SUPPLEMENTARY INFORMATION

Essential Spawning Grounds of Scottish Herring: Current Knowledge and Future Challenges

Reviews in Fish Biology and Fisheries

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Literature Review

A systematic literature review and examination of grey literature was undertaken from November 2020 to January 2021, searching information on herring spawning grounds in Scottish waters, as well as in the North Atlantic. The systematic searches were performed in Web of Science (Advanced Search, All Databases, All languages, Timespan – All years; 1900 – 2020) using the search terms defined in Table S1. In some searches, the terms "Pacific" and "gull" were excluded to eliminate literature not specific to Atlantic herring. Initially, The Web of Science search resulted in 922 hits (after removal of duplicates). Scanning these individually for potential relevance yielded 131 publications. These were scanned more thoroughly for environmental or temporal data on spawning, or for maps of spawning grounds/point locations of spawning herring. This in turn resulted in a final number of 30 papers relevant for this publication. Thirteen of these related to Scottish waters, the remaining 17 to the North Atlantic (United Kingdom and Ireland, Norway, Iceland, Baltic). In addition, Google Scholar and Mendeley were also searched using the defined terms (Table S2), yielding 19 further hits.

We additionally considered information from 'grey literature' to ensure all documents on herring spawning habitat in the Northeast Atlantic were included in this publication. The grey literature consisted mostly of government, industry, and scientific (ICES) reports, as well as of first-hand fisher accounts of the locations of spawning grounds (English 2000; Neervoort 2013). While this grey literature has not undergone the rigour of scientific peer-review, it nevertheless supplied valuable information not available elsewhere. The fact that different sources of grey literature often present similar results and/or observations suggests that the information is trustable and justified inclusion. Due to the volume of government reports (thousands of pages), we automated the search process by indexing the reports into an Elasticsearch database (https://www.elastic.co/elasticsearch/) and used the search criteria set out in Table S2 to return any candidate paragraphs containing the predefined terms (Frost et

al., in preparation). Scanned grey literature included: Annual Reports of the Fishery Board for Scotland (1883-1938): n = 55; Fisheries of Scotland Reports (1939-1980): n = 32; ICES historic documents (hundreds maintained in ICES SharePoint): n = 29 (relevant); Marine Scotland Science library & online catalogue: n = 88; historic books/publications from contacts: n = 12; theses: n = 2; and other dedicated government/industry survey reports: n = 22. Finally, the reference lists of all peer-reviewed and grey literature were searched for publications of relevance, resulting in 10 additional hits.

Maps of herring spawning grounds (see Table S2 for full list) were scanned and georeferenced by aligning the spatial data to a geographic grid. Spawning bed/ground/area polygons and/or point data were redrawn from georeferenced maps to a new layer in Esri ArcGIS (ArcMap 10.8.1), also including information on the method used to determine the spawning bed/ground/area, date, season, and substrate (when given). Additional data included maerl bed observations, retrieved from the Geodatabase of Marine features adjacent to Scotland (GeMS V9 i25) and available at https://www.spatialdata.gov.scot, as well as seabed substrate derived from data made available under the European Marine Observation Data Network (EMODnet) Seabed Habitats initiative and available at http://www.emodnet-seabedhabitats.eu/.

Table S1. Key terms in herring literature, as well as herring (*Clupea harengus*) stock definitions mentioned in the text.

Term	Definition
Spawning bed	Discrete patches of seabed where herring eggs are deposited (O'Sullivan et al. 2013).
Spawning ground	Geographic location of one or more spawning beds with the adjacent suitable spawning habitat or bottom substrate (O'Sullivan et al. 2013).
Ripe herring	Fish with roe ready to be laid; maturity stage IV.
Running herring	Fish in the process of releasing roe or milt (males); maturity stage IV
Pre-spawning herring	In the months prior to spawning, herring shoals that finished feeding congregate in conditions similar to those they will spawn in (Maravelias et al. 2000).
Spawny haddock	Haddock (*Melanogrammus aeglefinus*) that have recently fed on the spawn of herring; historically, this was used to identify herring spawning grounds.
West of Scotland (WoS)	Currently an autumn-spawning herring stock that spawns off Cape Wrath, in the NW of Scotland, in ICES Area VIaN and is separated from the North Sea autumn-spawning stock by the 4° west line of longitude (ICES 2014). *The spring-spawning WoS stock is not presently assessed by ICES due to the collapse of the fishery and supposed loss of the spawning component.*
North Sea autumn-spawning stock (NSAS)	Autumn-spawning herring stock that spawns in the North Sea to the east of the 4° west line of longitude in ICES Subarea 4 (Orkney/Shetland, Buchan, and Banks) and Divisions 3.a (Baltic and Skagerrak) and 7.d. (winter-spawning Downs).
Clyde herring stock	Spring-spawning stock that spawns in the Firth of Clyde with separate management from the WoS stock. No spawning or catches have been reported since 2014 (ICES 2019). Autumn-spawning herring were historically sometimes encountered in small numbers in the Clyde (Scottish Home Department 1967).
Norwegian spring-spawning stock (NSS)	Spring-spawning herring stock that spawns in ICES Subareas I, II, and VI, and divisions IV.a and XIV.a.
Western Baltic spring-spawning stock	Subspecies of herring (*Clupea harengus membras*) mostly spawning in ICES subdivisions 20-24 and the eastern part of Subarea IV (Skagerrak, Kattegat, and western Baltic); spawns in shallow, often brackish, waters on vegetation.
Spawning Stock Biomass (SSB)	The total weight of all individuals in a fish stock that have reached sexual maturity and are capable of reproducing; or the biomass of all fish beyond the age or size class in which 50% of the individuals are mature. SSB is often used instead of measuring egg production.
Atlantic Multi-decadal Oscillation (AMO)	An index of long-term sea surface temperatures in the North Atlantic, with an estimated period of 60-80 years; often used to describe multi-decade climate variability in the North Atlantic.

Table S2. Full list of search terms used in the Web of Science systematic literature search. The first search term was the same in all subsequent searches. Literature searches were conducted November 2020 to January 2021.

Term 1	Term 2	Term 3	Term 4
herring OR "Clupea harengus" OR "C. harengus"	spawn*	ground*	NOT Pacific
As above	spawn*	bed*	
As above	spawn*	Scotland	
As above	spawn*	Minch	
As above	spawn*	field	NOT Pacific
As above	spawn*	substrat*	
As above	spawn*	environment*	NOT Pacific
As above	spawn*	habitat	
As above	spawn*	ecolog*	
As above	spawn*	distribution	NOT Pacific
As above	spawn*	anthropogenic	
As above	spawn*	location	NOT Pacific
As above	spawn*	area	NOT Pacific
As above	spawn*	deposition*	
As above	spawn*	benth*	
As above	spawn*	demersal	
As above	spawn*	site	NOT Pacific
As above	egg	Scotland	NOT gull
As above	egg	Atlantic	NOT gull
As above	egg	Norway	
As above	larva*	Scotland	
As above	"west coast"	Scotland	
As above	maerl		
As above	gravel		
As above	seabed*		
As above	haddock	spawn*	
As above	haddock		
As above	cod		
As above	spawn*	whale	NOT Pacific
As above	spawn*	porpoise	NOT Pacific
As above	spawn*	seal	NOT Pacific

Table S3. Summary information on maps used to redraw historic herring spawning ground distribution, including geographic locations in the original maps, the decade the original mapped data was from, method(s) used in the original publication to delineate spawning grounds, substrate type at the spawning grounds (if given), and the reference containing the map.

Geographic Location	Decade	Method(s)	Substrate type	Reference
North Sea	1890	Fisheries	Not given	Fulton 1890
North Sea, Minch & Outer Hebrides	1920/1970	Spawny haddock & fisheries	Gravel	Rankine 1986*
North Sea & North Minch	1930	Fisheries	Not given	Wood 1930
Firth of Clyde	1930	Eggs	Small boulders, pebbles & *Laminaria* sp.	Marshall et al. 1937
Firth of Clyde	1950	Eggs	Gravel & small stones	Parrish et al. 1959
North Sea, Outer Hebrides & NW Atlantic	1950	Fisheries	Not given	Anonymous 1977
Minch & Outer Hebrides	1950	Fisheries	Not given	Baxter 1958
North Sea, Minch, Hebrides, NW Atlantic, Irish Sea, Celtic Sea & Channel	1950	Fisheries	Not given	Hodgson 1951**
NW Atlantic & Hebrides	1960	Larvae	Not given	Wood 1971
NW Atlantic, Minch & Hebrides	1970	Fisheries	Not given	Saville and Bailey 1980
North Sea	1980	Larvae	Not given	Corten 1988
North Sea, North Minch, Hebrides, NW Atlantic, Celtic Sea & Irish Sea	1980	Larvae	Not given	Bartsch et al. 1989
Minch, NW Atlantic, North Sea, Hebrides, Celtic Sea & Irish Sea	1990	Eggs, larvae & fisheries	Not given	ICES 1994
Firth of Clyde	1990	Eggs	Not given	Hopkins and Morrison 1991
North Sea, Minch, Hebrides, NW Atlantic, Irish Sea, Celtic Sea & Channel	1990	Larvae	Not given	Coull et al. 1998
North Sea	2010	Not specified	Not given	Corten 2013
NW Atlantic & Celtic Sea	2010	Larvae & fisheries	Gravel/broken rock	O'Sullivan et al. 2013

*Mapped spawny haddock polygons from the 1920s and catch point data of spawning herring from the 1970s. **Four different maps from this publication were redrawn, including maps for the months of February, March, September, and October when herring were spawning.

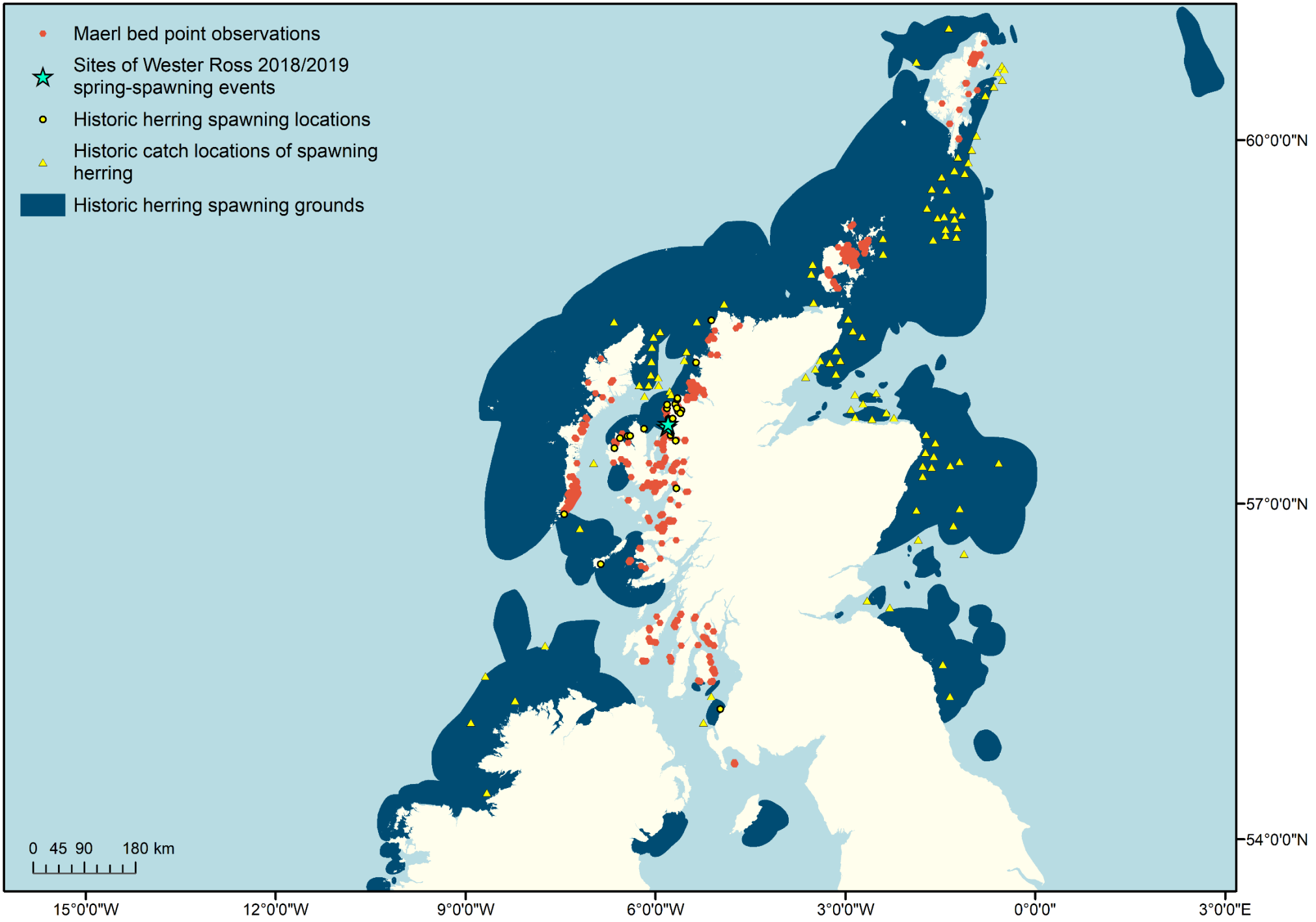
Maerl bed point observations
Sites of Wester Ross 2018/2019 spring-spawning events
Historic herring spawning locations
Historic catch locations of spawning herring
Historic herring spawning grounds
0 45 90 180 km
60°0'0"N
57°0'0"N
54°0'0"N
15°0'0"W
12°0'0"W
9°0'0"W
6°0'0"W
3°0'0"W
0°0'0"
3°0'0"E

Figure S1. Extrapolated herring reproductive grounds (e.g., spawning grounds and larval occurrences) with maerl bed point observations, based on the literature reviewed and local stakeholder interviews. Point locations of herring spawning events were derived from in situ filming in 2018/2019 by scallop divers and the BBC Blue Planet UK off the coast of Wester Ross, from historic catch locations of ripe or running herring (see Table S1 for definition of terms) reported first-hand by fishers, and from historic records with original mapped sources on herring reproduction. Known recorded distribution of maerl beds contributing to the 'Geodatabase of Marine features adjacent to Scotland' (GeMS V9 i25) collation of Scottish Priority Marine Features (PMF) is also included (https://www.spatialdata.gov.scot). Scottish PMF records included are consented for re-use under terms associated with either an Open Government Licence (http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/) or various Creative Commons licences (https://creativecommons.org/licenses/).

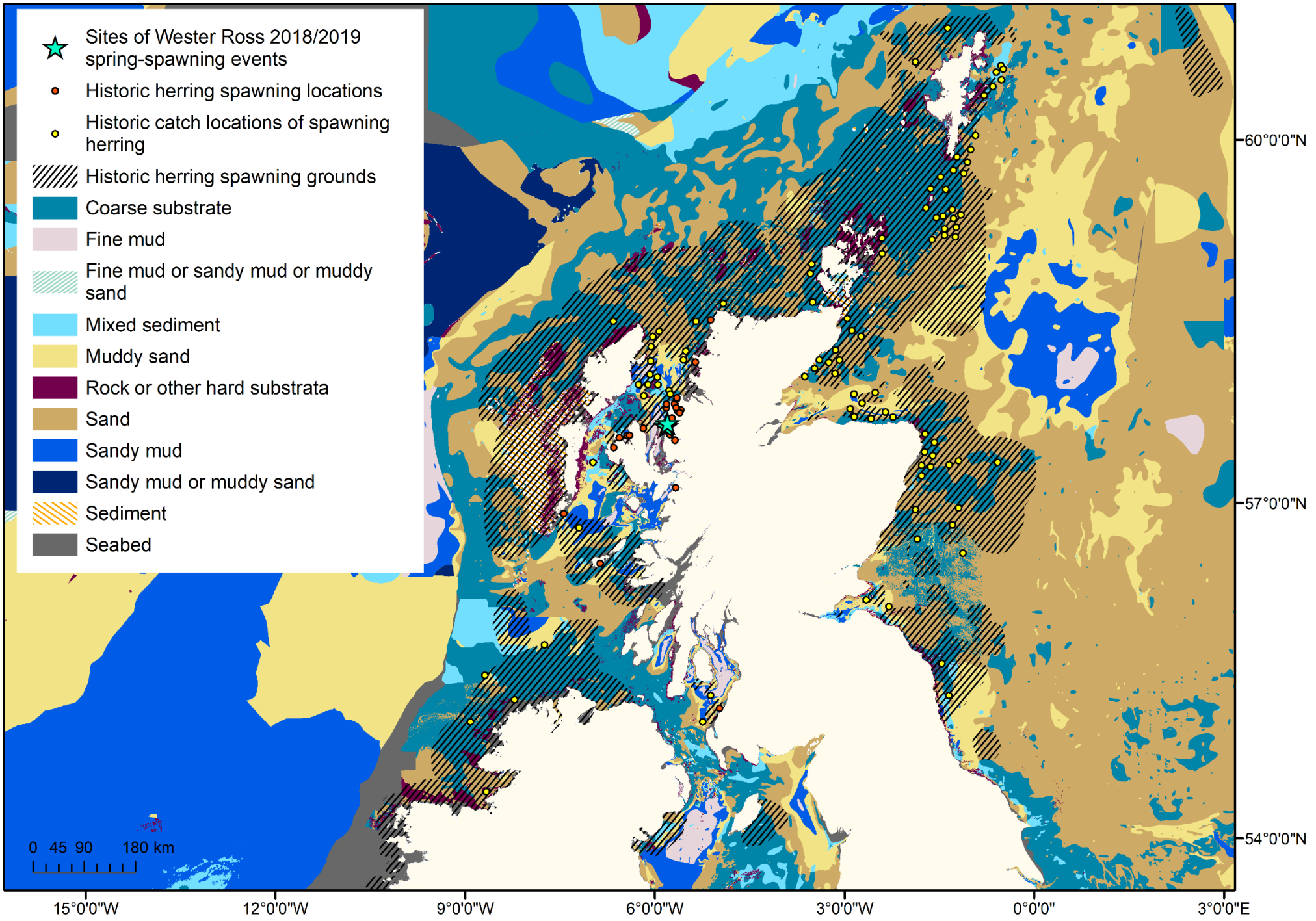
Sites of Wester Ross 2018/2019 spring-spawning events
Historic herring spawning locations
Historic catch locations of spawning herring
Historic herring spawning grounds
Coarse substrate
Fine mud
Fine mud or sandy mud or muddy sand
Mixed sediment
Muddy sand
Rock or other hard substrata
Sand
Sandy mud
Sandy mud or muddy sand
Sediment
Seabed
0 45 90 180 km
60°0'0"N
57°0'0"N
54°0'0"N
15°0'0"W
12°0'0"W
9°0'0"W
6°0'0"W
3°0'0"W
0°0'0"
3°0'0"E

Figure S2. Extrapolated herring reproductive grounds (e.g., spawning grounds and larval occurrences) with maerl bed point observations, based on the literature reviewed and local stakeholder interviews. Point locations of herring spawning events were derived from in situ filming in 2018/2019 by scallop divers and the BBC Blue Planet UK off the coast of Wester Ross, from historic catch locations of ripe or running herring reported first-hand by fishers/men and from historic records with original mapped sources on herring reproduction. Seabed substrate information contained here has been derived from data that is made available under the European Marine Observation Data Network (EMODnet) Seabed Habitats initiative (http://www.emodnet-seabedhabitats.eu/), financed by the European Union under Regulation (EU) No 508/2014 of the European Parliament and of the Council of 15 May 2014 on the European Maritime and Fisheries Fund.

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