Fisheries Innovation Scotland

FIS026 - MIMPACT
Developing best practice to mitigate benthic impact of demersal towed gears

A REPORT COMMISSIONED BY FIS
AND PREPARED BY

JNCC

Published by: Fisheries Innovation Scotland (FIS)

This report is available at: http://www.fiscot.org.

Suggested Citation: Arjona Y., Marra S., Fallon N.G., Pinder J., Tobin D., Fernandes P.G. (2019). Developing best practice to mitigate benthic impact of demersal towed gears. Report for Fisheries Innovation Scotland (http://www.fiscot.org/), project FIS026. Pp 60

Title: MIMPACT - Developing best practice to mitigate benthic impact of demersal towed gears

ISBN: 978-1-911123-18-7

First published: September 2019

European Maritime and Fisheries Fund

The Scottish Government
Riaghaltas na h-Alba

MIMPACT

Developing best practice to mitigate benthic impact of demersal towed gears

Fisheries Innovation Scotland project FIS026

Yolanda Arjona[1], Stefano Marra[1], Niall G. Fallon[2], Jordan Pinder[1], Declan Tobin[1], Paul G. Fernandes[2]

June/2019

ISSN 0963-8091

Fisheries Innovation Scotland

UNIVERSITY OF ABERDEEN

For further information please contact:

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough PE1 1JY
www.jncc.defra.gov.uk

This report should be cited as:

Arjona Y., Marra S., Fallon N., Pinder J., Tobin D., Fernandes P.G. (2019). Developing best practice to mitigate benthic impact of demersal towed gears. Report for Fisheries Innovation Scotland, project FIS026. Pp 60

This report is compliant with the JNCC Evidence Quality Assurance Policy http://jncc.Defra.gov.uk/default.aspx?page=6675.

Other contributors:

Dan Edwards, JNCC
Lynda Blackadder, Marine Scotland Science

[1] **Joint Nature Conservation Committee (Project lead)**
[2] **University of Aberdeen**

Executive summary

In recent years, there has been an increase in knowledge of the effects of fishing operations on the seabed, associated habitats and the diversity, structure and productivity of benthic communities. In particular, demersal towed gears, including otter trawls, demersal seines and dredges, are known to pose the greatest threat to benthic ecosystems. Consequently, there is a recognised need to mitigate the physical effects of those gears on the wider marine environment but to minimise the economic impacts on the fishing industry. Some governments, in conjunction with the fishing industry, are starting to develop tools and guidelines, often using fishermen's knowledge of fishing operations, to reduce the impact of demersal towed gears. To inform these tools there is a basic need to better understand the spatial distribution of both the species exploited and the underlying benthic habitats upon which they depend. There is also a need to understand the interaction between gears and seabed and the ability of different ecosystems to recover following impact. This is key to the delivery of a more ecosystem-based approach to fisheries management.

This project is a scoping exercise which will explore how benthic habitat sensitivity, spatial distribution of commercial marine species and abrasion pressure on the seafloor by bottom contacting gears, can be used to better inform mitigation measures to reduce the impact of demersal towed gears in Scottish waters (0-200 NM).

The three objectives of the project are : (1) to review actual mitigation measures used and tested worldwide that can be used to reduce the impact of demersal towed gears; (2) provide spatial distribution maps for Scottish waters for a) benthic habitats, b) seven exploited commercial marine species (anglerfish, saithe, cod, haddock, whiting, *Nephrops* and king scallops) and c) habitat sensitivity to demersal towed gears; and (3) as part of this report, to present to the Scottish fishing industry recommended mitigation options to reduce the impact of demersal towed gears.

Overall, reviewed mitigation measures can be divided between spatial measures and technical measures. Spatial measures include full or seasonal closures, as for example the use of Essential Fish Habitats, Marine Protected Areas and Habitat Credit Schemes; and the use of effort and spatial restrictions, for example the closure to selected types of gear. Technical measures include gear modifications on the components of trawl and dredge gears that have an effect on the seabed, for example, trawl doors or sweeps. However, most gear modifications focus on reducing by-catch and improving selectivity and there are few examples globally of technical measures introduced to minimise benthic impacts.

The study area (Scottish waters, 0-200NM) was divided using Charting Progress 2 (CP2) regions. The distribution maps for the marine species studied in Scottish waters show that the species distribution vary with seabed habitat type. As expected, some species have been found to be habitat dependent (e.g. *Nephrops*) whereas other species (e.g. haddock and whiting) are more evenly distributed (probability of occurrence) across habitat types in the study area.

Surface abrasion (<2cm penetration on the sediment) and sub-surface abrasion (≥2cm penetration) pressure maps were produced for the study area. Habitat sensitivity (resilience and resistance of benthic habitats) maps were created for the study area for sensitivity to surface abrasion and sub-surface abrasion. Results showed that there is a variability of sensitivity of benthic habitats, deep-sea habitats being the most sensitive.

In Scottish waters there was variability in both the sensitivity of habitats and also the probability of occurrence of the seven commercial marine species assessed. Information on habitat sensitivity and probability of commercial marine species occurrence can be used to provide

information to fishermen and managers on where (and where not) to focus fishing effort to minimise benthic impacts.

In conjunction with existing technical and spatial measures (e.g. Marine Protected Areas), the information presented from this study on habitat sensitivity and the spatial distribution of commercial species can be used as a tool to further mitigate the impact of demersal towed gears.

Table of Contents

Acronyms and abbreviations

CBD	Convention on Biological Diversity
CGS	Conditional Geostatistical Simulations
CP2	Charting progress 2
CPUE	Catch per unit effort
DRB	Boat dredges
EBFM	Ecosystem-based fisheries management
EEZ	Economic Exclusive Zone
EFH	Essential Fish Habitats
EMODnet	European Marine Observation and Data Network
EUNIS	European Nature Information System
FIS	Fisheries Innovation Scotland
GES	Good Environmental Status
GIS	Geographic Information System
HAPC	Habitat Areas of Particular Concern
HCS	Habitat Credit Scheme
IBTS	International Bottom Trawl Survey
ICES	International Council for the Exploration of the Sea
MMO	Marine Management Organisation
MPA	Marine Protected Areas
NIWA	National Institute of Water and Atmospheric Administration
NNS	Northern North Sea
NOAA	National Oceanic and Atmospheric Administration
NSIBTS	North Sea International Bottom Trawl survey
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OTB	Bottom otter trawl
OTT	Otter twin trawl
PMF	Priority Marine Features
PTB	Bottom pair trawl
SCN	Seine net
SDN	Danish seine
SSC	Scottish Seine
SWCIBTS	Scottish West Coast International Bottom Trawl Survey
UK	United Kingdom
UN	United Nations
UNCLOS	UN Convention on the Law of the Sea
VME	Vulnerable Marine Ecosystems
VMS	Vessel Monitoring System

1. Introduction

1.1 Background

In 2016, almost two thirds of all landings by UK vessels were caught from the Northern North Sea and West of Scotland, landing over 100,000 tonnes of demersal species with a value of £183 million (MMO, 2017). As well as providing important goods and services through fisheries products, benthic ecosystems also play an important role in a range of other services from nutrient recycling and biodiversity maintenance to climate regulation and carbon sequestration (Constanza *et al.,* 1997). As such, fishing operations that disturb the seabed may have significant effects on habitat, as well as on diversity, structure and productivity of benthic communities (Jennings and Kaiser, 1998; Clark and Koslow, 2007), which indirectly impact on the services that they provide (Jennings and Kaiser, 1998).

There are an increasing number of political and legal commitments (international and domestic) on Governments to ensure that marine resources, are sustainably exploited, ensuring their continued availability for future generations. The UN Convention on the Law of the Sea (UNCLOS) grants the UK the sovereign right to govern its Exclusive Economic Zone (EEZ)[1], recognising fish as one of the key natural resources. UNCLOS obliges states to manage its living resources in a sustainable manner. The UK, as a contracting party to the OSPAR Convention, is legally bound to implement its strategies to protect and conserve the North-East Atlantic and its resources. The OSPAR Commission advocates the ecosystem approach and promotes its implementation within the framework of the Convention on Biological Diversity (CBD). Moreover, under the EU Marine Strategy Framework Directive, the UK and Devolved Administrations are required to put in place measures to achieve Good Environmental Status (GES) for marine waters (EU, 2008; Borja *et al.,* 2010). Under Descriptor 6 of the Directive, (Sea-floor Integrity[2]) there is a requirement that the structure and function of ecosystems be safeguarded ensuring that benthic ecosystems are not adversely affected by human activities. Therefore, on consideration of all the above commitments, novel changes in fishing practices will be required to reduce the probability of impact on benthic ecosystems. These changes need to be supported by the development of effective measures to mitigate and manage the fishing footprint.

In recent years, our knowledge regarding the impact of bottom trawling on the seafloor has improved considerably. There is much more evidence available on how demersal trawl gears affect the seafloor and associated benthic communities (i.e. sensitivity of the seabed) particularly in relation to depletion and recovery of these benthic communities (Collie *et al.,* 2000; Kaiser *et al.,* 2006; Hiddink *et al.,* 2017). Mitigation of these impacts normally focuses on seasonal and temporal area closures, gear restrictions and/or technical measures. The impacts of these gears are known to vary according to seabed habitat (Jennings and Kaiser, 1998; Jennings *et al.,* 2001; Hiddink *et al.,* 2006), but the interaction of target fish and associated fisheries within those habitats is less well understood and have not been widely used in actual mitigation measures.

Better knowledge is needed for a more effective and holistic fisheries management approach, and to consider and integrate ecosystem function into 'ecosystem-based fisheries management' (Figure 1) (Pikitch *et al.,* 2004; Eigaard *et al.,* 2016). Understanding these interactions will enable managers to incorporate such information in designing more effective measures, with reduced impact on fishing opportunity.

---

[1] https://publications.parliament.uk/pa/ld201617/ldselect/ldeucom/78/7806.htm
[2] http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm

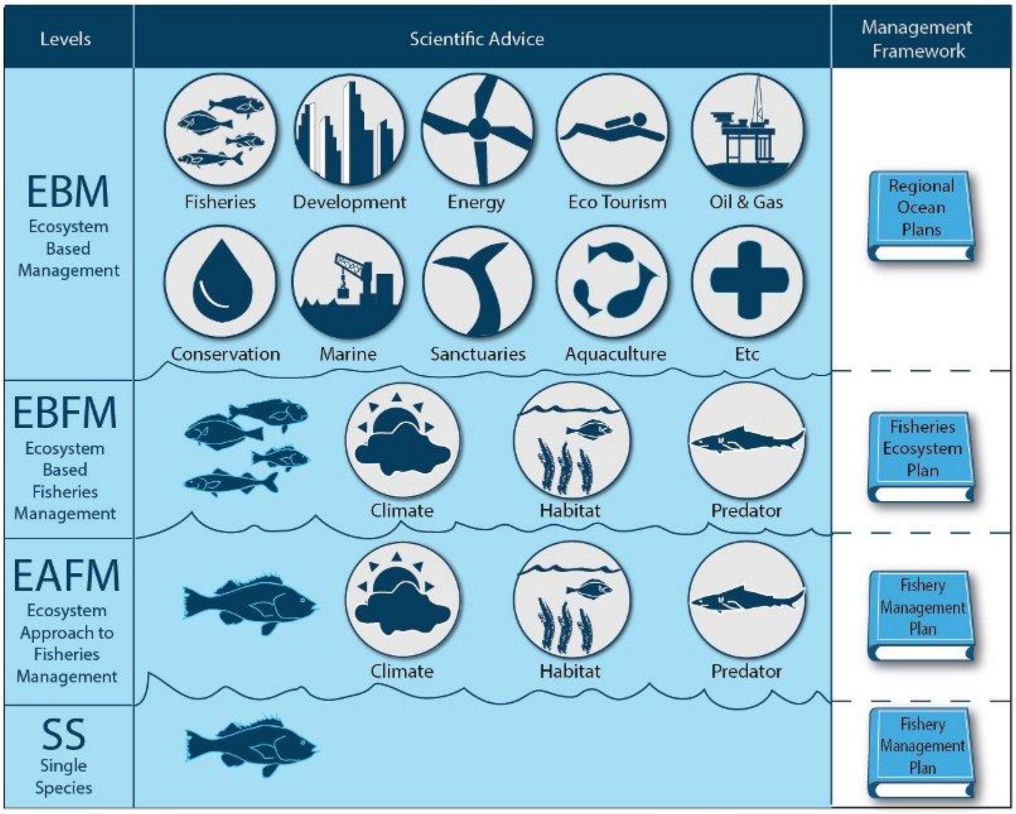

Figure 1. Diagram showing the interactions in the Ecosystem Based Fisheries Management. Figure taken from NOAA Fisheries (**https://www.st.nmfs.noaa.gov/ecosystems/ebfm/ebfm-levels**).

The Isle of Man queen scallop (*Aequipecten opercularis*) fishery[3] is a good example of how other relevant information, such as species distribution and behaviour, has resulted in a reduction in the impact of fishing gears without compromising catch. Queen scallops are active swimmers leaving the seabed to feed in the summer, and with fishermen having this information are able to use otter net trawling gears to catch queen scallops instead of dredges.

Another example of understanding the distribution and ecology of a marine species as a mitigation measure to reduce the impact of demersal towed gears is the case of the scallop fisheries in Canada. Detailed maps of the seabed and concentration of scallops (*Placopecten magellanicus*) were used to improve efficiency of fishing operations (He *et al*. 2004). While this is a good example where an ecosystem approach has been used to deliver better fishing practices for a species found in specific habitats, it is not well known how effective it might be for species where no strong correlation exists with their habitat.

However, traditional management has failed to achieve its objective to preserve marine ecosystems and ensure fishing is sustainable for the future (Caddy and Seijo, 2005; Hilborn *et al.,* 2015). There is now a need for more tactical ecosystem models that can respond dynamically to changing ecological and environmental conditions.

A wide range of information on stock distribution, trophic dynamics, the ecosystem impacts of fisheries and habitat sensitivity has become available. This allows for consideration of

[3]https://cert.msc.org/FileLoader/FileLinkDownload.asmx/GetFile?encryptedKey=Yxx3fvUpCzXPG8gziKfwDeLogcaKGyls511CyLFtX2zw6k7HZvP/jyIoO+sj8w5C

multispecies interactions and the impacts of fishing on habitats and food webs into fisheries management.

The ecosystem-based approach to fisheries management considers complex links across human and natural systems, identifies conflicts between competing ecosystem services, and considers both direct and indirect impacts of fishing activities on marine ecosystems. Scottish government seeks in its "Future of fisheries management in Scotland: national discussion paper"[4] to promote an ecosystem-based approach in Scottish waters. Therefore, detailed information on marine species distribution, seabed habitats, habitat sensitivity and fishing activity is in need in Scottish waters.

1.1.1 Study area: Scotland's seas

Scotland has a long and diverse coastline, with myriad of sea lochs, firths and islands. Scottish waters have some of the finest marine habitats in Europe, including rocky reefs covered in soft corals, sea fans and sponges, shallow beds of delicate maerl and cold-water coral reefs. Scottish waters and their rich ecosystems are home to many marine mammals such as dolphins, whales and porpoises, seabirds and a wide range of fish species, some of them commercially important for the Scottish economy.

Demersal towed gears are widely used in Scottish waters to catch commercial marine species including dredges, seine nets, otter trawls, and bottom trawls.

Currently, Scotland has a wide range of mitigation measures to manage the marine environment and protect its ecosystems from impact of fishing activities, such as:

- Area restrictions[5], sea area closures designated to protect stocks in the waters around Scotland. Some of the closures are on a seasonal basis (i.e. spawning grounds), or on a temporary basis (i.e. juvenile real time closures).
- Effort and gear restrictions (typically to protect fish stocks or reduce bycatch).
- Marine protected areas[6], designated to protect specific features of conservation importance (Figure 2).

[4] https://www.gov.scot/publications/national-discussion-paper-future-fisheries-management-scotland/
[5] https://www2.gov.scot/Topics/marine/Sea-Fisheries/management/restrictions
[6] https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork

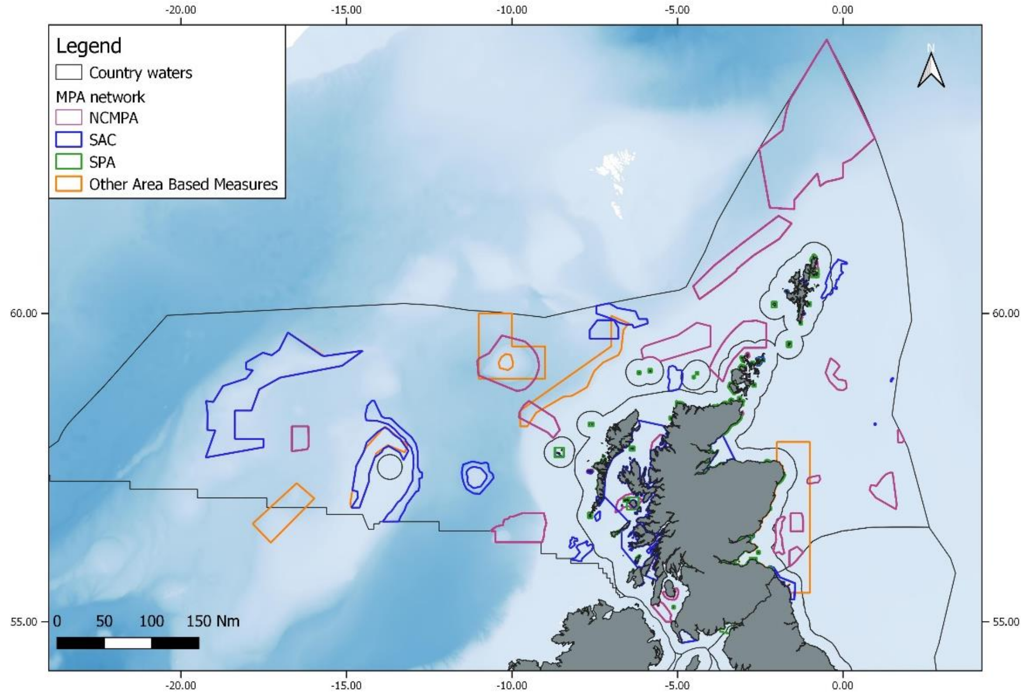

Figure 2. Map of Marine Protected Areas network for Scottish waters. NCMPA: Nature Conservation Marine Protected Area, SAC: Special Area of Conservation and SPA: Special Protection Area. Other Area Based Measures are other fisheries restrictions areas considered to afford protection to MPA search features.

1.2 Project objectives

The study area comprised Scottish waters covering from 0-200nm. The aims of the present study are: (1) to review examples of best practice used worldwide to mitigate the benthic impact of demersal towed gears; (2) to map selected commercial fish species distribution and seabed habitat types and consider the potential to use this information to mitigate impacts of demersal towed gears; and (3) to present recommendations to the Scottish fishing industry and to highlight areas for potential development regarding the mitigation of benthic impact in Scottish waters.

2. Best practice for demersal towed gears: a literature review

2.1 Search, screening process and results

A systematic search was conducted using the following online search engines: Scopus, Google Scholar and ResearchGate. Websites for the EU-funded BENTHIS project[7] and the Best trawling practices project[8] were also screened to ensure evidence from those recent research initiatives was captured. The literature review retrieved all published literature to 2018. The search was conducted during July-August 2018, and its content was searched in September 2018. The search terms used for the literature review were a combination of

[7] https://www.benthis.eu/en/benthis.htm
[8] https://trawlingpractices.wordpress.com/

“fisheries management” AND “benthic habitat” AND “impact” AND “best practice” AND “ecosystem based approach” AND “mitigation” AND “bottom trawling” AND “fish” AND “shellfish” AND “gear”.

The criteria used to select articles for the literature review are shown below:

Inclusion criteria:

- must be in the marine environment.
- must consider dredges, seine nets, otter trawls, demersal trawls and /or bottom trawls.
- must assess measures to reduce impact of demersal towed gears.

Exclusion criteria:

- Using static gears only.
- Study assessing strictly the impact of fishing gears.
- Study assessing by-catch or gear selectivity to reduce fish discards.

The search returned a total of 81 records. These records were then systematically searched to identify those containing information relevant to this review. Only articles published in English were considered however, all returned non-English articles were retained for potential use in future studies.

Some evidence was reported in more than one literature source; for example, the same study being reported in a technical report, journal article and in review documents. To prevent duplication, review documents and technical reports were only retained where results were not also reported in peer-reviewed articles.

Fifteen records were retained for further review. Having extracted the key information from the data sources, each of the records was allocated to a main evidence topic, in this case, mitigation measures used and whether they were spatial or technical in nature. The evidence comes in the form of 7 peer-reviewed articles, 8 technical reports and 1 record as a conference paper. Table 1 summarises records retained, with information about the type of mitigation used, species used, area of the study, habitat and gear type, and the type of evidence. For each of the topics, the aims of the research, methodology used, main results (as advantages and disadvantages) and constraints of evidence-gaps for the actual type of measure assessed in the study are summarised (Excel document FIS026 Literature review).

Table 1. Summary of records retained for review.

	Reference	Type of mitigation measure	Species	Area of study	Habitat type	Gear type	Type of evidence
1	Batsleer *et al.*, 2018	Spatial- Habitat credit scheme	cod, plaice, scallops, sole, sea bass, cephalopods	Eastern English Channel	rock, infralittoral coarse, circalittoral coarse, deep coarse, soft sediments	Scallop dredge and demersal otter trawl	Peer-review article
2	Rooper *et al.*, 2017	Spatial- Closure	deep-sea corals	US waters	deep-sea habitats	Bottom trawl	Peer-review article
3	Simpson *et al.*, 2017	Spatial- Essential Fish Habitats	various	Alaska	various	Demersal towed gears	Technical report
4	Ministry of Primary Industries (2017)	Spatial- Closure, marine reserve	various	New Zealand	various	Bottom trawl, dredge, seine net	Technical report
5	Stewart *et al.*, 2016	Spatial- Effort restrictions, seasonal closures, protected areas. Technical- Gear modification	scallops	European waters and North America	sedimentary habitat	Scallop dredge	Peer-review article
6	Frandsen *et al.*, 2014	Technical- Gear modification	blue mussels	North Sea	soft bottom sediments	Dredge	Peer-review article
7	Grieve *et al.*, 2015	Spatial- Closure, effort restrictions Technical- gear modification	various	Various	various	Various	Technical report
8	Sewell *et al.*, 2007	Spatial- Closure, effort restrictions Technical- gear modification	various	Various	various	Various	Technical report
9	Sutter *et al.*, 2013	Spatial- Essential Fish Habitats	various	US waters	various	Bottom trawl	Conference paper
10	Rose *et al.*, 2010	Technical- Gear modification	flatfish	Bering Sea, Alaska	sedimentary habitat	Otter trawl	Technical report
11	Hourigan 2009	Spatial- Gear restrictions	deep-sea corals	Alaska, Pacific west coast, US Northweast and US Southeast	deep-sea habitats	Bottom trawl	Peer-review article

	Reference	Type of mitigation measure	Species	Area of study	Habitat type	Gear type	Type of evidence
12	Ellis *et al.*, 2008	Spatial- Closure, effort restrictions	prawns	Torres strait, Australia	sedimentary habitats, reef habitats	Prawn trawl	Peer-review article
13	Valdemarsen *et al.*, 2007	Technical- Gear modification	various	Various	various	Demersal towed gears	Technical report
14	He *et al.*, 2004	Spatial- Use species distribution Technical- Gear modification	scallops, crab, pollock, shrimp	Georges Bank, Northwest Atlantic; Bering Sea; Labrador and Gulf of Maine	sedimentary habitat	Scallop dredge, pelagic trawl, shrimp trawl	Technical report
15	Robert 2002	Spatial- closures, effort restrictions	scallops	Canada	sedimentary habitat	Scallop dredge	Technical report
16	Kaiser *et al.*, 2000	Spatial- Seasonal and permanent closures	crab, lobster, scallops, plaice, sole	South Devon, UK	sedimentary habitat	Dredge and otter trawl	Peer-review article

Different mitigation measures were assessed across a wide range of habitats (sedimentary, deep-sea habitats and other hard substrata), and evidence was selected based on the success on measures implemented i.e. successful reduction of impact with minimal impact on fishing opportunities.

As a result, best practice measures used to reduce benthic impact of demersal towed gears can broadly be classified into two categories, spatial and technical measures (Table 2). Technical measures include gear modification to reduce the benthic impact, e.g. innovative/experimental gear. Spatial measures include full and/or seasonal closures, effort and gear restrictions.

Table 2. Summary of main mitigation measures, spatial and technical, on demersal towed gears to reduce benthic impact.

<table>
<tr><td rowspan="2">Technical measures</td><td>Trawl</td><td>– Reduce number of bobbins.
– Shorten the warp length and control door height with sensors.
– Rise the sweeps of bottom.
– Trawl door with high aspect ratio (heights/length).
– Trawl door with shorter shoe angle relative to the towing direction.
– Shorter warp length relative to the fishing depth.
– Off-bottom rigging of the trawl doors.
– Use pelagic or semi-pelagic gears.</td></tr>
<tr><td>Dredge</td><td>– Increase size of dredge belly rings.
– Smaller frame width and depressor plates.</td></tr>
<tr><td rowspan="2">Spatial Measures</td><td>Full/Seasonal closures</td><td rowspan="2">– Marine Protected Areas (MPAs)
– Essential Fish Habitats (EFH)
– Habitats Areas of Particular Concern (HAPC)
– Habitat Credits Schemes (HCS)</td></tr>
<tr><td>Effort/ gear restrictions</td></tr>
</table>

2.2 Spatial measures

Spatial mitigation measures have been used across all habitat types. Area closures have been used to control fishing mortality on target stocks (Murawski *et al.,* 2005) but this measure will automatically reduce the size of available fishing ground and therefore potentially affect the fishing fleet, if no other grounds with similar commercial species are in the vicinity. However, area closures may provide conservation benefits for vulnerable habitat, vulnerable species and for other species in a closed area (Halpern, 2003; Willis *et al.,* 2003; Ellis *et al.,* 2008;).

Some spatial measures, such as Marine Protected Areas (MPAs), Habitat Areas of Particular Concern (HAPC) or Essential Fish Habitats (EFH), have been used by governments as a conservation tool to protect vulnerable habitats, such as biogenic habitats, e.g. in the US (Hourigan *et al.,* 2009).

MPAs have been widely used around the world as a tool to conserve biodiversity and/or as a tool to manage fisheries, as they conserve fish stocks, improve breeding population, increase abundance of juveniles and act as nurseries (Bell, 1983; Russ and Alcala, 1998; Garcia-Charton *et al.,* 2004). Evidence suggests that a well-designated and managed MPA results in an increase in the size and abundance of exploited species (Gell and Roberts, 2003; Lubchenco *et al.,* 2003) therefore reversing the effects from fishing.

HAPCs represent sensitive or vulnerable areas and are derived from EFH, which consists of all waters and substrate necessary for spawning, breeding, feeding, or growth to maturity (Kenny *et al.,* 2018). This approach has been extensively used along the West Coast of North America, but the assessment if closures effectively reduce the impact of trawl fisheries and allow benthic habitat recovery needs a research time frame able to monitor the success of the measures (Simpson *et al.,* 2017).

In Scottish waters, MPAs have been used by government[9] to protect specific habitat features of conservation importance, such as the Priority Marine Features (PMF)[10] (Figure 2). The approach used to manage these areas is dependent on pressure and impact to the specific protected feature, so full, zoned and/or seasonal closures are widely used to remove the impact of demersal towed gears.

In other cases, knowledge of species behaviour has been used to reduce the impact of gears. For example, Ellis *et al.,* 2008 described a suite of management options for a trawl prawn fishery in Torres Strait (Australia), where a stakeholder group proposed four alternative options; 1) Reef buffer; 2) Moon closure; 3) Effort reduction, and 4) Area closure. From these four options, the moon closure option entails closing the prawn fishery around the time of the full moon. Therefore, fishers' knowledge and published information on how the lunar phase influences moulting in prawns (Griffiths, 1999) have been used to maximise catch when prawns are easier to catch, i.e. by avoiding the full-moon period.

Commercial species distribution can also be used to reduce impact of those gears, as for example in the case of the Canadian offshore scallop fishery. They used multi-beam bathymetry data to map benthic habitats and guide fishing activity to those areas with high densities of scallops (Robert 2002; Stevens *et al.,* 2008; Stewart and Howarth, 2016). Fishing vessels are therefore able to target areas with adult scallops, whilst avoiding concentrations of juvenile scallops or other sensitive habitats (He *et al.,* 2004). Given the success of this approach with the Canadian fishing industry, as fishing pressure is reduced and catch is maximised, it would certainly benefit other scallop fisheries in the world. This approach has shown success in sessile commercial species, but no studies have been found on the use of the approach for mobile commercial species, such as fish.

2.3 Technical measures

2.3.1 General approaches

Technical measures, mainly focused on gear modification of standard demersal towed gears, have been used to reduce the impact of demersal towed gears. Gear modifications that have been successfully implemented for maximising catch and reducing the effect on the seafloor are listed in figure 3. Alternative gears, mainly focused on decreasing or removing the heavier parts of the gears which have bottom contact with the seabed, have been successfully tested for sedimentary and soft sediments (Valdemarsen *et al.,* 2007, Rose *et al.,* 2010), but this approach will not reduce the impact on reefs and other hard substrata.

2.3.2 Gear modification for scallop dredges

Due to the penetrative nature and their close contact with the seabed, scallop dredges cause substantial physical and biological changes on the seafloor (Dayton *et al.,* 1995; Jennings and Kaiser, 1998; Kaiser *et al.,* 2000). The modification of seabed habitat can have serious

[9] https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork
[10] https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork/PMF

consequences on scallop recruitment affecting the settlement of scallops and other invertebrates (Bradshaw *et al.,* 2001; Kamenos *et al.,* 2004).

Dredges are designed to penetrate the seafloor to extract scallops directly from the seabed, therefore, one of the main challenges in reducing the impact of this gear will be reducing the need for such invasive seabed contact without affecting the efficiency of the gear (Stewart and Howarth, 2016). Another mitigation option used in inshore waters is to use divers to hand-pick scallops. While this option removes the benthic impact of the traditional scallop dredge, concerns for safety of divers and efficiency of the catch might arise.

Studies in the US and French scallop fisheries have shown that the increase in size of dredge belly rings seems to have helped to protect juvenile scallops and decrease the intensity of dredging on the seafloor (DuPaul and Rudders, 2007; Beukers-Stewart and Beukers-Stewart, 2009). Therefore, this mitigation option will still pose a pressure on the seafloor but might be considered effective if number of juveniles scallops caught and some benthic impact are reduced.

The Hydrodredge is another design which removes the metal teeth that rake into the sediment but instead uses “cups” to deflect water downwards, resulting in turbulence that lift scallops off the seabed. However, this design has shown poor efficiency in catching scallops (60-90% less compared to traditional techniques). In addition the dragging effects of the belly bag over the seabed has not been addressed when considering the environmental benefits of this type of modified scallop gear (Shephard *et al.,* 2009; Catherall and Kaiser, 2014; Stewart and Howarth, 2016).

A study in inshore waters in Denmark developed a mussel dredge with reduced ecosystem impact. The project tested a standard dredge (Dutch type) with a smaller and lighter frame width of 145.5 cm (normal frame is 200 cm) and total weights of 123.4 kg (normal weight is 235.6 kg), and an added depressor plate to improve bottom contact with the light dredge (Frandsen *et al.,* 2014). The results showed that the light dredge retained less sediment in comparison with the classical Dutch dredge, and it transferred less energy to the bottom. Moreover, fishermen reported a reduced consumption of fuel when using the light dredge. The disadvantage of this modified gear was that the standard dredge was 37.5% wider that the light dredge, so fishers might need to increase the number of hauls in order to cover the same area and obtain the same catch. Furthermore, the lighter gear still poses a pressure on the seafloor, and the environmental benefit of the lighter gear is still unclear.

The above study showed that the use of lighter components and amended materials in the mussel dredge can also be applied to scallop dredges, so further examination and collaboration with the scallop fishing industry is key when developing new gear components.

Other modified scallop gears, such as N-Virodredge, have been used for king scallop fisheries in Scottish waters, but given that the evidence for additional environmental benefits compared to standard scallop dredge is limited, such gear is not included in this literature review as an effective mitigation option to be used in Scottish waters (Catherall and Kaiser, 2014; ICES, 2016).

2.3.3 Gear modification for other demersal trawl gears

Other demersal towed gears considered in this section are: bottom otter trawl (OTB), otter twin trawl (OTT), bottom pair trawl (PTB) and seine net (SCN).

Several parts of the listed fishing gears are in contact with the seabed, which may include: tow warps in front of the door, the trawl doors, the door to net warps, the ground rope or parts of the ground rope and the belly of the net. Trawl doors and ground ropes are however in continuous contact with the seafloor and are hence more damaging. Therefore, worldwide studies (e.g. BENTHIS project) have focused on the modification of these gears to reduce impacts to the seafloor.

Seine nets have been used as an alternative to bottom trawls (Valdemarsen *et al.,* 2007), as they lack the heavy gear components (e.g. otter doors, trawl shoes) of other mobile demersal gears (Donaldson *et al.,* 2010; Suuronen *et al.,* 2012;), but studies on the physical impact of demersal seines have suggested a large overall footprint (Eigaard *et al.,* 2016). There are currently no studies showing modification of this gear to reduce the overall footprint.

A mitigation option to reduce the impact of the heavy doors in demersal trawls is the use of pelagic or semi-pelagic trawls (Figure 3). Pelagic trawls are designated to target fish in mid water, therefore with no intentional contact with the seabed. Pelagic trawls have different door shapes in comparison with bottom trawl doors and usually the gear does not have any ground gear to protect the bottom of the trawl. The modified pelagic trawl can be an option to reduce the benthic impact but must take fish behaviour and seabed conditions into account. Experiments to test the feasibility of semi-pelagic shrimp trawls with doors off bottom while leaving the trawl on the bottom have been carried out in the Gulf of Maine (He *et al.,* 2004) and Newfoundland (DeLouche and Legge, 2004). The modified gear demonstrated the potential of semi-pelagic trawling in this case for shrimp if the door height and the ground gear bottom contact can be controlled, as well as can save fuel consumption. But results suggested a technical challenge to keep the trawl door distance above bottom nearly constant (He *et al.,* 2006).

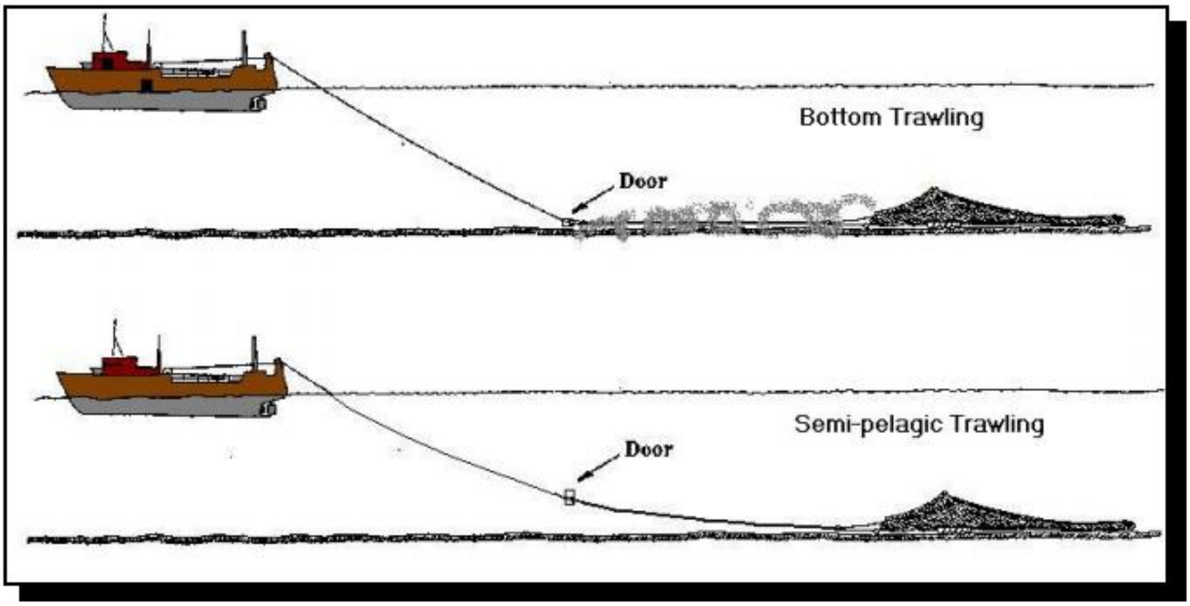

Figure 3. Diagram taken from Hall, 2002. Schematic representation (not to scale) of the bottom trawling and semi-pelagic trawling.

Other initial trials suggested that substrate or seasonal related behavioural differences in cod in reaction to gears, might affect catch efficiency (Gemba, 2001; Sala *et al.,* 2014). Nevertheless, the experiment did not account for temporal and spatial variation for in the comparison, so the results should be treated with caution.

In 1999, the Fisheries and Marine Institute in St. John's, Newfoundland and the Fishery Products International Ltd. initiated a project to evaluate and reduce seabed impact of the offshore shrimp fishery off Labrador (He and Foster, 2000). The project tested how the seabed contact from a standard shrimp trawl could be reduced by reducing the number of footgear bobbins, without altering catch efficiency. The fishing gear tested was a three-bridle Skjervoy

3600 shrimp trawl with 31 bobbins of 24" and 21" diameter. The full footgear weighed 5,698 kg in air and 2,984 kg in water. The modified 9-bobbin footgear weighed 2,187 kg in air and 1,306 kg in water. Results from the trial showed no changes in the stability of the trawl when the number of bobbins was reduced by 70%. Overall this gear modification might be well received by fishing industry in Scottish waters and allow reduction on the seabed contact. On the other hand, results also suggested that the trawl with fewer bobbins was more likely to incur damage, especially on grounds with rough sea and bottom conditions.

In the Bering Sea, Alaska, the effect of fishing on the essential fish habitats (EFH) of Alaska groundfish and subsequent considerations of mitigation actions were discussed between industry representatives, government and scientists (Rose *et al.,* 2010). As an alternative to further areas closures, the flatfish fishing industry collaborated with scientists to modify the standard otter trawl system to modified trawl sweeps to reduce bottom contact (Figure 4). The trawl sweeps modification consisted of raising the sweeps slightly above the seafloor by using discs, allowing small and flexible animals as well as other habitat structures to pass safely beneath. Catch composition did not change with the use of the discs and seafloor contact was also reduced. This gear modification was supported by industry, but sometimes this modification made gear handling a bit more complex and might require some changes to deck machinery.

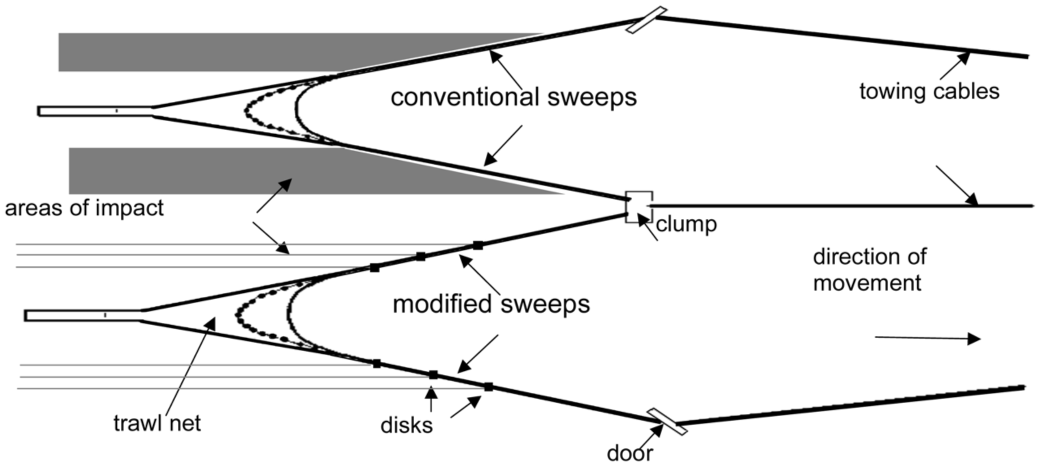

Figure 4. Diagram taken from Rose et al 2010. Schematic representation (not to scale) of the twin trawl system used to investigate modified sweeps. Shaded areas indicate bottom contact by sweeps.

Valdemarsen et al. (2007) published a technical report that reviewed options to mitigate bottom habitat impact of towed gears. Four methods were described to reduce the bottom impact of trawl doors, as listed below:

1) The use of trawl doors with higher aspect (height/length) ratio.
2) The use of trawl doors with a lower shoe angle relative to the towing direction.
3) The use of a shorter warp length relative to the fishing depth to achieve bottom contact.
4) Off-bottom rigging of the trawl doors.

High-aspect doors were proven to be more hydrodynamically efficient than low-aspect ratio doors and are commonly used as pelagic trawl doors. Moreover, the most effective method was to lift the doors off the bottom, however this measure has technical as well as catchability disadvantages and might not work in all fishing operations. Off-bottom trawl doors are an option for target species such as shrimps and *Nephrops* but technical challenge exist as reported by He *et al*. (2006).

3. Seabed habitat in Scottish waters

3.1 Seabed characteristics

Scotland has around 18,000 km of coastline and the area from the coast to the UK EEZ limits is around six times the size of the land area of Scotland.

Average water depths vary between 50 and 200 m for the shelf areas, being shallower around the south west of Scotland, and typically between 100 and 150 m to the west of the Hebrides and off the north coast. Scotland's offshore environment includes waters of depths greater than 2,000 m.

3.2 Seabed habitat data

Habitat data was collated from the UKSeaMap 2018 product[11], which is a by-product of the 2013-2016 activities of the EMODnet Seabed Habitats[12] consortium. It is a composite of two broad-scale maps arranged in the following priority order:

1. A roughly 100m[13] resolution broad-scale habitat map, which covers most of the UK shelf area;
2. EUSeaMap 2016[14], a coarser resolution broad-scale habitat map, which covers all European seas[15]

Both datasets were created using similar methods; the only difference is in the resolution of the seabed substrate input data and the source and resolution of the bathymetry data.

The principle of the broad-scale maps is to identify physical variables that are known to influence benthic communities (predictors), to classify them by finding biologically relevant thresholds and then match them to the relevant biotope classifications, such as the EUNIS classification[16]. The matching step is likely to be conclusive because the physical variables are drawn from the EUNIS classification, however there may be cases where a combination of physical variables does not correspond in EUNIS.

In most parts of the Atlantic and Arctic seas, levels 3 and 4 from the EUNIS classification are suitable for describing the variation in physical seabed habitat types (Annex B, table 1). The only area where the map differs from EUNIS version 2007-11 is in the deep sea, where recent studies have been able to show sub-zonation (Annex B, table 2) due to a combination of depth, salinity, temperature, dissolved oxygen and particulate organic carbon flux ranges (Bett and Jones, in prep). The biological relevance of these divisions have been found for some parts of the Atlantic and Arctic seas (Parry *et al.,* 2015) and further research is necessary to confirm it throughout the wider region however it is believed that there is sufficient scientific insight to extend the concept of such sub-zonation within the framework of broad-scale habitat mapping in this region.

---

11 http://jncc.defra.gov.uk/ukseamap
12 https://www.emodnet-seabedhabitats.eu/
13 3 arc seconds = 93m resolution latitudinally by between 44m (north) and 53m (south) longitudinally
14 7.5 arc seconds = 232m latitudinally by between 109m (north) and 155m (south) longitudinally
15 https://www.emodnet-seabedhabitats.eu/access-data/launch-map-viewer/?LAYERS=EUSM2016&zoom=3&Y=50&X=-11
16 EUNIS habitat type hierarchical view https://eunis.eea.europa.eu/habitats-code-browser.jsp

For this specific project, a selection of EUNIS biotope codes occurring within Scottish waters were extracted from the full UKSeaMap dataset (Table 3, Figure 5); this included all fine-scale habitat type (child biotope records). Although higher detail biotopes occur within the UKSeaMap, extracted biotopes were aggregated to EUNIS level 3 where possible; this is used for providing a broadscale view of present biotopes and is commonly used in MPA network assessments (Ellwood, 2014). Biotopes aggregated to EUNIS level 3 also include also sub-biotopes at higher resolutions (Table 2). Where EUNIS biotope data is not available in UKSeaMap 2018, less detailed habitat information is presented in the form of a specific biozone.

Table 3. All habitats extracted from UKSeaMap and their associated spatial coverage within Scottish waters. EUNIS biotope codes more detailed than level 3 would fall under the higher tier biotope, or the "parent" biotope; for example, A3.1112 is included in EUNIS level A3.1

Biotope Code	Habitat Description	Spatial Coverage (Km^2)
A3	Infralittoral rock and other hard substrata	0.407172
A3.1	Atlantic and Mediterranean high energy infralittoral rock	893.515657
A3.2	Atlantic and Mediterranean moderate energy infralittoral rock	392.985889
A3.3	Atlantic and Mediterranean low energy infralittoral rock	176.452283
A4.1	Atlantic and Mediterranean high energy circalittoral rock	2983.068815
A4.2	Atlantic and Mediterranean moderate energy circalittoral rock	2207.666451
A4.3	Atlantic and Mediterranean low energy circalittoral rock	1129.779912
A5	Sublittoral sediment	7704.487195
A5.1	Sublittoral coarse sediment	68245.70637
A5.2	Sublittoral sand	128896.7569
A5.3	Sublittoral mud	44747.1264
A5.4	Sublittoral mixed sediments	3697.39041
A6	Deep-sea bed	32794.86009
A6.1	Deep-sea rock and artificial hard substrata	6304.655681
A6.2	Deep-sea mixed substrata	46198.4712
A6.3	Deep-sea sand	28184.97069
A6.4	Deep-sea muddy sand	17828.25375
A6.4 or A6.5	Deep-sea muddy sand or Deep-sea mud	200163.7498
A6.5	Deep-sea mud	20514.16638
Circalittoral seabed	Derived from the UKSeaMap modelling process where no substrate data is available.	438.628558
Deep circalittoral seabed	Derived from the UKSeaMap modelling process where no substrate data is available.	276.543984
Infralittoral seabed	Derived from the UKSeaMap modelling process where no substrate data is available.	572.196683

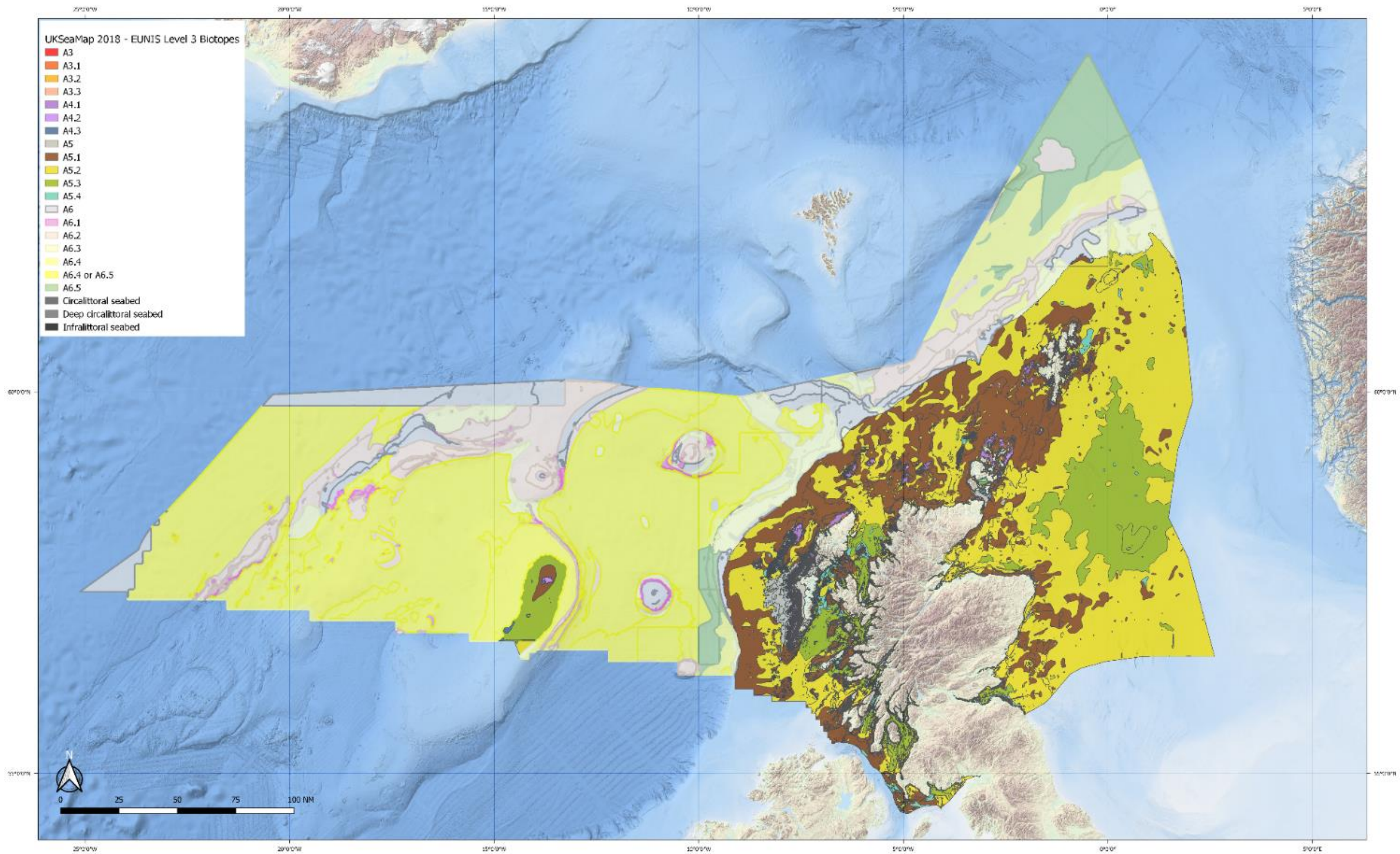

Figure 5. UKSeaMap 2018 classified at EUNIS level 3, where possible. Bathymetry layer was sourced from the EMODnet Bathymetry 2019 Digital Terrain Model[17].

17 http://www.emodnet-bathymetry.eu/data-products

4. Commercial marine species distribution

4.1 Introduction

Scientific survey data provides the most consistent representation of areal densities, when investigating spatio-temporal distributions of fish stocks. Through the deployment of appropriate sampling schemes, these surveys aim to collect a sample set which is representative of the entire distribution of stocks across the areas they occupy (Gunderson, 1993). For instance, the International Council for the Exploration of the Sea (ICES) International Bottom Trawl Surveys (IBTS) are designed to collect fisheries independent data measuring the distribution and relative abundance of a number of commercial and non-commercial fish species, from pre-recruits through their life cycle, in ICES areas (ICES, 2015). Given that data from IBTS surveys is used in benchmarked stock assessments and shown to consistently track population demographics through time (ICES, 2017), it is an ideal resource from which to develop representations of the spatio-temporal distributions of stocks of interest here. Conditional geostatistical simulations (CGS) may be used to generate multiple realisations of fish areal density which honour the densities observed in a survey, while reproducing observed spatial variability based on a statistical model (Rivoirard *et al.,* 2000; Woillez *et al.,* 2009). The only requirement for CGS is a survey sample set, and it is well suited to less migratory demersal species. Scientific surveys do have limitations in terms of measurement error, and data from scientific surveys may be subject to uncertainties arising from logistic limitations of survey sampling (e.g. spatial coverage) (Harwood and Stokes, 2003). Fortunately, CGS may also be used to evaluate spatial sampling error in fish survey data, thus providing spatially-explicit estimates of density across the survey domain (and thus a quantitative measure of zonal attachment) with sampling uncertainty measures (Woillez, *et al.,* 2009). The objective here is to use CGS based on empirical observations of fish areal densities to generate time-series of realistic maps of the actual spatial distribution of stocks from which the probability of occurrence of species of interest can be derived.

4.2 Methodology

Distribution maps were produced for six marine species of commercial value, using conditional geostatistical simulations:

- Fish species: haddock (*Melanogrammus aeglefinus*), monkfish/anglerfish (*Lophius budegassa*, *L. piscatorius*), cod (*Gadus morhua*), saithe (*Pollachius virens*) and whiting (*Merlangius merlangus*).
- Shellfish species: *Nephrops* (*Nephrops norvegicus*)

Data sources: Unless otherwise specified below, groundfish survey data were downloaded as IBTS exchange data from the ICES DATRAS online database, for years spanning 2009-2015. Swept-area densities (kg km^{-2}) per haul were calculated for each species by dividing the total weight caught by the product of distance trawled and wingspread. Anglerfish data (*Lophius piscatorius* and *L. budegassa* survey catches combined) were provided by Marine Scotland Science's (MSS) from the joint industry-science anglerfish survey, from which swept-area bottom trawl densities (kg km^{-2}) were derived for years spanning 2012-2015. *Nephrops* data was obtained from Marine Scotland as mean burrow density per haul collected during underwater television surveys (2009-2015) for a number of functional units (Clyde Sea, Devil's Hole, Firth of Forth, Fladen, Moray Firth, North Minch, Noup, Sound of Jura and South Minch). The spatial extent of the Scottish EEZ was obtained as a GIS shapefile from the Marine

Regions online database (Claus *et al.,* 2016), with the delineation of the Scottish adjacent waters boundary obtained as a shapefile from Marine Scotland[18] (Table 4).

Stock Areal Definitions: For the purpose of simulations, the areal extents of all groundfish stocks with the exception of anglerfish were assumed to encompass the shelf within Scottish waters, adjacent to the mainland or at the Rockall Bank to a depth of 300m. For Quarter 1 surveys (North Sea International Bottom Trawl Survey, NSIBTS, and Scottish West Coast IBTS, SWCIBTS) this included all waters adjacent to the mainland. For Quarter 3 surveys (NSIBTS), this included Scottish Waters east of 4°W. For Quarter 4 surveys (SWCIBTS), this included Scottish Waters west of 4°W. For anglerfish, the areal extent of the stock was assumed to encompass the shelf within Scottish waters, adjacent to the mainland or at the Rockall Bank to a depth of 1000m. Shellfish stock areas for simulations were defined by the areal extent of sampling in the case of each survey area or functional unit (e.g. Clyde Sea *Nephrops*) (Table 3). Once the simulations were completed, the spatial extent of each area was further constrained using appropriate information. *Nephrops* grounds were limited to areas of muddy substrate, and areas associated with fishing activity of <15m trawlers based on VMS data (ICES, 2013). East and West coast scallop areas were defined based on data on dredge trawlers and scallop divers, obtained from Scotmap (Kafas *et al.,* 2014). The Shetland scallop area was delineated based on UK Seamap substrate types within which survey dredges were collected.

Table 4. Timing and areal coverage of survey data used in conditional geostatistical simulations.

Stock	Area	Year range	Quarter
Anglerfish	Rockall	2011-2015	2 & 4
	Scottish Waters		
Cod	North Sea	2009-2015	3
	Scottish Waters		1
	West of Scotland	2009-2015; ex. 2010	4
Haddock	North Sea	2009-2015	3
	Rockall	2011, 2012	
	Scottish Waters	2009-2015	1
	West of Scotland	2009-2015; ex. 2010	4
Nephrops	Clyde	2009-2015	
	Devil's Hole	2009-2015; ex. 2013	
	Firth of Forth	2009-2015	
	Fladen		
	Moray Firth		
	North Minch		
	Noup	2014	
	Sound of Jura	2009-2015	
	South Minch		
Saithe	North Sea	2009-2015	3
	Scottish Waters		1
	West of Scotland	2009-2015; ex. 2010	4

[18] http://marine.gov.scot/node/12691

Whiting	North Sea	2009-2015	3
	Scottish Waters		1
	West of Scotland	2009-2015; ex. 2010	4

Conditional Geostatistical Simulations (CGS): CGS were implemented to generate 500 realisations of the spatial distribution of each stock (see Wollez *et al.,* 2009 for a full description of CGS methods). Trawl swept-area density (kg km^{-2}) was the variable simulated in the case of groundfish stocks, whereas shellfish simulations were based on the survey indices outlined above (Section 2.3.1.). The below CGS procedure was then carried out for each stock as a whole, and for immature and mature components of each stock separately in the case of groundfish stocks. The mature component of a given stock was defined by fitting logistic regression models to maturity-at-length data. Individuals whose length was greater than the length at which there was a 50% probability of being in a mature state being defined as mature. The first step in CGS involves characterising the spatial structure of fish density using variography (Rivoirard *et al.,* 2000): i.e. the calculation and modelling of variability in density as a function of sample separation distance. Variogram models were implemented in one of the following ways:

- Where density data contained both zero values and a small proportion of extreme high density values (these were the conditions observed in the majority of all stocks), data was transformed using an empirical Gaussian anamorphosis before calculation of experimental variograms on the truncated Gaussian-transformed variable. Sample densities with a value of zero were simulated in the Gaussian-transformed variable using a Gibbs sampler.
- Where density data contained extreme high density values but no zeros, the empirical Gaussian anamorphosis transformation was performed and the variograms calculated from the resulting normal distribution.
- Where a random spatial structure was observed in the experimental variogram, an average variogram was calculated on standardised data for all other surveys of the same stock where a spatial structure was detected, and used as a proxy (Fernandes and Rivoirard, 1999).

Once a satisfactory variogram model was obtained, 500 biomass or density surface realisations of each stock unit were generated using turning band simulations (Woillez *et al.,* 2009).

Rasters of probability of occurrence were also generated for each species/survey combination in order to summarise the spatial estimates of biomass across each time-series of simulations. For each grid square in each simulated realisation, biomass estimates were encoded as presence or absence of species. The probability of occurrence of a species in a given grid square was then calculated as the mean presence/absence value across all realisations for the entire time-series.

4.3 Results

The probability of occurrence of Rockall anglerfish was reasonably evenly distributed across the area, with some higher probability clusters to the centre, south and east of the bank. The mean probability of occurrence for the stock was 0.65, with variance 0.001. Anglerfish on the main Scottish shelf had a higher probability of occurrence towards the shelf edge, with overall probability of occurrence across the shelf followed a bimodal distributions with a mean of 0.33 (Annex B, figure 1). The probability of occurrence of cod followed a bimodal distribution with a mean probability of 0.64. The area of highest probability of occurrence was towards the northeastern end of the shelf around Shetland (Annex B, figure 2). Probability of occurrence of Rockall haddock followed a left-skewed distribution, with a mean of 0.92 and variance of 0.002. Probabilities were evenly distributed across the bank, with areas of lower probability to the centre and Northeast. On the main Scottish shelf, haddock was reasonably evenly distributed across the area. Probability of occurrence followed a distribution rising continuously from 0.3 to 1 with a mean probability of occurrence e of 0.89 (Annex B, figure 3). Probability of occurrence of saithe ranged from zero to 0.94, with a mean of 0.21. The species was most likely to be found to the northeast of Shetland (Annex B, figure 4). Whiting had a mean probability of occurrence of 0.84 in Scottish waters with higher probabilities found to the east of the shelf in ICES area IV (Annex B, figure 5).

Clyde *Nephrop*s had an evenly distributed probability of occurrence, with a lower probability area to the southeast, and a mean probability of occurence of 0.99. Devil's Hole *Nephrops* had a fairly evenly distributed probability of occurrence, with some lower values to the west of the area. Probability of occurrence followed a left-skewed density distribution with a mean of 0.58. Firth of Forth *Nephrops* followed a left-skewed density distribution with higher probabilities of occurence to the centre and east of the area. The mean probability of occurrence was 0.96. In Fladen, *Nephrops* had a higher probability of occurrence in the centre of the survey area. Probabilities followed a bimodal density distribution with a mean of 0.9495. Moray Firth *Nephrops* had a higher probability of occurrence in the west and centre of the area, with a mean probability of 0.85. North Minch *Nephrops* had higher probabilities of occurrence towards the south of the area, following a bimodal density distribution with a mean of 0.97. Noup *Nephrops* had a higher probability of occurrence towards the northeast of the area. The density distribution of probability of occurrence followed a left-skewed distribution with a mean of 0.79. Sound of Jura *Nephrops* had an evenly distributed high probability of occurrence across the area. Probability of occurrence followed a left-skewed density distribution with a mean of 0.99. South Minch *Nephrops* had higher probabilities of occurrence in inshore areas, following a left-skewed density distribution with a mean probability of 0.95 (Annex B, figure 6).

4.4 Scallop distribution

King scallop (*Pecten maximus*) data was obtained as dredge survey CPUE (scallop numbers caught per hour) from Marine Scotland Science's annual East and West Coast (2009-2015), and Shetland (2009-2013) surveys. Marine Scotland Science scallop surveys are conducted at fixed stations on established scallop tows, providing standardised survey catch rates at age data, which along with fishery catch at age data are used to estimate mortality in regional stock assessments.
The data was analysed using geostatistical simulations as explained in section 4.1, but data was not suitable to be analysed with geostatistical simulations, as this data is not aimed to provide information of scallop's distribution.

Therefore, VMS and logbook data for scallops was used instead to assess scallop distribution in Scottish waters.

4.4.1 Methodology

VMS and logbook data for 2015 were obtained from the MMO. Logbook data was not available for non-UK registered fishing vessels, so the analysis was restricted to VMS data from UK registered vessels. Processing of the data was done in R using the package VMS tools (Hintzen *et al.,* 2012). To reduce the size of the VMS data to reduce processing time, a spatial subset of data north of 54°N, encompassing all Scottish waters, was selected from the complete UK VMS data set. The data were then cleaned of impossible/unlikely points (lat

>360°or long >90° or speed >25knots), duplicates, pseudo-duplicates (pings with an interval between pings of less than 5 mins) and points that were within 3km of a known harbour. Points that appeared to be located on land were also removed (Annex B, table 1).

Logbooks which reported landings from an ICES statistical rectangle which fell within or partially within Scottish waters were selected. These data were then cleaned of duplicates, corrupted date/time reports, trips starting before the 1st of January, and incorrect records with port arrival time/date before the departure time/date. Logbooks were then selected where landings of a relevant species (cod, haddock, saithe, whiting, monkfish, *Nephrops* and scallops) exceeded 1kg, and where the relevant gear types (OTB, OTT, PTB, SSC, SDN and DRB) were used. This reduced the number of logbooks to just over 71,000 (Annex B, table 2).

VMS data were then linked to corresponding logbooks on the basis of date and time. In total, 56,827 logbooks could be matched with corresponding VMS activity (80% of the cleaned, relevant logbooks from Scottish waters), whilst 14,436 could not.

A speed filter was applied to the VMS data and all pings with speeds of 1-5 knots were selected and assumed to be fishing. Single pings <1knot temporally preceded and followed by a ping within the 1-5knot range were assumed to be hauling gear, and therefore still involved in fishing activity. These pings were identified and also assumed to be fishing. The landings from each logbook were then distributed amongst each assumed fishing ping during the relevant 24hr period, according to the time interval between each ping. Data were then clipped to the Scottish EEZ. Points were aggregated within a 0.05 decimal degree grid, and the landings of species within each grid cell were summed.

Table 5 shows the proportion of logbook landings recorded in Scottish waters that could be matched with VMS data. The primary reason for failure of a logbook to match to corresponding VMS data would be the vessel not being equipped with VMS. Vessel over 10m (and in some cases under 10m) are required to complete a logbook, however, the legal requirement to be equipped with VMS applies only to vessels over 12m, resulting in activity recorded in the logbook data set that is not represented in the VMS data set. Other failures may be due to corrupted or incorrectly recorded data.

Table 5. Logbook activity with corresponding VMS data

2015 VMS-Logbook data linking

	Number of trips (logbooks)	Number of vessels (logbooks)	Total landings kg (logbooks)	Number of trips (vms+logbook)	Number of vessels (vms+logbook)	Total landings kg (vms+logbook)	% of landings kg covered by VMS
Cod	5,940	318	12,272,900	5,624	284	12,104,764	99
Haddock	7,780	327	26,372,069	7,363	308	25,980,538	99
Saithe	3,784	202	10,984,908	3,722	198	10,874,975	99
Whiting	5,448	255	8,689,924	5,321	246	8,538,299	98
Monkfish	8,823	383	8,951,119	7,830	344	8,836,427	99
Nephrops	27,541	491	19,439,060	17,399	342	16,015,625	82
Scallops	9,643	232	13,158,284	6,993	188	11,004,709	84

4.3.2 Results

King scallops are associated with a range of habitat types in Scottish waters (Annex B, figure 7). These habitats are a range of mud, sand, coarse sediment and even in some rocky habitats comprising biogenic reefs type.
Due to a reliance on VMS data to assess scallop distribution, only fishing vessels >12m data were used. As such, fishing activity inshore is less likely to be captured by this data.

5. Fishing abrasion pressure and habitat sensitivity maps for Scottish waters

5.1 Background

There are a wide range of human activities that occur within the marine environment from the coastal and intertidal areas out to the deep-sea. These activities can influence the structure and condition of marine ecosystems. The mechanism through which an activity affects any part of the ecosystem is hereafter defined as “pressure”. The nature of the pressure is determined by activity type, intensity and distribution[19]. Abrasion of the seafloor by bottom contacting fishing is considered a major pressure affecting the condition of benthic communities (Eigaard *et al.,* 2016). The sensitivity of benthic habitats to this type of pressure depends on the characteristics of the community with larger more fragile species and those with longer recovery times being particularly sensitive (OSPAR Commission, 2017).

Mapping the distribution and intensity of pressures and the level of sensitivity of benthic habitats is therefore useful to assess the level of potential disturbance occurring in the marine environment. For this study we have focused on the abrasion caused by bottom fishing activities producing maps of pressure intensity and sensitivity to abrasion for selected habitat types on Scottish waters.

5.2 Abrasion pressure maps

5.1.1 Methodology

To distinguish between the different types of pressures caused by fishing gears on seafloor habitats, the penetration depth of different fishing gear components was assessed and classified as either surface or sub-surface abrasion (Church *et al.,* 2016). Abrasion pressure data were obtained using VMS data pre-processed by ICES (International Council for the Exploration of the Sea). For this project, surface and sub-surface abrasion pressure maps have been created. The pressure maps show the extent and intensity of aggregated fishing abrasion for the period 2009-2015 on a 0.05 x 0.05 spatial grid resolution. The pressure unit for the definition of abrasion intensity is the swept area ratio (the proportion of grid cell swept by fishing gear). Annual swept area ratio values are aggregated and converted to pressure scores using an intensity scale ranging from ‘none’ to ‘very high’ (Table 6).

[19] http://jncc.defra.gov.uk/page-7136

Table 6. Classification of the swept area ratios per gird cell

Pressure Score	Swept Area Ratio
None (0)	0
Very Low (1)	>0.00 – ≤0.33
Low (2)	>0.33 - ≤0.66
Medium (3)	>0.66- ≤1.00
High (4)	>1.00- ≤3
Very High (5)	> 3

5.1.2 Results

Two separate maps were produced for surface abrasion (< 2 cm penetration depth) and sub-surface abrasion (≥2 cm penetration depth) (ICES, 2018; Eigaard *et al.,* 2016).

The scores in figures 6 and 7, are ranked 1 to 5, with 1 representing the area of least pressure and 5 the area of greatest pressure.

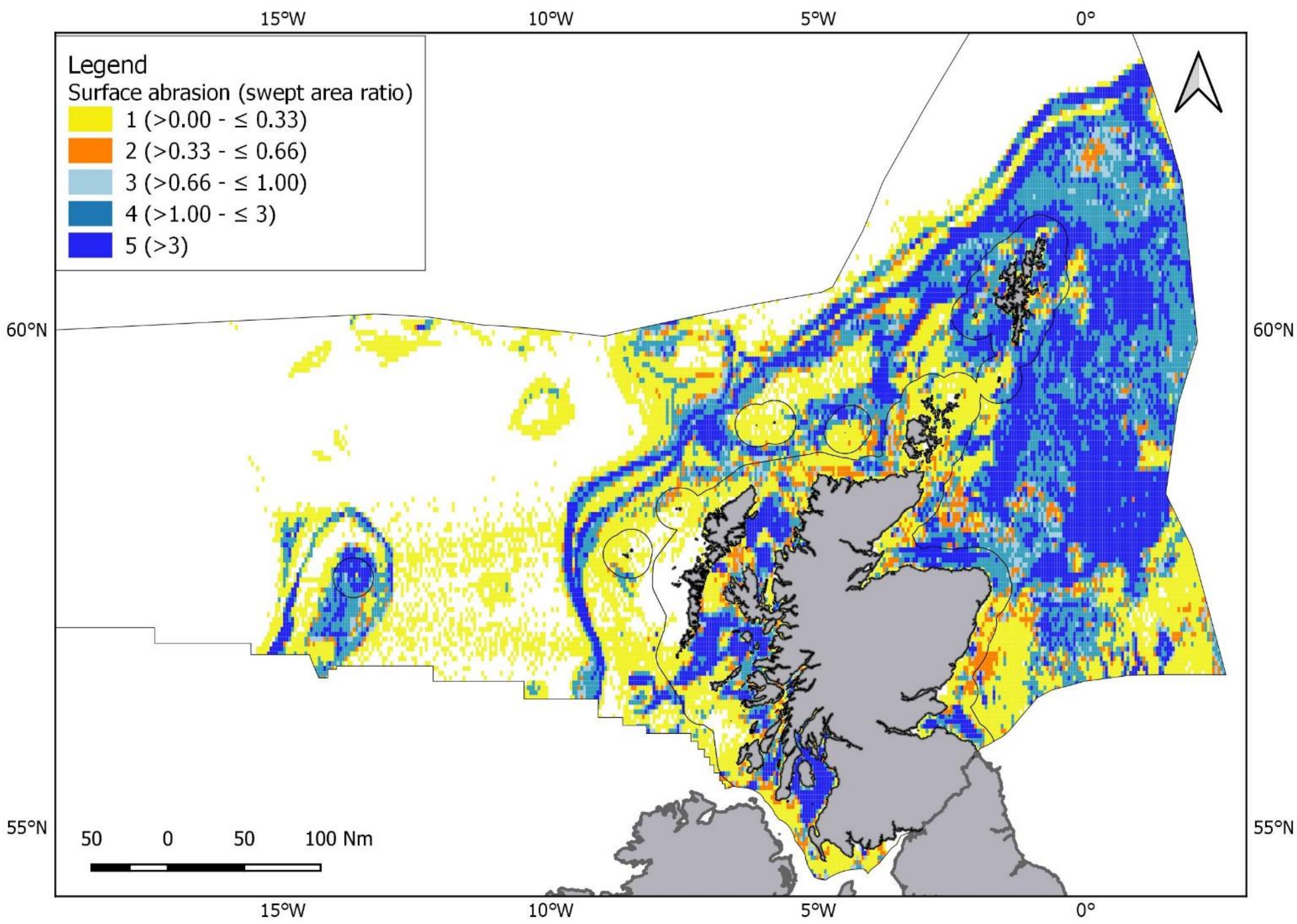

Figure 6. Pressure map of surface abrasion (<2cm penetration) for Scottish waters showing swept area ratios per grid cell.

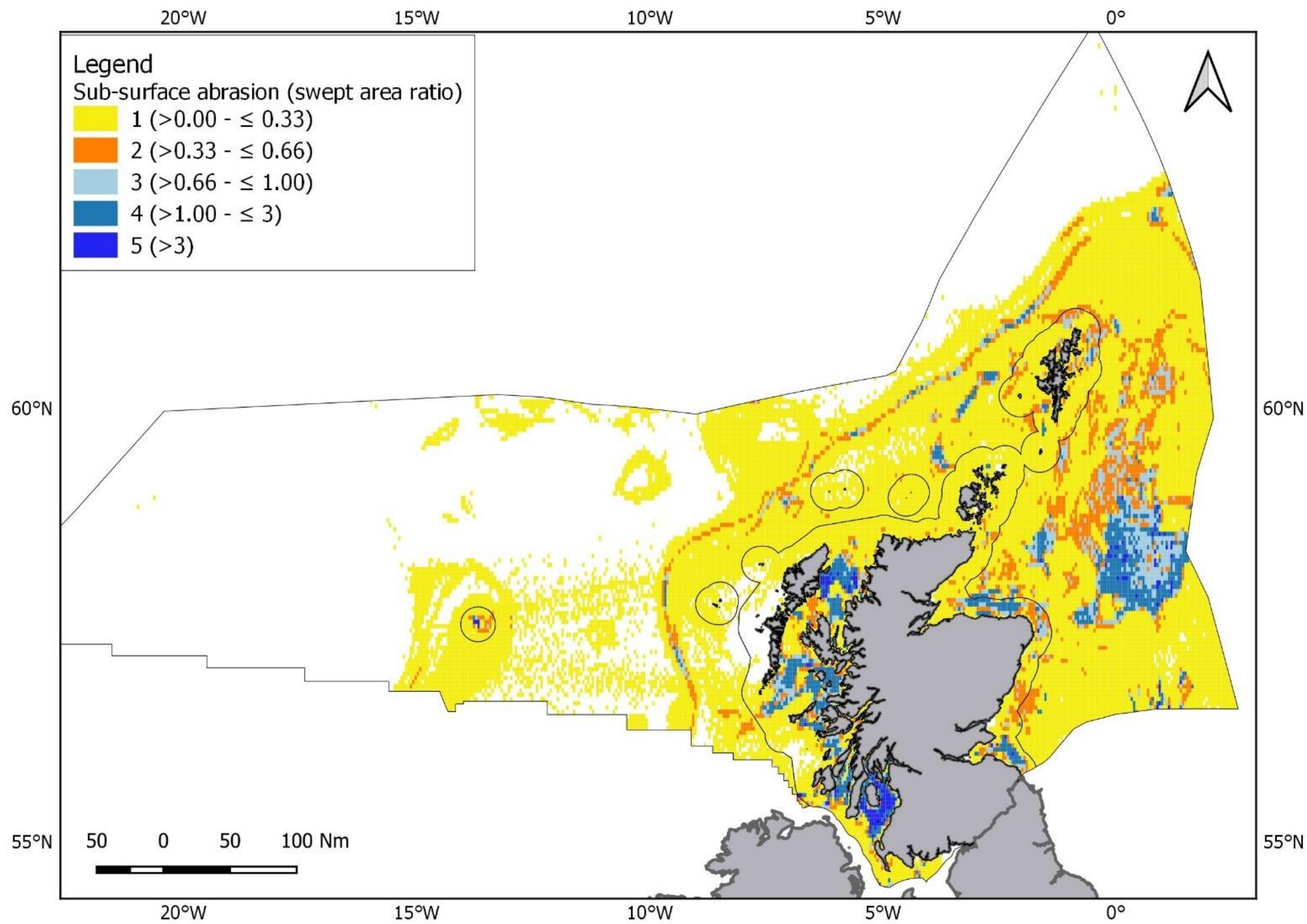

Figure 7. Pressure map of sub-surface abrasion (≥2cm penetration) for Scottish waters showing swept area ratios per grid cell.

The following table summarises the percentage area exposed to each pressure category within the different CP2 Regions. Percentages are shown both for surface and sub-surface abrasion in table 7.

Table 7. Abrasion pressure scores (in %) for each CP2 region in Scottish waters.

CP2 Region	Total Area (Km^2)	Abrasion type	Abrasion Pressure category (%)					
			0	1	2	3	4	5
Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel	40989.9	Surface	0	68.6	2.3	2.5	17.0	9.6
		Sub-surface	0	98.2	1.5	0.2	0.1	0.1
Minches & Western Scotland	8897.5	Surface	0	37.9	8.2	3.7	15.5	34.6
		Sub-surface	0	52.8	10.5	11.8	22.3	2.6
Northern North Sea	92151.7	Surface	0	17.2	5.3	5.0	31.5	40.9
		Sub-surface	0	65.5	15.2	9.9	8.5	0.8
Scottish Continental Shelf	51715.3	Surface	0	33.7	5.7	6.0	29.3	25.3
		Sub-surface	0	87.6	8.4	2.3	1.7	0.0
Irish Sea	1801.6	Surface	0	38.6	8.3	2.5	7.6	43.0
		Sub-surface	0	47.0	5.7	4.2	17.3	25.9

5.2 Sensitivity maps

5.2.1 Methodology

The sensitivity of benthic habitats is determined by the ability to withstand a disturbance event (resistance) and the recovery time needed to return to pre-disturbed levels (resilience) of key structural, functional and characterising species (Tillin *et al.,* 2010; BioConsult, 2013; Tillin and Tyler Walters, 2014).

Resistance (tolerance) of a species or habitat reflects the susceptibility to damage or loss as a result of a pressure on the seabed (Holling, 1973). The likely resistance is estimated with respect to a specified magnitude and duration of change in order to provide a standard level against which to assess. Resistance of a species or habitat is assessed according to the following scale (OSPAR Commission 2017[20]) (Table 8).

Table 8. Assessment scale used for determining resistance of a species or habitat.

Resistance	Description
None	Severe decline and/or physical-chemical parameters also affected e.g. removal of habitat that could cause a change of habitat type. A severe decline/ reduction relates to the **loss of more than 75 %** of the extent, density or abundance of the selected species or habitat element.
Low	Significant mortality of species with some effects on physical-chemical character of habitat. A significant decline/reduction relates to the **loss of 25%-75%** of the extent, density or abundance of the selected species or habitat element.
Medium	Some mortality of species without change to habitat type. 'Some mortality' relates to the **loss of up to 25%** of the extent, density or abundance of the selected species or habitat element.
High	No significant effects to the physical-chemical character of habitat and no effect on population viability of species but potential effects to biological processes like feeding, respiration and reproductive rates.

Resilience (recoverability) describes the ability of a habitat or species population to recover from damage sustained as a result of physical impact on the seabed (Holling, 1973). Resilience of organisms is especially dependent on the ability of the species to regenerate, regrow, recruit or recolonize and the extent of damage incurred. Recovery is only possible when the impact has stopped or has been removed. Resilience of characteristic species is assessed with the following scale (Table 9).

[20] OSPAR Commission, 2017. OSPAR CEMP Guidelines. Common Indicator: BH3 Extent of Physical damage to predominant habitats. https://www.ospar.org/documents?v=37641

Table 9. Assessment scale for resilience.

Resilience	Description
Very Low	At least **25 years** to recover structure and function
Low	Full recovery within **10-25 years**
Medium	Full recovery within **2-10 years**
High	Full recovery within **1-2 years**
Very high	Full recovery within **1 year**

For this project, two separate maps of sensitivity to fishing abrasion (one for surface and one for sub-surface abrasion) of habitats in Scottish waters were created using best available evidence. For the UK, the best available evidence of sensitivity is determined by species records held in the 'Marine Recorder' database combined with the sensitivities assigned via Tillin & Tyler-Walters (2014) for subtidal sediments and Maher *et al.* (2016) for rocky habitats. Species records associated to the EUNIS codes outlined in table 4 were therefore extracted from survey data stored in Marine Recorder and linked to their sensitivity scores. A habitat layer containing all EUNIS codes listed in table 4 was extracted from the Combined map, that is a combination of benthic survey data and modelled habitat data, and habitats' sensitivity scores were linked to each habitat polygon. Sensitivity scores obtained from species information have higher confidence than those obtained from habitats. For this reason, species' sensitivity scores were assigned to the surrounding polygons if species records were available. Habitat sensitivity scores were assigned to polygons where species records were not available. In polygons containing high density of species points (i.e > 1/20 Km^2), the sensitivity score was calculated using the modal species' sensitivity score observed. On the contrary, the maximal observed sensitivity score was assigned to polygons with low density of species points as a precautionary approach to avoid underestimating the sensitivity of polygons where scarce species information was available. the maximal observed sensitivity was assigned to polygons characterised by low species density. Finally, in areas where no species points are detected, the EUNIS level 3 sensitivity score for the underlying benthic habitat was assigned. The layers were then combined to create the sensitivity map (Figure 8 and 9) that show the highest confidence information across all areas. The map will therefore show the sensitivity of species (highest confidence) when this information is available, otherwise habitat sensitivity score (lower confidence) was used. Table 10 shows the sensitivity scores by combining resistance and resilience scores.

Table 10. Sensitivity matrix combing resistance and resilience scores to produce a sensitivity score ranging from 1 to 5, where 5 is the most sensitive.

	Sensitivity	**Resilience** very low (>25 yr.)	low (>10-25 yr.)	medium (>2-10 yr.)	high (1-2 yr.)	very high (<1 yr.)
Resistance	none	5	4	4	3	2
	low	4	4	3	3	2
	medium	4	3	3	2	1
	high	3	3	2	2	1

5.2.2 Results

Two separate maps were produced for sensitivity to surface abrasion (Figure 8) and sub-surface abrasion (Figure 9). Table 10 shows that sensitivity can range from 1 to 5, where 1 is the least sensitive species/benthic habitat score possible and 5 the most sensitive species/habitat. In the current study no areas were observed with a sensitivity score of 1 for surface and/or subsurface abrasion.

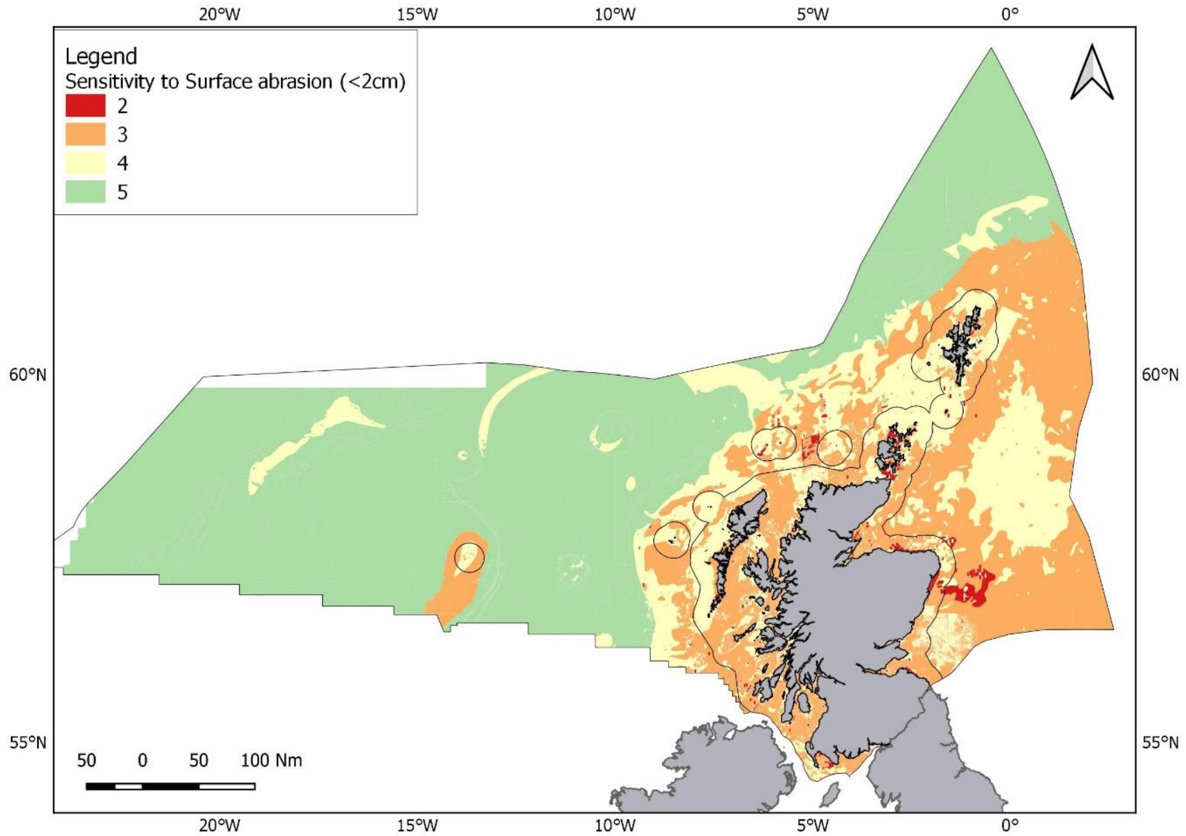

Figure 8. Map of sensitivity to surface abrasion for Scottish waters.

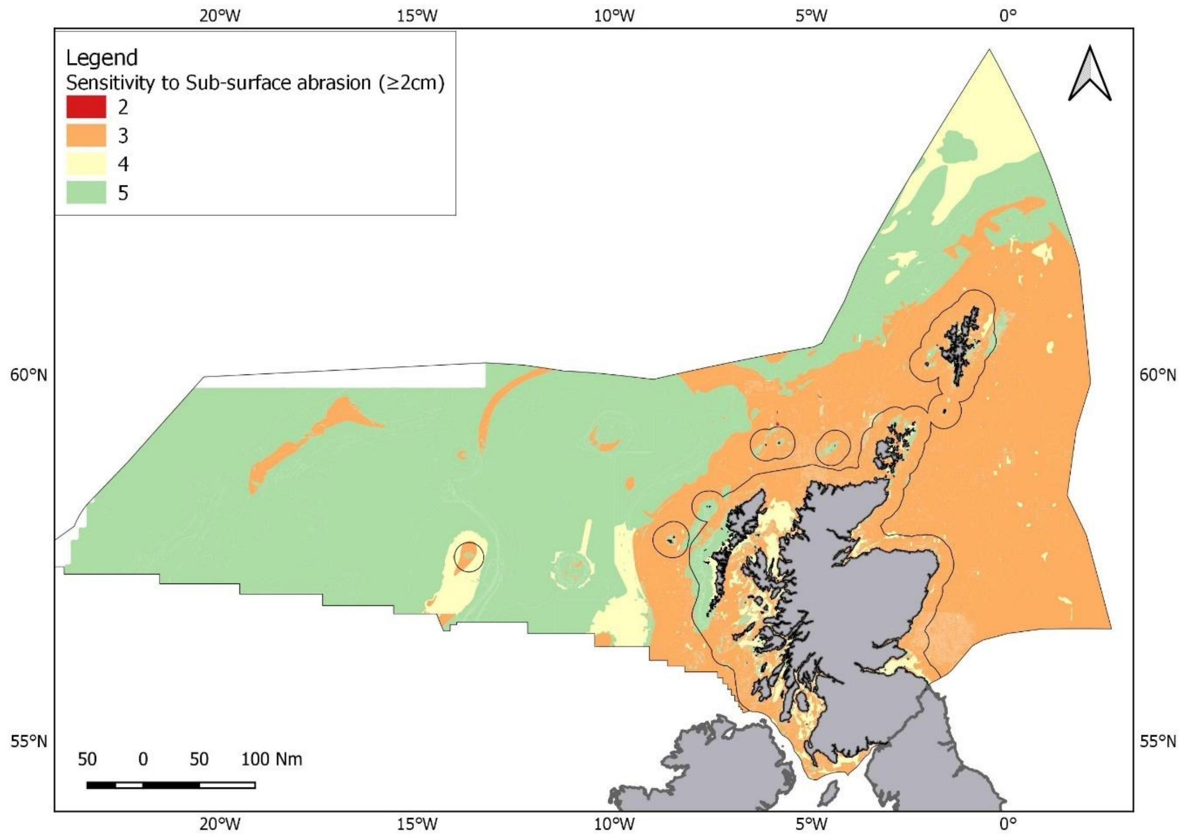

Figure 9. Map of sensitivity to sub-surface abrasion for Scottish waters.

Table 11 summarise the percentage of assessed area within each sensitivity category for the different CP2 Regions. Percentages are shown both for sensitivity to surface and sub-surface abrasion.

Table 11. Sensitivity scores (in %) for each CP2 region in Scottish waters.

CP2 Region	Total Area (Km^2)	Abrasion type	Sensitivity category (%)				
			1	2	3	4	5
Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel	326874.8	Surface	0	0.0	2.0	4.1	94.0
		Sub-surface	0	0.0	4.2	9.0	86.8
Irish Sea	7243.5	Surface	0	3.0	73.8	23.2	0.0
		Sub-surface	0	0.3	66.2	30.2	3.3
Minches and Western Scotland	49127.3	Surface	0	0.9	58.2	40.9	0.0
		Sub-surface	0	0.0	69.5	15.9	14.6
Northern North Sea	148558.8	Surface	0	2.0	65.0	32.9	0.0
		Sub-surface	0	0.0	97.0	2.1	0.9
Scottish Continental Shelf	68745.8	Surface	0	1.5	34.4	45.6	18.5
		Sub-surface	0	0.1	73.8	3.8	22.4

6. Recommendations for Scottish waters

Recommended mitigation measures were divided by Charting Progress 2 (CP2) region in Scottish waters (figure 10), considering habitat sensitivity, fishing pressure and spatial distribution of exploited marine species.

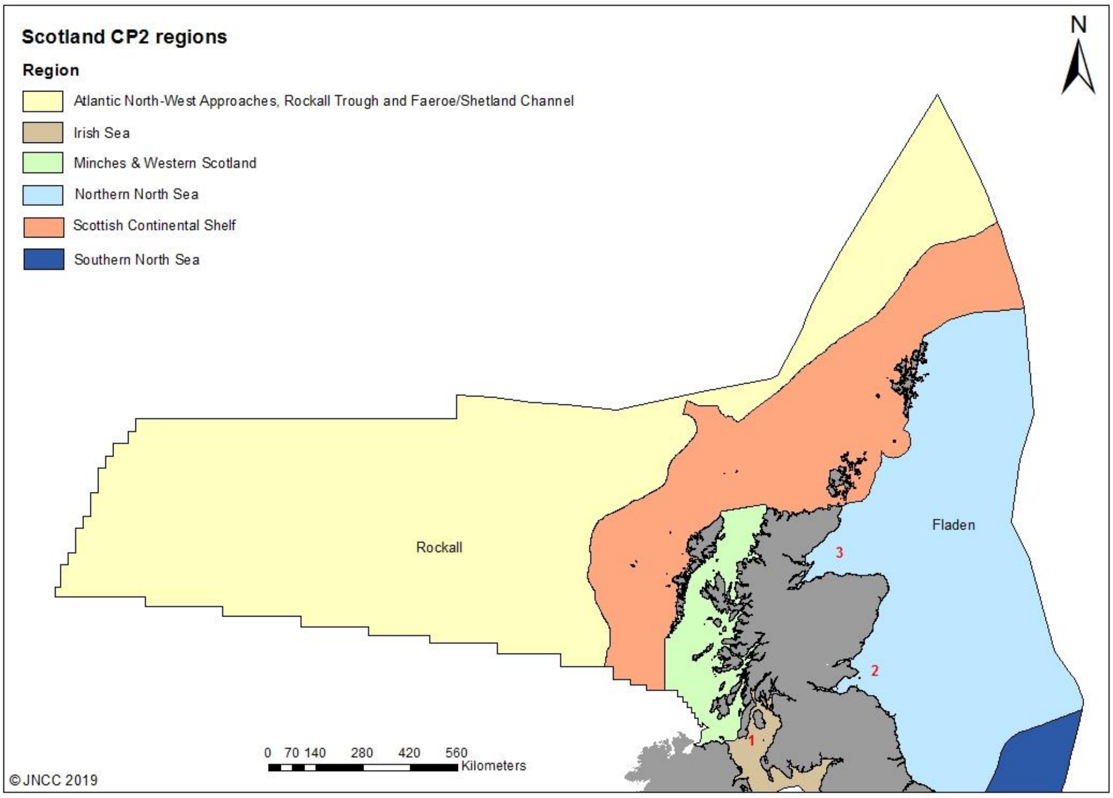

Figure 10. Map showing the CP2 regions in Scottish waters. Number 1 in red stands for Clyde area, number 2 stands for Firth of Forth area, and number 3 stands for Moray Firth area.

6.1 Review by fisheries regions

6.1.1 Northern North Sea

This area is predominantly composed of sand and mud habitats with some patchiness of coarse and mixed sediments.

Haddock and whiting have shown the most heterogenous distribution in Scottish waters, therefore, a strong pattern linking habitat to distribution seems unlikely. However, some patchiness has been found for both species with low probability of occurrence around the Firth of Forth area. Higher probability of occurrence for whiting has been found around the Fladen area, which is associated with higher sublittoral sand and sublittoral mud habitat component. Cod has a high probability of occurrence around the Fladen area, mostly overlapping sublittoral sandy habitat. Saithe is found in the north corner of the Northern North Sea CP2 region, and anglerfish show some probability of occurrence around the same area. As a mud-dwelling burrowing species (Johnson *et al.,* 2013), it is unsurprising that an association exists between *Nephrops* and sublittoral mud habitat. Scallops are found between the line of inshore and offshore waters predominantly associated with sublittoral sand and coarse sediment.

A large proportion of the area assessed in the Northern North Sea is exposed to high and very high surface abrasion levels. By areas in this CP2 region, pressure associated with shallow penetration of different fishing gear components (< 2cm) is categorised as high in the Firth of Forth, Moray Firth and Fladen area. By contrast, sub-surface penetration (≥2cm) pressure is categorised as high over muddier habitat areas around the Fladen, probably as the *Nephrops* fishery occurs in this area.

The majority of the assessed area has a medium sensitivity score (65% for sensitivity to surface abrasion and 97% for sensitivity to sub-surface abrasion) (table 9). On sublittoral mud sediments around the Fladen area, there is high sensitivity to abrasion by fishing gear components at surface level, meaning that the associated benthic community might be less resilience and resistance as a result of a physical impact on this seabed habitat type. In this area, several different types of seapen (e.g. *Funiculina quadrangularis, Virgularia mirabilis and Penatula phosporea)* can be found anchored in the muddy seabed, and the use of demersal towed gears might affect the density and distribution of these seapen species. As the sensitivity score is high for these habitats, the areas of burrowed mud subject to mobile fishing activity are likely to support a modified biological community with lower diversity, reduction or loss of long-lived filter-feeding species and increased abundance of opportunistic scavengers (Ball *et al.,* 2000).

In the Firth of Forth area, the sensitivity was scored as high where sublittoral coarse sediment is found. In this area, stable gravels often support a 'turf' of fragile species which are easily disturbed by trawling and recover slowly (Collie *et al.,* 2005; Foden *et al.,* 2010). Some particularly sensitive species may disappear entirely when trawling and dredging is used, and mortality is for fragile and long-lived species (e.g. Ocean quahog) (Eleftheriou and Robertson, 1992; Bergman and Van Santbrink, 2000).

Recommended mitigation measures

In the Eastern Channel, a combined catch quota and habitat credit scheme was modelled using a dynamic state variable model (DDVM) (Batsleer *et al.,* 2018). The application of credit management schemes have been suggested as a complement to traditional measures such as closed areas (Caveen *et al.,* 2015) as a conservation measure for ecosystem structure and function (Kraak, *et al.* 2012). Habitat impact credits were assigned to each fishing area based on the sensitivity of habitats to fishing activities, and results suggest that such systems incentivise fisherman to choose when and where to fish to make optimal use of their credits.

Therefore, given the information on habitat sensitivity scoring in the area, regulators could work with the Scottish fishing industry to explore options to apply a similar approach in Scottish waters.

MPAs are designated in the area and are aimed to protect marine species and habitats under national and international legislations. Fisheries management measures, where necessary, are put in place to protect sensitive features from fishing impacts, and therefore ensure conservation objectives are achieved. Fisheries management measures for inshore[21] (0-12NM) waters have been put in place via the first phase of fishery management measures for MPAs and consideration is given to the second phase of measures (due for consultation later in 2019). Some of the measures prohibit demersal trawl, beam trawl and dredging within the sites, therefore reducing benthic impact. Fisheries management measures have been proposed for offshore[22] (12-200NM) waters, even though they are not yet in place, some of

[21] Inshore MPA and SAC Management Phase 1: https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork/MPAMGT/protectedareasmgt
[22] Proposed fisheries management measures https://www2.gov.scot/Resource/0051/00516434.pdf

these draft measures propose spatial restrictions to remove or reduce the fishing activity of impacting gears, such as demersal towed gears.

Moreover, mitigation options to reduce the impact of demersal towed gears should be focused on concentrating fishing activity in those areas of high target species abundance, thus, decreasing fishing footprint but maximizing catch. In the case of mobile species, such as whiting and haddock, when there is patchy distribution with no detectable pattern of habitat dependency, mitigation measures should be focused on reducing the impacts from heavy gear components of trawl gears (see figure 3). The same approach will apply when fishing for cod.

Bottom otter trawl is the primary gear used to harvest *Nephrops* in the Northern North Sea (Russell, 2017). Therefore, mitigation options should be focused to reduce or eliminate gear components that contact the seabed. Semi-pelagic trawl gears (trawl doors "fly" through the water column rather than being dragged on the seabed) have been developed for whitefish and shrimp fisheries but are typically not used to catch *Nephrops*. For the shrimp fishery, He *et al*. (2004) demonstrated that the mouth area of a trawl determines the amount of catch and lifting the trawl door off the bottom resulted in reduction in fuel use but without reducing the capture efficiency of the gear. This option could be explored as a measure to reduce benthic impact while fishing for *Nephrops*. Fishermen's knowledge has suggested that the conventional trawling (using doors) has a herding effect for *Nephrops*, therefore, innovative gear to reduce bottom contact when fishing for *Nephrops* should be explore widely with the Scottish fishing industry. Other mitigation options as shown in figure 2, could include a reduction in the number of bobbins.

King scallop can be fished by hand-diving or scallop dredging. Scallop dredging is well known for its impact on the seabed, and mitigation options normally focus on removing such impacts. In Canada, detailed seabed habitat maps were used in conjunction with scallop biological data (e.g. known areas of juveniles and adults) to mitigate the impacts of fishing gear. Spatial distribution maps for scallops were used by fishermen to direct their effort to areas of high adult density.

Considering the patchiness of king scallop on habitat types in Scottish waters, Scottish fishing industry and managers will benefit from having detailed maps of spatial distribution of scallops and use a similar approach as in Canada.

6.1.2 Scottish Continental Shelf

This area is a large rift basin that separates the Scottish and Faroese continental shelves. Five different water masses with different temperatures and densities, meet in the continental shelf with depths down to 800m. The predominant benthic habitats in east and west Shetland are sublittoral sand, coarse sediment and some patches of mud. In inshore areas, infralittoral rock and other hard substrates are found. The Outer Hebrides are characterized by coarse sediment, sand and rocky substrata.

Anglerfish is normally found on sandy, muddy and occasionally rocky areas at depths below 500m (Hislop *et al.,* 2001). Therefore, as shown in the data analysed, the probability of occurrence in this area is high (>0.8) for anglerfish. Cod, whiting and haddock have also been found in this area, and the probability of occurrence varies between 0.7-0.9. Saithe show lower (0.5) probability of occurrence around the continental shelf. Scallop landing data show the fishery for this species is concentrated in inshore waters around Shetland and Orkney.

In this region, the aggregated score for surface abrasion (2009-2015) for demersal towed gears, is categorised between high to very high in more than 70% of the assessed area, and effort was focused along a clear depth contour along the continental shelf around 200m to

500m. Sub-surface abrasion was very low in most of the area (table 5). Most fishing in this area is associated with the deep-water fishery for saithe and anglerfish.

The continental shelf is characterised by deep-sea benthic habitats, such as deep-sea bedrock, deep-sea mixed sediments and deep-sea sand. The sensitivity of these types of habitats, is normally high, as deep-sea ecosystems are typically more stable and thus require longer recovery periods to pre-disturbed level (Clark *et al.,* 2016). Sensitivity to surface abrasion in this region is categorised as medium to high, mostly in the area where sand and coarse sediments are found. The impact of demersal towed gears on sand and gravel sediment is relatively well understood. In areas exposed to natural disturbance (e.g. normally closer to the coast), the associated fauna tend to be well adapted and more tolerant to fishing disturbance (Dernie *et al.,* 2003; Hiddink *et al.,* 2006). Muddy sands and sand in deeper water, sediments tend to be more stable and their associated fauna less tolerant of disturbance (Kaiser *et al.,* 2006; Hiddink *et al.,* 2006). In this area, very high sensitivity scores are more associated with the deep-sea habitat component due to the slow recovery rates of many deep-sea species.

Recommended mitigation options

Mitigation measures for deep-sea habitats should be focused particularly on reducing the contact between fishing gears and the benthic habitat. This could include, reduction in fishing effort and/or gear modifications such as reducing footrope or roller size on bottom-trawls, as shown by Hourigan *et al.,* 2009. Scotland already has some spatial mitigation measures, such as the deep-sea regulation (EC) No 2347/2002[23], where move-on rules apply when vulnerable marine ecosystems (VMEs) are encountered, and fishing with bottom trawls is restricted at depths below 800m. Moreover, there are designated MPAs in the area for the protection of habitats and species under national and international legislation. Fisheries management measures for inshore[24] (0-12NM) waters have been put in place via the first phase of fishery management measures for MPAs and consideration is given to the second phase of measures (due for consultation later in 2019). Some of the measures prohibit demersal trawl, beam trawl and dredging within the sites, therefore reducing benthic impact. Fisheries management measures have been proposed for offshore[25] (12-200NM) waters, even though they are not yet in place, some of these draft measures propose spatial restrictions to remove or reduce the fishing activity of impacting gears, such as demersal towed gears. Any other potential options for technical measures (see figure 2) could be explored with the Scottish fishing industry.

Mitigation options to reduce the impact of scallop dredge, could be to use detailed seabed habitat maps and spatial distribution of scallops by fishermen to direct their effort to areas of higher density and away from more sensitive biotopes.

6.1.3 Minches and Western Scotland

The area extends from the Mull of Kintyre to Cape Wrath, with a seabed which is characterised by rocky habitats around the coast with sand and coarse sediments in the inshore area. *Nephrops* is found in the area with a probability of occurrence between 0.94 and 1, being higher in the sandy mud to muddy sand habitat. Whiting and haddock are also found in the area, but the probability of occurrence is <0.70. Scallops are an important fishery in the area, as shown in the figure 6 Annex C.

[23] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R2336&rid=4
[24] Inshore MPA and SAC Management Phase 1: https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork/MPAMGT/protectedareasmgt
[25] Proposed fisheries management measures https://www2.gov.scot/Resource/0051/00516434.pdf

The region is exposed in a wide range of abrasion scores depending on the area, ranging from low to very high. The surface abrasion pressure (<2cm) is categorised very high in those areas with muddier sediments.

The sensitivity of benthic habitats to surface and sub-surface abrasion in this area varies between medium and high sensitivity. Medium sensitivity scores were due to greater resistance and resilience of sand and gravel sediments with associated fauna in areas exposed to high energy (i.e. of wave and/or tide exposed), being better adapted to disturbance. By contrast, stable gravels that support fragile species which are easily removed by trawling and recover slowly (Collie *et al.,* 2005; Foden *et al.,* 2010) were characterised as being highly sensitive to benthic fishing pressure.

Recommended mitigation measures

MPAs are designated in the area to protect habitats and species under national and international legislation. Fisheries management measures for inshore[26] (0-12NM) waters have been put in place via the first phase of fishery management measures for MPAs and consideration is given to the second phase of measures (due for consultation later in 2019). Some of the measures prohibit demersal trawl, beam trawl and dredging within the sites, therefore reducing benthic impact. Fisheries management measures have been proposed for offshore[27] (12-200NM) waters, even though they are not yet in place, some of these draft measures propose spatial restrictions to remove or reduce the fishing activity of impacting gears, such as demersal towed gears.

Complementing the proposed MPA measures, credit management schemes (Batsleer *et al.,* 2018) could be considered. Habitat impact credits could be assigned to each fishing area based on the sensitivity of habitats to fishing activities thus incentivising fisherman to choose when and where to fish to make optimal use of their credits.

Moreover, mitigation options to reduce the impact of demersal towed gears in the area should be focused on concentrating fishing activity in those areas of high species abundance, thus, decreasing fishing footprint but maximizing catch. In the case of mobile species, such as whiting and haddock, where there is patchy distribution with no specific habitat dependency, mitigation measures should be focused on reducing the impacts from heavy gear components of trawl gears (see figure 3). The same approach will apply when fishing for cod.

Bottom otter trawl is the primary gear used to harvest *Nephrops* in the Minches and Western Scotland (Russell, 2017). Therefore, mitigation options should be focused to reduce or eliminate gear components that contact the seabed. Semi-pelagic trawl gears (trawl doors “fly” through the water column rather than being dragged on the seabed) have been developed for whitefish and shrimp fisheries but are typically not used to catch *Nephrops*. For the shrimp fishery, He *et al*. (2004) demonstrated that the mouth area of a trawl determines the amount of catch and lifting the trawl door off the bottom resulted in reduction in fuel use but without reducing the capture efficiency of the gear. This option could be explored as a measure to reduce benthic impact while fishing for *Nephrops*. Fishermen’s knowledge has suggested that the conventional trawling (using doors) has a herding effect for *Nephrops*, therefore, innovative gear to reduce bottom contact when fishing for *Nephrops* should be explore widely with the Scottish fishing industry. Other mitigation options as shown in figure 2, could include a reduction in the number of bobbins.

King scallop can be fished by hand-diving or scallop dredging. Scallop dredging is well known for its impact on the seabed, and mitigation options normally focus on removing such impacts.

[26] Inshore MPA and SAC Management Phase 1: https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork/MPAMGT/protectedareasmgt
[27] Proposed fisheries management measures https://www2.gov.scot/Resource/0051/00516434.pdf

In Canada, detailed seabed habitat maps were used in conjunction with scallop biological data (e.g. known areas of juveniles and adults) to mitigate the impacts of fishing gear. Spatial distribution maps for scallops were used by fishermen to direct their effort to areas of high adult density.

Considering the patchiness of king scallop on habitat types in Scottish waters, Scottish fishing industry and managers will benefit from having detailed maps of spatial distribution of scallops and use a similar approach as in Canada.

6.1.4 Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel

The Atlantic North-West Approaches and Rockall area is situated in the North East Atlantic ranging across shelf, continental slope and deep sea with depths spanning from 200m to over 1000m. Predominant habitats include mixed sediments, sand and deep-sea muds but it also represents one of the most extensive sites for biogenic reef in the UK.

This area has an established fishery for anglerfish and haddock which is reflected in the high probabilities of occurrence for these species, ranging from 0.6 to 1.

Due to the depth profile, most of the area is characterised by very low levels of fishing pressure both for surface and sub-surface abrasion (respectively 68% and 98% of the area) (table 5). Fishing pressure is categorized as high (surface abrasion category 4-5) around the shallower areas, as effort is concentrated on the shelf and upper slope.

Despite this, sensitivity is also generally very high due to the fact that most of the area is characterised by the presence of deep sea muddy habitats, that are thought to be much less resilient than comparable shelf habitats (Clark *et al.,* 2016).

Recommended mitigation measures

Mitigation measures for deep-sea habitats should be focused particularly on reducing the contact between fishing gears and the benthic habitat. This could include, reduction in fishing effort and/or gear modifications such as reducing footrope or roller size on bottom-trawls, as shown by Hourigan *et al.,* 2009. Scotland already has some spatial mitigation measures, such as the deep-sea regulation (EC) No 2347/2002[28], where move-on rules apply when vulnerable marine ecosystems (VMEs) are encountered, and fishing with bottom trawls is restricted at depths below 800m. Moreover, there are designated MPAs in the area for the protection of habitats and species under national and international legislation. Fisheries management measures have been proposed for offshore[29] (12-200NM) waters, even though they are not yet in place, some of these draft measures propose spatial restrictions to remove or reduce the fishing activity of impacting gears, such as demersal towed gears. Any other potential option for technical measures (see figure 2) could be explored with the Scottish fishing industry.

6.1.5 Irish Sea

The Irish Sea is mostly characterized by mud and sand habitat types. *Nephrops* are found with a probability of occurrence >0.98, and a *Nephrops* fishery is well-established in the area. Cod,

[28] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R2336&rid=4
[29] Proposed fisheries management measures https://www2.gov.scot/Resource/0051/00516434.pdf

haddock and whiting are also found in this area but with lower probability of occurrence (<0.75).

The data suggests that fishing pressure is concentrated in specific areas with approximately 50% of the region exposed to surface fishing abrasion pressure ranging from high to very high but with 38% only very lowly exposed. For sub-surface abrasion, the highest proportion of the region (47%) is exposed to very low pressure values, whilst ~26% falls under very high pressure (table 5).

The sensitivity in the area ranges from medium to high to surface abrasion. The medium scoring can be explained by the resistance and resilience of sand and gravel sediments with the associated fauna in areas exposed to high energy locations (i.e. of wave and/or tide exposed) being better adapted to disturbance. Stable gravels or muddy habitats that typically support fragile species which are easily removed by trawling and recover slowly (Collie *et al.,* 2005; Foden *et al.,* 2010) were classed as "High" sensitivity in the Irish Sea area.

Recommended mitigation measures

As well as closed areas credit management systems (Batsleer *et al.,* 2018) could be considered. Habitat impact credits could be assigned to each fishing area based on the sensitivity of habitats to fishing activities and fisherman could be incentivised to choose when and where to fish to make optimal use of their credits.

MPAs are designated in the area and are aimed to protect marine species and habitats under national and international legislation. Fisheries management measures, where necessary, are put in place to protect sensitive features from fishing impacts, and therefore ensure conservation objectives are achieved. Fisheries management measures for inshore[30] (0-12NM) waters have been put in place via the first phase of fishery management measures for MPAs and consideration is given to the second phase of measures (due for consultation later in 2019). Some of the measures prohibit demersal trawl, beam trawl and dredging within the sites, therefore reducing benthic impact. Fisheries management measures have been proposed for offshore[31] (12-200NM) waters, even though they are not yet in place, some of these draft measures propose spatial restrictions to remove or reduce the fishing activity of impacting gears, such as demersal towed gears.

Bottom otter trawl is the primary gear used to harvest *Nephrops* in the Irish Sea (Russell, 2017). Therefore, mitigation options should be focused to reduce or eliminate gear components that contact the seabed. Semi-pelagic trawl gears (trawl doors "fly" through the water column rather than being dragged on the seabed) have been developed for whitefish and shrimp fisheries but are typically not used to catch *Nephrops*. For the shrimp fishery, He *et al*. (2004) demonstrated that the mouth area of a trawl determines the amount of catch and lifting the trawl door off the bottom resulted in reduction in fuel use but without reducing the capture efficiency of the gear. This option could be explored as a measure to reduce benthic impact while fishing for *Nephrops*. Fishermen's knowledge has suggested that the conventional trawling (using doors) has a herding effect for *Nephrops*, therefore, innovative gear to reduce bottom contact when fishing for *Nephrops* should be explore widely with the Scottish fishing industry. Other mitigation options as shown in figure 2, could include a reduction in the number of bobbins.

King scallop can be fished by hand-diving or scallop dredging. Scallop dredging is well known for its impact on the seabed, and mitigation options normally focus on removing such impacts. In Canada, detailed seabed habitat maps were used in conjunction with scallop biological data

---

[30] Inshore MPA and SAC Management Phase 1: https://www2.gov.scot/Topics/marine/marine-environment/mpanetwork/MPAMGT/protectedareasmgt
[31] Proposed fisheries management measures https://www2.gov.scot/Resource/0051/00516434.pdf

(e.g. known areas of juveniles and adults) to mitigate the impacts of fishing gear. Spatial distribution maps for scallops were used by fishermen to direct their effort to areas of high adult density.

Considering the patchiness of king scallop on habitat types in Scottish waters, Scottish fishing industry and managers will benefit from having detailed maps of spatial distribution of scallops and use a similar approach as in Canada.

6.2. Conclusions of mitigation measures for Scottish fisheries

Scottish waters are rich and diverse and have a variety of marine ecosystems upon which commercially harvested species rely. Fishery effects, such as the impacts of demersal towed gears, on ecological systems are complex and mitigation measures should consider those complexities.

Traditional fisheries management has focused on single species management for commercially valuable species. This type of management often ignores ecosystem considerations, such as species interactions, bycatch, changes in the ecosystem structure, and gear impacts on habitat (Trochta *et al.,* 2018).

In Scottish waters, where single-species management has traditionally been applied, the Scottish government has recently published "Future of fisheries management in Scotland: National discussion paper[32]" which expresses their desire to take an ecosystem-based approach to management ensuring sustainable, resilient stocks and avoiding damage to fragile habitats.

The most frequently mentioned principles in the ecosystem-based approach to fisheries management include; consideration of ecosystems connections, use of scientific knowledge, stakeholder involvement, maintenance of biodiversity and acknowledgement of uncertainty (Trochta *et al.,* 2018). Given the importance of the fishing sector to Scotland, those principles should be considered in developing a more holistic approach to future management, mitigating the wider impacts of demersal towed gears on the marine environment.

The most effective way to reduce the impact of demersal towed gears will be to recognise the spatial match between resource exploitation (a fishery) and biological productivity (stock unit). Therefore, predictive habitat and species distribution maps may play an important role in decision making when designing future mitigation measures to reduce the impact of demersal towed gears as shown in summary (Table 12) of recommended mitigation measures by area.

Spatial measures such as full or seasonal closures and/or effort and gear restrictions have been widely used in other countries. On the other hand, the use of closures might displace fishing effort elsewhere (Vaughan, 2017; Hilborn, 2018). Thus, closures should always be considered in a wider ecological context.

Some tools to mitigate the impact of demersal towed gears are already being used in Scottish waters. For example, licencing and effort control, as well as the restriction of fishing pressure in areas known to contain vulnerable ecosystems. The use of technical measures (e.g. innovative gears) should balance between maximising catch and reducing impact, and in the last years there has been an increase in the use of innovative gears. Despite this, the

[32] https://www.gov.scot/binaries/content/documents/govscot/publications/publication/2019/03/national-discussion-paper-future-fisheries-management-scotland/documents/future-fisheries-management-scotland-national-discussion-paper/future-fisheries-management-scotland-national-discussion-paper/govscot%3Adocument

innovation has been focused on selectivity and by-catch for the Landing Obligation[33] rather than to reduce benthic impact.

Given the scope of the project, it is acknowledged that the mitigation measures recommended here are necessarily broad and no consideration has been given to the detailed ecological drivers for species and habitat distribution. Thus, to refine the potential for area-specific management options, future work could focus on variables such as species distribution (incorporating differences by life stages), food web traits and variability within habitat types.

In conclusion, this project provides a better understanding of the tools available to manage seabed impact and examines how species distribution across habitat type can be used by both, managers and the fishing industry to target management to reduce benthic impact in Scottish waters. The ability to make more informed and balanced decisions is central to the success of mitigation measures to reduce benthic impact in Scottish waters. Using both habitat sensitivity maps and knowledge of species distribution in management decision making is a more strategic, transparent and inclusive approach when comparing with traditional fisheries management.

[33] https://www2.gov.scot/Topics/marine/Sea-Fisheries/discards/wlv17012019

Table 12. Summary table of recommended mitigation measures by CP2 region in Scottish waters.

Recommended mitigation measures	**Areas (CP2 region)**
Application of credit management schemes to incentivise fishermen to choose when and where to fish.	Northern North Sea Scottish Continental Shelf Minches and Western Scotland Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel Irish Sea
Use of detailed habitat maps in conjunction with habitat sensitivity maps to improve spatial management of demersal towed gears when the aim is to reduce benthic impact.	Northern North Sea Scottish Continental Shelf Minches and Western Scotland Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel Irish Sea
Explore the use of real time (if possible) spatial and temporal distribution of commercial marine species, to focus footprint in those areas where the return for fishermen is higher.	Northern North Sea Scottish Continental Shelf Minches and Western Scotland Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel Irish Sea
Explore innovative gears and investigate the reduction of bottom contact with the seabed by reducing the footrope or roller size on bottom trawls (i.e. technical measures in table 2).	Northern North Sea Scottish Continental Shelf Minches and Western Scotland Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel Irish Sea
Explore the use of detailed habitat maps and /or multi-beam data, and spatial-temporal distribution of adult and juvenile scallops to improve spatial management when fishing for scallop with dredges.	Minches and Western Scotland Irish Sea Northern North Sea
Explore the use of semi-pelagic trawls for whitefish/*Nephrops* with the aim to reduce bottom contact on the seabed.	Northern North Sea Scottish Continental Shelf Atlantic North-West Approaches, Rockall Trough and Faeroe/Shetland Channel Minches and Western Scotland Irish Sea

7. Recommendations for future work

As a scoping exercise for Scottish waters, data were considered on an annual basis with no reference to seasonality of commercial marine species and fisheries or differences between distribution of juveniles and adults, including possible differentiation between life stages in the use of marine habitats.

During the king scallop data processing, it was found that independent fishing data should be gathered for this species. Most maps of king scallop distribution are based on the scallop fishing distribution and/or scallop habitat. There are limitations when using this approach, for example fishing activity of <12m are not covered by VMS. Moreover, shallow waters on the west coast of Scotland fished by scallop divers are poorly represented on those maps, and this information might help when mapping species distribution. There are several initiatives and projects that there are currently developing to improve the management of scallops in UK waters, some of which recognise the need for improved mapping of scallop habitat and distribution. Thus, bringing together all these initiatives might help to coordinate efforts to produce better species distribution map outputs.

Improved resolution of habitat sensitivity maps would enable the reduction of the fishing footprint in specific habitat biotopes that may be more sensitive. Moreover, more integrated commercial species distribution mapping will provide fishermen and managers the ability to maximise revenue by optimising the catches reducing fuel consumption.

Therefore, it is recommended that any future work should focus on testing in practice the feasibility to manage fisheries to reduce impact of bottom contact gears, based on more refined habitat and species distribution information. A consortium between fishing industry, scientists and managers would be needed to agree a test area and test recommended mitigation measures.

8. Acknowledgements

This work was funded by Fisheries Innovation Scotland under the grant code FIS026. Marine Scotland Science contributed data for scallops and *Nephrops* in Scottish waters and their support is gratefully acknowledged.

9. References

Ball, B.J., Fox, G. and Munday, B.W. 2000. Long- and short-term consequences of a *Nephrops* trawl fishery on the benthos and environment of the Irish Sea. ICES Journal of Marine Science, **57**: 1315–1320.

Batsleer, J., P. Marchal, S. Vaz, V. Vermard, A. D. Rijnsdorp, and J. J. Poos. 2018. “Exploring Habitat Credits to Manage the Benthic Impact in a Mixed Fishery.” *Marine Ecology Progress Series* 586 (January): 167–79. https://doi.org/10.3354/meps12392.

BioConsult. 2013. Seafloor integrity - Physical damage, having regard to substrate characteristics (Descriptor 6). A conceptual approach for the assessment of indicator 6.1.2: ‘Extent of the seabed significantly affected by human activities for the different substrate types’. Report within the R & D project ‘Compilation and assessment of selected anthropogenic pressures in the context of the Marine Strategy Framework Directive’, UFOPLAN 3710 25 206.

Beukers-Stewart, B.D. Beukers-Stewart, J.S. 2009. Principles for the Management of Inshore Scallop Fisheries Around the United Kingdom. Marine Ecosystem Management Report No. 1. University of York.

Bergmann, M.J.N. and Van Santbrink, J.W. 2000. Fishing mortality and populations of megafauna in sandy sediments. In: Kaiser M.J. and de Groot S.J. (eds.) Effects of fishing on non-target species and habitats. Blackwell, Oxford.

Bradshaw, C., Veale, L., Hill, A., Brand, A.R. 2001. “The effect of scallop dredging on Irish Sea benthos: experiments using closed area.” *Hydrobiology* 465: 129–138. https://doi.org/10.1007/978-94-010-0434-3_13.

Caddy, J. F., and J. C. Seijo. 2005. “This Is More Difficult than We Thought! The Responsibility of Scientists, Managers and Stakeholders to Mitigate the Unsustainability of Marine Fisheries.” *Philosophical Transactions of the Royal Society of London* B: Biological Sciences 360 (1453): 59–75. https://doi.org/10.1098/rstb.2004.1567.

Catherall, C.L. and Kaiser, M.J. 2014. Review of king scallop dredge designs and impacts, legislation and potential conflicts with offshore wind farms. Fisheries & Conservation Report No. 39, Bangor University. pp. 40.

Church, N.J., Carter, A.J., Tobin, D., Edwards, D., Eassom, A., Cameron, A., Johnson, G.E., Robson, L.M. & Webb, K.E. 2016. JNCC Pressure Mapping Methodology. Physical Damage (Reversible Change) - Penetration and/or disturbance of the substrate below the surface of the seabed, including abrasion. JNCC Report No. 515. JNCC, Peterborough

Claus, S., De Hauwere, N., Vanhoore, B., Souza Dias, F., Oset Garcia, P., Hernandez, F., and Mees, J. 2016. MarineRegions.org. **http://www.marineregions.org** .

Clark, M.R., and Koslow, J.A. 2007. Impacts of fisheries on seamounts, in: T.J. Pitcher,nT. Morato, P.J.B. Hart, M.R. Clark, N. Haggan, R.S. Santos (Eds.), Seamounts: Ecology, Fisheries, and Conservation, Blackwell Publishing, Oxford, UK, 2007, pp. 413–441.

Clark, Malcolm R., Franziska Althaus, Thomas A. Schlacher, Alan Williams, David A. Bowden, and Ashley A. Rowden. 2016. “The Impacts of Deep-Sea Fisheries on Benthic Communities: A Review.” *ICES Journal of Marine Science* 73 (suppl 1): i51–69. https://doi.org/10.1093/icesjms/fsv123

Collie, J. S., Hall, S. J., Kaiser, M. J., and Poiner, I. R. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. *Journal of Animal Ecology* 69: 785–798.

Costanza, R., D’Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill., R.V., Paruelo, J., Raskin, R.G., Sutton, P., and van den Belt, M. 1997. The value of the world’s ecosystem services and natural capital. *Nature* 387, 253–260.

Dayton, P.K., Thrush, S.F., Agardy, M.T., Hofman, R.J. 1995. “Environmental effects of marine fishing.” *Aquatic Conservation: Marine and Freshwater Ecosystems* 5: 205–232. https://doi.org/10.1002/aqc.3270050305.

DeLouche, H. and G. Legge. 2004. Reducing seabed contact while trawling: a semi-pelagic trawl for the Newfoundland and Labrador shrimp fishery. Fisheries and Marine Institute. A report submitted Canadian Centre for Fisheries Innovation, St. John’s, Newfoundland.

Dernie, K.M., Kaiser, M.J. and Warwick, R.M. 2003. Recovery rates of benthic communities following physical disturbance. Journal of Animal Ecology, 72: 1043–1056.

Donaldson, A., Gabriel, C., Harvey, B.J., Carolsfeld, J., 2010. Impacts of Fishing Gears other than Bottom Trawls, Dredges, Gillnets and Longlines on Aquatic Biodiversity and Vulnerable Marine Ecosystems. DFO Canadian Science Advisory Secretariat. Doc. 2010/011. 84 pp.

DuPaul, W., and Rudders, D. B. 2007. Scallop dredge selectivity: a review of sequential ring size increases from 1994 to 2003 in the US sea scallop fishery. *Journal of Shellfish Research* 26(4): 1307-1308.

Eleftheriou, A., and Robertson, M. R. 1992. The effects of experimental scallop dredging on the fauna and physical environment of a shallow sandy community. *Netherlands Journal of Sea research*. 30: 289-299.

Eigaard, Ole R., Francois Bastardie, Mike Breen, Grete E. Dinesen, Niels T. Hintzen, Pascal Laffargue, Lars O. Mortensen, et al. 2016. “Estimating Seabed Pressure from Demersal Trawls, Seines, and Dredges Based on Gear Design and Dimensions.” *ICES Journal of Marine Science: Journal Du Conseil* 73 (suppl 1): i27–43. https://doi.org/10.1093/icesjms/fsv099.

Ellis, Nick, Francis Pantus, Andrzej Welna, and Alan Butler. 2008. “Evaluating Ecosystem-Based Management Options: Effects of Trawling in Torres Strait, Australia.” *Continental Shelf Research*, Marine resources, biophysical processes, and environmental management of a tropical shelf seaway; Torres Strait, Australia, 28 (16): 2324–38. https://doi.org/10.1016/j.csr.2008.03.031.

Ellwood, H. 2014. Creating a EUNIS level 3 seabed habitat map integrating data from maps from field surveys and EUSeaMap Version 1.0. http://jncc.defra.gov.uk/page-6655

Fernandes, P., and Rivoirard, J. 1999. A geostatistical analysis of the spatial distribution and abundance of cod, haddock and whiting in North Scotland. *Geostatistics for*

Environmental application 10, 201–212.

Foden, J., Rogers, S.I. and Jones, A.P. 2010. Recovery of UK seabed habitats from benthic fishing and aggregate extraction- towards a cumulative impact assessment. *Marine Ecology Progress Series*, 411: 259–270

Frandsen, Rikke Petri, Ole Ritzau Eigaard, Louise Kjeldgaard Poulsen, Ditte Tørring, Bjarne Stage, Dennis Lisbjerg, and Per Dolmer. 2015. "Reducing the Impact of Blue Mussel (Mytilus Edulis) Dredging on the Ecosystem in Shallow Water Soft Bottom Areas." *Aquatic Conservation: Marine and Freshwater Ecosystems* 25 (2): 162–73. https://doi.org/10.1002/aqc.2455.

Gell, F. R. & Roberts, C. M., 2003. Benefits beyond boundaries: the fishery effects of marine reserves. *Trends in Ecology and Evolution*, 18(9): 448–455

Gemba Consulting, 2011. Projekt: "Demonstrationsfartøj i Østersøfiskeriet med fokus på bedst kendte teknologier indenfor energieffektivitet i fangstredskaber under hensyn til selektivitet og dokumentation". Project report in Danish, 34 pp.

Griffiths, S.P., 1999. Effects of lunar periodicity on catches of Penaeus plebejus (Hess) in an Australian coastal lagoon. *Fisheries Research* 42 (1–2), 195–199.

Gunderson, D. R. 1993. Surveys of Fisheries Resources. Wiley, New York.

Hall, Morse. 2002. "Design and Model Test of a Semi-Pelagic Shrimp Trawl for the Pink Shrimp Fishery," 9.

Halpern, B. S. 2003.The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications*, 13: S117eS137

Harwood, J., and Stokes, K. 2003. Coping with uncertainty in ecological advice: Lessons from fisheries. *Trends in Ecology and Evolution* 18, 617–622.

He, P. and Foster, D. 2000. Reducing seabed contact of shrimp trawls. ICES Working Group on Fishing Technology and Fish Behavior, Haarlem, Netherlands. April 10-14, 2000

He, P., P. Winger, R. Fonteyne, M. Pol, P. MacMullen, S. Løkkeborg, B. Van Marlen, T. Moth-Poulsen, K. Zachariassen, and A. Sala. 2004. "Mitigation Measures against Seabed Impact of Mobile Fishing Gears." *Report of the ICES Fisheries Technology Committee Working Group on Fishing Technology and Fish Behaviour, Gdynia, Poland. ICES CM*, 160–172.

He, P., Hamilton, R., Littlefield, G. and Syphers, R.H. 2006. "Design and text of a semi-pelagic shrimp trawl to reduce seabed impact". Final report submitted to the Northeast Consortium. University of New Hampshire Durham, NH. UNFISH-REP-2006-029. 24pp

Hiddink, J.G, S. Jennings, M.J. Kaiser, A.M Queirós, D.E. Duplisea, and G.J. Piet. 2006. "Cumulative Impacts of Seabed Trawl Disturbance on Benthic Biomass, Production, and Species Richness in Different Habitats." Canadian Journal of Fisheries and Aquatic Sciences 63 (4): 721–36. doi:10.1139/f05-266

Hiddink, J.G., Jennings,S., Sciberras, M., Szostek, C.L., Hughes, K.M., Ellis, N., Rijnsdorp, A.D., McConnaughey, R.A., Mazord, T., Hilborn, R., Collie, J.S., Pitcher, C.R., Amoroso, R.O., Parma, A.M., Suuronen, P., Kaiser, M.K. 2017. Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. *Proceedings of the National Academy of Sciences* 114(3): 201618858.

Hilborn, R., E.A. Fulton, B.S. Green, K. Hartmann, S.R. Tracey, and R.A. Watson. 2015. "When Is a Fishery Sustainable?" *Canadian Journal of Fisheries and Aquatic Sciences* 72 (9): 1433–41. https://doi.org/10.1139/cjfas-2015-0062.

Hilborn, Ray. 2018. "Are MPAs Effective?" Edited by Linwood Pendleton. ICES Journal of Marine Science 75 (3): 1160–62. https://doi.org/10.1093/icesjms/fsx068

Hintzen N. T., Bastardie F., Beare D., Piet G. J., Ulrich C., Deporte N., Egekvist J., et al. VMStools: open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data, *Fisheries Research* , 2012, vol. 155–116 (pg. 31-43)

Hislop, J.R.G, Gallego, A., Heath, M.R., Kennedy, F.M., Reeves, S.A., Wright, P.J. 2001. A synthesis of the early life history of the anglerfish, *Lophius piscatorius* (Linnaeus, 1758) in northern British waters. *ICES Journal of Marine Science,* 58:70-86.

Holling, C, S. 1973. Resilience and Stability of Ecological Systems, Annual Review of Ecology and Systems, 4, 1-23.

Hourigan, T.F. 2009. "Managing Fishery Impacts on Deep-Water Coral Ecosystems of the USA: Emerging Best Practices." *Marine Ecology Progress Series* 397: 333–40. https://doi.org/10.3354/meps08278.

ICES. 2013. Report of the Benchmark Workshop on *Nephrops* Stocks (WKNEPH), 25 February–1 March 2013, Lysekil, Sweden. ICES CM 2013/ACOM:45. 230 pp.

ICES. 2015. Manual for the International Bottom Trawl Surveys.

ICES, 2016. Report of the Scallop Assessment Working Group (WGScallop), 5-9 October 2015, Trinity, Jersey, UK. ICES CM 2015/ACOM:23. 42 pp

ICES. 2017. Report of the Working Group for the Celtic Seas Ecoregion (WGCSE) (Copenhagen, Denmark)

ICES. 2018. Report of the Working Group on Spatial Fisheries Data (WGSFD), 11–15 June 2018, Aberdeen, UK. *International Council for the Exploration of the Sea*. CM 2018/HAPISG:16. Provisional report.

Jennings, S., Kaiser, M.J. 1998. "The effects of fishing on marine ecosystems." *Advances in Marine Biology 34*: 201–352. https://doi.org/10.1016/S0065-2881(08)60212-6.

Jennings, S., J.K. Pinnegar, N.V.C. Polunin, and K.J. Warr. 2001. "Impacts of Trawling Disturbance on the Trophic Structure of Benthic Invertebrate Communities." *Marine Ecology Progress Series* 213 (April): 127–42. doi:10.3354/meps213127.

Johnson, M.P., Lordan, C., Power, A.M., 2013. Habitat and Ecology of *Nephrops norvegicus*. *Advances in Marine Biology*, Vol. 64, pp. 27-63. https://doi.org/10.1016/B978-0-12-410466-2.00002-9

Kafas, A., McLay, A., Chimienti, M., Gubbins, M. 2014. ScotMap Inshore Fisheries Mapping in Scotland: Recording Fishermen's use of the Sea. Scottish Marine and Freshwater Science Volume 5 Number 17. Edinburgh: Scottish Government, 32p. DOI: 10.4789/1554-1

Kaiser, Michel J., Fiona E. Spence, and Paul J. B. Hart. 2000. "Fishing-Gear Restrictions and Conservation of Benthic Habitat Complexity." *Conservation Biology* 14 (5): 1512–25. https://doi.org/10.1046/j.1523-1739.2000.99264.x.

Kaiser, M. J., Clarke, K. R., Hinz, H., Austen, M. C. V., Somerfield, P. J., and Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. *Marine Ecology-Progress Series*, 311: 1–14.

Kamenos, N.A., Moore, G.P., Hall-Spencer, J.M. 2000. "Maerl grounds proide both refuge and high growth potential for juvenile queen scallops (*Aequipecten opercularis* L.)." *Journal of Experimental Marine Biology and Ecology* 313: 241–254. https://doi.org/10.1016/j.jembe.2004.08.007.

Kenny, Andrew J., Neil Campbell, Mariano Koen-Alonso, Pierre Pepin, and Daniela Diz. 2018. "Delivering Sustainable Fisheries through Adoption of a Risk-Based Framework as Part of an Ecosystem Approach to Fisheries Management." *Marine Policy* 93 (July): 232–40. https://doi.org/10.1016/j.marpol.2017.05.018.

Lubchenco, J., Palumbi, S., Gaines, S. D. & Andelman, S., 2003. Plugging a hole in the ocean: the emerging science of marine reserves. *Ecological Applications*, 13(1): S3–S7

Maher, E. & Alexander, D., 2016. Marine Rocky Habitat Ecological Groups and their Sensitivity to Pressures Associated with Human Activities, JNCC Report 589A.

Ministry for Primary Industries (2017). Aquatic Environment and Biodiversity Annual Review 2017. Compiled by the Fisheries Science Team, Ministry of Primary Industries, Wellington, New Zealand. 724pp.

MMO, 2017. UK Sea Fisheries Statistics 2016. London, National Statistics.

Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., and Mountain, D. G. 2005. Effort distribution and catch patterns adjacent to temperate MPAs. *International Council for the Exploration of the Sea,* Journal of Marine Science, 62: 1150e1167

Parry, M.E.V., Howell, K.L., Narayanaswamy, B.E., Bett, B.J., Jones, D.O.B., Hughes, D.J., Piechaud, N., Nickell, T.D., Ellwood, H., Askew, N., Jenkins, C. & Manca, E. 2015. A Deepsea Section for the Marine Habitat Classification of Britain and Ireland. JNCC Report No. 530 Joint Nature Conservation Committee, Peterborough.

Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde., E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., Sainsbury, K.J. 2004. Ecosystem-based fishery management. *Science* 305, 346-347.

Rijnsdorp, A.D., Eigaard, O.R., Kenny, A., Hiddink, J.G., Hamon, K., Piet, G., Sala, A., Nielsen, J.R., Polet, H., Laffargue, P., Zengin, M., Gregerson O. 2017. BENTHIS Final Report. Available at https://www.benthis.eu/en/benthis/Results.htm

Rivoirard J, Simmonds J, Foote KG, Fernandes P, Bez N, 2000. Geostatistics for estimating fish abundance. *Wiley-Blackwell* . 216 p.

Robert G,2002. Impact of multibeam survey on scallop fishing efficiency and stock assessment. In: ‘Bedford Institute of Oceanography 2001 in Review’ Canadian Offshore Scallop Industry Mapping Group, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, pp 40–41

Rose, C. S., Munk, E., Hammond, C. F., Stoner, A. 2010. Cooperative research to reduce the effects of Bering Sea flatfish trawling on seafloor habitat and crabs. AFSC Quaterly Report 1-6.

Rooper CN, Etnoyer PJ, Stierhoff KL, Olson JV. 2017. Effects of fishing gear on deep-sea corals and sponges in U.S. waters. In: Hourigan TF, Etnoyer PJ, Cairns SD, eds. The state of deep-sea coral and sponge ecosystems of the United States. NOAA Technical Memorandum NMFS-OHC-4. Silver Spring: NOAA

Russell, J. 2017. Analysis of nephrops industry in Scotland. Final report. Anderson Solutions (Consulting) Ltd. Pp.1-91.

Sala, A., Bastardie, F., De Carlo, F., Dinesen, G. E., Eigaard, O.R., Freekings, J.P., Frandsen, R.F., Jonsson, P., Krag, L.A., Laffarge, P., Magnusson, M.m Nielsen, J.R., Notti, E., Papadopoulo, N., Polet, H., Rijnsdorp, A.D, Sköld, M., Smith, C., van Marlen, B., Virgilli, M., Zengin, M. 2014. Report on options for mitigation fishing impacts in regional seas, Deliverable 7.7 BENTHIS project. 65p

Shephard, S., Goudey, C.A., Read, A., Kaiser, M.J., 2009. Hydrodredge: Reducing the negative impacts of scallop dredging. *Fisheries Research* 95 : 206-209. https://doi.org/10.1016/j.fishres.2008.08.021

Simpson, S. C., Eagleton, M. P., Olson, J. V., Harrington, G. A., and Kelly, S.R. 2017. Final Essential Fish Habitat (EFH) 5-year Review, Summary Report: 2010 through 2015. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-15, 115p

Stevens, G., Robert, J., Burke, L., Pouillioux, D., Roussel, D., Wilson, J., 2008. The evolution of management in Canada’s offshore scallop fishery. In: Townsend, R., Shotton, R., Uchida, H. (Eds.), Case Studies in Fisheries Self-Governance. FAO Fisheries Technical Paper No. 504, Rome, pp. 111-123.

Stewart, Bryce D., and Leigh M. Howarth. 2016. “Quantifying and Managing the Ecosystem Effects of Scallop Dredge Fisheries.” In *Developments in Aquaculture and Fisheries Science*, 40:585–609. Elsevier.

Sutter B, Hourigan TF, Lederhaus T, 2013. Integrating Habitat in Ecosystem-Based Fishery Management Proc Proceedings of Managing Our Nation’s Fisheries 3: Advancing Sustainability Conference May 6-9, 2013. Pacific Fishery Management Council.

Suuronen P., Chopin F., Glass C., Løkkeborg S., Matsushita Y., Queirolo D., Rihan D. 2012. Low impact and fuel efficient fishing-Looking beyond the horizon*. Fisheries Research* 119–120 :135-146. https://doi.org/10.1016/j.fishres.2011.12.009.

Tillin, H.M., S.C. Hull & H. Tyler-Walters, 2010. Development of a Sensitivity Matrix (pressures-MCZ/MPA features). Defra Contract No. MB0102 Task 3A, Report No. 22. http://jncc.defra.gov.uk/pdf/MB0102_Sensitivity_Assessment%5B1%5D.pdf

Tillin, H. & Tyler-Walters, H., 2014a. Assessing the sensitivity of subtidal sedimentary habitats to pressures associated with marine activities - Phase 1 Report, JNCC Report 512A. http://jncc.defra.gov.uk/page-6790

Tillin, H. & Tyler-Walters, H., 2014b. Assessing the sensitivity of subtidal sedimentary habitats to pressures associated with marine activities - Phase 2 Report, JNCC Report 512B. http://jncc.defra.gov.uk/page-6929

Trochta, John T., Maite Pons, Merrill B. Rudd, Melissa Krigbaum, Alexander Tanz, and Ray Hilborn. 2018. "Ecosystem-Based Fisheries Management: Perception on Definitions, Implementations, and Aspirations." *PloS One* 13 (1): e0190467

Valdemarsen, John Willy, Terje Jørgensen, and Arill Engås. 2007. Options to Mitigate Bottom Habitat Impact of Dragged Gears. *Food and Agriculture Organization*.

Vaughan, D., 2017. Fishing effort displacement and the consequences of implementing Marine Protected Area management- An English perspective. *Marine Policy* 84: 228-234.

Willis, T. J., Millar, R. B., Babcock, R. C., and Tolimieri, N. 2003. Burdens of evidence and the benefits of marine reserves: putting Descartes before des horse? *Environmental Conservation*, 30: 97e103.

Woillez, M., Rivoirard, J., and Fernandes, P.G. 2009. Evaluating the uncertainty of abundance estimates from acoustic surveys using geostatistical simulations. *International Council for the Exploration of the Sea,* Journal of Marine Science 66, 1377–1383.

Annex A

Biological zone	Substrate type							
	Rock / Reef			Coarse sediment	Sand	Muddy sand OR Sandy mud	Mud	Mixed sediment
	Energy class							
	High	Moderate	Low					
Infralittoral	A3.1 Atlantic and Mediterranean high energy infralittoral rock	A3.2 Atlantic and Mediterranean moderate energy infralittoral rock	A3.3 Atlantic and Mediterranean low energy infralittoral rock	A5.13 Infralittoral coarse sediment	A5.23 Infralittoral fine sand OR A5.24 Infralittoral muddy sand	A5.33 Infralittoral sandy mud	A5.34 infralittoral fine mud	A5.43 Infralittoral mixed sediments
Shallow circalittoral	A4.1 Atlantic and Mediterranean high energy circalittoral rock	A4.2 Atlantic and Mediterranean moderate energy circalittoral rock	A4.3 Atlantic and Mediterranean low energy circalittoral rock	A5.14 Circalittoral coarse sediment	A5.25 Circalittoral fine sand OR A5.26 Circalittoral fine sand	A5.35 Circalittoral sandy mud	A5.36 Circalittoral fine mud	A5.44 Circalittoral mixed sediments
Deep circalittoral	A4.12 Sponge communities on deep circalittoral rock	A4.27 Faunal communities on deep moderate energy circalittoral rock	A4.33 Faunal communities on deep low energy circalittoral rock	A5.15 Deep circalittoral coarse sediment	A5.27 Deep circalittoral sand	A5.37 Deep circalittoral mud	A5.37 Deep circalittoral fine mud	A5.45 Deep-circalittoral mixed sediments
Deep sea	A6.1 Deep-sea rock and artificial hard substrata	A6.1 Deep-sea rock and artificial hard substrata	A6.1 Deep-sea rock and artificial hard substrata		A6.3 Deep-sea sand OR A6.4 Deep-sea muddy sand	A6.5 Deep-sea mud	A6.5 Deep-sea mud	A6.3 Deep-sea mixed substrata

Table 1. EUNIS habitat types in Atlantic and Arctic seas at Level 3 and 4 which can be identified from the ecological unit categories seabed substrate, biological zone and, for rock substrate, energy class. Grey cells are for those combinations that do not have a EUNIS habitat equivalent.

Biological zone		Substrate type					
Name	Applicable regions	Rock	Coarse sediment	Sand	Muddy sand OR Sandy mud	Mud	Mixed sediment
Atlantic Upper Bathyal	All	Atlantic upper bathyal rock or reef	Atlantic upper bathyal coarse sediment	Atlantic upper bathyal sand or muddy sand	Atlantic upper bathyal sandy mud	Atlantic upper bathyal mud	Atlantic upper bathyal mixed sediment
Atlantic Mid Bathyal	GNCS, IBM	Atlantic mid bathyal rock or reef	Atlantic mid bathyal coarse sediment	Atlantic mid bathyal sand or muddy sand	Atlantic mid bathyal sandy mud	Atlantic mid bathyal mud	Atlantic mid bathyal mixed sediment
Atlanto-Mediterranean Mid Bathyal	IBM	Atlanto-Mediterranean mid bathyal rock or reef	Atlanto-Mediterranean mid bathyal coarse sediment	Atlanto-Mediterranean mid bathyal sand or muddy sand	Atlanto-Mediterranean mid bathyal sandy mud	Atlanto-Mediterranean mid bathyal mud	Atlanto-Mediterranean mid bathyal mixed sediment
Atlantic Lower Bathyal	GNCS, IBM	Atlantic lower bathyal rock or reef	Atlantic lower bathyal coarse sediment	Atlantic lower bathyal sand or muddy sand	Atlantic lower bathyal sandy mud	Atlantic lower bathyal mud	Atlantic lower bathyal mixed sediment
Atlantic Upper Abyssal	GNCS, IBM	Atlantic upper abyssal rock or reef	Atlantic upper abyssal coarse sediment	Atlantic upper abyssal sand or muddy sand	Atlantic upper abyssal sandy mud	Atlantic upper abyssal mud	Atlantic upper abyssal mixed sediment
Atlantic Mid Abyssal	GNCS, IBM	Atlantic mid abyssal rock or reef	Atlantic mid abyssal coarse sediment	Atlantic mid abyssal sand or muddy sand	Atlantic mid abyssal sandy mud	Atlantic mid abyssal mud	Atlantic mid abyssal mixed sediment
Atlantic Lower Abyssal	GNCS, IBM	Atlantic lower abyssal rock or reef	Atlantic lower abyssal coarse sediment	Atlantic lower abyssal sand or muddy sand	Atlantic lower abyssal sandy mud	Atlantic lower abyssal mud	Atlantic lower abyssal mixed sediment
Atlanto-Arctic Upper Bathyal	GNCS, Arctic	Atlanto-Arctic upper bathyal rock or reef	Atlanto-Arctic upper bathyal coarse sediment	Atlanto-Arctic upper bathyal sand or muddy sand	Atlanto-Arctic upper bathyal sandy mud	Atlanto-Arctic upper bathyal mud	Atlanto-Arctic upper bathyal mixed sediment
Arctic Mid Bathyal	GNCS, Arctic	Arctic mid bathyal rock or reef	Arctic mid bathyal coarse sediment	Arctic mid bathyal sand or muddy sand	Arctic mid bathyal sandy mud	Arctic mid bathyal mud	Arctic mid bathyal mixed sediment
Arctic Lower Bathyal	GNCS, Arctic	Arctic lower bathyal rock or reef	Arctic lower bathyal coarse sediment	Arctic lower bathyal sand or muddy sand	Arctic lower bathyal sandy mud	Arctic lower bathyal mud	Arctic lower bathyal mixed sediment
Arctic Upper Abyssal	Arctic	Arctic upper abyssal rock or reef	Arctic upper abyssal coarse sediment	Arctic upper abyssal sand or muddy sand	Arctic upper abyssal sandy mud	Arctic upper abyssal mud	Arctic upper abyssal mixed sediment

Table 2. Non-EUNIS classes used to add further discrimination to the deep sea zone in Atlantic and Arctic seas.

Annex B

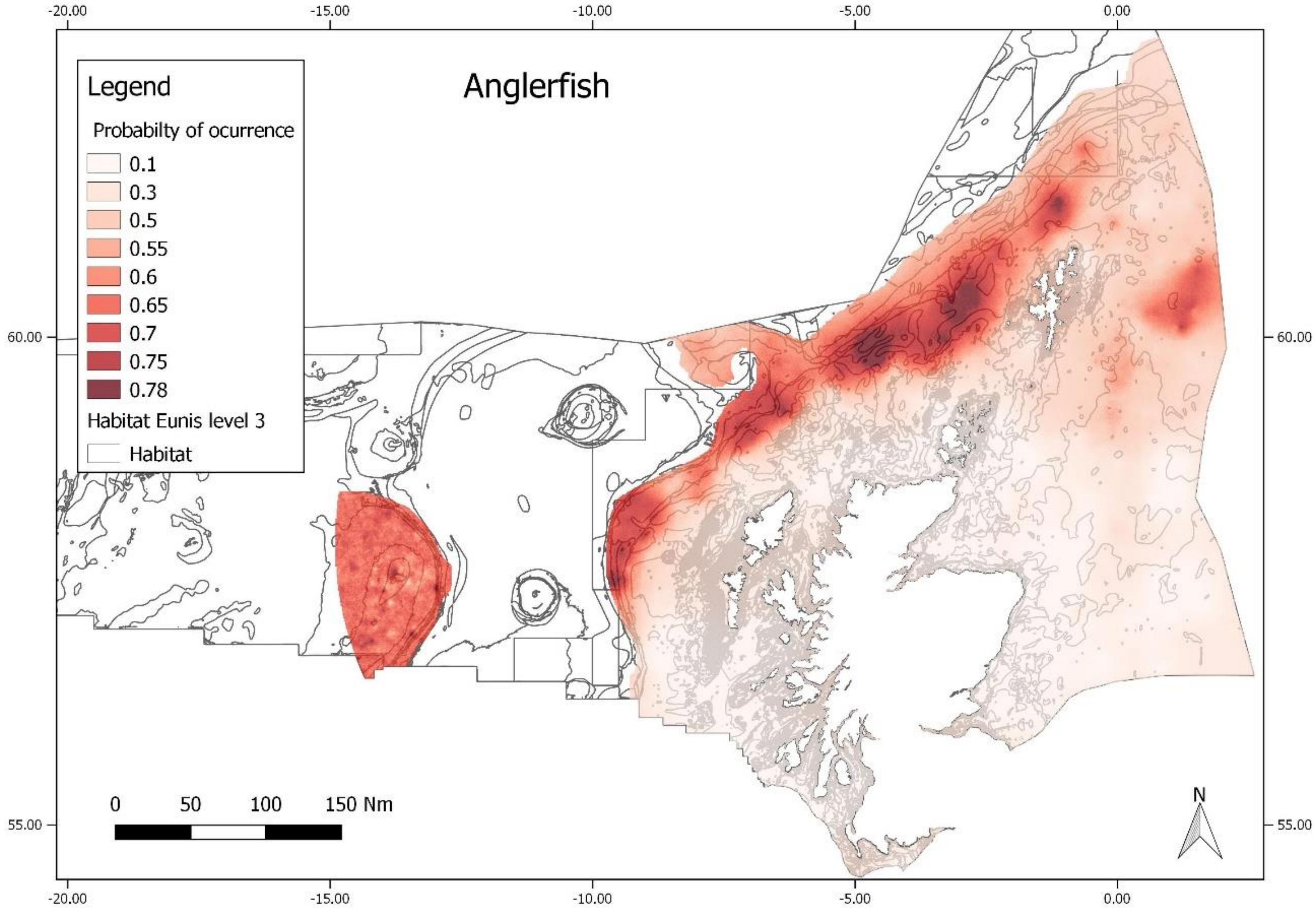

Figure 1. Probability of occurrence of anglerfish in Scottish waters.

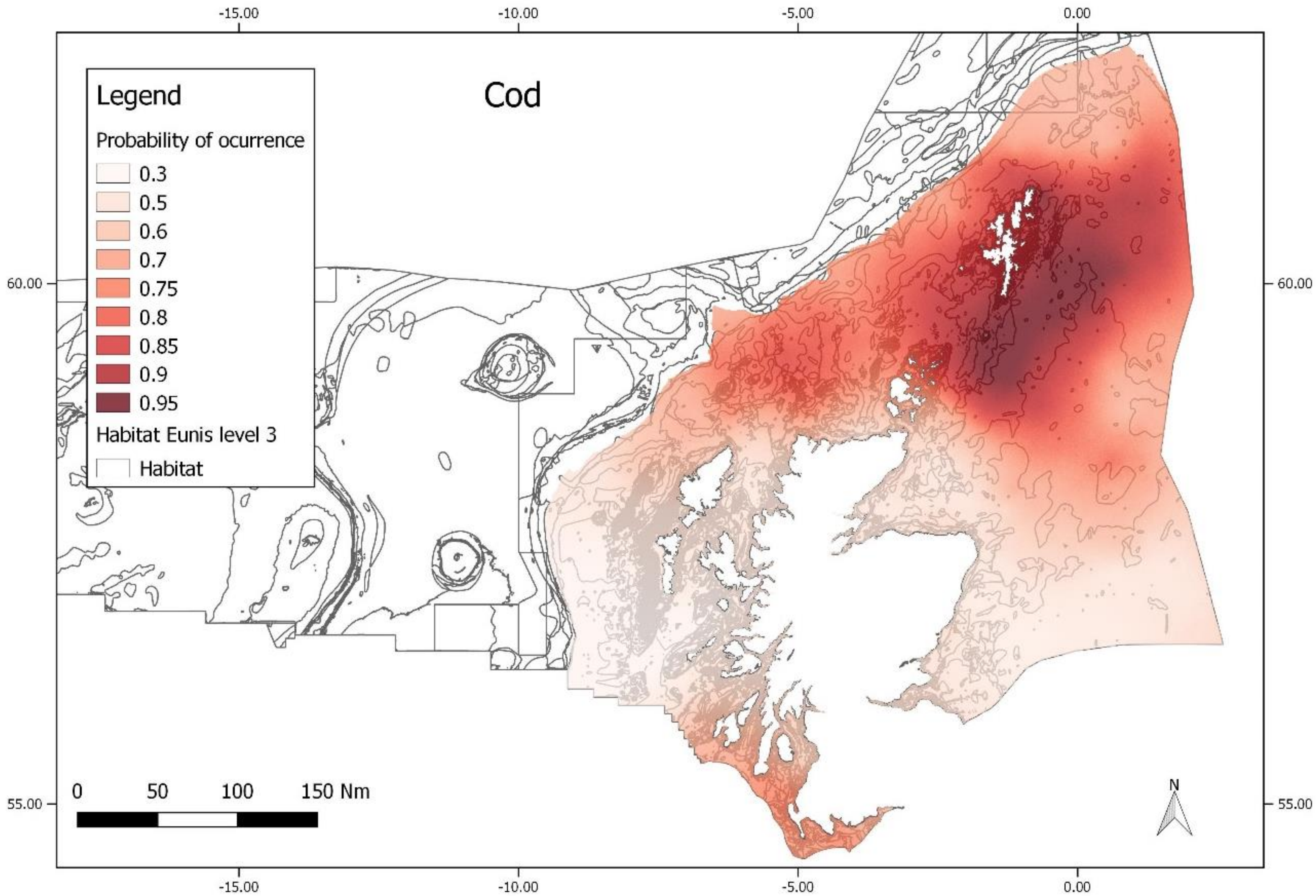

Figure 2. Probability of occurrence of cod in Scottish waters.

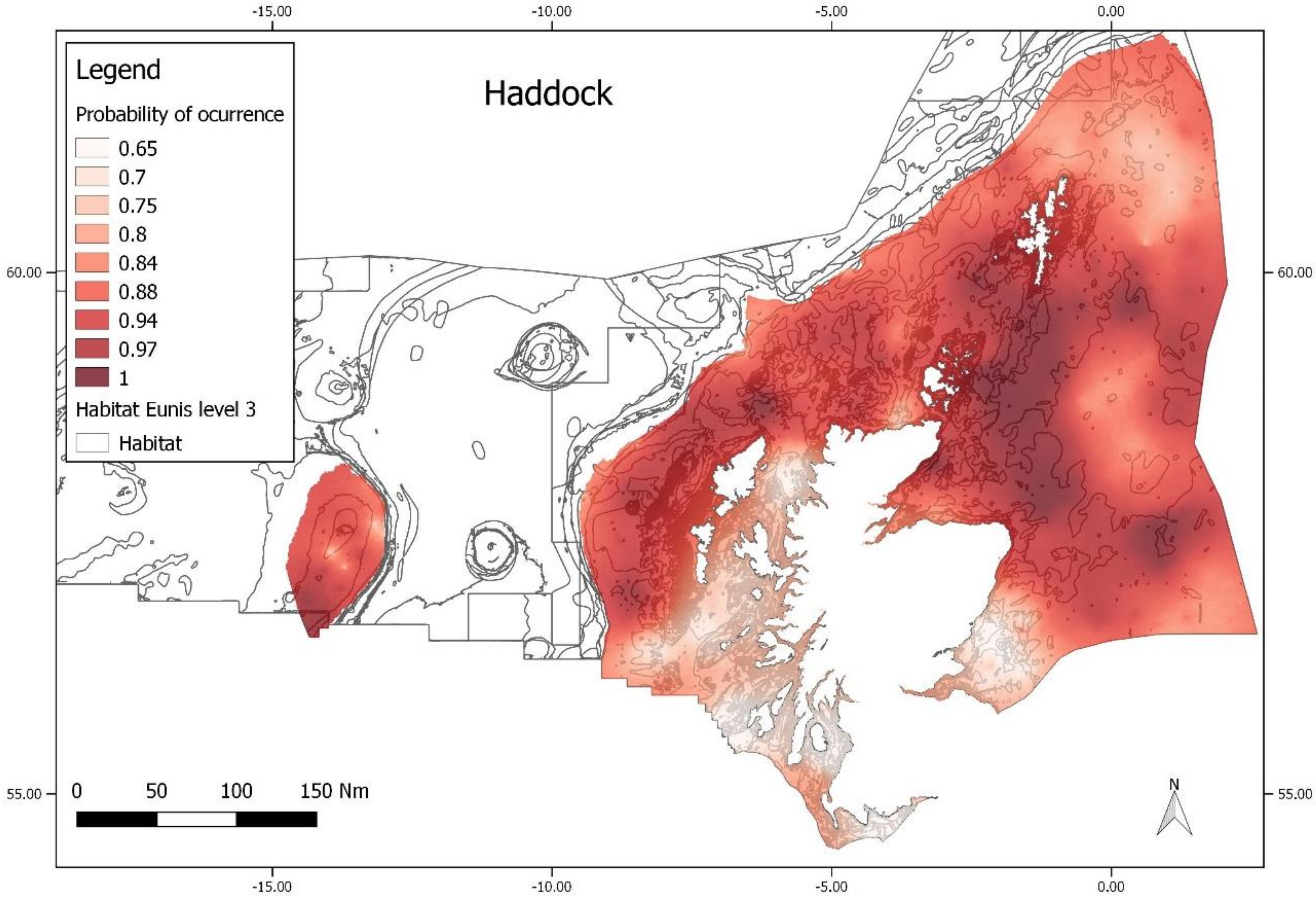

Figure 3. Probability of occurrence of haddock in Scottish waters.

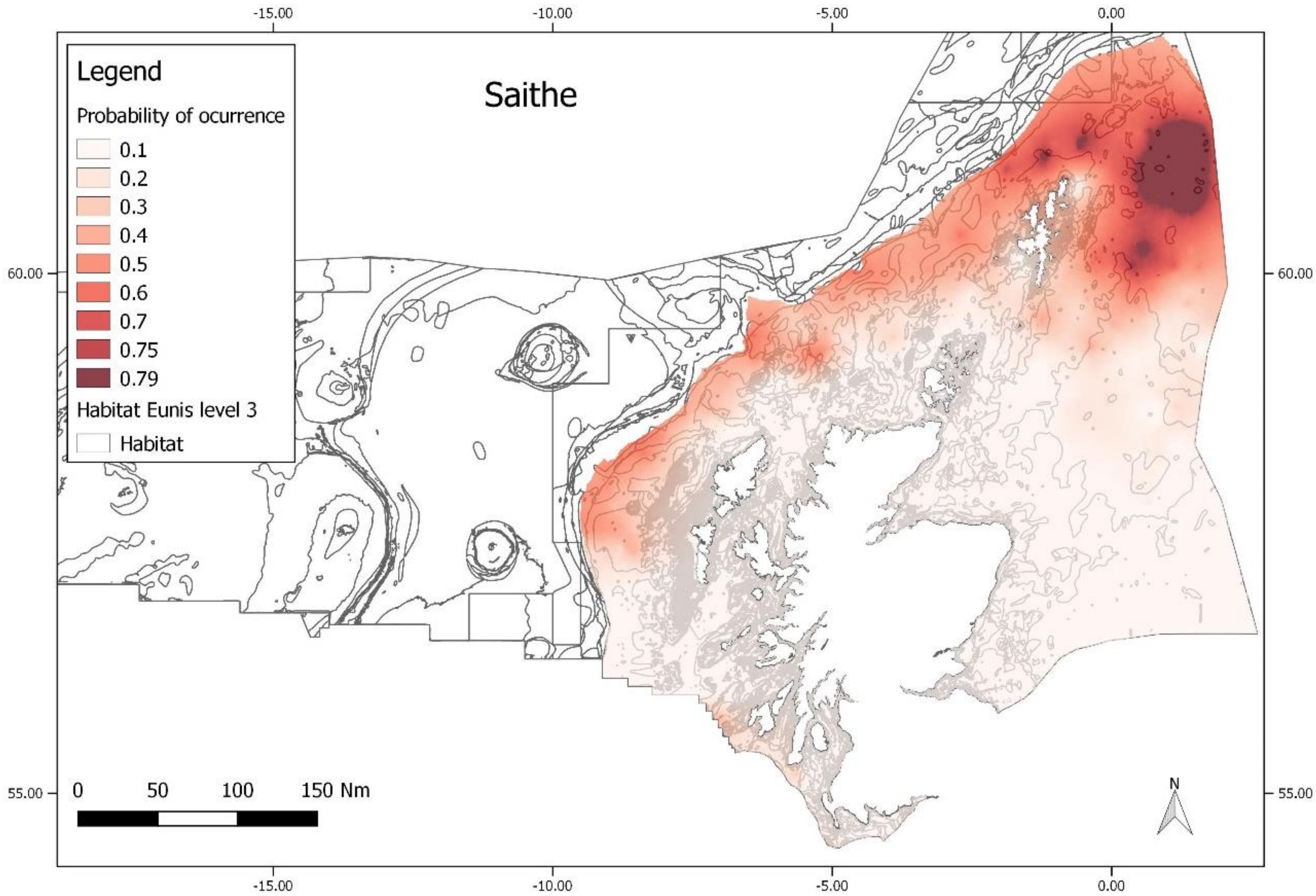
Saithe
Legend
Probability of ocurrence
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.75
0.79
Habitat Eunis level 3
Habitat
0 50 100 150 Nm
N
-15.00
-10.00
-5.00
0.00
60.00
55.00

Figure 4. Probability of occurrence of saithe in Scottish waters.

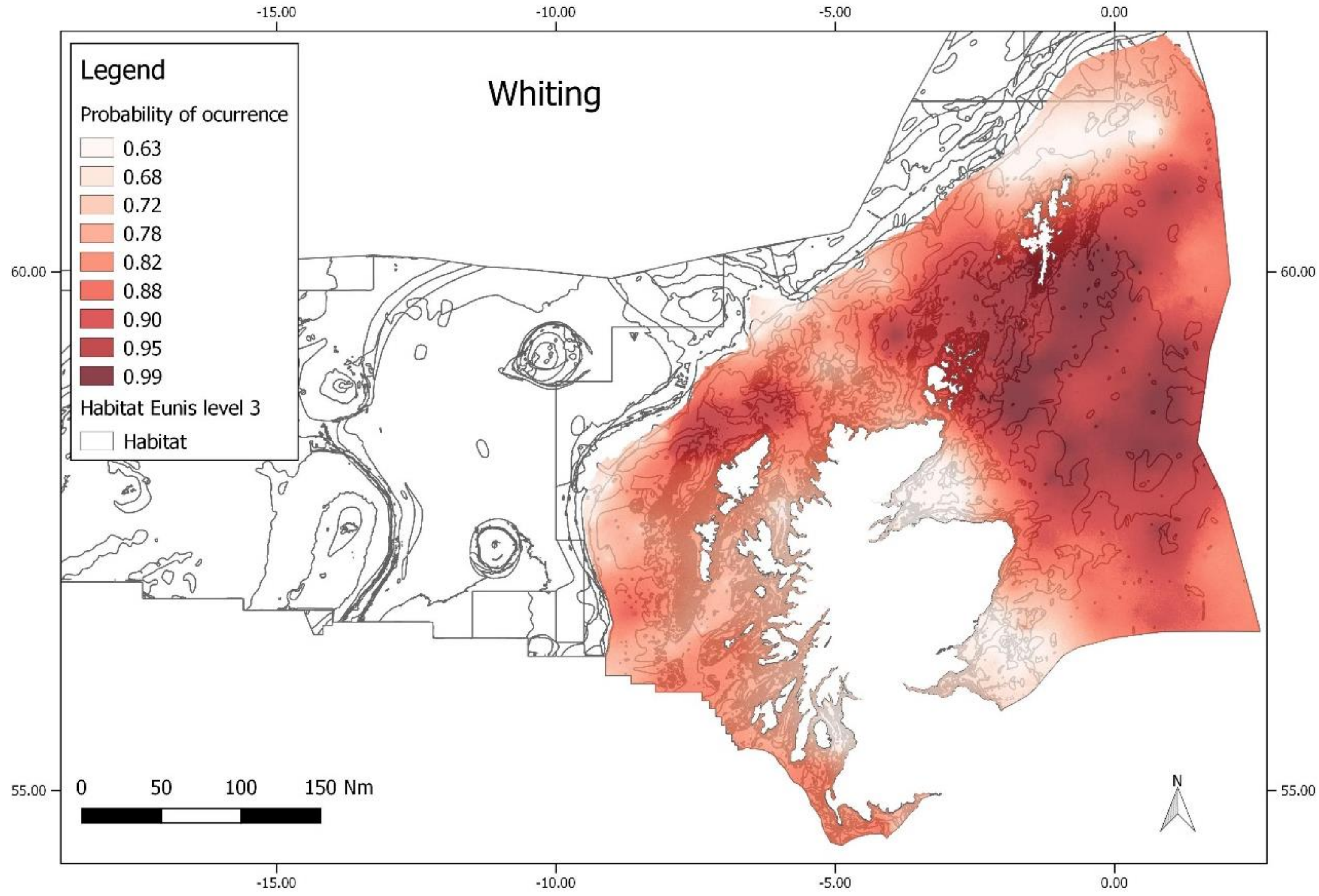

Figure 5. Probability of occurrence of whiting in Scottish waters.

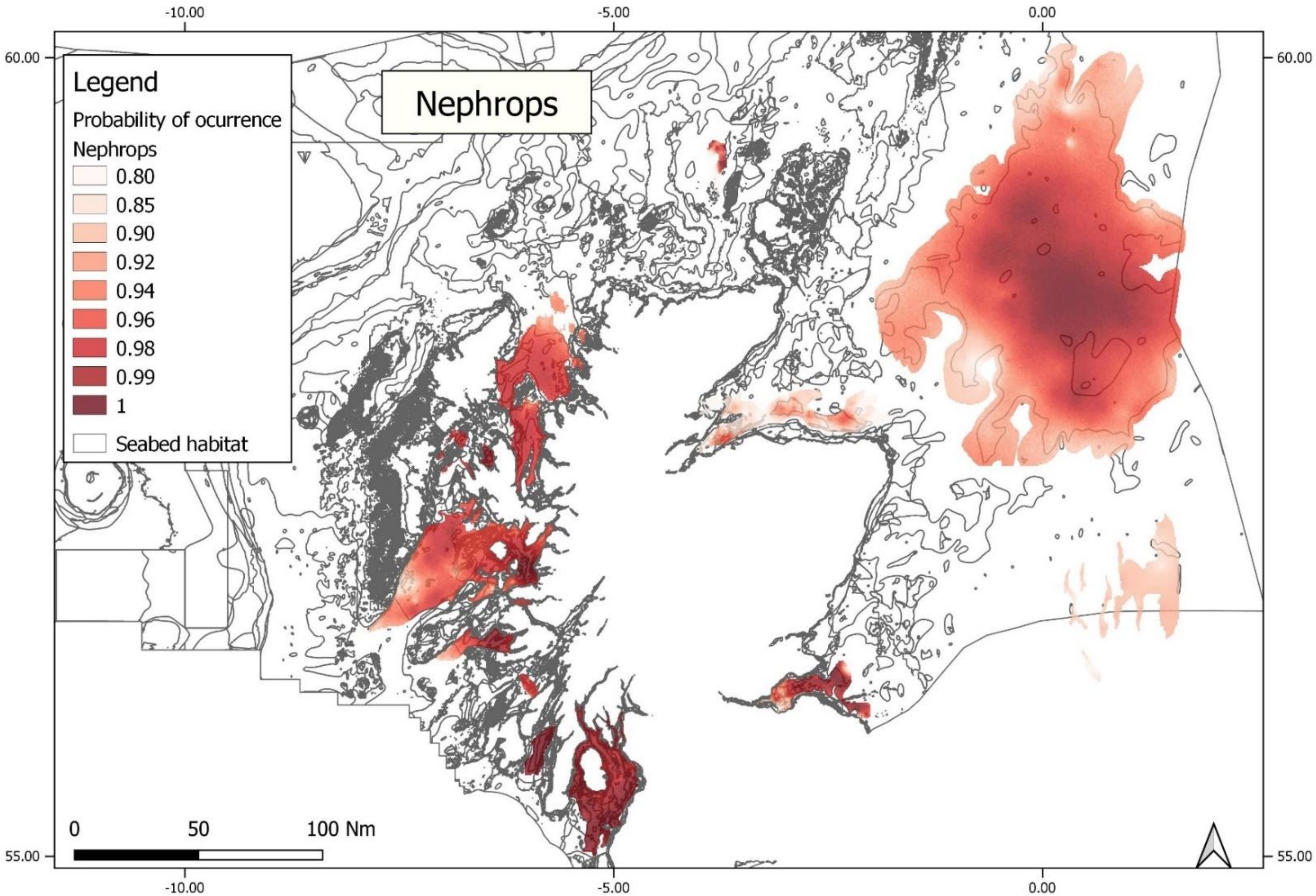

Figure 7. Probability of occurrence of *Nephrops* in Scottish waters.

Table 1. Quantity of VMS data removed in data cleaning and merging process

2015 VMS data cleaning		
	Number of pings	Percentage remaining
Total VMS pings	1877864	100
North of 54	1221215	65.03
Removed impossible values	1221177	65.03
Removed duplicates	1207558	64.3
Removed pseudoduplicates	1141722	60.8
Pings not harbour	1041953	55.49
Pings not on land	1031695	54.94
Merged to logbook	750862	39.98

Table 2. Quantity of logbooks removed during data cleaning and merging process.

2015 logbook data cleaning		
	Number of logbooks	Percentage remaining
total	307231	100
Scottish waters	127898	41.63
Not duplicated	127897	41.63
Not impossible time	127897	41.63
Not before 1st Jan	127876	41.62
Arrival/departure times possible	127863	41.62
Relevant species	86255	28.07
Relevant gears	71263	23.2
Merged with VMS	56827	18.5

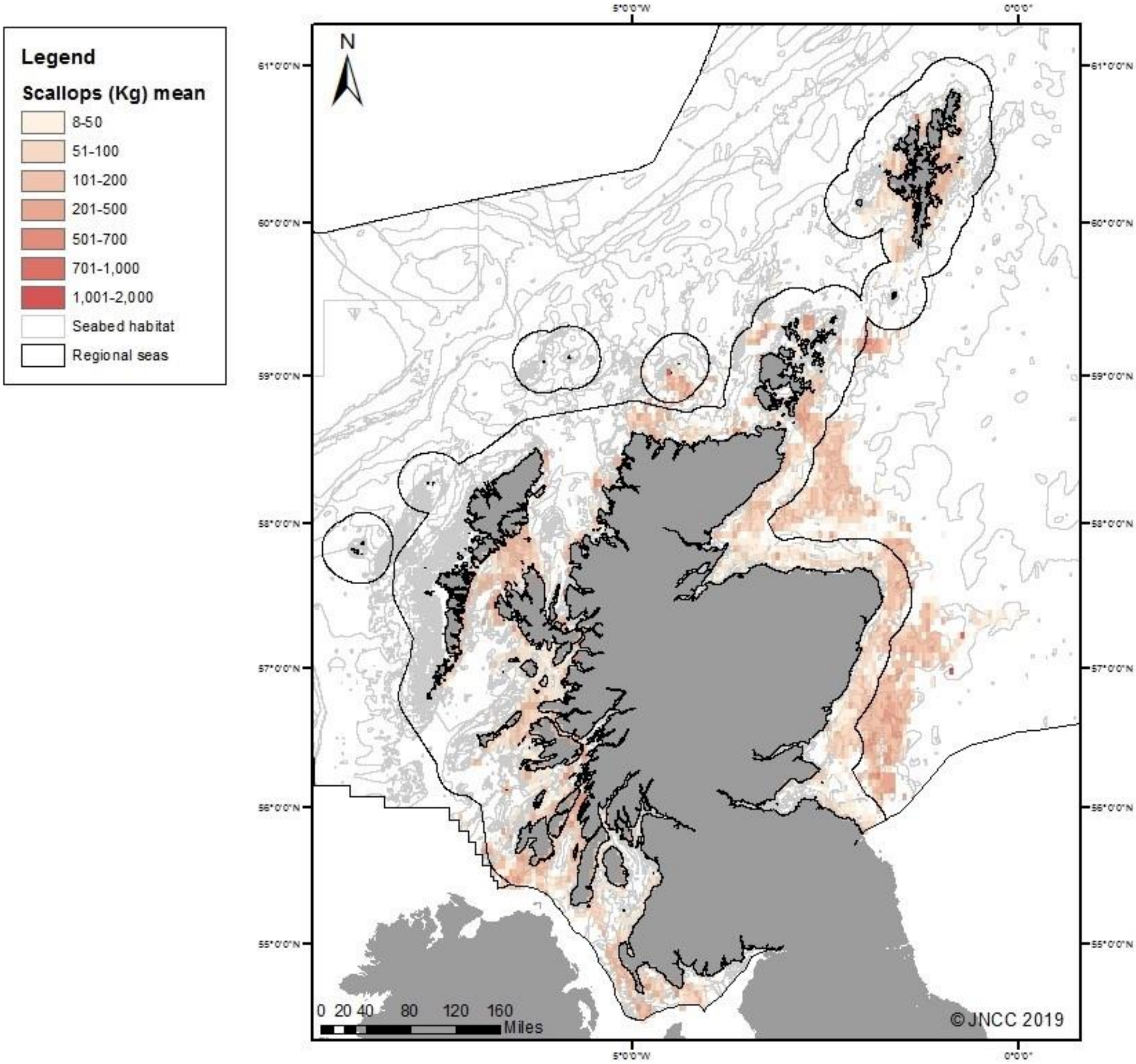

Figure 8. Scallops landings distribution from VMS and logbook data for the year 2015.

Fisheries Innovation Scotland

Scottish Charity Number SC045119

Company Number SC477579

FIS MEMBER ORGANISATIONS

Heriot Watt University

marine scotland

The Scottish Government
Riaghaltas na h-Alba

SFF Services Limited

Scottish Natural Heritage
Dualchas Nàdair na h-Alba
nature.scot

seafish

Young's Seafood Limited

Sainsbury's

Funding Fish

M&S
EST. 1884