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Sabellaria spinulosa reef: a scoring system for evaluating 'reefiness' in the context of the Habitats Directive

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'Reefs' are listed under Annex I of the Habitats Directive as a marine habitat to be protected by the designation of Special Areas of Conservation. Crucially for the implementation of the Directive, the distinction between what is considered as 'reef' and what is not is imprecise, particularly in relation to colonies of the tube-building polychaete *Sabellaria spinulosa*. Guidelines are proposed for the implementation of the Habitats Directive definition to provide a robust and transparent approach for the benefit of both regulators and offshore industry. Specifically, it is suggested that the conservation priority of a *S. spinulosa* aggregation could be determined using a scoring system based on a series of physical, biological and temporal characteristic reef features, weighted according to the perceived importance of each feature and augmented with a further score indicating the confidence in the feature score. Suggestions are given as to how these characteristics might be measured and scored, along with an example to illustrate the application of the approach.

INTRODUCTION

The 'ross worm', *Sabellaria spinulosa* Leuckart 1849, is a sedentary, epifaunal polychaete that builds rigid tubes from sand or shell fragments. It is a suspension feeder that is generally found living alone or in small groups but can be gregarious in favourable conditions. Colonies producing fused sand-tubes may form thin crusts or extensive reefs which can cover several square kilometres.

'Reefs' are listed under Annex I of the EC Habitats Directive (Council Directive EEC/92/43 on the Conservation of Natural Habitats and of Wild Fauna and Flora) as a marine habitat to be protected by the designation of Special Areas of Conservation (SACs). An explanation of this term is provided by the Interpretation Manual of European Union Habitats (EUR 25), which is used for the implementation of the Directive. Hereafter referred to as the Habitats Directive definition, this defines 'reef' as:

> 'Submarine, or exposed at low tide, rocky substrates and biogenic concretions, which arise from the seafloor in the sublittoral zone but may extend into the littoral zone where there is an uninterrupted zonation of plant and animal communities. These reefs generally support a zonation of benthic communities of algae and animal species including concretions, encrustations and corallogenic concretions.'
> (European Commission DG Environment, 2003)

The manual indicates that this definition specifically corresponds to several categories of the German classification system, including '030209—*Sabellaria*-Riff des Sublitorals der Nordsee' (*Sabellaria* reefs of the sublittoral North Sea), and thus indisputably encompasses some of the biogenic structures created by colonies of *S. spinulosa*. Therefore, as a signatory of the Convention on the Conservation of European Wildlife and Natural Habitats (Bern, 19 September 1979), the European Community is obliged, by means of the Habitats Directive, to maintain a favourable conservation status of such *Sabellaria* reef habitats.

A difficulty in implementing the Directive relates to the practical challenges in monitoring the status of such *S. spinulosa* reefs. The latter requires that they form a distinct entity, defined in such a way as to distinguish them from other habitats or biotopes. However, the growth forms of *S. spinulosa* cover a continuum from solitary individuals to extensive colonies, whilst the requirement for protection relates solely to the reef habitat provided by aggregations of the worm rather than the species itself. Crucially, the distinction between what is considered as 'reef' and what is not, is imprecise. The ambiguity is unsatisfactory both to regulators and to industry, particularly in relation to predicting the potential effects of proposed developments such as offshore windfarms, as well as other uses of the seabed such as trawling and aggregate dredging.

Debate as to what does and does not constitute reef stretches over decades in the scientific literature such that proposed definitions are perhaps as numerous as the reefs themselves. While some of the variations between definitions and interpretations are merely a question of semantics, others reflect different imperatives. Some definitions, for instance, are a reflection of the navigational hazardousness of the structure (McLeod, 1981); others are more concerned with ecosystem function (Holt et al., 1998), and yet others are concerned with the geological history. It is unlikely, therefore, that a single definition will suffice for all requirements.

In the case of *S. spinulosa*, the sole definition of statutory significance is that of the Habitats Directive, and hence

Table 1. *Levels of confidence that may be expected for reef characteristic scores based on a range of sampling methodologies with adequate survey strategies.*

Sampling method/ survey strategy	Characteristic features: Elevation	Consolidation	Extent/ area	Patchiness	*Sabellaria* density	Biodiversity (I) infauna (E) epifauna	Community composition	Longevity	Stability
Grabs/cores	G	G	P-M	P	G	(I) G; (E) P	G	P-M	P-M
Trawl/dredge	G	G	P	P	G	M	M	M	M
Drop-down video/ still photography	G	G	P-M	M	P-M	(I) P-M; (E) G	P-M	M-G	M-G
Diver	G	G	M	M	P-M	(I) P-M; (E) G	P-M	M-G	M-G
Short towed video	G	G	M-G	G	P-M	(I) P-M; (E) G	P-M	M-G	M-G
Remotely operated vehicle	G	G	M-G	G	P-M	(I) P-M; (E) G	P-M	M-G	M-G
Laser/scanning sonar	G	P	M-G	G	P-M	N/A	N/A	M-G	M-G
Sidescan—low frequency	P	P	P	P	N/A	N/A	N/A	P	P
Sidescan—high frequency	M	P	M-G	M-G	N/A	N/A	N/A	M-G	M
Swath bathymetry	P-M	P	P-M	P-M	N/A	N/A	N/A	P-M	P-M
AGDS/single beam	P	P	M	M	N/A	N/A	N/A	M	M

P, poor; M, moderate; G, good; N/A, not applicable; and AGDS, Acoustic Ground Discrimination Systems. Other methodologies such as traps and biomass measures for instance may also be useful but are not considered standard sampling procedures for *Sabellaria spinulosa* colonies.

consistency in the interpretation of this definition is of paramount importance. The primary aims of this paper, therefore, are to promote discussion on the ongoing efforts to distinguish between areas of biogenic reef and non-reef, specifically as it relates to *S. spinulosa*, and to recommend guidelines for the interpretation and application of the Habitats Directive definition in particular.

SCORING SYSTEM

The proposed approach for the interpretation of 'reef' reflects the latter's multifaceted nature. Specifically, it is suggested here that the classification of a particular *Sabellaria spinulosa* aggregation, and hence its conservation priority in the context of the Habitats Directive, could be determined using a scoring system based on a series of characteristic reef features. These features would be graded on a sliding scale of low–medium–high 'reefiness' adaptable to a variety of appropriate data types. Whilst the overall score summarizing a series of complex features which is provided by this method could be used to distinguish between reef and non-reef, reliance on the single score is likely to be an oversimplification.

The importance of the approach lies in the structured consideration of all the reef characteristics and the scoring process itself. It is, therefore, more helpful as a means of comparing the relative values of two different areas of *S. spinulosa* reef.

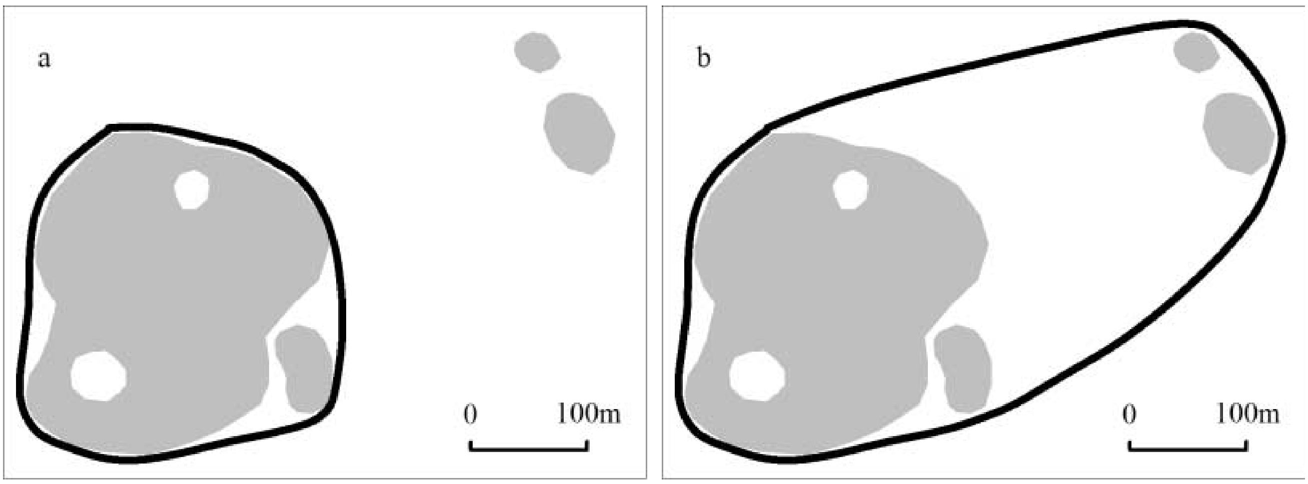

Figure 1. Two comparative interpretations of spatial extent and patchiness of *Sabellaria spinulosa* aggregations. The shaded area indicates aggregations of *S. spinulosa*, and the black line indicates possible interpretations of the colony boundary.

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Table 2. *Proposed scoring system for a variety of reef characteristics.*

	Characteristic score: Low … Medium … High 0 … 50 … 100		
	Low (0)	Medium (50)	High (100)
A. *Elevation score.*			
Average tube height	~10 cm	~15 cm	~20 cm
Maximum tube height	~15 cm	~20 cm	~30 cm
Indications from remote sensing	Undetectable	Colony produces an indistinct image	Colony produces a distinct image
B. *Sediment consolidation score.*			
Percentage cover of substratum by consolidated *Sabellaria* tubes	~30% cover	~45% cover	~60% cover
Degree of consolidation	Consolidation of sediment primarily an encrusting veneer of *Sabellaria* tubes, little concretion of substratum	Sediment consolidation by upright *Sabellaria* tubes, some concretion of underlying substratum	Substratum well consolidated by intertwined matrix of *Sabellaria* tubes
C. *Area score.*			
Extent of total area	Area ~600 m^2	Area ~900 m^2	Area ~1200 m^2
Extent of core area	Area ~200 m^2	Area ~350 m^2	Area ~500 m^2
Extent of peripheral area	Area ~500 m^2	Area ~750 m^2	Area ~1000 m^2
D. *Patchiness score.*			
Percentage cover of consolidated tubes within overall spatial extent of reef	~10% cover	~20% cover	~30% cover
E. Sabellaria spinulosa *density score.*			
Average density of *S. spinulosa* (/m^2)	~800 individuals	~1500 individuals	~3000 individuals
Maximum density (/m^2)	~500 individuals	~1700 individuals	~3500 individuals
F. *Biodiversity score.*			
Margalef's species richness	~5.0	~6.5	~8.0
Shannon diversity index	~2.5	~2.7	~3.0
Simpson's diversity index	~0.85	~0.87	~0.90
G. *Biotope score.*			
MNCR biotope code (see Table 3)	Other biotopes	CR.MCR.CSab.Sspi	SS.SBR.PoR.SspiMx
H. *Longevity score.*	No evidence for longevity of colony	Evidence of dense *S. spinulosa* aggregations found *repeatedly* but not *persistently* over time	Evidence of dense *S. spinulosa* aggregations found *persistently* over time

MNCR, Marine Nature Conservation Review.

It is further suggested that each individual reef characteristic score is augmented with a second score indicating the confidence in the former, and that both of these scores are weighted according to the perceived importance of the feature for the given application as outlined below. It is hoped that this approach will provide a relatively robust and transparent procedure for classifying a *S. spinulosa* reef.

Reef-like features

The characteristics which are important in the determination of the 'reefiness' of a structure are to some extent dependent on the context of the assessment and to the definition of reef being applied. This paper considers a variety of features that are considered to contribute to the 'reefiness' of a *S. spinulosa* aggregation in the specific context of the Habitats Directive definition, namely: (1) physical characteristics: elevation, sediment consolidation, spatial extent and patchiness; (2) biological characteristics: *S. spinulosa* density, biodiversity and community structure; and (3) temporal characteristics: longevity and stability. Various suggestions are given as to how these characteristics might be measured and scored, along with examples to illustrate their application.

It is recognized that in order to be of practical value for conservation management, the distinction between what does and does not constitute a 'reef' must relate to what can and cannot be distinguished in the field. Thus the criteria used to determine what constitutes a reef should be intimately bound to the survey techniques and sampling strategies adopted.

Threshold levels

While the absence of a particular feature should not necessarily be considered to preclude the designation 'reef', it is suggested that it would be appropriate for some features to have a threshold level below which a given aggregation of *S. spinulosa* tubes could be dismissed as constituting a reef. If, for example, the spatial extent of a particular *Sabellaria* aggregation was limited to 0.1 m^2, its small size is likely to preclude further practical consideration of the structure as a reef habitat irrespective of the scores for the other characteristic reef features. Conversely,

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an aggregation which does exceed the designated threshold does not necessarily qualify as being reef, it merely warrants further consideration. In more general terms, therefore, the more these reef-like characteristics are exhibited, the more is it justified to designate a particular aggregation as 'reef'.

Importance score

It is proposed that each of the characteristic scores are weighted according to the perceived importance of that feature through the application of a supplementary importance score. This will ensure the overall reefiness score would not be unduly biased by a high rank for a characteristic that is not considered to be of fundamental importance. It is expected that the importance ranking will be heavily modified with increasing experience, yet it is hoped that over time, consensus will work towards a default scale of importance.

The ability of the user to define their own importance ranking will also allow customization of the approach to a given application. If a regulator was trying to identify areas of reef that would benefit from a no-trawl zone, for instance, the importance of elevation to the assessment is likely to be heightened. The importance scores may also vary according to the statutory designations of particular areas.

Confidence score

Variable intensities of sampling and resolution of sampling methodology will inevitably mean that confidence in individual characteristic scores will vary. It is therefore proposed that each reef feature score is also given a confidence score. It is expected that this will reflect both the quantity and quality of information upon which a particular character score is based, and also the consistency of information where more than one source of data is available relating to a particular feature. Two methods for scoring confidence are proposed:

1. the user can grade their level of certainty on a relatively crude sliding scale from low–medium–high. For example, an average elevation score which is based on extensive, high-quality video imagery of a relatively uniform *Sabellaria* aggregation complemented with measurements derived from high frequency scanning sonar is likely to result in a high confidence score.
2. a temporal stability score which is solely based on a single anecdotal account is likely to score poorly in terms of confidence. Table 1 indicates the levels of confidence that might be expected from a range of standard survey techniques assuming a sound sampling strategy.

Whilst this method for scoring confidence is easily applied, it is highly subjective. It can be further refined by requiring the user to specify the likely maximum and minimum characteristic scores in addition to their 'best guess' score. The resulting range of potential scores for a given feature would then be a reflection of confidence. This method has the advantage of being more qualitative and more comparable to typical confidence intervals associated with statistical analysis.

The overall confidence score is a reflection of both individual characteristic scores, weighted according to perceived importance of a particular feature, and also the total number of characteristics scored. Thus the overall confidence in a particular aggregation being classified as a reef will be low if the assessment is based on a single characteristic, even if the confidence in that particular score is high.

PHYSICAL CHARACTERISTICS OF REEFS

The term 'reef' is thought to derive from the Old Norse term *'rif'*, meaning hazardous rib of rock, sand, or biological material that lies close to the surface of the sea (Wood, 1999). The term has evolved from its original nautical usage such that the navigational challenges posed by biogenic reefs are not a major consideration in the context of the Habitats Directive, but the term 'reef' is arguably still primarily a description of physical form. Consideration of the physical characteristics is therefore important in a working definition of 'reef'.

Elevation

The importance of elevation is manifest in the Habitats Directive definition which indicates that a biogenic concretion should 'arise from the sea-floor' if it is to be considered a reef (European Commission DG Environment, 2003). The significance is unsurprising considering the direct consequence of elevation on overall colony size as well as its broader influences on the distinctness of a biogenic reef biotope. It has been suggested, for instance, that the topographic relief of a reef will influence the degree to which it will modify the local depositional environment and processes of sedimentation (Wood, 1999). The level of influence is therefore likely to be commensurate with extent of elevation. While these assumptions seem reasonable, the converse may also be valid, namely that the degree of deposition and sedimentation in a given area will dictate the potential for reef formation. In such case, a measure of elevation can therefore be considered as an indication of the suitability of prevailing conditions for reef development.

It is likely, but not explicit, that the distinction of the Habitats Directive definition would exclude an encrusting *Sabellaria* colony from consideration as 'reef'. However, whilst many sessile organisms grow significantly raised above the substratum in order to increase their feeding efficiency and to avoid competition or smothering by sediment (Wood, 1999), in reality all epibenthic organisms produce some relief on the sea-floor. Hence, if the inclusion of this characteristic within a definition is to have any value, it is necessary to quantify the qualifying degree of elevation. In the case of the Habitats Directive definition, therefore, an arbitrary elevation threshold of 'greater than five centimetres' is suggested as an interpretation of 'arising from the sea-floor'. Structures not meeting this threshold can therefore be excluded from further consideration.

Sabellaria spinulosa individuals are less than 2 cm long, yet they have been reported to construct tubes up to 50 cm high (Hartmann-Schröder, 1971; Schäfer, 1972). Such heights appear uncommon, however, and most reports of *S. spinulosa* aggregations in UK waters refer to 'crusts' or 'sheets' of variable thickness, but which are rarely more than a few centimetres thick (Holt et al., 1998). Higher elevations have been reported for a few aggregations. The 'Saturn' reef off the Norfolk coast, for instance, was described as having 'a profile of around 10 cm in places' (BMT Cordah Ltd, 2003), whilst a reef off the Lincolnshire coast was reported to have heights of up to 60 cm (Foster-Smith & White, 2001). These reported values have been used as a basis for the proposed scoring scale which is presented in Table 2A. The measurements can be determined directly from *S. spinulosa* clumps collected by grab sampling or estimated from video imagery. Alternatively it is possible to get an indication of reef elevation from remote sensing techniques such as high-frequency side-scan sonar or swath bathymetry.

The BMT Cordah Ltd report from the visual remotely operated vehicle (ROV) survey of the Saturn reef provides an example of indirect height estimation from photographic images. The estimated profile of around 10 cm (BMT Cordah Ltd, 2003) would imply a fairly low elevation score. The elevation of a reef discovered to the west of Inner Dowsing by the Eastern Sea Fisheries Joint Committee, meanwhile, was determined to vary from 10 to 15 cm height through direct measurement of samples collected by dredge (Graves, 2005). This would therefore score slightly higher for elevation than the Saturn reef.

Consolidation of sediment

Sabellaria spinulosa constructs unbranched dwelling tubes using mucus to bind together sand grains and broken shell. In gregarious aggregations, the tubes intertwine to form a rigid structure which additionally collects sand, detritus, and also finer faecal material between the *Sabellaria* tubes. In a healthy colony, these detritus layers do not interrupt the normal growth of the individuals or of the colony as a whole (Schäfer, 1972). In reefs, the sediment comprising the *S. spinulosa* tubes is typically bounded together to such an extent that the reef effectively smothers the underlying substrate.

The importance of sediment consolidation to the distinctness of reef is indicated in the Habitats Directive definition of reef as 'biogenic concretion'. This is interpreted to mean the consolidation of stones and pebbles from the substratum by the biogenic matrix of worm tubes. This coalescence of substratum distinguishes the colonies from the surrounding unconsolidated sediments, the distribution of which is governed by processes such as winnowing and transport. The stability imparted by the structure allows many other associated species, including epibenthos and crevice fauna, to become established. As such, the fauna is distinct from other biotopes and species can become established in predominantly sedimentary areas where they would not otherwise be found (Foster-Smith et al., 1997; UK Biodiversity Group, 1999).

In contrast to colonies with an upright morphology, the consolidated tubes of crustose colonies typically form a thin veneer across the surface of the underlying substratum and do not necessarily concrete larger pebbles together. Their ability to trap sediment is also less. Furthermore, this growth form is frequently considered to be much less stable than a more upright morphology, being more susceptible to fragmentation during winter storms for instance and to damage from physical impacts (Holt et al., 1998). Thus, a score for the degree of sediment consolidation can give an indication of both the distinctness of the biogenic structure from the surrounding substratum, and also of the potential longevity of the structure.

The proposed scoring scale for sediment consolidation is given in Table 2B. As with elevation, an indication of the degree of sediment consolidation can be derived from vertical photography and video, or extrapolated from a series of sediment grab samples.

The report prepared by SubSea7 on the Saturn reef included numerous video clips and still images of the *Sabellaria* colonies (SubSea7, 2003). These indicated that in the two regions densely populated with *S. spinulosa*, consolidation of sediment consisted primarily of upright *Sabellaria* tubes which together covered perhaps 80–90% of the substratum in those areas. Both measures suggest a high sediment consolidation score for this reef. The consistency between the extensive imagery from this reef leads to a high level of confidence in both the sediment consolidation and elevation scores for this aggregation.

Spatial extent

Spatial extent is another important physical characteristic of a reef, a more extensive colony obviously having greater conservation significance than a smaller, but otherwise similar one. Problematically, however, the boundaries of *Sabellaria* reefs are rarely distinct and variation between investigators can be expected depending on which position is chosen as the edge. Dankers et al. (1999) have described a similar difficulty in quantifying of the aerial extent of mussel beds, and in both cases it is imperative to develop a protocol for comparative investigations.

Sabellaria aggregations often have a relatively substantial core which becomes increasingly patchy towards its margins. The characteristics of the whole structure can thus vary throughout its extent. In such cases it is suggested that the scoring of different reef features is focused on the core area of a colony, the boundaries of which should be the point at which the overall score begins to decrease due to the inclusion of areas of 'poorer' quality. Areas of *Sabellaria* aggregations which are still distinct from the surrounding area of seabed but which extend beyond the core section of reef can then be taken into consideration by a separate score for peripheral reef area.

Few reports of *S. spinulosa* aggregations in the literature give clear descriptions of the colonies, particularly in relation to their size. Some exceptions to this include the reef described by Linke (1951) which was 6–8 m wide, 40–60 cm high and 60 m long on the island of Norderney; and also an aggregation at the mouth of the Wash described from underwater video as protruding up to 60 cm above the surrounding seabed and extending more or less continuously for hundreds of metres (Foster-Smith & White, 2001). Sonar surveys indicated that a larger reef in the German Wadden Sea covered an area of 140 hectares (Vorberg, 2005). Less specific descriptions refer to huge colonies (Hartmann-Schröder, 1971), which occasionally cover several square kilometres (Schäfer,

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Table 3. *Summarized descriptions of the Marine Nature Conservation Review (MNCR) biotopes and variants in which* Sabellaria spinulosa *is considered to be common or abundant—from (Connor et al., 2004).*

MNCR biotope classification
SS.SBR.PoR—Polychaete worm reefs (on sublittoral sediment)
Sublittoral reefs of polychaete worms in mixed sediments found in a variety of hydrographic conditions. Such habitats may range from extensive structures of considerable size to loose agglomerations of tubes. Such communities often play an important role in the structural composition or stability of the seabed and provide a wide range of niches for other species to inhabit.
SS.SBR.PoR.SspiMx—*S. spinulosa* on stable circalittoral mixed sediment
The tube-building polychaete *S. spinulosa* at high abundances on mixed sediment. These species typically form loose agglomerations of tubes forming a low lying matrix of sand, gravel, mud and tubes on the seabed.
CR.MCR.CSab.Sspi—*S. spinulosa* encrusted circalittoral rock
This biotope is typically found encrusting the upper faces of wave-exposed and moderately wave-exposed circalittoral bedrock, boulders and cobbles subject to strong/moderately strong tidal streams in areas with high turbidity. The crusts formed by the sandy tubes of the polychaete worm *S. spinulosa* may even completely cover the rock, binding the substratum together to form a crust. A diverse fauna may be found attached to, and sometimes obscuring the crust, often reflecting the character of surrounding biotopes.
CR.MCR.CSab.Sspi.ByB—*S. spinulosa* with bryozoan turf and barnacles on silty turbid circalittoral rock
CR.MCR.CSab.Sspi.AS—*S. spinulosa* didemnids and other small ascidians on tide-swept moderately wave-exposed circalittoral rock
IR.MIR.KR—Kelp and red seaweeds (moderate energy infralittoral rock)
Infralittoral rock subject to moderate wave exposure, or moderately strong tidal streams on more sheltered coasts. On bedrock and stable boulders there is typically a narrow band of kelp *Laminaria digitata* in the sublittoral fringe which lies above a *Laminaria hyperborea* forest and park. Associated with the kelp are communities of seaweeds, predominantly reds and including a greater variety of more delicate filamentous types than found on more exposed coasts (KFaR).
IR.MIR.KR.Lhyp.Sab—*S. spinulosa* with kelp and red seaweeds on sand-influenced infralittoral rock
Laminaria hyperborea kelp forest on shallow infralittoral bedrock and boulders characterized by encrustations of *S. spinulosa* tubes which cover much of the rock, together with sand-tolerant red seaweeds.

1972). Such descriptions formed the basis of the scale suggested in Table 2C for scoring the spatial extent of a reef. A minimum threshold of $>5\,m^2$ is suggested.

In order to be valuable to management, any consideration of the size of a given reef must be measurable in practice. With present technology, however, it is difficult firstly to detect and accurately map the patchy distribution of reef biotopes at a fine scale, and secondly to determine any broad scale trends. Determination of the spatial extent and coverage of a reef is therefore likely to rely on a combination of sampling and detection strategies. Available methodologies include acoustic techniques such as sidescan sonar, Acoustic Ground Discrimination Systems (AGDS) and swath bathymetry as well as other sampling techniques such as towed video and sediment grabs. An example of the interplay of spatial extent and patchiness, together with suggested scoring is given in the following section.

Patchiness

Coupled to a score for spatial extent, the spatial patchiness of *S. spinulosa* aggregations should also be quantified during the assessment of a reef since video evidence suggests that this can vary greatly. In some areas, for instance, video tows have shown well developed reefs extending for many metres interspersed with occasional small patches of sand. In contrast, in other areas the colonies formed small patches of only a few metres extent or less dominated by surrounding sand. Such spatial differences influence the degree of distinctiveness of the reef habitat relative to the surrounding area. It also complicates the determination of spatial extent of a reef if the positions of the boundaries are consequently unclear. For instance, Figure 1 can be interpreted as a moderate-sized colony which is densely populated and surrounded by a few additional peripheral clumps (Figure 1A), or it can be viewed as a spatially extensive colony which is relatively patchy in nature (Figure 1B). It is hoped that the inclusion of a score for both extent and patchiness will counteract the potential range of interpretations of such a scenario, and it is suggested that colonies can be quantified according to both extent and patchiness with the boundaries of the overall structure being considered as that which gives maximum overall score.

Table 4. *Biodiversity measures recorded from* Sabellaria spinulosa *aggregations in a range of available datasets from the Wash and the Lincolnshire coast. Values are the averages recorded for the grab samples collected during the survey.*

Survey details	Number of grabs	Total species (S)	Total individuals (N)	Margalef's species richness (d)	Shannon diversity index ($H'(\log_e)$)	Simpson's diversity index ($1-\lambda'$)
Area 481	44	22	81	5.1	2.3	0.90
Wash	66	48	1287	7.0	2.6	0.84
Area 107	10	60	653	9.2	2.9	0.87
Long Sands	10	47	251	8.3	3.0	0.92
Lynn, Lincs and Inner Dowsing	29	41	290	7.3	2.7	0.87

A rough indication of the patchiness of the reef can most easily be estimated from videography. Herlyn (2005) developed a more quantitative approach to address a similar problem in the assessment of intertidal blue mussel stocks using combined methods of remote sensing (aerial photography), ground truth investigation and field sampling. It is possible that such an approach could be adapted for application to subtidal *Sabellaria* reefs. A suggested scoring scale is presented in Table 2D.

The Saturn reef serves as a useful example of the interplay of spatial extent and patchiness in determination of the size of a reef. This reef was first identified during an assessment of a proposed pipeline route, and surveyed visually using a ROV to determine its extent (BMT Cordah Ltd, 2003). Figure 2 illustrates the route taken by the ROV together with the locations of the video clips and photographs from which BMT Cordah derived boundaries for two densely populated regions of reef each of which were surrounded by less densely populated expanses. The area between the two mapped areas of *S. spinulosa* aggregations was unsurveyed.

The total area of the reef, as identified by BMT Cordah, is approximately 0.75 km^2, though this is variable in its patchiness. This would give a medium–low total area score. Perhaps more informative, however, is to consider two different zones of the reef separately according to *Sabellaria* density. Thus, the combined area of the two densely populated zones is approximately 0.25 km^2. This would acquire a relatively low score for spatial extent for the core area of reef. Video footage and still images from this area indicate the aggregation to be fairly solid, and hence the patchiness is given a medium score. Meanwhile, the remaining extents of the ross worm which were much more patchy were considered to cover a further area of approximately 500 m^2, which would also give a low score for the peripheral area. The degree of patchiness appears consistent throughout numerous good quality still images and video takes, hence confidence in the patchiness score is high. The confidence in the area scores, however, is less good since a large area between the two core zones was unsurveyed, and the boundaries of the eastern patch in particular were not intensively surveyed.

BIOLOGICAL CHARACTERISTICS OF REEFS

A biogenic reef is the product of biological response to a set of interdependent chemical, physical, geological and biological environmental factors (Fagerstrom, 1987). As such the biological aspects of a biogenic structure can be considered equally important to the physical characteristics in distinguishing the reef habitat. Methods of scoring the biological characteristics do, however, present a challenge.

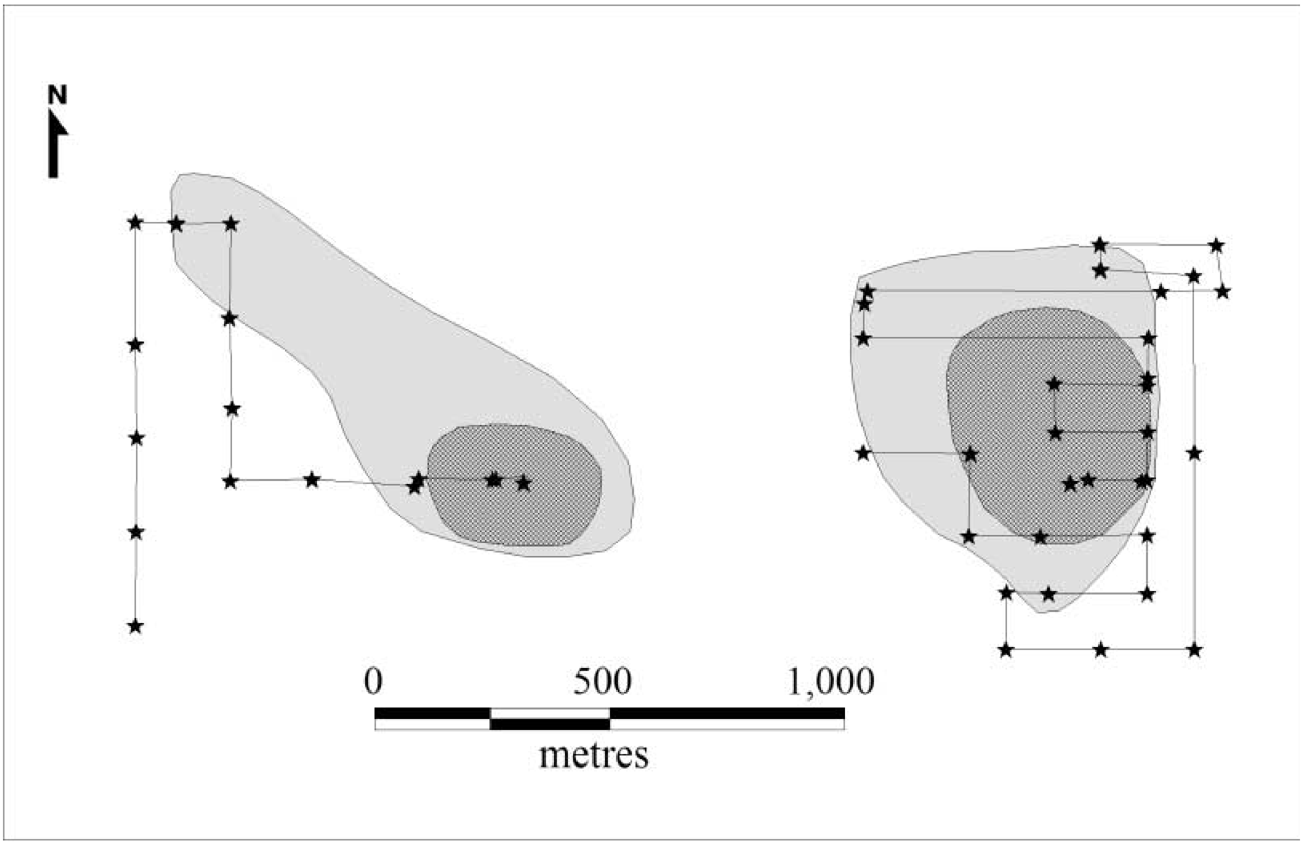

Figure 2. Remotely operated vehicle (ROV) route and derived extent of the Saturn reef, reproduced from BMT Cordah Ltd (2003). Shaded area indicates derived extent of reef, hatched area indicates densely populated area of ross worm, and stars indicate photograph locations.

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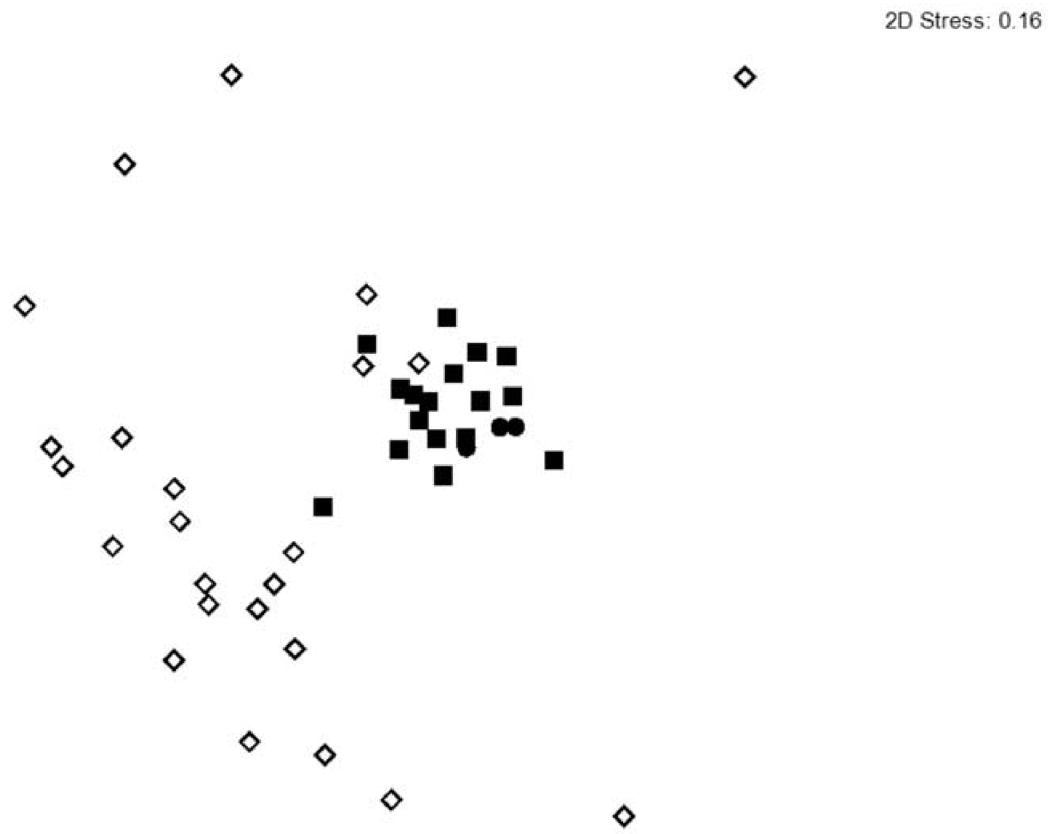

Figure 3. Multidimensional scaling (MDS) plot of infaunal data (excluding the *Sabellaria* count) from a *Sabellaria* aggregation off the Lincolnshire coast following a square root transformation and using a Bray–Curtis resemblance matrix. Open symbols indicate grabs that did not contain *S. spinulosa*, and solid symbols indicate those containing *S. spinulosa*. Solid circles indicate the highest density *S. spinulosa* grabs (2D Stress=0.16).

Sabellaria *density*

The characteristics of biogenic reefs are all linked to the density of aggregation. For instance, it has been suggested (Schwartz, 1932; Schäfer, 1972), that the growth morphology of *Sabellaria spinulosa* may be influenced by density, such that an upright growth form is a reflection of competition for space. This would suggest that a biogenic concretion produced by a high density aggregation of *Sabellaria* is more likely to result in a substantial, elevated structure than that of a lower density colony, though a colony in an early developmental stage may not yet have reached its full height. *Sabellaria* density could, therefore, be an indicator of potential future development. Similarly, the density of *Sabellaria* is fundamental to all other features of *S. spinulosa* aggregations, and hence where information is available, it is appropriate to score this characteristic of a colony also.

Recorded densities of *S. spinulosa* aggregations vary widely. Densities of up to 316/m^2 have been reported for the National Marine Monitoring Programme off Selsey Bill and of 120/m^2 by the Belfast Lough North Channel Disposal Ground Monitoring Survey (information from the *MarLIN* website: www.marlin.ac.uk). In denser aggregations, over 3000 *S. spinulosa* individuals/m^2 were reported for a reef sampled by Day grab in the Bristol Channel (George & Warwick, 1985), and densities of over 4500/m^2 were reported for a reef in the Wash (National Rivers Authority, 1994). Thus it is proposed that density is scored on a log scale, as suggested in Table 2E. While a rough estimate of density may be made by videography, density of *S. spinulosa* is best derived from infaunal analysis of grab samples.

Biotope codes

In many instances, it is expected that a *S. spinulosa* colony under assessment will have been categorized using the Marine Habitat Classification for Britain and Ireland (BioMar) which classifies biotopes according to their community composition and broad habitat type (Connor et al., 2004). The classification system recognizes three different biotopes in which *S. spinulosa* is considered to be common or abundant, one of which is sub-classified into two relevant variants (Table 3). The biotopes differ in their appropriateness for a substantial, reef formation and hence can be used as a basis for a biological community score as suggested in Table 1G.

The tautology of this approach is recognized in that the biotope will be classified on the basis of the community composition, and that the subsequent scoring of biological community on the basis of the biotope code is less than ideal. Despite this circularity, it is suggested that such an approach may still be useful for cases where the biotope code is the sole information available regarding the

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Table 5. *Example of scoring protocol applied to the Saturn reef. Reef-characteristics, confidence of score and perceived importance of feature are all scored on a sliding scale of low–medium–high.*

Characteristic reef feature	Score from assessment against criteria (Low Medium High)	Subjective confidence of data and methodology to support assessment score (Low Medium High)	Subjective value of the importance of each criteria as a contribution to total score (Low Medium High)	Basis of score
Elevation				Score based on video and still imagery providing good coverage of the colony
Consolidation				As above
Spatial extent				Score based on mapped extent of reef derived from ROV route by BMT Cordah Ltd (2003)—see Figure 2
Patchiness				Score based on video and still imagery providing good coverage of the core area of colony
Sabellia spinulosa density				No quantitative *Sabellaria* density data are available
Biodiversity				Infaunal assessment of grabs samples is indicative of a high biodiversity, but is limited to two samples
Community composition				Species counts from the two infaunal samples were not included in the reports
Temporal stability				Two surveys by Envision Mapping in 2004 and 2005 found no sign of the *Sabellaria* reef at this site. Anecdotal accounts from surveys undertaken by Cefas, however, suggest a degree of persistence at this site (D. Limpenny, personal communication)
Overall weighted scores as a percentage of maximum possible score	58%	55%		

ROV, remotely operated vehicle; Cefas, Centre for Environment, Fisheries and Aquaculture Science.

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Table 6. *Summary of reef-like characteristics considered important to the interpretation of the Habitats Directive definition of reef, together with proposed methods of measurement/detection on which to base a categorization of* Sabellaria spinulosa *reef.*

Feature/characteristic	Basis of definition	Potential means of measurement/ detection
Elevation	Average or maximum tube heights	Video and laser, stereo imaging, side-scan, imaging sonar Grab—retrieval of reef fabric
Sediment coalescence and stability	Colony should bind sediment and smother or replace existing substratum with new one	Vertical photography: drift or 'lander' and video Grab
Spatial extent	Area covered by aggregation	Acoustic techniques: sidescan; AGDS; swath Sampling: towed video; grabs
Cover/patchiness	Percentage cover of substratum by aggregation Dispersion—scattered vs clumped	As above
S. spinulosa density	Average or maximum density of *S. spinulosa*/m^2	Grab sampling
Biodiversity and species richness	Elevated relative to similar non-*Sabellaria* habitats in vicinity Qualitatively different (multivariate and randomization null models)	Video Grab Trapping/baited traps
Characteristic species	Contains species considered characteristic of the MNCR *Sabellaria* biotopes	As above
Temporal stability	Coarse—presence or absence Degree of presence—resolution and repeatability of detection important. Statistical power to discriminate	Repeat sampling Size-cohort analysis

MNCR, Marine Nature Conservation Review.
NB Whilst grab sampling has been listed as a possible methodology for scoring many of the reef characteristics discussed, its use should be limited due to the destructive nature of this technique. However, where information derived from this technique is pre-existing, it can provide a valuable insight into the nature of the colonial structure.

community composition, as long as the reservations in the approach are reflected in the importance weighting. This approach is likely to be of particular importance where non-destructive sampling techniques preclude all but a broad habitat classification.

Characteristic species

In cases where more detailed information is available regarding the community composition, it may be possible to distinguish biogenic reefs on the basis of their characterizing species. However, the biotope descriptions of the BioMar classification system illustrate the difficulties of this approach for *S. spinulosa* reefs. Of the 33 species considered to be characteristic of the SS.SBR.PoR.SspiMx biotope (Connor et al., 2004), for instance, only *Pholoe synophthalmica* and *Ampelisca diadema* are not additionally listed as characteristic species of other biotopes. *Pholoe* spp. and *Ampelisca* spp. are, however, both included in other biotope descriptions, and thus there are no species whose presence can be considered confirmatory of the classification of 'reef'.

Biodiversity

Instead of restricting an assessment to the presence or absence of particular species, faunal counts may be used to help distinguish reef from non-reef through assessment of the community as a whole. In many cases, for example, reef-forming organisms and other upright sessile epifauna are recognized as keystone species which provide complex structural habitats of high biodiversity (for example: biogenic reefs (Holt et al., 1998); *Sabellaria alveolata* (Dubois et al., 2002); mussel beds (Saier, 2002); *Limaria hians* (Hall-Spencer & Moore, 2000); hydroid colonies (Bradshaw et al., 2003). It is for this reason that reefs are listed under Annex I of the Habitats Directive. A comparison of biodiversity indices within and beyond the colonial aggregation may therefore be indicative of the distinctness of the habitat.

In the case of *S. spinulosa* aggregations, it has been suggested that a higher species diversity is found amongst the consolidated *Sabellaria* tubes than would occur on sediment or rock alone because species typical of both hard and sedimentary substrata occur in the aggregations (Hiscock, 2003). An elevation of biodiversity indices within a *Sabellaria* colony relative to those of the surrounding substratum can therefore be considered to contribute to the distinctness of the reef habitat as well as imparting a greater significance to the habitat in terms of conservation value.

Table 4 indicates a selection of biodiversity measures recorded in a range of available datasets from *S. spinulosa* colonies. This was used as the basis for the proposed scoring scale presented in Table 1F, which can be assessed through infaunal analysis of grab samples.

In contrast, larval substrate selection and rapid growth, which are common features of many gregarious distributions, can produce almost monospecific frameworks comprising individuals of the same sizes and shapes, for example oyster, vermetid, serpulid, bryozoan and stromatolites (Fagerstrom, 1987). In such cases, the competitive exclusion of other species by the gregarious reef-builder often reduces biodiversity within the area of the reef in comparison to what might have been expected in the absence of the reef. It should, however, be recognized that measures of biodiversity are scale dependent, and a low measure of biodiversity within the reef complex may still be of importance if it adds to the overall biodiversity of the wider area. Such an appraisal is considered beyond the scope of this scoring assessment. It may be sufficient, however, to allow for such a possibility merely by reducing the weighting of the biodiversity score in cases where the biodiversity indices of the reef are low.

Distinctness

A better indication of the distinctness of a reef community from the surrounding area can be achieved through multivariate analysis of the infaunal data. An illustrative assessment of data from a survey in the southern North Sea, for instance, indicates a significant difference between the community structure of grabs with *Sabellaria* (Figure 3; solid symbols) and those without any *Sabellaria* (open diamonds, analysis of similarity $P>0.1\%$, $R=0.418$; note the density of *S. spinulosa* itself was excluded from this analysis). Furthermore, the similarity in community structure was also found to be highest amongst the grabs with the highest density of *Sabellaria* (solid circles), indicated in Figure 3 by the close proximity of these points. Whilst both results support the contention that the infaunal community of high density *S. spinulosa* aggregations is distinctly different from that of the surrounding seabed, it does not indicate whether the reefs merely act as a 'magnet' to the surrounding species pool increasing density of species within the area of the reef, or whether the reef habitat selectively attracts or repels specific species and hence is composed of different species to the biota of the surrounding area. Efforts are ongoing to develop a 'null model' with which to distinguish between these two alternatives. Thus, whilst it would be useful to compare the community composition of the aggregation under assessment with a standard '*S. spinulosa* reef community' so that the distinctiveness of the community could be used to help define the reef, the complexity of this approach is considered beyond the scope of the current working definition the aims of which are to provide a simple and easily applicable scoring system.

Whilst the approaches for assessing and scoring the biological characteristics of reefs suggested here are less than satisfactory, it is hoped that at the very least they will stimulate discussion which will improve future progress in this difficult area.

TEMPORAL CHARACTERISTICS OF REEFS

It is expected that a long-lived, stable biogenic concretion would have greater value in respect of the aims of the Habitats Directive than an otherwise comparable habitat with an ephemeral nature. Indeed longevity has been used as justification for the distinction between encrusting colonies of *Sabellaria spinulosa* and reefs by the UK Biodiversity Group who note 'crusts are not considered to constitute true *S. spinulosa* reef habitats because of their ephemeral nature, which does not provide a stable biogenic habitat enabling associated species to become established in areas where they are otherwise absent' (UK Biodiversity Group, 1999). It is therefore suggested that consideration of both colony longevity and stability be given to the categorization of a reef habitat.

While the ephemeral nature of encrusting aggregations appears widely accepted, often being attributed to their vulnerability to winter storms (Holt et al., 1998), the long-term stability of reef biotopes is not assured. There are numerous reports in the literature of the disappearance of large *S. spinulosa* aggregations (e.g. Vorberg, 2005). In several cases, the declines have been attributed to anthropogenic disturbance such as the grinding with heavy gear by shrimp fisheries (Reise, 1982; Reise & Schubert, 1987), or to changes in the hydrological regime due to coastal engineering (Nehring, 1999). In other cases, the causes of decline appear to be more natural. In Dorset, for instance, a reef discovered in Poole Bay was found to have been overlain with sand to a depth of 20–30 cm two years later (Hiscock, 2004). Evidence for rapid burial of colonies has also been detailed by Schäfer (1972) in his descriptions of the palaeoecology of *Sabellaria* reefs. Thus while there is little concrete knowledge regarding the natural fluctuations that populations of *Sabellaria* undergo, the possibility that all such aggregations may naturally be temporally variable should be taken into consideration when distinguishing reef and determining the relative importance of different aggregations.

Deterioration of a *S. spinulosa* colony is not necessarily irreversible. Whilst some aggregations may be short-lived with the reef disintegrating and disappearing soon after the death of the reef-builders, in other cases the reefs may repeatedly develop and decline in a regular progression through resettlement after each successive generation has died. Larvae of *S. spinulosa* are strongly stimulated to metamorphose by the secretions of their own species, and therefore settle preferentially on sediment used previously by other *S. spinulosa* individuals (Wilson, 1970). Hence they may build on either the ruins of earlier reefs, or on still well-preserved or even partly inhabited older structures (Schäfer, 1972; Grotjahn, 2000). Whilst this preference can ensure continuous succession of generations, it can also promote recovery of a reef which had previously deteriorated, providing prevailing environmental conditions are still appropriate. Such a demise with subsequent recovery has been observed in an aggregation within the vicinity of the Wash and through continued monitoring of the Dorset reef (Sara Welton, personal communication 2005).

The recovery of an aggregation following damage or decline can be rapid. Average tube growth rates of 4.4 mm/d have been recorded *in situ* for colonies of the related species *Sabellaria alveolata*, following damage from trawling (Vorberg, 2000), for example, whilst laboratory observations indicate that *S. spinulosa* are capable of tube growth rates of at least 6 mm/d (V. Hendrick, unpublished data). Rapid growth has also been reported for a newly extant reef, challenging the contention that the establishment of a reef is necessarily lengthy to allow for the gradual colonization of layers of worms (Hiscock, 2004). Linke (1951), for instance, suggested a *S. spinulosa* colony

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arising from a single spawning event off Norderney, consolidated an estimated 800 to 1000 m^3 of sand in less than six months.

A fluctuating population structure with catastrophic declines and high recovery rate, is typical of 'r-strategists' of which *S. spinulosa* is considered to be an example (Holt et al., 1998; Hiscock, 2004). Such species typically exist well below the carrying capacity of their environments (MacArthur & Wilson, 1967), and have life history strategies which enable them to exist in variable or unpredictable environments, responding to suitable conditions with a high rate of reproduction and rapid development (Krebs, 1985).

An indication of the temporal stability of a *Sabellaria* colony can only be satisfactorily realized through repeat sampling. It may, however, be possible to get an indication of the longevity of a colony through size-cohort analysis of a *Sabellaria* sample, the presence of different size cohorts being suggestive that the colony has existed sufficiently long to experience different years of recruitment (George & Warwick, 1985). The suggested scoring categories for temporal stability (Table 2H) are applicable to both methods, though it is expected that the relative merits of the different approaches will be reflected in the confidence score, as will reliance on anecdotal evidence. Temporal variability should also be considered by monitoring strategies, with the limitations of a snap-shot assessment being taken into account.

EXAMPLE APPLICATION—SATURN REEF

As an illustration of how the proposed system can be applied, a summarized assessment of the Saturn reef is presented in Table 5. This reef was first identified in 2003 as a 'shadow' by a sonagraphic scan of the seabed during assessment of a proposed pipeline route. This was subsequently investigated by means of a sediment grab which was described as consisting of 'tubeworms'. A report by SubSea7 details a visual survey of the area using a ROV to determine the extent and identification of these worms, together with descriptions of two qualitative samples taken from the reef for infaunal analysis (SubSea7, 2003). The area of the Saturn reef was resurveyed the following year to test a swath system as a means of reef detection (Foster-Smith, 2005). The latter survey ran the swath tracks over the site which generously covered the reef coordinates given by the previous report, and also ran a video camera by drifting through the areas marked as reef on the SubSea7 map. Using this information together with subsequent anecdotal accounts, the characteristic features and associated confidence have been scored on a sliding scale from low–medium–high where possible. An algorithm translates these scores to a numerical scale which is multiplied by the subjective importance score in order to give a weighted assessment score for both the feature and confidence in that score.

The importance scores proposed in Table 5 give the greatest weighting to elevation, area and temporal stability. A low weighting is given to biodiversity and characterizing species due to the inherent difficulties in their classification. The weighted characteristic scores are then summed and compared to the maximum possible scores. In this case, the total weighted characteristic score was 58% of the possible total, i.e. moderate–high reefiness. The overall weighted confidence score was moderate, reflecting the paucity of information on the biological community as well as the lack of concrete information on the temporal stability of the aggregation.

The overall score would suggest that Saturn was a moderately good reef. More importantly, however, the breakdown of characteristics indicates a strong physical significance of this aggregation and highlights the paucity of data relating to the biological community and temporal persistence. At the very least, this assessment is strongly supportive of interest in the management of this colony from a precautionary perspective.

CONCLUSION

Whilst the primary aim of this paper is to promote discussion on the challenges posed by *Sabellaria spinulosa* reef, it is hoped that the scoring system summarized in Table 6 will help provide a valuable transparent and standardized procedure for classifying *Sabellaria* colonies which it is hoped will benefit both offshore industry and regulators. It is recognized, however, that numerous aspects of the scoring system will be subjective and that the practicalities of scoring each reef-feature may not be feasible in all instances. Nevertheless, it is expected that the breakdown of a particular assessment through focused consideration of multiple characteristics, each scored independently, will promote consistency of overall classification. Furthermore, whilst it is possible to allow for missing data in an algorithm to quantify overall reef quality, many of these features are interlinked and hence as long as available information gives some indication of the physical, biological and temporal characteristics of the colony it is hoped that the methodology will provide a reliable overall indication of the appropriateness of the categorization 'reef' and of its quality.

It is suggested that a further benefit of this approach lies in the flexibility of its application to a wide variety of data types and qualities together with its ability to be customized to particular applications and definitions through the manipulation of importance weighting. Whilst it is fully expected that the scoring protocol outlined here will be refined with use, if successful it is anticipated that the approach can be adopted for use in the classification of other biogenic reefs and habitats, though the scoring scales and threshold levels will need to be adapted appropriately.

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REFERENCES

BMT Cordah Ltd, 2003. Ross worm reefs and the Saturn development. Ross worm non-technical report, Report to SubSea7 as part of a contract for ConocoPhillips, 8 pp.

Bradshaw, C., Collins. P. & Brand, A.R., 2003. To what extent does upright sessile epifauna affect benthic biodiversity and community composition? *Marine Biology*, **143**, 783–791.

Connor, D.W. et al., 2004. *The marine habitat classification for Britain and Ireland version 04.05.* Peterborough: JNCC.

Dankers, N. et al., 1999. Blue mussels and blue mussel beds in the littoral. In *Wadden Sea Quality Status Report. Wadden Sea Ecosystem* no. 9 (ed. F. De Jong et al.). Wilhelmshaven, Germany: Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group.

Dubois, S., Retiere, C. & Olivier, F., 2002. Biodiversity associated with *Sabellaria alveolata* (Polychaeta: Sabellariidae) reefs: effects of human disturbances. *Journal of the Marine Biological Association of the United Kingdom*, **82**, 817–826.

European Commission DG Environment, 2003. Interpretation Manual of European Union Habitats. EUR15/2.

Fagerstrom, J.A., 1987. *The evolution of reef communities*. John Wiley.

Foster-Smith, R.L., 2005. Saturn Reef. Report to the Joint Nature Conservancy Council, Envision, Newcastle.

Foster-Smith, R.L., Sotheran, I. & Walton, R., 1997. Broadscale mapping of habitats and biota of the sublittoral seabed of the Wash. Final Report of the 1996 Broadscale Mapping Project (BMP) Survey.

Foster-Smith, R.L. & White, W., 2001. *Sabellaria spinulosa* in the Wash and north Norfolk cSAC and its approaches: Part I, mapping techniques and ecological assessment. A Report for the Eastern Sea Fisheries Joint Committee and English Nature.

George, C.L. & Warwick, R.M., 1985. Annual production in a hard-bottom reef community. *Journal of the Marine Biological Association of the United Kingdom*, **65**, 713–735.

Graves, K., 2005. Roxanne survey of an area to the west of the Inner Dowsing, conducted aboard ESF research vessel 'Three Counties' on 17 February 2005. Report of the Eastern Sea Fisheries.

Grotjahn, M., 2000. Benthosbiologische Untersuchungen im Zusammenhang mit der Sicherung der Hafenzufahrt Hooksiel. Erste Ergebnisse hinsichtlich der aktuellen Besiedlung mit Sabellaria spinulosa. Forschungsber. i. A. Niedersächsisches Hafenamt Wilhelmshaven. Unpublished report cited by Vorberg, R. (2005). *Sabellaria* reefs. Wadden Sea Quality Status Report 2004. Wadden Sea Ecosystem no. 19 (ed. K. Essink et al.). Wilhelmshaven, Germany: Trilateral Monitoring and Assessment Group, Common Wadden Sea Secretariat.

Hall-Spencer, J.M. & Moore, P.G., 2000. *Limaria hians* (Mollusca: Limacea): a neglected reef-forming keystone species. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **10**, 267–277.

Hartmann-Schröder, G., 1971. *58. Annelida, Bortenwürmer, Polychaeta*. Jena: Gustav Fisher.

Hiscock, K., 2003. Ross worm *Sabellaria spinulosa*—status and marine natural heritatge importance in relation to pipeline laying operations at the northern extremity of the Indefatigable Bank, North Sea.

Hiscock, K., 2004. Ross worm *Sabellaria spinulosa*—notes on status and marine natural heritage importance. *Report by the Marine Biological Association of the United Kingdom*, 2 pp.

Holt, T.J., Rees, E.I., Hawkins, S.J. & Seed, R., 1998. *Biogenic reefs (vol. IX): an overview of dynamic and sensitivity characteristics for conservation management of marine SACs*. Oban: Scottish Association for Marine Science (UK Marine SACs Project).

Krebs, C.J., 1985. *Ecology: the experimental analysis of distribution and abundance*. New York: HarperCollins Publishers Inc.

Linke, O., 1951. Neue Beobachtungen uber Sandkorllen-Riffe in der Nordsee. *Natur u. Volk*, **81**, 77–84. [Translated by S. Hendrick 2005.]

MacArthur, R.H. & Wilson, E.O., 1967. *The theory of island biogeography.* Princeton, NJ: Princeton University Press.

McLeod, W.T., ed., 1981. *Collins pocket dictionary of the English language*. London: Collins.

National Rivers Authority, 1994. *Wash Zone Report Part 2: analysis of macroinvertebrate samples from a survey of the Wash in August 1991, Report prepared for the NRA by Unicomarine*. Peterborough: NRA.

Nehring, S., 1999. Oyster beds and *Sabellaria* reefs. In *Wadden Sea Quality Status Report. Wadden Sea Ecosystem* no. 9 (ed. F. De Jong et al.), pp. 146–147. Wilhelmshaven, Germany: Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group.

Reise, K., 1982. Long term changes in the macrobenthic invertebrate fauna of the Wadden Sea: are polychaetes about to take over? *Netherlands Journal of Sea Research*, **16**, 29–36.

Reise, K. & Schubert, A., 1987. Macrobenthic turnover in the subtidal Wadden Sea: the Norderaue revisited after 60 years. *Helgoländer Meeresunters*, **41**, 69–82.

Saier, B., 2002. Subtidal and intertidal mussel beds (*Mytilus edulis* L.) in the Wadden Sea: diversity differences of associated epifauna. *Helgoland Marine Research*, **56**, 44–50.

Schäfer, W., 1972. *Ecology and palaeoecology of marine environments.* Chicago: University of Chicago Press.

Schwartz, A., 1932. Der Lichteinfluss auf die Fortbewegung, die Einregelung und das Wachstum bei einigen niederen Tieren. *Littorina, Cardium, Mytilus, Balanus, Teredo, Sabellaria. Senckenbergiana*, **14**, 429–454. Original reference not seen, cited by Schäfer, W. (1972). *Ecology and palaeoecology of marine environments*. Chicago: University of Chicago Press.

SubSea7, 2003. ConocoPhillips Saturn Project. *Assessment of* Sabellaria spinulosa *along Proposed Saturn Pipeline Route AB-R-RP-01212 Revision A*, ConocoPhillips.

UK Biodiversity Group, 1999. *Tranche 2 Action Plans*—Vol. V: *Maritime species and habitats*. English Nature.

Vorberg, R., 2000. Effects of shrimp fisheries on reefs of *Sabellaria spinulosa* (Polychaeta). *ICES Journal of Marine Science*, **57**, 1416–1420.

Vorberg, R., 2005. *Sabellaria* reefs. In *Wadden Sea Quality Status Report 2004. Wadden Sea Ecosystem* no. 19 (ed. K. Essink et al.). Wilhelmshaven, Germany: Trilateral Monitoring and Assessment Group, Common Wadden Sea Secretariat.

Wilson, D.P., 1970. The larvae of *Sabellaria spinulosa* and their settlement behaviour. *Journal of the Marine Biological Association of the United Kingdom*, **50**, 33–52.

Wood, R., 1999. *Reef evolution*. Oxford: Oxford University Press.

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