Evaluating artificial reef performance: approaches to pre- and post-deployment research

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The deployment of large man-made structures in inshore coastal areas has the potential for causing significant hydrographical and biological changes in the receiving environments. Often the ability to determine changes resulting from significant impacts has been compromised by the lack of pre-deployment data. The Loch Linnhe artificial reef is a 42 000 tonnes reef complex that is proposed for deployment in the period 2001–2004. A series of baseline data sets were generated in the 4 years preceding construction to facilitate multi-parameter post-reef deployment comparisons. Hydrographical data included a detailed assessment of tidal current dynamics over the complete spring–neap tidal cycle. Sedimentological research included broad-scale remote acoustic surveys coupled with sediment granulometric analysis. Seasonal changes in oxygen levels through the sediment column were also determined. The existing biological community at the proposed site was assessed through monthly diver observation and remote sediment grab sampling. These data sets will form the basis of a comprehensive evaluation of reef impacts and performance to be made post-reef construction.

Introduction

Many of the fundamental issues concerning artificial reef deployments relate to environmental impacts (Guiral et al., 1995), associated changes in local productivity (Grossman et al., 1997; Pickering and Whitmarsh, 1997) and the effects on biodiversity (Connell and Glasby, 1999). While artificial reefs are unlikely to increase either global productivity (but see Jones, 1998) or diversity, they may increase diversity on a local scale by increasing biotic and abiotic habitat complexity. The scale of the impact of artificial reefs can be limited (Ambrose and Anderson, 1990) or extend several hundred metres from the reef (Davis et al., 1982). Qualification and quantification of these effects has been achieved by making comparisons with data gathered prior to reef deployment (Haroun et al., 1994). Unfortunately, extensive multi-disciplinary research into the proposed deployment site is often initiated following reef construction (Gomezbuckley and Haroun, 1994) reducing the value of subsequent scientific research (Underwood, 1996). In addition, such research is frequently compromised by a lack of replication of the reef system (Hurlbert, 1984). While it is possible to gain insights into processes through observation on non-replicated sources of impact (Underwood, 1993), such designs are less powerful and can be avoided by partitioning the reef materials into several separate units.

The Loch Linnhe Artificial Reef is a proposed 42 000 tonnes reef planned for deployment to the north of Eilean Dubh, off the east side of Lismore Island in the Lynn of Lorne, Scotland. Construction started in August 2001 and completion is expected to take up to 3 years. The purpose of the reef is to facilitate scientific research into impacts and performance of a replicated suite of reef types with the over-riding objectives of quantifying and evaluating the economic potential for similar reefs deployed with target fisheries [in this case...
the European lobster (*Homarus gammarus* L.) in mind. Any experimental evidence used to evaluate reef impacts and performance will benefit from the comparison of pre- and post-deployment data sets and, in particular from establishing the degree of temporal and spatial variance of the assessment parameters.

Our aim is to demonstrate how various standard techniques can be combined in a multi-disciplinary study to produce a holistic description of a reef site prior to reef deployment. We also examine how these pre-deployment surveys can be employed to indicate where research effort intended to evaluate overall reef performance should be focused following deployment.

Materials and methods

Station designation

The site for the artificial reef complex was chosen based on a consultation process followed by a detailed assessment of its biotic and abiotic characteristics (Sayer and Wilding, 2002). The site is located at approximately 56°32′N 5°27′W and occupies approximately 1 km².

Eleven sampling stations (Figure 1) were chosen to be representative of the whole area taking into account the existing depth gradient, based on initial broad-scale surveys of the area with particular emphasis on the mid-depth region where the reefs are planned for deployment (Figure 2). Two stations were located in relatively shallow water (S1 and S2; approximately 10 m), 6 stations were mid-depth (M1–M6; 18 m), and 3 were in deep water (D1–D3; 26 m).

In addition, three permanent transects (T1–T3) were established at approximately 14 m depth. Each transect was constructed using two lengths of leaded polypropylene rope (14 mm; Cosalt, UK), which were held parallel to each other using five equally spaced 1.5 m propylene rope (14 mm; Cosalt, UK), which were held parallel to each other using five equally spaced 1.5 m lengths of 25 mm diameter PVC pipe (DuraPipe, Staffordshire, UK). Thus, each transect was divided into 4 × 10-m-long sections, each with a surface area of 15 m².

Acoustic ground discrimination sonar survey

The seabed was initially characterized using acoustic ground discrimination sonar (AGDS). The system used was the RoxAnn® (Marine Microsystems, Aberdeen, UK) system, which was set at default RoxMap® settings and integrated with the onboard echosounder (JMC V-122) set at 50 kHz. The speed of the research vessel used (RV “Calanus”) was kept at approximately 5 knots throughout the survey. The survey area was traversed in an approximate northeast to southwest and north to south direction so that the maximum distance between boat tracks was maintained at 100 m. Positional information was supplied by differential global positioning systems (d-GPS). The d-GPS data were manually prefiltered prior to interpretation where positional errors were evident. The RoxAnn data were then interpolated using the kriging function in Surfer® (Golden Software, CO, USA) to generate contour maps of seabed roughness (Figure 1), hardness (Figure 2), and depth. The survey was undertaken within approximately 1 h either side of high water when current speeds were at their minimum. Hardness and roughness are expressed in arbitrary units (the scale depending on the maximum and minimum for surveys employed).

Hydrography

Four InterOcean S4 current meters (InterOcean, CA, USA) were deployed simultaneously at stations M1, M2, M4, and M6 for a total of 22 days. Every 10 min, the mean current speed and direction over a 1-min period was calculated and recorded resulting in 3200 records per station. Each current meter was set level on a small concrete plinth approximately 50 cm above the sediment.

Granulometric analysis

One to three cores (58-mm internal diameter, ID) were taken by SCUBA diver at each station. Each core was cut into 1-cm sections using a thin plastic slicer. Granulometric analysis was undertaken as described by Buchanan (1984) with the exception of the use of a Whatman 42 filter paper to remove electrolytes. The washed sediments were separated using test sieves (4, 2, 1, 0.5, 0.25, 0.125, and 0.063 mm; Endecotts, London, UK) stacked on an automatic sieve shaker (Omron Model SV001) and left to shake for 10 min. The silt/clay fraction (material passing the 0.063-mm sieve) was not subject to further analysis. The proportion of the total (excluding the >4-mm fraction) made up by each fraction was calculated. The >4-mm fraction was not included in the analysis as 58-mm ID cores were considered too small to get a representative sample of coarser size fractions. The contribution of each size fraction for the whole sediment core (consisting of six sediment slices) was calculated. These data were plotted using non-parametric multidimensional scaling (MDS; Primer®, Plymsolve, Plymouth, UK) to demonstrate where differences and similarities in granulometric structure were occurring.

Single value parameters quantifying sediment coarseness and structure were required to allow comparisons of the sediment at different stations. Median particle size (MDp; log₁₀ scale where larger numbers represent finer sediments), quartile deviation (QDp), and ϕ quartile skewness (skew) were calculated by pooling data from replicate cores within stations and plotting cumulative percentage against ϕ (Buchanan, 1984).
Along transects T1, T2, and T3, the percentage stone cover was estimated by placing a 0.25 m² rigid mesh consisting of 100 cells at the four corners of each section of each transect. A stone was counted if it lay under a mesh intersection (cross) giving a direct estimate of percentage cover. Stone cover was assessed during March 1999 and the transects were compared using the Ryan–Einot–Gabriel–Welsch Multiple Range Test (Westfall et al., 1999).

Redox analysis

Additional cores (58-mm ID) were taken by SCUBA diver at stations M1, M2, and M4. Measurements of electrical conductivity (redox) on between six and eight cores at each station were taken five times over the period September 1998 to August 1999. Conductivity measurements were started immediately following collection using redox probes and following the protocol of Pearson and Stanley (1979). The probes (Russel pH Ltd, Auchtermuchty, Scotland, UK, Model CMPtR106/300 mm) were mounted on a Palmer stand and lowered in 0.5-cm intervals from the sediment surface to 4-cm sediment depth and in 1-cm intervals thereafter to a maximum depth of 8 cm. Readings were also made 1 cm above the sediment surface. If the probe was obstructed (by, for example, a stone), measurements were discontinued. Before use in each core, the redox probes were calibrated by immersion in a standard solution (Zobell, 1946) and rinsed in distilled water.

Prior to analysis, the data for each set of six to eight cores were pooled to generate a mean redox value for each depth at each station sampled. Preliminary analysis was conducted using repeated measures 2-factor ANOVA where the repeated factor is core within station and the factors (fixed) are station and time. Interactions

Figure 1. Roughness at the proposed reef site (Surfer® interpretation of RoxAnn® data) in arbitrary units. The location of sampling stations (S1, S2, M1–M6, and D1–D3) and transects (T1–T3) is indicated.
between the repeated measure and the fixed factors were determined independently and estimated using four parameters (Wilk’s Lambda, Pillai’s Trace, Hotelling–Lawley Trace, and Roy’s Greatest Root; Littel et al., 1991). Where necessary, the range of these estimates for rejecting the null hypothesis of no interaction is given.

Macro- and megafauna sampling
Stations M1 and M4 were located using d-GPS and eight replicate sediment samples were collected at each site using a 0.1 m² van Veen grab (Duncan Associates, Cumbria, UK) deployed remotely from the sea surface. Each sample was transferred to a 45 cm diameter, 1 mm sieve (Endecotts, London, UK) and washed using a Wilson Autosieve table (Gardline Survey, Great Yarmouth, UK). Large stones were discarded and the remaining material fixed, using borax buffered 4% formaldehyde containing 1 g l⁻¹ rose bengal (Sigma; Holme, 1971), for at least 4 days. Following fixation, the formaldehyde was removed by washing the samples in tap water for at least 2 h. The samples were then preserved in 99% industrial methylated spirits (Holme, 1971). Sorting was conducted on a white tray, initially to phylum only. ANOVA was used to determine if numbers of animals per grab were significantly different between stations.

The three transects were surveyed by the same scuba diver swimming in the same direction each time at a standardized speed of 2.5 m min⁻¹ (4 min per section) and recording species presence and abundance. Preliminary surveys identified 16 non-transient, relatively common and conspicuous species suitable for inclusion in the survey.

To facilitate preliminary statistical analysis, the data (collected between November 1998 and April 1999) from...
The redox discontinuity zone was found between approximately 1 and 3 cm at all stations and at all times of the year sampled (Figure 4). Conductivity fell below 0 mV only during September 1998 (at sediment depths >2.5, >5, >5.5 cm at stations M1, M2, and M4, respectively). The drop in electrical conductivity from +1 to −8 cm depth was significant for all months at all stations (p<0.0001, n=22–31). The relationship between month and depth changed at all stations, although this interaction was less significant at station M2 (M1: p=0.02–0.0004, n=31; M2: p=0.19–0.0003, n=22; M4: p=0.005–0.0001, n=29). In addition, when the correlations between conductivity at different depths (repeated variable) were ignored (Littel et al., 1991), temporal differences were significant (p<0.0001, n=22–31). The trend in the depth station interaction was less clear and predominantly non-significant.

Macro- and megafauna
The macrofauna at the two stations (M1 and M4) was dominated by echinoderms (brittle stars), bivalves, chitons, and crustaceans (Figure 5). Numbers of bivalves per grab were not significantly different between stations, but brittle stars were significantly more abundant at M1 than at M4 (p<0.0001, n=7–10). In contrast, crustaceans and chitons were significantly more abundant at M4 than at M1 (p<0.0001, n=7 and 10, respectively). The five most abundant members of the 16 species surveyed by SCUBA (averaged across the three transects) were Asterias rubens L., Munida rugosa Fab.,

Table 1. Summary of current speeds (cm s⁻¹) and direction (° magnetic) at the four stations in the proposed reef deployment area (cf. Figure 1).

<table>
<thead>
<tr>
<th>Station</th>
<th>Direction</th>
<th>Residual</th>
<th>Speed Maximum</th>
<th>Speed Mean</th>
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<td>M1</td>
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<td>4.42</td>
</tr>
<tr>
<td>M2</td>
<td>251</td>
<td>1.68</td>
<td>20.1</td>
<td>3.39</td>
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<tr>
<td>M4</td>
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<td>35.9</td>
<td>4.73</td>
</tr>
<tr>
<td>M6</td>
<td>210</td>
<td>3.64</td>
<td>38.4</td>
<td>7.33</td>
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</table>
Echinus esculentus L., Virgularia mirabilis Lam., and Liocarcinus depurator L. There were clear differences in the abundance of some species among transects (Figure 6). For example, V. mirabilis was absent from transect 3, rare in transect 2 but the most abundant species in T1. M. rugosa was significantly less abundant in T1 than in the other two. Differences in the density of L. depurator were not significant. A. rubens was more abundant during summer and autumn compared with winter and spring in T2 and T3, with the variation being particularly large during autumn in T3.

Discussion

The pre-deployment surveys have enabled a holistic and detailed understanding of the physical and biological factors and their interactions at the reef deployment site. Several of the physical factors measured are likely to be related and should, at least in part, determine the observed distribution and abundance of the fauna. Quantification of the interactions between reef modules and the receiving environment is expected to be greatly facilitated by this pre-deployment research.

The deployment site ranges between 10 and 30 m in depth and consists of silty sand overlain by cobbles and stones. The energy gradient across the site, with higher energies in the northeast part, may account for the gradient in sediment coarseness observed caused by sediment scouring and re-suspension in the high-energy areas and subsequent deposition in the low-energy areas. The differences in current regime and sediment are expected to be important factors in determining the observed distribution of benthic epifauna and infauna. This may, in part, be mediated through the role of water movement in the delivery of oxygen to the benthos (Forster et al., 1996; Huettel et al., 1996; Ziebis et al., 1996a, b). The redox potential at the site is typical of Scottish sea lochs and suggests that the sediment is not subject to high organic loadings (Pearson and Stanley, 1979). Differences among stations at certain times of the year are possibly a consequence of the different tidal dynamics. It is possible that deployment of reefs in the area will cause local alterations in the current regime that may lead to changes in sediment oxygenation. The development of sediment hypoxia may be exacerbated by the trapping and subsequent decay of commonly occurring macro-algal detritus in areas around reef modules where current velocities are reduced. Local reduction in oxygen availability will have a profound impact on the existing infauna following reef deployment (Pearson and Stanley, 1979; Rosenberg et al., 1991; Nilsson and Rosenberg, 1994; Ziebis et al., 1996b; Nilsson, 1999, 2000).

Table 2. Summary of sedimentary characteristics at the 11 sampling stations (cf. Figure 1; N: number of sediment slices used in the analysis; depth in m below sea level – chart datum; φ – 1 to 5: cumulative percentages made up by each fraction where – 1φ represents the coarsest sediment measured; %<63: percentage silt and clay; MDφ: median particle size; QDφ quartile deviation as a measure of sorting; Skew: φ quartile skewness, Buchanan, 1984).

<table>
<thead>
<tr>
<th>Station</th>
<th>S1</th>
<th>S2</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
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<th>D2</th>
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<td>24/6</td>
<td>18/9</td>
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<td>22/9</td>
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<td>3.5</td>
<td>0.8</td>
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<td>1.9</td>
<td>2.8</td>
<td>3.7</td>
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<td>2.3</td>
<td>11.6</td>
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<td>18.6</td>
<td>9.0</td>
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<td>22.9</td>
<td>23.0</td>
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<td>31.6</td>
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<td>47.2</td>
<td>37.5</td>
<td>74.0</td>
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<td>0.56</td>
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</table>

Figure 3. Non-parametric multidimensional scaling of granulometric data from the 11 sampling stations based on the Bray–Curtis similarity matrix of untransformed proportion data (see Table 2). Minimum stress: 0.01 for both two and three dimensions following 10 iterations.

Echinus esculentus L., Virgularia mirabilis Lam., and Liocarcinus depurator L. There were clear differences in the abundance of some species among transects (Figure 6). For example, V. mirabilis was absent from transect 3, rare in transect 2 but the most abundant species in T1. M. rugosa was significantly less abundant in T1 than in the other two. Differences in the density of L. depurator were not significant. A. rubens was more abundant during summer and autumn compared with winter and spring in T2 and T3, with the variation being particularly large during autumn in T3.
The megafaunal surveys identified a number of species with high monitoring potential because of their abundance, low temporal variation and ease of identification and/or collection. Such key species (e.g. *M. rugosa* and *E. esculentus*) offer potential for evaluating reef effects. The use of key species can help to focus sampling effort and increase the value of subsequent research (Cheal and Thompson, 1997). In combination with the identification of environmental factors that could influence the population density, this also facilitates the design of powerful experiments to quantify reef impacts on the surrounding community. Species that show high spatial and temporal variability, such as *V. mirabilis*, are not considered useful indicator species as their inherent variability is likely to reduce the power of subsequent statistical analysis (Underwood, 1997). Knowledge of temporal variation in abundance is also extremely
valuable in designing further experiments. For example, the considerable temporal variation in the abundance of *A. rubens* could complicate any experimental design using this species as an indicator.

In any sampling programme, there is a trade-off between number of stations sampled and the number of replicate samples taken per station: for a given number of samples analysed, the scope of a monitoring programme can only be extended at the cost of statistical power (Underwood, 1997). The ultimate choice depends on the objectives and these are sometimes difficult to define at the pre-deployment stage. However, the macrofaunal survey has helped in generating *a priori* hypotheses by identifying and quantifying the most abundant and least variable species. In this particular case, brittle stars showed low variation and therefore would appear ideal for testing the stated hypothesis post-reef deployment.

The pre-deployment research has aided the development of a working hypothesis in which benthic impacts are mediated through current regime modification and subsequent changes in granulometry and sediment oxygenation. This is enabling the design of post-deployment experiments that will more cost-effectively address some of the fundamental issues relating to the impacts of artificial reefs.

**Acknowledgements**

This work is part of Project Reef 2000 (coordinated by the Marine Resource Initiative) and was funded by Foster Yeoman Limited, Argyll and the Islands Enterprise and Lochaber Limited and EU PESCA. Our thanks to the late N. McDougal for assistance in the use of the *ROXAnn* system, Dr. P. Provost for deploying current regime modification and stakeholder consultation in an artificial reef development, and Dr. P. Provost for deploying current regime modification.

References


