							
	START	START	LAT							
	END	END	LONG							
	START	START	LAT							
	END	END	LONG							
	START	START	LAT							
	END	END	LONG							

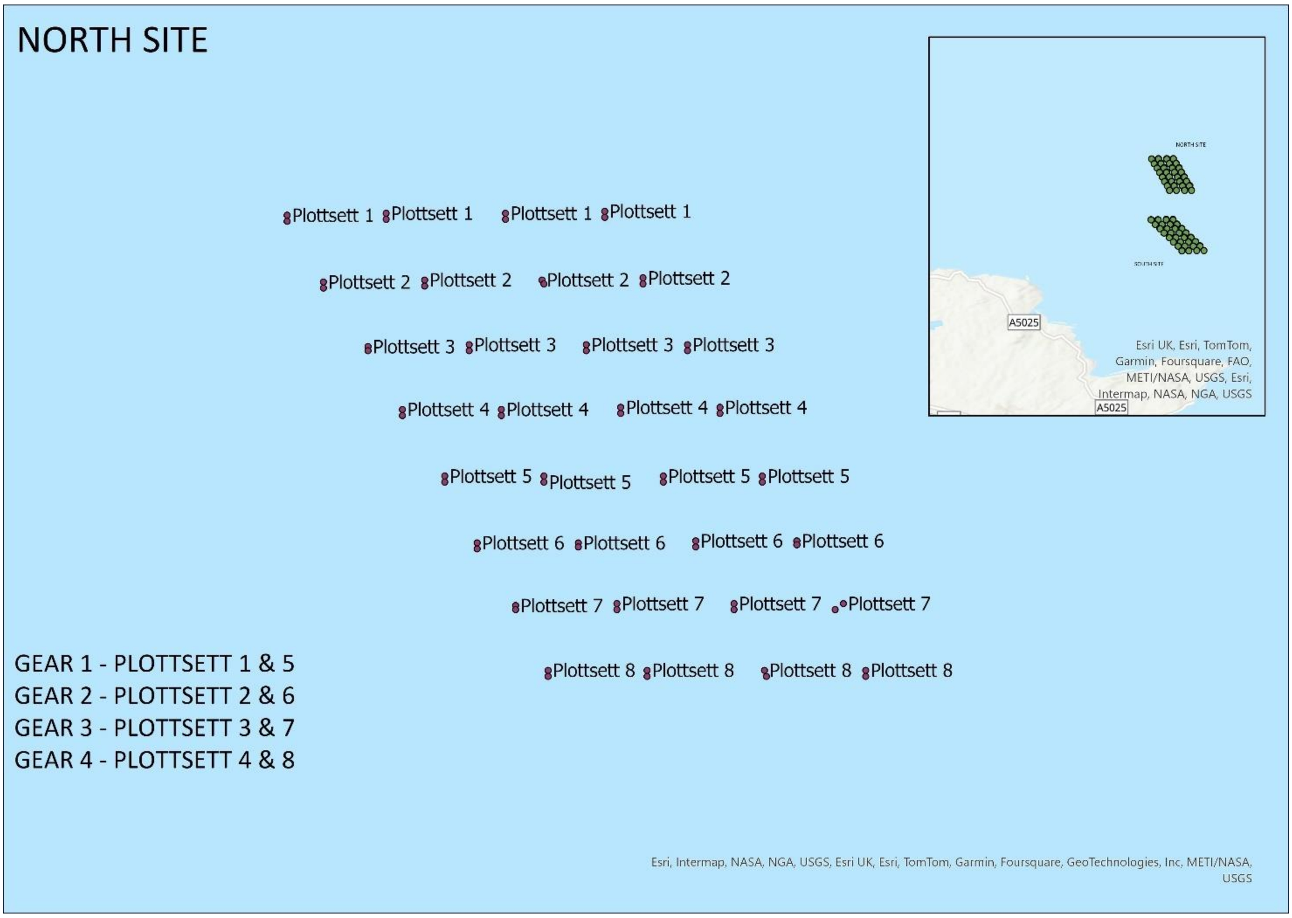


Figure 4A: A map of the North site locations used during WKP4 which was circulated to both the fishing and research vessel.

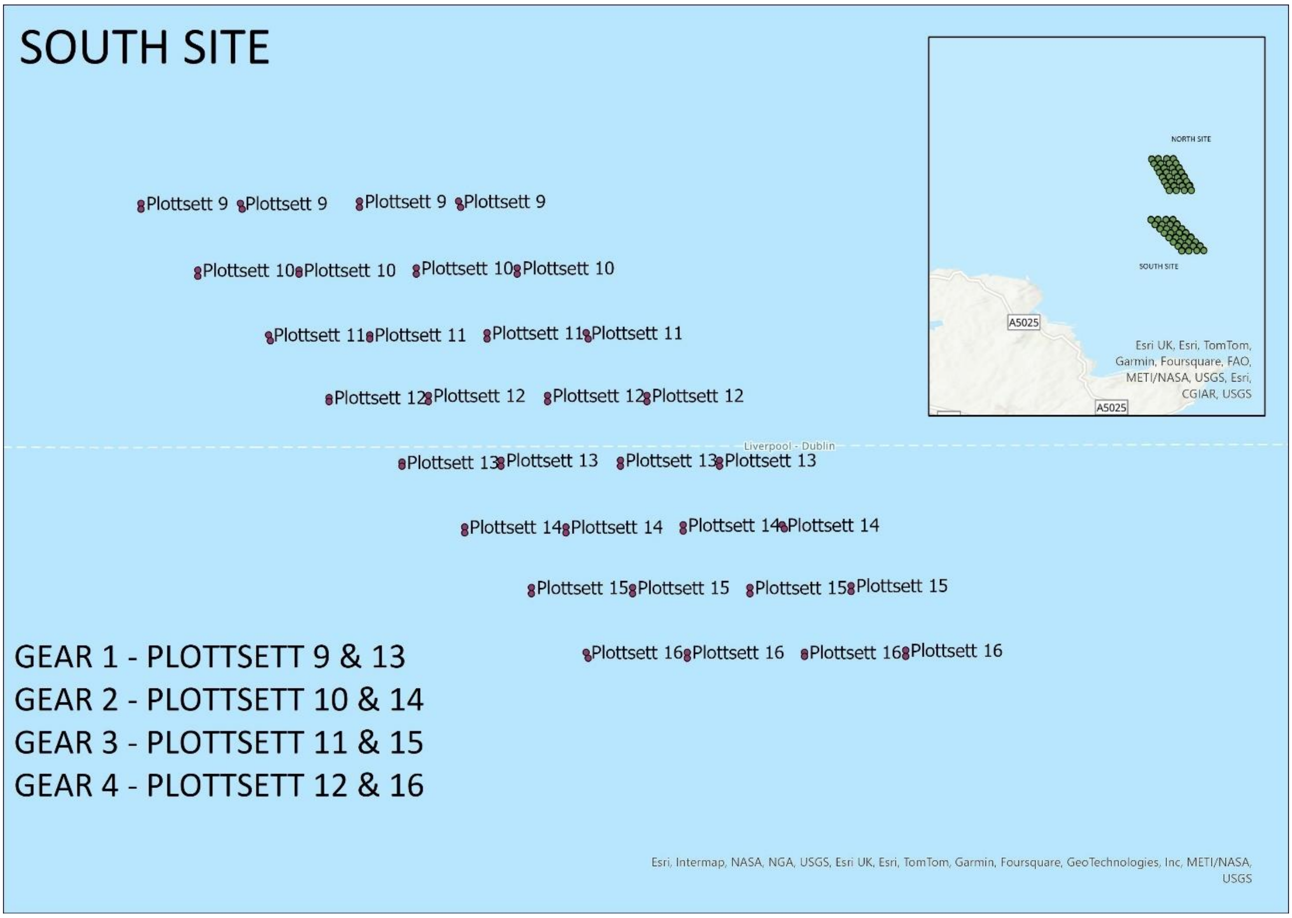
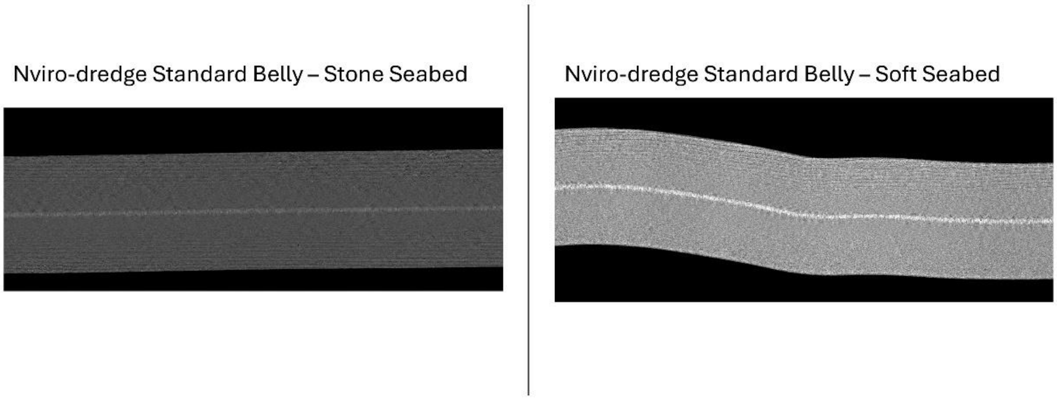


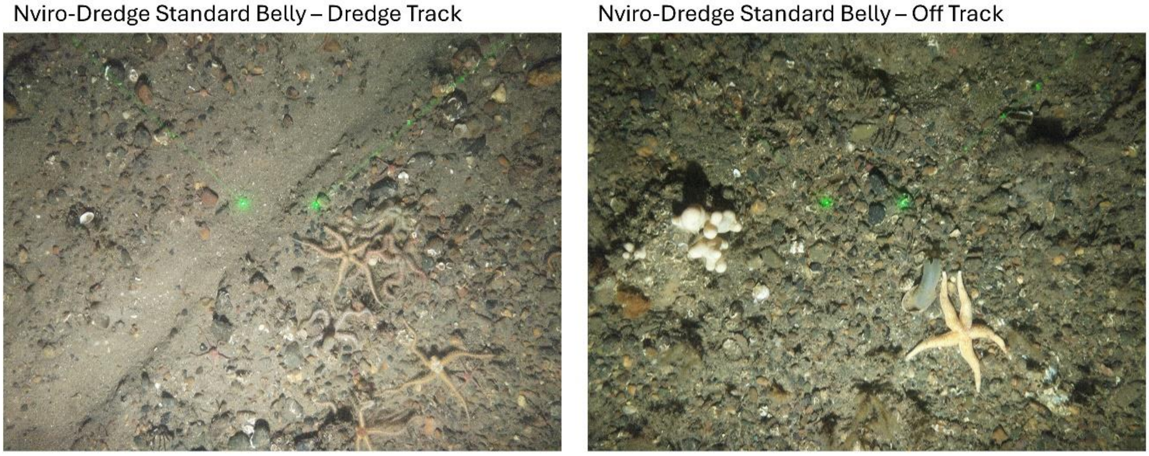
Figure 4B: A map of the South site locations used during WKP4 which was circulated to both the fishing and research vessel.



Nviro-dredge Standard Belly – Stone Seabed

Nviro-dredge Standard Belly – Soft Seabed

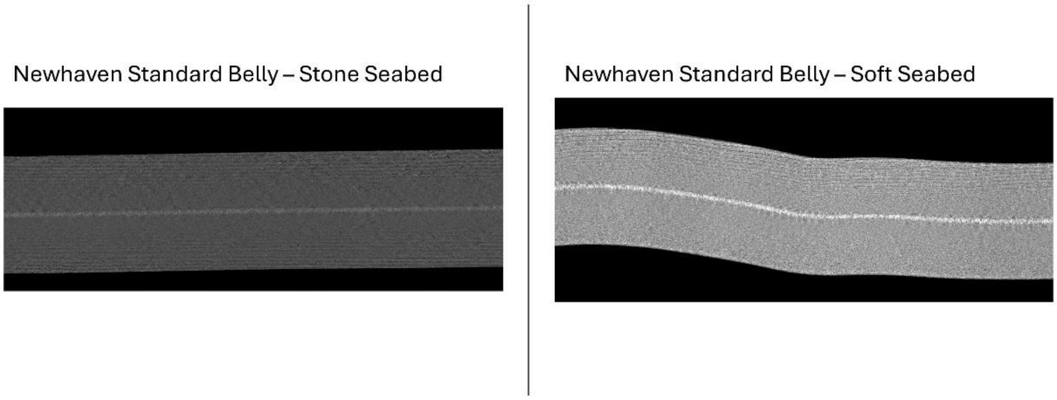
Figure 4C: Nviro-dredge mosaic images from both seabed types produced following processing corrections described in section 6.2.3. The image was created by Envision (18/12/2024).



Nviro-Dredge Standard Belly – Dredge Track

Nviro-Dredge Standard Belly – Off Track

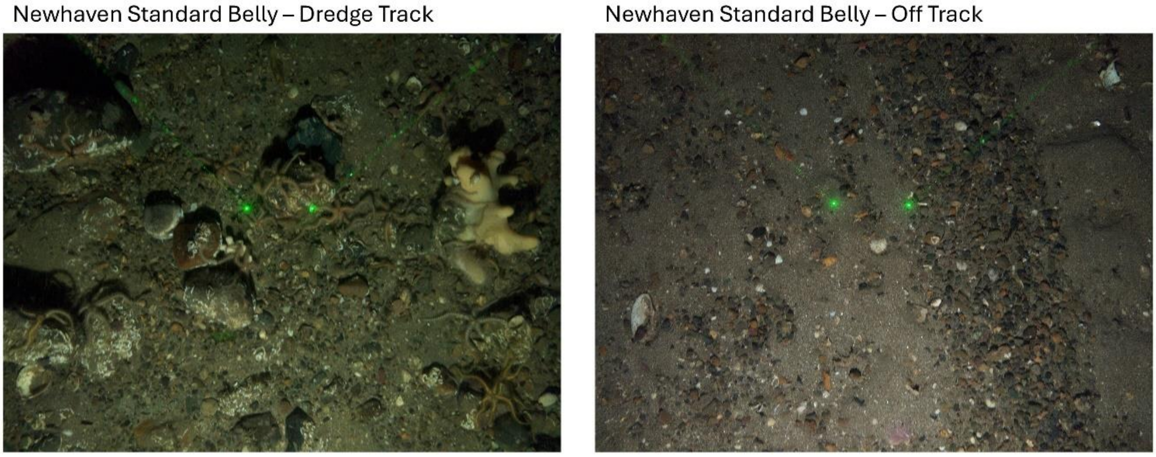
Figure 4D: Camera still images taken from off track for Nviro-dredges without skids within the stone & gravel study area of WKP4.



Newhaven Standard Belly – Stone Seabed

Newhaven Standard Belly – Soft Seabed

Figure 4E: Newhaven dredge mosaic images from both seabed types produced following processing corrections described in section 6.2.3. The image was created by Envision (18/12/2024).



Newhaven Standard Belly – Dredge Track

Newhaven Standard Belly – Off Track

Figure 4F: Camera still images taken from off track for Newhaven dredges without skids within the stone & gravel study area of WKP4.