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PRIMARY RESEARCH PAPER

# Restoring degraded European native oyster, *Ostrea edulis*, habitat: is there a case for harrowing?

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**Abstract** Habitat degradation is a contributory factor to poor recruitment and sustainability of the European native oyster, *Ostrea edulis*. Bed cleaning (harrowing) is a widely referenced but little studied habitat management measure aimed at exposing clean shell for oyster larvae to settle upon. This study carried out a large-scale field experiment in Lough Foyle on the border of Northern Ireland and Ireland over 3 years aimed at investigating the effects of harrowing on oyster spat settlement, substratum condition, suspended particulate matter and associated faunal assemblage. The results demonstrated that *O. edulis* spat settlement was higher in unharrowed areas and there was no significant difference in bivalve settlement between the two treatments. Harrowing had no significant effect on percentage cover of fouling organisms, but there was a significant difference between assemblages in harrowed and unharrowed treatments. This study concluded that harrowing is not suitable for all oyster production areas and should only be employed with caution.

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## Introduction

Habitat degradation and loss have been put forward as a contributory factor to the decline of native stocks of *Ostrea edulis* throughout European waters (Korringa, 1946; Kennedy & Roberts, 1999; OSPAR, 2011). Historically, according to Cole & Knight-Jones (1939), the importance of a lack of suitable surfaces for settlement contributing to poor recruitment was often underestimated.

In species such as *O. edulis* with planktonic dispersal stages, suitable substratum is a key habitat feature that influences settlement and recruitment (Caddy & Stamatopolous, 1990). Oyster larvae will only settle and metamorphose where there is suitable hard substratum (Waugh, 1972; Walne, 1974; Brown et al., 2010). Although a large volume of research has been published regarding the settlement preferences of native oyster larvae, much of this was carried out in laboratories and tanks and the selectivity of larvae in their natural environment remains unclear (Cole & Knight-Jones, 1939; Korringa, 1940; Bayne, 1969; Walne, 1974). There is evidence that oyster larvae are negatively phototactic, seeking shaded surfaces and prefer live oysters or clean, dead shell with little silt for successful settlement (Cole &

Knight-Jones, 1939; Cole, 1956; Walne, 1974; UMBSM, 2007; Fulford et al., 2011).

Habitat can become degraded through activities such as dredge fishing, changes in hydrographic regime or storm events. For example, it was postulated during studies of *Ostrea chilensis* fishery in the Tasman Bay, New Zealand that fishing had modified the seabed by increasing sediment and "homogenising benthic habitat", influencing recruitment (Brown, 2011). During a shellfish stock survey in Lough Foyle (Northern Ireland and Republic of Ireland border), intensive dredging and the use of conveyor systems on fishing vessels appeared to be breaking shell into coarse sand, considered less suitable for spat settlement (Palmer et al., 2007). The patchy distribution of surviving Scottish *O. edulis* populations has been attributed to lack of settlement substrata (UMBSM, 2007). Historically, early complaints were made regarding the poor state of beds and recruitment in the Wadden See owing to management mistakes such as removing large oysters and shell, siltation and competition with other filter feeders (Berghahn & Ruth, 2005). Many of the filter and suspension feeding epifauna associated with oyster shell habitat, including sponges (Porifera), ascidians, Bryozoa, barnacles (Cirripedia), calcareous tube-dwelling polychaetes and other Bivalvia, have similar settlement requirements to oysters and may compete spatially or for food resources with oysters (Korringa, 1951; Mackenzie, 1970; Smyth & Roberts, 2010). Siltation can especially be an issue in shallow water, estuarine systems, burying shell and smothering spat (Orton, 1937; Berghahn & Ruth, 2005).

To ensure surfaces are available for spat settlement, habitat management measures such as harrowing to bring buried shell material to the surface and cultch addition are advocated for maintaining or restoring oyster beds (Abbe, 1988). In the Blackwater fishery in Essex, habitat management measures including harrowing have traditionally been carried out for at least a century and are part of the licence requirements (Fowler, 1893; Haward, 2012, pers. comm.). However, some wild fisheries such as those in the Fal, Cornwall and Lough Foyle are reliant upon natural processes that do not involve such intervention (Spencer, 2002).

Harrowing is a process whereby an implement is dragged along the seabed with the aim of turning over fouled shell, dislodging silt, weed and other debris, and killing epifauna to expose cleaner surfaces for oyster spat settlement (Cole, 1956; Waugh, 1972; Abbe, 1988; Laing et al., 2005). Types of harrow are selected according to specific aims and include skeleton dredges (oyster or scallop dredges with the bag removed); grass and agricultural harrows; other spiked or toothed implements; hybrids of these types or custom-designed harrows (Cole, 1956; Abbe, 1988). It is apparent from the literature that, despite numerous recommendations that harrowing can be beneficial for the sustainability of oyster fisheries (Abbe, 1988; Laing et al., 2005; UMBSM, 2007), there has been little actual study of the method. The only published, peer-reviewed study of the effects of harrowing is that of Waugh (1972), which produced findings that questioned the efficacy of the method. At a native oyster restoration workshop in 2012, it was observed that "a re-evaluation of traditional methods" is much needed (Askew, 2012).

However, intervention that involves increasing the availability of suitable settlement surfaces for oyster larvae such as harrowing and cultch addition may not increase recruitment. Poor spatfall and recruitment may be owing to factors other than habitat quality, including perturbations of reproductive processes and predation (Brumbaugh et al., 2006; Mann & Powell, 2007; Campbell et al., 2011).

Substratum availability has been suggested as limiting oyster recruitment in Lough Foyle, one of the few remaining *O. edulis* wild fisheries in European waters. Only 3–5% of the known area was considered to be suitable for oyster settlement at the time that initial observations were made in the early 1990s, leading to recommendations of bed cleaning (harrowing) over the ensuing decades (Cunningham, 1991; McKelvey, 1996; Andrew, 2002; Palmer et al., 2007; McGonigle et al., 2011). This study therefore experimentally investigated whether harrowing on an industrial scale increased oyster settlement. The aims were firstly to determine if harrowed areas attract significantly more oyster spat settlement than unharrowed areas. Secondly, whether harrowing exposes cleaner, less fouled shell; significantly alters substratum composition; and dislodges and removes silt from oyster beds. Thirdly, the effect of harrowing on oyster bed macrofaunal assemblages was also investigated.

## Materials and methods

### Study area

The experiment was carried out in the Lough Foyle (55.116°N 7.083°W) native oyster fishery, an enclosed sea lough occupying ca. 186 $km^2$ on the border between Northern Ireland (UK) and the Republic of Ireland. The experimental area was located in Redcastle bed (55.10°N 007.05°W). Historically, the bed was productive and is mentioned in a report of Irish oyster fisheries published in 1903 (Browne, 1903). Since the fishery resumed in the late 1970s, catch has declined and the bed consistently records one of the lowest stock densities (0.037oysters/$m^2$) in the lough, now being considered unproductive and mainly uneconomical to fish (McGonigle & Scott, 2012). Whilst the substratum has quantities of large old oyster shell, much of this is heavily fouled, and despite bivalve larvae including *O. edulis* being recorded in plankton samples, there has been little evidence of recruitment on the bed in recent years (McGonigle & Cavanagh, 2011). Prior to the start of the experiment, observations of the experimental area (between 55.10.12°N 007.04.134°W and 55.10.587°N 007.04.067°W) were carried out via a Seabotix ROV (remote operated vehicle) on 1st June 2012 and ROV and dredge survey on 26th June 2012. The experimental area was closed to fishing activity by the Loughs Agency under the Foyle Area (Control of Oyster Fishing) Regulations 2008 on 11th September 2012 until 28th September 2014.

### Harrowing and substratum characteristics

Six plots of two hectares each were delineated using ArcGIS in a line parallel to the shore, with a buffer between each plot (Fig. 1). Harrowed and unharrowed (control) treatments were randomly allocated to each plot using the random number function in MS Excel (Table 1).

A pilot experiment was carried out in 2012 to develop the methods and the results used to inform the experiments in 2013 and 2014. The three plots designated for harrowing were harrowed at the end of June 2012 and in mid-May 2013 and 2014. Each time, the plots were left undisturbed over the breeding season, with sampling scheduled for November in 2012 and 2013 and, owing to operational reasons, 27th and 28th September 2014, to allow spat to grow to an identifiable size.

Harrowing was carried out from the 10.8 m vessel, FV "*Una Marie*". A standard 1.2 m oyster dredge with the mesh bag removed to leave the skeleton frame and blade was used as a harrow. The harrow was deployed from the starboard side of the vessel via a winch and repeatedly towed at a speed of 1.5 to 2 knots through each plot assigned the harrowed treatment. The harrowing tracks were recorded on a handheld Trimble Juno Series GPS unit, enabling progress to be monitored and ensuring that good coverage of each plot was achieved and that unharrowed (control) plots remained undisturbed. The recorded tracks were then visualised in ArcGIS. In 2013 and 2014, to assess the behaviour of the harrow on the seabed, a GoPro Hero 3 camera in a waterproof housing was attached by a standard handlebar attachment accessory to the dredge frame during harrowing.

The 2012 pilot data were used to inform evaluation of subsamples in 2013 and 2014. Additional data were therefore collected in 2013 and 2014: shell length and width (mm), measured with Vernier callipers; shell weight (g); and colour of shell.

### Suspended particulate matter

To investigate whether harrowing contributed to increased suspended particulate matter (SPM), two litre water samples were taken at three locations each year (north and south of the experimental area and in the middle of the experimental area), (Table 2). Samples were collected at each of the three stations prior to, during and after harrowing each year 2012–2014. The water samples were processed by filtration through pre-prepared ashed and weighed GF-F 47 mm filters. Once the well-mixed sea water sample was filtered, the filter was rinsed twice with 10 ml of 0.5 M ammonium formate to remove salt. The filters were then dried at 60°C for 48 h and 40°C for 7 days. The filters were then weighed to assess total particulate matter (TPM). To provide controls, two blank filters were processed in the same manner for each collection day.

### Biotic settlement (*Ostrea edulis*, other bivalves and "fouling" organisms)

To evaluate biotic settlement on hard substrata in the harrowed and unharrowed treatments, stratified

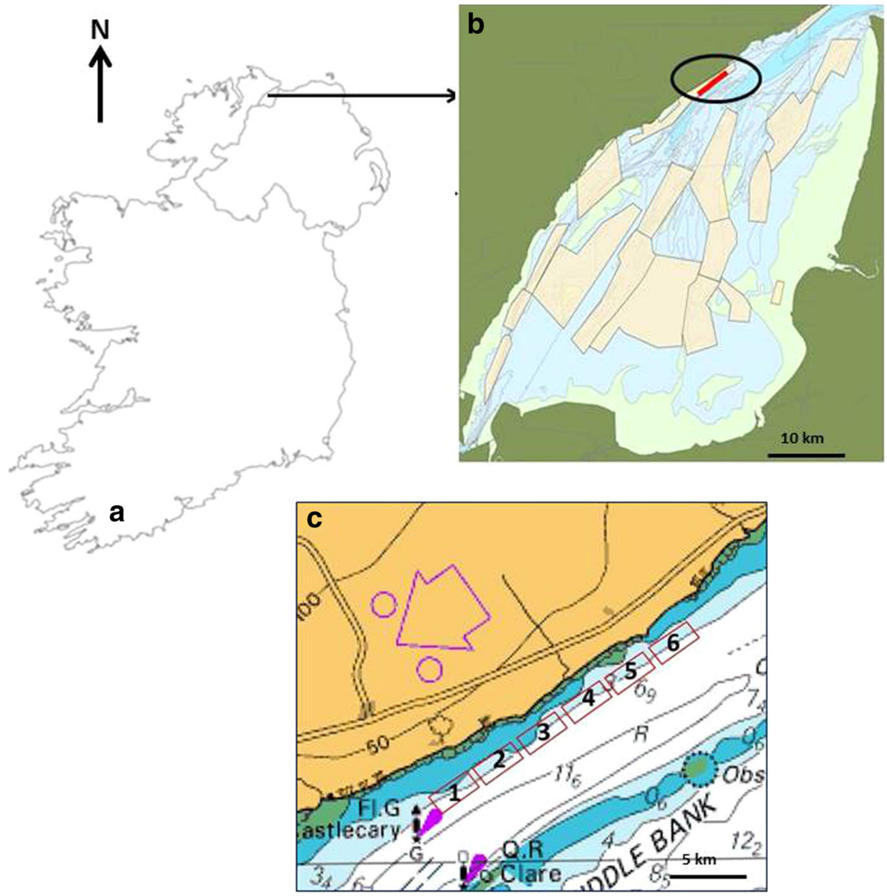


**Fig. 1** **a** Location of Lough Foyle in the island of Ireland and **b** location of the experimental area within the lough. The outlined polygons throughout the lough indicate the location of known, fished oyster beds in the lough. **c** Layout of each of the six 2 hectare plots to which the management treatments ("Harrowed" and "Unharrowed") were allocated

**Table 1** Random number allocation of treatments "Unharrowed" and "Harrowed" for the 2012 pilot, 2013 experiment and 2014 experiment

| Plot number | Treatment 2012/2013 | Treatment 2014 |
|---|---|---|
| 1 | Unharrowed | Harrowed |
| 2 | Unharrowed | Unharrowed |
| 3 | Harrowed | Unharrowed |
| 4 | Harrowed | Harrowed |
| 5 | Unharrowed | Harrowed |
| 6 | Harrowed | Unharrowed |

random sampling was carried out in each of the six plots by taking a series of dredge tows using a standard bagged 1.2-m oyster dredge. A subsample of each haul was taken to the laboratory for detailed examination. To standardise the volume of subsample collected, a 20-l plastic bucket was filled with a random sample of the dredge catch.

Observations of the condition and type of each shell within each subsample were noted. Spat settlement (number and size (mm) of *O. edulis* and other bivalve species) was recorded, together with any remains of juvenile oysters attached to shell (attachment scars,

**Table 2** Water sampling stations

| Station | Latitude (N) | Longitude (W) | Depth (m) | Location |
|---|---|---|---|---|
| 1 | 55°10.119 | 007°05.236 | 8.0 | South of plot 1 |
| 2 | 55°10.268 | 007°04.706 | 7.3 | Between plots 3 & 4 |
| 3 | 55°10.444 | 007°04.254 | 8.0 | North of plot 6 |

damaged or complete attached valves or articulated shells).

From field observations, fouling on shell surfaces was defined as consisting of live and dead specimens of the epifaunal taxa *Pomatoceros triqueter*, Polychaeta (calcareous tubes cemented to shell, empty or containing the living polychaete); barnacles, Cirripedia: *Chthamalus spp.* and *Austrominius modestus* (live barnacles or empty calcareous plates); encrusting bryozoans (live colonies or calcareous remains of colonies) and the coralline red alga, *Lithothamnium calcareum* (Rhodophyta). The amount of fouling was evaluated as percent cover of the shell substratum—from 0% (clean, zero live or dead epifauna) to 100% (entire shell covered in live or dead epifauna). Differences between percentage cover of fouling between harrowed and unharrowed plots would provide an indication that the harrow was effective in exposing cleaner shell, either by bringing buried shell to the surface or by dislodging fouling attached to the shell. The presence and absence of the boring organisms *Cliona celata* (Porifera) and *Polydora ciliata* (Polychaeta) was also recorded.

### Macrofaunal assemblage

To assess whether harrowing influenced community assemblage other than the pre-defined main fouling organisms, epifauna and mobile macrofauna associated with the sampled shell substratum were identified to the lowest possible taxonomic level and quantified.

### Statistical analyses

Data were analysed using Sigmaplot v. 12 (Systat, 2012), R v. 3.1.2 (R Development Core Team, 2008) and Primer v 6 (Primer Ltd, Plymouth, UK; Clarke & Gorley, 2006). Normality of distribution was assessed and the appropriate transformations applied wherever required prior to univariate and multivariate analyses. Univariate tests of difference amongst samples were carried out via *t* tests (two samples) and one-way ANOVA (three or more samples). Where transformations failed to address deviation from the normal distribution, the appropriate non-parametric tests were used. Significance was defined as $\alpha = 0.05$, and errors throughout are the standard error of the mean.

To evaluate differences between management treatments in Primer, distance matrices were produced using the Bray Curtis coefficient (Bray & Curtis, 1957; Clarke, 1993) and non-Metric Multidimensional Scaling (nMDS) was used to ordinate the data. Kruskal's stress value (Kruskal, 1964) acts as a measure of the goodness of fit, with values of <0.10, indicating approximation to an ideal ordination and therefore true dissimilarity between samples; <0.20 is viewed as representing a useful ordination and values >0.20 are random results (Clarke, 1993). Ordinations were carried out with 100 random restarts. PERMANOVA, a non-parametric means of analysing difference in structure or abundance amongst groups was used, with 9999 permutations specified to increase the ability to detect actual dissimilarities. Anderson & Walsh (2013) found PERMANOVA to be less affected by heterogeneity and more powerful at detecting changes in assemblage structure than ANOSIM or Mantel tests. SIMPER (similarity percentage analysis) was used to examine the average contribution of individual species to the average dissimilarity between samples.

## Results

### Harrowing and substratum characteristics

The recorded harrowing tracks for 2012–2014 showed that good coverage of each of the plots was achieved. Shell and debris caught on the dredge blade confirmed that the dredge had been working whilst on the seabed. The video recorded via the GoPro camera attached to the dredge in 2013 and 2014 clearly showed that the dredge blade works by pushing the shell and other debris followed by catching and dislodging the shell upwards off the seabed and back over the top of the blade and finally by turning and mixing the shell in the process. Plumes of sediment could also be seen behind the dredge.

Before harrowing, dredge hauls consisted of 95–100% shell, with only two live oysters recorded. Substratum was 70–80% oyster shell. The oyster shell was large, thick and heavy, and, although mostly *O. edulis*, it is possible that some of the largest shells may have been *Crassostrea virginica*, which was once imported to Irish oyster beds. The remainder of each haul consisted of a mixture of bivalve shells (*Arctica islandica*, clam sp., *Cerastoderma edule*, *Acanthocardia aculeata*, *Ensis* sp., *Mytilus edulis*, scallop (*Pecten maximus*, *Aequipecten opercularis* and *Chlamys* *varia*), gastropod shells (*Buccinum undatum* and *Turritella communis*), shell gravel and occasional stones.

Before harrowing was carried out, the shell was heavily fouled with *Pomatoceros triqueter* and Cirripedia spp. (*Chthamalus* sp., *Austrominius modestus* and occasional *Balanus balanus*). There was also evidence of shell boring by *Cliona celata*, although only occasional shells contained the live sponge. Where live *Cliona* was present, the shell was spongy and highly friable. Another significant component of dredge hauls was *Alcyonidium diaphanum*. The number of colonies on individual shells ranged from 0 to more than 30, and loose colonies were present in the water column.

During the camera survey before harrowing, the white calcareous tubes of *Pomatoceros triqueter* were clearly visible on the shell, and occasional (20 in the whole area) oysters were observed. Patches of bare sediment and blue clay amongst the shell were also visible via the camera, the largest area being at 55 10.121°N 007 05.71°W. Small amounts of blue clay were brought up in dredge hauls.

After harrowing in 2013, there was no significant difference in the weight of the shells making up the substratum between harrowed and non-harrowed plots (*t* test: $t_{691} = 1.468$, $p = > 0.05$). In 2014, the mean weight of the sampled shell substratum was heavier in harrowed than non-harrowed plots (*t* test: $t_{184} = 5.412$, $p = <0.001$). Whilst mean weight of shell in harrowed plots was higher and more variable in 2014 than in 2013 (166.2 g ± 10.6 v. 97.6 g ± 8.3), mean weight of shell in the non-harrowed plots was similar in 2013 and 2014 (88.9 g ± 8.3 and 90.0 g ± 8.9). This difference between the management treatments between years was significant ($F_{11,867} = 11.594$, $p = < 0.001$) (Fig. 2). Individual weights of shells retrieved during sampling ranged from 3.2 g to 599 g.

There was a significant difference between management treatments in terms of the composition of the shell substratum, with harrowed plots containing a higher percentage of oyster shell than non-harrowed ($\chi^2 = 13.834$, df = 6, $p = < 0.05$) (Fig. 3). In 2013, samples contained 9–14 types of shell compared to 6–10 types in 2014. Shell collected from the plots was 76–84% oyster shell. Other shell was a similar mix of the species of bivalves and gastropods observed before harrowing, with *Mya truncata* shells and a *Pholas dactylus* shell additionally recorded in the samples. Only oyster and scallop shells were common to all plots in both years. Small- to medium-sized stones were also recorded. Harrowed plot samples contained significantly higher quantities of dark-coloured shell than non-harrowed plots ($\chi^2 = 13.834$, df = 6, $p = < 0.01$).

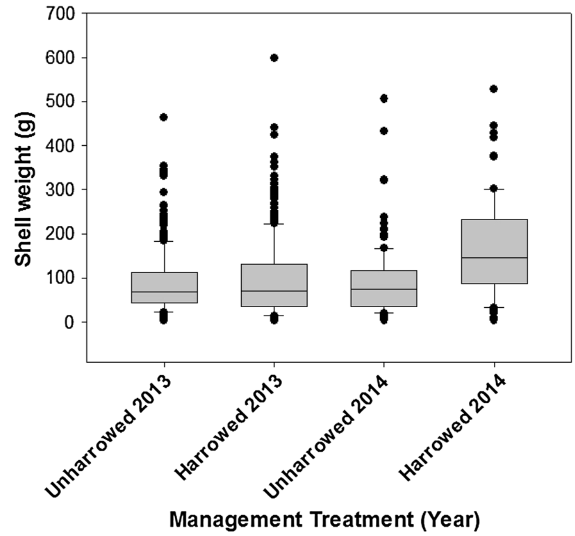


**Fig. 2** Weight of shell in unharrowed and harrowed plots in 2013 and 2014. The *boxplots* indicate mean, standard error of the mean and range of values around the mean (outliers)

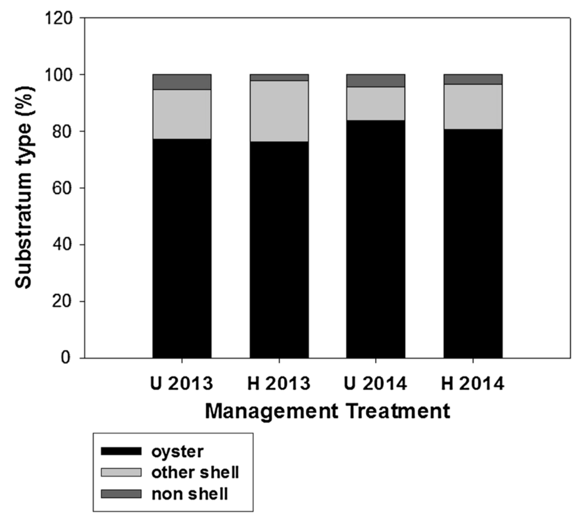


**Fig. 3** Composition of substratum between management treatments (U—unharrowed; H—harrowed) in 2013 and 2014

## Suspended particulate matter

Harrowing had no significant effect on the amount of suspended particulate matter (SPM) present in the water column. A three-way ANOVA reported no significant difference for the factor of sampling site ($F_{2,35} = 0.197$, $p = 0.824$), not amongst the years 2012, 2013 and 2014 ($F_{2,35} = 3.477$, $p = 0.064$). There was a significant difference reported for timing of sampling (i.e. before, during or after harrowing) ($F_{3,35} = 12.493$, $p = < 0.001$). A Holm-Sidak post hoc test showed this to be owing to a significant difference ($p = 0.04$) between the 2014 samples and the controls. SPM in 2012 and 2013 samples was not significantly different to the controls, irrespective of whether they were collected before, during or after harrowing. There was no mud in any of the dredge samples in any of the years.

Biotic settlement ("fouling organisms")

Percentage cover of fouling (live and dead epifauna) of shell in each plot in 2013 and 2014 ranged from 0 to 100%. The main fouling organisms (live or dead) on collected shell were *Pomatoceros triqueter*, Cirripedia (*Chthamalus* sp. and *Austrominius*), encrusting bryozoans and *Lithothamnium calcareum*. Evidence of boring by *Cliona celata* was recorded in 19% of shell sampled from the harrowed plots and 22% from the non-harrowed plots in 2014. The live organism was only present in five shells, which were heavily infested and spongy/friable. The presence/absence transformation provided the best fit for the data, producing an nMDS with a stress of 0.12, representing a useful fit for the data (Fig. 4). PERMANOVA found no significant differences in fouling of shell between treatments ($F_{1,59} = 3.0773$, $p = >0.05$), but there was a significant difference in fouling between years ($F_{2,59} = 7.7547$, $p = <0.001$). The outliers (subsamples b and c, Plot 6, 2014; subsamples b and d, Plot 4, 2014; and subsample e in Plot 5, 2014) were explained by lower but more variable levels of fouling than the other samples.

Macrofaunal assemblage

In addition to the five main fouling taxa attached to shell and the two shell boring taxa analysed in relation to the substratum, a total of 76 other epifaunal and mobile macrofaunal taxa were recorded over the 3 years. These 76 taxa were examined to assess similarities and differences in assemblages between the harrowed and non-harrowed plots after harrowing. The nMDS plot produced by presence/absence transformed data indicated a Kruskal stress value of 0.19, representing a poor but still "useful" fit for the data (Fig. 5). The nMDS showed no clear separation between samples from harrowed and unharrowed sites for other organisms. An outlier formed by one subsample (a, Plot 4, 2012) was explained by the presence of only a single clam in the subsample. Whilst there was a significant difference between management treatments (PERMANOVA: $F_{1,72} = 1.9513$, $p = < 0.05$), year had a more significant influence on the variation between samples (PERMANOVA: $F_{2,72} = 6.1917$, $p = < 0.01$). There was no significance to any interaction between year and management treatment (PERMANOVA: $F_{1,72} = 1.2945$, $p = > 0.05$).

From SIMPER analysis of management treatment and year for all data, the average similarity among the epifaunal and mobile macrofaunal assemblage in non-harrowed plots was 41.05%, compared to 36.17% in harrowed plots. Similarity was accounted for by seven taxa (91.67%) in non-harrowed plots and five taxa in harrowed plots (90.66%). Comparing the two treatments irrespective of year, SIMPER analysis reported an average dissimilarity of 63.04% between harrowed and non-harrowed plots, with 90.54% of this dissimilarity accounted for by 25 taxa. Of these, 16 taxa had higher abundances in non-harrowed plots, compared to 9 in harrowed plots (Table 3). Apart from *Flustra foliacea*, it was apparent that disturbance-sensitive erect and delicate epifaunal taxa such as solitary and colonial ascidians and anemones were more abundant in non-harrowed plots.

Amongst the years, the macrofaunal assemblage in 2012 was highly dissimilar to 2013 and 2014 (80.94 and 85.88%), whilst 2013 and 2014 were more similar to each other (67.94%). There was also less similarity between management treatments in 2012 (18.08%) than in 2013 and 2014 (47.86 and 39.14%), with 9 taxa contributing to 91.02% of the variation compared to 6 in 2013 and 2014 (9.54 and 93.4%).

The most ubiquitous taxa in both treatments and in all years were porcelain crabs (*Porcellana longicornis*), the non-native ascidian, *Corella eumyota*, *Anomia ephippium* and *Alcyonidium diaphanum*. Live adult *O. edulis* were more common in non-harrowed plots and in 2012. Of the potential predators of *O. edulis*, no starfish (*Asterias rubens* or *Crossaster papposus*) were recorded at any point during

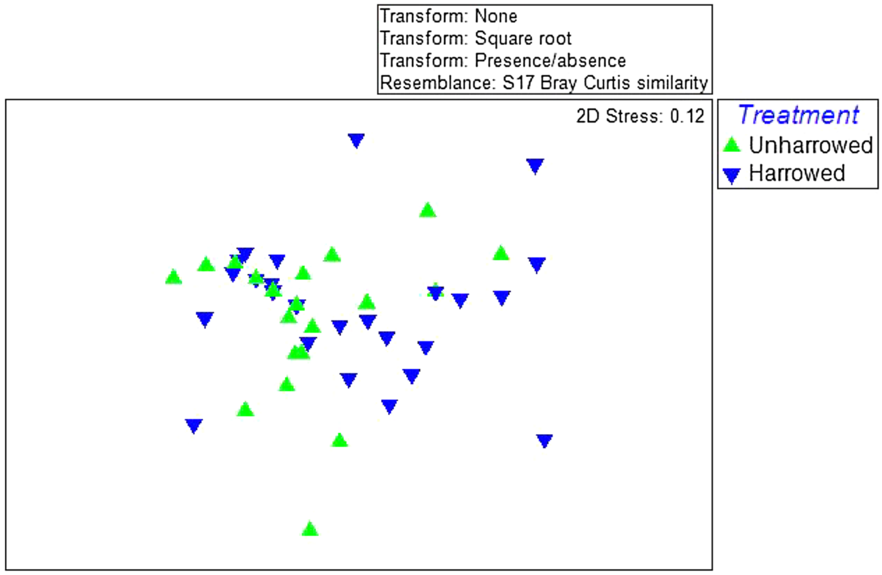


**Fig. 4** nMDS plot for presence/absence of fouling in harrowed and unharrowed plots

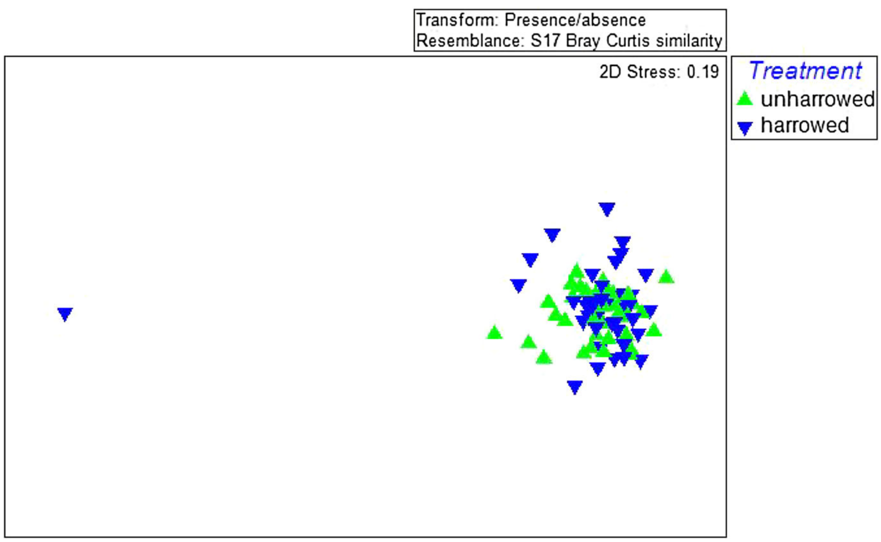


**Fig. 5** nMDS plot of macrofaunal assemblage in each management treatment

sampling. The oyster drill, *Ocenebra erinacea*, and dog whelk, *Nucella lapillus*, were more abundant in non-harrowed plots, whilst green crabs, *Carcinus maenas*, and common whelks, *Buccinum undatum*, were more abundant in harrowed areas (Table 3).

Settlement of *Ostrea edulis* and other bivalve spat

No live *O. edulis* spat was recorded in the harrowed or unharrowed plots in 2012 and 2013. The only evidence of settlement was the remains of spat attached to shell (16 and 36 mm lower valves and 8 and 15 mm attachment scars in 2012; and 5, 18 and 24 mm lower valves in 2013) in both harrowed and unharrowed plots.

In 2014, 12 live *O. edulis* spat were collected—nine from the non-harrowed plots and three from the harrowed plots. Mean maximum shell width was 15.9 mm ± 2.6 (range 2–40 mm). One of these was recorded settled on a live oyster. Another had settled on a small dahlia anemone (*Urticina felina*) attached to an oyster shell. The remainder were settled on

**Table 3** SIMPER analysis (Primer) comparison of abundances of epifaunal and mobile macrofaunal assemblage accounting for 90.54% of the 63.04% dissimilarity between harrowed and non-harrowed plots (across all years)

| Taxon | Average abundance non-harrowed | | Average abundance harrowed |
|---|---|---|---|
| *Porcellana platycheles* | 9.73 | < | 12.39 |
| *Anomia ephippium* | 7.7 | > | 8.32 |
| *Corella eumyota* | 8.22 | > | 4.78 |
| *Alcyonidium diaphanum* | 4.78 | > | 2.93 |
| *Dendrodoa grossularia* | 3.22 | > | 1.56 |
| *Flustra foliacea* | 1.54 | < | 2.05 |
| *Gibbula umbilicalis* | 2.08 | > | 1.78 |
| *Harmothoe* sp. | 1.00 | > | 0.59 |
| *Ostrea edulis* | 0.54 | > | 0.24 |
| *Buccinum undatum* | 0.43 | < | 0.44 |
| *Carcinus maenas* | 0.30 | < | 0.41 |
| Clam sp. | 0.43 | < | 0.63 |
| *Lepidopleurus asellus* | 0.68 | > | 0.29 |
| *Onchidoris bilamellata* | 0.65 | > | 0.32 |
| *Nucella lapillus* | 0.27 | > | 0.20 |
| *Rissoa parva* | 0.62 | > | 0.61 |
| *Trivia monacha* | 0.32 | > | 0.10 |
| *Calliostoma zizyphinum* | 0.27 | < | 0.29 |
| *Ocenebra erinacea* | 0.51 | > | 0.24 |
| *Actinia equina* | 0.32 | < | 0.20 |
| *Botryllus schlosseri* | 0.14 | < | 0.37 |
| *Urticina felina* | 0.38 | > | 0.12 |
| *Pagurus bernhardus* | 0.11 | < | 0.15 |
| *Metridium senile* | 0.35 | > | 0.10 |

< and > symbols indicate the direction of the dissimilarity

oyster shell. Only one spat was settled on clean shell. The rest were settled on shells 60–100% fouled by *Pomatoceros triqueter*. Remains of three spat (11, 12 and 15 mm) were recorded on shell from one of the harrowed plots.

The abundance of bivalve taxa over the years was significantly different ($\chi^2 = 292.484$, $df = 45$, $p = <0.001$). Settlement by five bivalve taxa was recorded in 2012, seven in 2013 and four in 2014. Only *Anomia ephippium* and clam sp. were present in all years (Table 4). The total abundance of settled bivalves was low in 2012 (67) and 2014 (55), with much higher numbers in 2013 (572). In 2014, *O. edulis* accounted for 31% of settlement in non-harrowed plots and 12% in harrowed plots. The saddle oyster, *Anomia ephippium*, was more prevalent in harrowed plots (73%) than non-harrowed (55%) in 2014 (Fig. 6). More than 90% of the settled bivalves in both treatments in 2012 and 2013 were *Anomia*. There was no significant difference between treatments over the 3 years (PERMANOVA: $F_{1,61} = 0.10459$, $p = >0.05$).

## Discussion

Harrowing had no effect on oyster spat settlement. Where live spat were recorded in 2014, three times as many were settled in unharrowed than harrowed plots. Indeed, the majority of spat were recorded in Plot 2, the only plot which remained fallow for the 3 years. This supports a previous finding that harrowed areas did not receive as much settlement as fallowed areas (Waugh, 1972). The results support the view that where a fishery is reliant on natural spatfall, there is little that harrowing can do to influence settlement (Spencer, 2002). Recruitment in Lough Foyle is highly subject to natural variations in reproductive cycles (McKelvey et al., 1996; Andrew, 2002), and in 2012 and 2013, there was poor settlement throughout the lough (Bromley, 2015). Other than *Anomia ephippium*, settlement by other bivalves was equally low and unpredictable with, for example, *Pecten maximus* only recorded in 2012 and 2013 but not in 2014. *Anomia ephippium* would not represent a good proxy for oyster settlement. This species was recorded in comparably high abundances in both management treatments and in years with poor *O. edulis* recruitment. Nor did it appear to be selective of substratum, settling on clean and heavily fouled shell and non-shell substrata.

The numbers of spat were very low, and it is difficult to draw firm conclusions with regard to substratum preferences. However, together with observations from other work in the lough (Bromley, 2015), that all but one oyster had settled on oyster shell lends some support to the view that *O. edulis* preferentially settles on live oysters or oyster shell (Cole & Knight-Jones, 1939). However, the amount of fouling appeared to be less important, with only one oyster settled on clean shell.

Harrowing did have some effect on substratum composition. The weight of shell and the percentage of non-oyster shell had decreased in the harrowed plots

**Table 4** Mean numbers with standard error of the mean (±) of total bivalve species and bivalve species per sample by management treatment (U = Unharrowed, H = Harrowed) and year

| Species | U 2012 | U 2013 | U 2014 | H 2012 | H 2013 | H 2014 |
|---|---|---|---|---|---|---|
| Total species | 1.3 ± 0.6 | 3.3 ± 0.8 | 2.3 ± 1.1 | 1.7 ± 1.2 | 1.2 ± 1.1 | 2 ± 1 |
| *Ostrea edulis* | 0 | 0 | 0.6 ± 1.1 | 0 | 0 | 0.2 ± 0.6 |
| *Anomia ephippium* | 2.0 ± 2.2 | 16.2 ± 3 | 1.1 ± 1.2 | 2.1 ± 1.8 | 19.1 ± 2.7 | 1.3 ± 1.3 |
| Clam sp. | 0.2 ± 0.9 | 0.7 ± 0.9 | 0.1 ± 0.6 | 0 | 1.5 ± 1.2 | 0.2 ± 0.7 |
| *Pecten maximus* | 0 | 0.1 ± 0.5 | 0 | 0.1 ± 0.5 | 0 | 0 |
| *Mytilus edulis* | 0 | 0.1 ± 0.5 | 0.1 ± 0.7 | 0 | 0.1 ± 0.5 | 0 |
| *Mya truncata* | 0 | 0.1 ± 0.5 | 0 | 0.1 ± 0.5 | 0.1 ± 0.5 | 0 |
| *Aequipecten opercularis* | 0 | 0 | 0 | 0 | 0.1 ± 0.7 | 0 |
| *Chlamys varia* | 0 | 0.1 ± 0.5 | 0 | 0 | 0 | 0 |
| *Hiatella arctica* | 0 | 0.1 ± 0.5 | 0 | 0 | 0.1 ± 0.5 | 0 |
| *Dosinia exoleta* | 0 | 0 | 0 | 0 | 0 | 0.1 ± 0.5 |

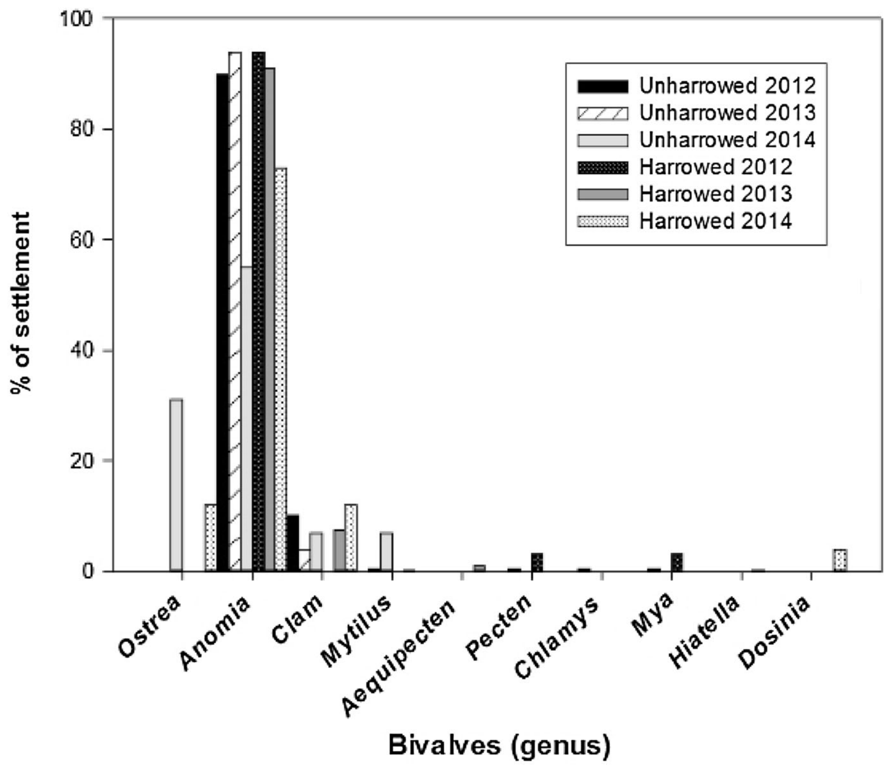


**Fig. 6** Percentage settlement by bivalve taxa in unharrowed and harrowed plots in 2012, 2013 and 2014

by 2014. Clean, darker shell had also become more common in the harrowed plots. This type of shell has been buried for some years and is regarded as useful in the Blackwater because *O. edulis* spat are believed to seek out dark-coloured settlement surfaces (Cole & Knight-Jones, 1939; Walne, 1964; Haward & Bird, 2012, pers. comm.). Blackened shell was discarded in the 1972 study of harrowing because it had been buried, though no reason is given for this (Waugh, 1972). Unfortunately, given the low spatfall, we were unable to prove or disprove this hypothesis. Shell bored by *Cliona celata* was less common in harrowed plots. As such shell is fragile, this indicates that harrowing may have caused it to disintegrate. The results indicate that harrowing is analogous to the reported effects of dredging in terms of homogenising substrata and breaking up shell (Kaiser et al., 2000; Brown et al., 2010; Tully & Clarke, 2012). It has been observed that whilst dredging can be beneficial to some beds, too much of it can turn shell to sand and reduce the size of the oyster beds (Holt, 1903). Similarly to bivalve settlement, significant differences in the amount of fouling by organisms such as *Pomatoceros triqueter* and barnacles can be attributed to inter-annual cycles in setting intensity, rather than the effects of harrowing (Knight-Jones & Stevenson, 1950; Knight-Jones, 1953).

There were suggestions in the data that harrowing could have a negative effect on the community associated with oyster beds. Harrowing reduced the number of species contributing to both similarities and dissimilarities between plots. Reduced species richness and higher abundance of predators and scavengers such as *Buccinum undatum*, *Carcinus maenas* and *Pagurus bernhardus* are indicators of disturbance (Collie et al., 1997; Murawski et al., 2000). This may impact on fishery and conservation management objective under European directives (Tully & Clarke, 2012). In addition to Features of Conservation Interest (FOCI) species such as *O. edulis* and *Arctica islandica*, the Annex I species/habitat eelgrass (*Zostera marina*) is present in the lough and studies have shown that harrowing or raking can damage eelgrass beds (Fonseca et al., 1984; De Jonge & De Jonge, 1992; Everett et al., 1995; Tallis et al., 2009).

References to harrowing and long-standing use of the technique in some oyster production areas (Fowler, 1893; Laing et al., 2005; Haward, 2012, pers. comm.) may suggest to managers that harrowing should be adopted to recondition oyster beds in their location. However, managers need question whether it is indeed necessary and whether, for example, cultch addition may be a more effective use of resources.

Cole's (1956) manual for oyster cultivation is the source of many recent references, suggesting the use of harrowing for habitat remediation. However, this manual for oyster cultivation did not consider harrowing to be a "one size fits all" method. The main context within which it was recommended was (i) for removing silt accumulated on neglected grounds and (ii) preparing cultivated areas for laying spat or halfware brought in from elsewhere for on-growing (analogous to a farmer ploughing a field ready for planting seed) (Cole, 1956). Indeed, the author suggested that reconditioning barren or neglected grounds may not work, work can be expensive, and may damage stock or spread disease (Cole, 1956). Habitat restoration work may need to be carried out for many years and still have no effect (Korringa, 1951).

The only previous published study of the effects of harrowing concluded that harrowing did not increase settlement, and had long-term adverse effects on the growth and survival of existing stock (Waugh, 1972). It was recommended that any such work should be "carefully considered and weighed up against potential long-term interference" (Waugh, 1972). More recently, the oyster bailiffs in the Fal have not only harrowed where they have identified a problem, for example, after an outbreak of bonamiosis, left one bed derelict but also found that the technique had no effect in reconditioning the bed (Ferris, 2012).

In an active fishery, harrowing may be redundant. Harrowing was advocated for the Lough Foyle beds 20 years ago owing to oysters being buried under piles of cultch (Cunningham, 1991). However, a later study found little evidence of this, suggesting that increased fishing activity has redistributed cultch (McKelvey, 1996). It has been stated that there is no need or only occasional need to carry out harrowing as a "maintenance measure" where there is regular fishing (Webster & Merritt, 2011; Woolmer et al., 2011). It was also concluded during the experiments in the Rivers Crouch and Fal that dredge harvesting was more effective than harrowing at preparing oyster grounds for spat collection (Waugh, 1972). Although not experimentally tested, it was apparent in Lough Foyle in 2014 that Perch bed, one of the most heavily fished beds, attracted much higher spatfall than Redcastle (*pers. obs*. and unpublished Loughs Agency data).

One of the main tasks for which harrowing is recommended is removal of silt (Cole, 1956; Webster & Merritt, 2011). The one scenario where harrowing may indeed be necessary in fisheries which are located in depositing systems in estuarine salt marsh creeks and muddy substrata, where silt build-up can smother newly laid stock and inhibit spat settlement (Dean, 1893; Fowler, 1893; Knight-Jones, 1953; Hancock, 1955; Webster & Merritt, 2011). This, together with the control of the invasive *Crepidula fornicata*, is the explanation for annual harrowing being carried out in the Blackwater (Hancock, 1955; Haward, 2012, pers. comm.). The Lough Foyle results indicate that silt build-up in the experimental area is unlikely to be the cause of lack of oyster settlement. Although at certain times, the water column in the lough can carry high sediment loads, tidal currents in Redcastle are sufficiently strong to remove sediment. The fact that only the 2014 samples were significantly different from the controls and there was no significant difference between sampling stations suggests that 2014 sampling coincided with a period of high turbidity. Other than the small amounts of the blue clay noted during pre-experiment camera work, there was no mud in the dredge samples, especially compared to the amount of mud which is present in dredge hauls on mussel beds in Lough Foyle or in the Blackwater (*pers. obs*.).

Dislodging and disturbing sediment may also have negative effects. It has been suggested that estuarine sediments may act as an important winter food reservoir for oysters and other shellfish in the Foyle (McKelvey, 1996). Also, in locations with a long history of shipping traffic, such as Lough Foyle, heavy metals and the now banned antifouling agent tributyltin (TBT), associated with imposex in molluscs, may be sequestered in the sediment and could be released back into the water column (Arakawa et al., 1971).

In areas such as the experimental site in this study where habitat enhancement efforts have proved ineffective, other causes need to be investigated to identify the best regeneration strategy (Fowler, 1893; Cole, 1956). In addition to the influence of inter-annual variations in reproductive cycles, it would be reasonable to suggest that with such a low stock density (0.037 oysters/m$^2$), reproductive output would be low due to the Allee model (Allee et al., 1949). This also means that, if the presence of conspecifics is an important driver of settlement substratum selection in oysters, there are too few oysters left on the bed to attract spat (Cole & Knight-Jones, 1939). The strong currents (>1.5 knots) that can occur in the area could assist in removing silt but may also inhibit settlement and transport larvae away from the bed (Woolmer et al., 2011).

Also, previously, productive grounds can cease to support oysters owing to changes in abiotic conditions. This may be indicated by benthic community composition. Abundant starfish were considered to be an indicator of suitable oyster ground, together with ascidians, whelks, hermit crabs and slipper limpets (Cole, 1956). Absence can thus be as informative as presence. For example, the common starfish, *Asterias rubens*, can be a major oyster predator but can be excluded by fluctuating or low salinities (Hancock, 1955, 1969; Mackenzie, 1970). In this study, ca. 50% of the shell examined was fouled with either all or a proportion of dead *Pomatoceros triqueter* and barnacle spp. Dead fouling organisms on shell either show that the shell has been buried (which was interpreted in this study as another indication that harrowing had exposed buried shell) or indicates that abiotic conditions have changed and are less suitable for oysters than they were in the past (Cole, 1956; Burke et al., 2008).

In the absence of dredge fishing, the remains of spat (valves and attachment marks) found in all 3 years indicates losses through natural mortality. Present in dredge samples were a number of potential oyster spat predators—*Ocenebra erinacea*, *Nucella lapillus*, *Cancer pagurus*, *Carcinus maenas* and *Buccinum undatum* (Mackenzie, 1970; Smyth & Roberts, 2010). In common with the *O. edulis* spat, *Ocenebra erinacea* was more common in unharrowed plots. This disagreed with the observation that the favoured conditions for spatfall (clean shell with little silt) are also favoured by oyster drills (Cole, 1956).

Although there was no modern experience of harrowing in Lough Foyle, the methods for the experiment were based on advice from the published literature (Cole, 1956; Waugh, 1972) and Blackwater oystermen (Haward & Bird, 2012, pers. comm.). It was confirmed that the dredge was working on the seabed and the 2012 pilot was used to refine the methods for 2013 and 2014. There are some aspects which could have influenced the results. A skeleton dredge may not be the most efficient harrow type. Although these have been viewed as “particularly useful for disturbing cultch at the beginning of the breeding season” (Cole, 1956), in the USA, agricultural harrows are perceived to be better at maintaining habitat than bagless dredges, partly because the latter are narrower and cover less ground (Webster & Merritt, 2011). This was addressed by having small areas (2 ha each) to be harrowed and ensuring that the harrowing was carried out to ensure all the plot was covered repeatedly. Debris was also regularly removed from the dredge to prevent this impinging on its action on the seabed (Cole, 1956). Timing should not have influenced the results. The 2012 pilot was carried out at the end of June, after the oysters had started spawning, and harrowing in 2013 and 2014 was carried out at the end of May to ensure that the work was completed before spawning commenced. It has generally been recommended for harrowing to start in June but also that this needs to take into account local conditions, for example, starting at the end of May in the Blackwater so that beds are ready for spatfall at the end of June (Cole, 1956). Having addressed as many potential confounding factors as possible, and, in view of poor settlement throughout the lough in 2012 and 2014 and the few significant differences in the results, we believe these considerations to be insufficient to cause any change to the conclusions.

The recommendation of this study would be that harrowing should never be carried out on productive oyster beds which are already subject to intense fishing activity. Neither should harrowing ever be carried out once native oysters have commenced spawning as this carries the risk of damaging or disturbing newly settled spat. Whether harrowing may be applied to reconditioning long-neglected beds should be assessed on an individual basis for each proposed site. Potential effects on the benthic faunal and floral assemble should be taken into account, especially where conservation protections are applicable.

## Conclusion

"Harrowing of grounds as a preparation for spatfall is valueless" was the conclusion of the only previous published study of the effects of this habitat management method (Waugh, 1972). From the results of our study, and the evidence presented by Waugh (1972), we conclude that harrowing is not the panacea that accepted wisdom may suggest (Cole, 1956; Abbe, 1988; Laing et al., 2005). Certainly for the Lough Foyle fishery, harrowing would be of little value, and we would not recommend adopting this technique—most beds are intensively fished (and therefore effectively "harrowed" repeatedly) during the fishing season, and Cole's manual (Cole, 1956) and Waugh (1972) specifically state that regularly harvested beds should not be subjected to additional, specialist harrowing activity. We would suggest managers should instead investigate other methods of enhancing recruitment such as broodstock and cultch addition or artificial spat collection. Such enhancement methods should be trialled on a small scale before being adopted as a management strategy.

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