ENGLISH NATURE

Report Number
543

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Number 543

Sabellaria spinulosa reef in The Wash and North Norfolk cSAC and its approaches: Part III, Summary of knowledge, recommended monitoring strategies and outstanding research requirements

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March 2003

A report for the Eastern Sea Fisheries Joint Committee and English Nature

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ISSN 0967-876X

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1. 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 individually but can be gregarious in favourable conditions, and colonies consisting of fused sand-tubes may form thin crusts or extensive reefs [48, 25].

The reefs, commonly known as 'Ross', are solid albeit fragile structures which can be up to several metres across and raised above the sea bed by up to 30cm [21]. Significantly, the reefs can persist for many years and as such, they provide a biogenic habitat that allows many other associated species, including epibenthos and crevice fauna, to become established [50]. 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 [20, 50]. In this guise, therefore, *S. spinulosa* has been identified as a priority habitat under the Biodiversity Action Plan (BAP), the UK's initiative to maintain and enhance biodiversity. In addition, the reef-building sabellariids (*S. spinulosa* and *S. alveolata,* Linne) have formed a theme in the LIFE programme promoting management of the candidate Special Areas of Conservation (cSACs).

To date, in the UK, well-developed and stable *S. spinulosa* reefs are only known within the Wash and its surrounding waters [30]. Thus within the Wash and north Norfolk Coast cSAC, biogenic sand reefs built by *S. spinulosa* are an interest feature which has recently been upgraded from being a sub-feature of the Large Shallow Inlet and Bay to a 'reef' interest feature in its own right. It is important, therefore, to test many of the assumptions about the importance of this species to the overall pattern of species diversity and richness in the Wash, and also to clarify the anecdotal evidence which has suggested a decline in the abundance and distribution of this species in the area [20].

2. The Wash

2.1 The Wash, its conservation status and it's uses

The Wash, the largest estuarine system in Britain, is internationally important for its nature conservation value. It has international and national recognition as a Special Protection Area (SPA - EC Conservation of Wild Birds Directive 79/409), as a Ramsar Convention Site (Wetland of International Importance) and as a Site of Special Scientific Interest (SSSI - Wildlife and Countryside Act 1981). Together with the north Norfolk Coast, the Wash is also one of the most diverse coastal systems in Britain, and as such it was also proposed as a marine SAC under the Habitats Directive primarily for its intertidal and subtidal sand, mudflats and its common seal populations (*Phoca vitulina*).

In addition to its nature conservation value, the Wash supports a nationally important shellfish industry which has significant socio-economic implications for the area [56]. Target species include both molluscan (mussel *Mytilus edulis,* and cockle *Cerastoderma edule*) and crustacean shellfish (brown shrimp *Crangon crangon,* and pink prawn *Pandalus montagui*). Offshore, commercially exploited stocks include whelks, queen scallops, edible crab and lobster. The latter two species are also fished from the Boston Deeps within the Wash. Demersal fishing using fixed nets, longlines or trawls also takes place throughout the region. Although the latter is restricted as to the size of beam trawls used and the mesh size of nets, until recently there were no such restrictions for shrimp fisheries. This has led to concerns over the effect shrimp fishing might have on juvenile demersal fish and nursery grounds [56]. The destructive effects of trawling have also been attributed as a potential cause of the decline in *Sabellaria spinulosa* reefs in the region. A similar contention has been advanced in relation to physical damage to reefs by aggregate dredging and coastal protection work (see later sections).

Management objectives for the region have predictably taken into account such concerns regarding both the commercial and nature conservation interests. Inevitably, however, there is a conflict between monitoring status of specific biotopes, interest features and species and of the overall health of the area including the fishing interests.

To supplement the brief description given here, a more detailed account of the Wash can be found in the Wash Estuary Management Plan [56], whilst the wider region is described in the Coastal Directories Series Report for Region 6: Flamborough Head to Great Yarmouth [3], and the Marine Nature Conservation Review series: Coasts and Seas of the United Kingdom [26]. A description of the geology of the area, including the more recent, quaternary sediments on the sea floor, is to be found in the *Geology of the southern North Sea*, a publication by the British Geological Survey [7].

2.2 Background to Wash surveys

As part of the development of the Management Scheme for the Wash and North Norfolk cSAC it is necessary to establish the baselines and condition and compliance monitoring programmes for the features of interest in order to determine whether the conservation objectives have been, or are in the process of being achieved. With this objective in mind, SeaMap, University of Newcastle upon Tyne and the Eastern Sea Fisheries Joint Committee (ESFJC) have undertaken a series of surveys in this area starting with the Broadscale Mapping Project (BMP) in 1997.

The BMP surveys were designed to map the distribution of a wide range of biotopes using remote sensing techniques, classified using ground truth data. The surveys showed that there were clear broad scale trends to the distribution of biotopes, and although *S. spinulosa* reefs were not specifically targeted, the surveys were able to predict their most likely distribution. The surveys indicated that high densities of *S. spinulosa* within the Wash were most likely to be located on the northern side of the Lynn Deeps near Longsands, and also on the opposite side near Hunstanton. The predicted distribution extended along the sides of the Lynn Deeps northeast to Scott Patch near the licensed sand extraction area 107, and well-developed reef was confirmed here.

The video evidence of *S. spinulosa* reefs collected from the northern margins of area 107 (outside of the cSAC), brought their existence to the attention of English Nature and prompted the current interest. Although poor underwater visibility at the time of the surveys precluded direct observation of reefs within the Wash cSAC itself, the evidence suggested that reefs might also occur within the cSAC.

SeaMap conducted three further surveys (1999, 2000 and 2001) with varying objectives. In 1999 the primary objective was to provide a basis for monitoring changes in the distribution of major habitats and biotopes at selected representative locations within the Wash. Again, *Sabellaria* was not specifically targeted, but the results suggested a decrease in *Sabellaria* between 1997 and 1999. No high-density populations or reefs were observed within the cSAC and area 107 was not sampled.

The primary aim of the 2000 survey was to compare and contrast the use of acoustic ground discrimination systems (AGDS) and sidescan sonar for mapping *S. spinulosa* reefs. As such, it was the first survey to specifically target *Sabellaria*, incorporating direct observation using remote video. Two sites were selected for the survey – one within the cSAC just south of Long Sands, and the other predominantly within sand extraction area 107. The survey was partially successful in that the acoustic techniques were tested over observable reefs at 107, but they did not give a distinctive image using sidescan. The reefs were more readily detected using AGDS, but this system is not high resolution and differences between systems and interpretation of the data result in different boundaries. Conversely, neither reefs nor high density *Sabellaria* populations were found at the Long Sands site, despite video observations of reefs made by ESFJC here in the previous year.

The 2001 survey was planned to try to address some of the outstanding issues from the previous surveys, particularly the assessment of patchiness and variable development of reefs and possible broad scale trends. Specifically, the objective was to identify the distribution of *S. spinulosa* within the area of the Wash, and to help design future surveys with a view to assessment of the natural change in *S. spinulosa* colonies.

The surveys outlined above are reviewed in greater detail under the heading 'Review of Previous Reports', and are presented in full in the reports listed below. This report aims to provide an overview of the findings to date of the *S. spinulosa* survey programme.

FOSTER-SMITH, R. 2000. *Establishing a monitoring baseline for the Wash subtidal sandbanks*.

FOSTER-SMITH, R. 2001. Sabellaria spinulosa *in the Wash and north Norfolk cSAC and its approaches: Part II, fine scale mapping of the spatial and temporal distribution of reefs and the development of techniques for monitoring condition.* A report for the Eastern Sea Fisheries Joint Committee and English Nature.

Report of the field survey for the 2001 *Sabellaria spinulosa* project.

FOSTER-SMITH, R., DAVIES, J. and others. 1999. *Broad scale remote survey and mapping of sublittoral habitats and biota*: *Technical report.* Final technical report of the Broadscale Mapping Project. Edinburgh: Scottish Natural Heritage.

FOSTER-SMITH, R., SOTHERAN, I. and others. 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. & W. WHITE. 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.

3. *Sabellaria spinulosa* – General review of the literature

This section provides a general review of the published literature regarding *Sabellaria spinulosa*, and was heavily reliant on several previously published reviews [28, 30, 50, 32]. The later section reviewing reports by SeaMap, meanwhile, focuses more specifically on the species within the Wash and surrounding area.

3.1 Distribution

As a consequence of its few key requirements and its tolerance of poor water quality (see later sections), *S. spinulosa* is widespread in its distribution encompassing the northeast Atlantic, the North Sea and the English Channel [25, 43, 28, 50]. It has also been reported in the Mediterranean Sea [5]. *S. spinulosa* is known from all European coasts, except for the Baltic [52], and is naturally common around the British Isles, being found in the subtidal and lower intertidal/sublittoral fringe.

While many authors indicate, either directly or by inference, that *S. spinulosa* is most commonly found in a solitary form (eg [60, 23]), dense aggregations have also been reported (eg Bristol Channel [23]; Dorset [1]; Southern North Sea [35]; The Wash [41, 33, 20]).

Although widespread, *S. spinulosa* colonies are thought to be patchily distributed [16]. Several surveys (eg [20, 21]) have shown very variable densities of *S. spinulosa*, with only moderate numbers recorded on some surveys/sites and very dense *S. spinulosa* recorded on others. Video evidence, meanwhile, has suggested that the ground at some of the sampling locations might be heterogeneous at very fine scales (certainly from metre to metre) [15].

3.2 Biotope classification

Blab, and others.[6] defined biotopes, or biotope types, as the spatial components of an ecosystem characterized by "specific ecological, unique and more or less constant environmental conditions". On this basis, *S. spinulosa* habitats have been classified according to the biotopes listed in Table 1.

Table 1: *Sabellaria spinulosa* biotopes of five different classification systems

Classification Code	Biotope(s)	Description
Britain / Ireland (MNCR BioMar – 97.06)		
CMX.SspiMx	*S. spinulosa* and *Polydora* spp. On stable circalittoral mixed sediment	The tube-building polychaete *S. spinulosa* at high abundances on mixed sediment, with *Polydora* spp. tubes attached. Infauna comprise typical sublittoral polychaete species, together with the bivalves *Albra albra* and *Nucula nitidosa*. Epifauna comprise calcareous tubeworms, pycnogonids, hermit crabs and amphipods. This biotope is considered a biogenic reef since *Sabellaria* performs an important stabilising function on the substratum.
MIR.SedK.SabKR	*S. spinulosa* with kelp and red seaweeds on sand-influenced infralittoral rock	*S. spinulosa*, sediment-tolerant red seaweeds and occasional *Laminaria hyperborea* characterise this biotope. Some of the richer examples of this biotope (eg Luce Bay) also have a rich fauna of ascidians, sponges, hydroids and bryozoans. A similar biotope is also found in the circalittoral zone, where it lacks the algal component (MCR.Sspi). NB This biotope is not considered a biogenic reef.

Classification Code	Biotope(s)	Description
MCR. CSab.Sspi	*S. spinulosa* crusts on silty turbid circalittoral rock	Bedrock in moderately exposed, slightly tide-swept conditions with high turbidity with an almost entire crust of *S. spinulosa* tubes; few other species present. *Ciona celata, Alcyonium digitatum* and *Hypoglossum hypoglossoides* present in NE England, very extensive *Mytilus edulis* in South Wales (Gower). The fauna attached to the *Sabellaria* crust in many cases seem to reflect the biotopes on nearby rock. NB This biotope is not considered a biogenic reef since many of the associated species are capable of living on the rock irrespective of the presence of *S. spinulosa*
MCR.As MolPol.Sab	Dense ascidians, bryozoans and hydroids on a crust of *S. spinulosa* on tide-swept circalittoral rock	Tide-swept rock in areas with high levels of suspended sand with a *S. spinulosa* crust which supports a wide variety of other species. A dense carpet of ascidians *Molgula manhattensis, Polycarpa* spp. and *Polyclinum aurantium*, a turf of bryozoans (*Cellaria sinuosa*, *Bugula plumosa* and *Flustra foliacea*) and sponges such as *Scypha ciliata* and *Polymastia* spp., bryozoans *Alcyonidium diaphanum* and *Scrupocellaria* spp. and *Antedon bifida* may also be present. In some cases this biotope occurs adjacent to MolPol although in deeper water and more tide-swept (scour/turbulent) conditions. NB This biotope is not considered a biogenic reef.
Biodiversity Action Plan Priority Habitats (UK)		
	S. spinulosa reefs	
Europe (EUNIS Nov. 1999)		
A3.6/B-MCR.Csab	*S. spinulosa* communities on circalittoral rock	See MNCR MCR.CSab
A4.4/B-CMX.SspiMx	*S. spinulosa* and *Polydora* spp. on stable circalittoral mixed sediment	See MNCR CMX.SspiMx
A3.234/B-MIR. SedK.SabKR	*S. spinulosa* with kelp and red seaweeds on sand-influenced infralittoral rock	See MNCR MIR.SedK.SabKR
A3.631/B-MCR. CSab.Sspi	*S. spinulosa* crusts on silty turbid circalittoral rock	See MNCR MCR.CSab.Sspi
A3.6721/B-MCR.As. MolPol.Sab	Dense ascidians, bryozoans and hydroids on a crust of *S. spinulosa* on tide-swept circalittoral rock	See MNCR MCR.As.MolPol.Sab
Wadden Sea (1996)		
03.02.09	Sublittoral *Sabellaria* reef	
France (ZNIEFF-MER)		
III.3.3.1	Faciès à *S. spinulosa*	
III.5.1.1	Faciès d' épifaune à *S. spinulosa*	

3.3 Biology

3.3.1 Reproduction and development

Spawning

The reproductive seasonality of *S. spinulosa* is unclear, although spawning probably occurs largely over winter with settlement in early spring [28]. Working in the Plymouth area, for instance, Wilson [60] generally found a spawning period from January to March, with a settlement period from March to April. This concurs with observations in the Bristol Channel of the appearance of a new cohort in March [23]. Conversely, however, Garwood found larvae in the plankton from August to November on the northeast coast of England [22], whilst the Marine Biological Association reported the breeding season according to three separate authorities as “May”, “September” and “Jan-Sept” in the Plymouth area [36].

Bhaud [5] reported larvae of *S. spinulosa* in the plankton from December to March in Mediterranean populations and in August in Scandinavian populations. The breeding season of several other temperate polychaetes were also retarded in Scandinavian populations as compared to Mediterranean populations, leading to the suggestion that the breeding season is correlated with the thermal regime; breeding does not occur below or above a specific temperature, but is restricted to an optimum value, which appears to be a physiological species characteristic [5].

The larvae spend between six weeks and two months in the plankton [60], and so dispersal range is likely to be considerable.

Settlement

Following their pelagic development, a series of experiments has shown that when *S. alveolata* larvae are able to metamorphose, they crawl actively over any solid surfaces with which they happen to make contact, seeking indicative characters distinctive of their normal adult environment [59]. If these are not found, the larvae are able to postpone metamorphosis for several weeks, remaining in a developmental state able both to swim and crawl. If delayed too long, however, some may metamorphose in the absence of normal environmental stimuli, whilst others often become incapable of metamorphosing normally or may die without metamorphosing.

Purely physical factors have only minor influences on settlement [59], but experimental lab work has shown that *S. spinulosa* are strongly simulated to metamorphose and settle on contact with the cement secretions of other *S. spinulosa*, whether the latter are adult, newly settled young, or old, deceased colonies [60, 48]. In the absence of any other individuals however, they will eventually, after two or three months in the plankton, settle onto any suitable substratum [30, 14]. Scallop shells, particularly *Pecten maximus*, also appeared to have some slight settlement inducing properties, though oyster shells, with which *S. spinulosa* are often associated in the southern North Sea, were not tested. While *S. alveolata* larvae were stimulated to metamorphose by cement secretions of *S. spinulosa*, the opposite was rare [60].

The ability of newly settled young to stimulate the settlement of other larvae suggests that they can ‘accelerate’ the settlement process once it has started [28]. This may help explain the massive colonisation described by Linke [35], in an area previously only colonised by scattered individuals [61].

Conversely, it has been suggested that growth and recruitment of *S. spinulosa* could be inhibited or even prevented by dense populations of the brittle star *Ophiothrix fragilis*, through prevention of adequate food particles from reaching the worms [23]. This is thought to have been the reason behind very low recruitment and growth of *S. spinulosa* in an area of the Bristol Channel in 1976. Fecundity of the adults in the colony was also severely reduced, possibly for the same reason. The possibility that the larvae themselves could be filtered out by very dense *O. fragilis*, or by other filter feeders such as *Mytilus*, was not mentioned but should also be considered [28].

Recruitment

Long term studies of the related *S. alveolata* at Duckpool, north Cornwall, have shown that they have good and bad years for recruitment [61]. Though less work has been undertaken on recruitment of *S. spinulosa* populations, the evidence suggests that their fecundity and recruitment may also be very variable, at least in some areas (eg Bristol Channel [23] and the southern North Sea [35, 39]). Such inherent variability has important implications for the recovery potential of populations following disturbance.

Wilson also found experimentally that the larvae of both *S. alveolata* and *S. spinulosa* have varied rates of development ([59, 60] respectively) which accords well with his field observations of varied times of settlement on the shore [61].

Growth

Although no detailed reports were found concerning the growth of *S. spinulosa*, either of individual worms or of reefs, it appears to be rapid. Very rapid growth is implied, for instance, by the observations of Linke [35]. Moreover, an experiment to assess the damage caused to *S. alveolata* reefs by shrimp trawls found that all traces caused by the fishing gear had disappeared four to five days later due to the building activities of the worms [52]. It is assumed that *S. spinulosa* will be similarly proficient at rebuilding their tubes.

Maturation

Holt [30] reported that *S. spinulosa* reaches sexual maturity in its first year, whilst Linke described the spawning of intertidal *S. spinulosa* reefs in the southern North Sea as having taken place during the first and second years [35].

3.3.2 Reef development

The tube structure and typical growth over hard objects suggests that *S. spinulosa* worms build independently of each other (unlike the related *S. alveolata*), and that their tubes coalesce and grow upwards away from the seafloor at high worm densities. This is not an obligatory growth form, however, and lack of a well-developed reef structure does not imply sub-optimal conditions for growth [16]

Although colonies may support large numbers of adult individuals, over 6000 individuals/m^2 have been reported in the Bristol Channel for example [23], dense populations of *Sabellaria* do not necessarily correspond to the occurrence of visible reef. Foster-Smith, for example, found very dense populations of *S. spinulosa* in one area surveyed, despite the apparent recent disappearance of reef from this location [16].

The alternative growth form of thin crusts of *S. spinulosa* can also be extensive though they may only be seasonal features, being broken up during winter storms and quickly reforming through new settlement the following spring. There are extensive samples of this form of colony on the west Wales coast, particularly off the Lleyn Peninsula and Sarnau cSAC and the Berwickshire and North Northumberland coast cSAC. Due to their ephemeral nature, these crusts are not considered to constitute true *S. spinulosa* reef habitats since they do not provide a stable biogenic habitat enabling associated species to become established in areas where they are otherwise absent [14].

3.3.3 Longevity and temporal stability

To date, there have been no studies of the longevity of individual *S. spinulosa* worms or of their colonies. However, long-term studies have found that the closely related *S. alveolata* may live for at least 10yrs [62], and it is possible that *S. spinulosa* may be similarly long lived.

It has been suggested, meanwhile, that the age of a colony may greatly exceed the age of the oldest individuals present, since empty concretions of *S. spinulosa* sand tubes are frequently found and must be able to persist for some time in the marine environment [60, 50]. In contrast, Schafer [48] noted that some reefs of *S. spinulosa* survive for one or two years only, unless re-inforced by new settlement, suggesting a shorter life span. Furthermore, samples taken in similar locations on different surveys have sometimes shown very marked changes in *S. spinulosa* densities, further bringing into question the temporal stability of the reefs. Foster-Smith, for example, illustrated large changes in the overall proportion of some key species between 1997 and 1999 and there appeared to be a decline in the relative abundance of *S. spinulosa* [21]. From his work around the Wash and North Norfolk coast, Foster-Smith suggested that the reefs appear well developed and relatively stable offshore, but become more variable further into the Wash [21]. Although these differences may indicate widespread changes in *S. spinulosa* over time, the apparent decline may equally have been due to small differences in position of the samples between the two surveys coupled with a naturally patchy distribution. Thus assessing temporal change may be complicated by patch dynamics of the reef system including reef build-up and break-down involving other related *S. spinulosa* biotopes [21].

In general terms, however, it is thought likely that stability of the reefs is to some degree a function of stability of the substratum. The more transient reefs that have been reported (reviewed by Holt, and others. [30]) probably occur principally on relatively unstable substrata, while longer lasting reefs could be a product of more stable substrata [10, 28].

3.3.4 Fragility

The fragility, or otherwise, of *S. spinulosa* colonies, whether in the form of reefs or thin crusts is unclear. Many studies, for instance, have found that *S. spinulosa* colonies are sufficiently brittle to be quantitatively sampled using grabs [23, 2, 20]. Holt, meanwhile, has reported that crusts of *S. spinulosa* on cobble and boulders off the Northumberland and North Yorkshire coasts often break up during winter storms [28, 30]. Indeed, in an assessment of the potential impacts of climate change, *S. spinulosa* was considered to be most vulnerable to increased storminess [51].

In contrast, Vorberg calculated the load-bearing capacity of sample sections of *S. alveolata* reef, finding the average compressive strength to be 0.22Nmm^{-2}, corresponding to 2.2kg cm^{-2} [52], whilst Wilson [60] reported that the tubes of *S. spinulosa* are harder and stronger than those of *S. alveolata*. This suggests that sabellarian reefs are highly robust structures, as is necessary to withstand water currents [48].

3.4 Environmental requirements

3.4.1 Temperature

There is little specific information on the temperature tolerance of *S. spinulosa*. Nevertheless, its widespread distribution together with its predominantly subtidal habitat suggests that it is likely to be much less sensitive to temperature variations than the predominantly intertidal *S. alveolata* [28]. Indeed during the cold winter of 1963-4, the latter suffered high mortalities at a number of UK locations suggesting that *S. alveolata* is severely affected by low winter temperatures, whilst *S. spinulosa* was unaffected [11]. It should be noted, however, that *S. alveolata* is probably existing near to its temperature threshold in British waters, and would probably be considered less sensitive to temperature fluctuations if studied in warmer waters [28].

As a corollary to this, Viles did not consider *S. spinulosa* to be particularly vulnerable to climate change in general or to changes in sea surface temperature in particular, although, as noted previously, he did consider *Sabellaria* to be sensitive to increased storminess which is considered to be a indirect consequence of climate change [51].

3.4.2 Depth

S. spinulosa is found from the low intertidal to offshore, inhabiting a variety of depths ranging from a few metres to over 40m depth [10, 30]. More specifically, Killeen and Light found *S. spinulosa* in grab samples from 5m depth in the River Crouch estuary [34], while dense reefs reported in the Bristol Channel were found at a depth of 41m [23]. Individuals can certainly occur intertidally, and dense crusts have been reported in the infralittoral [34]. Dense reefs, however, are found almost entirely subtidally, and there are no reports of intertidal *S. spinulosa* reefs in Britain. Nevertheless, sporadic dense intertidal reefs have been reported from the Wadden Sea [35], although it has been proposed [28] that one of the few references to a sizeable intertidal population [39] may have been a misidentification of *S. alveolata*.

3.4.3 Suspended sediment / water movement

The most important environmental requirement of *S. spinulosa* appears to be a good supply of sand for tube building, which is put into suspension by strong water movement [14]. The relative importance of tidal versus wave induced movements is, however, unclear [10]. Thus *Sabellaria* reef communities are typically associated with weak or moderately strong tidal flows [32], and favour locations such as the edges of sand banks or areas where there are sand waves [16].

3.4.4 Substratum requirements

S. spinulosa favours substrates which include bedrock; boulders, cobbles, mixed substrata; and mixed sediment [10]. More specifically, Rees and Dare [43] describe the habitat preference as being typically shell (especially oyster valves), sandy gravel or rocky substrates, which concurs well with the findings of other authors [49, 42].

Although a somewhat firm substrate is presumably required for the establishment of a colony, however, it has been suggested that *S. spinulosa* can subsequently increase in extent by addition to the existing colony without the need for hard substrate [28]. Indeed, several studies have reported extensive *S. spinulosa* colonies in essentially sandy areas (eg [55, 48, 54]), whilst others have reported high densities of *S. spinulosa* in grab samples which would be unlikely from hard bottoms unless the reefs were extremely thick and very brittle (eg [23,2]).

3.4.5 Salinity

Little firm information was found on salinity requirements of *S. spinulosa* although well-developed reefs seem to be restricted mainly to deeper waters where salinity would be expected to be more or less fully marine. However, records of *S. spinulosa* have been reported from estuaries such as the Crouch and Mersea [34], whilst the reports by McIntosh [37] of dense aggregations of *S. alveolata* being particularly common in estuaries such as the Tees and Humber are thought to be misidentifications of *S. spinulosa* [30].

3.5 Ecological functioning

3.5.1 Reef habitats

Biogenic reefs can have a number of important effects on the physical, and probably chemical environment (reviewed by Holt [30]). In addition to *S. spinulosa*, examples of such inshore biogenic reefs include those of *S. alveolata*, *Mytilus edulis*, *Modiolus modiolus*, and *Serpula vermicularis*. Important influences they convey on their environments can include the stabilisation of sands, gravels and stones; the tubes or shells of the organisms themselves provide hard substrata for attachment of sessile organisms; they may provide a diversity of crevices, surfaces and sediments for colonisation; and they can accumulate faeces, pseudofaeces and other sediments which may be an important source of food for other organisms. For these reasons many biogenic reefs have a very rich associated fauna and flora, which at least in terms of macrofauna is often much richer and more diverse than in surrounding areas. *Sabellaria* reef, for example, was amongst the most diverse and richest described biotopes of the BMP surveys [18]. Biogenic reefs are consequently of high importance to the ecological functioning of the habitats in which they are found.

3.5.2 Associated species

As might be expected for a biogenic reef, the thicker, and probably more permanent, crusts or reefs of *S. spinulosa* seem to have a considerable influence on the benthic community structure [9]. George and Warwick [23], for instance, reported that *S. spinulosa* reefs contained a more diverse fauna than nearby areas, whilst the National Rivers Authority [41] found that sites in the Wash associated with *S. spinulosa* had more than twice as many species and almost three times as many individuals (excluding the *Sabellaria* themselves) as sites with low, or no, *S. spinulosa*. In the latter survey, the distinction between '*S. spinulosa* sites' and 'low or no *S. spinulosa*' was made at only 100 individuals per 3 grab samples (covering

0.3m^2), raising the possibility that even relatively sparse *S. spinulosa* can strongly influence community structure.

Naturally, numerous species have been reported in association with *S. spinulosa*, although virtually all are found widely in other communities. Connor, and others . [10] for instance, describe *S. spinulosa* communities with attached *Polydora* tubes, and with an infauna of typical sublittoral polychaete species, as well as the bivalves *Abra alba* and *Nucula nitidosa*, and an epifauna including tubeworms, pycnogonids, hermit crabs and amphipods. From his studies in the Wash, Foster-Smith has also reported associated anemones, as well as high densities of shrimp like organisms, probably mysids, which could be seen immediately above the reef on video footage.

The commercially valuable pink shrimp, *Pandalus montagui*, seems to have a particularly strong association with *S. spinulosa* reefs to the extent that fishermen pursuing *Pandalus* have been reported to use small trawls to search for lumps of *S. spinulosa* which they regard as an indication of good fishing grounds [55].

3.5.3 Competitors and predators

As noted above, an association between the pink shrimp *Pandalus* and *Sabellaria* reefs has long been appreciated [55, 54]. Although laboratory observations of feeding have demonstrated a predatory capability [54], the association may be as much a function of the often prolific nature of the benthic food supply associated with ross colonies, as of the presence of the worms themselves [43].

Other polychaetes such as *Lepidonotus* have also been reported as predators of *Sabellaria* [48], whilst George and Warwick [23] have suggested that growth recruitment of *S. spinulosa* could be inhibited or even prevented through competition for feeding space by dense populations of the brittle star *Ophiothrix fragilis*. They proposed that the brittle stars may monopolize the suspended food resource with an umbrella of feeding arms, preventing all but a few particles from becoming available to other species below. It is conceivable that other filter feeders such as *Mytilus* may have similar competitive potential.

3.5.4 Parasites

In a biogeographical study of molluscs around the British Isles and the north coast of France, Killeen and Light [34] found a recurring association between the two sabellariids in this region *S. spinulosa* and *S. alveolata* and two marine snails: the pyramidellid gastropod *Noemiamea dolioliformis,* and the aclid, *Graphis albida*. The Pyramidellidae is a family of small, white gastropods, all of which are ectoparasites of other marine organisms, particularly polychaetes and molluscs. Whilst few are considered to be host-specific, the evidence from this study indicated that living animals of *N. dolioliformis* are only ever associated with *Sabellaria* spp., though there is no evidence for a preference for either species. Though aclids are principally parasites of echinoderms, *G. albida* also showed a clear relationship with *Sabellaria* spp. As yet, however, there is insufficient evidence to determine whether it associates only with these polychaetes.

Killeen and Light [34] also recorded four other pyramidellids from their *Sabellaria* samples: *Partulida spiralis*, *Odostomia turrita*, *O. plicata*, and *O. unidentata*, and inferred that all of these species were feeding on the *Sabellaria* worms.

The work did not establish whether the snails live within the tubes or around the apertures of the worms, though they inferred *Graphis* probably do live within the tubes or attached to the worm bodies, but that the adult *Noemiamea,* at least, live around the worm tube apertures and feed on the worms whilst the prey itself is feeding.

3.6 Conservation and protection status

Tables 2 and 3 below indicate the conservation and protection status respectively of *Sabellaria* reefs, as listed in Jones, and others. [32].

Table 2: The conservation status of *Sabellaria spinulosa* reefs.

Region	Status
OSPAR area	Not known
Wadden Sea	Threatened by complete destruction
UK	Significantly declined in extent and quality
Other sub-regions	Not known

Table 3: The protected status of *Sabellaria spinulosa* reefs

Protection Mechanism	Habitat
EC Habitats Directive	Can be protected as *Reefs* and may also occur within *Estuaries* and *Large shallow inlets and bays*.
UK Biodiversity Action Plan	*S. spinulosa* reefs (Habitat Action Plan)

3.7 Sensitivity

In accordance with Holt, and others. and McLeod [29, 38], both sensitivity, defined as the likelihood that an organism or community will suffer damage or death when exposed to an external factor, and vulnerability, defined as the likelihood of exposure to an external factor, have been taken into consideration under the general heading of 'sensitivity' here.

3.7.1 Sensitivity to natural events

No published evidence was found of any strong sensitivity by *S. spinulosa* to natural events, though the fact that it often acts as a fast growing annual lead to the proposal that its colonies may be a resilient phenomena [30]. Nevertheless, the apparent rarity of well-developed, stable reefs could be interpreted such that an unusual set of environmental factors and/or circumstances is required for their formation. Consequently a degree of sensitivity to an external factor(s) might be expected.

One aspect to which *Sabellaria* reefs are likely to be susceptible is variability in recruitment success. Thus the sensitivity and vulnerability of *Sabellaria* to all external factors exerting an influence on fecundity and/or recruitment should be contemplated. However, due to the paucity of knowledge in this regard, any discussion to this effect would be merely speculative.

As mentioned previously, competition with the brittle star *Ophiothrix fragilis* is thought to have been the reason behind very low recruitment and growth of *S. spinulosa* in an area of the Bristol Channel in 1976 [23]. This not only supports the suggestion that variability in recruitment is important to the success of *S. spinulosa*, but also that fluctuations in the populations of other species could have incidental affects on *Sabellaria*. The scant knowledge regarding the predators and competitors of *S. spinulosa*, however, provides little on which to assess likely sensitivity to changes in populations of other species.

Again, as discussed previously, it is likely that stability of the reefs is to some degree a function of stability of the substratum [30]. This, in turn, is likely to be influenced by events such as storms. Increased storminess was, coincidentally, considered to be the impact to which *S. spinulosa* was most vulnerable in the event of climate change [51].

Finally, *S. spinulosa* does not appear to be particularly sensitive to changes in water quality (see below) except perhaps in the unlikely event of the supply of sand with which to build its tubes being removed. Such an event is, perhaps, more likely to be associated with anthropogenic activities rather than with natural events.

3.7.2 Sensitivity to human activities

The greatest vulnerability of *S. spinulosa* reefs is considered to be physical disturbance, typically from fisheries activities or aggregate dredging [14]. Both such disturbances are reviewed in turn in the next two sections. Rees and Dare [43], for example, using a four point numerical scale of assessment of 'risk of extinctions through natural and anthropogenic factors' for a number of benthic species, considered that the risk for *S. spinulosa* from trawl/dredge effects was high, scoring the maximum of 4. Although it is generally accepted that *S. spinulosa* reefs can be severely damaged by physical damage in the short term at least, the speed of recovery from such damage is presently unknown [28]. Regeneration of this habitat is classified as 'difficult' (15-150 years) in the Wadden Sea Red List [14], though conversely it has also been suggested that recovery may be rapid as the worms are effectively annual [24].

Fishing

Trawling for shrimp or finfish, dredging for oysters and mussels, net fishing and potting are all believed to cause physical damage to erect *S. spinulosa* reef communities [14]. The impact of mobile gear is thought to break the reefs down into small chunks, thus changing the habitat for the rich infauna and epifauna associated with this biotope. The individual worms, meanwhile, are apparently unable to re-build tubes once dislodged from them [48].

The fishery most commonly implicated in the decline of *S. spinulosa* reefs, appears to be that of the pink shrimp, *Pandalus montagui*. The loss of large *S. spinulosa* reefs between 1924 and the 1980s from the subtidal shallows and channels of the northern Wadden Sea, for instance, is thought to have been a consequence of the long-term effects of shrimp-fishing trawls [44, 46, 45]. Local fishermen were reported to have deliberately ground the reefs with heavy gear because the reefs ripped apart the nets when fishing for shrimp, destroying the associated shrimp fishery in the process [46]. Shrimp trawling still occurs in these areas and the *S. spinulosa* reefs have effectively been replaced by beds of mussel, *Mytilus edulis*, and sand-dwelling amphipods, *Bathyporei* spp [45], though this may be partly attributed to an increase in coastal eutrophication, favouring *Mytilus* [45, 14].

Damage to *S. spinulosa* reefs in the Thames Estuary and the Wash has also been attributed to the pink shrimp fishery. Here it was reported that "the accepted practice among commercial fishermen [was] to search with a small hand dredge for the polychaete worm *S. spinulosa* and then trawl for shrimp in areas where this was found" [55].

Prawn fisheries were similarly implicated in the loss of *S. spinulosa* reefs in the approach channels to Morecambe Bay [24]. Recent surveys suggest recovery of *S. spinulosa* has not occurred in the Bay despite the cessation of fishing many years ago [47], and this seems most likely to be due either to lack of larval supply, or to permanent or ongoing alterations to the habitat [30]. It is worth noting that the brown shrimp, *Cragon cragon,* are still fished commercially in the general area [47].

An intensive beam-trawl fishery for brown shrimps also occurs along the German North Sea coast, and here fishing effort has increased constantly over recent decades [4]. This has been simultaneous with the changes in benthos of the Wadden Sea, further reinforcing the view [44] that beam-trawl fisheries in the Wadden Sea have been responsible for the decline of *S. spinulosa* reefs.

Using underwater video techniques, however, Vorberg [52], has made direct observations of the fishing gear of the *Crangon* fishery in action on the sea bottom and found that the shrimpers did not cause visible damage. These findings were corroborated by his field experiments on the reefs of *S. alveolata* and empirical calculations on the load of fishing gear and the compressive strength of the reef. From this he concluded that the trawls used in *Crangon* fisheries cannot cause serious damage to reef constructions, and instead proposed that the decline may have been due to natural disturbances such as changes in currents or to other anthropogenic measures such as dyking or the building of coastal-protection structures [52].

Although the natural growth and repair capacity of *S. spinulosa* is such that they can rebuild destroyed parts of their dwellings within a few days, provided they are not killed or removed from their tubes, the findings of Vorberg [52] relate exclusively to short-term effects following once-only disturbance. The possibility of impairment by shrimping in the medium to long-term cannot be ruled out in the event of intensive fishing, despite the relatively light gear. The variability in recruitment success adds a further element of unpredictability to recovery rates.

Aggregate extraction

The wide distribution of *S. spinulosa* together with its association with areas of mixed sediment means that aggregate extraction is also very likely to occur in areas where *S. spinulosa* is found. Furthermore, it is clear that in the short term at least, extensive aggregate dredging activities are likely to inflict severe, direct damage on *S. spinulosa*. Again, the speed of recovery from such damage is presently unknown. In comparison to fishing impacts however, gravel extraction is likely to be more controlled and more limited in extent, both spatially and temporally, so that direct damage may be less severe, and the potential for recovery from adjacent undamaged areas would be higher [28]. Consequently, aggregate extraction is not considered to be as significant a threat as commercial fisheries, provided that environmental assessments identify reefs, exclude them from licensed areas and/or establish ‘refuge’ zones, avoid other reef habitats while dredging, and carry out appropriate monitoring and biological study [14].

The likelihood of damage due to sediment plumes in areas adjacent to gravel extraction is presently less clear, since there is no knowledge of the effects of differing particle sizes upon *Sabellaria*, for example. However, given *S. spinulosa*’s preference for somewhat turbid waters, the suspension of fine material during adjacent dredging activity is not considered to be likely to have serious detrimental effects on the habitat [30], though this has yet to be demonstrated conclusively. Indeed it is worth noting that in a study of the Wash, Foster-Smith [16] found that the best reefs seen in the area were associated with ground clearly scarred by dredging activity, and suggested that this may be a result of a reduction in the overburden of sand having resulted in a cobble/sand habitat more suitable for *S. spinulosa* colonisation.

Shoreline development

The predominantly intertidal *S. alveolata* is considered to be potentially vulnerable to changes in sediment regime as a result of shoreline development plans since both large scale increases and decreases in sand could be potentially damaging. In most cases, however, this is likely to be on a local scale only. Sensitivities of subtidal reef areas can only be guessed at present, but are likely to be similar to those of *S. spinulosa* [30]. Similar arguments would apply to other physical activities such pipelaying and cable trenching [30].

Water quality

Studies in relation to sewage [53] and other pollution [27] suggest that *S. spinulosa* is generally tolerant of changes in water quality [14]. This may not, however, be the case for associated biota [10]. For example, Hoare and Hiscock investigated the distribution of marine organisms around the outfall from a bromide extraction plant in North Wales [27]. The effluent had a pH of 4, and among other contaminants contained free halogens. Species richness and diversity was markedly reduced within 150m of the outfall both intertidally and subtidally, with red algae *Antedon bifida* and *Helcion pellicidum* being particularly sensitive. *S. spinulosa* was found closer to the outfall than any other organism, however, and was found in larger numbers at intermediate distances than further away.

Meanwhile, following surveys of sewage discharge and dumping in Dublin Bay, surveys by Walker and Rees [53] indicated that sludge dumping may actually encourage the establishment of *Sabellaria*. They reported that “in the dumping area and in the southeast of the bay downtide of the dump site, where depths are greater, the faunas resembled the *Nucula / Sabellaria (spinulosa)* community of Caspers . As well as having pollution indicator species, this latter community generally had greater faunal densities and diversities than elsewhere in the bay (except low diversities at the dump sites in 1971). Apart from a possible effect of depth, this suggests that the dumping was having an enriching rather than a degrading effect, although the probable sediment change since 1874 may imply a change in community type”.

Despite *S. spinulosa*’s tolerance of poor water quality, pollution is, nevertheless, listed as one of the major threats to *S. spinulosa* in the Wadden Sea. The *Sabellaria* reefs lost from this area, probably as a consequence of fishing activities (see previous), have been replaced by beds of mussel, *Mytilus edulis,* and sand-dwelling amphipods *Bathyporei* spp. This has been partly attributed to an increase in coastal eutrophication, favouring *Mytilus* [14].

Although *S. spinulosa* can probably be regarded as being relatively insensitive to changes in water quality induced by man's activities, the exception to this will be situations in which sediment loadings are reduced, perhaps by changes in water movement as a result of a construction. Pollution in the form of increased sediment loading is probably more usual, however, for example due to dredging activities, though it is unlikely *S. spinulosa* will be unduly sensitive to this.

Chemical contaminants

Although direct evidence is limited, it is considered unlikely that *S. spinulosa* shows any special sensitivity to chemical contaminants [30]. As discussed previously, *S. spinulosa* was relatively unaffected by an outfall from a bromide extraction works containing free halogens [27]. The only other information found relating to the sensitivity of *S. spinulosa* to chemical contaminants, however, was in connection with work on oil dispersants. Larvae of *S. spinulosa* were 'intensely irritated' by a 1ppm concentration of an oil dispersant (detergent BP 1002). Although they initially appeared to recover following the evaporation of the solvent fraction, they nevertheless died several weeks later while larvae in uncontaminated control experiments all survived [57]. Concentrations of 2-5ppm killed the larvae within a day or two. Since the toxicity of detergents varies enormously and no other species were tested, however, it cannot be concluded that this represents a strong sensitivity by *S. spinulosa* to such chemicals. Further experiments in which larvae were provided with sand that had been soaked in stronger concentrations of the detergent found that larvae crawling onto the sand were damaged, though the toxic effect disappeared after some days [58].

4. Review of previous reports

4.1 1997 BMP survey

FOSTER-SMITH & SOTHERAN. 1999. *Broad scale remote survey and mapping of sublittoral habitats and biota of the Wash and the Lincolnshire and the north Norfolk coasts.*

The BMP surveys were designed to map the distribution of a wide range of biotopes. Remote sensing was used to map the full range of biotopes present in the area and the field sampling was designed to be representative of these biotopes (1) for descriptive purposes and (2) to be ground truth data for classification of the remote data.

Unless they are also exhaustive, broad scale map-based surveys can only be indicative about biotope distribution and are accompanied by a variable and often high level of uncertainty. Nevertheless, the BMP surveys showed that there were clear broad scale trends to the distribution of biotopes. The descriptions based on video and grab sample data also showed that many of the infaunal biotopes were very similar in species composition or had a large area of overlap.

Although *Sabellaria spinulosa* reefs were not specifically targeted, the surveys were able to predict their most likely distribution. They indicated that high densities of *S. spinulosa* within the Wash were most likely to be located on the northern side of the Lynn Deeps near Longsands, and also on the opposite side near Hunstanton. The predicted distribution extended along the sides of the Lynn Deeps northeast to Scott Patch near the licensed sand extraction area 107 and well-developed reef was confirmed here.

Video evidence of well-developed *S. spinulosa* reefs collected from the northern margins of the sand extraction area 107 (outside of the cSAC), brought their existence to the attention of English Nature. Although poor underwater visibility at the time of the surveys precluded direct observation of reefs within the Wash cSAC itself, comparison of the infaunal composition of grab samples taken from certain sites within the Wash and the observed reefs in area 107 suggested that reefs might also occur in the cSAC. Certainly, extremely dense populations of *Sabellaria* were found. This survey described the range of biotopes found and it was suggested that *Sabellaria* biotopes ranged from low-density populations, through high-density communities with poor reef development to well developed reefs. In other words, there was likely to be a continuum between similar biotopes.

The effectiveness of acoustic ground discrimination systems for detecting and mapping *S. spinulosa* reefs remained in question, and it was suggested that the use of other techniques, such as sidescan sonar, might be more appropriate.

4.1.1 Data available

The three *RoxAnn* surveys of the BMP project were conducted over a three year period, the dates for which were as follows: Wash 1-14 August 1996; Wash, north Norfolk and south Lincolnshire coasts 1-18 July and 15-20 September, 1997; and, north Lincolnshire coast 3-7 August, 1998. Ground truth data comprised of Day grab samples, video inspections and trawls and dredges.

4.1.2 Summary of findings

The BMP surveys showed that there were clear broad scale trends to the distribution of biotopes. The descriptions based on video and grab sample data also showed that many of the infaunal biotopes were very similar in species composition or had a large area of overlap. The survey described the range of biotopes found and it was suggested that *Sabellaria* biotopes ranged from low-density populations, through high-density communities with poor reef development to well developed reefs. In other words, there was likely to be a continuum between similar biotopes.

The habitats of the Wash survey area are largely comprised of sediment, ranging from muddy sand to cobbles with smaller areas of soft mud at one extreme and silty boulders at the other. Many of the biotopes could only be described from an analysis of animals and sediment collected using a Day grab, which revealed no sharp divisions between biotope types. Instead, the samples could be arranged with overlapping species assemblages into a scheme that had as its basis a core of common species. The predicted distributions of the infaunal biotopes are illustrated in Figure 15. *S. spinulosa*, which was most effectively sampled using remote video, was often abundant and was observed to form extensive reefs. This biotope was the most diverse and richest described. The probability maps for both the *Sabellaria/Lanice,* and the *Sabellaria* reef biotopes are illustrated in Figure 15.

4.2 1999 survey

FOSTER-SMITH, R. 2000. *Establishing a monitoring baseline for the Wash subtidal sandbanks.*

In 1999 the primary objective was to provide a basis for monitoring changes in the distribution of major habitats and biotopes at selected representative locations within the Wash. The strategy adopted was based on a nested survey design. The justification for selecting representative sites was to keep survey costs down to an acceptable level and this remained an important consideration in the design of subsequent surveys. Again, *Sabellaria* was not specifically targeted.

4.2.1 Data available

The 1999 survey was conducted between 22 and 24 June, 1999. Four belt transects about 250m wide were surveyed using *RoxAnn* ™ AGDS and rapid ground truth sampling, particularly video. The four transects were positioned in order to cross major features and be representative of the range of ground types in the Wash, determined on the basis of previous surveys. Three of the transects were positioned in the Wash itself running north west/south east across the main depth profile of the Wash, whilst the fourth ran south west/north east along the centre of the Boston Deeps (see Figure 1). Eight monitoring stations were then positioned within the transects and at each site three replicate grab samples were taken. A dredge towed for a short distance was used to supplement grabs with one dredge sample being taken for transects 1, 2 and 3 but lack of time prevented a sample being collected from transect 4.

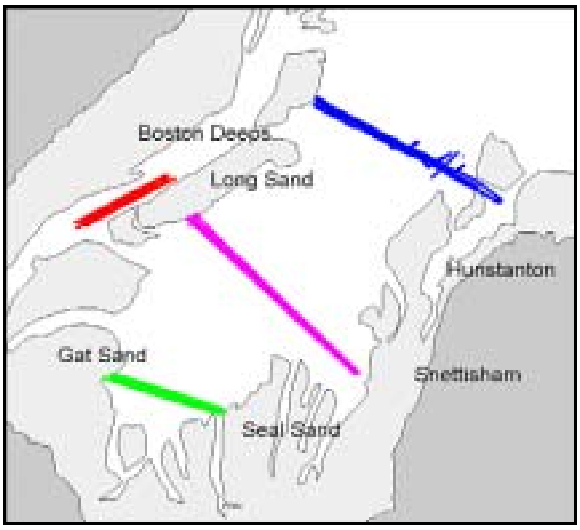

Figure 1: Location of the monitoring baseline transects showing the actual positions of the AGDS tracks

4.2.2 Summary of findings

Although this is a baseline survey, the data were compared with similar data from 1997 and there were indications that the numbers of some species had fluctuated markedly. In particular it appeared that *S. spinulosa* and the small deposit feeding bivalve *Abra alba* declined markedly, whilst the sand mason *Lanice conchilega*, the bivalve *Ensis americanus* and tubificid worms increased markedly.

4.3 2000 survey

FOSTER-SMITH & WHITE. 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.

The 2000 survey was the first stage in an endeavour to study the extent and variability of *S. spinulosa* reefs, to study their local ecosystem and identify the impacts, if any, of current fishing practices on these features. Consequently, the survey concentrated on fine-scale mapping of the spatial and temporal distribution of the reefs.

The primary aim of the survey was to compare and contrast the use of acoustic ground discrimination systems (AGDS) and sidescan sonar for mapping *S. spinulosa* reefs. As such, it was the first survey to specifically target *Sabellaria*, incorporating direct observation using remote video. Two sites were selected for the survey – one in the cSAC just south of Long Sands and the other was area 107. The survey was partially successful in that the sonar techniques were tested over observable reefs at 107, but did not give a distinctive image using sidescan. They were more readily detected using AGDS, but this system is not high resolution and differences between systems and interpretation of the data result in different boundaries. However, no reefs (or high density *Sabellaria* populations) were found at the Long Sands site and poor weather prevented repetition and confirmation of the results of the acoustic trials over known reefs at 107. This was despite video observations made by ESFJC in the previous year of reefs at the Long Sands site.

4.3.1 Data available

There were three main components of this survey:

1. A broad-scale acoustic survey of trial areas to map variations in substrate and to identify smaller areas of reef systems, incorporating a comparison of *RoxAnn* with *QTC Impact.*

2. Detailed sidescan survey of selected sections of the trial areas run in conjunction with *RoxAnn* to provide high-resolution topographic and sediment surface feature images.

3. Underwater video and Day grab samples to categorise *S. spinulosa* communities and to ground-truth the acoustic data. The grab samples were sorted and the *S. spinulosa* counted, the samples were preserved for faunal analysis.

Table 4: **Data collected during the 2001 surveys**

Date	Surveys	Analysis
July	*RoxAnn* surveys of Wash trial area and 107. Sidescan/*RoxAnn* surveys of 'reef' sections within trial areas. 15 video samples and 5 replicate Day grabs at two stations in Wash trial area and three stations at 107. Samples preserved.	Supervised and un- supervised classification of *RoxAnn* data. Mosaic sidescan. Categorisation of all field sample data (used in supervised classification). Grab samples analysed for *Sabellaria*.
October	Grab and video data collected for Wash: Infauna preserved for future analysis.	Categorisation of all field data
November	*QTC* and *RoxAnn* surveys of the intensely surveyed area within the Wash trial area. Habitat data from 10 grab samples within the Wash: no samples retained for infaunal analysis.	Unsupervised and supervised classification of *RoxAnn* and *QTC* data. Samples categorised.

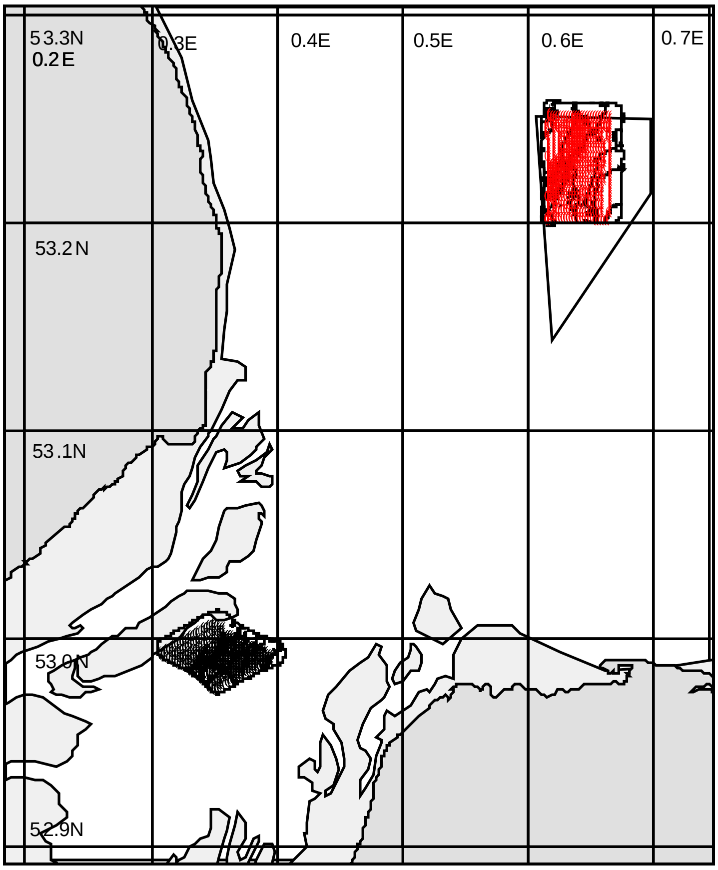

Figure 2: **Site map of area with trial sites marked by the track lines run on the July survey. Area 107 is also shown for reference**

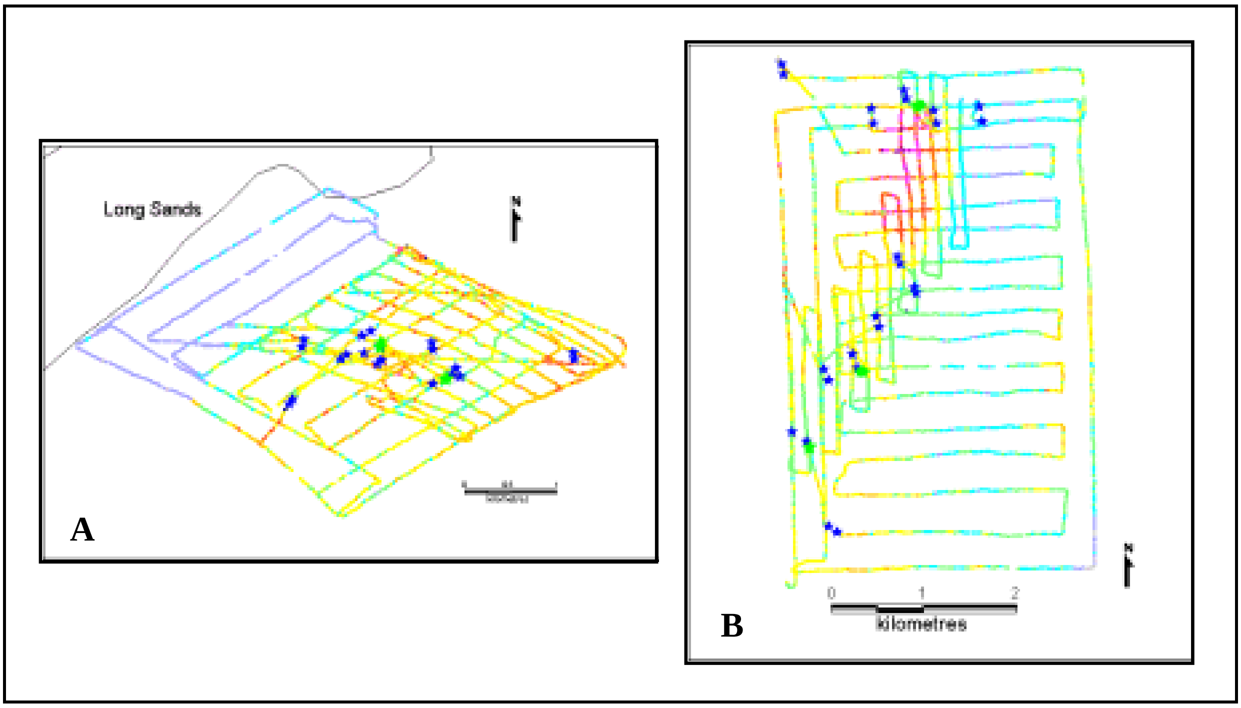

Figure 3: ***RoxAnn* tracks over the Longsand site (A) and the Area 107 site (B) coloured according to E1 values. The green and blue stars are indicative of the positions of the grab stations and video samples respectively. The area selected for sidescan is indicated by the closely spaced *RoxAnn* tracks**

4.3.2 Summary of findings

July survey

Sabellaria reef was only positively identified at the reference site of 107. The sidescan sonar as used in this survey was unable to clearly distinguish *Sabellaria* reef from other sandy gravel habitats, although it is possible that differences in sidescan deployment might be more successful. In contrast *RoxAnn* did appear to be able to predict the distribution of reef, although there was no opportunity to test the predicted distribution by further field sampling. Thus neither system can be considered to give accurate positions of *Sabellaria* reef over the full coverage of the map, and at best it is only possible to map the likely distribution of the reef within the resolution of the *RoxAnn* system. Although this may be sufficient for monitoring coarse changes in distribution, it cannot be used to map small changes in distribution at a fine scale with a comprehensive coverage.

Doubt still remains as to the integrity of the reef system as distinct from other related biotopes in which *Sabellaria* is a characteristic species. Although reefs might be distinguished from other biotopes using video samples, the method is limited by visibility and the handling capability of the drop down system in strong currents. Consequently, it is likely that the full range of *Sabellaria* biotopes can only be defined with confidence with infaunal analysis of grab samples.

Repeat of Longsands survey

It is an inescapable conclusion that AGDS mapping is dependent upon the ground truth samples (since it does not 'see' the benthic habitats directly) and also upon the AGDS system used. However, the interpretation is bound to be problematic because (1) the ground appears to be highly heterogeneous and (2) the biotopes and habitat types are all very similar and grade into each other.

The biotopes are probably very patchily distributed, which would make accurate and detailed mapping very difficult. The problem is compounded because the various biotopes are not clearly distinct even from the field samples. They have many of the same component habitat features and conspicuous species, but in varying proportions. The distinctive nature of the reef biotope is discussed in a later section of this report.

4.4 2001 survey

FOSTER-SMITH. 2001. Sabellaria spinulosa *in the Wash and north Norfolk cSAC and its approaches: Part II, fine scale mapping of the spatial and temporal distribution of reefs and the development of techniques for monitoring condition.*

The primary objective of the 2001 field survey was to identify the distribution of *S. spinulosa* within the Wash. Specifically, it aimed to map the maximum likelihood distribution of *S. spinulosa* in selected survey boxes along a transect from the inner Wash to beyond the cSAC boundary offshore, and to test techniques by assessing the application of different acoustic survey and ground-truthing methods for identifying and measuring *S. spinulosa* reefs at different stages in development.

4.4.1 Data available

The survey design was based on stratified and nested sampling of selected sites based on the broad scale predictive maps from previous surveys. Sites were selected along a transect from the inner Wash, along the Long Sands/Lynn Deeps to further offshore outside the cSAC boundary in order to detect any broad offshore/onshore trends (see Figure 4).

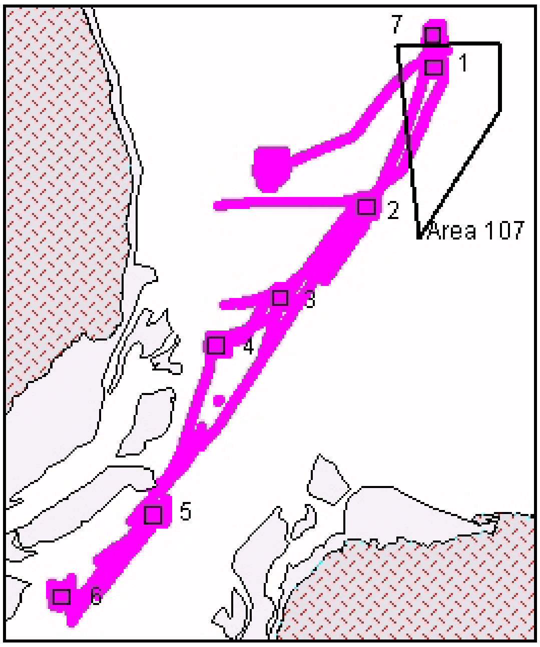

Figure 4: **The AGDS tract of the 2001 field survey showing the location of the transect and sample boxes.**

Ten grab samples were collected from randomly selected stations within seven $1km^2$ quadrats, and these were assessed visually for reef development, sediment granulometry estimation and then the infauna were extracted and preserved for later identification. Each grab sample site was also sampled with a drop down video in order to assess the physical scale of reef development, and also to gauge patchiness of the biotopes at a broader scale than the grab sample. Acoustic techniques – AGDS and sidescan – were also used to try to obtain a broad coverage of the boxes. The field work was carried out over two consecutive neap tides in weeks beginning July 30th and August 13th, 2001.

4.4.2 Summary of findings

The sampling strategy adopted by this survey successfully stratified the area into habitats likely to support *Sabellaria* and associated infaunal communities and those areas less likely to support these communities. It found that dense populations of *Sabellaria* were associated with a wide range of acoustic ground types, although they did not necessarily correspond to the occurrence of visible reef. The reefs of Area 107 appear to have disappeared, for instance, although dense populations of *Sabellaria* remain, despite the clear signs of dredging activity.

Assessment of survey methodologies showed that video is the only technique able to determine if well developed reefs are present, although grab sampling is the only tested way to sample the full range of *Sabellaria* communities. Finer scale patterns, however, can only be detected through remote sensing.

4.5 Summary of data available

Table 5: **Table to summarise data collected by the SeaMap surveys**

Report	Survey Technique				
	AGDS	Sidescan Sonar	Day Grabs	Dredges and Trawls	Video
1997 BMP Survey	.	-	.	.	.
1999 Survey	.	-	.	.	.
2000 Survey	.	.	.	-	.
2001 Survey	.	.	.	-	.

5. Summary of main outcomes from the SeaMap Wash reports

The previous SeaMap reports cover many issues, and the objectives of the various surveys have changed over the years. This section brings together some of the most pertinent information to emerge from the survey reports regarding the status of *Sabellaria spinulosa* in the Wash and its environs, and identifies three main topics :-

1. Effective means of Detection and Sampling: Remote detection through acoustic technologies and methods for sampling *Sabellaria* biotopes.
2. Definition of 'Reef': Physical definition of reefs, specific structures and growth forms, species composition of associated fauna and population structure.

3. Spatial and Temporal Distribution of *S. spinulosa*: Predicted mapped broadscale distribution, proven point density distribution, patchiness (spatial heterogeneity) and temporal stability.

The final section of this report ('Outstanding Issues and Future Work') then examines the need for additional information and survey.

5.1 Effective means of detection and sampling

5.1.1 Remote detection through acoustic technologies

Inevitably, with any survey, there will need to be a compromise between demands regarding size of survey area, completeness of coverage, resolution, discrimination, accuracy and repeatability. The objectives of a particular survey must, therefore, be clearly defined. The specific survey requirements will in turn determine which technology and survey strategy will be most appropriate. With present technology, for instance, it is difficult to both (a) detect and accurately map the patchy distribution of reef biotopes at a fine scale, and (b) determine any broad scale trends. The incompatibility between survey objectives is particularly acute if the patches cannot be 'seen' with reasonably fine scale resolution over large areas. Furthermore, the environmental causes for the distribution patterns will be very different at the two extreme scales so that the justification for survey will be quite distinct. The different survey options for monitoring *S. spinulosa* are discussed below, though the equipment and their capabilities as well as the procedures for data collection and analysis are well documented elsewhere [17, 18, 21].

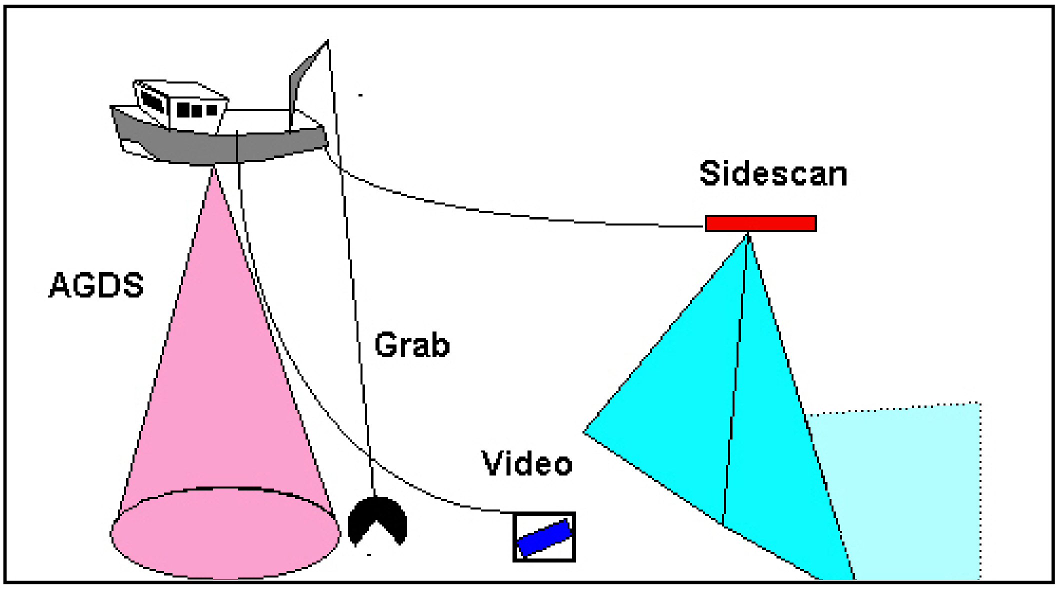

Figure 5: **Remote survey techniques for monitoring reefs.**

Acoustic Ground Discrimination Systems (AGDS)

Acoustic ground discrimination systems (AGDS) have been successfully used for broad scale and indicative survey of a range of biotopes, and for the predictive distribution of *S. spinulosa* reefs in particular [18]. The RoxAnn⊗ #system, for instance, interprets the signals from an ordinary shipboard echo sounder of the type routinely used for measuring depth (see

Figure 5). Analogue signal processing hardware is then used to select two elements from the echo and to measure signal strength (in millivolts) integrated over the time.

The first selected segment of the echo is the decaying echo after the initial peak. This measure of time/strength of the decaying echo is termed 'Echo 1' (or 'E1'), and is taken to be a measure of roughness of the ground. The beam width of the sounder is important for E1 since a wide beam will give greater scope for measuring signal decay away from the perpendicular than a narrow beam. The second segment is the whole of the first multiple echo and is measured by the *RoxAnn* processor as 'Echo 2' (or 'E2').

The two paired variables (E1 and E2) can be displayed on a Cartesian XY plot, and this is the basis of the *RoxAnn* real-time display as used in the data logging and display systems, eg, *Microplot*™ and *RoxMap*™. Areas on the Cartesian plot can be colour-coded and displayed on the track plot in order to identify records lying within a particular section of the plot (see Figure 6 below for an example of how this process has been adapted for predicting *S. spinulosa* occurrence). The plot is then calibrated against known seabed types so that the predictive plot can then be used to rapidly collect information on seabed type over large areas. More sophisticated post survey processing can also be used to interpret AGDS data using image classification procedures [19]. Information is, however, only obtained from the seabed directly below the boat and is restricted to the tracks of the survey vessel, thus AGDS does not give a continuous coverage. (Note that a second proprietary AGDS - QTC™ - has also been tested in the Wash and this gave a comparable performance to the RoxAnn™ system [21]).

AGDS have been successfully used for very broadscale mapping (see Figure 15). However, the resolution of the broadscale maps is very low and a much higher level of patchiness would be expected from a higher resolution map. Consequently, more detailed AGDS surveys were undertaken over 1km blocks in an attempt to explain patchiness in grab samples. This showed trends and patches of sediment within the blocks with a reasonable correlation between predicted sediment types and the sediment samples. However, the interpretation of the AGDS data in terms of *Sabellaria* densities was not as successful. It is likely that *Sabellaria* is associated with a wide range of sediment types and, accordingly, with a wide range of acoustic ground types. This is illustrated by Figure 6, in which areas of the E1/E2 plot associated with varying densities of *Sabellaria* have been determined from track data from the neighbourhood of the grab samples taken from the 2001 survey. The *Sabellaria* densities for the E1/E2 paired values have been interpolated to create density contours. However, it can be seen that:-

1. The E1/E2 values associated with the higher *Sabellaria* densities are wide ranging, although mostly characterised by elevated E1 values.
2. These values are also associated with many samples with low *Sabellaria* densities.

This reinforces the conclusions from analysis of the ground truthing samples that *Sabellaria* has a wide tolerance of sediment conditions but, conversely, *Sabellaria* is not unique for any one set of conditions (see also the section on the association of *S. spinulosa* with sediment types). This is probably typical of many ubiquitous species that inhabit disturbed environments. It also points up the problem of acoustic discrimination of biotopes distinguished by biota rather than sediments.

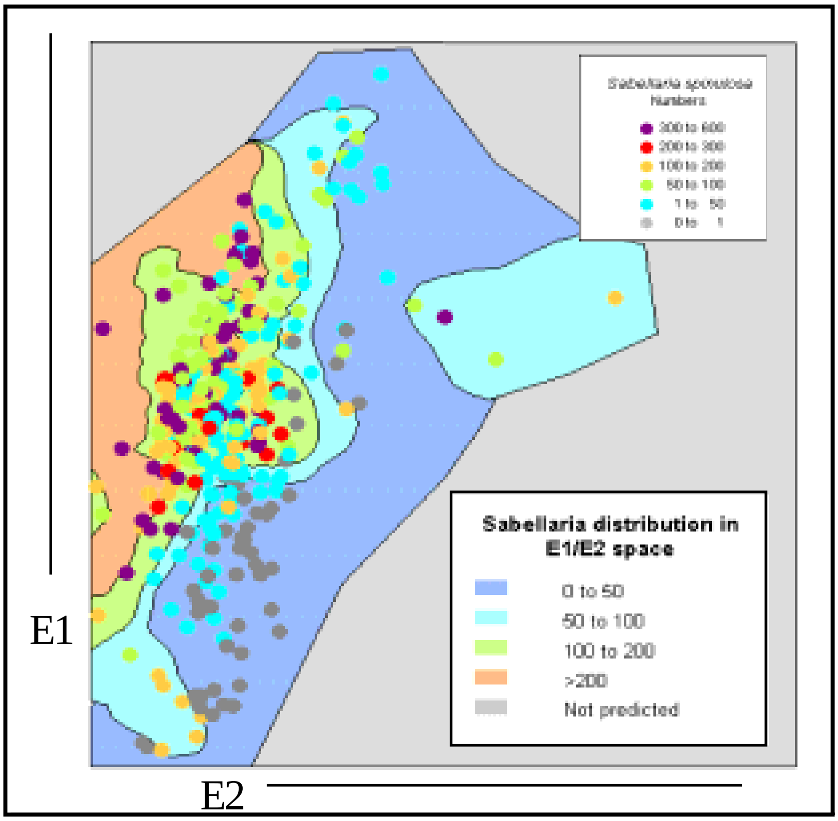

Figure 6: **Track points within sample buffer zones have been displayed in E1/E2 space and colour-coded to show increasing densities of *Sabellaria*. These point data have been interpolated to produce a contoured plot of density within E1/E2 space which has been used as a backdrop for the point data to highlight E1/E2 values most associated with *S. spinulosa*.**

Despite these limitations, the discriminatory powers of AGDS are relatively good, and comparative studies with sidescan has shown that AGDS is more likely to be able to distinguish between *Sabellaria* reefs and other sandy gravel biotopes. However, the images produced by interpreting AGDS do not have a very high spatial resolution (usually much greater than 25m), and are associated with high levels of uncertainty. In consequence, AGDS technology is not sufficiently repeatable for fine scale monitoring and may not be the most appropriate tool for mapping reefs, particularly if they form very small patches.
A useful overview of the use and limitations of RoxAnn⊗ #bottom discrimination can be found by Worsfold and Dyer [63] and Foster-Smith & Sotheran [19]. The reader is referred to Chivers, and others. [8] for detailed technical information, and to Davies, and others. [12] for a more detailed assessment of the technique's application.

Sidescan sonar

Sidescan technology is an alternative remote survey technique which can be used to measure *Sabellaria* reefs and to map their patchiness. Sidescan sonar uses a dedicated sonar source mounted in a 'fish' that is towed on an umbilical behind the boat some 5-10 metres (in the case of the Wash surveys) below the sea surface. The transducer emits a fan-shaped signal of high frequency sound (200 or 400 kHz) to port and starboard of the fish many times per second (see
Figure 5). Through interpretation of the return signal, an image of the seabed can be produced which is based upon both topography and 'hardness/softness' of the bottom (see Figure 7).

This image can typically cover an area of up to a few hundred metres on either side of the boat.

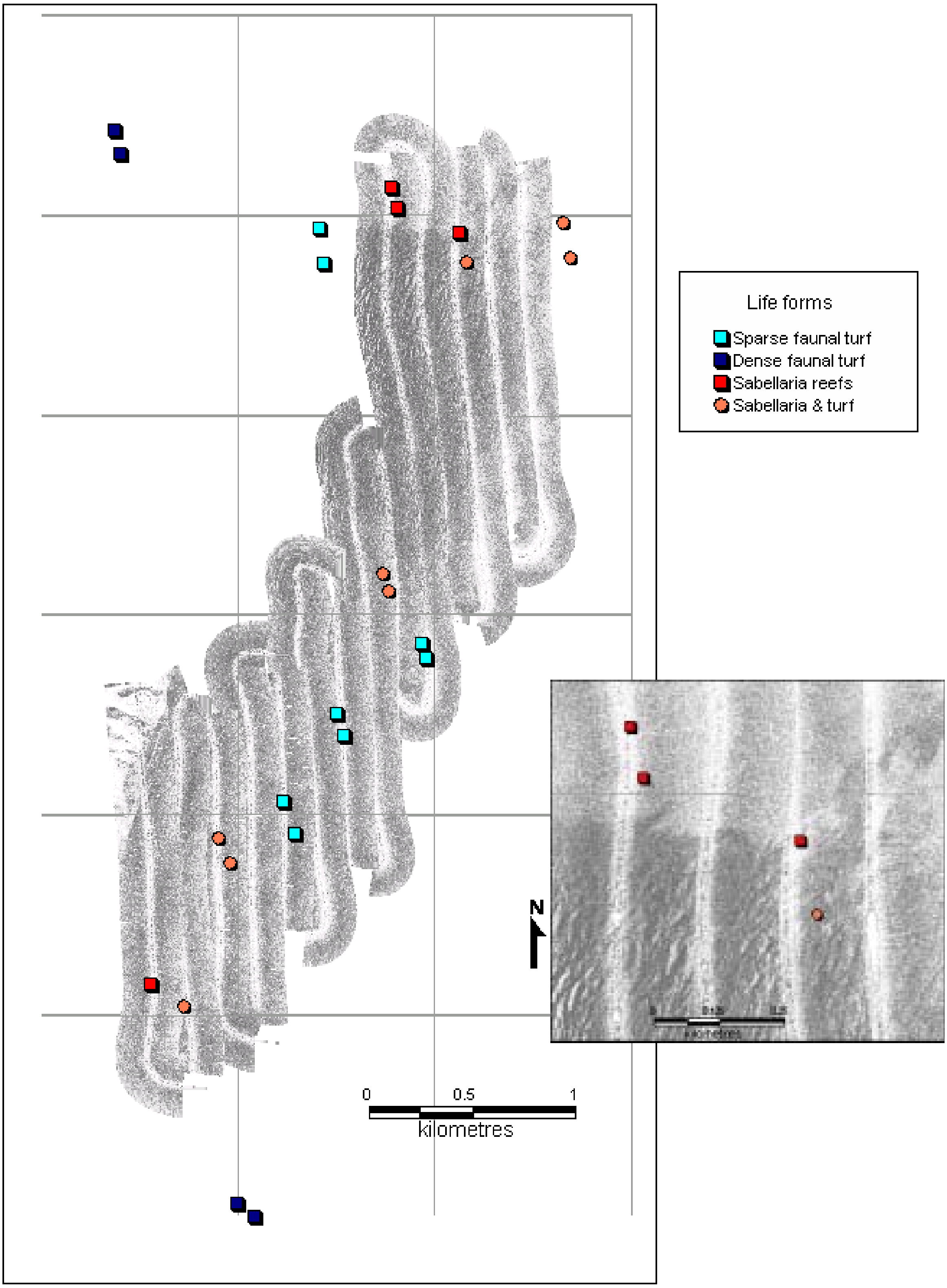

Figure 7: **Mosaic of several sidescan tows over the Area 107 site with biotope samples superimposed. Inset: the enlarged area at the north of 107 showing a sharp delineation between reef (red squares) and faunal turf and sparse *Sabellaria* on silty gravel. The observable features are dredge tracks whilst the reefs are found on parts of the images that are relatively featureless.**

Use of sidescan for mapping biological features has been successfully used where the features are physically distinct and/or obvious, including for a number of biogenic reef features, particularly *Modiolus* reef areas.

The main advantage of sidescan is that it can provide high resolution images (approx. 30cm pixel size) with good positional accuracy if it is combined with pitch, heave and roll sensors as well as differential GPS (dGPS). However, the problems with this approach are (a) that this technology has yet to obtain clear and distinctive images of *Sabellaria* reefs, and (b) if reefs are variably developed then it might be difficult to detect the full range of reefs against a background of other habitats.

Swath bathymetric systems

Other acoustic swath systems, such as interferometric systems, can give much finer resolution (3cm pixels) and might provide an ideal survey tool, but at present, no swath system has the capability of discriminating different sediment types on a pixel-by-pixel basis and feature definition requires the interpretation of contiguous pixels, rather like interpreting photographs.

Novel technologies

The use of novel technologies such as acoustic 'cameras' based on scanning sonar and laser scanners might be able to achieve the high definition required in order to detect reefs (eg, *Imagenex* digital imaging scanning sonar). These technologies have not been tried, however, and the coverage they provided would also be limited.

5.1.2 Methods for sampling *Sabellaria* biotopes

In addition to mapping the extent of *Sabellaria* reefs themselves, monitoring the population structure of the reef forming species together with their associated flora and fauna, also requires careful consideration of available technologies. Options include drop-down or towed video, ROV, hand held diver video, fixed quadrat photography, or diver direct observation. All of these methods would, however, be limited to macrobiota. Monitoring of infauna and cryptic fauna can only be carried out with destructive sampling techniques such as cores, grabs, dredges and trawls. These techniques are reviewed below.

Video and digital cameras

The use of videos to survey population structures is restrictive in that only a limited number of conspicuous organisms can be confidently quantified. However, the video and digital cameras is the only technique that has been shown to be able to detect reefs with confidence [18]. Not only does the use of video for field sampling have the benefits of direct viewing, but it is also less destructive to *Sabellaria* reefs than grab sampling making it the preferred technique for detection and field sampling of reefs. Although the area covered using cameras is small, video and digital images can be mosaiced together if positional information is accurate, through the use of sonar beacons for example. Nevertheless, video surveys can cover larger areas than fixed quadrat photography or diver surveys.

Unfortunately, however, the Wash and its environs are prone to periods of extremely poor visibility and, unless conditions are ideal, the identification of either non-reef *S. spinulosa*, or of poorly developed reef is difficult since other tubes such as those of *Lanice* and *Sabella discifera* may be confused with *Sabellaria*. Video is also difficult to control in high tidal streams such as those that are often encountered in the Wash. Thus, cameras and video can be deployed in one of two very distinct strategies: (a) they might be used to map very small areas in detail and in a repeatable way, or (b) they could be deployed to randomly sample areas for the presence/absence of reefs as part of a nested sampling design for statistical analysis.

Diver observation and sampling

Divers can provide a very versatile 'platform' for observation, measurement and sampling of the sea bed and biota. Divers were used by Hoare & Hiscock, for example, to estimate the abundance of prominent subtidal animals near an outfall of a bromide extraction unit [27]. Although they fixed the diver's position with a compass from shore when the diver surfaced to relay his position, a higher positional accuracy could be achieved through use of sonar beacons.

However, the conditions under which divers can operate are even more restricted than for video and cameras, particularly in the Wash where visibility is unreliable and often poor. Furthermore, the cost of such precision surveys is likely to preclude their use from all but specialist recording from selected locations. Therefore, whilst of scientific interest for the study of *Sabellaria* dynamics, the use of divers might be hard to justify for monitoring the status of reefs.

Grabs, dredges, trawls and infaunal analysis

The high diversity that is associated with *S. spinulosa* is one of the characteristics of reefs that make them important to the natural history interest of the area. This can only be determined through the analysis of infauna, which confirms the presence of *Sabellaria* and also enables measurement of associated species diversity. Methodologies include trawls, dredges and grab sampling. Such techniques are readily available and relatively inexpensive. However, there is increasing evidence that both benthic trawling and dredge sampling cause extensive impact to the seabed and to the benthic community [31]. Repeated dredge sampling of the azooxanthellate scleractinian, *Lophelia pertusa,* in the relatively easily assessable Norwegian fjord sites, for example, is thought to have been severely damaged by this destructive sampling method [40].

In comparison to a dredge or trawl that is typically towed for hundreds of metres to sample *Sabellaria* reefs, a benthic grab with an area of $<1m^2$ causes minimal damage to the sea bed. The recovery of samples from a single locality on the seabed also confers greater positional accuracy with the latter technique. Nevertheless, the positional accuracy of grabs is not high, and hence grab sampling is usually part of a statistical (perhaps nested) survey. This is particularly important in patchy habitats such as those of *Sabellaria*, where the small sample area is subject to a 'hit and miss' approach. To overcome this, high numbers of samples are required and thus analysis, unless restricted to a visual assessment on-board, is very expensive. Sonar location can increase positional accuracy, but the destructive nature of grab sampling will mean that very accurate redeployment is meaningless.

When sampling scattered colonies, grab sampling can be more effective if it is video-assisted, giving the added advantage of providing slightly broader scale information for the interpretation of the grab data. This method has been used successfully to study the azooxanthellate scleractinian, *Lophelia pertusa* [40].

5.1.3 Summary

In order to monitor *S. spinulosa* reefs, as opposed to annually forming thin crusts, it is important to be able to distinguish and detect their whereabouts and extent. If they are very dynamic, as seems to be the case, a technique for 'seeing' the reef would be invaluable in mapping the way reefs fluctuate. Such detailed maps could be used to help evaluate the significance of changes in the reef at any precise point, whether or not the change is due to fine scale dynamics or to some broader scale trend, for example.

Traditional destructive sampling methods are of limited use in regard to such monitoring, although no clear choice for the remote surveying of *Sabellaria* has emerged. Recent experience has suggested that neither AGDS nor sidescan survey alone is as useful for mapping the extent of reefs. Sidescan failed to distinguish clearly between *S. spinulosa* reef and nearby patchy hard bottoms, whilst AGDS has a resolution greater than 25m. Nevertheless, RoxAnn⊗ did show some potential for identifying likely areas of *S. spinulosa* and for confirming suspected boundaries, but groundtruthing, probably by a combination of video and grab sampling, is a necessary supplement. It is possible that the accuracy and repeatability required for mapping small reefs could be achieved by use of other sonar techniques, but these are untried.

Interpretation of the results of any such monitoring program is likely to impart complications comparable with those of the choice of methodology. There is little concrete knowledge regarding the natural fluctuations that populations of *Sabellaria* undergo, though it appears that they can be quite extensive. Hence the limits of acceptable change for monitoring and management purposes are also going to be very difficult to determine [30]. It is possible, for instance, that the complete loss of reefs could be regarded as 'normal'. The abundance and diversity of the associated fauna and flora will inevitably have their own sources of variation in recruitment, growth and survival superimposed upon the variations in the 'supporting' reef populations; in general terms one can expect richer and more diverse communities on older and more stable reefs than on younger or less stable ones, but determining acceptable limits of change will again be very difficult in most cases. At this stage, therefore, the primary benefit of many surveys will be in giving information about typical levels of natural variation, assuming that there are no major human influences [30].

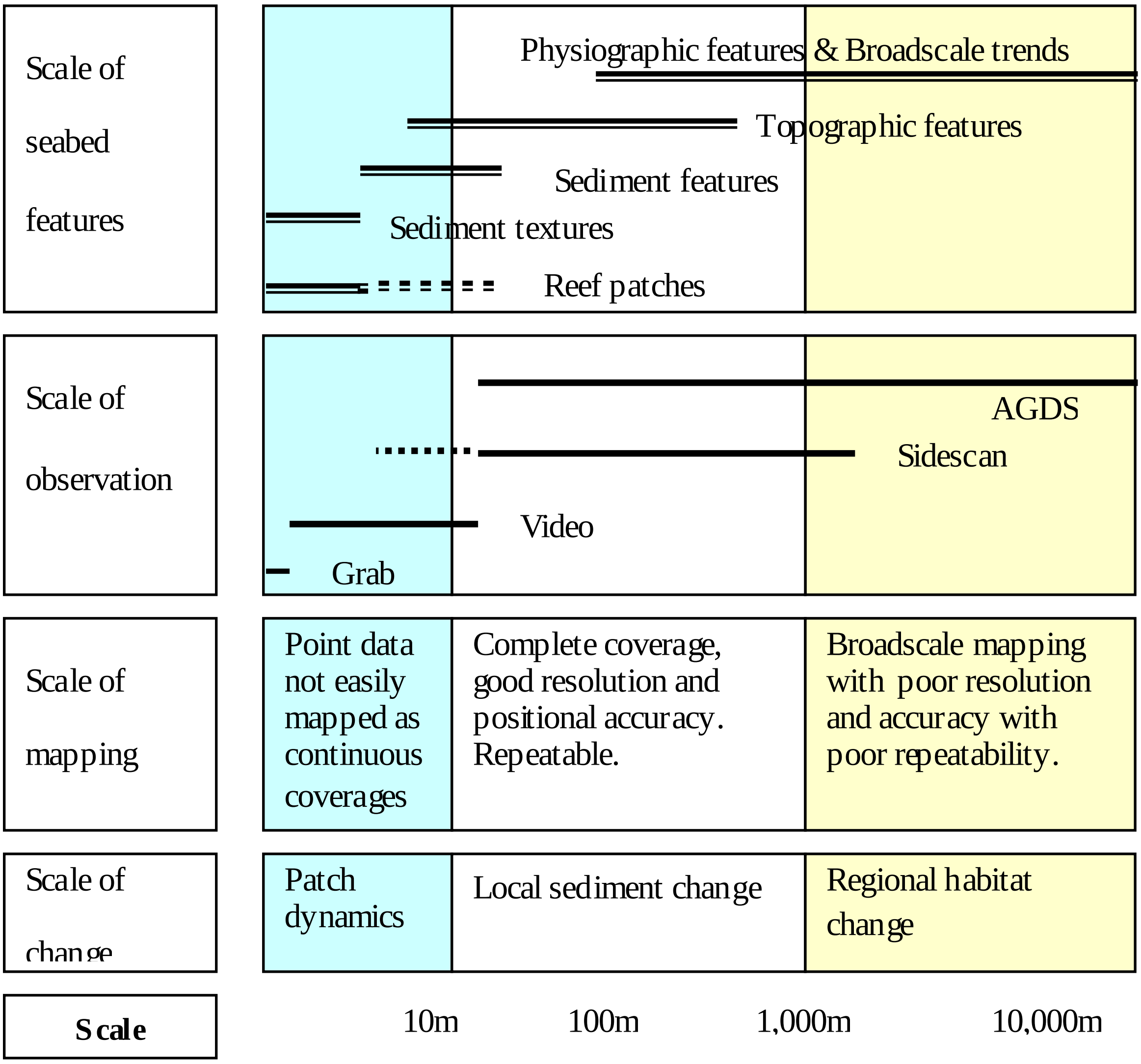

Figure 8: **Summary of the correspondence of the scale of observation of the different remote sensing and direct sampling techniques and the scale of environmental features.**

5.2 Definition of 'reef'

The ability to monitor the status of *S. spinulosa* reef requires that reefs form a real entity that can be defined in such a way as to separate this from other biotopes characterised by lower densities of *S. spinulosa* [21]. Reefs, then, might be defined by:-

1. Physical form: A specific structure and growth form;

2. Species composition: A unique and rich associated fauna; or

3. Population structure: Especially high densities of *S spinulosa* (an 'explosion' over and above other growth forms).

Video evidence of *S spinulosa* colonies would seem to leave no doubt about what should constitute a reef: this shows intertwined tubes growing upwards away from the sea floor forming biogenic mounds up to 30cm tall that extend over large areas (see Figure 9 and Box 1). However, grab and trawled samples show that *Sabellaria* can also form low encrustations on cobbles or be mixed with gravel as part of other communities. A review of all grab sample data collected by SeaMap backed up the suggestion that *S. spinulosa* reef development was one extreme expression of the *Sabellaria* community and that various other communities overlapped with reefs in terms of both *Sabellaria* density and species composition. The analyses were summarised in a schematic diagram (Figure 10) which illustrates how the communities overlapped.

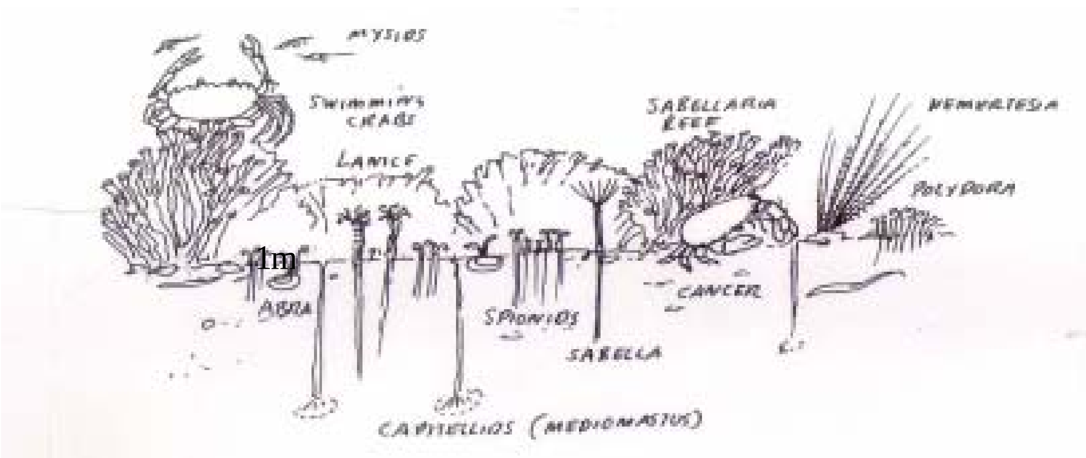

Figure 9: The high diversity *Sabellaria* reef biotope and its rich infauna.

Box 1. The original description of the reef used by SeaMap [20] is included below and this serves as a basis for a definition of a reef:. Note, SA = super abundant, A = abundant, C = common, O = occasional.

Biotopes with super-abundant *Sabellaria* (including visually verified reefs)

Species	Abundance
Sabellaria spinulosa	SA
Pholoe inornata	A
Pisidia longicornis	A
Scoloplos armiger	A
Harmothoe indet.	C-A
Mytilus edulis	C-A
Autolytus prolifera	C
Eulalia ornata	C
Eumida ockelmanni	C
Exogone hebes	C
Mediomastus fragilis	C
Nereis longissima	C
Abra alba	O-C
Ampharete lindstroemi	O-C
Caulleriella zetlandica	O-C
Protodorvillea kefersteini	O-C

Provisional biotope CMX.SspiMx.reef (Wash) as a subdivision of CMX.SspiMx

Justification for this biotope is based on superabundance of *Sabellaria spinulosa* and video evidence of reef structures. This community is otherwise similar in composition to the *Sabellaria/Lanice* community. Silty sandy gravel.

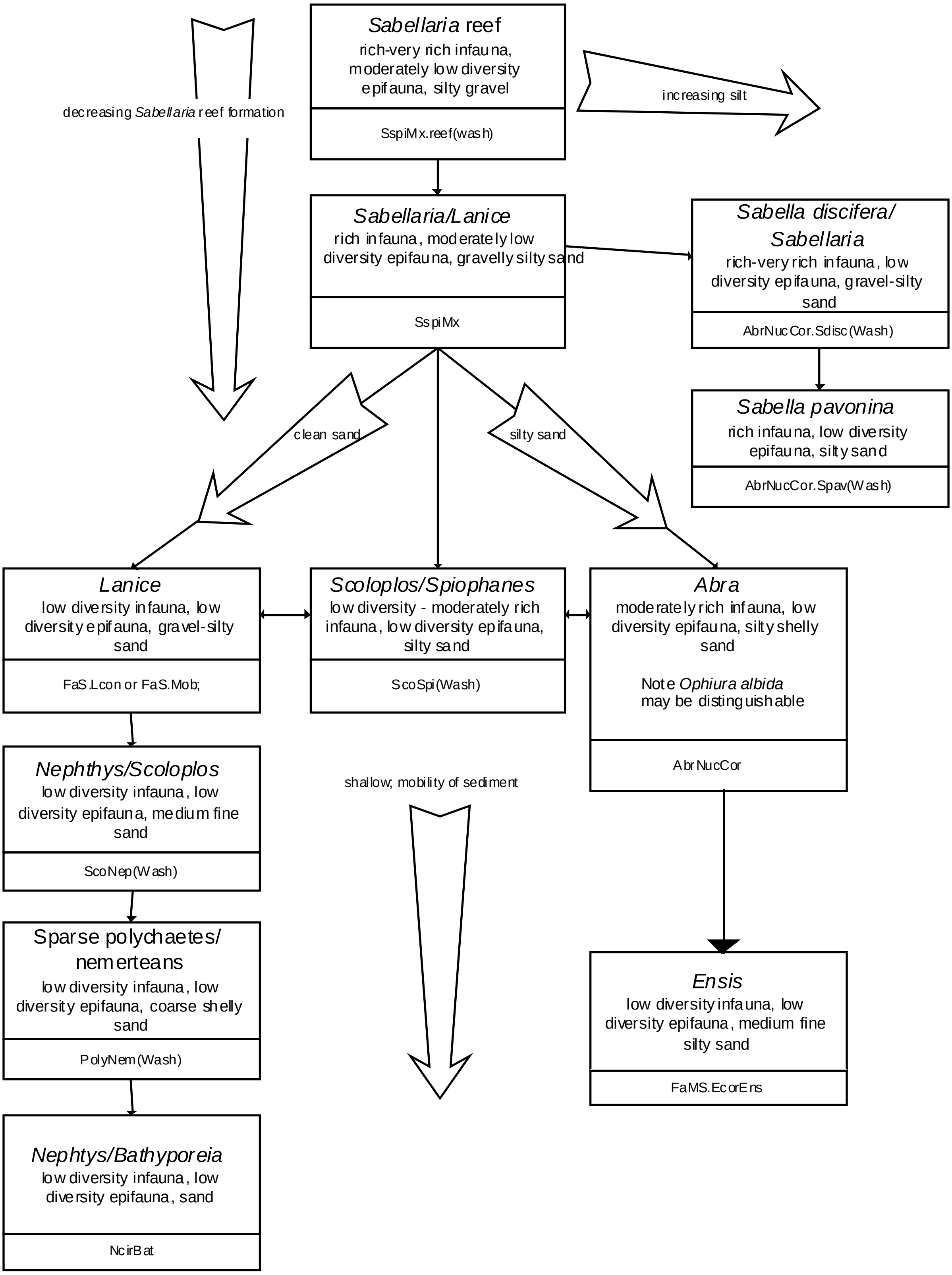

Figure 10: Schematic representation of the relationship between the main infaunal biotopes.

Of particular interest is the association between *S. spinulosa* and species richness. The overlap between high density *S. spinulosa* samples, and species rich but non high density *S. spinulosa* samples, is further illustrated by the MDS plot of all grab samples in Figure 11 below. A reference 'site' (or datum) has been produced from the average faunal composition of the records with the highest densities of *Sabellaria*, and then a percentage similarity was calculated for each real data point relative to the reference datum (with *S. spinulosa* excluded from the calculation). These similarity values were interpolated within the coordinates of the MDS plot and contoured (Figure 11).

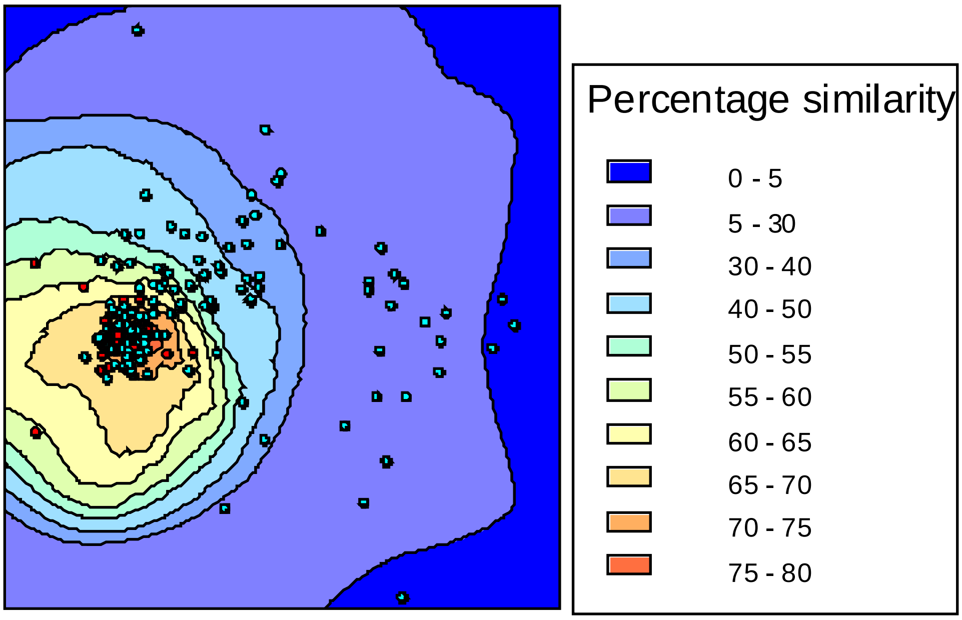

Figure 11: A multivariate plot (MDS) of all SeaMap grab data with sites with more than 20% *Sabellaria spinulosa* shown in red. The contours show the similarity of the samples to a reference 'site' derived from the average species composition of sites with high densities of *Sabellaria*.

Two important points are illustrated by this plot. Firstly, the majority of the *Sabellaria* sites are between 65% and 80% similar to the reference site, as compared to the much wider range within the complete data set. Secondly, many sites with lower densities of *Sabellaria* (the blue circles) are still similar in species composition to the high density *Sabellaria* sites. Further assessments of the association between species diversity and *S. spinulosa* density have been made on all BMP data, which covered a wide range of biotopes (Figure 12), and also with the 2001 samples targeted in areas likely to support *S. spinulosa* biotopes (Figure 13). The former shows that although *S. spinulosa* is associated with samples with a species count greater than 35, that the reverse, namely a high species diversity being associated with high *S. spinulosa* numbers, is not necessarily the case.

The 2001 data is even more equivocal, and no relationship could be identified between species diversity and *S. spinulosa* density at all. It should be noted, however, that low species diversity sites were not sampled due to the nature of the stratified survey. In summary, it would seem that high density *S. spinulosa* is associated with moderately high to high species diversity, but that neighbouring samples with low *S. spinulosa* density may have equally high species diversity and similar species composition. It is clearly not obligatory that high *S. spinulosa* density is a requirement for high species diversity in areas that could support *S. spinulosa*.

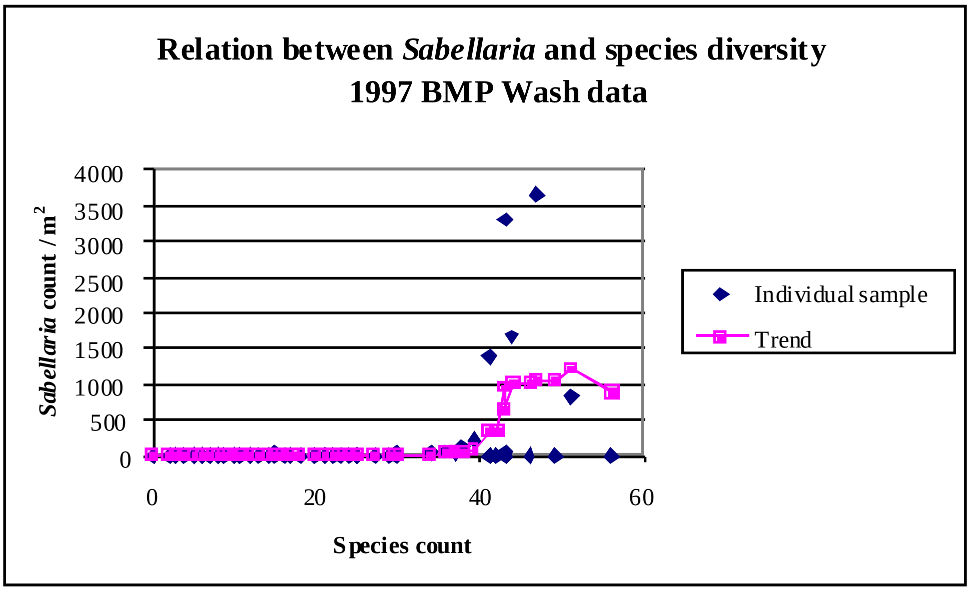

Figure 12: The association between *S. spinulosa* and species diversity for samples from the BMP surveys which covered a wide range of biotopes, including many with very sparse infauna. A trend line (mean numbers of *S. spinulosa* over 5 consecutive samples of increasing species count) has been included to show the association between high *S. spinulosa* numbers and species diversity.

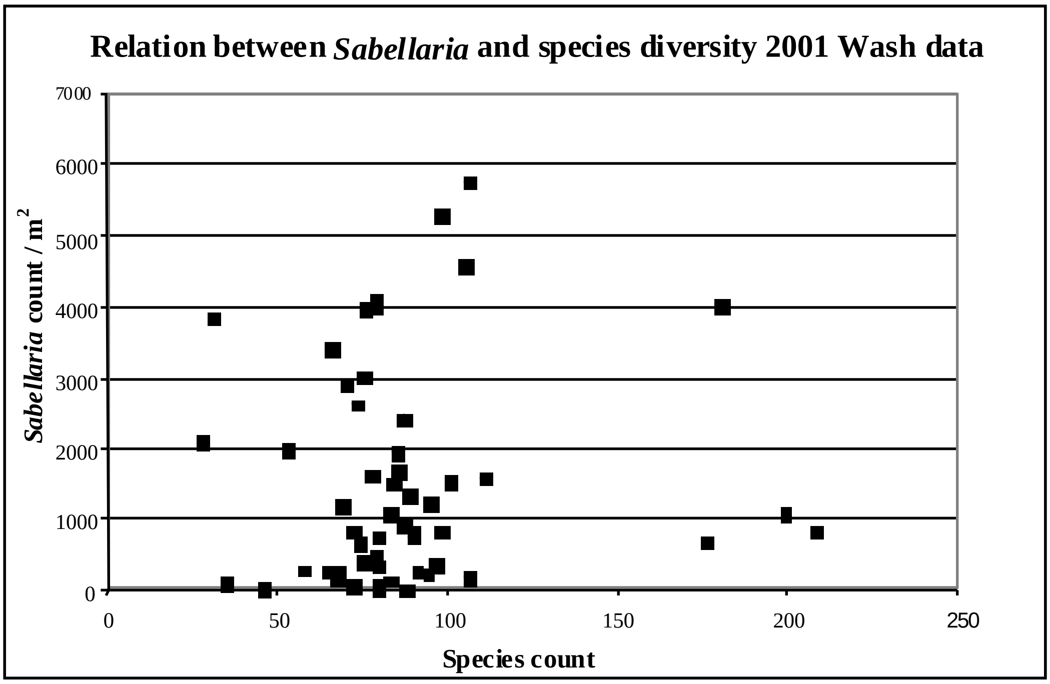

Figure 13: The association between *S. spinulosa* and species diversity for samples from the 2001 survey which covered a restricted range of biotopes excluding those with very sparse infauna.

However, whilst *S. spinulosa* biotopes merge into each other, there is some evidence that reefs are sufficiently distinct from other biotopes to justify a definition in terms of density (>375/0.1m^2), and associated fauna [21].

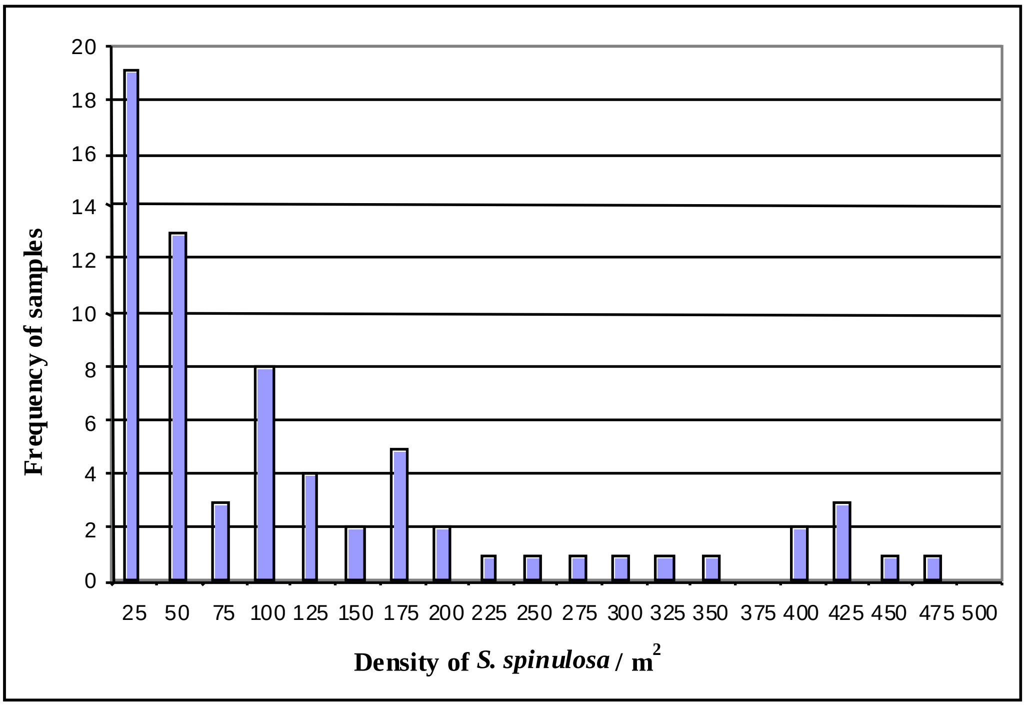

Figure 14: Frequency/density plot for *S. spinulosa* from the 2001 survey. This indicates that there may be more samples with densities greater than 375/0.1m^2 than might be expected.

An analysis of all SeaMap samples prior to 2001 gave a hint that *Sabellaria* reefs have a distinctive population structure [21], with a slight increase in the frequency of high density *S. spinulosa* samples above what might have been expected from an exponential decrease. However, one of the criticisms of the analysis was that *S. spinulosa* reefs, once located, were sampled repeatedly because of their intrinsic interest. Consequently, the analysis was repeated using only the 2001 randomly located samples and the same slight but anomalous increase in frequency was observed (Figure 14). This suggests that reefs might form a population with a distinctly high density.

5.2.1 Association of *S. spinulosa* with sediment types

In order to assess the association between *S. spinulosa* and sediment types, sediment categories were matched to biotope classes from the 2001 sample data using (1) infauna and (2) video classes. From this it appears that *Sabellaria* favours silty, cobbley habitats rather than sandy habitats (Table 1). Note that the dense epifauna on the cobbley gravel habitat as observed on the video might have obscured *Sabellaria*, and this could account for the apparent disparity between cobbley gravel habitats supporting seven records of *Sabellaria* communities as judged by the infaunal composition as opposed to just one single record as observed from the video (and 10 epifaunal records).

Table 6: Association between *Sabellaria* (1) infaunal class and (2) video class and the sediment type as observed from both the video and the sediment in the grabs.

Habitat	Infaunal class *Sabellaria*	Others
Cobbley gravel	7	5
Silty cobbley gravel	6	3
Silty, shelly gravel	5	4
Shelly gravel	4	0
Gravel	3	2
Gravelly sand	3	3
Silty gravel	2	6
Silty cobbley sand	1	2
Cobbley sand	0	1
Shell sand	0	2
Silty sand	0	2
Silty shell sand	0	13

Habitat	Video class *Sabellaria*	Epifauna	Others
Silty cobbley gravel	8	1	0
Silty, shelly gravel	6	2	1
Gravel	2	3	3
Silty gravel	2	2	6
Cobbley gravel	1	10	5
Silty shell sand	1	2	11
Gravelly sand	0	3	3
Shelly gravel	0	3	2
Cobbley sand	0	1	0
Shell sand	0	1	1
Silty cobbley sand	0	3	3
Silty sand	0	0	2

5.3 Spatial and temporal distribution of *S. spinulosa* within the Wash and its environs

5.3.1 Predicted distribution

The distribution of the different biotopes predicted by the Broadscale Mapping Project using both acoustic and ground truth data are illustrated in Figure 15. The map has been prepared through the classification of interpolated AGDS data (see Foster-Smith & Sotheran [19] for methodology), and is coded according to the most likely biotope for each pixel. The predictive maps should be interpreted bearing in mind that some pixels are tagged according to the highest probability biotope although the probability of it representing another biotope may be similar albeit lower. Secondly, the probability of a pixel representing the biotope with which it has been tagged may, nevertheless, be low, ie the predicted biotope has a high level of uncertainty. It should also be noted that these predictions are based on sparse and incomplete information and hence are not adequate for mapping the detailed distribution of *Sabellaria*. The map merely indicates the most likely locations of the different biotopes.

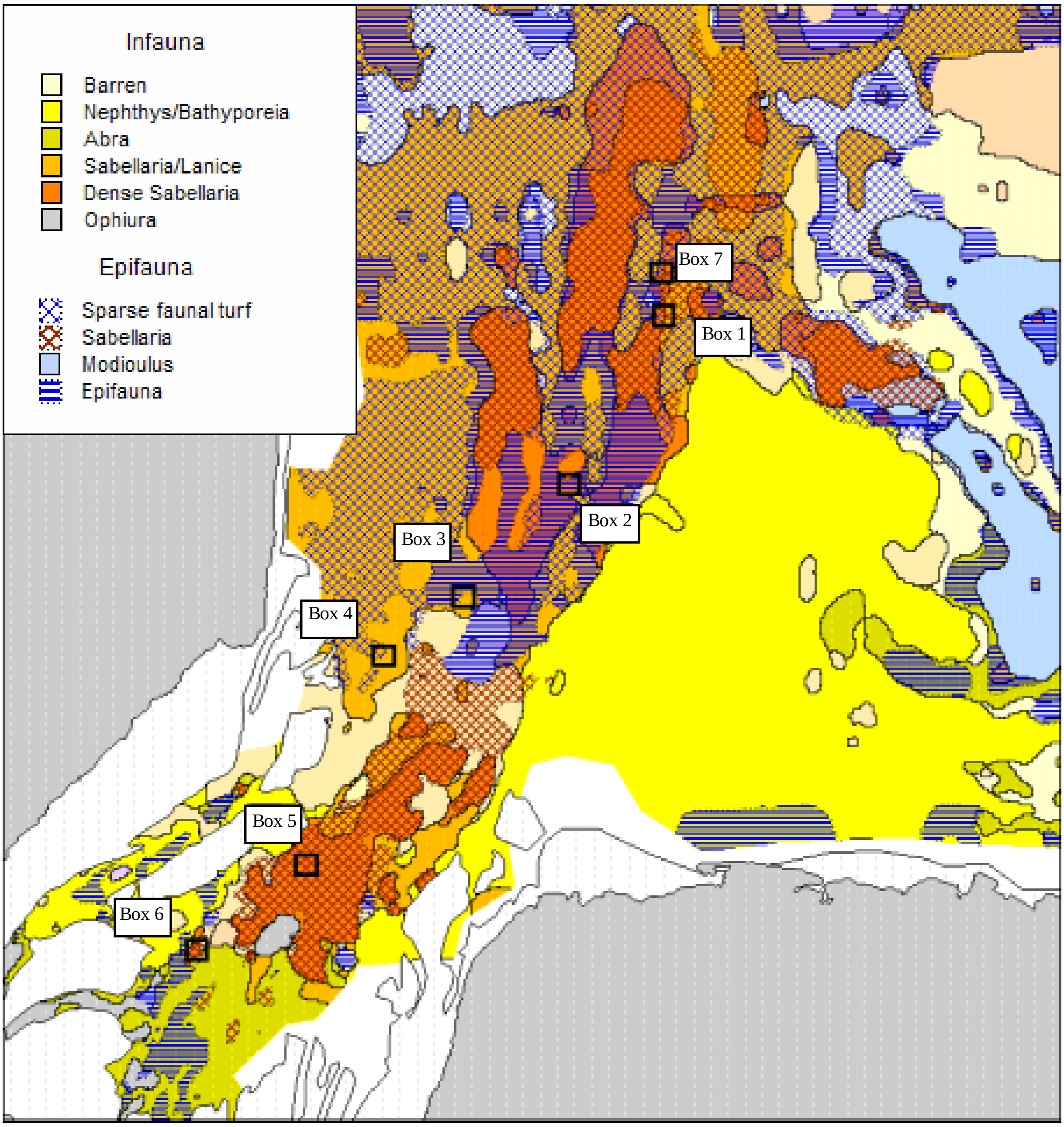

Figure 15: Distribution of the biotopes in the Wash and its environs predicted by the BMP project. Infaunal and *Modiolus* biotopes are represented by the background colour and the epifaunal biota by the overlaying hatching. Note that *S. spinulosa* appears as both infauna and, as observed by video, as epifauna. The map also shows the position of the seven 1km boxes used for the 2001 survey

5.3.2 Point sample distribution

Distinct to the predicted distribution of *Sabellaria* biotopes shown in Figure 15, the actual proven occurrence of *S. spinulosa* is shown in Figure 16. All the *Sabellaria* data from the NRA[41], CSD[13] and BMP surveys[20], as well as the 1999[15], 2000[21] and 2001[16] monitoring surveys have been summarised using a five-point abundance scale. The point data were then interpolated to create a continuous coverage in order to illustrate spatial trends using shades of violet. The analysis was performed in *Surfer* using an inverse distance square algorithm. The samples are also shown as points of graduating colour.

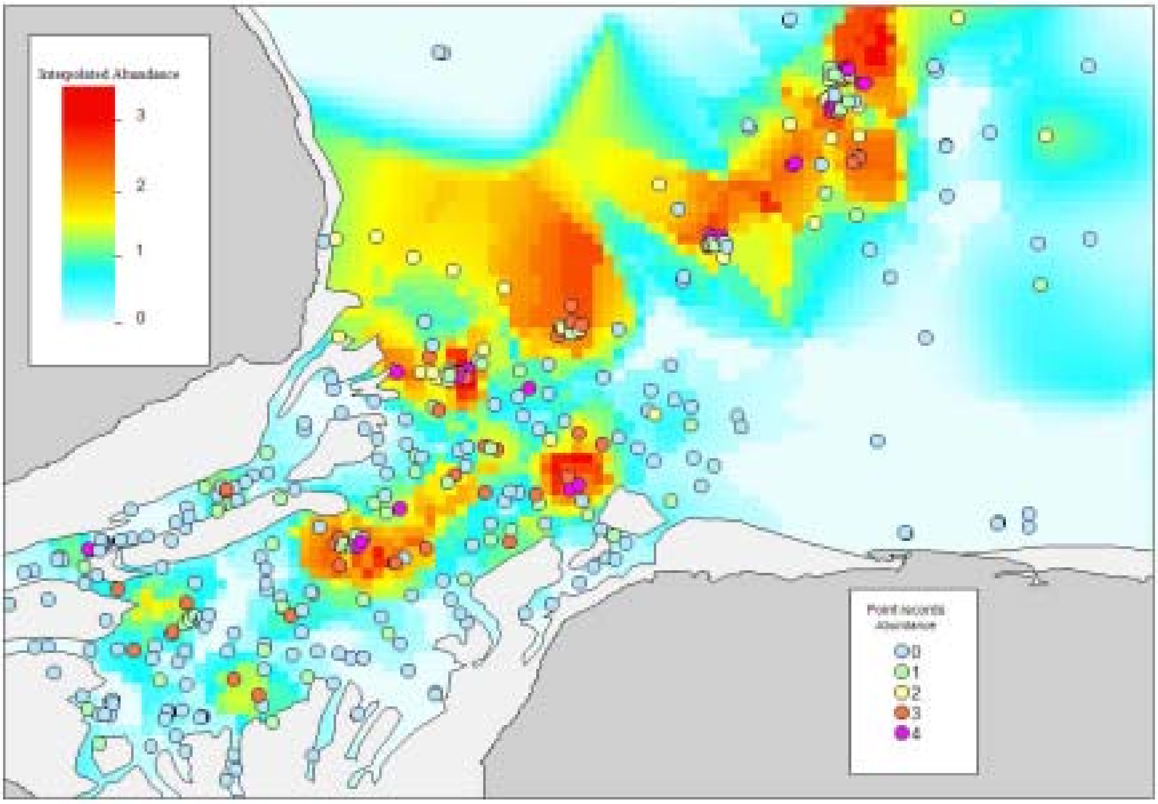

Figure 16: Trends in *Sabellaria spinulosa* distribution within the Wash. The data is a summary of all records available. The abundances of individual point samples are shown on the interpolated surface.

Three main points can be made from the analysis summarised in Figure 16:-

1. The data is spatially very variable with high densities of *Sabellaria* lying close to samples with low densities;

2. There are clearly areas where *Sabellaria* has not be observed in any of the surveys and other areas where *Sabellaria* has been observed at moderate to high abundance levels quite frequently.

3. There is a broad scale trend in *Sabellaria* distribution which transcends the fine scale variability, and confirms the predicted distribution from the Lynn Deeps to Scott Patch. There may also be lower densities extending well into the Wash.

To summarise, the results of the SeaMap surveys suggest that *Sabellaria* reefs are well developed and relatively stable offshore, and are more variable further into the Wash. The overall distribution of samples where *Sabellaria* was found at moderate to high densities certainly indicates a gradual reduction in their frequency of occurrence the further these sites are into the Wash.

5.3.3 Patchiness

Video evidence suggests that reefs can be very patchy. In some areas video tows showed well developed reefs extending for many metres interspersed with patches of sand (area 107 in years before 2001), whereas in other areas, the reefs formed small patches of a few metres extent surrounded by sand (see Box 4 from the 2001 survey, Figure 15).

In order to quantify this variability, indices of patchiness have been derived from the grab samples based on measurements of similarity between samples at different spatial separations (lag distance). From this, it appears that there is no greater similarity in overall species composition between samples lying within 25m of each other than those with a lag of up to 1km (see Figure 17).

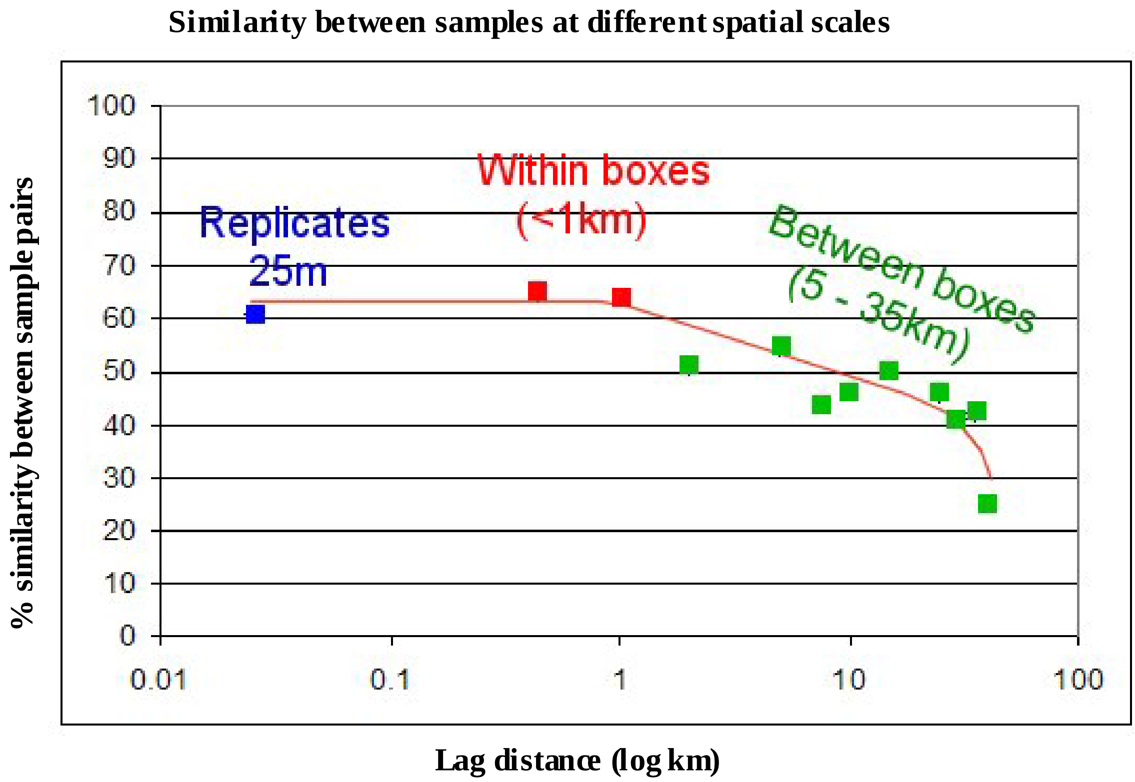

Figure 17: The similarity between samples at different inter-sample distances (lag distances) from the 2000 survey (replicates) and 2001 survey (within boxes and between boxes). The results have been averaged for 25m, 50-500m, 500-1km, 1-2km, 2-5km, 5-7.5km, 7.5-10km, 10-12.5km, 12.5-15km, 15-20km, 20-25km, and 25-30km.

Numbers of *Sabellaria* can be used to calculate the index of dispersion Moran's I, the basis of which is to create two site/site matrices of (1) separation (lag) distance, and (2) similarity, and then to calculate the cross-product of corresponding cells in the matrices. The value of the Moran's index approaches -1 when the sites over a given lag distance are more dissimilar than might be expected (negatively correlated) and +1 when are more similar (positively correlated). The indices can be calculated for different lag distances and this gives an indication of the way dispersion/aggregation changes with increasing distance separating the sites. Moran's indices have been calculated for increments in the lag distance from 150 m up to just over 1 km and Figure 18 summarises the pattern for all seven Boxes. This indicates that there is no marked spatial correlation with numbers of *S. spinulosa* found in grabs over short lag distances.

Although there are clear patterns in the distribution of biotopes at broad scales, spatial patterns at fine scales are hard to quantify. It would appear that there is no spatial correlation between samples separated by distances ranging from the minimum inter-sample distance (approximately 25m) up to 1km, although some spatial trends may begin to emerge at or above this upper distance.

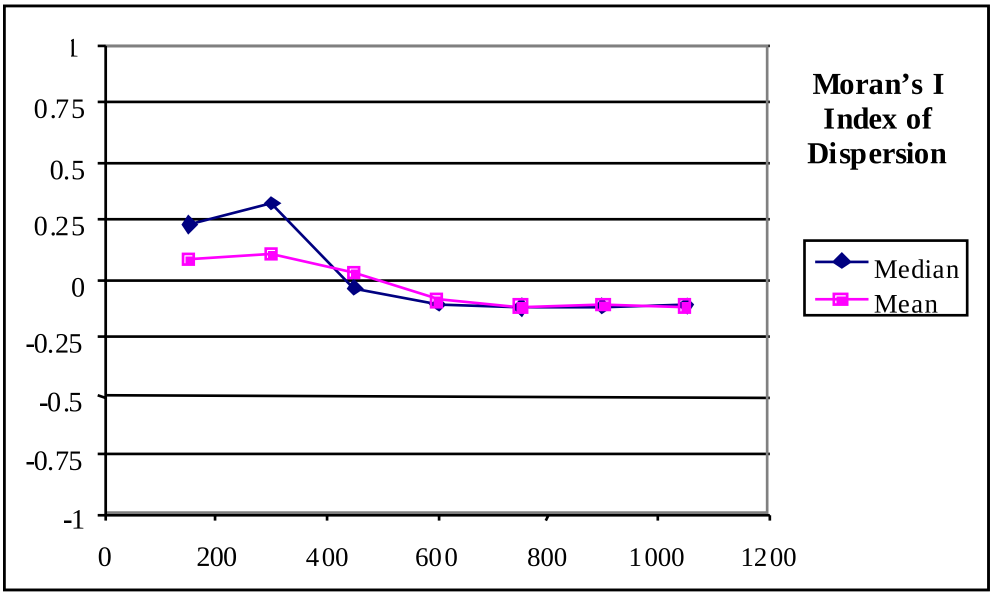

Figure 18: Median and mean Moran's I calculated from the data for all of the seven Boxes for lag distances ranging from 150m to 1050m.

5.3.4 Temporal stability

Although it may seem very likely that the observed patterns of spatial patchiness would also be matched by temporal instability, there is great uncertainty in interpreting the temporal data for the Wash. Assessing such temporal change is complicated by the patch dynamics of the reef system including reef build-up and break-down involving other related *S. spinulosa* biotopes.

Within the SeaMap surveys, only one area can be regarded as having been comprehensively surveyed over more than one year which shows real changes in *S. spinulosa*. Namely, the previously enduring reef in 107 which apparently came to a sudden end between 2001/2. This is a site which has been intensively sampled within a relatively small area ($1km^2$), and it is unlikely that the reef was missed in 2002. Thus we can be confident that the reefs broke down in the intervening period. This is also the experience of CEFAS (Bill Meadows, personal communication).

All other records must be regarded as being compromised by differences in position set against the likelihood of patchiness. The point samples for all the SeaMap grab sample data available have been separated into their respective surveys in Figure 19. No firm conclusions can be drawn although it would appear that sporadic high density *S. spinulosa* samples are set against the background of generally low densities in the inner Wash, whilst high density samples are consistently found in the outer Wash. However, as exemplified by area 107, the long term presence of *S. spinulosa* in an area does not necessarily imply stability of the population.

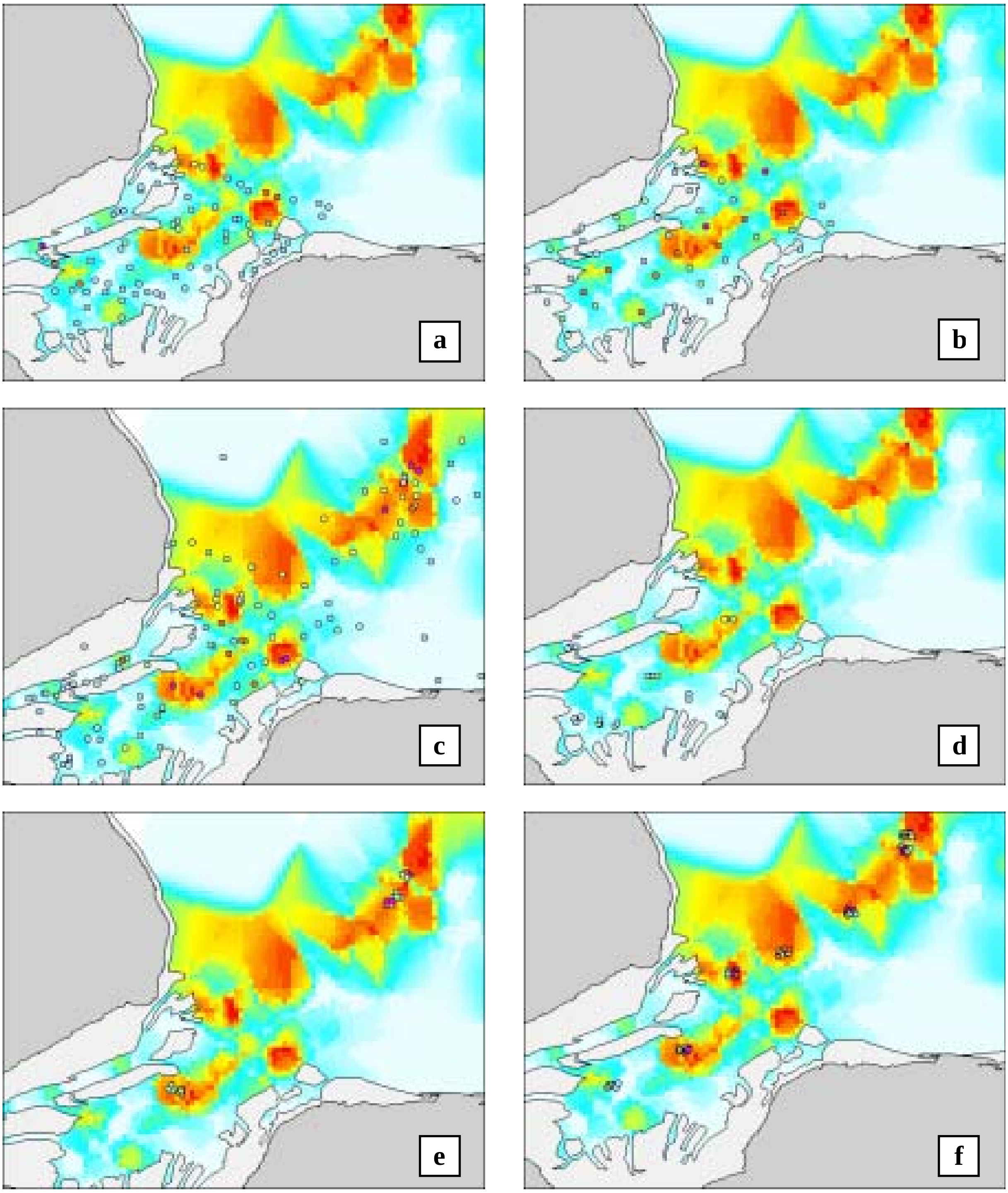

Figure 19: Grab sample data from different surveys are shown superimposed on a raster map of all data interpolated (see Figure 15 for legends) (a) CSD report (1985)[13]; (b) NRA (1994)[41]; (c) BMP (1997)[20]; (d) SeaMap (1999)[15]; (e) SeaMap (2000)[21]; (f) SeaMap (2001)[16].

5.3.5 Disturbance

Patchiness and temporal instability are often characteristics of naturally and/or anthropogenically disturbed habitats. Disturbance through fishing is undoubtedly an issue in the Wash, but sand extraction gives us the most geographically clear-cut example of physical disturbance. Figure 7 illustrates the very definite boundary between dredged and non-dredged areas. However, there are no obvious links between the boundaries of the licensed area 107 and *S. spinulosa* densities (Figure 20). It would appear that the high density *S. spinulosa* lie along the western edge of the channel that runs southwest/northeast through 107 avoiding the shallower cobble to the west and the deeper siltier sediment to the east.

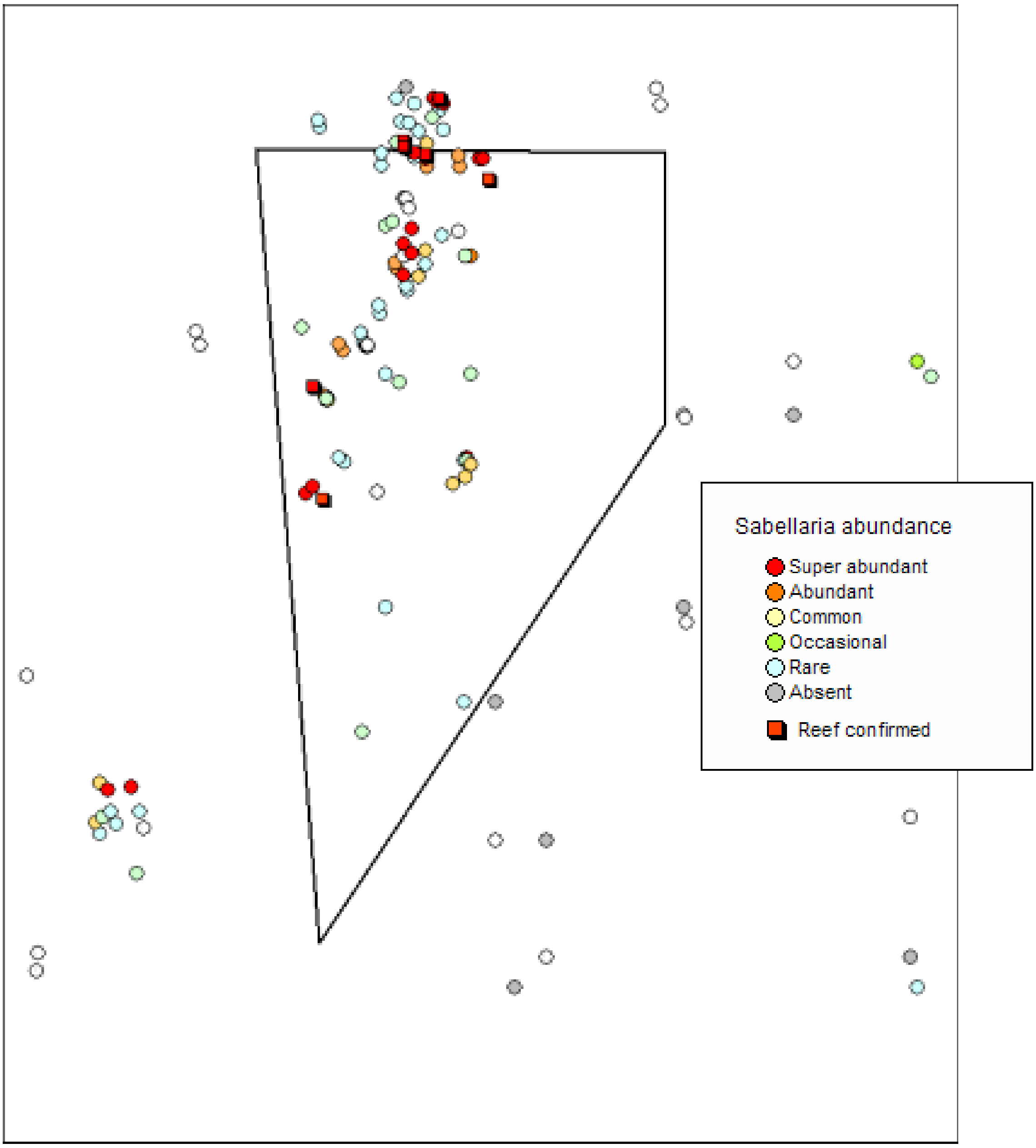

Figure 20: *S. spinulosa* point sample densities for all surveys in the vicinity of the licensed dredge area 107.

6. Conclusions on the status of *S. spinulosa* in the Wash and outstanding issues

It is clearly important to understand the nature of *Sabellaria* reefs in order to be able to assess their status and monitor their condition. Additionally, the reefs are not an isolated feature and they may play an important role in the functioning of the wider local ecosystem. The discussion below is centred on a number of critical questions. In many cases the results of the surveys to date do not provide definitive answers to these questions.

6.1.1 Are reefs a distinct feature?

All indications are that *Sabellaria spinulosa* is a common species throughout the British Isles that reaches high levels of abundance in a wide range of habitats where it may co-occur with other conspicuous biotope-forming groups, particularly epifaunal species. The community on well developed reefs does not appear to be qualitatively very distinct from dense non-reef *S. spinulosa* communities. Although *S. spinulosa* is associated moderate to high species diversity, neighbouring samples with low *S. spinulosa* density may have equally high species diversity and similar species composition. The tube structure and typical growth over hard objects suggests that the worms build independently of each other (unlike the related *Sabellaria alveolata*) and these tubes coalesce and grow upwards away from the seafloor at high worm densities. But this is not an obligatory growth form and lack of a well developed reef structure does not imply sub-optimal conditions for growth.

Remaining issues:-

∉ Is the population structure of *S. spinulosa* in reefs significantly different from other growth forms?

∉ Although infaunal species associated with reefs may not be distinct, are there any special associations with productive communities of motile epifauna, fish and shellfish stocks?

∉ Does it make sense to differentiate the forms of *Sabellaria* reef when assessing status.

6.1.2 Are reefs relatively stable or very dynamic?

All evidence suggests that spatially, *S. spinulosa* is very patchily distributed, even in areas (such as 107) where it has been most consistently recorded. Temporal stability is harder to determine. The regular recording of reefs in area 107 from 1997 until 2001, when no reefs were observed, is the most direct evidence for the timeframe for change. More anecdotal evidence from ESFJC suggests that reefs within the Wash cSAC have been recorded on video in spring/early summer and then not recorded later the same year.

Remaining issues:-

∉ How long do reefs take to form, how long do they last?

∉ To what extent is reef formation driven by recruitment of large numbers of juveniles or the growth established worms?

∉ Do reefs decline when the cohort that establishes the reef dies, or can reefs persist for many generations?

∉ What is the cyclical pattern of reef growth and decline?

∉

6.1.3 How do reefs relate to other biotopes?

S. spinulosa appears in greater or lesser numbers in many biotopes in the Wash, and the various biotopes grade into one another with no hard distinctions to be made either in terms of species composition or the physical nature of their habitat. What is not clear is how these biotopes relate to each other in terms of their dynamics. Can one biotope evolve into another through recruitment, growth and death? Is one biotope a common precursor to another or a legacy from a previous biotope?

The disappearance of well-developed reefs is not an indication that the *Sabellaria* communities have been eliminated from an area. In area 107, for example, reefs seem to have been replaced by moderate to high density, non-reef *S. spinulosa* biotopes. In other areas, very low densities of *S. spinulosa* were found where previously high densities have been recorded. They may well recover from an existing local population of *Sabellaria*. It would seem unwise, therefore, to rely entirely on direct observation, and sampling (such as grab samples) might be considered necessary to fully assess the status of the *Sabellaria* population and associated diverse infauna.

Remaining issues:-

∉ Is the targeting of sites likely to support *S. spinulosa* a valid basis for a survey strategy?

6.1.4 How do reefs contribute to productivity and richness?

Although reefs might be an extreme expression of biotopes in which *S. spinulosa* occurs, reefs contain such high numbers of individuals that it is likely to be a major contributor to biomass and (depending upon growth and predation) productivity. Interestingly, although a prolific deposit/filter feeder, large numbers do not appear to reduce the range or numbers of other species. Thus, it might be that *S. spinulosa* adds considerably to the productivity of an area, rather than the situation being simply the replacement of one productive species by another.

Remaining issues:-

∉ What is the productivity of *S. spinulosa* biotopes, and of reefs in particular?

∉ What is the productivity of alternative, non-*Sabellaria* biotopes?

6.1.5 What is the role of *S. spinulosa* (particularly reefs) biotopes in the wider ecosystem?

A more holistic approach could also be justified on ecological and general area management grounds, although this might present problems with the more restricted objectives of condition monitoring of selected features. *Sabellaria* is just one of the important structuring species found in the Wash. Others are *Modiolus* (the Horse Mussel), *Lanice* (the Sand Mason), and epifaunal species (hydroids and bryozoans). Yet other species occur in such large numbers that they must contribute greatly to the trophic web in the Wash. *Sabellaria* overlaps and interacts with other biotopes characterised by all these species and life forms. Ultimately, the richness of these biotopes will be reflected in the abundance and population structures of predators, some of which are commercially exploited fish and shellfish. Monitoring these populations may provide a useful integration of the health of many biotopes over a wide area and reduce the need for exhaustive survey of the biotopes at the bottom of the food chain. For example, a small survey of selected biotopes might give a very rough indication of the likelihood of major changes in the benthos whilst monitoring fish catches would alert management to possible broad scale stresses in the ecosystem, so providing an overall health-check. This might have the advantages of (1) linking in with other management objectives within the Wash, (2) making use of other on-going monitoring and (3) reduce sampling sensitivity to patchiness and fluctuations in populations.

Remaining issues:-

- What other types of surveys are taking place in the Wash? What critical information is lacking to construct an ecological model?
- How should the information from surveys targeted on *S. spinulosa* link with a more holistic approach to management of the Wash?

6.1.6 Are there scales of long term stability given dynamism?

If, as would seem to be the case, *S. spinulosa* biotopes are both spatially patchy and temporally dynamic, at what spatial and temporal scales must we step back to see the broader picture?

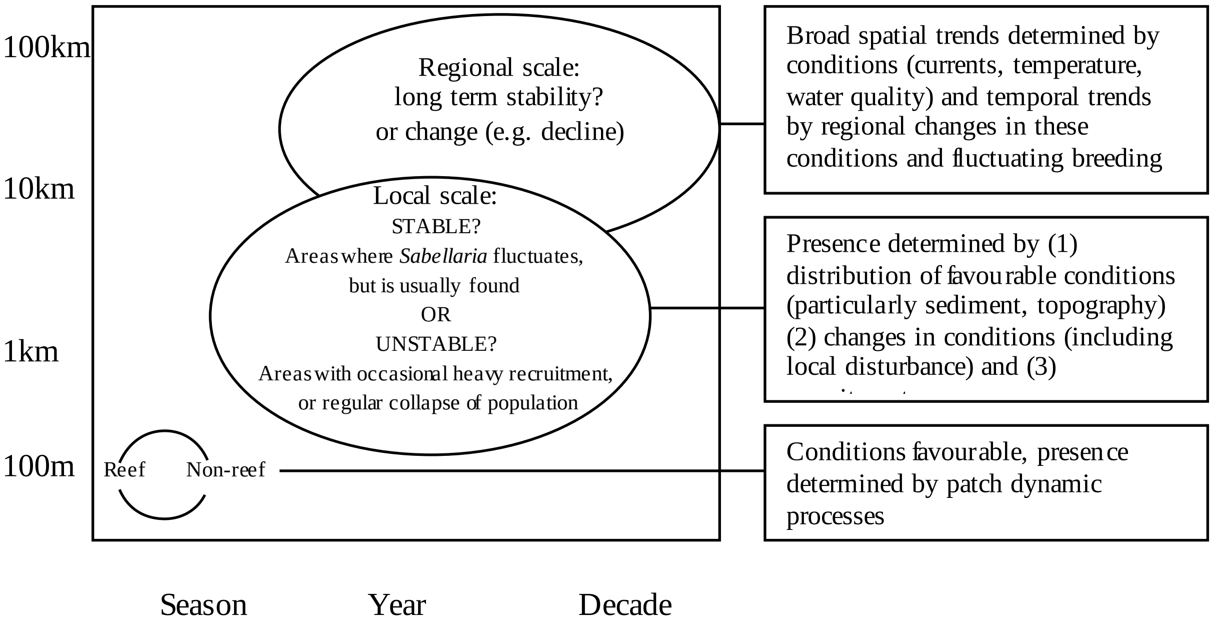

Figure 21: Diagram to illustrate the dynamic nature of *Sabellaria* reefs.

6.1.7 How should reefs be sampled?

Direct observation (video or diver observation) is the only technique able to determine if well developed reefs are present. Lower growth forms are not easily detectable by video when they are obscured by rich epifauna. Thus, grab sampling is required to complement video and is the only tested way to sample the full range of *Sabellaria* communities.

Remaining issues:-

- How do the differences in scale of observation between video (10s of metres) and grab ($0.1 m^2$) affect detection of reefs?
- Can we measure *S. spinulosa* biomass and age?

6.1.8 What is the future for remote detection?

AGDS can be used for broad scale mapping (10s km) and, through intensive tracking, moderately fine scale detection of patterns of sediment distribution (1km quadrats). The broader scale mapping has proved useful for selecting sample areas likely to support substantial populations of *Sabellaria.* AGDS may also be useful in prospecting for likely areas for *S. spinulosa*. Sidescan has not proved very successful to date, but deployment nearer the sea floor may be useful. Other acoustic technologies, such as swath interferometry, may prove useful.

Remaining issues:-

- Testing AGDS as a prospecting tool.
- Deployment of near seabed sidescan.
- Testing high definition interferometric systems.

6.1.9 What are the conditions favourable for reef development and can we predict where reefs might occur?

Conditions favourable for *Sabellaria* would seem to be silty sand and cobble/shell often on areas where sand supply might be high, such as the edges of sand banks and where there are sand waves. However, these associations are very approximate and not quantitative and there may be other features that could be better predictors of *S. spinulosa* occurrence. It should be possible to identify a wide range of potentially suitable sites within the Wash and ‘prospect’ for *Sabellaria*, measure the parameters and ground truth using grabs/video and relate *Sabellaria* presence to these habitat conditions. This could rapidly provide information on critical habitat characteristics and the likelihood of *Sabellaria* colonisation.

Remaining issues:-

- Can we model and predict suitable sites for colonisation?
- What proportion of potentially favourable conditions are colonised?

6.1.10 What human activities are most likely to be detrimental and can we measure their effects on reefs and on the wider ecosystem?

Area 107 supports dense populations of *Sabellaria* and all indications are that this is bounded (within 107) by shallow cobble ground to the west and deeper silty sand to the east. It is also bounded by clean sand to the north and this habitat change coincides exactly with the northern boundary of 107. There are very clear signs of dredging activity south of this boundary, none to the north. This is a striking distribution linked to dredging activity.

Remaining issues:-

- The relationship between habitat, reef and dredging activity (past and present) requires more detailed investigation.
- More diffuse effects of fishing also requires investigation.

6.1.11 How can the condition of *S. spinulosa* biotopes be monitored?

The primary requirements of a monitoring program (linked to the processes and scales listed in the boxes in Figure 21 above) need to be matched to sampling strategy. If *S. spinulosa* biotopes are dynamic and we can accept Figure 21 as a framework for expressing change, then monitoring programs must be designed with consideration to:-

- Scale of observation of samples in relation to scale of processes likely to determine infaunal composition and inherent variability (between replicate samples). Scale will range from very small for grab and core samples (<$0.1m^2$) to 10s of metres for video.
- Nature of the data from observations: The nature of data from sampling technologies may be qualitative/semi-quantitative for video and quantitative (numbers, biomass) for grab samples. Other measurements might also be considered, such as ageing (if feasible). Other sampling methods might also be required for sampling large and/or motile species (trawls, dredges, traps).
- A combination of sampling techniques may be used to cover a range of scales and data requirements
- Strategy for sampling: (1) Random sampling within a quadrat chosen to be homogeneous at a 'local' scale (estimated as 0.5 – 1 km square quadrats); (2) targeted (stratified) sampling determined by prior knowledge (derived from remote sensing).
- Nesting samples within region to reflect broadscale spatial trends: Deploying quadrats to reflect broadscale trends, themselves determined through analysis of existing knowledge, and baseline surveys.
- Statistical validity: Any sampling programme for monitoring must be able to provide statistically robust data. However, statistical power depends upon the effect size (size of change to be detected) and significance levels chosen as being critical to assessing change – the smaller the effect size and higher the significance level the greater the number of samples needed to prove change.
- Role of spatial analysis: Assessing the significance of change given our knowledge of scales of spatial heterogeneity/homogeneity requires the application of spatial statistics and power analysis.
- Evolving theoretical framework: The relevance of data from monitoring schemes cannot be regarded from a static theoretical viewpoint, even if the monitoring sampling strategy remains unchanged. The interpretation of the data must keep pace with advances in knowledge. It should be the aim of survey and monitoring to feed data into an evolving model explaining and predicting *S. spinulosa* distribution.

The need for a nested approach to sampling arises because of the prohibitive cost of a comprehensive spatial sampling program. However, a nested program must be well planned and linked to a theoretical/statistical framework for scaling up information to the broader local or regional scale.

Remaining issues:-

- Perhaps the single most important issue for the Wash and north Norfolk coast cSAC remains the establishment of a sustained long term monitoring program(s) that is likely to provide the information most required for management of reefs.

- The appropriate effect size and significance levels need to be considered for setting thresholds for change.

6.1.12 Is there a need for baseline survey?

It is important that general statements about the distribution of a biotope on a regional or national basis can be supported statistically by the data. Are the data representative or heavily biased due to (1) scarcity of information or (2) sampling techniques used. Comprehensive broadscale surveys for baseline information or repeat surveys to update baseline information may be required (as opposed to monitoring surveys). The strategy for such surveys could follow the methodology adopted in the Broadscale Mapping Project, but updated to accommodate new acoustic technologies, particularly swath systems. These surveys may be commissioned periodically to act as assurance that information based on more indirect modelling (as above) is a true reflection of the distribution of biotopes.

An alternative survey strategy could be based on prospecting for likely reef sites. Favourable situations could be modelled and linked to remote sensing techniques. One-off sampling surveys could then test these predictions. Are there any geographic differences in distribution 'rules'? The advantages of this strategy would be (1) it would test a wider range of conditions than is possible with the more focussed quadrat survey, (2) it is predictive, and (3) the rules could be applied to new areas and any differences in favourable conditions determined.

Remaining issues:-

- Determine the requirement and frequency for repeat broadscale survey.
- Instigate a cost effective strategy for improving our knowledge of the regional and country-wide distribution of *S. spinulosa* on a basis that is truly representative and statistically valid.

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English Nature is the Government agency that champions the conservation of wildlife and geology throughout England.

This is one of a range of publications published by:
External Relations Team
English Nature
Northminster House
Peterborough PE1 1UA

www.english-nature.org.uk

Cover printed on Character Express, post consumer waste paper, ECF.

ISSN 0967-876X

Cover designed and printed by Status Design & Advertising, 2M, 5M, 5M.

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Peter Wakely/English Nature 17,396
Middle left: Co_2 experiment at Roudsea Wood and Mosses NNR, Lancashire.
Peter Wakely/English Nature 21,792
Bottom left: Radio tracking a hare on Pawlett Hams, Somerset.
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