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Macroalgal vegetation on a north European artificial reef (Loch Linnhe, Scotland): biodiversity, community types and role of abiotic factors

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Abstract

Very little is known about the marine macroalgae of artificial reefs—especially in the North Atlantic—despite the growing number and extent of man-made structures in the sea, and even though seaweed communities have paramount importance as primary producers, but also as feeding, reproductive and nursery grounds in coastal ecosystems. This paper explores the macroalgal diversity of a large system of artificial reefs in Loch Linnhe, on the west coast of Scotland, in a quantitative and qualitative study based on diving surveys and correlates the observations with the prevalent abiotic factors. The study was conducted in order to test the hypothesis that artificial reefs can enhance seaweed habitats—in particular, for kelps—and that there is a clear correlation with substrate type. While the reef is home to a large range of biota and abundance of early-successional species of turf and bushy macroalgae, totalling 56 taxa and with *Delesseria sanguinea* as the dominant species, canopy-forming perennial kelp species are conspicuously relatively rare. Macroalgal vegetation is explored in correlation with reef geometry/geography and depth. Statistical analysis shows benthic communities were strongly affected by substrate type, with turf algae and invertebrates dominating the artificial reefs, while bushy algae dominate the natural ones. Common macro-invertebrates associated with the phytobenthic communities are assessed qualitatively.

Keywords Artificial reef · *Delesseria* · *Laminaria* · Phytobenthic communities · Seaweeds · Turf algae

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10811-019-01918-2>) contains supplementary material, which is available to authorized users.

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Introduction

Artificial reefs (ARs) are artificial underwater structures which are usually built to protect or enhance marine biodiversity, including commercial species, in areas with an otherwise featureless sea bed (Sayer 2019). Other approaches aim at diverting existing impacts from recreational scuba diving from heavily impacted natural reefs (Tynyakov et al. 2017). In many cases, they are built with objects which originally had a different purpose—such as oil platforms, shipwrecks, vehicle tires or subway carriages. There is growing interest in artificial reefs also in the context of offshore oil platform decommissioning. ‘Rigs to Reefs’ schemes are widely applied especially in the Gulf of Mexico, but the practice has been largely outlawed in Europe and Australia (Techera and Chandler 2015). The increasing development of offshore wind farms and other marine renewable energy installations has also raised interest in artificial reefs—ideally, in order to address several objectives in parallel such as power generation, coastal protection and enhancement of fish stocks and marine biodiversity (Lopes de Almeida 2017). On the other hand,

reckless use of ARs has also raised scientific concerns in regard to natural habitat destruction, contaminant release, food-web alterations and invasive species propagation (Salomidi et al. 2012, 2013; Sedano et al. 2019).

An important question is, to what extent can artificial reefs replace nearby natural reefs? That depends very much on the building material and topography of the artificial reef. A case study on molluscs in NW Sicily (Badalamenti et al. 2002) found significant differences in average number of species and in diversity values, while differences in the abundance of specimens were not significant. Three years after deployment, mollusc assemblages of ARs in the Gulf of Castellammare remain entities that are distinct from those of nearby natural reefs.

Seaweed colonization on artificial reefs has not been studied in the European Seas, unlike California or Japan where such studies have been conducted. However, given the importance of canopy-forming algae in structuring sublittoral coastal ecosystems in cold-temperate seas, this is an important gap of knowledge with implications for offshore renewable developments and oil platform decommissioning. This contrasts with the situation in Japan, where artificial reefs have been deployed since the 1600s (UNEP 2009)—including for the enhancement of perennial algal stocks, including kelps. Already in the late 1980s, 9.3% of the Japanese coastline had artificial reefs (Thierry 1988) and this proportion is almost certainly higher now. Their colonization by benthic organisms and the ecology of such communities in Japan is relatively well studied (Choi et al. 2002a, b)—including in the aftermath of the 2011 tsunami after the Tohoku Earthquake (Muraoka et al. 2017). Similarly, in southern California, a multi-year study has investigated whether an artificial reef can be the replacement substrate for giant kelp (*Macrocystis pyrifera*) forest, for compensating the impacts of the warm, turbid plume of the nearby San Onofre Nuclear Power Station (Reed et al. 2006; Arkema et al. 2009; Schroeter et al. 2015). More recently, Layton et al. (2019) used an array of artificial reefs to address more fundamental questions in kelp forest ecology, namely how ecosystem engineering by the kelp *Ecklonia radiata* is affected by reductions in patch size and kelp density, and whether this feeds back to influence the species' demographic rates. This study found that ecosystem engineering by adult *E. radiata* modified the environment to reduce sub-canopy water flow, sedimentation and irradiance, and overall, that ecosystem engineering by adult *E. radiata* facilitates development of juvenile conspecifics.

Loch Linnhe is a dynamically wide estuary on the west coast of Scotland, where hydrodynamic conditions are influenced primarily by wind forcing, freshwater input and tides (Rabe and Hindson 2017). A large rainfall catchment area produces a significant freshwater inflow into Loch Linnhe which, combined with its connection to the open sea, leads to salinity gradients in the horizontal and vertical (Rabe and

Hindson 2017). Numerous studies have explored the biodiversity and geochemistry of the natural environment of Loch Linnhe. Examples include the planktonic ecosystem (Heath 1995), rocky reef fish populations (Magill and Sayer 2002; Magill and Sayer 2004), sandy bay flatfish (Gibson et al. 2011), macrofaunal populations (Sayer and Poonian 2007) and rare brown algae (Yang et al. 2014).

The Loch Linnhe Artificial Reef is deployed in this area. Its primary goal is to facilitate research into fundamental and applied aspects of marine science, particularly in relation to the changes associated with the deployment of offshore structures. Artificial reefs interact with the environment immediately after deployment and impact the flow of seawater around them. This has a series of knock-on consequences which need to be understood in order to predict how artificial reefs will perform in the abiotic and biotic marine environment. Understanding fluid-flows in the context of tidal dynamics around the reef was studied by Al-Bourae et al. (2013). The flow-interaction can be assessed using a variety of methods and some of these, including innovative sediment trap development, were developed (Mills 2009) and assessed in terms of impacts on macrobenthic infauna and sediment oxygenation (Wilding 2006, 2014). The productivity of structures, in terms of the number of secondary producers (urchins, *Echinus esculentus*) formed the basis of two studies (Cross 2012; Purcell-Milton 2014). For a number of conspicuous fish and invertebrate species, abundance levels were 2–3 times higher on some of the more complex artificial reefs than natural reef habitats (Hunter and Sayer 2009). Those results supported the forecasts made by Sayer et al. (2005), based on a series of ecosystem simulation models constructed to examine the potential consequences to selected fisheries of different scales and types of intervention using artificial reefs, centred on the one in Loch Linnhe. Consequently, the Loch Linnhe Artificial Reef offers a great opportunity to address the gap of knowledge in terms of algal colonization on artificial European reefs, which is considered in the present paper.

Seaweeds are major benthic primary producers on hard substrates in coastal waters around the world, where they are typically subject to a strict zonation as a function of depth with light availability, hydrodynamics and tidal exposure being the major abiotic drivers (Lobban and Harrison 1997). In contrast, soft substrates are largely devoid of seaweeds where microalgae have a dominant role as primary producers (Lobban and Harrison 1997). Kelp forests are widely considered climax communities of high ecological value in cold-temperate and polar seas (Steneck et al. 2002). With this background, this study tested the hypothesis that artificial reefs can enhance seaweed habitats by providing hard substrates—in particular, for kelps—and that there is a clear correlation with substrate type.

Materials and methods

The reef

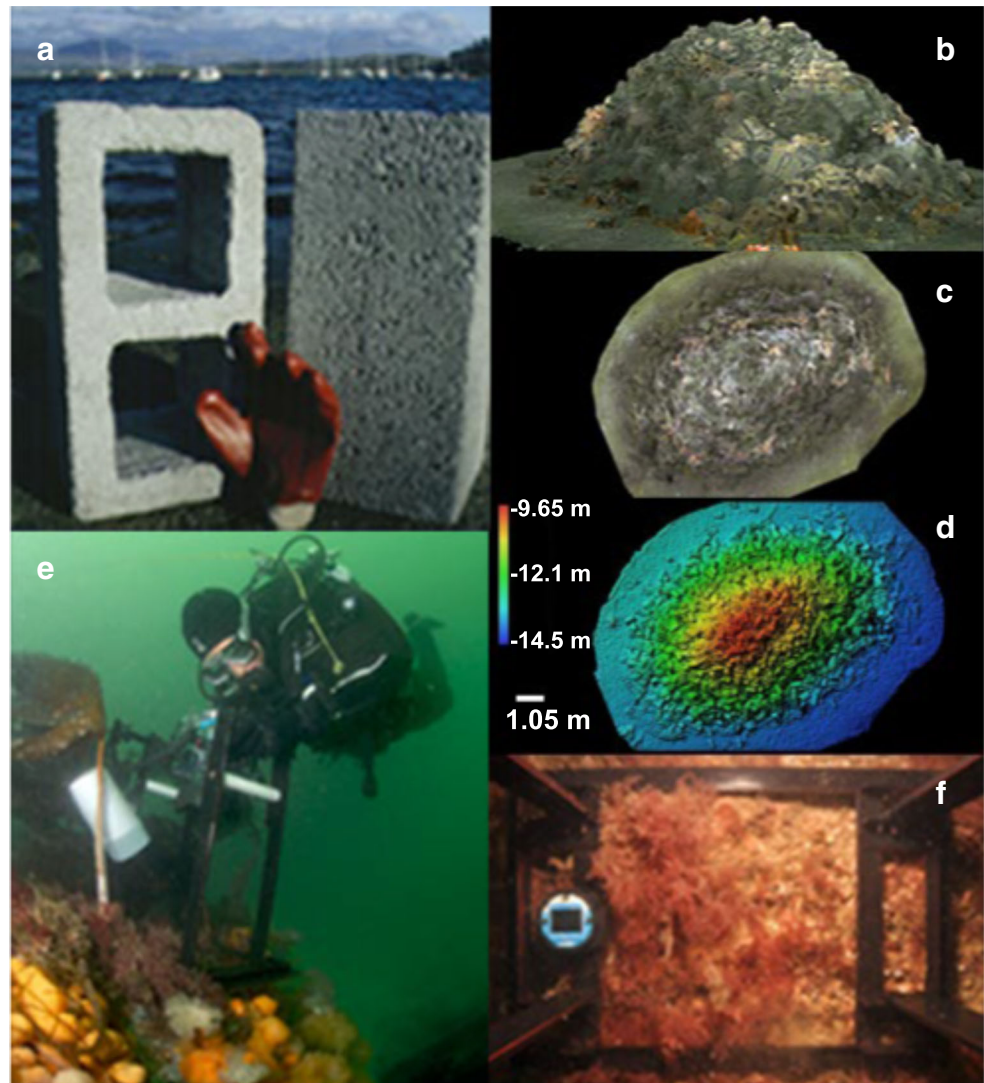
The Loch Linnhe Artificial Reef is a purpose-built experimental set of reef structures constructed in Loch Linnhe, off the east side of Lismore, on the west coast of Scotland (56° 32' N, 5° 27' W; for a detailed map: Wilding 2014). Construction of the reefs began in May 2001 and was completed in August 2005 (Supp. Table S1). Each module was constructed from approximately 4000 concrete blocks in an area of approximately 0.4 km² (Sayer and Brown 2010). Two types of block were used in the reef, termed 'simple' and 'complex' (solid vs. hollow; Fig. 1a), both having external dimensions of 200 × 200 × 400 mm, made in part from low-value washings from a nearby aggregate quarry (Foster Yeoman, Morvern); the blocks were made using moulds that made breeze blocks used in the construction industry. The simple blocks were solid

while the complex blocks contained two voids each of 130 × 130 mm (Wilding et al. 2007; Sayer and Brown 2010). The main experimental part of the reef consists of 30 separate reef modules, with five groups each with six modules (three constructed completely with simple blocks and three completely made from complex blocks). All reef modules were constructed by deploying the concrete blocks by dropping at the water surface over a point-target in water 14–30 m in depth. The blocks accumulated on the seabed in a roughly conical mound of 3–4.5 m in height with a circumference of 40–60 m (Fig. 1b–d; Wilding et al. 2007).

Sampling design and materials

Diving surveys were conducted from July 21 to 25, 2014 at depths between 12 and 22 m (Fig. 1e, f). Beyond this depth, very little seaweed vegetation occurs on the reefs due to lack of light. Deeper parts of the reef were therefore not

Fig. 1 A Loch Linnhe artificial reef module. **a** Construction blocks; left: a hollow block used in the construction of 'complex' reef modules (400 × 200 × 200 mm, with two 200 × 130 × 130 mm voids), and right: a solid block used for constructing 'simple' reef modules (400 × 200 × 200 mm). **b** A stereophotogrammetric model (*Agisoft Metashape*) of a complex reef module (Module B2C; 4100 blocks, deployed 12 Aug 2003) made from 1847 in situ photographic images, showing the conical shape of the structure. **c** A stereophotogrammetric plan view of module B2C showing the spread area of the module. **d** A bathymetric stereophotogrammetric plan view of module B2C showing the conical shape of the structure, a minimum water depth over the module of 9.7 m and a maximum depth at the base of 14.5 m; a maximum reef height of 4.8 m. **e** Diver conducting photoquadrat survey on the Loch Linnhe AR within the framework of this study. **f** Typical photoquadrat image generated within the framework of this study



investigated. Seven sampling sites were selected, of which five were artificial (three simple and two complex modules), and two reference environments, namely a rocky reef (Ardmucknish Point, ARD_N) and a long-established WW2 wreck of the *SS Breda* (BR_N; sunk in 1940). Modules selected were of comparable volume and surface areas but slightly variable in depths and heights (Supp. Table S2). The rocky reef was located close to Ardmucknish Point (56° 28.397' N, 5° 27.642' W) and consisted of a series of linked bedrock ridges with depths ranging from 0 to 21 m. Ardmucknish Point is within Ardmucknish Bay which is part of the Loch Linnhe system. In Ardmucknish Bay, the western face of a natural rocky reef (56° 53.4813' N, 5° 52.8393 W), near the *SS Breda* wrecksite, which is the closest to the artificial reef site was further surveyed in order to establish the depth distribution of kelp (*L. hyperborea*) forest. The dive was at LW Oban, which was 0.7 m above chart datum.

Photographic sampling was conducted based on the same equipment and methodology developed by van Rein et al. (2011). The present study used a Nikon D70 digital single-lens reflex (DSLR) camera in an *Ikelite* underwater housing with a single *Ikelite* strobe mounted in a purpose-built aluminium frame with an attached 25 × 25 cm quadrat extended 40 cm outwards from the camera lens.

At the artificial modules, sampling targeted all available depth contours at 1-m interval, at all four cardinal directions (N, E, S, W), thus resulting in four replicate samples per contour. At the reference sites, i.e. natural reefs, sampling targeted similar depth contours within the originally occurring slope aspects (Supp. Table S3).

Collection and identification of macroalgae

For taxonomic purposes, selective destructive random sampling was performed by means of manually collecting the species present at every reef module surveyed. It was attempted to capture the entire macroscopically visible seaweed diversity of every reef module, avoiding sampling bias by collecting at least one specimen of every species. Specimens were subsequently kept in a mesh bag, which was kept in a bucket of fresh seawater on the boat afterwards until further investigation at the lab. Immediately following each day of diving, herbarium specimens were prepared by mounting algal thalli on Bristol paper, or samples were fixed as permanent mounts on microscope slides, using acetocarmine and 50% Karo Syrup and subsequently sealed with nail polish once dried (Küpper and Müller 1999). They were deposited in the herbarium of the University of Aberdeen (Aberdeen, UK). For taxonomic and nomenclatural aspects of the identified seaweeds, we followed the on-line data provided by Silva (2018) and Guiry and Guiry (2019).

Collection and identification of invertebrates

For a general understanding of the macroinvertebrates associated with the AR communities, representative samples were collected within 2 AR sites surveyed (B3c and D2c) and kept in 4% formal/seawater (Supp. Table S4).

Sample analysis

A total of 970 photoquadrats (25 × 25 cm) were analysed at the laboratory. Conspicuous algal species were identified to the lowest possible taxonomic level and assigned to one of four morpho-functional group categories, i.e. canopy, bushy, turf and crustose, based on Murray et al. (2002). Two additional groups were used for invertebrate coverage and bare substrate. Percent cover values per taxon were estimated using a superimposed digital grid in the Adobe Photoshop CS5 image editing environment.

Statistical analysis

The examined dataset of benthic cover by functional groups was tested for the normality and homogeneity of variances using Shapiro-Wilk's and Levene's test respectively. Since the data of the examined variables significantly deviated from normality, the non-parametric tests Kruskal-Wallis (H) test and Mann-Whitney *U* test (*U*) (for post hoc analysis of significant differences between the different levels of the examined factors), respectively, were used. The data were organized in two matrices: (i) benthic cover by functional groups (6 variables: canopy algae—CA, bushy algae—BA, coralline algae—CLA, turf algae—TA, bare rock—BR, invertebrates—INV) that were arcsine (sqrt) transformed to improve the spread of the data, and then normalized to standardize the contribution of variables measured as percent cover; (ii) 'environmental' (4 variables: substrate, artificial substrate type, orientation, depth). Within- and among-reef variation was assessed using ordination methods on dissimilarity matrices in the statistical software PRIMER-E v7; correlation-based principal components analysis (PCA) on Euclidean distances for the benthic cover matrix (as the data is continuous and needed to be normalized). Groupings presented in PCA were assessed by overlaying slices from a hierarchical cluster analysis using group averaging of the same Euclidean distance matrix.

Results

A total of 56 macroalgal taxa were identified across our sample size, of which 7 were green, 13 brown and 36 red algae (Table 1). In terms of presence/absence, about half (29) of the taxa encountered occurred both on artificial and natural

Table 1 List of macroalgae encountered in the study area

Functional group	Species	Reef type	
		Artificial	Natural
Bushy	<i>Bonnemaisonia asparagoides</i> (Woodward) C. Agardh	+	+
Bushy	<i>Bornetia secundiflora</i> (J. Agardh) Thuret	+	+
Bushy	<i>Bryopsis</i> sp.	+	
Bushy	<i>Calliblepharis jubata</i> (Goodenough & Woodward) Kützing	+	
Bushy	<i>Chorda filum</i> (Linnaeus) Stackhouse	+	+
Bushy	<i>Cryptopleura ramosa</i> (Hudson) Newton	+	+
Bushy	<i>Dictyota dichotoma</i> (Hudson) Lamouroux	+	+
Bushy	<i>Dictyota implexa</i> (Desfontaines) Lamouroux	+	
Bushy	<i>Dilsea carnosa</i> (Schmidel) Kuntze		+
Bushy	<i>Furcellaria lumbricalis</i> (Hudson) Lamouroux	+	+
Bushy	<i>Heterosiphonia plumosa</i> (Ellis) Batters	+	+
Bushy	<i>Lomentaria</i> sp.	+	
Bushy	<i>Metacallophyllis laciniata</i> (Hudson) Vergés & Le Gall	+	+
Bushy	<i>Odonthalia dentata</i> (Linnaeus) Lyngbye	+	+
Bushy	<i>Palmaria palmata</i> (Linnaeus) Weber & Mohr		+
Bushy	<i>Petalonia fascia</i> (Müller) Kuntze		+
Bushy	<i>Phycodrys rubens</i> (Linnaeus) Batters	+	+
Bushy	<i>Plocamium cartilagineum</i> (Linnaeus) Dixon	+	+
Bushy	<i>Porphyra</i> sp.		+
Bushy	<i>Ptilota gunneri</i> Silva, Maggs & Irvine	+	+
Bushy	<i>Rhodophyllis divaricata</i> (Stackhouse) Papenfuss	+	+
Bushy	<i>Schizymenia dubyi</i> (Chauvin ex Duby) J. Agardh	+	
Bushy	<i>Schottera nicaeensis</i> (Lamouroux ex Duby) Guiry & Hollenberg	+	
Bushy	<i>Stilophora tenella</i> (Esper) Silva	+	
Bushy	<i>Ulva compressa</i> Linnaeus	+	
Bushy	<i>Ulva lactuca</i> Linnaeus	+	
Bushy	<i>Ulva rigida</i> C. Agardh	+	
Bushy	<i>Ulva</i> sp.		+
Bushy	<i>Cystoclonium purpureum</i> (Hudson) Batters	+	+
Bushy	<i>Delesseria sanguinea</i> (Hudson) Lamouroux	+	+
Canopy	<i>Desmarestia aculeata</i> (Linnaeus) Lamouroux	+	+
Canopy	<i>Desmarestia ligulata</i> (Stackhouse) Lamouroux		+
Canopy	<i>Fucus spiralis</i> Linnaeus	+	+
Canopy	<i>Laminaria hyperborea</i> (Gunnerus) Foslie	+	+
Canopy	<i>Laminaria digitata</i> (Hudson) Lamouroux		+
Canopy	<i>Saccharina latissima</i> (Linnaeus) Lane, Mayes, Druehl & Saunders	+	+
Canopy	<i>Saccorhiza polyschides</i> (Lightfoot) Batters	+	+
Coralline	Coralline algae	+	+
Turf	<i>Apoglossum ruscifolium</i> (Turner) J. Agardh	+	+
Turf	<i>Chaetomorpha aerea</i> (Dillwyn) Kützing		+
Turf	<i>Cladophora</i> sp.	+	
Turf	<i>Compsothamnion gracillimum</i> De Toni	+	+
Turf	<i>Dasya corymbifera</i> J. Agardh	+	
Turf	<i>Dasya punicea</i> (Zanardini) Meneghini	+	+
Turf	<i>Dasya</i> sp.	+	+
Turf	<i>Ectocarpus</i> sp.		+
Turf	<i>Erythrotrichia carnea</i> (Dillwyn) J. Agardh	+	

Table 1 (continued)

Functional group	Species	Reef type	
		Artificial	Natural
Turf	<i>Halurus flosculosus</i> (Ellis) Maggs & Hommersand	+	
Turf	<i>Haraldiophyllum bonnemaisonii</i> (Kylin) Zinova	+	+
Turf	<i>Hypoglossum</i> sp.		+
Turf	<i>Membranoptera</i> sp.		+
Turf	<i>Nitophyllum punctatum</i> (Stackhouse) Greville	+	+
Turf	<i>Polysiphonia</i> sp.	+	+
Turf	<i>Pterothamnion plumula</i> (Ellis) Nägeli	+	
Turf	<i>Rhodymenia</i> sp.		+
Turf	<i>Vertebrata byssoides</i> (Goodenough & Woodward) Kuntze	+	+

substrates, while 15 taxa were found only on the artificial reef and 12 taxa only on the natural reef reference sites (Table 1). In terms of abundance, *Delesseria sanguinea* was the dominant species on the artificial reefs, while *Heterosiphonia plumosa* and *Plocamium cartilagineum* were dominating on the natural substrates (Table S5). The kelps *Saccharina latissima*, *Laminaria digitata* and *L. hyperborea* were found on both artificial and natural substrate but with low overall abundance on the artificial reef. *S. latissima* was the most common of the 3 kelp species on the artificial reef. *Laminaria digitata* and *L. hyperborea* occurred on nearby natural rocky reefs as canopy-forming keystone species.

Benthic communities were strongly affected by substrate type, with turf algae and invertebrates (mostly hydrozoa, serpulids and barnacles, accompanied by limpets, ascidia, ctenoids, bryozoa, sponges and polyplacophores; generally suspension feeders—also a few seastars and sea urchins) dominating the artificial reefs (sites: B1, B2, C1, D2, E3), while bushy algae dominated the natural ones (ARD, BR; Fig. 2, Table S6). Similarly, significant differences were detected even between AR modules built by simple and complex types of blocks, respectively, with bushy algae dominating the former and turf and invertebrates the latter ones (Fig. 3, Tables S6, S7), respectively.

Although no statistical significance was revealed for factors such as orientation or depth on biota (Table S7), bushy algae were more abundant at depths of 10–16 m and were replaced by invertebrates in deeper horizons, while canopy algae remained restricted to shallow depths, hardly deeper than 12 m.

The first principal component (PC1) axis of the PCA differentiated sites along a gradient from low turf algae cover (< 20%) at negative PC1 scores, to high bushy macroalgae cover (up to 98%) at positive PC1 scores (Fig. 4). A separation from invertebrates to canopy algae, coralline algae and bare rock was represented by PC2. A slice through a cluster analysis at a

Euclidean distance of 0.7 represented two groupings in the data at extreme ends of PC1 (Fig. 4).

The survey of the natural reef closest to the artificial reef on January 24, 2019, revealed that the deepest extent of kelp forest is at 6.5 m (though very patchy—contiguous forest was 5.5 m), that the lowest extent of kelp park (i.e. single kelp thalli, without contiguous canopy; Burrows et al. 2014) is at 10.7 m, and that the lowest extent of individual kelp plants (very small, < 20 cm stipes) is at 13.4 m. These observations were confirmed by horizontal surveys along these depth contours.

Common invertebrates (4 molluscs, 1 sponge, 2 balanoid crustaceans, 1 tunicate and 2 echinoderms) associated with the macroalgal communities on AR modules which were assessed qualitatively are listed in Supp. Table S4. It is worth noting that the canopy-forming red alga *D. sanguinea* was host to a high density of a small bivalve, *Turtonia minuta*, and of the snail *Lacuna vincta*. Under the algal canopy, the ascidian *Asciidiella aspersa* and the sponge *Suberites ficus* were common. At all sites, feather stars (*Antedon bifida*) were highly abundant.

Discussion

Seaweeds are a key feature of the UK's marine biodiversity and the changes and threats that it faces (Küpper and Kamenos 2018). Large brown algae, kelps (Laminariales) and fucoids (Fucales), are major structuring elements on rocky shores of the UK, forming large intertidal and subtidal forest-like communities. Such brown algal forests are important feeding, reproductive and nursery grounds for a plethora of marine animals (including commercial fish and shellfish species), and enhance coastal protection (Bartsch et al. 2008) and coastal atmospheric/climatic processes (e.g. cloud formation as a consequence of iodine emissions; Küpper et al. 2011).

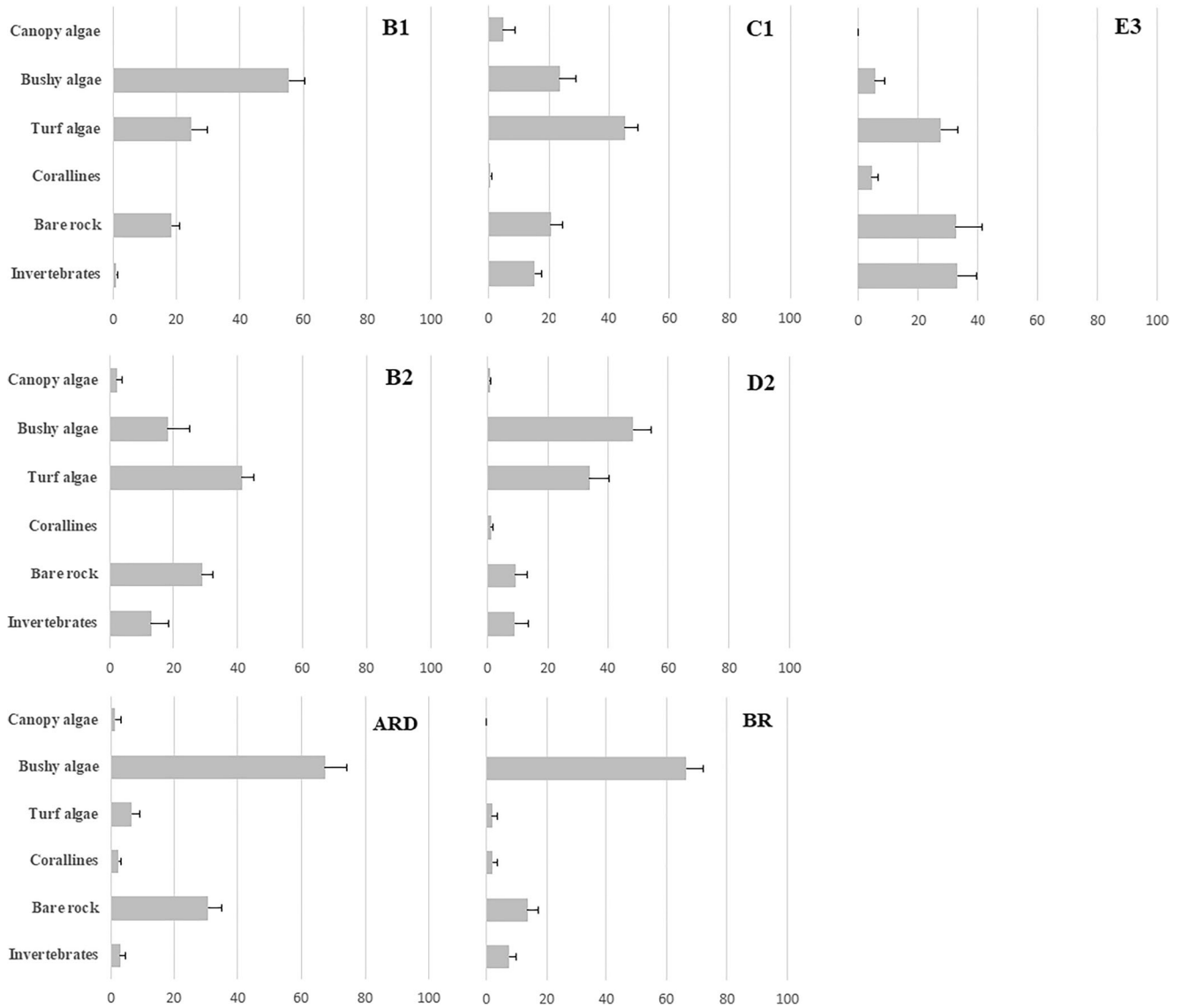


Fig. 2 Percent cover (with ± SE error bars) of the benthic functional groups of all the reefs (artificial, natural) assessed at the study area

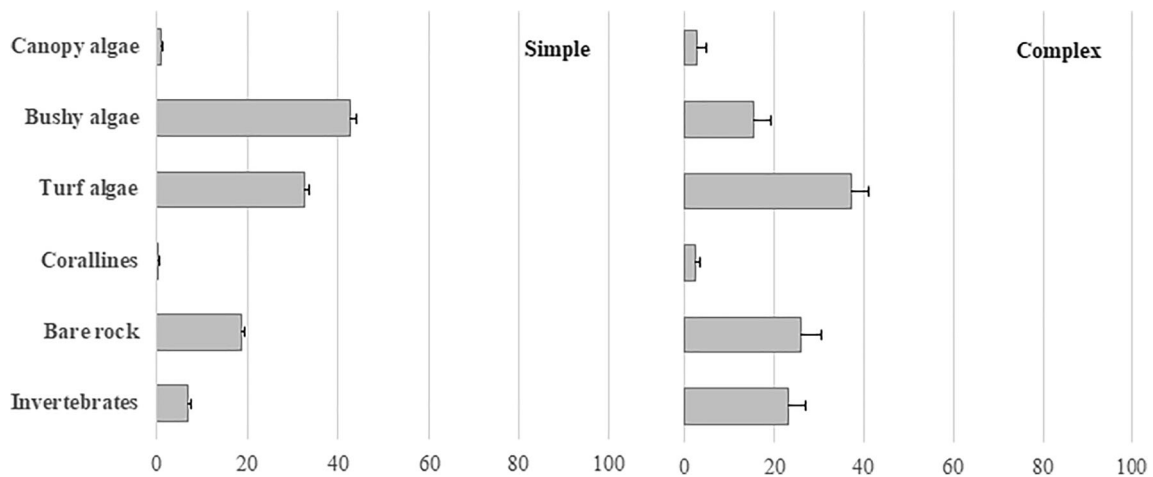


Fig. 3 Percent cover (with ± SE error bars) of the benthic functional groups in different types (simple, complex) of artificial reefs

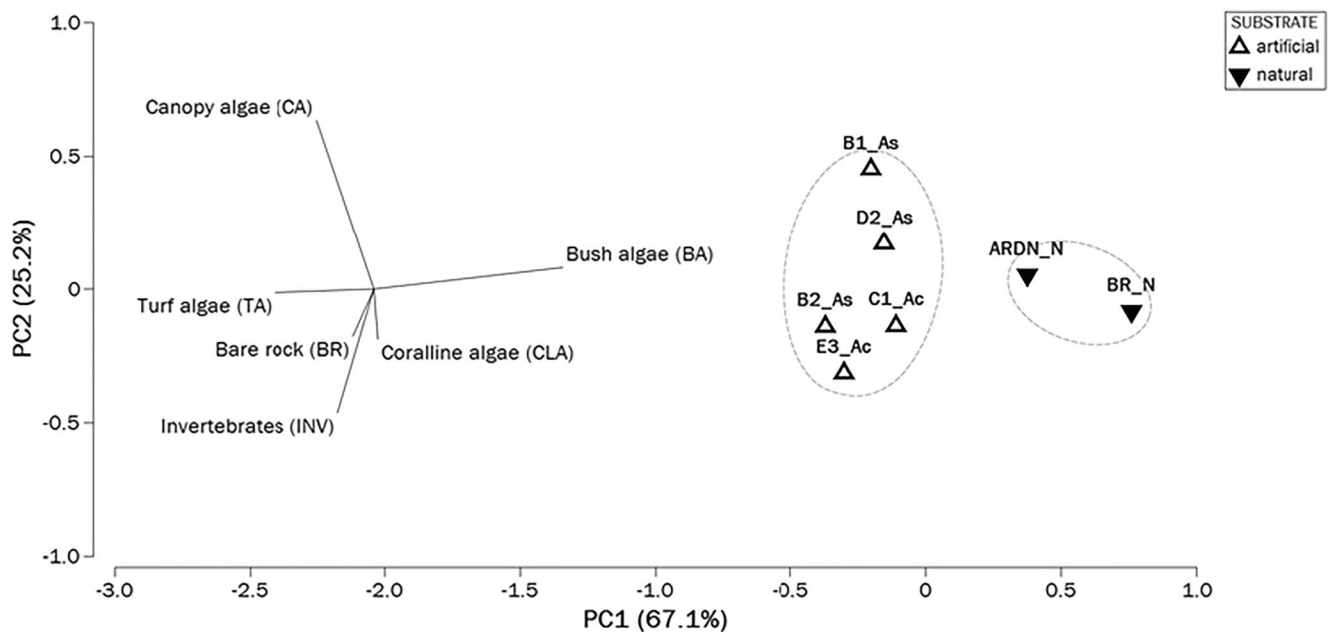


Fig. 4 Principal component analysis of benthic cover variables. Spatial variation in benthic cover on artificial and natural reefs, shown for the first two components from a principal component analysis on arcsine (sqrt) transformed data. Ellipses show groupings calculated from a slice taken

through a hierarchical cluster analysis at a Euclidean distance value of 0.7. The relative contribution of the six benthic cover categories to the observed variation in reef benthic cover condition shown as overlaid eigenvectors

Despite their overall ecological importance, algae have rarely been studied in the context of artificial reefs—even though such structures are getting more and more common, in the UK and worldwide, intentionally (like in the case of the Loch Linnhe Artificial Reef, studied here) and unintentionally (like in the case of shipwrecks, etc.).

The results presented here show that the Loch Linnhe AR harbours mostly turf and some bushy algae and very occasionally also kelps (mostly *S. latissima*, and much more rarely *L. digitata* and *L. hyperborea*). This is a key outcome demonstrating that even though this AR system provides ample hard, sufficiently rough substrate, it has not led to the establishment of climax communities of perennial, long-lived kelps forming contiguous canopies as at nearby natural sublittoral rocky reefs (this study for immediately adjacent natural rocky reefs in Loch Linnhe; Smale and Moore 2017 for rocky reefs of the UK in general), and unlike ARs in California (Reed et al. 2006; Arkema et al. 2009) and Japan (Choi et al. 2002b). Instead, it is characterized by an abundance of bushy algae, in particular the red alga *D. sanguinea* and turf algae. In this context, it might be mentioned that *D. sanguinea* has a high biotechnological interest (e.g. Luhn et al. 2014) and that this study highlights that ARs of the design of that in Loch Linnhe might be suitable for the sustainable production and harvesting of this species.

Of course, a question is whether the > 10 years that had passed since the completion of reef deployment until the surveys reported here are sufficient for *Laminaria* species to establish themselves as climax community. Indeed, it can be

argued that over a decade is more than enough for the establishment of a kelp forest, which is a notion supported by a number of studies. Christie et al. (1998), working in Norway where the same kelp species occur as in our study site on the Scottish west coast, found that in an area cleared of adult kelp thalli, recruitment is quite quick (1–2 years) with complete recovery of populations after 4–5 years. A study with settlement panels in Western Australia (Smale et al. 2011) showed that settlement and recruitment of kelps can occur within 14 months, while a similar study in California observed recruitment of kelp within 13 months (Muth 2012)—it could be expected to be the same for *L. hyperborea* in Scotland (Smale, personal communication). Finally, zoospore dispersal is reasonably far and one could certainly expect zoospores to arrive at the artificial reef site (Fredriksen et al. 1995). Another, much more likely possibility is that most of the Loch Linnhe AR is simply too deep for contiguous *Laminaria* kelp forests, given that most nearby kelp forests are concentrated between the low water mark approx. 4–5 m (Smale and Moore 2017) and confirmed by the surveys of the nearest natural reef, showing that the deepest extent of kelp forest was at 6.5 m, the lowest extent of kelp park at 10.7 m and the lowest extent of individual kelp plants at 13.4 m.

A key conclusion from this study for UK coastal waters is that encouraging ecologically desirable kelp settlement on artificial structures may be limited to shallow water deployments. However, these could present a navigational hazard to surface vessels and therefore may not obtain the relevant licencing.

Compared to other aspects of marine biodiversity and ecology in the context of artificial reefs, very few studies, anywhere in the world, have considered seaweeds. In an artificial reef study in Murohana, Ikata, Japan (Choi et al. 2002a, b), it was found that the climax stage established itself at the reef within only 18 months, comprised 2 large canopy-forming brown algae, *Sargassum* spp. and *Ecklonia kurome*, as well as *Padina arborescens*. The Murohana ARs concerned are slightly shallower (starting at 8-, 10- and 13-m depth and consisting of single blocks which are 1.2 m high, respectively; Choi et al. 2002a) than the Loch Linnhe AR, but of course this is not directly comparable given the different species involved and totally different hydrography between Japan and the Scottish west coast. The same study (Choi et al. 2002a, b) observed that *Ulva* (*Enteromorpha*) *intestinalis* and *Colpomenia sinuosa* were dominant pioneering species in spring. The settlement of kelp, such as *E. kurome*, was promoted by reduced sand cover as a result of turbulence. Large-scale surface roughness seems to play a role in maintaining the communities after initial establishment; i.e. smooth surfaces are unsurprisingly less suitable for seaweed colonization (Choi et al. 2002a, b).

In their study off the southern California coast, investigating a 9-ha large artificial reef near the San Onofre Nuclear Power Station off San Clemente, CA, USA, Reed et al. (2006) found that all six configurations of reef material and bottom coverage tested provided suitable habitat not just for giant kelp (*Macrocystis pyrifera*) but also for kelp forest fishes. Fish standing stock, density, species richness and recruitment on all the artificial reef designs were either similar to or greater than that observed at two nearby natural reefs. The amount, but not the type, of reef material had a substantial influence on the fish assemblage, with higher densities and numbers of species occurring on artificial reef modules with greater coverage of hard substrate. This is clearly an important subject for further research at the Loch Linnhe AR. A multi-year study (Arkema et al. 2009) evaluated the effect of giant kelp on the relative abundance of algae and invertebrates by experimentally manipulating kelp abundance on these large artificial reefs. The experiments revealed a negative effect of giant kelp on both light availability and understory algal abundance and a positive effect on the abundance of sessile invertebrates, which was consistent with an indirect effect mediated by shade from the kelp canopy. In a further follow-up, Schroeter et al. (2015) observed that the percent cover and slope of hard substrate were significantly related to the abundance and species richness of both understory algae and sessile invertebrates. The abundance and richness of colonizing algae were significantly related to location (i.e. proximity to the nearest natural reef), while that of sessile invertebrates was not. The type of hard substrate (quarry rock vs. concrete rubble) was unrelated to the abundance and diversity of either algae or invertebrates at any time during the 5-year study.

Where it is not possible to avoid the construction or removal of human infrastructures in the sea, eco-engineering approaches aiming to design appropriate ARs, which are mindful of site characteristics, the local species pool, conservation targets and project goals, can assist in minimizing the ecological footprint (Strain et al. 2018). In this sense, AR design might aim to create habitats also supporting ecologically high-value keystone seaweed species such as kelps.

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