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Evaluation of Catch Performance and Environmental Impact of Technical Gear Modifications for a More Sustainable Scallop Dredging Fishery

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ABSTRACT

The scallop fishing sector is central to UK fisheries. Traditional dredging with Newhaven dredges poses ecological risks, creating pressure to adopt more sustainable practices. This study assessed the catch and environmental outcomes of modified scallop dredge designs aimed at reducing environmental impact without compromising catch efficiency. Four gear designs were tested: (1) N-Viro dredge with conventional belly bag, (2) N-Viro dredge with skid belly bag, (3) Newhaven dredge with skid belly bag, compared to the (4) standard Newhaven dredge with conventional belly bag. Results showed that the N-Viro dredge alone did not increase catches of market-sized king scallops (*Pecten maximus*); however, pairing it with a skid belly bag improved catches by 14%–19%. The N-Viro dredge reduced undersized scallop catch by 42% and stones by 67%, with further reductions when combined with a skid belly bag. Bycatch levels remained unchanged. Fuel consumption fell by 30% with N-Viro dredges, equating to annual CO_2 reductions of 164,571 kg CO_2-e/year for vessels over 15 m and 37,235 kg CO_2-e/year for vessels under 15 m, alongside annual fuel cost savings of £46,250 and £10,465, respectively. Seabed impact assessment indicated that skid belly bags reduced gear footprint by 55%, with the lowest impact from the N-Viro dredge with skid belly bag. These findings demonstrate that combining N-Viro dredges with skid belly bags can substantially cut environmental impacts and emissions while maintaining catch efficiency, offering a promising pathway towards more sustainable scallop dredging in UK waters.

1 | Introduction

The scallop fishery is a vital part of the economies of many coastal communities where they support the fishing fleet and the wider seafood supply chain. In 2023, the king scallop fishery (*Pecten maximus*) provided around £60 million to the UK economy equating to 76,245 tonnes of live weight (Wright 2024). However, scallop dredging has also been associated with substantial negative environmental impacts. Empirical studies show that low fishing frequencies between one to three times per year can reduce the abundance of sessile epifauna (e.g., cnidarians and bryozoans) by 39%–70% (Lambert et al. 2017; Sciberras et al. 2018), and sensitive habitats such as maerl beds may experience up to 70% mortality of living maerl within dredge tracks (Hall-Spencer and Moore 2000). Dredges penetrate 3–10 cm into sediments, depending on substrate type, flattening seabed structures and leaving ridges that can persist for months in low-energy habitats (Currie and Parry 1996). Furthermore, fuel use and related carbon emissions are under growing scrutiny within the fisheries sector. In the case of the king scallop (*P. maximus*) fishery, fuel use averages 0.54 L/kg of scallop meat, resulting in emissions of 8.6 to 13.61 kg CO_2-e/kg of product (Bloor et al. 2021; Walsh 2010).

These figures place the scallop fishery among the more carbon-intensive, low-yield forms of meat production, where the energy cost of extraction outweighs the nutritional gain (Cortés et al. 2022). High energy prices and greater awareness of ecosystem impacts are realities and present major challenges for the viability of the fishery. With ongoing 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. Furthermore, the fishery faces economic pressures as operational costs continues to increase primarily due to rising fuel prices and higher material costs, such as steel for gear production. Quintana and Wilkie (2022) estimated that operational costs increased by 10% for vessels under 15 m and by 27% for vessels over 15 m between 2020 and 2021. In the light of this, transitioning to a low-impact, less fuel-intensive scallop dredge gear would represent a win-win situation for both the fishery and the environment.

Currently, the UK king scallop fishery is managed by measures such as gear design regulations, minimum conservation reference size (MCRS) and 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) (Defra 2023). Typically, *P. maximus* is fished using the Newhaven (spring-toothed) dredge, of which 95% of the UK *P. maximus* catch comes from this dredge design (Defra 2023). The Newhaven dredge relies on the direct contact of the dredge teeth with the seabed to collect 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 benthic fauna is impacted. Impact varies with fishing frequency, ground type and duration of tow length, where longer hauls equate to greater collection of target species, bycatch, stones and other detritus that increase the weight and abrasion of the gear on the seabed (Lambert et al. 2017; Maguire, Coleman, et al. 2002; Maguire, Jenkins, et al. 2002; Sciberras et al. 2018). Technical gear modifications are among several management strategies and industry-led actions that can help minimize these impacts on target stocks and the broader environment.

In recent years several alternative scallop dredge designs have been tested in the United Kingdom (Lart 2021). One modification involving the addition of ‘skids’ to the bottom of the belly bag to reduce seabed contact resulted in significantly higher catches (+15%) of marketable scallops, lower seabed contact and lower gear wear compared to the Newhaven dredge (Fenton et al. 2024; Sciberras et al. 2022). 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). Repeated catching of undersized scallops has been shown to reduce growth and gonad mass of scallops by 19%–24% (Kaiser et al. 2007). Therefore, increasing catch selectivity to prevent repeated capture of undersized scallops would enhance stock health, whereas reducing fuel consumption would simultaneously lower industry expenses and CO_2 emissions, delivering both economic and environmental benefits. The N-Viro dredge gear modification has shown promising results on this front; gear trials in French and Canadian waters indicated a 50% reduction in stones caught (Chevarie and Chevarie 2020; Filippi 2013) and a 12%–30% decrease in fuel consumption (Filippi 2013). The reduction in sorting time and fuel costs could therefore lead to more efficient fishing operations and lower environmental footprint.

This study conducted gear trials at sea on board fishing vessels to compare the performance of three scallop dredge modifications (the Newhaven dredge with the skid belly bag, the N-Viro dredge with the conventional belly bag and the N-Viro dredge with the skid belly bag) relative to the industry standard (Newhaven dredge with the conventional belly bag). These trials allowed us to isolate and understand the influence of individual gear modifications on overall performance and impact. For gear modifications to be adopted by the fishing industry, they must be both practical and economically viable as reductions in target catch or increased operational costs can significantly hinder the uptake of new gear designs. Therefore, gear performance was evaluated in terms of target catch selectivity and catchability, bycatch damage and survivability, fuel use and wider ecosystem impacts including epifaunal depletion and gear footprint on the seabed. The influence of seabed type on gear performance was also examined. It was hypothesized that raising the belly bag off the seabed using skids would help reduce contact with the seafloor and, therefore, lessen the disturbance to benthic communities, whereas employing the N-Viro dredge would provide benefits such as reduced catch of stones and fuel consumption.

2 | Methods

2.1 | Dredge Designs and Dimensions

Dredge designs included the N-Viro dredge with the conventional belly bag (Nviro), the N-Viro dredge with the skid belly bag (Nviro-skid), the Newhaven dredge with the skid belly bag (Newhaven-skid) and the standard Newhaven dredge with the conventional belly bag (Newhaven). The N-Viro dredge, which is a modification of the dredge frame and teeth designed and patented by Deeside Marine Ltd. (Kirkcudbright), weighed 51.5 kg and incorporated nine individually mounted, coiled steel tines (120–139 mm in length, 8 mm width) attached to a detachable front tine bar (Figure 1a). Skids on each end of the N-Viro dredge frame support the weight of the tine bar, moving the weight of the dredge from the teeth onto the side of the dredge frame, hence reducing the pressure at the teeth and reducing drag during the fishing activity. The industry-standard Newhaven dredge weighed 56 kg and utilized a fixed, spring-loaded steel tooth bar (77 cm wide) fitted with nine 115 mm long ‘swords’ spaced 8 cm apart (Figure 1b). The conventional retaining belly bag consisted of a belly section made up of interlocking metal rings (internal diameter 75 mm in Scottish waters and 85 mm in Welsh waters) and a netting top and rear section (diamond stretched mesh aperture 100 mm) and weighed 53 kg. The modified retaining belly bag had two skids, each 3 cm high, 4 cm wide and 40.1 cm long, attached to a steel frame (73 cm long, 72 cm wide), which lifted the bag off the seabed by a height of 13.5 cm (Figure 1c). The weight of the modified belly bag was 57 kg. Skids were bolted on the skid frame, allowing the skippers to replace only the worn skids instead of the entire belly bag. An image of the fully modified dredge, Nviro-skid, is provided in Supporting Information Figure A1.

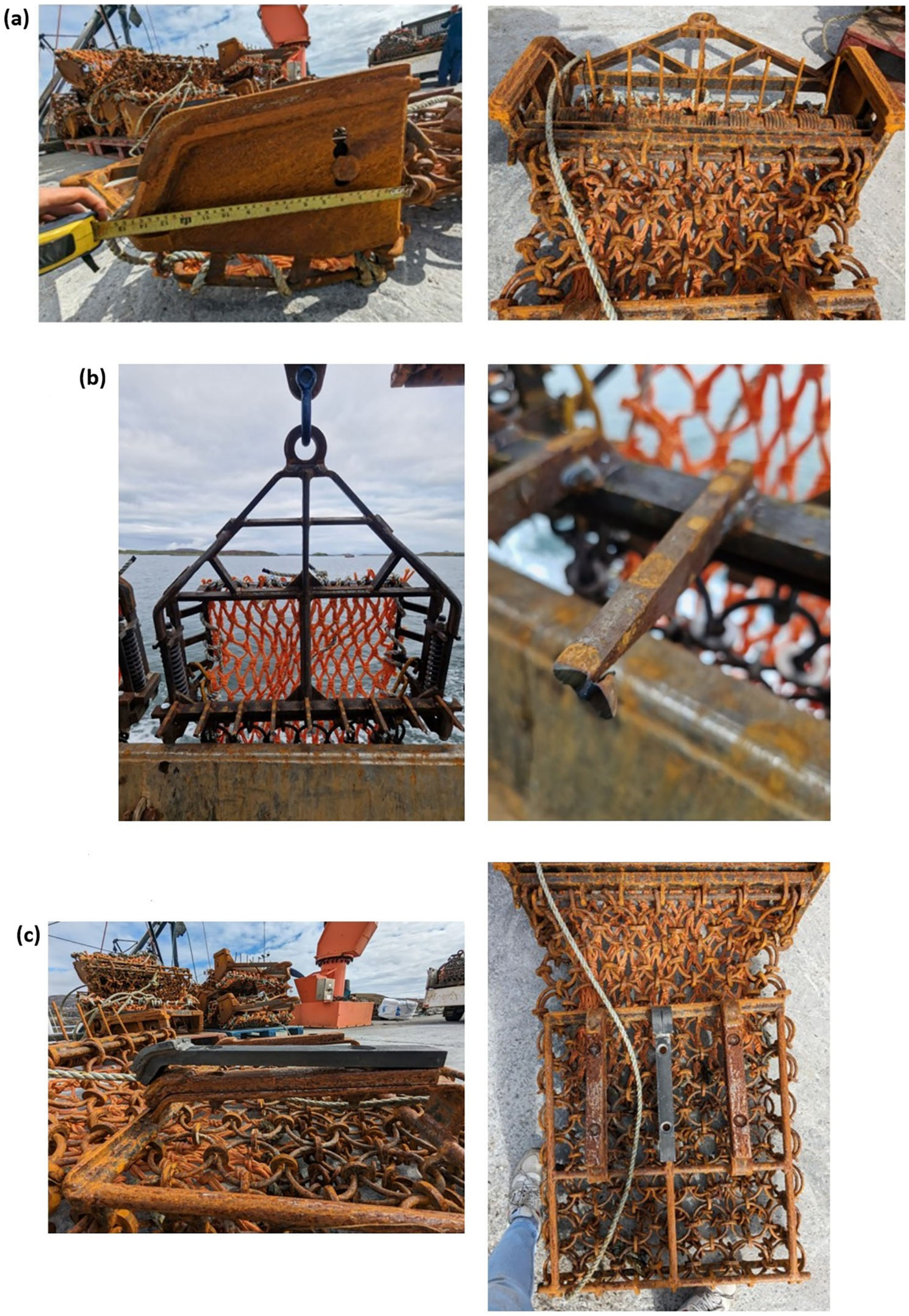

FIGURE 1 | Images of the components of both N-Viro dredge and Newhaven dredges studied. Components shown in part (a) are associated to the N-Viro dredge mouth showcasing the dredge skids integrated into the mouth with the individually sprung tines spaced across the bar. Components in part (b) show the spring-loaded Newhaven dredge mouth and tooth bar. Components shown in part (c) show the skid belly bag frame, featuring a used skid (16 h of fishing) and a new skid for comparison (grey skid).

2.2 | Data Collection Overview

Four surveys were conducted in UK waters over a 2-year period to evaluate various aspects of gear performance and environmental impact. Gear trials comparing catch yield, selectivity and bycatch damage between modified gears and the Newhaven dredge were conducted in Scottish waters from 2 to 27 August 2023 aboard the fishing vessel *Valaura*, a 13.5 m vessel fishing with six dredges aside. A second survey on the *Valaura* took place from 13 to 18 May 2024 to assess bycatch survivability associated with the Newhaven and N-Viro dredge gears. Surveys took place across a variety of sediment types on the east coast of Uist in the Outer Hebrides (Figure 2a), ranging from a mixture of sand and finer sediment to a mixture of coarse sand, cobbles and boulders (Supporting Information Figure A2). A third survey, focusing on seabed impact—specifically epifaunal depletion and surficial disturbance—was conducted between 28 July and 1 August 2024 in conjunction with the fishing vessel *Harmoni*, a 15 m vessel tow-

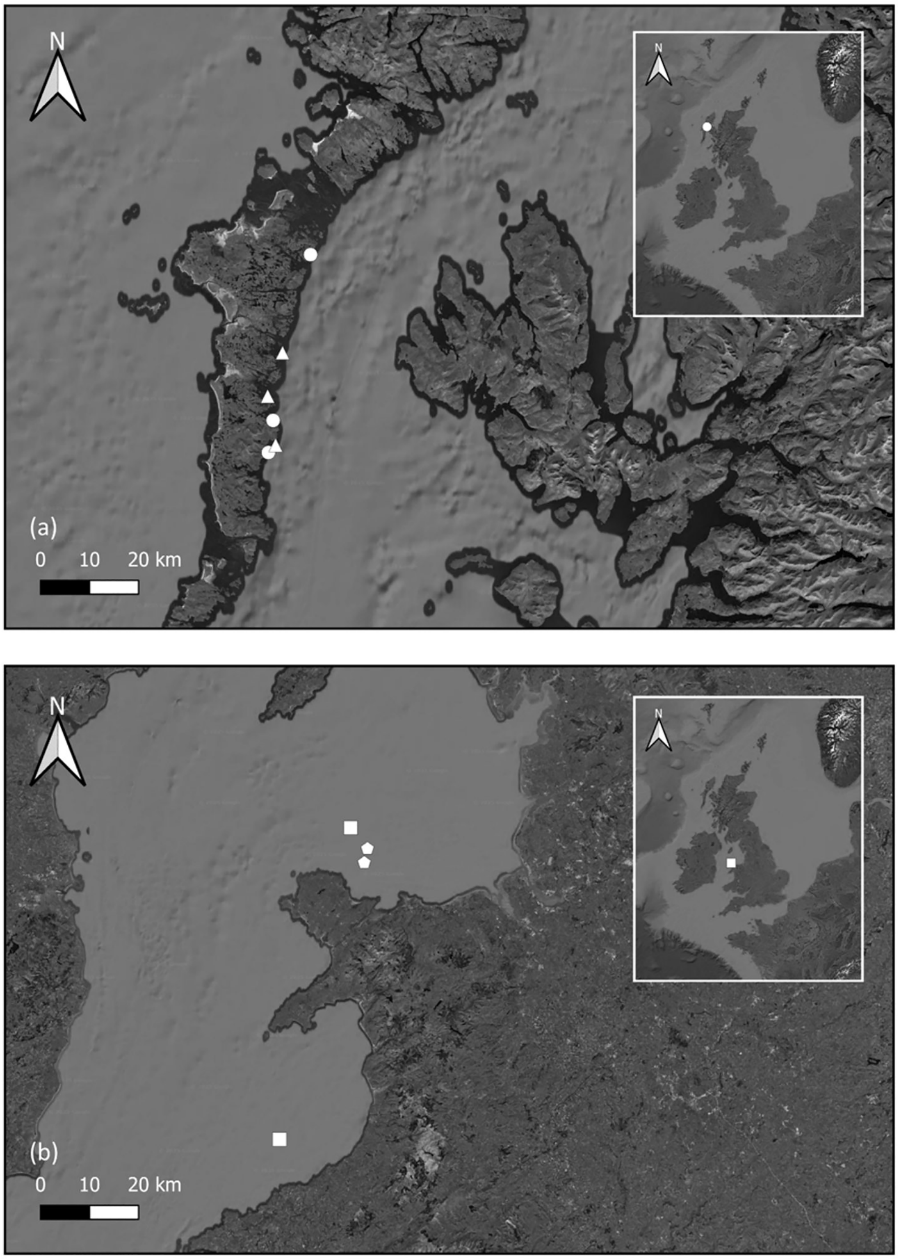

FIGURE 2 | Locations of fishing gear trials across the West coast of Scotland (a) and Wales (b), UK. Catch comparison and bycatch survivability trials took place in the Outer Hebrides, whilst the fuel consumption and seabed impacts trials took place in North Wales, UK. Circles indicate the location of the catch comparison study, triangles indicate location where fauna was collected for the bycatch survivability survey, squares indicate the location where fuel data was collected, and pentagons indicate the location of seabed impact assessment.

ing seven dredges aside. This survey took place in the northeast of Anglesey, Wales, across two habitat types: stone and pebble and sand and gravel (Figure 2b). Station locations for each of the three surveys were selected using bathymetry and sediment maps from the UKSeaMap Predictive Habitats Map (2018), together with fishers' local knowledge of seabed characteristics and scallop distribution. Lastly, fuel consumption data were collected by the *Harmoni* during regular commercial fishing operations in Cardigan Bay, Wales (Figure 2b), between November 2024 and March 2025, coinciding with the *P. maximus* fishing season, which runs from 1 November to 30 April (Welsh Government 2010). 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 and from the Welsh Government for those carried out in Welsh waters.

2.2.1 | Comparison of Catch Yield and Bycatch Damage

In total, 61 hauls were conducted: 30 with the N-Viro dredge and 31 with the Newhaven dredge, each of approximately 30 min duration. A paired-tow experimental design was employed for each haul, where the dredge with the 'conventional belly bag' was towed on the starboard side of the vessel and the modified 'skid belly bag' was towed on the portside. This design was implemented to avoid confounding effects that could arise from

TABLE 1 | Operational and environmental characteristics for catch yield and bycatch damage trials.

Gear type	No. of hauls	Towing time (min)	Towing speed (kn)	Depth (m)	Sea state
Newhaven	31	32.50 ± 0.85	2.14 ± 0.02	36.4 ± 1.29	2.26 ± 0.22
Nviro	30	31.62 ± 0.62	1.98 ± 0.01	31.8 ± 0.96	2.13 ± 0.21

Note: Skid variations have been grouped by the dredge mouth used. Towing time and speed, water depth and sea state data are shown as mean ± SEM.

TABLE 2 | Description of damage indices assigned to each bycatch individual retained across the sampling period.

	Damage index 1 (*D*1)	Damage index 2 (*D*2)	Damage index 3 (*D*3)	Damage index 4 (*D*4)
Decapoda	No damage	Pereiopods missing/small carapace cracks	Major carapace cracks	Crushed/Dead
Asteroidea	No damage	Arms missing	Minor disc damage/arm damage/worn	Major disc damage/dead
Echinoidea	No damage	<50% spine loss	>50% spine loss/minor cracks	Crushed/Dead
Gastropoda	No damage	Edge of shell chipped	Shell cracked or punctured	Crushed/Dead
Bivalvia	No damage	Edge of shell chipped	Hinge broken/large cracks	Crushed/Dead

Note: Damage indices for *Pecten maximus* individuals were those described for bivalves.
Source: Adapted from Jenkins et al. (2001).

variations in sea state, tidal conditions, towing speed and warp length between different tows and survey days. Replicate hauls were carried out with the N-Viro dredge gear, before switching to the Newhaven dredge gear. To prevent entanglement during towing, the skipper paid out extra cable (5–10 m) on one side of the vessel. The side with the longer cable was alternated between successive hauls to minimize bias and errors in catch data associated with warp length. GPS coordinates and timestamps were recorded at both the start (when the gear hit the seabed) and end (when the gear left the seabed) of each haul. Additional parameters, such as water depth, sea state, towing speed and the warp length of the dredge cables, were also recorded (Table 1).

After each haul, the catch was sorted into market-size *P. maximus* (above the MCRS, 105 mm in Scotland), undersized *P. maximus* (below the MCRS of 105 mm), bycatch (any fauna which is not king scallop) and stones and debris. The number, total catch weight (kg) and individual shell length (mm) of scallops above and below the MCRS were recorded for each haul and gear type. For hauls with a large volume of scallops, a random subset of 90 individuals was selected for shell length measurements. All bycatch species were identified to the lowest taxonomic level, and morphometric measurements such as length (mm) and weight (g) were recorded using a motion-compensated scale (with precision 5–10 g).

Scallop and bycatch species were also assigned a damage index, described in Table 2, to assess the injury sustained during the fishing operation. The weight of stones and debris was also recorded for each haul. Count and weight values, recorded from onboard observations, were standardized to number of individuals per 30-min haul and kg per 30-min haul, respectively. It was not feasible to use start and end GPS coordinates to calculate the swept area during a tow to standardize catch values as the fishing vessel rarely towed in straight lines due to the highly variable bathymetry. However, the towing speeds and environmental conditions during the surveys were quite consistent (Table 1); thereby, using haul duration rather than tow length to standardize catch data was deemed adequate.

2.2.2 | Bycatch Survivability

In total, 25 60-min hauls (12 hauls for N-Viro dredge, and 13 hauls for Newhaven dredge) were conducted to collect fauna for the bycatch survivability study. Because bycatch survivability is expected to be primarily influenced by interactions with the dredge teeth rather than the belly bag, analyses focused on differences between the N-Viro dredge and Newhaven dredge, and not between skid and standard belly bags. Individuals from damage categories 1 to 3 in Table 2 (no damage, minor and major damage) were selected for six of the most commonly caught bycatch species in the study area: undersized *P. maximus*, *Asterias rubens*, *Cancer pagurus*, *Marthasterias glacialis*, *Luidia ciliaris* and *Echinus esculentus*. During onboard sampling, specimens were held in aerated ambient seawater and were kept in a temperature-controlled room at 5°C, to match bottom seawater temperature (4.92°C ± 0.23°C) at the time of the study. Water temperature (°C) and oxygen levels (mg/L) were monitored at setup and post-haul, with one instance of seawater replenishment due to detritus buildup. Individuals were tagged with coloured cable ties to indicate gear type and damage level. For *C. pagurus*, ties were secured to the terminal pleopod, whereas for starfish species, ties were placed around the central disc. *E. esculentus* individuals were each marked with a polystyrene float affixed to a cable tie, which was gently inserted among the spines. Undersized *P. maximus* specimens were housed in individual baskets within the aquarium facility, each marked with a designated cable tie. All cable ties were attached in a manner that minimized physical stress and avoided impairment of normal movement or function.

At the end of each fishing day, all individuals were transferred to a land-based facility with 2.62 m × 2.04 m × 0.48 m flow-through seawater tanks (exchange rate 43 L/min) and retained over a period of 7 days. Dissolved oxygen and water quality were assessed using *Tetra Test 6-in-1 and* Tetra Test O_2 Strips every 12 h. Bycatch from Newhaven and N-Viro dredges were housed separately, as were different species, to reduce stress and interspecies interactions. Tanks were checked for mortalities every 12 h. Dead individuals were removed, weighed and size measured. After the 7-day period, individuals' weights and lengths were recorded, and live individuals were released back into the sea.

2.2.3 | Comparison of Fuel Consumption

A total of 287 hauls were conducted over 3-week trials for each gear type, comprising 106 hauls from four trips using the Newhaven dredge, 42 hauls from two trips with the Newhaven-skid, 60 hauls from two trips using the N-Viro dredge and 79 hauls from two trips with the Nviro-skid. Hauls were conducted under normal commercial operations, with locations of hauls targeted towards maximizing scallop catch and avoiding undesirable habitats. During each fishing trip, the same gear type was used on both the port and starboard sides of the vessel to prevent unbalanced drag, which could skew performance and fuel consumption. On average, haul duration was 1.74 ± 0.16 h. Towing speeds differed between the Newhaven dredge (2.91 ± 0.03 kn) and the N-Viro dredge variants (2.20 ± 0.22 k), as the N-Viro dredge performs best at lower towing speeds. Fishing operations were conducted over mixed substrate comprising gravel, sand and stone at depths ranging from 25 to 50 m (35.23 ± 6.18 m). Fuel consumption (L/haul) was measured aboard the *Harmoni* using an Akaike information criterion (AIC) 908 flowmeter linked to a BC3034 display unit. For each haul, fuel levels (L) were recorded at both the start and end of the operation. The skipper additionally documented a suite of operational and environmental variables, including haul start and end positions (latitude, longitude), haul duration and distance dredged (nautical miles), vessel speed (kn), sea state (Beaufort scale), tidal current (surface drift, kn), water depth (m) and dredge type deployed. This standardized data collection protocol ensured consistency and accuracy in fuel consumption estimates across variable environmental and operational conditions.

2.2.4 | Comparison of Seabed Impacts

A dredging disturbance experiment was conducted off the north-east coast of Anglesey at depths of 20–40 m to evaluate seabed impacts across two sedimentary habitats: stone—pebble and sand—gravel. Disturbance plots were created by the fishing vessel *Harmoni*, and subsequent impact assessments were conducted using instrumentation deployed from the research vessel *RV Prince Madog*. For each gear-sediment type combination, two lanes measuring 2.8 km in length and 50 m in width were dredged, resulting in a total of 16 experimental lanes. Fishing vessel tracks were logged in OpenCPN using AIS data and transmitted in real time to the *RV Prince Madog* to ensure precise spatial alignment of post-dredging surveys. To enhance positional accuracy of underwater scientific instrumentation inside and outside dredge tracks, an ultra-short baseline (USBL) system (Applied Acoustics Easytrack Nexus Lite, 1319A Micro Beacons) was employed.

2.2.4.1 | Epifaunal Impact. To assess biological impact, each dredge lane was divided into two 500 m × 50 m survey rectangles, totalling 32 areas surveyed by underwater cameras. A benthic sled was fitted with a 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°. The camera system was deployed 4–8 h after the fishing disturbance to assess seabed fauna inside and outside the dredge lanes for each gear and sediment type. A digital still (area = 0.45 m^2) was captured every 10 s, resulting in a total of 2642 digital still images. Of these, 1560 images were taken from within the dredge tracks, and 1082 were from undisturbed areas outside the tracks (Supporting Information Figure A3). The images were geo-referenced using USBL GPS and side scan sonar (SSS) for alignment with the dredge tracks and classified accordingly. A random sample of 50 images per replicate was selected for analysis. The images were processed, using the Bio-Image Indexing and Graphical Labelling Environment software (BIIGLE) (Langenkämper et al. 2017), and benthic species were annotated on the basis of the World Register of Marine Species (WORMS) database (Horton et al. 2017). Counts of individuals were standardized to a spatial area of 10 m^2.

2.2.4.2 | Gear Footprint. SSS data were acquired using an Edgetech 4125i dual-frequency system both prior to and within 2 h following dredging operations in order to evaluate the spatial extent of gear impact in relation to dredge scar features on the seabed. The system was operated via a standalone laptop, integrated with the vessel's GPS and configured to operate at 400–900 kHz in accordance with manufacturer guidelines. Data acquisition was conducted using EdgeTech Discover software, with the towfish maintained at an altitude of 3–5 m above the seabed. SSS mosaics were generated from both high- and low-frequency datasets using SonarWIZ v7 and subsequently imported into ArcGIS for quantification of dredge furrow (scar) widths (Supporting Information Figure A4). For each 1.5 nm dredge lane, six points were randomly selected for width measurements, with six replicate measurements collected per point. In total, 570 measurements were obtained (72 per dredge design per habitat).

2.3 | Statistical Analysis

All statistical analysis was conducted using 'RStudio' (version 0.06.2023 Build 421) (R Core Team 2025). The models described in the subsequent section examined interaction terms, with those exhibiting a variance inflation factor (VIF) greater than 3 excluded to minimize multicollinearity (Zuur et al. 2013). All combinations of the explanatory variables were tested and ranked according to the AIC. The highest ranked model, along with all models within two AICc units, was selected using the *arm* and *MuMIn* R packages (Gelman and Su 2024; Barton 2025). AICc was used as it applies a small-sample correction to AIC and reduces the risk of overfitting when the number of parameters is large relative to the sample size. Model validation included assessment of residual normality via the Kolmogorov–Smirnov test and quantile–quantile plots. Influential outliers were identified using Cook's distance, whereas heteroscedasticity was evaluated with Levene's test and by inspecting scatterplots of standardized residuals against fitted values and covariates. Prior to applying Gaussian models, overdispersion was assessed, and in cases where overdispersion was detected ($n > 1$), negative binomial models were employed. Statistical significance was determined at $p < 0.05$.

2.3.1 | Comparison of Scallop, Bycatch and Stone Catches

Catch data for market-size and undersized scallops, bycatch and stones were systematically compared across the four dredge configurations (Newhaven, Newhaven-skid, Nviro and Nviro-skid). A two-tiered analytical approach was applied using two complementary metrics. The first metric, standardized biomass (kg/haul), was used to compare catches between the Newhaven dredge and the N-Viro dredge, independent of belly bag type. The second metric, the natural log-transformed catch ratio (lnRR), was employed to compare catches between skid belly bags and standard belly bags for each dredge type (Newhaven vs. Newhaven-skid and Nviro vs. Nviro-skid). Catch ratio was calculated using the following formula:

$$\mathrm{lnRR} = \ln\left(\frac{\text{Biomass in skid belly bag}}{\text{Biomass in standard belly bag}}\right)$$

LnRR value of 0 indicates no difference between the catch of the two gear types. Positive lnRR values indicated a higher biomass collected using skid belly bags relative to standard belly bag, whereas negative values indicated the opposite. LnRR of 0.1 indicates an 11% increase, lnRR of 0.5 = 65% increase, and lnRR of −0.2 = 18% decrease. Catch ratio values were calculated from paired-tow data to minimize the influence of environmental and operational variability, including sea state, tidal flow and spatial heterogeneity in scallop distribution on the seabed. Direct comparison of standardized biomass values across all four dredge types within a single statistical model was deemed inappropriate, as data for skid and standard belly bag configurations were obtained from paired hauls on the same vessel, resulting in non-independent replicates.

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

a. Standardized biomass (kg/haul) = Gear type × Stone

which examined catch differences between different gears (Newhaven vs. N-Viro dredge irrespective of belly bag type) and ground type using standardized biomass data, and

b. lnRR = Gear type × Stone + WL

which examined the influence of gear type (Newhaven vs. Newhaven-skid and Nviro vs. Nviro-skid), ground type and warp length on the performance of the gears with and without the skid belly bag.

The variable 'Stone' ranged from 0 to 1 and represents the normalized standardized stone weight, serving as a proxy for ground type. Normalization was necessary because Newhaven dredges consistently collected more stones than N-Viro dredges; hence, the variable was scaled to facilitate comparison. WL (warp length) was classified as either short or long and was included in the model to determine whether the amount of cable paid out during towing had a significant influence on dredge catch. A statistically significant interaction term in either model would indicate that catch differences between the gear types were dependent on the seabed characteristics, as reflected by the amount of stone collected. This would suggest that gear efficiency is not uniform across ground types, with certain dredge configurations performing more effectively in specific substrate conditions.

2.3.2 | Comparison of Scallop Size Selectivity

To determine whether the modified dredges caught significantly more or fewer scallops of any given length class compared to the standard Newhaven dredge, a catch-comparison analysis was conducted using the 'selfisher' package in R (Brooks et al. 2022). Scallop shell length data were grouped into 10 mm size classes to increase sample sizes at the extremes of the size spectrum. For each length class, the number of scallops caught and the proportion of scallops retained by the modified dredge relative to the total catch of both gears were calculated.

The catch-comparison analysis modelled the length-dependent retention probability of scallops in the modified dredge relative to the Newhaven dredge as a function of shell length. Alternative candidate models were fitted that differed in the functional form used to describe this relationship, including a fourth-order polynomial and a spline-based formulation with five degrees of freedom implemented using the 'splines' R package. Model selection was performed using AIC to identify the most parsimonious model describing the size-dependent selectivity pattern.

From the selected model, catch ratios were derived as the ratio of expected catches in the modified dredge relative to the Newhaven dredge across scallop size classes. Predictions were generated for the range of observed scallop lengths and represent the model-based expected catch ratios under the experimental conditions represented in the dataset. Uncertainty in predicted catch ratios was quantified using bootstrapped, pointwise confidence intervals generated with the 'bootSel' and predict functions in the 'selfisher' package (Brooks et al. 2022).

2.3.3 | Comparison of Scallop and Bycatch Damage

Physical damage has the potential to reduce the commercial value of market-sized scallops and adversely affect the survivability of undersized scallops and bycatch species. A Chi-squared analysis was conducted to assess whether a statistically significant association existed between species-specific damage levels and dredge type, thereby evaluating whether certain gear types were more detrimental to particular species. It was further hypothesized that the extent of bycatch damage was influenced by the quantity of stones retained in the belly bag. The relationship between standardized stone weight (Log_{10}-transformed, Stone (Log_{10})) and the proportion of animals in each of the four damage categories (Damage Index) was analysed using a generalized linear model (GLM) with a binomial family and a logit link function:

$$\text{Proportion} = \text{Gear type} + \text{Species} \times \text{Damage index} + \text{Damage index} \times \text{Stone}\,(\mathrm{Log}_{10})$$

Damage was expected to be species-specific; therefore, the variable 'Species' encompassed the different taxonomic groups of bycatch assessed in the study. A statistically significant positive interaction between Stone and Damage Index would indicate that higher stone loads within the dredge are associated with increased levels of faunal damage. Conversely, a significant interaction between Species and Damage Index would suggest that the extent of damage is species-dependent, reflecting differential vulnerability of bycatch taxa to dredging impacts.

2.3.4 | Comparison of Species Survival Rates

Species survival rates were analysed using Kaplan–Meier survival analysis implemented in R using the *survival* package (Therneau 2020) and visualized with *survminer* (Kassambara et al. 2025). The Kaplan–Meier estimator is a non-parametric method that calculates how species' survival probabilities change over the 7-day study period and examines whether survivability differs between gear types, species' identity and injury level sustained through the fishing activity (Kaplan and Meier 1958). The model uses the number of dead and live individuals at the end of each 24 h observation period and added cumulatively across the entire study period. Separate survival curves were generated to evaluate differences in survival associated with gear type, damage index and species identity. The analysis assumes that individuals are independent and that dead individuals have the same underlying risk of mortality as those that continue to be observed. Differences between survival curves were tested using log-rank tests.

Post-dredging mortality was further analysed using Cox proportional hazards models, which estimate the hazard function ($h(t)$) describing the instantaneous risk of mortality at time t, conditional on survival up to that time point (Cox 1972; Hosmer et al. 2008). This framework allows the inclusion of multiple covariates, including species identity, gear type and damage level, to identify key predictors of post-dredging mortality. Model outputs are expressed as hazard ratios (HRs), where values greater than 1 indicate increased mortality risk and values less than 1 indicate reduced risk relative to a predefined reference category (e.g., lowest damage level, focal species or least damaging gear type).

2.3.5 | Comparison of Fuel Consumption

Linear mixed-effect models were used to examine differences in fuel consumption, expressed as litres per hour of fishing (FLH, L/h), across the four gear types and under varying environmental conditions:

$$\text{FLH} = \text{Gear type} \times \text{Sea state} + \text{Gear type} \times \text{Tidal current} + \text{Water depth},\ \text{random} =\sim 1|\text{Trip ID}/\text{Date}$$

A random intercept model for individual days (Date) nested within each fishing trip (Trip ID) was applied to account for correlations between hauls conducted on the same day and fishing trip. Although 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.

Predicted reductions in $\mathrm{CO_2}$ emissions and fuel savings for scallop dredge vessels over 15 m and under 15 m in the UK fleet were calculated using (1) the average reduction in fuel consumption when the N-Viro dredge is used instead of the Newhaven dredge (30% reduction), (2) average daily fuel consumption (L/day) reported in Wright (2024) and (3) average fuel price of £0.78/L. The average daily fuel consumption values were converted to kg carbon dioxide-equivalent emissions ($\mathrm{CO_2}$-e) per annum, based on the emission conversion factor of 2.77547 kg $\mathrm{CO_2}$-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).

2.3.6 | Seabed Impacts

The proportional change in benthic fauna abundance inside and outside the dredge lanes was calculated using the natural log response ratio (lnRR), using the formula:

$$\ln\text{RR} = \ln\left(\frac{\text{Number of individuals inside dredge track}}{\text{Number of individuals outside dredge track}}\right)$$

Positive lnRR values indicate a higher number of benthic species inside dredge tracks, whereas negative values indicate fewer species. Due to exceptionally high counts of *Ophiothrix fragilis* (over 1000 individuals per 10 m^2) in some images, *Ophiothrix* was removed from the lnRR calculations to avoid skewed results.

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

$$\ln \mathrm{RR} \sim \mathrm{Geartype} \times \mathrm{Habitattype}$$

$$\text{Furrow width} \sim \text{Gear type} \times \text{Habitat type}$$

3 | Results

3.1 | Comparison of Scallop, Bycatch and Stone Catches

Catches of market-size scallops were variable, but on average, catches were significantly higher for Newhaven dredge (35.5 ± 2.9 kg/haul) than for N-Viro dredges (26.9 ± 1.9 kg/haul), and catches increased significantly on stonier grounds for both dredge types (Figure 3a, Supporting Information Table A1). The use of skid belly bags improved catch performance for both dredges relative to the conventional belly bag, with an average increase of 19% in market-size scallop catch when a skid belly bag was used with N-Viro dredge (lnRR = 0.18 ± 0.06) and 14% increase when a skid belly bag was used with Newhaven dredge (lnRR = 0.13 ± 0.05) (Figure 3b; Supporting Information Table A2). Catches of undersized scallops were significantly lower for N-Viro dredges (3.5 ± 0.5 kg/haul) than for Newhaven dredges (6.1 ± 0.8 kg/haul) across all ground types (Figure 3c, Supporting Information Table A1). On stonier ground, the N-Viro dredges with skid belly bags caught lower catches of undersized scallops than those with conventional belly bags but higher catches of undersized if fishing with Newhaven-skid dredges (Figure 3d; Supporting Information Table A2). Catch comparison modelling indicated that Newhaven dredges with skid belly bags caught significantly more individuals within the size class of 110–120 mm compared to Newhaven dredges with conventional belly bag, whereas N-Viro dredges with conventional belly bag caught significantly fewer individuals in the 95–120 mm size class, and N-Viro dredges with skids caught significantly fewer individuals in the 100–115 mm size class, all represented by the confidence intervals sitting above and below 1 (Figure 4). 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.

Newhaven dredges (59.4 ± 14.9 kg/haul) caught significantly more stones than N-Viro dredges (19.5 ± 4.9 kg/haul)—on average three times more (Figure 3e, Supporting Information Table A1). Dredges with skid belly bags collected significantly more stones than standard belly bag for Newhaven dredge, but not for N-Viro dredge (Figure 3f; Supporting Information Table A2). The bycatch composition across all scallop dredge designs primarily comprised *L. ciliaris* (22.2%), *C. pagurus* (22.9%), *M. glacialis* (13.6%), *E. esculentus* (10.3%) and *A. rubens* (9.9%), equating to 81.9% of the overall bycatch species retained. Biomass of bycatch was higher for stonier grounds irrespective of whether a Newhaven dredge or N-Viro dredge was used (Figure 3g). Skid belly bags caught more bycatch than standard belly bags, and this difference was more pronounced for N-Viro dredge (lnRR = 0.54 ± 0.13, 72% higher in skid bellies) than Newhaven dredge (lnRR = 0.25 ± 0.09, 28% in skid bellies) (Figure 3h; Supporting Information Table A2).

3.2 | Comparison of Scallop and Bycatch Damage

Overall, scallops predominantly sustained minor injuries, whereas other bycatch species exhibited comparatively higher incidences of major injuries and mortality (Figure 5). An average of 25% of bycatch individuals were dead (Damage Index 4), and 18% sustained major damage (Damage Index 3) (Figure 5). In contrast, only 1.3% and 1.1% of scallops were recorded in damage categories 4 and 3, respectively (Figure 5). A strong association between the scallop damage and gear type was found (Chi-square test, $\chi^2 = 247.98$, $p < 0.05$) (Supporting Information Table A3), with the N-viroskid design associated with higher numbers of individuals sustaining no damage ($D1 = 21.74\%$) compared to the conventional Newhaven dredge ($D1 = 8.8\%$). No significant association was detected between dredge type and bycatch damage (Chi-square test: $\chi^2(9) = 7.65$, $p = 0.57$) (Supporting Information Table A4).

Although Newhaven dredges retained more stone than the N-Viro dredges, we did not find a significant relationship between the quantity of stone in the belly bag and species damage (Table 3). However, we found a significant Species × Damage interaction term suggesting that fauna damage is species-specific (Table 3). *A. rubens* experienced the least damage, as it had the highest proportion of individuals with no damage (*D*1) and lowest proportion of individuals with minor (*D*2) and major (*D*3) injuries. Conversely, *Marthasterias*, *Echinus*, *Cancer* and *Luidia* all experienced significantly more damage, as they had higher proportion of organisms in *D*2 and *D*3 than *Asterias*. *Luidia* experienced the highest damage by dredging.

3.3 | Comparison of Species Survivability

Organisms with no damage (*D*1) exhibited the highest survival probability, with survival rates of 93.8% (95% CI: 90.8%–97.0%) after 7 days (Figure 6). Individuals with minor damage (*D*2) showed reduced survival, decreasing to 77.7% (95% CI: 72.5%–83.2%) over the same period. In contrast, survival for organisms with major damage (*D*3) dropped to 87.1% (95% CI: 83.0%–91.5%) after 3 days and to 48.1% (95% CI: 42.2%–54.9%) after 7 days, indicating that more than half of these individuals had died by the end of the study period (Figure 6). Although no significant differences in survival were detected between gear types ($\chi^2 = 0.1$, df = 1, $p = 0.8$), survival differed significantly among species ($\chi^2 = 110$, df = 5, $p < 0.05$). *E. esculentus* showed the steepest decline, with survival decreasing to 84.6% by Day 4 and further to 37.4% by Day 7. In contrast, *M. glacialis* exhibited the highest survival, maintaining 95.8% by Day 5 (Figure 7, Supporting Information Figure A6). Other species demonstrated intermediate survivability, with survival ranging from 67.5% to 79.3% by Day 7, and showed smaller deviations between observed and expected mortalities (Figure 7).

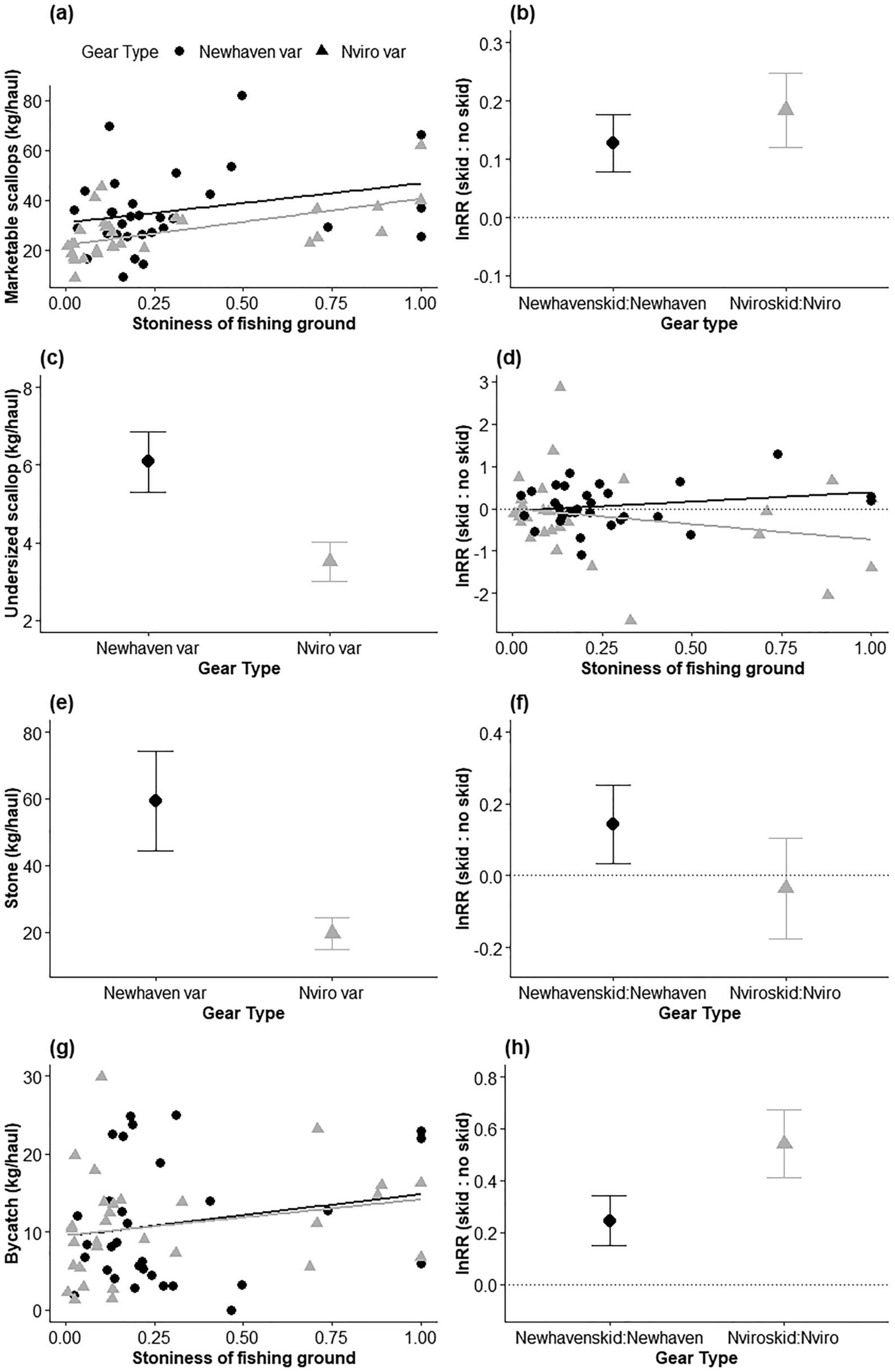

FIGURE 3 | Standardized biomass (kg/haul) of (a) king scallops above conservation reference size (MCRS, 105 mm), (c) undersized scallops, (e) stones and (g) non-scallop bycatch, separated for Newhaven and N-Viro dredges across different ground types (stoniness). The relative catch (lnRR) compares skid versus standard belly bags for Newhaven and N-viro dredges separately (b, d, f and h). The horizontal dashed line indicates equal catch between designs (lnRR = 0). Positive lnRR values denote higher catches with skid designs, whereas negative values indicate lower catches. Confidence intervals (95%) not overlapping zero denote significant differences.

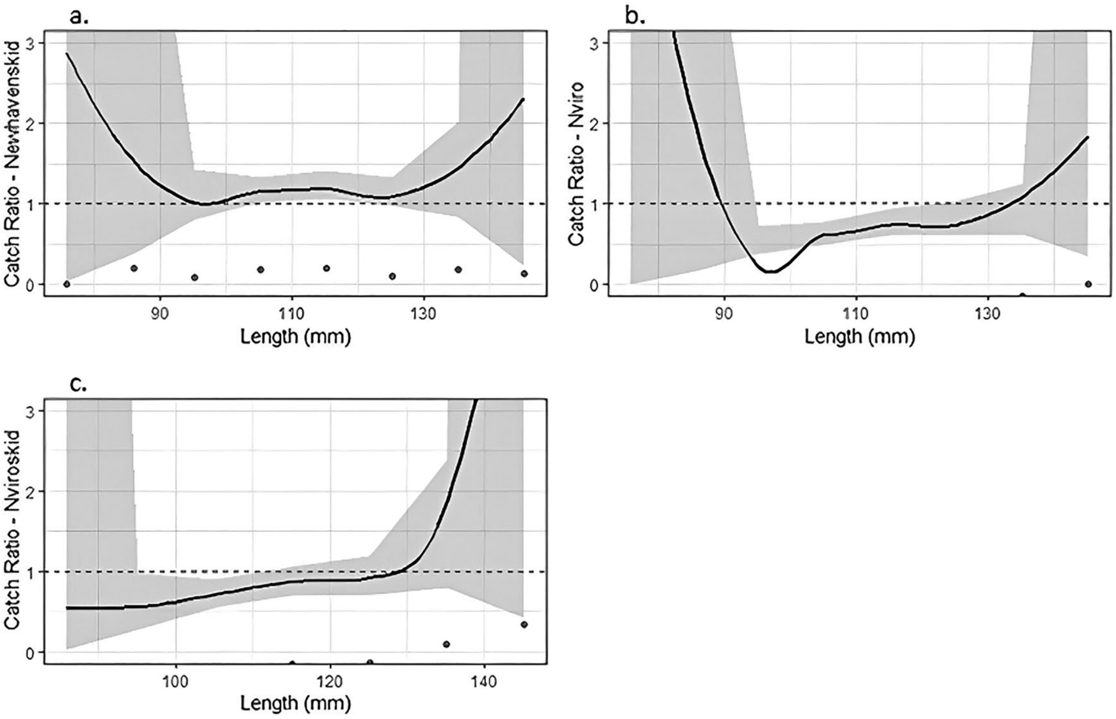

FIGURE 4 | The modelled catch ratio showing difference between the modified dredges and Newhaven dredge across different scallop size classes for *Pecten Maximus:* (a) comparison of Newhaven-skid versus Newhaven dredge, (b) comparison of N-Viro dredge versus Newhaven dredge and (c) comparison of Nviro-skid dredge versus 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).

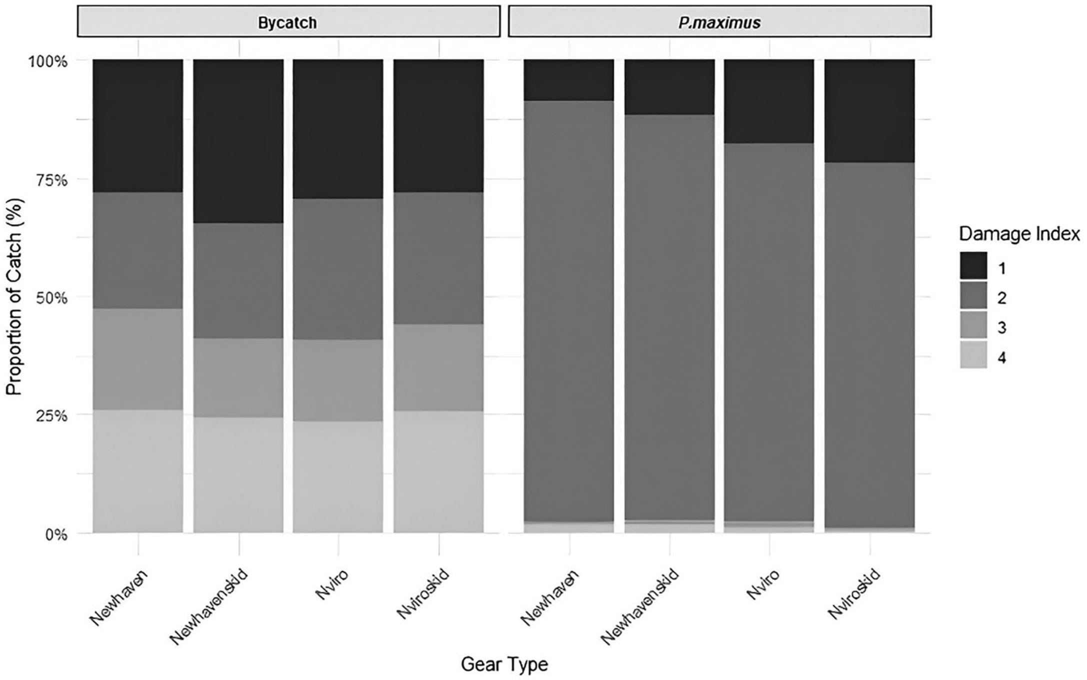

FIGURE 5 | The percentage of scallop and bycatch fauna (%) with no damage (*D*1), minor injuries (*D*2), major injuries (*D*3) and dead (*D*4) caught using the four dredge types (Newhaven, Newhaven-skid and N-viro, Nviro-skid).

TABLE 3 | Relationship between dredge type, bycatch damage and stone retention.

Model					**AIC**
Full model: Prop ~ Gear type + Species × Damage index + Damage index × Logstone					2341.1
Best model: Prop ~ Species + Damage index + Species: Damage index					2228.6
	Estimate	Std. error	*t* value	*p* value	
Intercept	1.18	0.19	6.39	3.36e − 10	
N-Viro dredge	−0.00	0.07	−0.07	0.94	
Cancer pagurus	−1.82	0.21	−8.72	<2e − 16	
Echinus esculentus	−1.51	0.25	−6.09	2.05e − 09	
Luidia ciliaris	−3.32	0.28	−11.68	<2e − 16	
Marthasterias glacialis	−1.18	0.23	−5.23	2.39e − 07	
*D*2	−2.01	0.25	−8.08	3.43e − 15	
*D*3	−3.05	0.65	−4.71	3.07e − 06	
*D*4	−3.72	0.72	−5.18	3.05e − 07	
*Cancer pagurus: D*2	1.86	0.29	6.43	2.59e − 10	
*Echinus esculentus: D*2	1.01	0.41	2.46	0.014	
*Luidia ciliaris: D*2	3.43	0.35	9.85	<2e − 16	
*Marthasterias glacialis: D*2	1.76	0.31	5.64	2.60e − 08	
*Cancer pagurus: D*3	1.68	0.68	2.47	0.014	
*Echinus esculentus: D*3	2.19	0.70	3.12	0.0019	
*Luidia ciliaris: D*3	4.47	0.69	6.46	2.12e − 10	
*Marthasterias glacialis: D*3	1.62	0.69	2.34	0.020	
*Cancer pagurus: D*4	3.51	0.73	4.78	2.22e − 06	
*Echinus esculentus: D*4	4.24	0.76	5.61	3.09e − 08	
*Luidia ciliaris: D*4	5.32	0.76	7.02	5.84e − 12	
*Marthasterias glacialis: D*4	1.90	0.80	2.36	0.019	

Note: A generalized linear model was used to assess the effect of gear type and stone retention (Log_{10}-transformed weight) on the proportion of animals across the four damage categories (*D1*—no damage, *D2*—minor injuries, *D*3—major injuries, D4 - dead). Parameter estimates are shown on the logit scale. Damage index level 1 and the reference species were used as baselines. Model selection was conducted using binomial AIC, and the selected model was refitted using a quasibinomial error structure to account for overdispersion.
Abbreviation: AIC, Akaike information criterion.

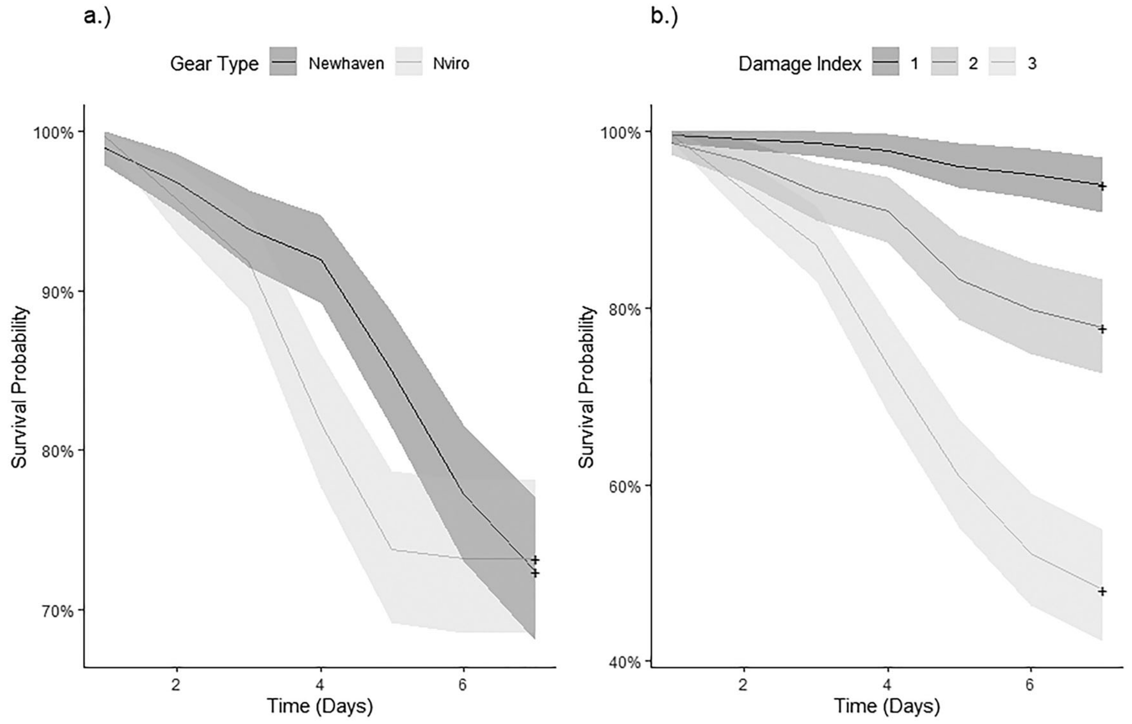

FIGURE 6 | Survival probability curves of bycatch species grouped by (a) gear type and (b) damage category throughout the duration of the 7-day observation period in land-based aquaria facility.

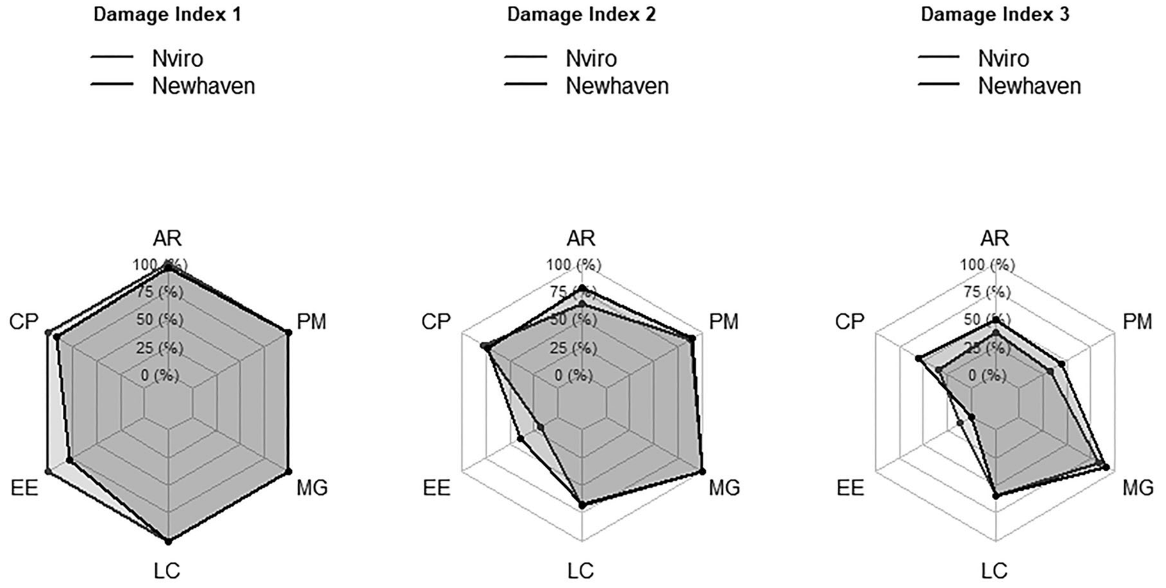

FIGURE 7 | The percentage of surviving individuals across the three damage categories for each of the six studied species at the end of the 7-day monitoring period. Data are also shown for the two scallop dredge gears tested: the Newhaven dredge and the N-Viro dredge. AR, *Asterias rubens*; CP, *Cancer pagurus*; EE, *Echinus esculentus*; LC, *Luidia ciliaris*; MG, *Marthasterias glacialis*; PM, *Pecten maximus*.

3.4 | Fuel Consumption

Fuel consumption was significantly reduced when fishing with the N-Viro dredge (Nviro) and the Nviro-skid; on average, fuel consumption was reduced by 30% relative to the conventional Newhaven dredge (Figure 8a, Supporting Information Table A7). The addition of the skid belly bag did not affect fuel consumption when used in combination with either the Newhaven dredges or the N-Viro dredges (Figure 8a). The fuel consumption for Nviro-skid dredges was 24.43 ± 0.44 L/h of fishing (mean ± SEM), whereas that for the N-Viro dredge with conventional bellies was 22.91 ± 0.29 L/h of fishing. Conversely, the fuel consumption for Newhaven-skid dredges was 32.89 ± 0.42 L/h of fishing, whereas that for the Newhaven with conventional bellies was

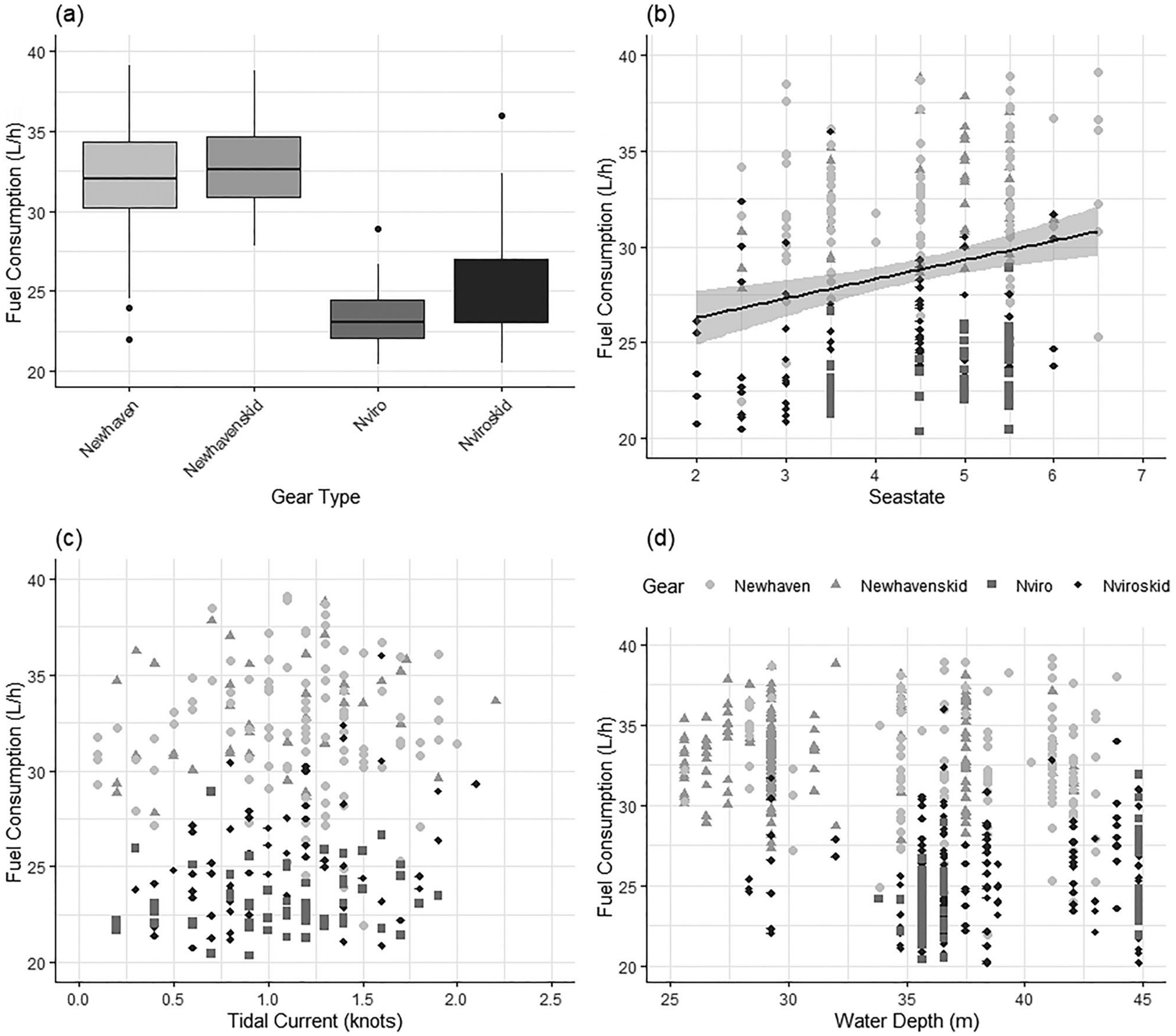

FIGURE 8 | Fuel consumption (litres used per hour of fishing, L/h) when fishing with the conventional Newhaven dredge (Newhaven, circle), Newhaven dredge with skid belly bag (Newhaven-skid, triangle), N-Viro dredge with conventional belly (Nviro, square) and N-Viro dredge with skid belly bag (Nviro-skid, diamond) (a). The influence of sea state (b), surface tidal current (c) and water depth (d) on fuel consumption for each gear type is shown. 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).

32.03 ± 0.34 L/h of fishing (Figure 8a). An average reduction in fuel consumption of 30% with N-Viro dredges equates to annual CO_2 reductions of 164,571 kg CO_2-e/year for vessels over 15 m and 37,235 kg CO_2-e/year for vessels under 15 m, alongside annual fuel cost savings of £46,250 and £10,465, respectively (Supporting Information Table A5).

Fuel consumption increased significantly with sea state (Figure 8b; Table 4) for all gear types, but there was no significant effect of surface tidal current or water depth (Figure 8c,d, respectively). The fitted model for fuel consumption and sea state indicates that for each unit increase in sea state (e.g., from force 2 to 3), fuel consumption increases by approximately 0.93 ± 0.13 L/h (Table 4).

3.5 | Seabed Impact: Epibenthic Fauna Depletion and Gear Footprint

Gears with standard belly bags produced significantly larger furrows compared to those with skid belly bags, which reduced the gear footprint on the seabed by approximately 55% (Table 5). The best-fitting model (furrow ~ gear type × habitat; AIC = −1116.86) further indicated that Newhaven gear with skid belly bags generated significantly larger furrows in softer substrates compared to stony ground (Supporting Information Table A6).

Fauna depletion was lowest for N-Viro dredge with skid belly bags (Figure 9). Both the Newhaven and N-Viro dredge designs with standard belly bags led to an average 20% reduction in fauna abundance inside the dredge lanes relative to outside (Figure 9).

TABLE 4 | Output for the linear mixed-effects model with significant terms, showing a significant influence of sea state and gear type on fuel consumption (L/h of fishing).

Fuel consumption (L/h)				
	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
Newhaven	−0.41	0.93	0.43	0.68
Nviro-skid	−7.61	1.03	7.41	<0.001
Nviro	−9.61	1.04	9.25	<0.001

TABLE 5 | Furrow width measurements across different ground types and the four scallop dredge designs.

Gear type	**Furrow width (m)**	
	Stone	**Soft**
Newhaven	0.85 ± 0.01	0.86 ± 0.01
Newhaven-skid	0.38 ± 0.01	0.45 ± 0.01
Nviro	0.89 ± 0.01	0.89 ± 0.01
N-viroskid	0.35 ± 0.01	0.37 ± 0.01

Note: Data are presented as mean ± SEM.

Overall, the effects on epifauna were comparable across the two ground types examined, except for the Newhaven dredge with skid belly bag, which caused greater fauna depletion in stony ground relative to sediment composed of sand and gravel (Figure 9). Despite these observed trends, fauna depletion did not differ significantly between gear and habitat types. 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 could confirm the observed trends.

4 | Discussion

Transitioning from conventional fishing gears associated with high fuel consumption and substantial impacts on marine ecosystems to gears that reduce ecological footprint offers opportunities to protect ecosystems and enhance food security. However, a major barrier to adopting innovative fishing gear by the industry is the potential for reduced catch and income unless offset by improvements in catch quality or reductions in operational costs such as fuel use and gear maintenance. This study provides novel insights into the effects of modified scallop dredge gears on catch performance, selectivity and environmental impact, relative to the Newhaven dredge commonly employed in the UK king scallop fishery. The incorporation of skid belly bags improved the market-sized scallop yields of both the N-Viro dredge and Newhaven dredge, resulting in a 19% and 14% increase, respectively; however, the N-Viro dredge alone did not significantly improve catch rates of marketable scallops relative to the conventional Newhaven dredge. The N-Viro dredge with skid belly bag conferred clear benefits in reducing the capture of undersized scallops and stone, fuel consumption and seabed impact, highlighting its potential as a more selective and environmentally efficient alternative. These findings underscore the complexity of optimizing fishing gear for both ecological sustainability and economic performance, emphasizing the need for a balanced approach in the development and adoption of sustainable fishing technologies.

4.1 | Catch Yield

Our results show that the lower biomass of market-sized scallops, caught by the N-Viro dredges, could be partially offset by using skid belly bags instead of the conventional belly bags. The enhanced performance associated with skid belly bags is likely to result from increased gear stability and more effective seabed contact, which can influence catchability (Fenton et al. 2024; Miller et al. 2019). The cause for reduced catches with the N-Viro dredge remains unclear, as surveys were conducted under consistent conditions, comparable areas and water depths, suggesting that differences in dredge–tooth interaction with the seabed may play a role. Catch rates were higher on stony grounds for both gear types. Although increased ground roughness may affect gear–seabed interaction, differences in scallop abundance among stony and softer substrates is likely to explain the observed higher catches in stony ground. Scallop populations are known to be affected by multiple environmental factors, including seabed complexity, the presence of cobbles and stones, water currents and food availability (Orensanz et al. 2006; Stewart et al. 2003). Furthermore, selective avoidance of stonier areas by fishers to reduce gear fouling during commercial operations may result in patches of higher scallop abundance on stonier grounds, hence resulting in the observed higher catch performance on stonier ground. These findings highlight the need for further investigation into the interactions between dredge design, seabed

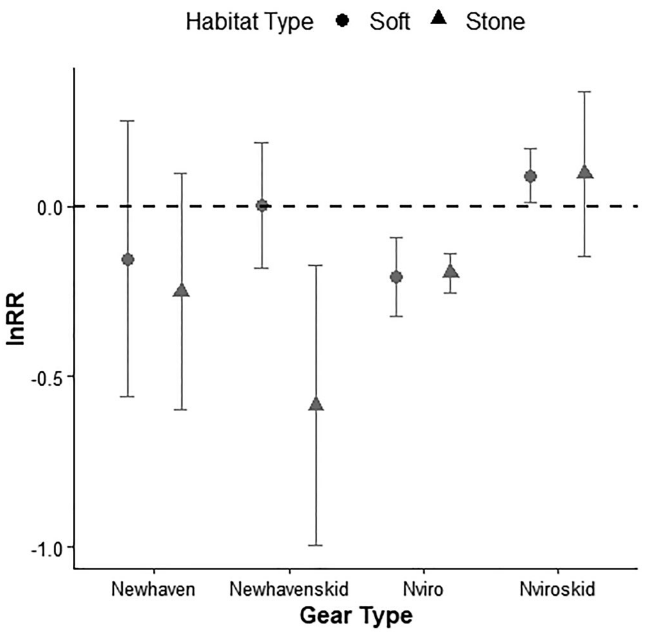

FIGURE 9 | Epifaunal depletion estimate (lnRR, mean ± SEM), calculated from abundance of benthic marine fauna caught inside and outside dredge lanes for different gear and ground type combinations. The dashed horizontal line indicates no difference in fauna abundance between inside and outside the dredge lane. Positive lnRR values indicates higher abundance in dredge lanes compared to outside, negative lnRR values indicates lower abundance in dredge lanes. A significant difference occurs when the 95% CI does not overlap lnRR = 0.

characteristics and scallop habitat preferences to optimize catch efficiency.

4.2 | Catch Selectivity and Fuel Performance

Enhanced catch selectivity provides long-term benefits to scallop fisheries by reducing the capture of undersized scallops, which are vulnerable to cumulative stress from repeated catch-and-release (Kaiser et al. 2007), increased predation risk owing to slower righting and reburial times (Maguire, Coleman, et al. 2002), and impaired escape responses following air exposure (Jenkins and Brand 2001). Our findings show that both the Nviro and Nviro-skid dredges significantly reduced bycatch of undersized scallops (−42%) and stones (−67%) relative to Newhaven dredges. Reducing stone bycatch not only decreases sorting time, thereby improving fishing efficiency, but also minimizes seabed disturbance, helping to preserve habitat complexity essential for juvenile scallop settlement (Bradshaw et al. 2003; Veale et al. 2000). Hard substrates colonized by epifauna such as hydroids and bryozoans provide critical settlement habitats for juvenile king (*P. maximus*) and queen scallops (*Aequipecten opercularis*) (Bradshaw et al. 2003). These fragile species are among the first to be removed by repeated dredging, with the return of stones further contributing to habitat degradation (Veale et al. 2000). Because small-scale habitat complexity is central to structuring benthic communities, minimizing stone retention and displacement through improved dredge design could aid in conserving key biological structures, supporting both ecosystem integrity and the long-term fishery sustainability.

Although fuel consumption did not differ significantly between dredges with skid belly bag and conventional belly bag, the N-Viro dredge demonstrated significantly lower fuel use (~30% reduction) compared to the traditional Newhaven dredge. This is likely attributable to a reduction in hydrodynamic and contact drag, facilitated by the N-Viro dredge's skid-equipped frame and independently sprung tines, which collectively reduce resistance against the seabed during towing. The N-Viro dredge has been reported to operate optimally at a lower towing speed (~2 kn) than the Newhaven dredge (~3 kn) (DSM Ltd., pers. comm.). Lower towing speeds may contribute to further efficiency gains. Modelling studies, such as by Prat et al. (2008) on otter trawls, indicate that drag, and thus fuel consumption, increases with the square of vessel speed; however, preliminary data from this study suggest that the N-Viro dredge retains its fuel-saving advantage even as towing speeds increase from 2.1 to 2.6 kn (Supporting Information Table A7). Reduced towing speeds also decrease the area swept, potentially lowering catches unless offset by improved catchability or higher scallop density. Ultimately, towing speed must be balanced with catch efficiency, which varies depending on factors like sea state, vessel propulsion design, gear drag and seabed type (Poos et al. 2013; Suuronen et al. 2012; Walsh 2010). Future work should evaluate trade-offs between fuel savings, catch-per-unit-effort (CPUE) and environmental benefits across varying towing speeds to guide the sustainable optimization of scallop dredge design.

Our results on catch selectivity and fuel consumption are consistent with previous trials across European and North American fisheries, which similarly reported reductions in stone retention, undersized scallops and fuel use for the N-Viro dredge (Bethoney et al. 2023; Chevarie and Chevarie 2020; Filippi 2013). In the Bay de Seine, the N-Viro dredge reduced stone retention and achieved fuel savings of 12%–31% compared with spring-tooth dredges (Filippi 2013). Trials in the Gulf of St. Lawrence reported 50% lower stone capture and 20% lower fuel consumption relative to the Digby dredge (Chevarie and Chevarie 2020). Similarly, comparisons with the New Bedford dredge showed improved fuel efficiency, reduced habitat disturbance, and a 50% decrease in fish bycatch (e.g., skate, monkfish and windowpane) (Bethoney et al. 2023).

4.3 | Bycatch and Seabed Impact

None of the modified dredge designs tested reduced overall bycatch rates or improved bycatch survivability relative to the Newhaven dredge. Although the N-Viro dredge reduced stone retention, this advantage did not extend to bycatch fauna, presumably because its sprung tines still exert sufficient force to dislodge benthic organisms into the collector bag. Bycatch survivability was species-specific and closely linked to injury severity. Species with robust shells experienced mostly minor shell chippings and low mortality (2%–3% $D3$–$D4$), and starfish such as *A. rubens*, which has been shown to recover from fishing stress relatively quickly (Bergmann 2001), exhibited intermediate resilience. Fragile taxa such as echinoids and decapods suffered severe injuries in >40% of cases, with over half of these individuals dying within 7 days, suggesting significant mortality of live individuals for these species once discarded back into the sea. With bycatch accounting for about 22% of the live catch (i.e., excluding stones) in our catches, reducing bycatch in a scallop fishery that relies on dredge teeth to collect the target catch remains a challenge. Potential strategies to reduce bycatch include increasing tooth spacing, though this may reduce scallop catch efficiency (Lart 2021; Lart et al. 2003). Alternative gear designs, such as the Hydrodredge, which replace dredge teeth with hydrocups that create a downward jet to lift scallops from the seabed, have been shown to reduce bycatch relative to the Newhaven dredge; however, their low CPUE has limited economic viability (Shephard et al. 2009). Diver-caught scallops and novel approaches such as the use of light stimulus on creel pots to catch scallops (Enever et al. 2022) are low-impact alternatives; however, these can only supply limited quantities of scallops because the harvest area covered during a single dive or deployment is much smaller than that of a commercial dredge haul. Although no link was found here between stone retention and fauna damage, previous studies suggest that shorter tow durations could lessen abrasion injuries (Bradshaw et al. 2001; Howarth and Stewart 2014), albeit at the cost of increased handling effort. This study primarily focused on damage and mortality from gear effects; however, handling duration and air exposure are critical determinants of bycatch survivability (Breen and Catchpole 2021). Future research should examine tow duration and post-capture handling practices as a means to reduce bycatch mortality and enhance the sustainability of scallop dredge fisheries.

Seabed impacts of Newhaven dredges associated with the dragging of the gear along the seabed are 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 replacement of the conventional belly bag with the skid belly bag has significantly reduced the gear footprint on the seabed. Although benefits are still expected to be limited for erect sessile organisms such as sea pens, this study has shown that benefits are greater for low-lying organisms such as sponges, ascidians, ophiuroids, small asteroids and echinoids when the N-Viro dredge with a skid belly bag is used. Although skids concentrate pressure over a smaller area, which is likely to increase gear penetration depth, conventional belly bags distribute weight evenly across a larger surface area and therefore impact larger seabed areas. We found that the overall impacted surface area was reduced by more than 50% when the skid belly bag was used, thereby conferring clear benefits in terms of reducing epifauna mortality. We observed furrow width to be higher in sandy ground than in stony ground. As the belly bag fills with the catch, it sinks deeper into soft seabeds. In contrast, on stony ground, the gear's weight is supported by stones and other stable substrates, resulting in shallower furrows (Howarth and Stewart 2014). Observations by O'Neill et al. (2024) have shown that gear penetration depth increased both on softer sediments and with increased weight but decreased with faster towing speeds. Future research comparing the penetration depth of N-Viro dredge tines and skid belly bags across various sediment types and when towed at different speeds would provide valuable insights into gear-seabed interactions. Furthermore, research on the effects of the N-Viro dredge with skid belly bags on infaunal abundance, relative to traditional dredges and non-dredged areas, would enhance understanding of ecological impacts and inform the development of more sustainable harvesting practices.

4.4 | Conclusion

Through technological improvements, capture fisheries can decrease the damage to benthic ecosystems, reduce emissions and lower fuel costs without excessive impacts on fishing efficiency. The adoption of low-impact fishing techniques should be viewed as one strategy to improve fishery outcomes; the integration of these measures within an effective Ecosystem Approach to Fisheries (EAF) management system that regulates overall fishing effort would support the transition to more sustainable fishing practices. The use of the N-Viro dredge with skid belly bag offers tangible opportunities to reduce the environmental impact of scallop dredging in UK waters, with notable reductions in fuel use, carbon emissions, seabed disturbance and undersized scallop catch, while maintaining a profitable fishery. Adoption of this modified gear would be a step-change towards partially reducing the negative environmental impacts associated with scallop dredging.

Author Contributions

Blair Easton: data curation (lead), formal analysis (equal), investigation (equal), methodology (supporting), visualization (equal), writing – original draft preparation (equal), writing – review and editing (equal). **Caleb Moffat**: investigation (supporting), writing – review and editing (equal). **Moritz Eichert**: investigation (supporting), writing – review and editing (equal). **Aisha Abdallah**: investigation (supporting), writing – review and editing (equal). **Natalie Hold**: conceptualization (supporting), funding acquisition (supporting), resources (supporting), writing – review and editing (equal). **Michel J. Kaiser**: conceptualization (supporting), funding acquisition (supporting), writing – review and editing (equal). **Marija Sciberras**: conceptualization (lead), formal analysis (equal), funding acquisition (lead), investigation (equal), methodology (lead), project administration (lead), resources (lead), supervision (lead), validation (lead), visualization (equal), writing – original draft (equal), writing – review and editing (equal).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data files are available through MEDIN data repository (https://doi.org/10.17031/6887591a374a8).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: aff270225-sup-0001-SuppMat.docx