PROJECT UK

DELIVERING FISHERY IMPROVEMENTS
IN THE NORTH EAST ATLANTIC

Review of alternative measures that minimise mortality of unwanted catch and reduce habitat impact in UK king scallop (*Pecten maximus*) fisheries.

Authored By: William Lart

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For further information please contact

William Lart
Sustainability and Data Advisor
Seafish | Origin Way, Europarc, Grimsby DN37 9TZ
T: 01472 252 323
M: 07876 035 729
Email William.Lart@seafish.co.uk

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Executive Summary

The MSC Fisheries Assessment Methodology requires that fisheries adequately consider the MSC Principles & Criteria in relation to gear selectivity. This review summarises;

- the current legal requirements for dredge design for the four nations of the UK and the Isle of Man;
- the research and development, designed to understand and mitigate adverse of effects of dredging on scallops, benthic habitats and bycatch organisms;
- the various innovations which have been tested, as far as is possible, in terms of their main environmental effects.

The effects of capture in terms of selectivity, damage and stress on scallops and other organisms which the dredge encounters are described. The main findings were:

- That much of the lethal damage to scallops occurs at the first point of contact with the dredge's teeth with the damage rates related to shell strength and varies between grounds.
- Retention in the gear and sorting on deck causes sublethal stress in undersized scallops and the main benefits of selectivity are that this stress is reduced.
- The low efficiency of the dredges means that observations of catch and bycatch of mega-faunal species including scallops landed on the deck only gives a limited indication of levels of damage caused by dredging to these species. More information is available from observations by divers and possibly ROV[1]s post dredging.

The performance of the various gear innovations researched and tested are compared in the terms of the dredges' effects:

- on benthic habitats and species,
- selectivity, and level of stress in scallops,
- damage to catch and/or bycatch and
- commercial viability in terms of handling and safety, catching and fuel efficiency, and durability,

are compared and discussed where feasible, and the properties of materials available for dredge construction are discussed. So far experimental work has been designed to compare the various innovations with standard dredges. However, the analysis in this review has highlighted the

[1] Remotely Operated Vehicles

opportunities for combining the various innovations available to improve the overall performance of the gear.

Interactions between scallop dredging activities and Endangered, Protected and Threatened (ETP species) and vulnerable habitats as are reviewed, and possible approaches to mapping, assessing and reducing these interactions are discussed.

Version		Author	Date
1	First draft V1	William Lart	05-2021
2	Comments on first draft	Reviewer	07-2021
3	Version 2	William Lart responded to comments	
4	Version 3	Additional information on ETP species added and an update on the scallop collector **Error! Reference source not found.**	03-2022
5	Version 4	William Lart Information on the Low Impact Scallop Innovation Gear (LISIG) Project and discussion added	06-2022
6	Version 5	Added further discussion, put robot dredge and light capture effects in appendix	03-2023

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1 Introduction

The MSC Fisheries Assessment Methodology (MSC, 2019) requires that fisheries adequately consider the MSC Principles & Criteria, in relation to gear selectivity, namely that fisheries should:

"make use of fishing gear and practices designed to avoid the capture of non-target species (and non-target size, age, and/or sex of the target species); minimise mortality of this catch where it cannot be avoided, and reduce discards of what cannot be released alive" (Criterion 3B.12).

In addition, FAO (1995), states that;

"selective and environmentally safe fishing gear and practices should be further developed and applied, to the extent practicable, in order to maintain biodiversity and to conserve the population structure and aquatic ecosystems and protect fish quality. **Where proper selective and environmentally safe fishing gear and practices exist, they should be recognized and accorded a priority in establishing conservation and management measures for fisheries."**

To ensure this, the MSC has recently added a "Review of alternative measures" to several performance indicators to encourage the development and implementation of technologies and operational methods that minimise mortality of unwanted catch or endangered threatened or protected (ETP) species", the desired outcomes being:

- To motivate fishers to continually "think smart" about their impact on the environment (species and habitats); both in delivering the sustainable impact most efficiently - and continuing to reduce their impact beyond that.

- To balance this desire with efficiency by not spending a lot of money and time generating only marginal improvements.

To achieve this for species, the scoring issue has been added to the P1 Harvest Strategy ((Performance Indicator (PI) 1.2.1) and P2 Species Management PIs (PI 2.1.2, 2.2.2, 2.3.2) requiring fisheries to continually review alternative measures to encourage the development and implementation of technologies and operational methods that minimise mortality of unwanted catch or ETP species, taking into account the practicality of the measures, their potential impact on other species and habitats and on the overall cost of implementing the measures.

Fisheries need to either review alternative measures that are shown to minimise mortality of the species or species group in question. Fisheries also need to consider alternative measures to reduce impacts on habitats. Fisheries should also take account of the potential for both positive and negative impacts of alternative measures on species and habitats when considering whether such measures should be implemented.

Alternative measures should avoid capture of the species in the first place or increase its survivability if released. Alternatively, in the case of in-scope species, they could utilise the unwanted catch in some way so that it would no longer be 'unwanted'. If there are no unwanted species, the scoring issue on reviewing alternative measures does not need to be scored in that PI.

Alternative Measures Definition for unwanted catch: Fishing gear and practices that have been shown to minimise the rate of incidental mortality of the species or species type to the lowest achievable levels.

Alternative Measures Scoring Guideposts

SG 60 There has been **a review** of the potential effectiveness and practicality of alternative measures to minimise UoA-related mortality of unwanted catch of the target stock/secondary species/ ETP species.

SG 80 There is a **regular** review of the potential effectiveness and practicality of alternative measures to minimise UoA-related mortality of unwanted catch of the target stock/secondary species/ ETP Species and they are implemented as appropriate.

SG 100 There is a **biennial** review of the potential effectiveness and practicality of alternative measures to minimise UoA-related mortality of unwanted catch of the target stock/secondary species/ ETP Species., and they are implemented, as appropriate.

''As appropriate" in scoring guideposts 80 and 100 in the context of implementing reviewed measures relates to situations where potential alternative measures reviewed are:

a. Determined to be more effective at minimising the mortality of unwanted catch than current fishing gear and practices,
b. Determined to be comparable to existing measures in terms of effect on target species catch, and impacts on vessel and crew safety,
c. Determined to not negatively impact on other species or habitats, and
d. Not cost prohibitive to implement

Table 1 Tabulation of scoring guideposts

Performance indicator and scoring issue	Species group	Comment
1.2.1 Harvest strategy f	Target species	Related to unwanted catches of target species, e.g., below minimum conservation reference size.
2.1.2 Primary species management strategy e	Main species	Related to the part of the catch that the fisher did not intend to catch but could not avoid and did not want or chose not to use. Includes observed and unobserved mortality.
2.2.2 Secondary Species management strategy e	Secondary species	
2.3.2 ETP species management strategy e	ETP species	

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2 UK scallop dredge technical measures relating to dredge design

The UK devolved administrations have introduced their own technical measures for scallop dredge tooth spacing and mesh size, partly based on the results of the Ecodredge project (Lart editor. 2003), these are shown in

Table 2, together with the regional Minimum Conservation Reference Sizes (MCRS). Table 3 shows the applicable European regulations on Minimum Conservation Reference Size (MCRS) for scallops. Note that there are other technical regulations which control fishing effort in terms of dredge numbers within designated fisheries zones.

The regulations are expressed in different ways regionally.

1. The internal dimension of the ring or tooth spacing is given in millimetres

2. The number of rings or teeth across the dredge are used to define the characteristics of the gear taking into account 'turn ups' of one ring at each side of the dredge which are not fixed to the bar.

The latter regulations (2) are designed to enable surveillance to consist of simply measuring total width of the dredges and counting the number of teeth across the bar and rings hanging from the bar. This approach was designed to avoid having to measure internal diameters of the rings, because rings are likely to be distorted, by wear and tear.

The tooth spacing is expressed as number of teeth per bar in some administrations or as tooth spacing in others. The English, Northern Irish and Isle of Man regulations are all are designed to result in 75 mm inside diameter belly rings, with 10 mm diameter wire. The Welsh regulations are designed to result in a ring size of 85 mm with 10 mm wire.

Table 2 Current scallop dredge selectivity measures (2021). Please refer to the original legislation for definitive information.

Administration	Measures and effective dimension (>80 cm dredges; the numbers of rings and teeth are adjusted for smaller <80 cm dredges)			Selectivity of belly ring size measure based on Ecodredge results; L_{50}[2] See section 3.6	MCRS shell length (mm)	Other measures	Ref
	Teeth Bar length = 705 mm	Rings	Mesh (mm)	Rings (wire=10mm)			
England Outside relevant area	9 teeth/bar if teeth are ≤12 mm width 12mm=75 mm spacing Or 8 teeth/bar if any tooth measures > 12 mm width	8 rings hanging from bar= 75 mm id	No reg	L_{50} = 85 mm	100	Must have a spring-loaded tooth bar. No attachments or diving plates. Maximum weight 150 kg. No attachments obstructing the belly rings	The Scallop Fishing (England) Order 2012
England Inside relevant areas which is; Irish Sea N. of 52°30' excluding Scottish waters and all of ICES Division 7d	8/bar 12 mm width spacing = 87 mm	8 rings hanging from bar = 75 mm id.	No reg	L_{50} = 85 mm	110		
Wales	8/bar and not more than 22 mm dia. and 110 mm long. Tooth spacing approx. 75-87 mm	7 hanging from bar = 85 mm id	No reg	L_{50} = 97 mm	110		The Scallop Fishing (Wales) (No.2) Order 2010
Northern Ireland	75 mm spacing	75 mm id	100	L_{50} = 85 mm	110	No French dredges	Conservation of scallops (Northern Ireland) 2008
Isle of Man	75 mm 9 teeth/bar (12 mm teeth)	Clear opening of 75 mm id.	100	L_{50} = 85 mm	110	No French dredges	Licence conditions under Isle of Man Sea fishing licence
Scotland	9 teeth/bar if teeth are <12 mm width or 8 teeth/bar if any tooth measures > 12 mm width max tooth length	8 rings hanging from bar= 75 mm id. Same for backs	No reg	L_{50} = 85 mm	105	No attachments that obstruct netting or rings French dredges are banned.	The Regulation of Scallop Fishing (Scotland) Orders 2005 and 2017

[2] L_{50}= Length at 50% retention rounded to the nearest mm

Table 3 European Union regulations (REGULATION (EU) 2019/1241)

Locations	MCRS (shell length; mm)
All EU waters except below	100
In ICES division 7a (Irish Sea) north of 52° 30′ N, and ICES division 7d (Eastern English Channel)	110

Article 8 requires that 95% by live weight of catch consists of bivalve or gastropod molluscs or sponges.

3 Process and effects of scallop dredging

Spring toothed (or 'Newhaven') scallop dredges (Figure 1) are towed in gangs of several dredges behind towing bars as shown in Figure 2. Apart from the rubber wheels at the ends of the bars, teeth form the first major penetrative contact with the seabed, and it is the interaction between the teeth and the scallops that enables the capture of the scallops. The mechanism for capture has been investigated in the Ecodredge[3] project, and a hypothesis of the capture mechanism is based on frame by frame video camera observations is shown in Figure 3. The mean depth of penetration has been found to be approximately 25 mm on sand-gravel, with deeper penetration 35-59 mm on more gravelly substrates.

Following behind the teeth, the steel ring collector bag the lower part of which is referred to as the dredge belly is towed over the seabed. There is usually a build-up of catch and stones, which substantially increases the weight of the bag (16-78 kg per bag have been estimated, the amount dependent on the amount of stones and catch picked up from the seabed) hence its effect on the seabed and the organisms present increases with the length of the tow. Tensions on the shackles which attaches each dredge frame to the bar have been estimated at 100-180 Kgf. Dredges have been observed to bounce across the seabed apparently mediated by resonance in the springs' action.

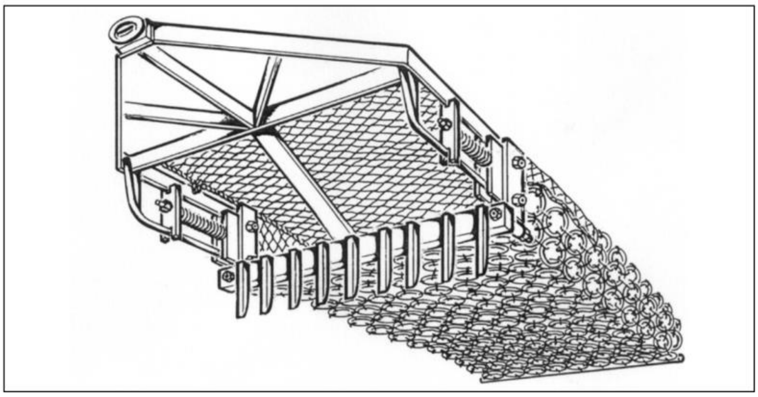

Figure 1 Newhaven 'spring' Scallop dredge

[3] For full details see Section 3.1.1.1 Ecodredge Investigations Volume 2 (Lart, ed 2003)

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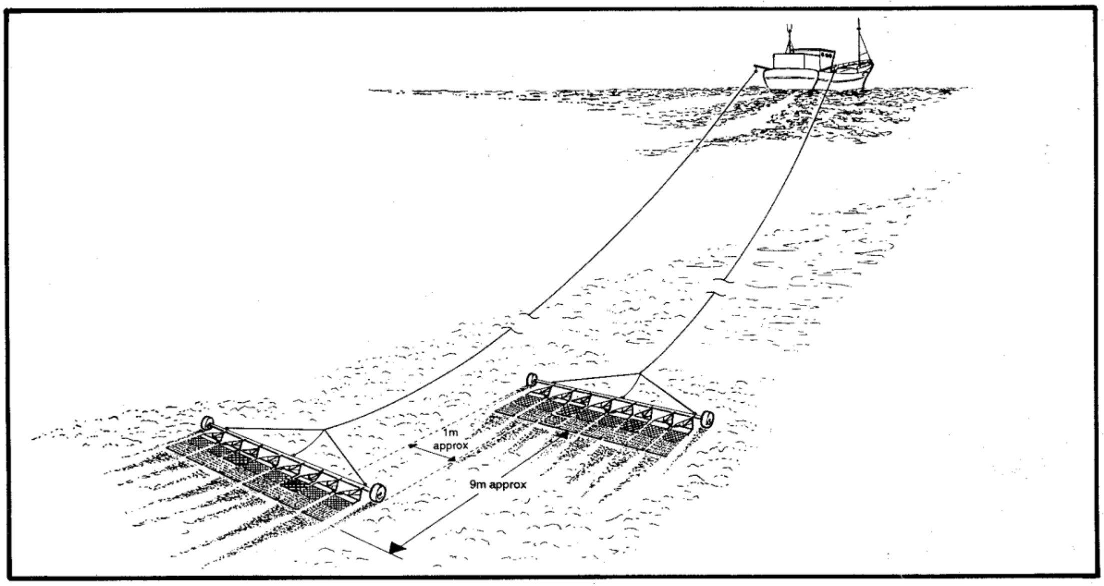

Figure 2 Newhaven 'Spring' scallop dredge: Fishing operation. Note, not all vessels use the staggered towing method, some tow with equal length warps from booms positioned forward in the vessel

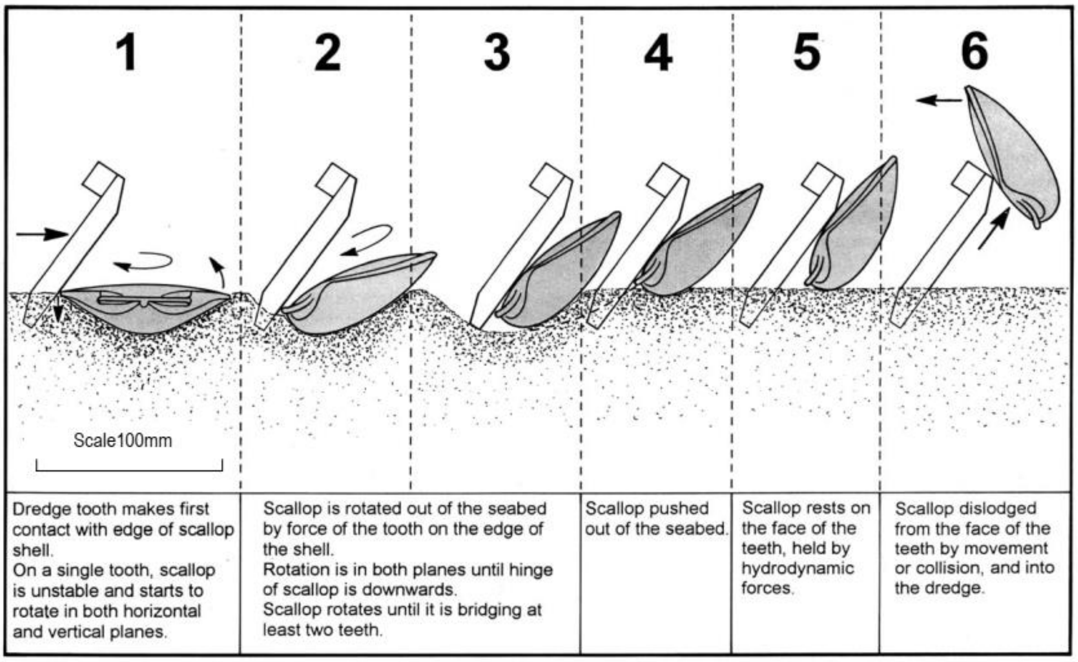

Figure 3 Hypothesised method of scallop capture by spring toothed dredge based upon video observations. Tooth angle set at 55˚ the mean angle and depth of penetration measured on sand-gravel substrate

3.1 Implications of damage rates and dredge efficiency

In order to fully evaluate the effects of scallop dredging on the encountered biota there is a need to study the effects of dredging on both the organisms captured and retained by the gear and those encountering the gear but left on the seafloor. Methods have been developed (Veal et al, 2001) to describe the levels of damage, in terms of damage scores (see Table 4), and subsequent survival under laboratory conditions, for a variety of megafauna species. These methods have been used to examine the damage and survival potential of both those specimens captured and retained by the gear and those left in the dredge track (Jenkins et al., 2001).

Key findings were;

- The mean level of damage to several common megafaunal species was compared between captured organisms landed on deck (bycatch), and those encountering the dredge but left on the seabed. For many species including scallops, the mean damage rates were similar. For some species such as brown crab (*Cancer pagurus*) damage rates were higher for those specimens left on the seafloor, suggesting that passage under the dredge was more damaging than being retained by the dredge.

- The low level of efficiency of capture by the dredges combined with roughly equivalent levels of damage between the bycatch (ie the catch landed on deck) and animals left on the seabed for most species studied, means that observation of bycatch alone gives only a limited indication of levels of damage to megafauna (see Figure 4).

- Combining the damage rates for those animals left on the seabed and those landed on deck for the mega faunal species enables an overview of the percentage by number of the damage rates of species encountering the gear (Table 4)

Dredge efficiency studies for scallop dredges have been comprehensively reviewed by Delargy et al., (2022), focussed on the use of dredges in stock assessments for scallops. Considerable variation in catch efficiency for scallops exists among studies (0.1 to 0.7) and it is important to that this variation is accounted for during surveys and stock assessments. Scallop size and substrate type were the two most common reporting categories discussed in the studies and consequently should be considered the two most important drivers of catch efficiency. Other important factors such as gear specifications, and scallop species were featured in some studies.

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Table 4 Predicted level of damage to megafauna in the path of spring toothed scallop dredges (bycatch and non-captured animals combined) as a percentage of individuals with each damage score, from Jenkins et al., (2001). Damage scores are calibrated from 1; no visible damage, 2; some slight damage, through to 3 – 4 lethal damage; see Veale et al., (2001) for a full description of scores.

Species	Damage score 1	2	….3	…. 4
Asterias rubens	93.2	6.2	0.4	0.2
Crossaster papposus	92.1	7.6	0.0	0.3
Astropecten irregularis	67.5	26.8	4.6	1.1
Porania pulvillus	99.8	0.2	0.0	0.0
Luidia ciliaris	53.3	38.6	15.3	20.4
Echinus esculentus	53.3	1.1	29.3	16.4
Neptunea antiqua	76.7	23.2	0.1	0.0
Cancer pagurus	36.8	13.9	6.1	43.2
Liocarcinus spp.	50.0	6.1	7.7	36.3
Pecten maximus	93.0	1.8	2.9	2.3

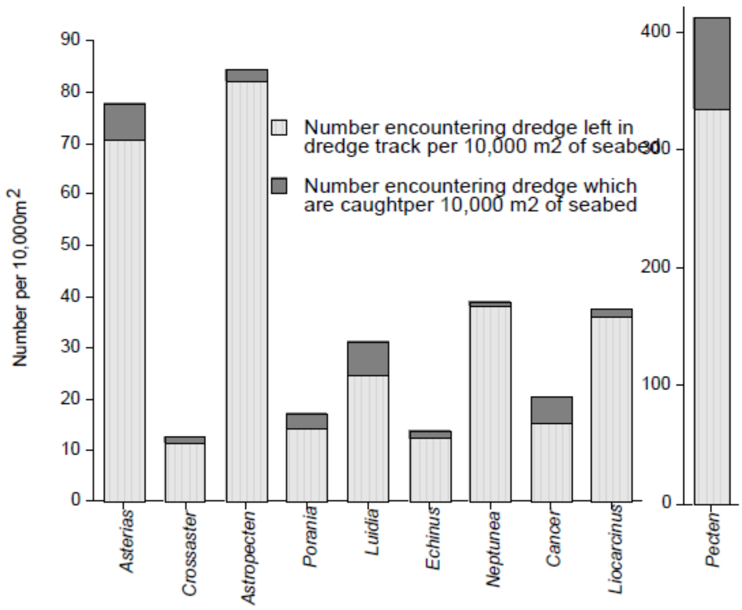


Figure 4 Density (calculated as number per 10,000m² of seabed) and efficiency of capture by spring toothed scallop dredges of 10 megafaunal species (Jenkins et al., 2001)

3.2 Effects on king scallop

The effects of capture and selection at the dredge and capture followed by selection on deck were examined by the Ecodredge project using field and laboratory studies of the effects of dredging and simulated dredging on scallops. Stress in scallops was estimated using the Adenylate Energy Charge (AEC) levels (see Appendix 1) in the straited adductor muscle which is the muscle that the scallop uses for swimming (Maguire et al., 2002a,b). In essence, this is an index of the immediately available energy which the scallop can use for swimming, jumping and recessing.

Stress was also examined through behavioural observations; the rate at which scallops reburied in the sediment (Maguire et al., 2002a,b) and the behavioural response of the scallops to predators (Jenkins and Brand, 2001). The effects of damage and stress factors on attraction of predators and consequences of predation were investigated using baited cameras (Jenkins et al., 2004).

Key findings were;

- The stress effects as elicited by AEC and behavioural studies in scallops were related to the duration of dredging and severity of the acceleration which the scallops were subjected to during dredging. AEC levels were recovered in between 6 and 24 hours after dredging, but certain aspects of the scallop's behavioural response to predators continued for 24 hours or more.

- The AEC levels in scallops which were collected from the dredge track by divers were found to be similar to those which had undergone simulated dredging for 16 minutes. Scallops which had been towed for 45 minutes within the dredge bag were considerably more stressed (lower AEC levels) than those collected from the dredge track.

- Damage levels of scallops in the catch and recovered from the dredge tracks were not significantly different. Further studies of damage rates and other factors including volumes of stones in the dredges lead to the conclusion that the majority of the damage occurred during initial impact with the dredge teeth (see also Section 4.2). Variation in shell thickness, structure and strength of scallops' shells appeared to be the principal driver for variation in damage levels between scallop fishing grounds (Stewart et al., 2021).

The consequences of damage and stress were examined by observations of scallops placed before cameras in experimental plots (stressed by simulated dredging and application of minor or major shell damage) by Jenkins et al., (2004). Batches of scallops which were undamaged, lightly damaged, and badly damaged were tested:

- Density of scavengers at the stressed but undamaged scallops was equivalent to the density during un-baited periods, which suggests that stressed scallops do not attract scavengers.

- For the damaged scallops there was a significant increase in scavenger density over the study period of 96 hours

- The badly damaged scallops were all eaten within just over 24 hours for each of the 2 replicate periods.

- The scallops that were lightly damaged survived longer, but survival rates differed among replicates.

These results indicate that the mortality of undersized scallops discarded back onto the grounds they were fished on is more likely to be related to shell damage than stress induced by dredging.

However, these results should be caveated by the fact that the predators prevalent in a particular location may be highly variable. The predators and scavengers which the scallops were exposed to were markedly different by comparison with those of a previous study, at the same site, four years previously. The previous study found large aggregations of the predatory starfish *Asterias rubens* and *Astropecten irregularis*, and the crabs *Liocarcinus* species and *Pagurus* species. In general, the scavenger community observed in this study differed markedly, with a greater dominance of fish and an increased importance of the edible crab *Cancer pagurus.*

Therefore, it is conceivable that the results may have been different had the stressed but lightly or undamaged scallops been exposed to more starfish, as in the previous study. It is notable that although the AEC levels of experimentally stressed scallops recovered within 6 to 24 hours, their response to starfish was affected for at least this period in experimental studies (Jenkins and Brand, 2001).

Figure 5: The N-Virodredge design (left) separate from the steel belly bag, with individually sprung tines and side skids; compared to the Newhaven dredge (right) with a fixed tooth bar. Source: Filippi, (2013).

3.3 Effects of changes in teeth spacing and design

There is good evidence (see above) that much of the lethal damage to scallops occurs at contact with the teeth, so understanding the effects of tooth design is an important element in understanding measures taken to reduce the effects of dredges.

Teeth spacing

Minimising the amount of time the scallops spend in contact with the gear will minimise stress on the scallops (see section 3.2). There is evidence that increasing tooth spacing improves selectivity (Figure 6) which happens instantly at the teeth, so regulating tooth spacing is a valid option for controlling selectivity. The experimental results for so called 'French' teeth of 12 mm width, consistently showed increasing selectivity with increasing spacing. The English regulations (

Table 2) require 8 teeth/bar in areas (North Irish Sea and Eastern English Channel) where the MCRS is 110 mm, but 9 teeth/bar elsewhere. The Welsh regulations in Welsh waters require 8 teeth/bar. Evidence for the spacing of the 'peg' teeth of 20 mm diameter influencing the selectivity of the gear is not available.

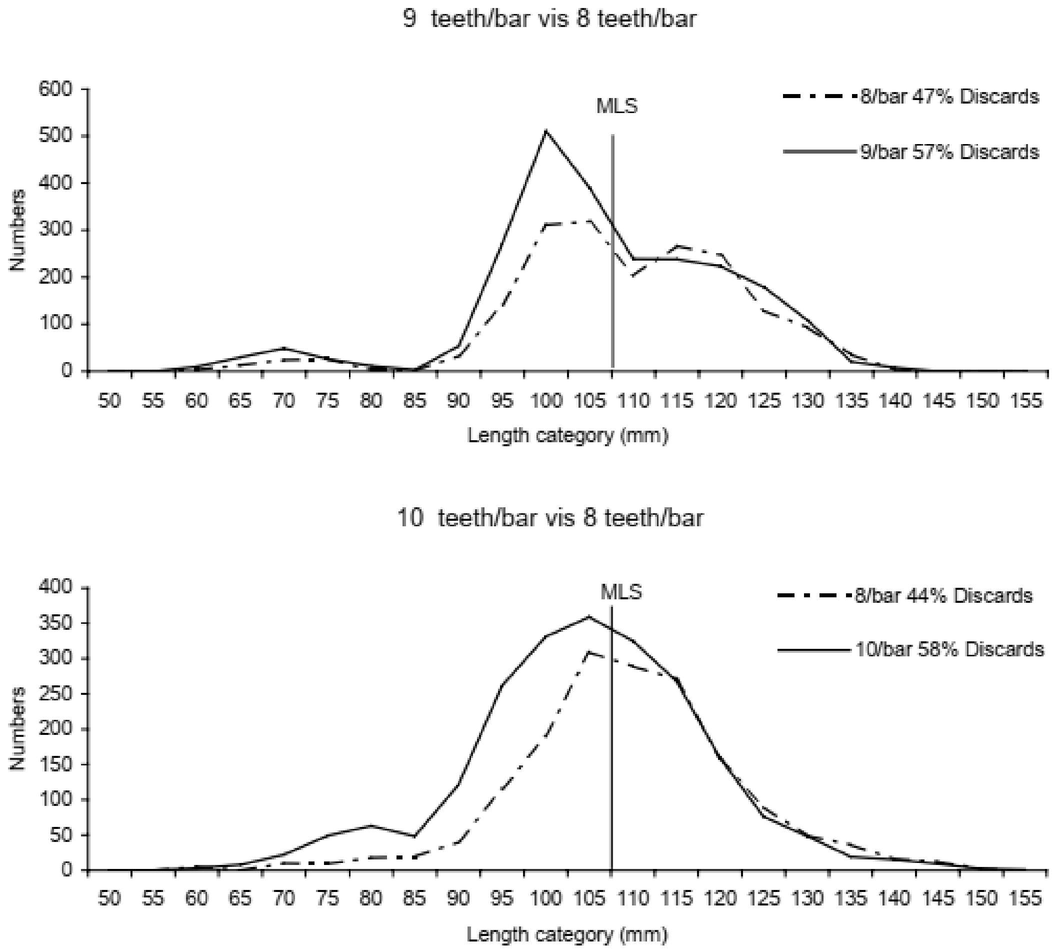


Figure 6 Length frequency distributions for catch comparisons between 8, 9, and 10 teeth to the bar for 12 mm wide teeth. Both these plots show evidence of selectivity (Lart ed., 2003)

N-Virodredge™

The N-Virodredge™ [4] is a modification of the Newhaven dredge designed and patented by Deeside Marine Ltd (Kirkcudbright). The sprung tooth bar is replaced by individually sprung tines around 17 cm long and 8 mm wide. Skids on each end of the tine bar support the weight of the bar (Figure 5). The intention behind this design is to move the weight of the dredge from the teeth on to the side skids, hence reducing the pressure at the teeth, and the design enabling the tines to move independently (Chris Bird pers. comm). Trials in the Bay de Seine (Fillippi, 2013) comparing the N-Virodredge™ with spring tooth dredges (although not on the same vessel) over a period of 3 months with 4 vessels showed at least equivalent

[4] http://n-virodredge.com/

levels of efficiency and yields, although influenced by seabed composition. The results also indicated;

- A virtual absence of chipped or broken shells and less off size scallops (presumably small scallops) captured
- A reduction in the quantity of stones retained by the gear
- Fuel savings estimated at between 12.2 and 31.4%.

The main operational issues were related to the durability of the teeth, provided the teeth lasted for a minimum of 2 days, the maintenance cost of the dredges was 10% less for the N-Virodredge™ compared with standard spring toothed dredges. However, advances in hardening technology since this study was carried out mean that N-Virodredge™ teeth are reported to have approximately the same lifespan as the standard spring teeth (Richard Gidney pers. comm), therefore improving maintenance cost savings.

The N-Virodredge™ has been tested in Canadian waters in comparison with 'Digby' dredges targeting sea scallop (*Placopecten magellanicus*) off the Îles-de-la-Madeleine, Gulf of St Lawrence. The N-Virodredge™ had a 50% reduction in stones captured and reduced capture of undersized scallops. There was no difference in the catch-per-unit-effort of the two gears and a reduction of 20% in fuel consumption in one of the two trial vessels (Chevarie and Chevarie, 2020).

A study reported to ICES WGScallop (2015) in 2015 compared the effects of N-Virodredge™ on with standard spring toothed scallop dredges on sandy and mixed sediments (EUNIS class A5.33 and 5.43; (see (https://eunis.eea.europa.eu/habitats.jsp) in Clew Bay on the west coast of Ireland both in terms of bycatch and environmental effects post dredging using diver observations. They report:

- Catch rates for scallops in the N-Virodredge™ were slightly higher than standard spring toothed dredges and with less variability
- Bycatch was similar in both dredges and there was no apparent difference in selectivity
- Sources of physical impact include the rollers at the end of the dredge beam, the dredge teeth in standard dredges and tines of the N-Virodredge™ and the weight of the dredge bags (chain mat)
- Tracks from both dredges were clearly visible in the days following dredging. However, diver surveys were not able to detect a difference in the impact of the two dredge types

- The N-virodredge™ teeth were observed to penetrate the seabed up to their full extent (12-15 cm). However, this may be a reflection of the habitat present (relatively fine sand for scallop dredging) and may not be typical.

Overall effects of damage at teeth

Lethal and sub lethal damage rates of scallops observed in the catches of standard spring toothed dredges are relatively low; around 2-11%, and related to shell strength which has been found to vary between grounds (Stewart et al., 2021). However, the low efficiency of the dredges (Figure 4) means that there are more scallops and other organisms affected by dredging than appear in the catches. Therefore, any reduction in damage, as has been reported to be achieved for with the N-Virodredge™ tooth design (see above), would be beneficial in reducing the effects of dredging on non-retained scallops.

3.4 Effects of alternative mechanisms for lifting scallops out of the seabed

As the scallop dredge teeth have been identified as an important source of damage to scallops and bycatch several investigations were carried out during the Ecodredge project (Lart, ed 2003) and also subsequently by Sheperd et al., (2008; 2020) to understand the viability of different mechanisms for lifting scallops out of the seabed. Tests were carried out on the following mechanisms.

- **The Magnus** effect, which is the effect of water pressure differences around an immersed rotating cylinder. Incorporated into a dredge design using two contra rotating cylinders it has the potential for removing the scallops from the seabed via an upward flow of water between the two cylinders.

  It was found possible to exploit this effect to lift scallops from the seabed using two rotating cylinders powered by hydraulics (Figure 7). However, the efficiency of the dredge was low and larger scallops were not lifted from the seabed. The necessity to supply power to the cylinders meant that the dredge was heavy and complicated.

- **Hydrodynamic foils** are used to improve stability and seabed contact in certain dredge fisheries. This investigation examined whether the foil could be used to generate sufficient lift to remove scallops from the seabed. Tests were carried out using flume tank observations and computer modelling of flows around the foil (Figure 8). The study concluded that water speed under the foil is probably sufficient to remove the scallops from the seabed but insufficient to lift the scallops off the seabed and into the collector bag. There may be a role for the use of the use of hydrodynamic effects to remove sediment from around scallops to expose them for collection and it is plausible that this may already be happening in some foil dredge fisheries.

- The **Hydrodredge** (Figure 9) design is intended use hydrodynamic effects to lift the scallops into the bag with cup shaped foils set in the dredge mouth and no teeth.

During trials on the scallop (*Pecten maximus*) beds around the Isle of Man in 2007 (Shepherd et al., 2008) this dredge was found to be 60-90% less efficient at catching scallops than the standard spring toothed dredge and removal of the cups had no effect on the catch of the hydrodredges. Damage rates for lethal damage (score 4 see Table 4) were significantly higher in the spring toothed dredges. In a further experiment (Shepherd et al., 2020) similar results were obtained in relation to damage rates, but for the single tow without cups the hydrodredge was less efficient, catching only a few small scallops. Further work would be needed to fully understand this effect.

- A modified **hydraulic or water-jet dredge** (Figure 10) with jets at varied angles to the seabed, but mostly set at 45° to the seabed designed to drive the scallops on the seabed surface into the collecting bag, was tested during the Ecodredge project (Lart ed., 2003). This was tested in the French fishery in the Bay of Brest and compared with a fixed toothed French 'classical dredge' (no dive plate or sprung teeth) for capture efficiency (assessed by divers as the fraction of scallops retained by the gear compared with those left on the seabed), damage rates and length distributions. The mean capture efficiency was 13% for the hydraulic dredge and 47% for the classical dredge. Damage rates of scallops encountering the hydraulic scallop dredge (both in the catch and the seabed) were a factor of 4 lower than the classical dredge. The hydraulic dredge in the form tested is too complex and inefficient for commercial use.

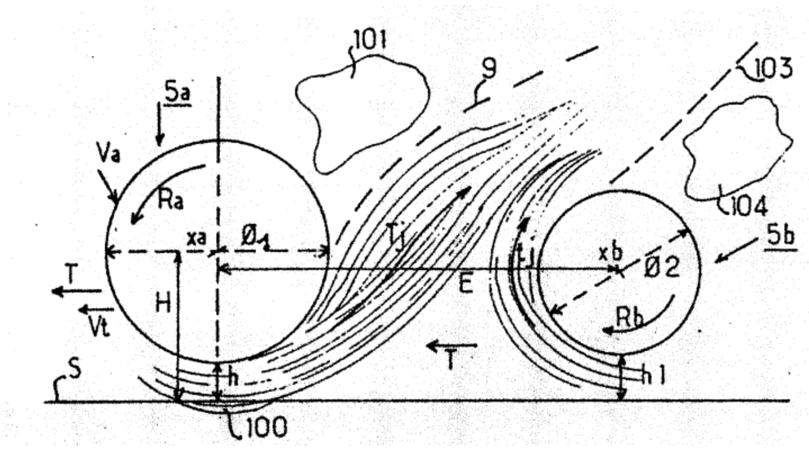


Figure 7 Functioning principle of the Magnus effect dredge with 2 cylinders. Ra and Rb: Rotating direction, T: Translating movement relatively to the sea floor, Vt: Towing speed, Va: Peripheral speed, Tj: Trajectory of water particles, h and h1: Ground clearance (NB there was a patent on this dredge in 2003)

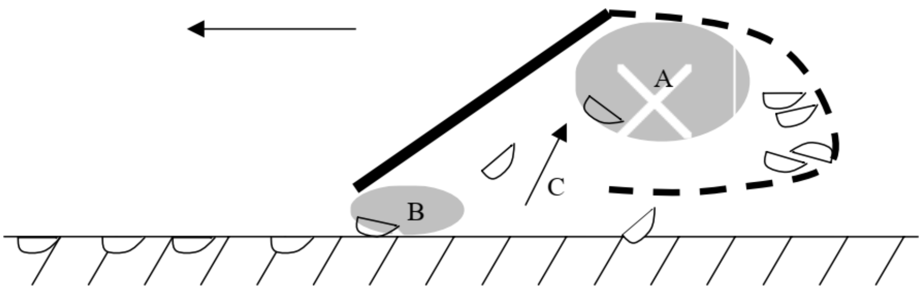


Figure 8 Principal scheme of the foil (bold line) lift effect dredge: the low of pressure in A is intended to create suction at B which removes the scallops from the seabed. The scallops are collected in the basket (discontinued line). Direction of tow from left to right as per horizontal arrow.

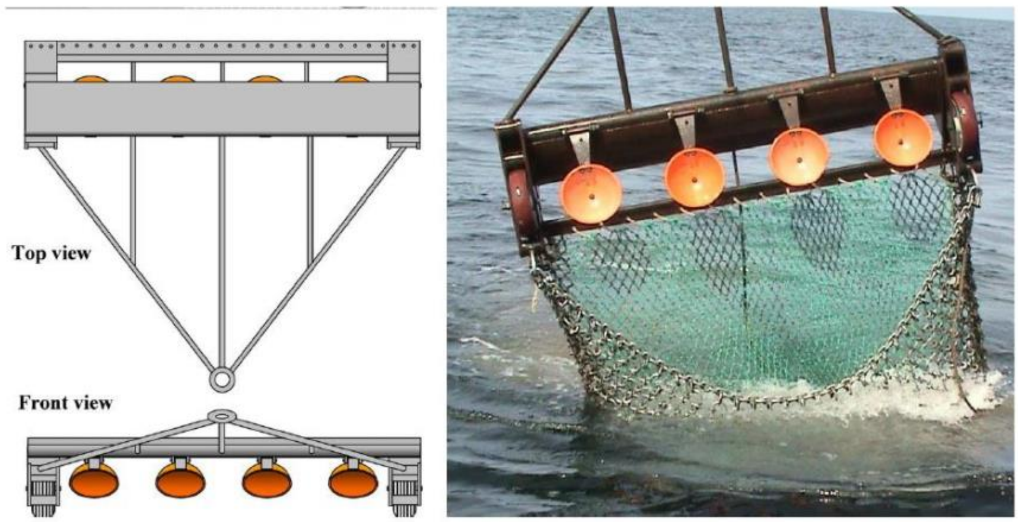


Figure 9 The Hydrodredge; the four cup shaped structures are intended to create turbulence enabling the scallops to be lifted into the bag

Figure 10 The hydraulic or water jet dredge, designed and built by IFREMER for the Ecodredge project for catching scallops. The angle of the water jets was varied, but mostly set at 45º see Lart ed., (2003)

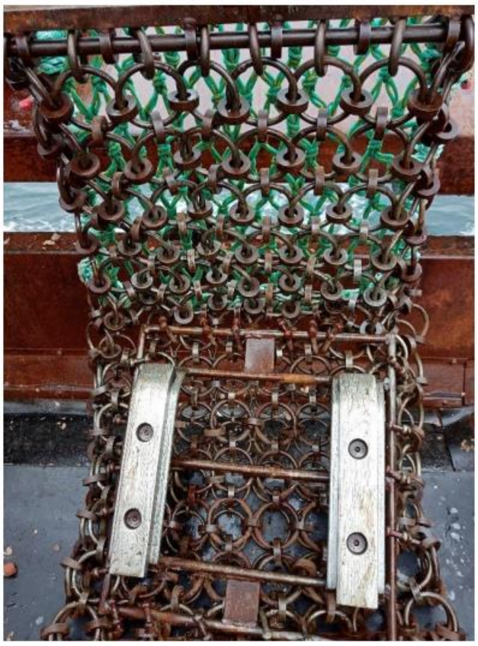


Figure 11 Right; skids attached to dredge bellies used in the LISIG project compared with left standard Newhaven bellies.

3.5 Effects of changes in dredge belly design

The observation that dragging a heavy steel chain mail scallop dredge belly over the seabed can have a serious abrasive effect, breaking up surface dwelling biota and causing physical alteration of the seabed has led to investigations of dredge belly designs that potentially reduce this effect. Examples are;

- 'Skid dredges' designed under the Low Impact Scallop Innovation Gear (LISIG) project (Sciberras et al., 2022; derived from a design by Cyclone Marine Ltd and Gannet Marine Ltd) that have supportive skids shackled underneath the dredge belly. These lift the dredge belly off the seabed and so reduce the surface area in contact with the seabed (Figure 11). The extra weight of the skids can be offset by reducing the thickness of the belly rings, because the bellies are subject to less abrasion.

  Beach trials indicated that although there was impact from the teeth and skids, organisms can pass under the dredge and remain intact. Sea trials have included catch and bycatch comparison and post dredging observations using divers (Sciberras et al., 2022). Overall, the proportion of fatally damaged organisms (damage level 4) was more severe in soft sediment compared to mixed sediment, and damage was higher in the standard dredge tracks than in the skid dredge tracks. This may reflect a deeper penetration of the dredge into a softer seabed and a larger area of contact with the seabed for the standard dredge. Bycatch rates varied between grounds and species; more crabs, flatfish, starfish and less skates and rays in the skid dredge.

  These sea trials found that skid dredges were more profitable, because they retained more scallops and improved durability of the dredge bellies. Sciberras et al., (2022), discuss how this improved profitability could be managed.

- Alternative materials for belly designs have been tested by Oban Scallop Gear Ltd (Figure 12) These use synthetic plastic materials instead of the hardened steel belly rings, reducing weight of the dredges. There is some evidence of reduced catches of stones. However, durability of materials is likely to be an issue (see section 4).

These results support the view that it is possible to alter the design of the dredge belly in ways which reduce its abrasion of the seabed. Altering the design may have other benefits such as reduced stone retention, seabed friction, wear on the bellies and fuel consumption.

Figure 12 Sea trials of the Oban dredge (centre two dredges) compared with standard spring toothed dredges

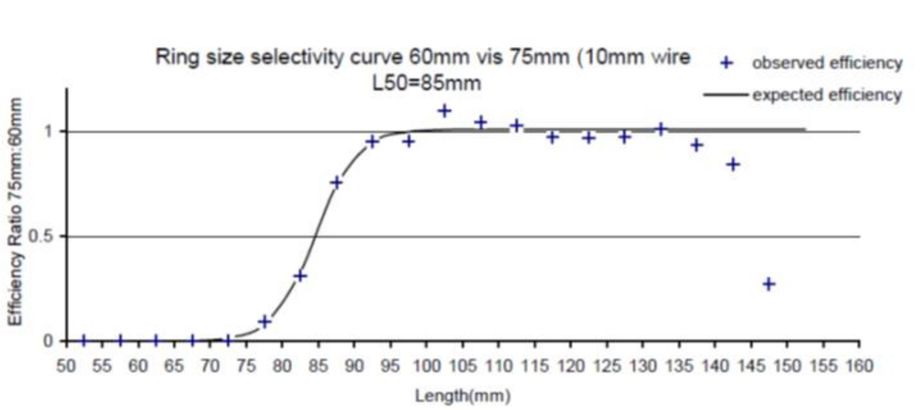
3.6 Scallop belly ring selectivity

The Ecodredge project (Lart ed., 2003) studied the effect of tooth spacing, belly ring size and mesh size of the backs of dredges (where fitted) on dredge selectivity. Of these components tooth spacing (discussed above) and ring size were found to contribute to dredge selectivity.

In UK waters the English, Northern Irish and Isle of Man technical measures result in an L_{50} of 85 mm and the Welsh measures result in an L_{50} of 97 mm (see Figure 13; note length of shell is across the flat side of the shell parallel to the hinge, the same dimension as the MCRS).

The MCRS's of 100, 105, and 110 mm (and the EU MCRS)

Table 2 and Table 3, are larger than the L_{50}s and implies that there will be some discarding of undersized scallops, the amount dependent on the size distributions of the scallop populations encountered. Measures which could reduce this quantity would be increasing the belly ring size. The main benefit which would accrue from increasing selectivity of the dredges would be to reduce the time the scallops spend in the gear, hence reducing stress on the scallops as discussed in Section 3.2. However, there are issues with the durability of larger rings (see section 4).



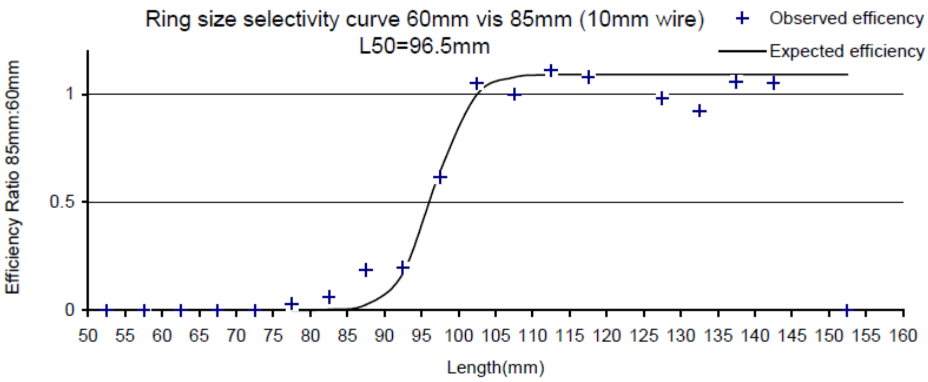


Figure 13 Selectivity curves and L_{50} for three internal diameters of scallop dredge belly rings using 10 mm wire. More selectivity information is available in the Ecodredge report Lart ed (2003)

4 Materials used in dredge construction.

The harsh operating conditions in the dredge fishery, most notably the severe abrasion which the dredges are subjected to in being towed across the seabed has led to investigation of wear patterns of the scallop dredge belly rings and the relative strength of different rig sizes and also the relative hardness of other materials with potential use in dredge construction.

Scallop dredge belly rings are subject to point erosion, both on the rings and washers which join the rings together (Figure 14 overleaf). This means that as bellies age they tend to become less efficient at retaining scallops and more prone to damage.

To understand the implications of increasing ring size to improve selectivity, the relative strength of several different sizes of new belly rings was estimated using engineering formula. The results are shown in Table 5 (overleaf). This table shows the tensile strength of the bellies relative to 75mm bellies based on stress calculations and allowing for the different numbers of rings across the different bellies. For new 75mm rings (10mm wire) the force required to bend them is a load of around 200kgf per ring. This compares with the load on the dredge at the point of attachment to the bar of 100-180kgf.

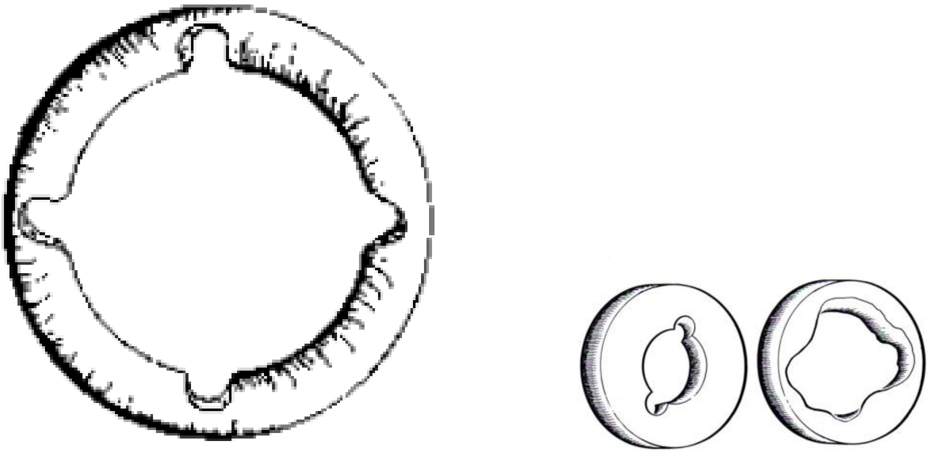


Figure 14 Left; scallop dredge belly ring with characteristic notching of point wear points, right; worn and severely worn belly ring washers.

Table 5 Relative strength of bellies (10mm wire 9 rings across) to a 75mm ring (10mm wire belly 10 rings across) based on Warnock and Benham (1965)

Ring internal diameter mm	Wire thickness	Relative Strength %
80	12	141
85	10	81
88	12	132
92	10	76

If all the tension from one dredge came on one ring (as when an obstruction was encountered) then new rings might be bent, but for normal circumstances, they are well in excess of requirements. Thus, the elongation of the rings is most likely a consequence of the rings losing material around the points where the washers abrade them (Figure 14). This will not only result in reduced thickness at this point and hence a loss of strength but also a concentration of the stress at these points in the rings. Hence avoiding the notching of the rings and washers is the key to longer lasting bellies, and improved endurance for larger belly ring sizes. Hardened steel is used to counter this abrasive effect.

Abrams (2009; Appendix A) compares the properties of various possible polymer materials which might be considered for use on dredges with standard carbon steel and hardened and tempered Carbon steel.

These results are shown in construction.

Table 6. The steel is characterised by increased hardness (higher Brinell hardness) indicating more resistance to abrasion and increases tensile strength than the polymers. Such information should help guide choice of materials for dredge construction.

Table 6 Material properties of two grades of carbon steel to BS specifications compared with various polymers. UTS = ultimate tensile strength. The Brinell hardness scale is a description of the resistance a material exhibits to permanent deformation by penetration of another harder material (from Abrams, 2009).

080M40 (EN8) BS970: 1991 (1955)

Composition	Carbon	Manganese	Phosphorus	Sulphur
%	0.36-0.44	0.6-1	0.05 max	0.05 max

Mechanical properties	UTS N/mm^2	Yield N/mm^2	Elongation %	Brinell Hardness
Normalised	550	280	16	152-207
Hardened and tempered	625-775	435	12	179-229

070M55 (EN9) BS970: 1991 (1955)

Composition	Carbon	Manganese	Phosphorus	Sulphur
%	0.5-0.6	0.5-0.9	0.05 max	0.05 max

Mechanical properties	UTS N/mm^2	Yield N/mm^2	Elongation %	Brinell Hardness
Normalised	700min	355	12	201-255
Hardened and tempered	850-1000	595	9	248-302

Polymers

Name	UTS N/mm^2	Elongation %	Shore Hardness	Brinell*** Hardness	Relative Density
HDPE	32	55	D69	50	0.94
ABS	38	20	-	-	1.04
Polycarbonate	72	100	D80	60	1.35
Nylon*	79	50	D60	46	1.15
Nylatron**	86	25	85	63	1.16
PEEK	110	20	D85	63	1.31

*Nylon 6-6
**MoS2 filled type 6/6 polyamide
*** Approximation

5 Discussion

5.1 Environmental effects

The characteristics the dredge designs described above against a set of criteria related to environmental effects and commercial viability (Appendix 2) are shown in Table 7 and compared between designs based on literature information. These results indicate that there has been progress with dredge designs and testing over the past 10 years.

The main effects of changes to tooth spacing and ring size are to improve the selection of scallops and hence reduce stress. Of the more radical designs N-virodredge^{TM} is currently in use in commercial fisheries and the skid dredge has been used in a long-term commercial trials. Both these designs have been shown to have features which reduce environmental effects compared with standard Newhaven sprung toothed dredges.

Given that they operate on different parts of the dredge, the N-virodredge^{TM} at the teeth, and the skid dredge at the belly, it would be useful to be able to examine these two design features in combination on the same dredge to see whether an overall improvement in performance can be achieved. Also the use of skids in combination with larger ring sizes might improve the durability of the larger ring sizes, by providing some protection for the rings against abrasion. Hence providing the opportunity to increase selectivity of the dredges and consequently reducing stress on the scallops.

- The Nviro^{TM} and skid dredges are designed to alter the physical action of the dredge on the seabed and benthic habitats and fauna. However, dredging.

also highlights the lack of information about the physical effects of the different designs on the benthic habitats and fauna columns 1-2; point loading, shearing and penetration and damage to benthic organisms. Examining the physical effects of dredges on the seabed and fauna would therefore be important further work. Several approaches may be considered:

- Sciberras et al, (2022) point out the use of Remotely Operated Vehicles (ROVs) may help to avoid the use of divers to inspect post dredging effects.

- The Ecodredge study examined the use of dredge instrumentation to study the physical effects of spring toothed dredging.

- The use of dredge mounted cameras as were used to elucidate capture mechanisms (Figure 3) may have value in further understanding and mitigating the environmental effects of dredging.

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Table 7 (Overleaf) Performance of alternative dredge designs compared to the standard Newhaven sprung tooth scallop dredge, based on current literature and research: – ✓ performs better; X performs worse; ~ equivalent performance; NA - no data available.

Criteria	Alteration of seabed habitat			Effects on catch				Commercial viability			
	Point loading, shearing, penetration	Damage to benthic organisms	Retention of Stones/debris	Selectivity of scallops	Stress in scallops	Species selectivity	Damage to catch and/or by catch	Handling and safety maintained	Catching efficiency	Fuel efficiency	Durability
Scallop collection methods											
Increased tooth spacing	NA	NA	NA	✓	✓	NA	NA	~	~	~	~
Nvirodredge™	NA	NA	✓	✓	✓	Variable	✓	~	~	✓	~
Magnus effect	NA	NA	NA	X	NA	NA	NA	X	X	NA	NA
Foil Effects	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrodredge	NA	NA	NA	NA	NA	NA	✓	~	X	NA	NA
Hydraulic dredge	NA	NA	NA	~	✓	NA	✓	X	X	NA	NA
Belly design											

Criteria	Alteration of seabed habitat			Effects on catch				Commercial viability			
	Point loading, shearing, penetration	Damage to benthic organisms	Retention of Stones/debris	Selectivity of scallops	Stress in scallops	Species selectivity	Damage to catch and/or by catch	Handling and safety maintained	Catching efficiency	Fuel efficiency	Durability
Increase belly ring size	NA	NA	NA	✓	✓	NA	~	~	~ New bellies	~	X
Skid dredge	NA	✓	Variable between grounds	~	~	Variable	~	~	~ On some grounds ✓	~	~
Oban dredge	NA	NA	✓	NA	~	~	~	~	~	~	NA

5.2 . Effects of seabed type

Both Sciberras et al, (2022) for the skid dredge and Fillipi (2013) for the N-Viro dredge report differences in commercial and environmental performance between the different types of seabeds. Delargy et al., (2022) report variations in efficiency between seabed type. Hence, experiments with novel designs should cover a broad range of seabed types

5.3 Management aspects

Both N-Viro dredge and the skid dredge designs have the potential to increase the economic efficiency of the fishery, through reduced fuel consumption and increased belly ring life and some increase in capture efficiency, thereby providing an incentive for the use of these gears on suitable seabed types.

However, Sciberras et al, (2022) point out that to fully benefit from such improvements the there is a need to consider the overall management of the fishery, to avoid undesirable effects such as excessive increases in fishing effort.

5.4 ETP species

The following species are listed as in scope ETP species for the scallop dredge fishery;

Burrowing sea anemone (*Arachnanthus sarsi*), fan mussel (*Atrina fragilis*), heart cockle (*Glossus humanus*), northern feather star, (*Leptometra celtica*) ocean quahog (*Arctica islandica*), pink sea fingers (*Alcyonium hibernicum*), white cluster anemone, (*Parazoanthus anguicomus*).

5.5 Sensitive habitats

Whilst there is a focus is on bycatch ETP species, the nature of scallop dredging means that it can have an effect on habitat forming species, and some habitats are considered sensitive. Fenton (pers comm) lists the following habitats as sensitive:

- Blue mussel beds
- Flame shell beds
- Horse mussel beds
- Sabellaria spinulosa reefs
- Northern sea fan and sponge communities
- Sea grass beds
- Maerl beds
- Serpulid reefs
- Offshore deep muds
- Tidal swept algal communities
- Tide swept coarse sands with burrowing bivalves
- Kelp and seaweed communities on sublittoral sediment
- Offshore subtidal sands and gravels

- Carbonate mound communities
- Cold water coral reef

Currently the FIP is engaged in assessing the effects of scallop dredge fishing effort on sensitive habitats, using information on fishing effort and the known extent of these habitats. The FIP is also developing Identification Guides and Excel databases to enable fishers to log the presence of species observed in the catches, although note that efficiency of retention is likely to be low (see Section 3.1).

Many of the sensitive habitats and ETP species are included in the Government efforts to conserve them through spatial management under the MPA programme.

5.6 Use of ground discrimination technology to avoid sensitive habitats.

Many scallop dredging vessels are equipped with sophisticated ground discrimination systems based on echo-sounders and other devices. It would make sense to examine how these systems could be used to help fishers avoid sensitive habitats. Using habitat mapping, ground discrimination and ground truthing, it would be worth investigating whether sensitive habitats could be distinguished by the ground discrimination systems.

It may be possible to make fishers more aware of the presence of sensitive habitats, using their own onboard systems, and hence adjust fishing strategies to avoid them. This approach would be appropriate in areas where the sensitive habitats are not well mapped and where other measures are not in place to protect them.

Appendix 1 Adenylate Energy Charge (AEC) as a stress indicator

This indicator relates to the quality of immediately available chemical energy in the form of Adenosine tri-phosphate and it's derivatives in the scallop's adductor muscle.

AEC is defined by the ratio: AEC = (ATP + 0.5ADP) ÷ (ATP + ADP + AMP)

Where: ATP = adenosine tri-phosphate, ADP = adenosine di-phosphate and AMP = adenosine mono-phosphate.

The tri-phosphate bond of the ATP molecule has maximum energy, the di-phosphate bond of ADP is half as rich and the monophosphate bond (AMP) lacks energy.

The AEC ratio ranges from 0 to 1 i.e. 0 (all nucleotides are AMP) and 1 (all nucleotides are ATP). Therefore, the level of these bonds can be used as a measure of the energy directly available to the cells at that particular time. High AEC levels (>0.8) have been found in organisms living in optimal conditions where the animals were growing and reproducing. Levels between 0.5 and 0.7 have been found in organisms whose environment was limiting in some way, such animals had reduced growth rates and did not reproduce but recovered when returned to optimal conditions. Organisms whose AEC levels were less than 0.55 had a negative scope for growth and did not recover. Scallops appear to be more tolerant of low AEC levels see Maguire et al (2002a,b)

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Appendix 2 Possible dredge design criteria and indicators.

- These criteria are used as a basis for the headings in dredging.

Criteria	Possible indicators
Alteration of seabed habitat	Reduction in catch of stones and other inorganic matter
	Reduced point loading, shearing and penetration into the sediment
	Reduced damage to seabed living (benthic) organisms
Improved survival of affected organisms through; Reduction in effects on scallops	
	Reduced damage rates
	Improved size selectivity
Reduction in effects on non target organisms	
	Improved species selectivity
	Improved survival of bycatch species such as crabs
	Improved survival of other organisms encountered on the seabed
Commercial viability	
	Catching efficiency maintained
	Handling and safety improved or maintained
	Fuel consumption maintained or reduced
Legislative	
	UK legislation in force specifies dredges with a certain level of species and scallop size selectivity. Innovative dredges would have to meet or improve on these standards.

Appendix 3; Other scallop capture methods

This Appendix describes other experimental capture methods outside the scope of the Unit of Assessment; “Mechanised dredge operated by UK vessels”.

Robotic dredge designs

The advent of underwater technology used in Remotely Operated Vehicles (ROVs) has led to speculation that building an autonomous scallop harvester which is allowed to seek out and harvest scallops in a less invasive way than standard dredges may be feasible. This approach has been reviewed in Bent and Moody (2004). Figure 15 shows a design that has been developed and operated in the west of Scotland, which relies on a human operator to actuate the harvesting mechanism when scallops are observed on a video link. This would be considered viable at relatively high densities of scallops around 7 scallops per m^2. For more information contact the author.

Figure 15 Scallop collector

Use of light stimulus for catching scallops

Recently Enever et al, (2022) report trials which investigated the use of artificial battery powered white lights added to crustacean pots. The results showed significant increases in scallop catches compared with control posts set without lights; two scallops caught in the controls compared with 249 scallops in the experimental pots across the whole experiment (see Enever et al., 2022) for details.

The scallops were caught in a mixed fishery with edible crabs (*Cancer pagurus*) European spider crabs (*Maja brachydactyla*), European lobster (*Homarus gammarus*) and crawfish (*Palinurus elephas*), with small quantities of fish and cephalopods. Of the crustacean species caught, only spider crabs showed any increase in catches in the experimental pots compared with the controls.

Whilst the authors discuss the potential for using this effect as a method for reduced environmental effects of scallop capture, it is premature to make quantitative comparisons between this gear and dredge gear.

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