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Marine Strategy Framework Directive Indicators for UK Rocky Shores
Part 1: Defining and validating the indicators

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Summary

JNCC commissioned a consortium of the Scottish Association for Marine Science (SAMS), the Marine Biological Association of the United Kingdom (MBA), and the National Oceanography Centre Southampton/University of Southampton (NOCS) to develop several indicators of Good Environmental Status (GES) for UK intertidal rocky habitats for the Marine Strategy Framework Directive (MSFD).

In Section 1 of this report the rationale for indicator development and recommendations for their use is provided. After supplying some background on UK rocky shore distribution patterns, the approach to indicator development in the context of the MSFD, including the descriptors of GES, is scoped out, in particular with regards to the "*prevailing physiographic, geographic and climatic conditions*" aspect of the MSFD Descriptor 1 (see below). Proposed indicators are then presented and assessed using existing data before making recommendations on their use.

The proposed indicators are designed to address the needs of the MSFD. GES for the MSFD relies on eleven descriptors of which four are relevant for these relatively undisturbed and unexploited habitats. The relevant descriptors are:

Descriptor 1: Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.

Descriptor 2: Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems.

Descriptor 4: All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.

Descriptor 5: Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms and oxygen deficiency in bottom waters.

The approach for the development of rocky shore indicators has been taken from the principle embodied within Descriptor 1 above: "*The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*". Furthermore, this contract is seeking to address the Commission Decision (2010) indicator 1.6.1 - *Condition of the typical species and communities* - for intertidal rocky habitats in UK waters. Thus, a GES target within this context would reflect that species are present as expected, given the presence of the kind of habitats where they normally occur, and given the prevailing physical conditions. The availability of data on the abundance of rocky shore species allows an objective analysis of patterns with respect to spatial gradients and temporal changes that can give indicators with a degree of supporting evidence.

The data requirements and methods for data collection of the proposed indicators are presented in Section 2. These methods are designed to collect information that demonstrates how the abundance and diversity of conspicuous and easily identifiable species are responding to major environmental drivers. The methods are designed to collect categorical species abundance (SACFOR) data for individual sites in a relatively rapid and repeatable way that is both compatible and comparable with efforts to define the

biogeography of rocky shore species going back to the 1950s, and so offering the best chance of detecting significant change in a well-documented long-term context. Although the basic methodology for surveying rocky intertidal communities adopted by the MarClim project has remained purposefully unaltered since the 1950s, new methods for recording, storing and sharing digital images and for locating survey positions offer ways of supplementing and improving data collected during surveys.

In Section 3, recent technological advances and their potential utility for rocky intertidal surveys are reviewed. These include: GPS-enabled digital cameras providing images that are automatically geo-referenced; smartphone identification (ID) guides and wildlife recording applications (‘apps’) that enable non-experts to contribute species records for additional evidence; and guiding expert surveys. The authors recommend that handheld imaging and location-sensing devices be used to supplement current expert-based survey methods. Existing technology (quadrats, measuring devices), however, will always be needed. Low-level aerial photographic surveys are likely to become an important tool for intertidal surveying, but some development of these methods is still needed.

The proposed implementation of this system of indicators derived from basic ecological data is outlined within Section 4. The authors recommend that existing rocky shore survey sites, surveyed during the MarClim project (2001-2006 and continuing since) form the basis of periodically (ideally annually) repeated surveys to assess the status of rocky shores over broad regions. Variability in indicator values at the level of individual sites, influenced by the availability and extent of suitable habitat, and operator error result in a degree of ‘noise’ around the signal. It is therefore recommended that surveys are formed into campaigns that span many sites to average out this variability, and that any changes in indicators are considered by comparisons across groups of sites, between different time periods and different areas, and not at the level of single sites.

Analyses of the data can take many forms, but it is anticipated that the primary ones will be (1) comparisons of present-day and past data, (2) comparison between areas with and without localised pressures (preferably using ‘Before-After-Control-Impact’ survey designs), and (3) comparison of observed communities with those expected for the “*prevailing physiographic, geographic and climatic conditions*” aspect of the MSFD Descriptor 1.

Ultimately, the designation of the thresholds of the proposed indicators that define GES lies beyond the scope of this report, and will require further research and discussion to define.

Contents

Glossary

ABP	Associated British Ports
AVHRR	Advanced Very High Resolution Radiometer
CCI	Climate Change Indicator (proposed indicator)
CCW	Countryside Council for Wales (now Natural Resources Wales)
EA	Environment Agency
EQR	Ecological Quality Ratio
EQS	Ecological Quality Status
EUNIS	European Nature Information System
EXIF	Exchangeable Image File Format
DAAC	Distributed Active Archive Centre
DF	Degrees of Freedom
GCP	Ground Control Point
GES	Good Environmental Status
GEcS	Good Ecological Status
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
JNCC	Joint Nature Conservation Committee
MBA	Marine Biological Association of the United Kingdom
MODIS	Moderate Resolution Imaging Spectroradiometer
MSFD	Marine Strategy Framework Directive
MTL	Mean Tide Level
N(algae)	Number of macroalgal species (proposed indicator)
N(other)	Diversity of other species (proposed indicator)
N(total)	Total number of species (proposed indicator)
NASA	National Aeronautics and Space Administration
NNI	Non-Native Species Indicator (proposed indicator)
NOCS	National Oceanography Centre, Southampton
NRW	Natural Resources Wales
QA	Quality Assurance
QC	Quality Control
RPA	Remotely Piloted Aircraft
SAMS	Scottish Association for Marine Science
SD	Standard Deviation
SE	Standard Error
SST	Sea Surface Temperature
UAV	Unmaned Aerial Vehicles
WFD	Water Framework Directive
WFDMT	Water Framework Directive Macroalgal Tool
WFD RSL	Water Framework Directive Reduced Species List
WQI	Water Quality Index (proposed indicator)
WXI	Wave Exposure Index (proposed indicator)

1 The Development of Status Indicators

1.1 Introduction

The overall aim of this report is to develop several indicators of Good Environmental Status (GES) for UK intertidal rocky habitats for the Marine Strategy Framework Directive (MSFD) (2008/56/EC[1]). In this introductory Section the rationale for indicator development and recommendations for their implementation is provided.

There is a rich heritage of descriptive studies on British rocky shores (e.g. Crisp and Southward, 1958) that provide valuable baselines from the 1940s and 1950s against which to judge responses to climate such as shifts in ranges and changes in abundance of species (see Hawkins *et al*, 2008; Hawkins *et al*, 2009, for reviews) plus more subtle phenological shifts (Moore *et al*, 2011). There are also valuable time-series assessments of key species such as barnacles that chart responses to climate fluctuations from the 1950s to the 1980s (Southward, 1991; Southward *et al*, 1995) and, more recently, responses to rapid climate change since the late 1980s (Poloczanska *et al*, 2008; Mieszkowska *et al*, 2012). This archive was exploited by the MarClim project[2] which re-surveyed on a broad-scale and re-started time-series assessments (Mieszkowska *et al*, 2006a).This past, and more recent, work is built on for the purpose of this contract. In particular, this contract explores whether the approaches developed by the MarClim project to describe and measure responses to climate change can be adapted and employed to meet the challenge of describing GES as required by the MSFD. Potential relevant indicators are then proposed and validated using the MarClim database before recommendations are made on their use.

The proposed indicators are designed to address the needs of the MSFD. The approach taken reflects discussions which took place at an expert workshop (Birmingham, April 2011) that resulted in the proposals for UK MSFD targets and indicators presented to UK Government in Moffat *et al* (2011). GES for the MSFD relies on eleven descriptors of which four are relevant for these relatively undisturbed and unexploited habitats. The relevant descriptors are:

Descriptor 1: Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.

Descriptor 2: Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems.

Descriptor 4: All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.

Descriptor 5: Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms and oxygen deficiency in bottom waters.

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF

[2] The MarClim project was a four year multi-partner funded project created to investigate the effects of climatic warming on marine biodiversity. In particular the project aimed to use key intertidal species, whose abundances had been shown to fluctuate with changes in climatic conditions, as indicators of changes occurring in the intertidal and offshore. The project used historic time series data, from the 1950s onwards, and contemporary data to provide evidence of changes in the abundance, range and population structure of intertidal species and relate these changes to recent rapid climatic warming.

The approach for the development of rocky shore indicators has been taken from the principle embodied within Descriptor 1 above: "*The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*". Furthermore, this contract is also seeking to address the Commission Decision (2010/477/EU[3]) indicator 1.6.1 - *Condition of the typical species and communities* - for intertidal rocky habitats in UK waters. Thus, a GES target within this context would reflect that species are present as expected, given the presence of the kind of habitats where they normally occur, and given the prevailing physical conditions. The availability of data on the abundance of rocky shore species allows an objective analysis of patterns with respect to spatial gradients and temporal changes that can provide indicators with a degree of supporting evidence. Finally, the implementation of the proposed indicators in relation to GES is assessed.

The aims of this Section are thus threefold:

1) Define and validate potential indicators of climate change impacts on intertidal rocky habitats based on enhancing the scope and coverage of the current MarClim project.
2) Define and validate indicators of the condition of intertidal rocky habitat communities based on expanding the biological scope (i.e. species list) of the current MarClim protocols. Identify any human pressure(s) which such indicators respond to (and can therefore detect the impacts of).
3) Define and validate a community based indicator which responds to the pressure of boulder turning on intertidal rocky habitats.

1.2 Influences on the distribution of rocky shore species in north-west Europe

Distribution patterns on rocky shores are shaped by two major local environmental gradients operating on scales of 10-1000s of metres: the vertical intertidal gradient between fully marine conditions at low tide to fully terrestrial conditions beyond the reach of salt spray; and the horizontal exposure gradient between sheltered bays out to wave-beaten headlands (see Ballantine, 1961; Lewis, 1964; Hawkins and Jones, 1992; Raffaelli and Hawkins, 1996 for reviews). Physical factors can directly set distributions of organisms due to intolerance to stress at higher shore levels, disturbance at more-exposed sites or siltation at sheltered sites. These gradients also have an indirect influence by modifying the strength of biological interactions such as competition, predation, facilitation and biological disturbance such as shading or whiplash effects from canopy algae (see Raffaelli and Hawkins, 1996, for review).

The sharpness of these gradients for the largely marine organisms inhabiting rocky shores often leads to clearly defined distribution patterns. Vertically, species can occur in conspicuous bands or zones. Upper limits, especially at the upper shore are set directly by intolerance to stress associated with tidal emersion, particularly desiccation but also high temperatures (Schonbeck and Norton, 1978; Hawkins and Hartnoll, 1985). Upper limits of mid- and low-shore species can be set by biological factors: grazing can limit the upward extent of low-shore algae (Southward and Southward, 1978; Boaventura *et al*, 2002); and competition has been shown to limit the upper extent of mid-shore fucoids (Hawkins and Hartnoll, 1985; Jenkins *et al*, 1999; Jenkins and Hawkins, 2003; Ingolfsson and Hawkins, 2008). Most lower limits are set by the biological interactions of competition (Connell, 1961a; Schonbeck and Norton, 1980; Hawkins and Hartnoll, 1985; Jenkins *et al*, 1999) and predation (Connell, 1961b; Paine, 1969). Zonation patterns are particularly clear on sheltered shores where canopy-forming fucoid algae completely saturate space. On

[3] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:232:0014:0024:EN:PDF

moderately exposed shores, zonation still occurs, but it is more diffuse and disturbance and biological interactions create patchy conditions (see Hartnoll and Hawkins, 1985; Burrows and Hawkins, 1998; Johnson *et al*, 1998 for model).

The influence of the horizontal exposure gradient between sheltered bays and wave-beaten headlands operates differently for different taxa. Some species such as filter feeders do better in wave-exposed conditions. Other species such as large seaweeds thrive in shelter. Some species have optima at intermediate levels of exposure and some are affected by siltation (Airoldi and Hawkins, 2007) which is greater in sheltered areas. Again, biological interactions are important along these gradients. In the North-East Atlantic, grazing by limpets prevents establishment of seaweeds on more exposed shores (Jones, 1948; Southward, 1964; Southward and Southward, 1978; Hawkins, 1981; Hawkins and Hartnoll, 1983; Jenkins *et al*, 2005; Coleman *et al*, 2006). Recent work has shown that whilst grazing of limpets prevents establishment of algae, increased wave action reduces persistence of algae (Jonsson *et al*, 2006) emphasizing the interaction of physical and biological factors. Low on the shore *Laminaria digitata* in moderately sheltered areas outcompetes *Alaria esculenta* which is an opportunistic species tolerant of wave-exposed conditions and *Saccharina latissima* which is typical of more-sheltered conditions (Hawkins and Harkin, 1985).

The clearly defined patterns evident on rocky shore habitats prompted many broad-scale descriptive studies charting patterns of zonation and leading to ‘universal’ classifications both in the British Isles (Lewis, 1964) and worldwide (Stephenson and Stephenson, 1949; Ricketts and Calvin, 1992). These led to similar qualitative descriptions through the world (Morton and Miller, 1968; Morton and Miller, 1973; Raffaelli and Hawkins, 1996). This huge archive of beautifully illustrated habitat descriptions still provides a descriptive framework within which to understand the processes shaping patterns on rocky shores – in the British Isles and Ireland, Lewis (1964) still remains an invaluable resource.

Within this broad-framework of habitat description it is important to realise that, at a local scale, rocky shores can be spatially and temporally variable. In particular, the mid-eulittoral region of moderately sheltered to moderately exposed shores are patchy and temporally variable (Burrows and Lodge, 1951; Hawkins and Hartnoll, 1983; Hartnoll and Hawkins, 1985; Hawkins and Hartnoll, 1985; Johnson *et al*, 1997; Burrows and Hawkins, 1998; Johnson *et al*, 1998) with a combination of recruitment variation, disturbance and biological interactions of both positive and negative signs driving patchiness and fluctuations. This is reinforced by the behaviour of the key grazers, *Patella vulgata*, which aggregates under clumps of fucoids for shelter (Hawkins and Hartnoll, 1983; Hartnoll and Hawkins, 1985; Moore *et al*, 2007) and food (Davies *et al*, 2008). Mussel-barnacle mosaics and *Sabellaria* reefs (Wilson, 1971) can also be highly variable (Lewis and Bowman, 1975). This innate variability in some rocky shore assemblages should be taken into account and should be borne in mind when using phase 1 biotope-based mapping at levels of assemblage resolution beyond biotope complexes, up to EUNIS level 3. The same area of shore can switch from one biotope to another over time just due to natural patch dynamics. In contrast the low and high regions of shores tend to be less temporally variable, as are the extremes of shelter and exposure (Southward and Southward, 1978; Hawkins and Hartnoll, 1985). Seaweed-dominated sheltered shores can be particularly stable, but once disturbed by practices such as *Ascophyllum* harvesting, will take at least 10 years to recover (Jenkins *et al*, 2004; Ingolfsson and Hawkins, 2008).

In addition to the major vertical and horizontal gradients, assemblage composition and community structure can be affected by smaller scale (<10m) habitat and microhabitat variability. This topographic template results from interactions of erosion and geological attributes of the shore creating channels, boulder fields, pools, overhangs and changes in aspect, crevices, cracks and small-scale surface roughness (Johnson *et al*, 2003).

Bioerosion can also contribute to surface texture at the millimetre to centimetre scale in softer rocks (Pinn *et al*, 2008). This small-scale variability can be addressed by appropriate stratification of sampling for quantitative studies, such as using flat, seaward facing rock for counts of barnacles and limpets. The semi-quantitative approach adopted by MarClim works well on heterogeneous shores.

Superimposed on these local gradients is the very gentle geographical gradient generated by latitudinal and longitudinal changes in climate (Lewis, 1964). The southern and western waters of the British Isles and Ireland experience milder weather and warmer seas - especially in the winter when isotherms run north to south into the colder and more-enclosed Irish Sea, Eastern English Channel and Southern North Sea. Vertical zonation patterns also reflect this pattern, with the warm-water barnacle *Chthamalus montagui* increasingly squeezed by its cold-water competitor *Semibalanus balanoides* into a high-shore refuge towards the northern end of its range in northern Scotland where water and air temperatures become cooler (Connell, 1961a; Poloczanska *et al*, 2008).

There are also changes along the latitudinal gradient with algal turfs replacing kelp such as *Laminaria digitata* in southern Europe. The balance of fucoid algae to barnacles also shifts along the wave exposure axis – fucoids recede more into shelter further south in Britain and Europe (Ballantine, 1961). The probability of fucoid recruitment in the absence of grazers is much less in southern Britain than in the north (Jenkins *et al*, 2005; Coleman *et al*, 2006). This implies that the outcomes of biological interactions are modified by the climate regime in different regions and that these will also shift over time as climate changes (Helmuth *et al*, 2006; Hawkins *et al*, 2008; 2009).

Fortunately there is a rich legacy of broad-scale biogeographical surveys of rocky shore habitats starting in the 1930s (Fischer-Piette, 1936; Moore and Kitching, 1939b), and continued in the 1940s (Fischer-Piette, 1948) and 1950s (Southward and Crisp, 1954a). These provide a superb baseline for a suite of common rocky shore species from Shetland down to Senegal using similar semi-quantitative methods formalized by Crisp and Southward (Crisp and Southward, 1958) into abundance scales. Episodic partial resurveys occurred, picking up the effect of the extreme cold winter of 1962/1963 (Crisp, 1964).

In the North-East Atlantic the 1950s were a relatively warm period. Thus the surveys from that period are an extremely useful baseline against which to judge the accelerated warming seen from about 1987 until the mid-2000s. It is worth noting that in recent years British winters have been colder and summers less hot than in the period 1987-2005. There has been a return to North Atlantic Oscillation index negative winters with a stronger continental influence with 2010/2011 being the coldest winter since 1962/1963.

For some species, such as barnacles, amenable to quantitative sampling, the broad-scale surveys evolved into time-series studies (Southward and Crisp, 1954a; Southward, 1967; 1991; Southward *et al*, 1995; Mieszkowska *et al*, 2012). Jack Lewis also started his career with some classic broad-scale descriptive work, following in the footsteps of the Stephensons (1949). He also pioneered work on key species at Robin Hood's Bay, North Yorkshire. The work by Lewis and co-workers in the 1970s and 1980s provided a baseline for some species during the colder period between the early 1960s and late 1980s. Quantitative broad-scale population data for trochid (topshell) species at their range limits has proved particularly valuable and formed a key part of the MarClim project (Mieszkowska *et al*, 2005; Mieszkowska *et al*, 2006a; Mieszkowska, 2009).

1.3 Past Indicators of environmental status on rocky shores

1.3.1 Community-level metrics

The use of indicators to assess 'environmental status' is not a new concept for rocky shores. Patterns of change in community structure across wave-action gradients were long recognised by early workers (e.g. Cotton, 1909) and thoroughly described by Lewis (Lewis, 1964) in his classic textbook. The stereotypical response of rocky shore communities to wave exposure led this response to be used as diagnostic for wave exposure. Ballantine was the first to propose a wave-exposure index based partly on the presence and abundance of characteristic species (Ballantine, 1961) and partly on the openness to waves and the extent of wave fetch. Changes in response to wave action over latitudinal gradients were recognised. There are problems of circular reasoning inherent in this approach, since the change of composition of communities and abundance of species is a response to variation in wave action, and cannot be used to directly measure wave action itself.

A preferable approach is to directly measure the driver itself or another proxy, and relate the response directly to that driver. Changes in rocky shore communities can be seen to vary directly with wave fetch (Thomas, 1986; Burrows *et al*, 2008) and the nature of this response gives a prediction of the community composition for a certain level of wave action.

More recently, one indicator relevant to intertidal rocky shore habitats has been specifically developed for the implementation of the Water Framework Directive (WFD) (2000/60/EC[4]) - the rocky shore Macroalgal Tool (WFDMT). This tool involves the assessment of the presence or absence of approximately 70 species of macroalgae (the Reduced Species List, RSL[5]) to derive the Ecological Quality Status (EQS) of a shore. This is calculated as a ratio (Ecological Quality Ratio, EQR), which is then scored against a five point scale from high through to bad quality (Table 1) derived from macroalgal species richness and species composition (Wells *et al*, 2007). The intertidal macroalgal species and resultant assemblages selected for the WFDMT respond to changes in nutrient status and problems of eutrophication, toxic substances, habitat modification and general stress.

Table 1. The metric scoring system with classification status ranges for macroalgae species richness, Chlorophyta, Rhodophyta and opportunist proportions, Ecological Status Group ratios and shore descriptions as described and calculated from the field sampling sheet (Wells *et al*, 2007).

Quality EQR	Bad 0–0.2	Poor 0.2–0.4	Moderate 0.4–0.6	Good 0.6–0.8	High 0.8–1.0
Species richness	⩽5	6–19	20–31	32–54	⩾55
Proportion of chlorophyta	61–100	46–60	36–45	26–35	⩽25
Proportion of rhodophyta	0–15	15–24	25–34	35–44	⩾45
ESG ratio	0–0.1	0.1–0.29	0.3–0.39	0.4–0.64	⩾0.65
Proportion of opportunists	41–100	31–40	21–30	16–20	⩽15
Shore descriptions	N/A	15–18	12–14	8–11	1–7

[4] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060
[5] Ideally a "full species list" (FSL) is used; however, the identification of over 700 intertidal seaweed species requires high levels of taxonomic expertise. Therefore a "reduced species list" (RSL) was derived. There are 3 RSLs for the UK comprising around 70 taxa each and 100 taxa overall.

The WFDMT requires the on-site collection of material for microscopic analysis (Wells *et al*, 2007), and a high level of taxonomic expertise for smaller, less-conspicuous species. The indicator therefore requires considerable taxonomic training and considerable time on the shore to collect the necessary data to implement it. However, experience with the method (Sarah Peaty, Environment Agency (UK), pers. comm.) has shown that when taken in context of the programme requirements as a whole (with the number of sites and frequency of sampling) it is not an intensive programme. The requirements of a less-stringent programme may mean that more monitoring events are needed. Consequently, the view should be of the overall time needed to obtain 'similar' data. This, combined with the low frequency of this programme (every six years), means that the overall effort can be considered low.

The WFDMT is designed to detect changes in water quality at a local scale (e.g. estuaries or sections of coastlines) predominantly identifying acute impacts resulting from changes in nutrient levels, introduction of toxic substances or localized physical effects. In contrast, the MarClim indicators are designed to detect changes in species abundance and relative dominance in response to changes in climate, water quality, wave exposure, and invasive species across multiple spatial scales from local (within a shore and between neighbouring shores) to regional, national and biogeographic scales (using the European MarClim dataset). Cross-calibration and comparison of the WFDMT with the rapid assessment indicator for water quality using both macroalgae and invertebrates derived from the MarClim project would be of benefit going forward, particularly to identify their applicability for particular settings. The MSFD/WFD comparison factsheet[6] clarifies the relationships between these two frameworks. The cross-calibration would also serve to confirm that the UK targets and indicators for GES have been aligned, as far as possible, with existing WFD assessment tools and criteria.

1.3.2 Species-level metrics

Ecological changes in response to driving factors have often been measured by changes in the relative proportions of pairs of species. For example, Russell (1935) used two planktonic *Sagitta* species as indicators of warm-water and cold-water conditions in the English Channel in the 1930s. Southward (1967; 1991; Southward *et al*, 1995) similarly used the relative proportions of warm-water and cold-water barnacles to do the same from the 1950s onwards: warm-water *Chthamalus* species and the cold-water *Semibalanus balanoides* species. Southward's 'Warm Index' has closely tracked changes in climate in the North Atlantic from the 1950s to the present day (Mieszkowska *et al*, 2012), demonstrating the best relationship with the Atlantic Multidecadal Oscillation: the detrended change in sea-surface temperature in the North Atlantic.

1.4 Scope and approach adopted to indicator development

Many of the patterns in species abundance and distribution on UK rocky shores have been recorded, documented and described primarily from the middle of the 20th century to the present day. Most of this information is available as abundance data for rocky shore species, and, as such, permits an objective analysis of patterns in respect to spatial gradients and temporal changes that can provide indicators with a degree of supporting evidence. This contract adopts this approach and proposes and evaluates indicators using the data collected by the MarClim project and subsequent activities between 2002 and 2008.

[6] http://archive.defra.gov.uk/environment/marine/documents/legislation/msfd-factsheet1-waterdirective.pdf

1.4.1 The UK and Ireland MarClim project (2001 to date) and the legacy of Alan Southward, Dennis Crisp and Jack Lewis

After the pioneering early descriptions of zonation patterns by Stephenson and Stephenson (1949), a systematic attempt to document the biogeography of intertidal species in the British Isles began in 1953 by Alan Southward, based at the Laboratory of the Marine Biological Association in Plymouth, and by Dennis Crisp in 1947, at the University College of North Wales laboratories in Menai Bridge, North Wales. These two began working together and produced a series of studies that showed that not only did the presence of rocky shore species and the composition reflect the local climate, but also that the proportions of warm- and cold-water species changed with shorter term changes in climate (Southward, 1951; Southward and Crisp, 1954a; Southward and Crisp, 1954b; 1956; Crisp and Southward, 1958). Their work mirrored similar studies by Fischer-Piette in France, Spain, Portugal and French North Africa, which commenced in the 1930s and resumed after the Second World War (e.g. Fischer-Piette,1948; Crisp and Fischer-Piette,1959).

With climate change rapidly rising up the scientific and political agenda at the end of the 20th century, Steve Hawkins successfully proposed a project that would revisit this early work. The MarClim project (Mieszkowska *et al*, 2005; 2006b; 2008) aimed to rediscover and collate the original data from the earlier surveys by Southward and Crisp, and, where possible, re-survey the original study sites. Re-surveys were to be done using entirely comparable methods, but also with the addition of quantitative, replicated counts of abundance for key species of barnacles, limpets and topshells to also permit robust univariate and multivariate statistical analysis of population dynamics. The 65 species of invertebrates and macroalgae initially used has increased over the 13 years since the inception of MarClim to also include non-native species and additional species showing recent shifts in distribution in the UK.

While technology and sampling methods had moved on considerably in the 50 years since the early studies, the approach outlined by Crisp and Southward (1958) of assigning abundance at survey sites to distinct categories was repeated, using extended scales for abundance classes above the previous maximum (Abundant) and for groups not considered by Crisp and Southward (Hiscock, 1981). The abundance scales are commonly referred to as ‘SACFOR’ scales, after the initial letters of each category (Super-abundant, Abundant, Common, Frequent, Occasional and Rare). A full review of the methods involved in collecting the MarClim data is presented in Section 2 of this report.

1.4.2 Other monitoring approaches not considered here

Many of the more recent assessments of intertidal habitats have relied on classification of the combination of assemblages and the underlying physical habitats into biotopes, using Common Standards Monitoring Guidance according to the National Marine Habitat Classification for Britain & Ireland (Connor *et al*, 2004), and more recently with the Marine Conservation Zone process and also the EUNIS classification scheme[7]. Indices presented within this report are not specifically tailored to predict or measure the presence of specific biotopes because the indicators operate at the level of an entire shore rather than at the within-shore habitat scale. Changes in the prevalence, extent and location of biotopes at shore and coastline scales should reflect, and will be driven by, changes in the abundance and distribution of their constituent species and the outcome of any subsequent biological interactions. Biotope mapping remains a valid tool for condition assessments in the context of the EC Habitats Directive (1992/43/EEC[8]) as well as providing a framework for stratification of quantitative sampling within a site. Detecting species-level change has

[7] See http://jncc.defra.gov.uk/page-3365 for comparative classifications.
[8] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0043:20070101:EN:PDF

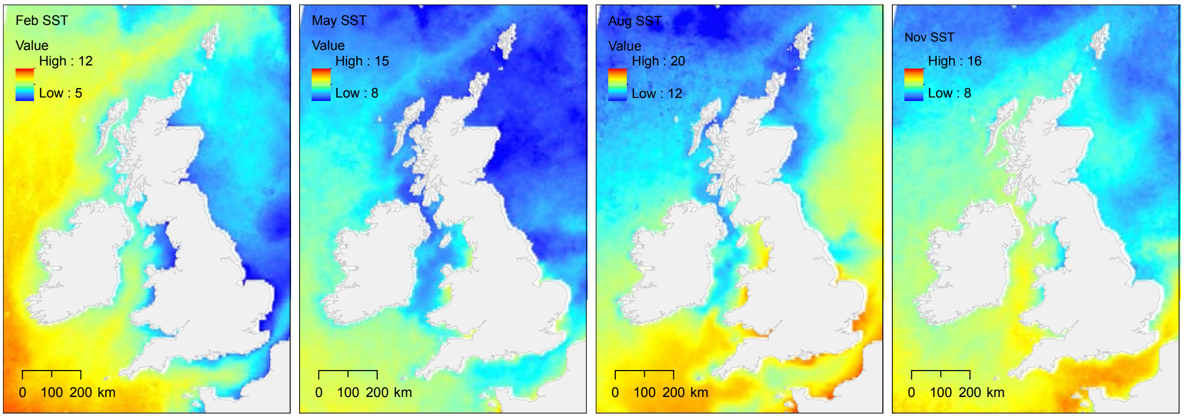
remained the basis of surveying and monitoring since the 1950s. Therefore, monitoring and detecting changes in species and hence assemblages using long-term time series on intertidal rocky habitats forms the basis of the indicator recommendations within this report.

1.5 The pattern of “prevailing physiographic, geographic and climatic conditions” around the UK and Ireland

Since the authors’ proposed approach to the development of GES indicators relies on the relationships between species abundance and underlying patterns in predictor variables, an account of the major gradients in environmental drivers for rocky shore communities in the UK is presented here. Satellite remote sensing of the optical and thermal properties of the ocean surface provides useful synoptic views of the conditions around the UK. Those properties that cannot be so imaged can be illustrated by mapping model outputs. Wave height and tidal flow fall into this category.

The wider European context of these conditions is also important. Ramos *et al* (2012) have classified a similar set of environmental conditions for rocky macroalgae (sea-surface temperature (SST), light, wave height, tidal range and salinity) for the WFD in order to classify (create typologies for) stretches of coastline, and thereby separate ‘*biotypes*’ where conditions are considered similar.

1.5.1 Temperature



(A) Feb (B) May (C) Aug (D) Nov

Figure 1. Sea surface temperature around the UK for (A) February, (B) May, (C) August, and (D) November; from averages over the period 2000-2006 obtained from the NASA Giovanni Data Portal (DAAC, 2008).

Temperature is a major driver, setting geographic patterns of distribution of marine species (Hutchins, 1947; Vermeij, 1978; Lüning, 1990), although other proximate factors such as habitat type and extent and local hydrography can determine local abundance and can contribute to setting range edges. SST derived from satellite images, is a widely available variable which can be used for biogeographic studies.

Maps of average patterns of SST: winter (February), spring (May), summer (August) and autumn (November) show the general pattern of decreasing temperatures from the south to the north around the UK (Figure 1). The axis of change varies from summer to winter, with February SST generally higher in the west (Atlantic and Irish Sea) than in the east (North Sea), and August SST warmer in the southern areas of both east and west coasts of the UK. Regional-scale patterns also vary between summer and winter. Summertime patterns show evidence of stratification, mostly delineated by the presence of tidal fronts (Pingree and Griffiths, 1978), such as the Islay and Celtic Sea fronts, separating stratified areas with warmer surface water from tidally well-mixed areas with cooler surface water. Locally cooler areas such as the north-west tip of Cornwall may also influence the relative proportions of cold and warm water species, and are important to note.

Most rocky shore species whose distributions reach their northern limits in the UK follow a distribution pattern similar to that of February SST, being most likely to be present in the west and south, and least likely in the north and east (Lewis, 1964). The strength of association with the February pattern of temperatures was therefore used to select species for inclusion in a climate change index (see Section 1.6.2 for a description of the indicator).

1.5.2 Water quality

Here the large-scale patterns in water quality that result from spatial variation in the biomass of phytoplankton and the quantity of suspended material per unit volume are considered. This mostly reflects the eutrophication status of inshore waters. Data on contaminant concentrations are available, as in Charting Progress 2 for example (U.K. Marine Monitoring Assessment Strategy Community, 2010), but not so widely or with such spatial resolution as satellite remote sensing.

General patterns of contaminant concentrations follow the patterns of phytoplankton and sediment load, with highest values around population centres. Phytoplankton and sediment influence the spectral characteristics of reflected sunlight, but are not always easy to distinguish. The presence of significant amounts of suspended sediments makes estimation of the chlorophyll concentration problematic. As a consequence, inshore coastal waters are considered differently from offshore oceanic waters (see, for example, Joint and Groom, 2000). Notwithstanding such issues, the influences of phytoplankton biomass and suspended sediment on rocky shore biota are likely to be similar and, for the purposes of developing indicators, can be considered together. Increased phytoplankton and suspended sediment increases the attenuation of light through the water, reducing the depth to which sufficient light penetrates to allow photosynthesis (‘compensation depth’ – where respiration of plants exceeds the photosynthesis). The euphotic depth is much reduced in areas of high sediment and phytoplankton, such as in the Bristol Channel, southern North Sea coasts and Liverpool Bay (Figure 2B). The abundance of subtidal macroalgae is much reduced in these areas (Burrows, 2012).

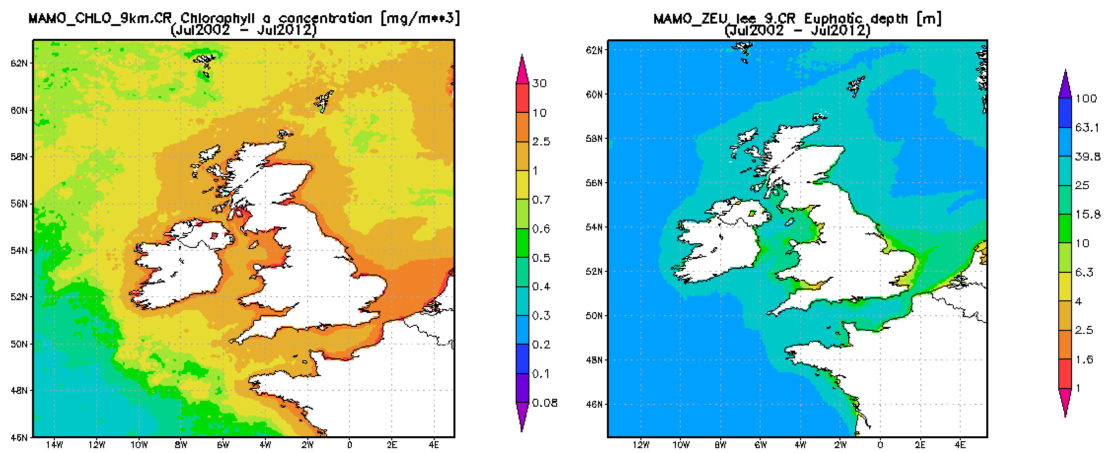


Figure 2. (A) Chlorophyll a concentration (mg/m^3), (B) Euphotic depth (m) in UK and Irish waters.

Here chlorophyll *a* concentrations are referred to as mg/m^3 in the full knowledge that these values are influenced by suspended sediment, and that the probable effects on rocky shore communities are due to a complex set of interrelated processes, probably due to a combination of shading of macroalgae, greater retention of larvae of suspension feeders and enhanced feeding conditions for this same group (Burrows, 2012). The chlorophyll *a* data were obtained from the NASA MODIS Aqua satellite sensor and averaged over the period from July 2002 to July 2012. The coarser resolution of the NASA satellite models is used rather than finer-scale models such as the 4.5km light penetration model for UKSeaMap 2010 (McBreen *et al*, 2011) and the 1km resolution model used for EUSeaMap (Cameron and Askew, 2011). The greater resolution of these latter models may appear advantageous, but may misrepresent the highly dynamic nature of phytoplankton concentrations at this scale. The data used for this contract are aimed at resolving differences on 10 to 100km scales in a primarily biogeographic or coastal cell context; it is appropriate that for MSFD purposes data are used with similar resolution. Ultimately if the proposed indicators are adopted there will be a need to validate satellite derived information with data collected from inshore surveys. A first attempt at this analysis (Section 0, Figure 13) shows that the Environment Agency (EA) WFD data is related to satellite-derived chlorophyll estimates, though it is clear that determining the appropriate spatial and temporal scale of satellite data to compare with survey results requires further effort.

1.5.3 Wave height and wave exposure

Wave height is generally highest on open Atlantic-facing coasts, especially in the north and west of Scotland, west of Ireland and along the Western Isles and least along the coasts of the semi-enclosed Irish and North Seas and the English Channel (Figure 3A). Importantly, however, the influence of offshore oceanic waves is strongly modified by coastal topography. The local shelter offered by headlands and islands much reduces wave action, and very enclosed areas such as firths, channels and sea lochs have very little wave action (Figure 3B). Wave fetch, the distance over which winds blow before reaching any piece of land, is a good predictor of wave height. Wind-generated waves follow well-understood physical laws, and wave heights and spectral characteristics (mixture of short-period and long-period waves) directly depend on the length of time that winds of specified velocities blow over the water surface. Even without including the more complex physics, simple indices of wave exposure have proven effective in predicting patterns in coastal ecosystems. Wave exposure indices range from relatively simple, such as a count of the number of sectors open to the sea (Baardseth, 1970) to complex, using a sum of wave fetch values in all directions open to the sea, and weighted by the incidence and average speed of winds from those directions from local meteorological data (Thomas, 1986). Fetch-only indices can perform as well as those including wind information, especially over areas where the wind pattern is relatively consistent (Burrows *et al*, 2008).

Here the measure of wave fetch produced during the MarClim project is used to establish the prevailing physical conditions at any given survey site, and derive expectations for the composition of the community at that site. The index is based on the minimum distance (km) to the nearest land in each of sixteen 22.5°angular sectors, up to a maximum of 200km per sector. Given the wide range of values around the UK, from 1 to 32,000km, it has been most appropriate to express these as log base 10 values from 0 to 4.5 (Figure 3B). The model has a spatial resolution of 200m, around the maximum extent of the average MarClim survey. Thus it is well matched to the effective averaging of abundance that the MarClim protocols achieve over that spatial scale.

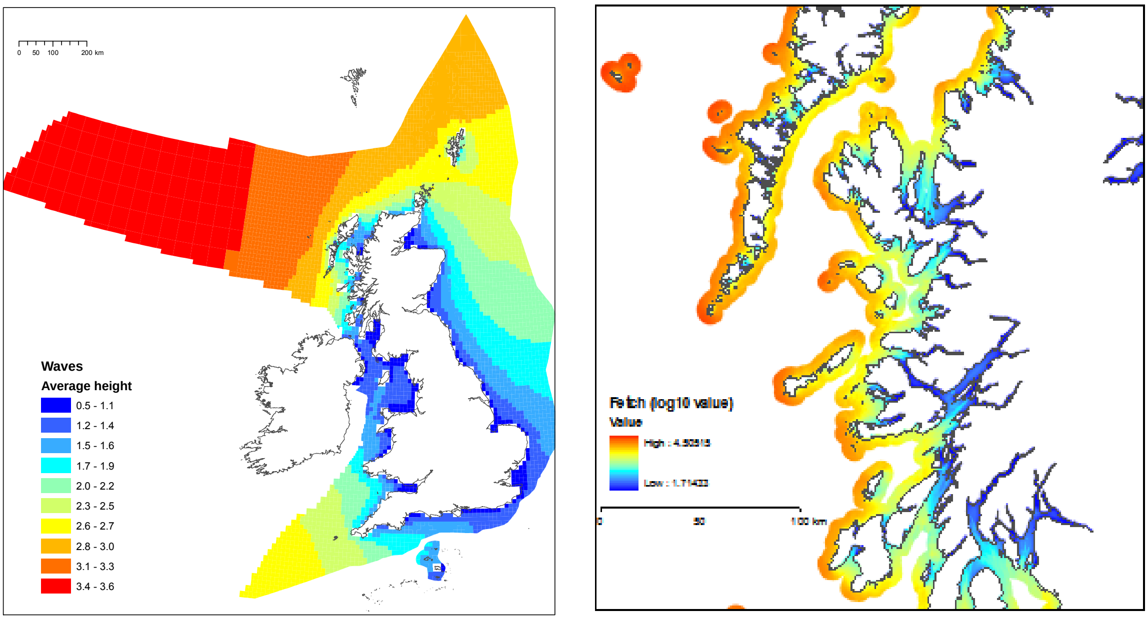


Figure 3. (A) Offshore wave height around the UK and (B) inshore wave exposure derived from wave fetch (<5km from the coast). Offshore wave height data has been obtained from the UK Atlas of Marine Renewables (ABP Marine Environmental Research Ltd, 2008), and patterns of inshore wave fetch from a model described in Burrows (2012).

1.5.4 Other factors: Tidal flow, tidal range, geology

Tidal flow is relatively high in regions of restricted flow between larger water masses, such as the connections between the North Atlantic and North Sea through the Pentland Firth and between Orkney and Shetland. Headlands also present barriers and cause flows to accelerate around them. Flows are also high at the mouth of macro-tidal estuaries such as the Bristol Channel and, to a lesser extent, the Solway Firth. A consequence of the latter effect is that there is a reasonably strong correlation between flow and wave exposure.

Effects of tidal flows on rocky shore species and communities are not well understood, although, where these are strong, greater flow may promote the growth of suspension feeders (Sanford *et al*, 1994; Leonard *et al*, 1998; Sanford and Menge, 2001) with consequential effects on community structure. Potentially, the more important effects of tidal flows on rocky shore communities may be indirect. Sediment transport is driven by tidal flows, with rapid flows generally associated with coarser sediment or no sediment at all. The high flows around estuaries and in general in the southern North Sea have a strong influence on the amount of suspended material in the water (Figure 4A, and see Figure 2B above), and this may have a stronger influence on attached animals and plants than the flow itself. Intertidal species are generally exposed to much greater flows and forces during breaking waves (Denny, 1988) than those exerted by the relatively gentle tidal flows.

Areas (microtidal) of locally restricted tidal ranges (with a spring tidal range of less than 1.0m such as in the Sound of Jura and in the area from Swanage to the Isle of Wight) contrast with macrotidal areas, such as the Bristol Channel and eastern Irish Sea. Reduced tidal ranges may result in less-available habitat for intertidal species, and potentially reduced diversity.

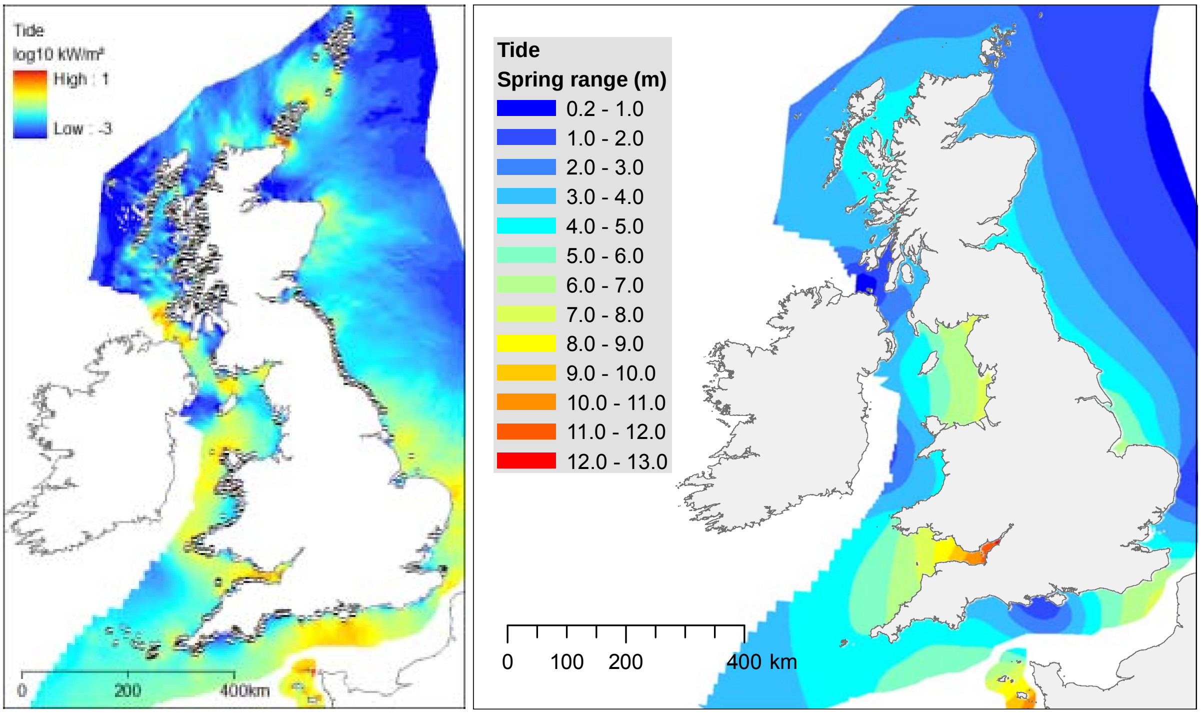


Figure 4. (A) Estimated tidal power at the seabed (kW/m^2) from a 1.8-km resolution model produced by the Proudman Oceanographic Laboratory, and (B) spring tidal range (m), taken from the UK Atlas of Marine Renewables (ABP Marine Environmental Research Ltd, 2008).

Rock type is not considered by rocky shore ecologists as a major driver of species distributions on bedrock and stable boulder shores. The exception is very soft rock such as chalk and shale (e.g. in Dorset) that does have a distinctly different biota, dominated by red algae and generally much reduced from that seen on hard rock in similar conditions due to higher erosion rates dislodging sessile species (Connor *et al*, 2004). The softness of the available rock may set distribution range limits in the English Channel since some species may not be able to colonise such substrata (Crisp and Southward, 1958; Herbert and Hawkins, 2006; Keith *et al*, 2011). Differences in community composition among different rock types from limestone ledges, conglomerates, granite and slate, for example, are less well documented but most likely reflect the differences in surface complexity and diversity of habitats (Frost *et al*, 2005). The reduction in available habitat for rocky shore species on sediment-dominated coasts, such as along eastern Irish Sea coasts of North Wales, Lancashire and Cumbria, and North Sea coasts from Kent to Flamborough Head, may further reduce the diversity of rocky shore species.

1.6 Community composition indicators

1.6.1 Building sets of indicator species

Trends in abundance of rocky shore species recorded by the MarClim project along UK environmental gradients were used as the basis for identifying candidate species for inclusion as indicators of community responses to climate change and eutrophication, and changes in wave exposure related to changes in storminess and invasive non-native species. These indicators lay the framework against which GES targets can be defined. The MarClim data are from all around the UK, but Shetland is not represented and coverage of the east coast of England is patchy.

This section of the report takes the descriptions of the important prevailing conditions outlined in Section 1.5 and demonstrates how these can be used to identify the drivers that determine the community composition of rocky intertidal habitats. Indicators of GES for rocky shores must reflect the responses of species distributions to variation in these primary drivers, resulting from both natural processes and anthropogenic pressures.

A version of the MarClim database produced in February 2009 was used to begin to select indicator species. This included 726 surveys conducted between 2002 and 2008 inclusive, with abundance data for 118 species and taxa. A filter was applied at the site level to remove any site surveys where less than 15 species were recorded. This usually indicated a partial survey due to bad weather/swell conditions, limited shore extent, time limitation or ad-hoc surveys that were additional to the core surveys and targeted only the core set of climate-sensitive species originally recorded by Southward and Crisp. A further reduction to the remaining set of 57 species recorded by all MarClim survey teams ensured that only those species for which data were available across the UK and Ireland were considered (see Appendix 1, Table A1for the core list of MarClim species).

The sensitivity of each species to temperature, water quality and wave exposure was evaluated as the trends emerging from a multiple regression analysis of abundance against three predictor variables. The response data analysed were the integer equivalent of the SACFOR score (Super-abundant=6, Abundant=5, Common=4, Frequent=3, Occasional=2, Rare=1 and Not Seen=0). The three predictor variables were:

1) February sea surface temperature (SST) average from 2000-2006 using the 9-km resolution data from the Pathfinder AVHRR satellite (obtained from the NASA Giovanni Data Portal (DAAC, 2008)), averaged across a 30km radius;
2) Estimated 9-km resolution data for chlorophyll *a* concentration from the NASA MODIS Aqua satellite sensor (NASA, 2009), averaged over the period from July 2002 to July 2012;
3) An index of wave fetch as a proxy for wave exposure[9] (Burrows *et al*, 2008).

Values for the three predictor variables for the location of each of the 726 surveys were extracted using a GIS (ArcGIS 9.3) using the values for the nearest raster grid cell.

Although linear regression of integer-equivalent SACFOR abundance scores provides reliable estimates of the relative sensitivity of each species, multinomial ordinal logistic regression is a statistically stronger approach to the analysis of data in ranked categories. The authors chose not to adopt this latter approach since it demands a larger quantity of data for robust parameter estimation than was available for the rarer or less frequently recorded species in the dataset. Regression parameters were successfully calculated for 55 of the reduced set of 57 taxa, the remaining two species being too rare to estimate regression parameters (Appendix 1: Table A1).

The slope values from these regressions were used to select species and taxa that were relatively sensitive to one predictor (temperature, chlorophyll *a* or wave exposure), but insensitive to the other two. The goal was to identify sets of species that were positively and negatively influenced by each predictor, and use the relative proportions of these positive and negative responders to build sensitive indices of the collective response of the community. By excluding those species that were sensitive to more than one predictor (such

[9] Wave fetch is the distance to the nearest land over a specified direction. Since wind waves increase in height with an increase in the distance over which the wind blows, the sum of wave fetch over all seaward directions gives a good indication of likely wave exposure for any coastal locality. The wave fetch index was calculated as the summed fetch over sixteen 22.5-degree angular sectors.

as wave fetch plus chlorophyll) as far as possible to avoid covariation, the indices should follow the patterns in the underlying predictors. This selection process did not reduce the power of the indicators to detect change. Conspicuous and relatively abundant species were desired too, so a minimum average abundance was also used as a selection criterion. The criteria used for species selection criteria for inclusion in each index are given in Appendix 2, Table A2.

1.6.2 Climate change indicator (CCI)

The Climate Change Indicator (CCI) for rocky shore communities is designed to measure the status of UK rocky shores in relation to climate. GES can only be considered in relation to any change in this indicator, due to the fact that Descriptor 1 of GES states that "*the quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*". The limits of change in this indicator which can be considered 'good' remain to be defined, but this would involve value judgement outside the scientific framework of assessment. Mitigation and management measures triggered by a change outside this range require further development. One possible approach would be to take the warm period of the 1950s as a baseline given the extensive data available for that period.

i. Species selection

The minimum temperature sensitivity for inclusion in the set of CCI species was at least one SACFOR category increase for every 2.5°C rise in February mean SST (Table A2). Species were also required to be insensitive to wave exposure: a species must change by less than one SAFCOR category per 1.7 orders of magnitude change in wave fetch (the full span of fetch values around the UK was three orders of magnitude: from 1.5 to 4.5), and to chlorophyll *a*: the maximum allowed sensitivity to chlorophyll *a* was one SACFOR category per 0.25 orders of magnitude change in chlorophyll *a* concentration. Average abundance was required to be at least 0.5 in integer SACFOR units; while low this value permitted inclusion of species present over only a limited proportion of the warmer parts of the UK coast.

Three northern cold-water species were selected using this approach:

Alaria esculenta	Dabberlocks
Semibalanus balanoides	Acorn barnacle
Littorina littorea	Common periwinkle

Twelve southern warm-water species were also selected;

Actinia equina	Beadlet anemone
Anemonia viridis	Snakelocks anemone
Chondrus crispus	Carrageen
Chthamalus montagui	Montague's barnacle
Melarhaphe *neritoides*	Small periwinkle
Bifurcaria bifurcata	Brown alga
Perforatus perforatus	A volcano barnacle
Patella depressa	Black footed limpet
Gibbula umbilicalis	Purple topshell
Phorcus (Osilinus) lineatus	Toothed topshell
Himanthalia elongata	Thongweed
Lichina pygmaea	Black lichen

The reason that more warm-water species were selected than cold-water ones reflects the fact that fewer species become more abundant in cooler waters around the UK, while many increase in abundance towards the south-west. The changes in the indicator are, as expected, driven mostly by changes in warm water species.

The MarClim approach is a species-level interpretation of changes on rocky shores in relation to climate. Selection of species for the initial MarClim surveys was not based on formal selection criteria, but was rather based on a general understanding of the climate sensitivity of a range of species, with species selected on the basis of their ease of assessment. Crisp and Southward (1958) chose the initial list, with subsequent modification by the MarClim team. The more conspicuous and community dominant species were added to the assessment to provide the ecological context for the abundance of the climate-sensitive species. For this CCI the MarClim species-level data has been used to produce a new metric of the status of the whole community, against which future change can be judged.

ii. Calculation from survey values

Table 2. A worked example of calculating the CCI from categorical abundance information (Super-abundant (SA) =6, Abundant (A) =5, Common (C) =4, Frequent (F) =3, Occasional (O) =2, Rare (R) =1 and Not Seen (NS) =0).

Climatic affinity	**Species**	**Clachtoll, NW Scotland 28/05/02 SACFOR**	**Numerical SACFOR score**	**Wembury, SW England 07/02/03 SACFOR**	**Numerical SACFOR score**
Northern	*Alaria esculenta*	NS	0	NS	0
Northern	*Semibalanus balanoides*	A	5	F	3
Northern	*Littorina littorea*	F	3	A	5
	Total		8 8/15 = 0.53		8 8/15 = 0.53
	Actinia equina	A	5	A	5
Southern	*Anemonia viridis*	NS	0	F	3
Southern	*Bifurcaria bifurcata*	NS	0	A	5
Southern	*Chondrus chrispus*	NS	0	F	3
Southern	*Chthamalus montagui*	A	5	C	5
Southern	*Gibbula umbilicalis*	C	4	A	5
	Lichina pygmaea	NS	0	C	3
Southern	*Melarhaphe neritoides*	NS	0	C	4
	Himanthalia elongata	C	3	A	5
Southern	*Osilinus lineatus*	NS	0	A	5
Southern	*Patella depressa*	NS	0	A	5
Southern	*Perforatus perforatus*	NS	0	A	5
	Total		4 17/60 = 0.29		39 53/60 = 0.89
	CCI		0.29/(0.29+0.53) **0.35**		0.89/(0.89+0.53) **0.62**

The CCI was derived as the ratio of the abundance of warm-water species, scaled to a maximum, to the total abundance of warm- and cold-water species, also scaled to their maximum abundance values (Equation 1). The scaled abundance of warm-water species was calculated as the sum of the abundance values for the 12 warm-water species divided by their potential maximum score (12 species x Abundant 5 = 60) at each survey site. Scaled abundance of cold-water species was derived similarly as the sum of abundance values divided by the maximum score (3 species x Abundant 5 = 15). The index was thus formed as the scaled abundance of warm-water species divided by the scaled abundances of warm- and cold-water species added together.

Equation 1

$$CCI = \frac{(\sum A/\sum A_{max})_{warm}}{((\sum A/\sum A_{max})_{warm} + (\sum A/\sum A_{max})_{cold})}$$

iii. Validation

Validation of the CCI was achieved by relating survey-site scores for the CCI to local average temperatures. The highest CCI values were obtained from MarClim data from surveys in south-west England and the Channel Islands, and the lowest values from parts of the Eastern Irish Sea, northern Scotland and the North Sea.

February SST (Figure 5) predicted CCI values satisfactorily (Figure 7: linear regression R^2 = 0.44, correlation r = 0.66; Regression equation CCI = -0.800 + 0.1498 × February SST), but November SST (Figure 6) performed better as a predictor of the CCI values (Figure 8: linear regression R^2 = 0.57, correlation r = 0.76; Regression equation CCI = -1.507 + 0.1557 × November SST). The strength of these relationships is given by the R^2 values of the regressions. This varies between 0 for no association and 1 for a perfect prediction of the response by the independent variables, in this case February and November SST. The regression equation describes the form of the relationship, for example, the estimated CCI value is equal to the November SST multiplied by 0.1577 and minus 1.507.

A more-robust approach to the regression of an index constrained between 0 and 1 is through logit transformation of the index (log(x/(1-x)), since simple linear regression permits prediction of impossible index values below 0 and above 1 towards and beyond the extremes of February SST. This analysis was carried out and is presented in Figure 7 (see curved line in Figure 7). This analysis is merely a better approach to the description of the relationship between CCI and temperature, and not a modification of the index itself.

The plots (Figure 7 and Figure 8) below show the strength of the relationships between the CCI and local SST in February and November. The trend in CCI values is well indicated by November temperatures. Variation around the trend lines is produced by variation in abundance of the warm-water or cold-water species, either not related to temperature and due perhaps to variation in habitat availability or the variable status of local populations, or due to some local microclimatic influences such as variation in local air temperature. Variation around predicted trend lines is entirely expected for any statistical relationship, particularly involving community assemblage data.

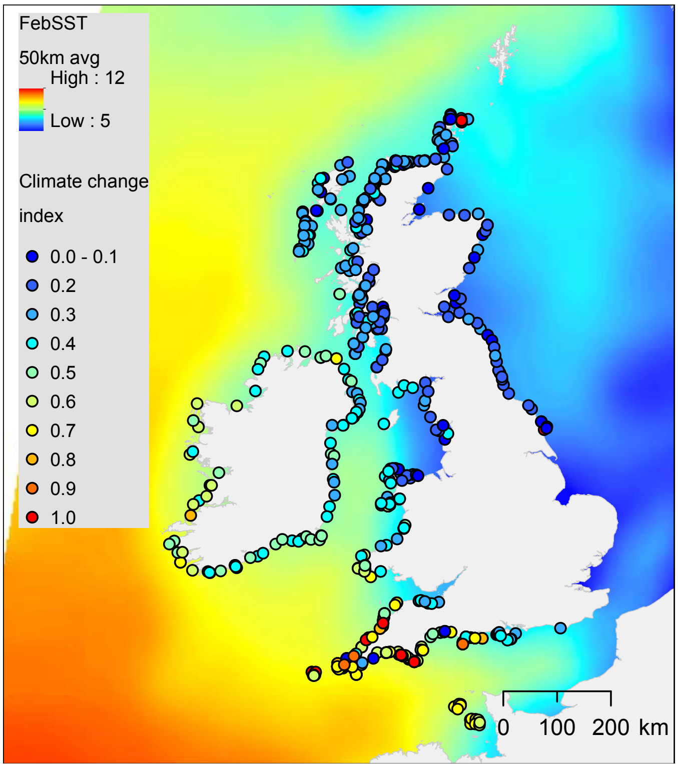


Figure 5. Distribution of Climate Change Index (CCI) values around the UK and February sea surface temperature (SST) (Pathfinder AVHRR) averaged over a 50-km radius for the years 2000 to 2006, inclusive.

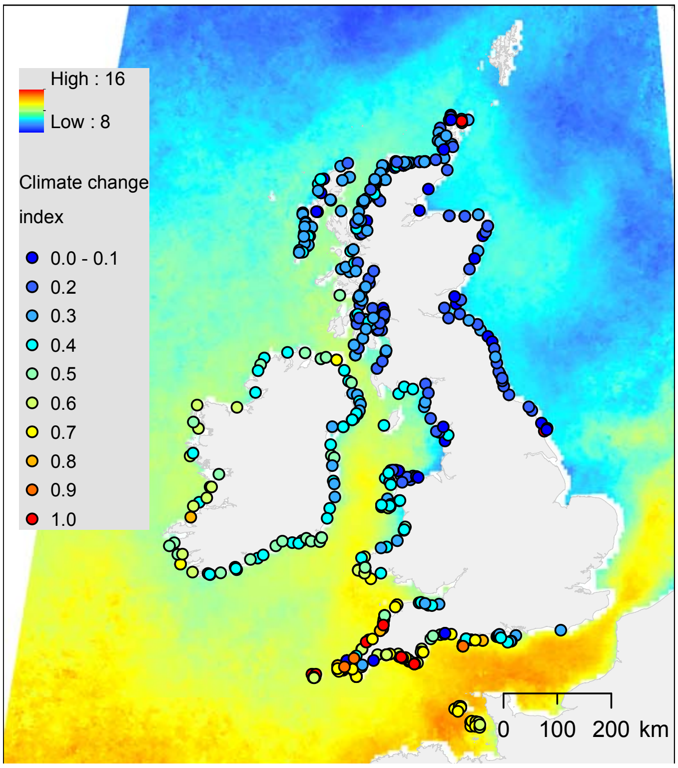


Figure 6. Distribution of Climate Change Index (CCI) values around the UK and average November sea surface temperature (SST) (Pathfinder AVHRR) for the period 2000 to 2006 inclusive.

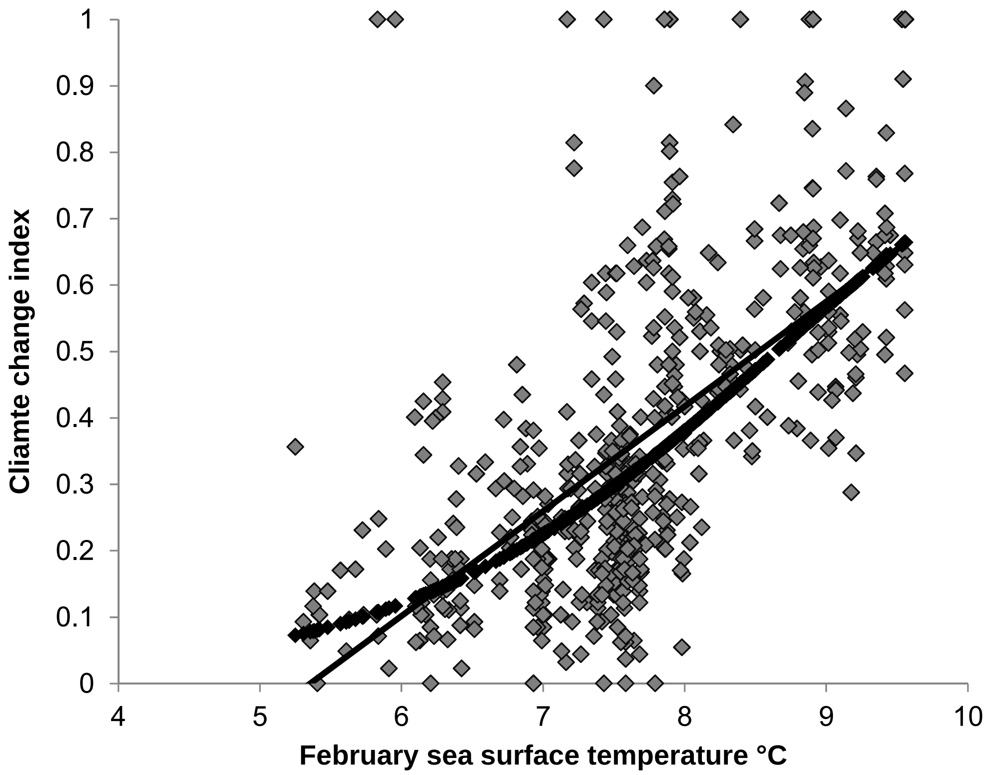


Figure 7. Climate Change Index (CCI) values around the UK plotted against February sea surface temperature (SST). The solid line shows the linear regression line while solid symbols show the fitted regression to the logit-transformed CCI.

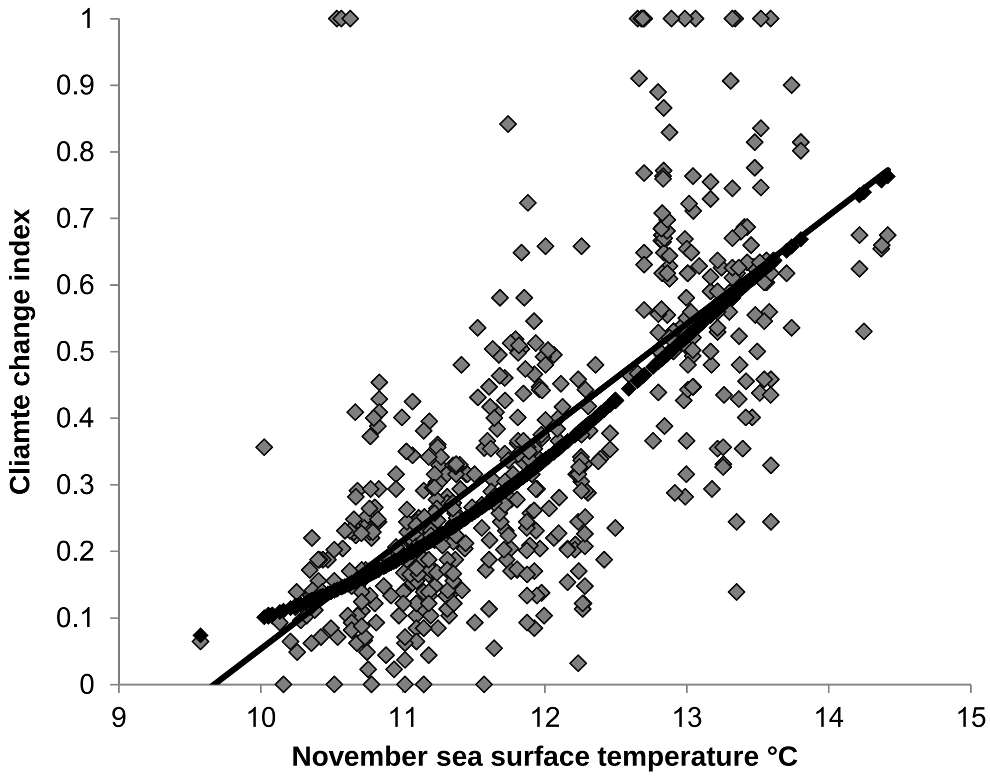


Figure 8. Climate Change Index (CCI) values around the UK plotted against November sea surface temperature (SST). The solid line shows the linear regression line while solid symbols show the fitted regression to the logit-transformed CCI.

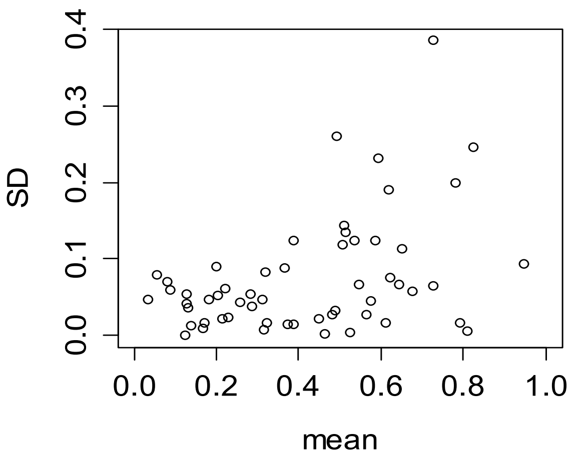


Figure 9. Variability in Climate Change Index (CCI) values from repeated MarClim surveys plotted against the mean CCI values for individual sites. Most sites were visited at least twice (37 sites were visited twice, 11 sites three times, one site four times and two sites five times; SD = standard deviation).

Repeatability and variability in CCI values can be assessed by considering the standard deviation (SD) of the mean CCI for each site from repeated visits. Fifty-one sites were visited at least twice from 2002 to 2009. The average SD of the site mean CCI was 0.076, and the average standard error (SD / √ times visited) was 0.050. If CCI values follow the normal distribution, this means that 68% of observations will be within one SD of the mean. Variability is higher for high to intermediate CCI values, suggesting that the CCI may be better able to detect changes at lower CCI values, that is, in colder northern areas of the UK (Figure 9). The arrival of warm-water species at northern sites is likely to trigger increases in CCI values, and these increases will be detected, given the lower variability in CCI at these low levels.

1.6.3 Water Quality Indicator (WQI)

i. Species selection

For the Water Quality Indicator (WQI), the approach used for CCI was also used here. Two groups of species that were especially sensitive to chlorophyll *a* concentrations, either negatively or positively were selected. A minimum sensitivity to chlorophyll *a* was set at one SACFOR category per order of magnitude change in chlorophyll *a* concentration (see Appendix 2, Table A2). Maximum sensitivities to February SST and wave fetch were set at one SACFOR change per 1.25°C and per order of magnitude change in wave fetch.

Ten species were selected as negatively influenced by chlorophyll *a* concentrations (‘Low chlorophyll *a*’ species):

Alaria esculenta	Dabberlocks
Fucus serratus	Serrated wrack
Halichondria panicea	Breadcrumb sponge
Halidrys siliquosa	Sea-oak (an alga)
Himanthalia elongata	Thongweed
Laminaria digitata	Kelp
Nucella lapillus	Dogwhelk
Patella vulgata	Common limpet
Pelvetia canaliculata	Channel wrack
Semibalanus balanoides	Acorn barnacle

Four species were chosen as ‘High chlorophyll *a*’ species:

Anemonia viridis	Snakelocks anemone
Chondrus crispus	Irish moss, Carrageen
Austrominius modestus	Australasian barnacle
Littorina littorea	Common periwinkle

While *Austrominius modestus* is a non-native species, its distribution is now well established and is no longer expanding. It is a particularly good indicator of high sediment load environments, and adds considerably to the index in terms of being able to detect the impacts of changes in water quality.

This selection of species is a much smaller set compared to that for the WFDMT (Table 3), which uses a set of 70 species comprising largely filamentous macroalgae (the Reduced Species List or RSL). The proposed WQI uses a balanced number of animals (7) and plants (7). More species responded negatively than positively to increases in chlorophyll *a* concentrations, in line with the general expectations of impoverished marine communities in areas of poor water quality. This general pattern was also reflected in the diversity of intertidal species in the MarClim dataset, and is used as the basis for further diversity-based indices (see Section 1.7).

ii. Calculation from survey values

As with the climate change indicator, the WQI was derived as the ratio of the abundance of high chlorophyll *a* species, scaled to a maximum, to the combined scaled abundance of low and high chlorophyll *a* species (Equation 2).

Equation 2

$$WQI = \frac{(\sum A/\sum A_{max})_{hichla}}{((\sum A/\sum A_{max})_{lochla}+(\sum A/\sum A_{max})_{hichla})}$$

iii. Validation

High WQI values (>0.7) were obtained from MarClim surveys in the Irish Sea, especially along the Cumbrian and Lancashire coasts, in Cardigan Bay and in the Bristol Channel. The Clyde Sea and Firth of Forth also had shores with high WQI values (Figure 10). Low WQI values (<0.3) were calculated from surveys along the north and west coasts of Scotland, including Orkney. This pattern reflects the underlying distribution of $\log_{10}$ chlorophyll *a* concentrations: high chlorophyll occurs in the Irish Sea and at the mouth of muddy estuaries, while clearer, bluer waters with low chlorophyll content are found along the remote coasts of the far north of Scotland. Thus, more algae (abundance and diversity) tend to be found in clearer waters, and less in areas of high light attenuation.

The relationship between WQI values and $\log_{10}$ chlorophyll *a* concentrations was moderately strong (Figure 11: linear regression $R^2 = 0.45$, correlation $r = 0.59$; Regression equation WQI = -0.2463 + 0.5496 × log10 chlorophyll *a* concentration (mg/m^3). The R^2 value of 0.45 indicates that 45% of the variation in the WQI index is explained by variation in the logarithm to base 10 ($\log_{10}$) of the estimated chlorophyll *a* concentration from ocean colour sensing satellites. Scatter around the trendline is most likely due to habitat availability and natural variability in the abundance of the species making up the index. This degree of scatter is to be expected from ecological data.

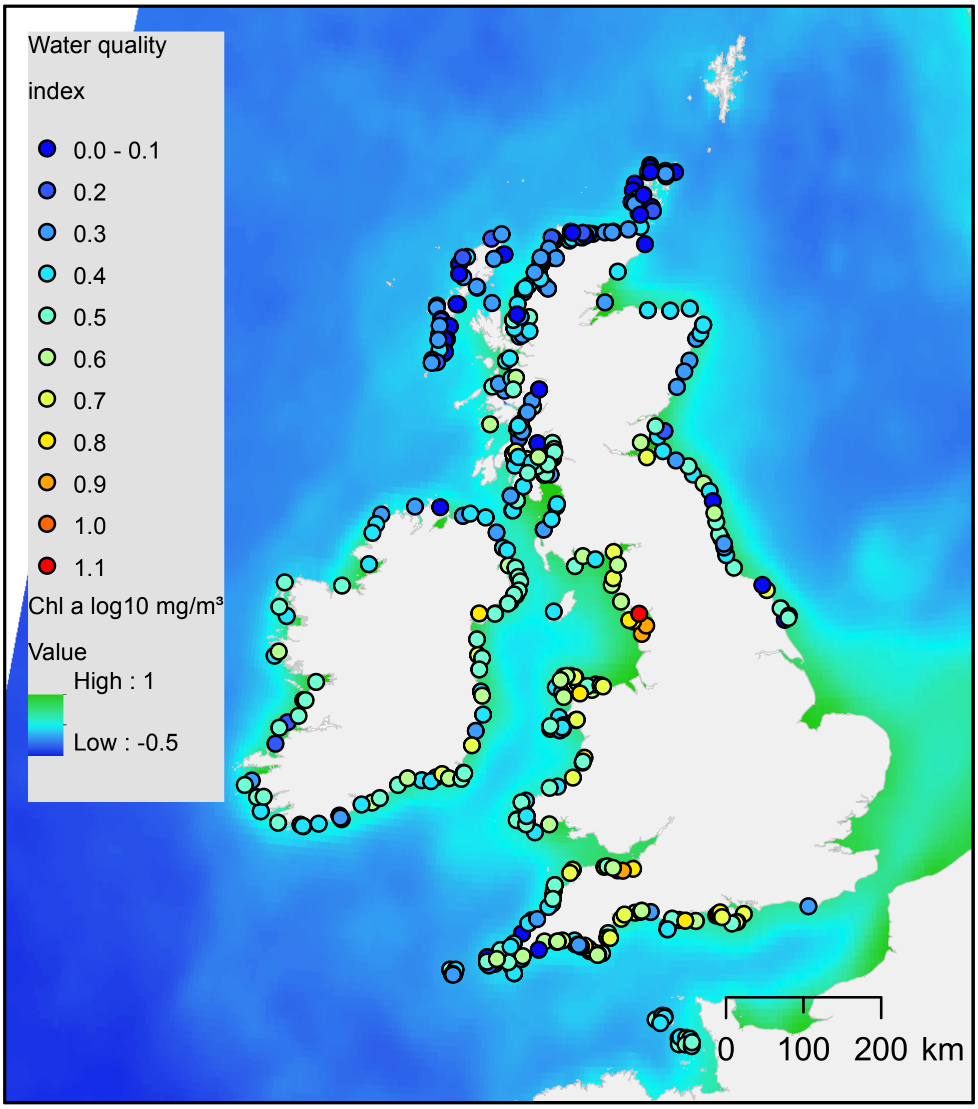


Figure 10. Distribution of WQI values around the UK and $\log_{10}$ chlorophyll *a* concentration (Chl a log10 mg/m^3) from MODIS-Aqua data averaged over every month from July 2002 to July 2012.

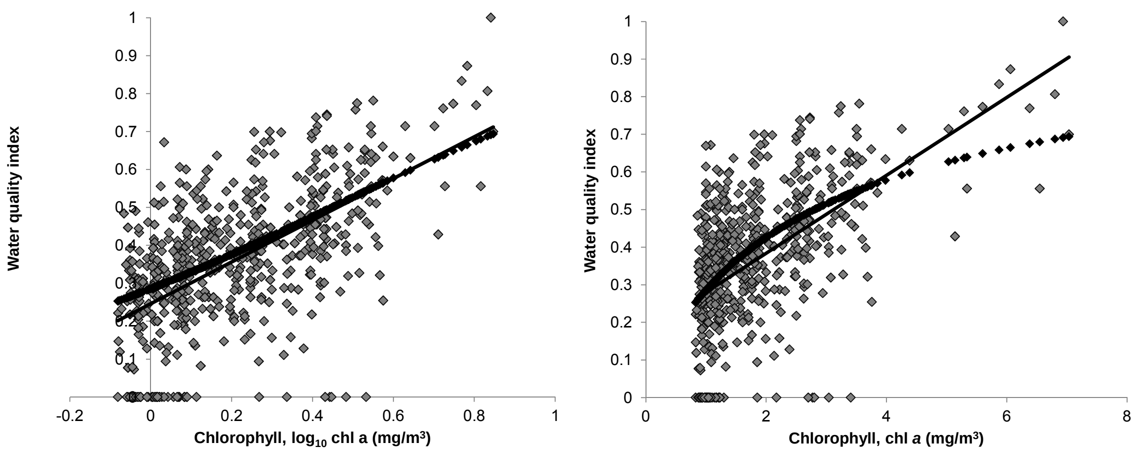


Figure 11. WQI values related to local $\log_{10}$ chlorophyll *a* concentration on logarithmic (left) and linear (right) scales.

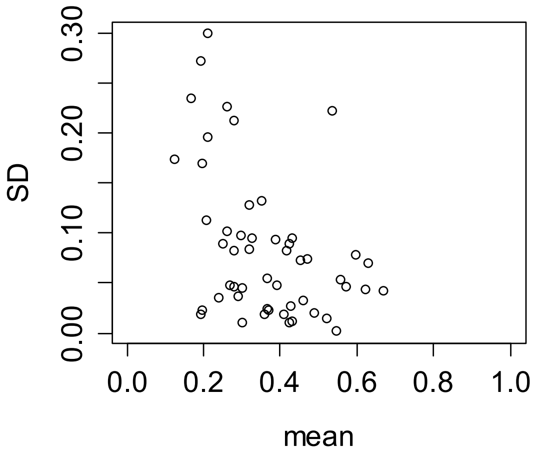


Figure 12. Variability in Water Quality Index (WQI) values from repeated MarClim surveys, expressed as the standard deviation (SD) plotted against the mean WQI values for individual sites.

As for the CCI index, variability and repeatability in WQI can be assessed by considering the standard deviation (SD) and standard error (SE) of WQI values achieved by repeated visits to the same sites. Variability was similar to that for the CCI (SD 0.085, SE 0.055). The standard deviation declined with increasing WQI values (Figure 12), suggesting that the power of WQI to detect change will be higher in poorer water quality areas.

iv. Comparison of the WQI with the WFD Macroalgal Tool (WFDMT)

The WFDMT is presently used to judge Good Ecological Status (GEcS) for rocky shores. To compare with the proposed WQI, WFDMT data was obtained from the Environment Agency environmental data portal[10] and analysed in a similar way to WQI data (Figure 13). The data available were from south-west England and Wales, and from the Cumbrian coast and north-east England, covering 32 sites (but with one missing spatial information) surveyed in the summers of 2007 and 2008.

In areas of good water quality with estimated $\log_{10}$ chlorophyll *a* concentrations less than 0.6 (south-west Britain, <4mg/m^3), the WFDMT was relatively insensitive to changes in chlorophyll *a*. In areas of poor water quality ($\log_{10}$ chlorophyll > 0.6, >4mg/m^3), the WFDMT declined sharply with increasing estimated chlorophyll *a*, with only 20 out of 70 species on the Reduced Species List (RSL) found at the one WFD site where estimated chlorophyll *a* exceeded 10mg/m^3 (Maryport in Cumbria). This latter site is most likely to be strongly influenced by suspended sediment in the Solway Firth. The WFDMT therefore works well, especially at higher estimated chlorophyll levels (and probably high sediment loads). More research establishing the link between measured cholorophyll in inshore waters and the composition of rocky shore communities may reveal more localised effects in near coastal areas where satellites may be less able to effectively measure chlorophyll.

The strength of the relationship between the WQI and water quality (R^2=0.45) is similar to that between the WFDMT and water quality (R^2=0.48) over the whole range of chlorophyll *a* values. However, the WQI appears to perform worse than the WFDMT in poor water quality, albeit based on the performance of the latter at just a few (5-6) sites below a quality threshold. This suggests that the WFDMT may be a better option for highly impacted areas than the WQI index, though a more-thorough analysis of the WFDMT data from more low- and high-quality sites and using validated chlorophyll data from inshore sites is needed before this can be definitively concluded.

[10] http://www.geostore.com/environment-agency/WebStore?xml=environment-agency/xml/ogcDataDownload.xml

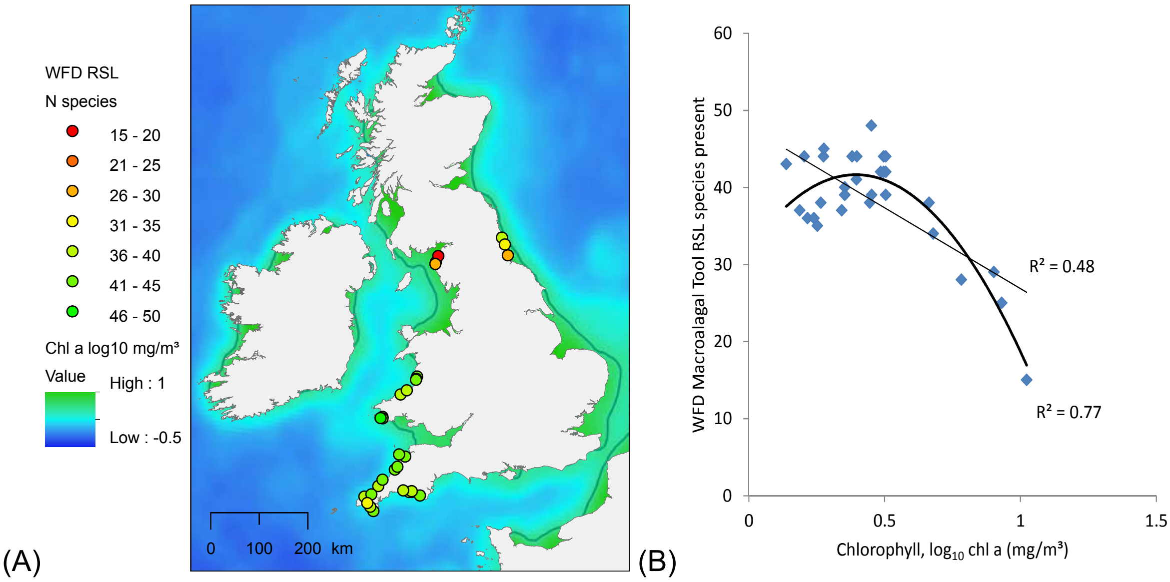


Figure 13. Water Framework Directive Reduced Species List (WFD RSL) values based on the number of species recorded out of a total of 70 possible species on the RSL. (A) The location of UK sites surveyed in 2007 and 2008, laid over estimated chlorophyll *a* concentrations and (B) related to local $\log_{10}$ chlorophyll *a* concentration. The line on the map in (A) shows the 4mg/m^3 contour for chlorophyll *a* concentration ($\log_{10}$ chl *a* mg/m^3 = 0.6)

Comparison of Figure 11 and Figure 13 demonstrates that the WQI continues to respond to changes in water quality above the <4mg/m^3 threshold, while the WFDMT is unresponsive. This suggests that the MarClim WQI is more useful than the WFDMT in areas outside the 4mg/m^3 contour (Figure 13A): the Channel coast, South-West England and Wales, excluding the Bristol Channel, West, North and North-East Scotland. The WFDMT may be more useful (if the limited data are representative) in areas including the Bristol Channel, the Irish and Clyde Seas, the Moray Firth and large parts of the East coast of England.

Ultimately, the choice between the WQI and the WFDMT may depend on several factors. The WQI can be derived from data collected for multiple indices, as proposed in this report, and relies on a lesser taxonomic skill level than the WFDMT requires. The WQI species are large, conspicuous animals and plants that do not require microscopic examination to be reliably and confidently identified. The MarClim species are all identifiable in the field and several sites can be effectively surveyed in a single low tide, provided that the sites are reasonably close together.

The sparse WFDMT data suggests that this approach offers greater sensitivity than WQI in poor water-quality areas, but at the cost of expensive taxonomic training for the surveyors and carrying the need for specialist specimen examination equipment. This additional cost will not be problematic where trained surveyors are available.

The differences between the two indices largely relate to their provenance as (i) detectors of large scale biogeographical patterns (MarClim-derived WQI), and (ii) indicators of local-scale poor water quality (WFDMT). GES for the MSFD demands an understanding of both these issues, and the ultimate choice will be down to available resources (MarClim indicators may be cheaper to monitor) and the goal of the indicator (the WFDMT may perform better in heavily impacted areas). The broader issues of defining GES for the MSFD are discussed in more detail in Section 1.9.

Table 3. Species selected for the Water Quality Indicator (WQI), alongside those on the the Water Framework Directive Macroalgal Tool Reduced Species List (WFDMT RSL), showing species common to both lists in bold, and the frequency with which species were recorded for MarClim and recorded as present for 32 WFD surveys in 2007 and 2008.

WQI species	(1: on WFD list, 0 WQI/MD only)		**WFD Reduced Species List**	(1: on WQI list, 0 WFD only)				
Low chlorophyll species	*			*	Present (n=32)		*	P
Alaria esculenta	0	Dabberlocks	*Ceramium nodulosum*	0	31	*Chaetomorpha mediterranea*	0	16
Fucus serratus	1	Serrated wrack	***Chondrus crispus***	1	31	*Catenella caespitosa*	0	15
Halichondria panicea	0	Breadcrumb sponge	*Enteromorpha* spp.	0	31	*Plocamium cartilagineum*	0	15
Halidrys siliquosa	1	Sea-oak (an alga)	***Fucus serratus***	1	31	*Dilsea carnosa*	0	14
Himanthalia elongata	1	Thongweed	***Fucus vesiculosus***	1	31	*Ectocarpus* spp.	0	14
Laminaria digitata	1	Kelp	*Ulva lactuca*	0	31	*Membranoptera alata*	0	14
Nucella lapillus	0	Dogwhelk	*Elachista fucicola*	0	30	***Pelvetia canaliculata***	1	14
Patella vulgata	0	Common limpet	***Fucus spiralis***	1	30	*Chaetomorpha melagonium*	0	13
Pelvetia canaliculata	1	Channel wrack	*Calcareous encrusters*	0	29	*Cystoclonium purpureum*	0	13
Semibalanus balanoides	0	Acorn barnacle	*Corallina officinalis*	0	29	***Halidrys siliquosa***	1	13
High chlorophyll species			***Mastocarpus stellatus***	1	29	*Polysiphonia lanosa*	0	13
Anemonia viridis	0	Snakelocks anemone	*Palmaria palmata*	0	29	*Dumontia contorta*	0	12
Chondrus crispus	1	Irish moss, Carrageen	*Laminaria digitata*	0	28	***Laminaria saccharina***	1	12
			Cladostephus spongious	0	26	*Polyides rotundus*	0	12
Marclim macroalgal diversity species	*	Recorded (n=726)	*Rhodothamniella floridula*	0	26	*Rhodomela confervoides*	0	11
Fucus vesiculosus	1	638	*Lomentaria articulata*	0	25	*Ceramium shuttleworthanium*	0	9
Pelvetia canaliculata	1	635	*Osmundea hybrida*	0	25	*Plumaria plumosa*	0	9
Fucus serratus	1	626	*Polysiphonia fucoides*	0	25	*Scytosiphon lomentaria*	0	9
Fucus spiralis	1	623	*Hildenbrandia rubra*	0	24	*Hypoglossum hypoglossoides*	0	8
Ascophyllum nodosum	1	607	*Osmundea pinnatifida*	0	24	***Himanthalia elongata***	1	7
Lichina pygmaea	0	607	*Ralfsia* spp.	0	24	*Chorda filum*	0	6
Halidrys siliquosa	1	595	*Blidingia* spp.	0	23	*Gracilaria gracilis*	0	6
Laminaria saccharina	1	593	*Ceramium* spp.	0	23	*Leathesia difformis*	0	6
Mastocarpus stellatus	1	592	*Cladophora rupestris*	0	23	*Saccorhiza polyschides*	0	6
Himanthalia elongata	1	588	*Cryptopleura ramosa*	0	23	*Halurus equisetifolius*	0	5
Alaria esculenta	0	580	*Gelidium* spp.	0	23	*Furcellaria lumbricalis*	0	4
Chondrus crispus	1	562	*Porphyra umbilicalis*	0	23	*Halurus flosculosus*	0	4
Laminaria hyperborea	1	508	*Aglaothamnion/callithamnion* spp.	0	20	*Phyllophora* spp.	0	4
Codium spp.	0	423	*Polysiphonia* spp.	0	20	*Gastroclonium ovatum*	0	3
Fucus distichus	0	375	*Ahnfeltia plicata*	0	19	*Heterosiphonia plumosa*	0	3
Sargassum muticum	0	351	*Cladophora sericea*	0	19	*Asperococcus fistulosus*	0	2
Bifurcaria bifurcata	0	335	*Dictyota dichotoma*	0	19	*Bryopsis plumosa*	0	2
Cystoseira spp.	0	332	*Pilayella littoralis*	0	19	***Laminaria hyperborea***	1	2
Laminaria ochreoleuca	0	310	*Erythrotrichia carnea*	0	18	*Dictyosiphon foeniculaceus*	0	1
Fucus indeterminate	0	181	*Ascophyllum nodosum*	1	17	*Nemalion helminthoides*	0	1

1.6.4 Wave Exposure Indicator (WXI)

i. Species selection

Two groups of species were selected as being sensitive to wave exposure either negatively or positively, yet relatively insensitive to chlorophyll *a* concentration and February SST. A minimum sensitivity to wave exposure was set at 0.35, being the change in average integer SACFOR category per order of magnitude change in summed wave fetch (see Appendix 2, Table A2). Maximum sensitivities to February SST and chlorophyll *a* were set at one SACFOR change per 1°C and 5 SACFOR categories per order of magnitude change in chlorophyll *a* concentrations.

Five sheltered-shore species were selected:

Ascophyllum nodosum
Fucus spiralis
Fucus vesiculosus
Littorina littorea
Pelvetia canaliculata

Eight exposed-shore species were selected:

Actinia equina
Alaria esculenta
Bifurcaria bifurcata
Himanthalia elongata
Laminaria digitata
Mastocarpus stellatus
Patella depressa
Sargassum muticum

Most species selected are ubiquitous in the UK, but two exposed shore species are restricted to the south and west coasts (*Patella depressa* and *Bifurcaria bifurcata*) and one is an invasive species (*Sargassum muticum*) that is prevalent in rockpools on exposed shores. The distributions of the other species are, however, also mildly influenced by temperature along UK gradients (see Appendix 2, Table A2), with most of the exposed shore species increasing with temperature (*Actinia equina, Himanthalia elongata, Mastocarpus stellatus* and potentially leading to confounded associations of exposed shore species with warmer temperatures, as may be the case with *H. elongata*) and only *Alaria esculenta* increasing in colder temperatures. All of the sheltered shore species are negatively related to temperature, being more abundant in cooler February SST. The exposed low shore macroalgae included are also negatively affected by increased chlorophyll *a* concentrations. The consequence of the sensitivity to more than one factor is that the response of this index to local wave conditions is modified by the prevailing temperatures and water quality in whichever region is considered. This modification of the community response to wave exposure has long been recognised, particularly by Ballantine (1961) who proposed biologically defined wave exposure indices for shores that were modified at different latitudes.

ii. Calculation from survey values

The calculation was similar to the climate change (CCI) and water quality (WQI) indices. The Wave Exposure Indicator (WXI) was derived as the ratio of the abundance of exposed shore species, scaled to a maximum, to the combined scaled abundance of exposed and sheltered shore species (Equation 3).

Equation 3

$$WXI = \frac{(\sum A/\sum A_{max})_{exposed}}{\left((\sum A/\sum A_{max})_{exposed} + (\sum A/\sum A_{max})_{sheltered}\right)}$$

iii. Validation

The relationship between WXI values and $\log_{10}$ wave fetch in km was not as strong as for the other two indices (CCI & WQI) and their predictors (Figure 14: linear regression R^2 = 0.24, correlation r = 0.49; Regression equation WXI = 0.1584 + 0.1779 × $\log_{10}$ wave fetch (km)). The relatively weak nature of this relationship at a UK scale is most likely due to the modifying influence of temperature and water quality on the abundance of the major indicator species. This is evident when comparing the outcome of this analysis with a similar exercise on a regional subset of these data (Burrows *et al* 2008) which resulted in a much stronger relationship between wave exposure and indices of rocky shore community structure (R^2 = 0.53). With wave-exposure indicator species varying with factors other than wave exposure, the reduction in strength of the relationship between WXI and wave fetch at a UK scale is not surprising.

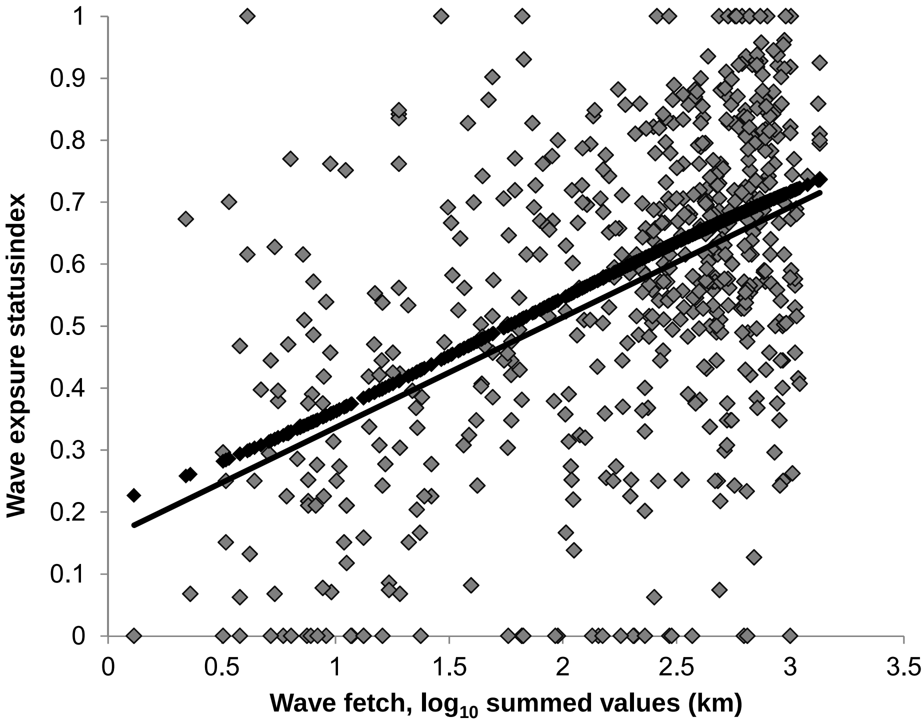


Figure 14. UK Wave Exposure Index (WXI) values related to local $\log_{10}$ wave fetch.

WXI values varied on a much more local scale than the CCI and WQI (Figure 15), as expected from the patterns of wave exposure around the coasts (Figure 3B). Exposed headlands are often in close proximity to sheltered inlets and embayments, especially on complex coastlines such as the West coast of Scotland.

As with the CCI and WQI, repeated MarClim surveys of the same sites give an estimation of the repeatability of the WXI index, yielding similar estimates of standard deviation and standard error to the other two indices (SD 0.098, SE 0.065). Some larger values for SD were obtained (>0.1) but there was no trend towards higher SDs in either exposed or sheltered shore data (Figure 16).

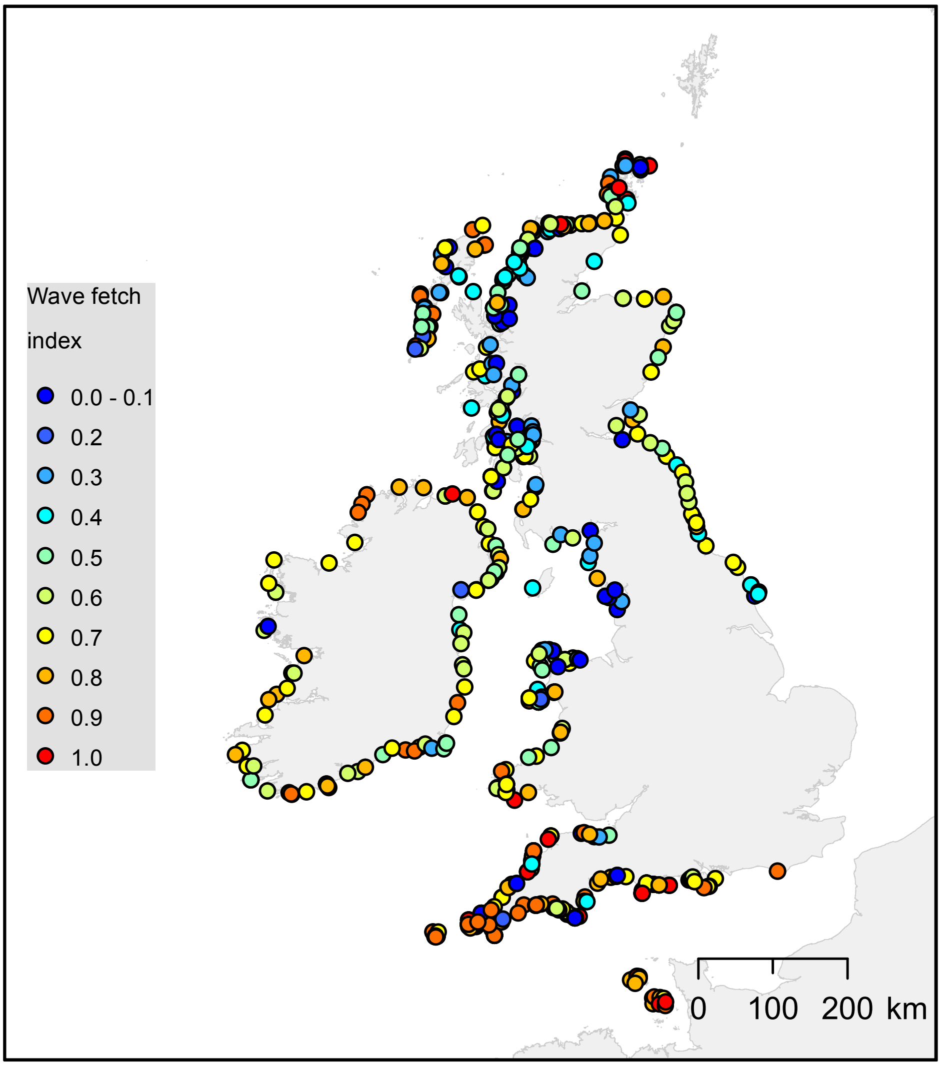


Figure 15. Distribution of Wave Exposure Index (WXI) values around the UK and $\log_{10}$ wave fetch.

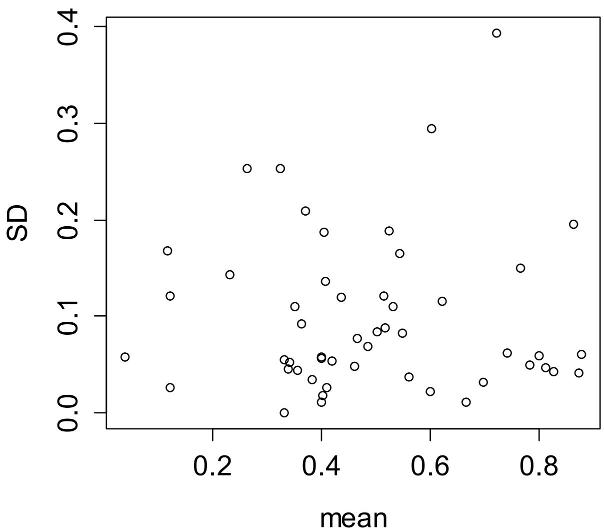


Figure 16. Variability in Wave Exposure Index (WXI) values from repeated MarClim surveys, expressed as the standard deviation plotted against the mean WXI values for individual sites.

WXI values establish the wave-exposed nature of the community at the site. As the wave-exposure indicator may be less sensitive to change than the CCI or WQI, as suggested by the weaker relationship between the WXI and the primary driver of spatial variation in wave fetch, and the confounding influence of temperature and water quality, it may be less relevant to GES than the other two indicators. Changes in the wave-exposed nature of rocky shore communities has rarely been demonstrated, but may be expected as a result of changes in wind patterns associated with climate change (Davies and Johnson, 2006). This indicator may have greater long-term relevance, especially given plans for major wave energy farms around British coasts and the consequent modification of the inshore wave climate and potential knock-on impacts for GES.

In summary, the difficulties in constructing an index that is sufficiently robust to regional variations in indicator species and that retains a strong relationship with variation in wave exposure means that the WXI is not likely to be useful for the MSFD. The data required to calculate this index will be needed for the other indicators, and so the index will be able to be evaluated at a future date if this approach is adopted.

1.6.5 Non-native Species Indicator (NNI)

The MarClim project currently records the abundance and distribution of 12 invasive species. Two indicators are proposed: (1) the relative abundance of invasive species compared to native species; and (2) the number of invasive species compared to the number of native species. These indicators will provide information on whether arrival of, and numbers of invasive species in a community increase, decrease, or have no effect on the native biodiversity and alpha diversity of a community.

i. Relative abundance of invasive species compared to native species

This index is calculated as:

Equation 4

$$NNI_A = \frac{\sum A_{invasive}}{(\sum A_{invasive} + \sum A_{native})}$$

The numerator is the sum of the abundance (numerical SACFOR category for all invasive species where Not Seen = 0 to Abundant = 5) and the denominator comprises the sum of the abundance of invasive species plus the sum of the abundance of native species (Equation 4).

ii. Relative number of invasive species compared to native species

The other index is the number of invasive species compared to the number of native species. Here the number of invasive species present is divided by the total of the number of invasive species added to the number of native indicator species usually present in that habitat (Equation 5).

Equation 5

$$NNI_P = \frac{N_{invasives}}{(N_{invasives} + N_{natives})}$$

iii. Species Selection

The species list for these indicators is again drawn from the MarClim list. Invasive species were selected for inclusion in the MarClim list based on the foci species identified in the UK Marine Aliens Project[11]. Three habitats within rocky intertidal systems are suggested for application of these invasive indicators as most invasive species are habitat specific: Rock pools, Open Rock and Kelp Zone.

<u>Rockpools</u>

Invasive species:

Sargassum Bactrophycus muticum	Wireweed
Asparagopsis armata	Harpoon weed
Grateloupia turuturu	Devil's tongue weed

Native species:

Bifurcaria bifurcata	Brown alga
Fucus serratus	Serrated wrack
Halidrys siliquosa	Sea oak
Cystoseira spp.	Chain bladder
Himanthalia elongata	Thongweed

<u>Open Rock</u>

Invasive species:

Austrominius modestus	Australasian barnacle
Crassostrea gigas	Pacific oyster
Crepidula fornicata	Slipper limpet
Corella eumyota	Orange tipped sea squirt

Native species:

Chthamalus montagui	Montagu's barnacle
Chthamalus stellatus	Poli's stellate barnacle
Semibalanus balanoides	Acorn barnacle
Mytilus spp.	Blue mussel
Patella vulgata	Common limpet
Patella depressa	Black footed limpet

<u>Kelp Zone</u>

Invasive species:

Undaria pinnatifida	Wakame

Native species:

Laminaria digitata	Oarweed
Laminaria hyperborea	Cuvie
Laminaria ochroleucha	Devil's Apron
Saccharina latissima	Sugar kelp
Saccorhiza polyschides	Furbellow
Alaria esculenta	Dabberlocks

[11] http://www.marlin.ac.uk/marine_aliens/

iv. Validation

Validation for either of the non-native species indicators has not been attempted as yet, but data collected for validation in 2013 will feed into the next phase of the work on developing these indicators further.

1.6.6 Boulder-turning indicator

Boulder turning is an activity associated with the collection of bait ('peeler' crabs of the species *Carcinus maenas*) and the harvest of some intertidal species (winkles of the species *Littorina littorea* and the edible crab *Cancer pagurus*). The intensity of this activity impinges on the status of Descriptors 1 ("*Biological diversity is maintained*"), 3 ("*Populations of all commercially exploited fish and shellfish species are within safe biological limits*") and 6 ("*Seafloor integrity is....not adversely affected*") of the MSFD, and it is therefore important to consider an indicator which addresses these impacts. The GES of intertidal rocky habitats in regard to this pressure is currently not monitored on a large scale in the UK.

The boulder-turning index developed by Morris *et al* (2012) for the Countryside Council for Wales (CCW, now Natural Resources Wales, NRW) is currently the only available tool for assessing the impact of boulder turning on rocky shore communities. The NRW 'boulder turning index' was developed as a method for rapid assessment of the intensity of boulder turning activities that required only limited ecological expertise (Morris *et al*, 2012). The assessment involved two types of survey: (1) a visual assessment of the number of bait collectors and their methodology over a fixed time period and (2) an in-situ transect assessment of previous boulder turning activity. In this Section, the boulder-turning assessment method is presented, its utility evaluated and, alternatives considered given the recognised limitations of the approach.

i. The NRW boulder-turning assessment method

The assessment of bait collection effort by NRW was carried out by driving along the length of the area of coastline selected for the survey and stopping at each pre-selected site to record the number of collectors at each site on the same tide. On a separate day the boulder turning surveys were carried out at the same sites.

Site location was selected with a start point at an easily recognizable and re-locatable boulder in the middle of the lower eulittoral zone of the intertidal area. Twenty metres of tape was laid out from the start point parallel to the waterline running horizontally along the lower eulittoral zone. Each boulder within two metres either side of the transect was scored using the methodology outlined below. The latitude/longitude of the start point, the date, time and surveyor were recorded. The transect was also photographed in its entirety. Three horizontal transects were surveyed at each site.

Suitable boulders for surveying along the transect were defined as boulders that have the potential to be turned for bait collection purposes, i.e. larger than approximately human-head sized, not too large and also not embedded in sediment.

For each boulder the assessment consisted of collecting the following data:

- Using the definitions of different boulder turning categories defined by Moore *et al* (2010) and presented in Figure 17, identify whether the boulder was;
    - Very recently turned
    - Recently turned
    - Historically turned
    - Not turned
- The presence of particular under-boulder communities (dense sponge/anthozoan/bryozoan communities);
- The presence of peeler crabs, edible crabs and winkles (as the main target species for bait collection and consumption);
- Any other notes about the life under the boulder which might be of conservation interest (for example, an abundance of eggs);
- For boulders providing a good example of one of the four boulder-turning categories; a typical under-boulder community; or some other point of interest, a photograph was taken and the photo ID noted on the survey form;
- General notes were also recorded for each transect on the survey form, including the presence of anglers or collectors, or other shore based activities, which might help to explain the condition of boulders at the time of survey;
- Photographs of each boulder were taken.

Limitations of the survey methodology were that the surveys were just a snapshot of one short timeframe and the results of the collection activity assessments cannot be used to extrapolate to the number of total collectors over time. Bait collection tends to happen at wave-sheltered sites where natural disturbance rarely produces boulder turning. An annual survey at a specific site would give information as to the repeated incidence of boulder turning.

Assessment of this approach by potential users has shown the method to be very labour-intensive and time-consuming. The original approach has not been validated or adopted, mostly due to concerns around the feasibility of implementation in the field, especially alongside existing methods for measuring the abundance of intertidal species. Currently the MarClim protocols focus on rocky shores comprised mostly of bedrock and lacking suitable boulders for turning, and as such the MarClim approach may be less easily adapted for this purpose. The assessment scale (very recently turned, recently turned, historically turned and not turned) does not provide direct information on the condition of the shore.

Given these difficulties, the adoption of this approach to give a GES indicator for boulder-turning status is not recommended. Informal feedback from NRW (Brazier per. comms at an April 2013 workshop) confirmed this view.

VERY RECENTLY TURNED (note algae growth)

Boulder sitting proud of the substrata, often with seaweeds beneath and obvious under-boulder species facing upwards, such as red crust sponges, white sponges, dogwhelk eggs, and rock encrusting bryozoans, colonial and solitary ascidians. Low cover of acorn barnacles (<20%)

RECENTLY TURNED (note anoxic fucoid stipes)

Seaweeds that are trapped beneath the boulder are showing signs of anoxia. Remains of dogwhelk eggs, dried solitary and colonial ascidians on the upward facing surfaces. Low cover of acorn barnacles (<20%).

HISTORICALLY TURNED (note fresh growth of young fucoids).

Upward facing dense empty barnacle tests, no large fucoids, but may be dense small fucoid plants (10cm?) and green seaweeds.

Figure 17. Photographic examples of the state of boulders according to the boulder turning index (Moore *et al*, 2010).

ii. Potential alternatives

The human pressures that drive boulder turning may be more easily measured than the frequency and state of turned boulders. Bait collection, and harvesting of winkles and crabs may be directly observable, and when quantified provide a direct assessment of the ecosystem service provided by shores with boulders. The development of an indicator of this nature may require a social science approach.

1.7 Species diversity indicators: trends with environmental drivers

While the assemblage composition indicators of climate change, water quality and wave exposure (CCI, WQI, WXI) and invasive species indicators (NNI) reflect changes in the composition of rocky shore communities, the absolute numbers of species recorded in a MarClim survey acts as a proxy for total diversity at a site. This is important to consider since Descriptor 1 of the MSFD requires that "*Biological diversity is maintained.*" The community composition indicators (see Section 1.6 above) address how the balance of different species might be expected to change but not the overall condition of the habitat. Condition is more likely to be reflected in species richness of a site and the indicators proposed here quantify this richness using the standardised MarClim protocols.

The MarClim survey protocol allowed for restricted surveys of climate-sensitive species only because time limitations, restricted habitat extent and weather conditions prevented full surveys in some instances. The number of species recorded as present (at least Rare on the SACFOR scale) in any one survey may be influenced by the extent of available habitats and skills of the surveyors. All surveys were, however, done in a circumscribed fashion: completed by one or two individuals on a single low-tide visit of one to four hours duration, usually during a spring tide to allow access to the lowest tidal levels. Throughout the 13-year duration of MarClim to date, one or more of the same four core surveyors Mieszkowska, Hawkins, Burrows and Harvey have been present at every survey. Here, the analysis is restricted to only those MarClim surveys with ≥15 species recorded to exclude partial surveys. The relationships between numbers of species and the three primary drivers of wave exposure, water quality and temperature were described by simple linear regression of species number with summed wave fetch ($\log_{10}$ km), $\log_{10}$ chlorophyll (9km data, averaged over a 5x5 cell neighbourhood, equivalent to a 25km radius), and February SST (averaged over a 50km radius).

Regression analyses were made using the R statistical package, and the maps below were produced with the raster calculator in ArcMap 10, taking layers for wave fetch up to 5km offshore (Burrows 2012), chlorophyll *a* concentration and February SST as inputs. The offshore wave fetch values allow areas of predictions of sufficient size to become visible at the UK scale, but are inflated beyond those normally found along the coast.

1.7.1 Total number of species: *N*(total)

The number of species recorded as present (≥ Rare) out of the 57 core MarClim species (see Appendix 1, Table A1 for a full list) was positively related to February SST (with an increase of four species per 1°C rise), negatively related to chlorophyll *a* concentrations (a loss of 17 species per order of magnitude increase), and slightly positively related to wave exposure (1.8 species per order of magnitude). Wave exposure across the range of UK MarClim sites spans three orders of magnitude (see Figure 3), so this latter relationship equates to an increase in diversity of six species across this range. The negative effect of chlorophyll *a* on diversity was amplified at higher temperatures, indicated by a positive interaction of chlorophyll and temperature effects. The regression predicted highest diversity on rocky shores in the west of Ireland and in south-west England (Figure 18), with the lowest values along the Solway coast, Liverpool Bay and parts of the Essex coast and Thames estuary. The regression explained 41% of the variance in species number (Table 4 and Figure 19).

Table 4. Regression parameters for total number of species, *N*(total), versus February SST, $\log_{10}$ chlorophyll *a* concentration and wave fetch. Regression R^2: 0.411; 557 degrees of freedom (d.f.).

	Estimate	Standard Error	t value	Pr(>|t|)	
(Intercept)	-17.432	2.594	-6.72	4.51E-11	***
February SST	3.986	0.332	12.03	< 2e-16	***
Log_{10}(chl *a* mg/m^3)	-15.228	7.690	-1.98	4.82E-02	*
Wave fetch, Log_{10}(km)	1.818	0.330	5.51	5.39E-08	***
SST× Log_{10}(chl *a*)	2.926	1.059	2.76	5.93E-03	**

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

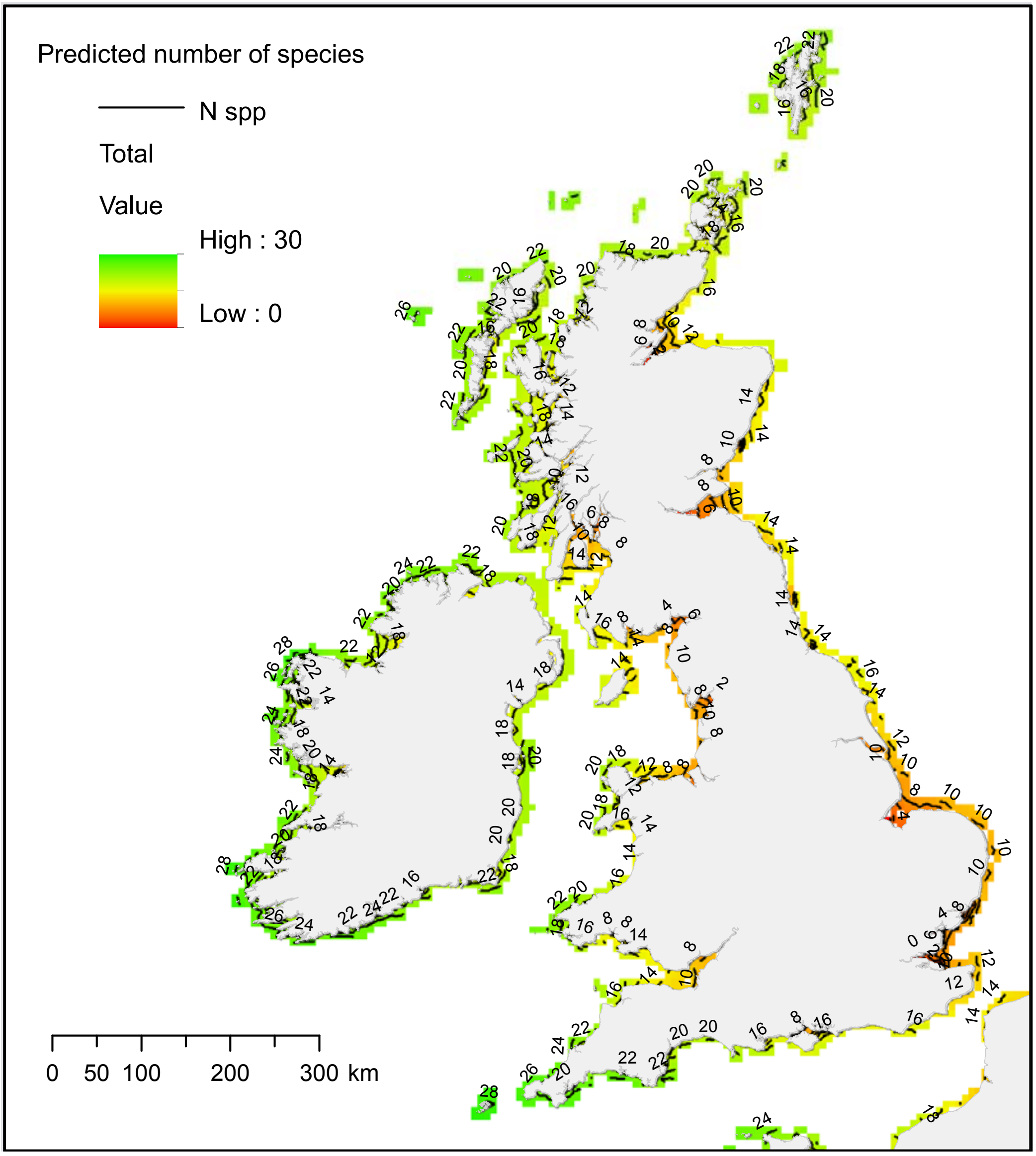


Figure 18. Predicted total number of rocky shore species, *N*(total), around the UK, from a linear regression of species number on wave fetch, February SST and chlorophyll *a* concentration. Numbers give expected number of species for adjacent contour lines.

Differences in sampling effort among survey teams had less influence than expected on the total number of species recorded in surveys. Most survey teams recorded numbers of species in line with expectations from the regression equation (Figure 19), although many of the numbers of species recorded by the Republic of Ireland (ROI) team fell above the line of equality, with a single survey by Natural Resources Wales (NRW) lying well above the line. Some of the apparent variability among teams may stem from actual regional deviations in abundance from the general biogeographical UK scale trends; different teams may have been sampling inherently more or less diverse areas.

Repeated visits to the same MarClim sites allowed the repeatability and variability in total number of species recorded *N*(total) to be assessed by considering the standard deviation (SD) of the mean number of species for each site. This gave an average SD value of 2.78 species across 51 sites visited more than once, and an average standard error (SE) of 1.79 species, based on 37 sites visited twice, 11 visited three times and three sites visited more than four times. SD of repeated estimates of diversity was thus 14% of the mean number of species recorded at the 51 sites (20.2).

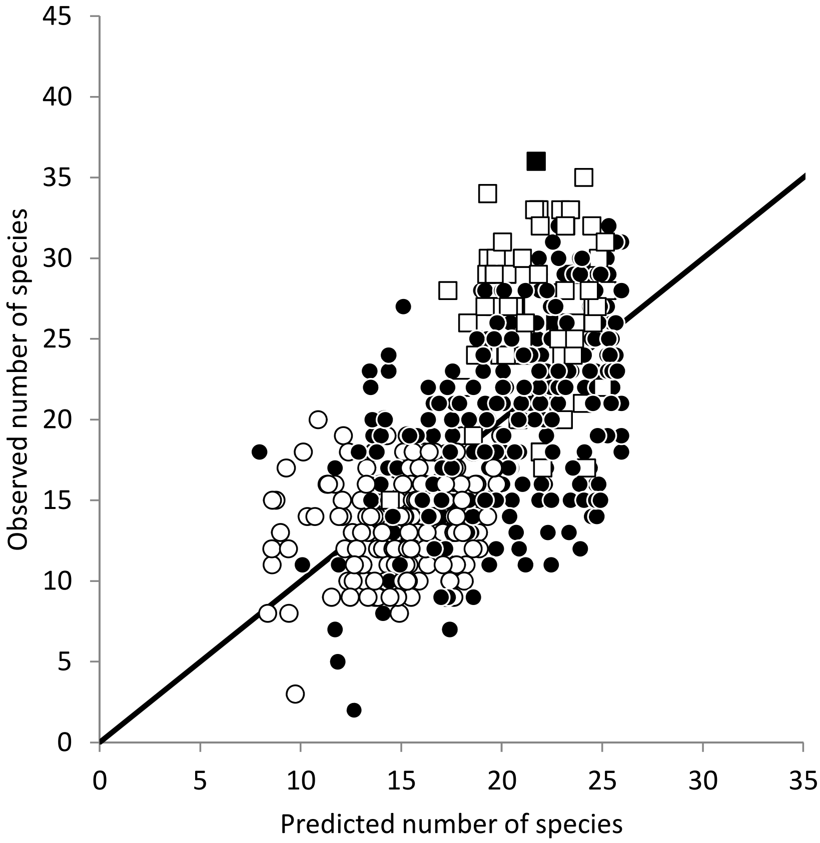


Figure 19. Observed total number of species, *N*(total), plotted against predicted number. Symbols show each MarClim survey team: open circles (Scottish Association for Marine Science), closed circles (Marine Biological Association), open squares (Republic Of Ireland) and closed squares (Natural Resources Wales).

1.7.2 Macroalgae, number of species: *N*(algae)

The number of species of macroalgae was derived from the number of algae present (≥ Rare) out of 21 in the core set of MarClim species (for abbreviations, see Appendix 1, Table A1: Cospp, Lahyp, Ladig, Lasac, Laoch, Alesc, Hielo, Samut, Asnod, Pecan, Fuspi, Fuves, Fuser, Fudis, Fuind, Cyspp, Hasil, Bibif, Maste, Chcri, Lipyg).

Expected number of species of macroalgae varied from less than four in Liverpool Bay, the Wash and the Thames estuary and in the inner Firths of Forth and Solway, up to ten on the outer coasts of western Ireland and Scotland and south-west England (Figure 20). This reflected the relatively stronger negative influence of chlorophyll *a* concentrations on macroalgae than on the total number of species. A comparison with the pattern of the observed number of species of macroalgae (Figure 21) confirmed the general utility of this regression prediction.

Table 5. Regression parameters for number of species of macroalgae, *N*(algae), versus February SST, $\log_{10}$ chlorophyll *a* concentration and wave fetch. Regression R^2: 0.235; 558 degrees of freedom (d.f.).

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-2.563	1.159	-2.21	2.74E-02	*
February SST	1.188	0.143	8.30	7.63E-16	***
Log_{10}(chl *a* mg/m^3)	-2.338	0.670	-3.49	5.22E-04	***
Wave fetch, Log_{10}(km)	0.663	0.177	3.76	1.91E-04	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

There are some local and regional disparities between observed macroalgal diversity, as represented by *N*(algae), and that predicted by the regression equation (Figure 20 and Figure 21). Areas with fewer than expected macroalgae species include the Outer Hebrides, and bays along the western coasts of England and Wales. The reasons for these deviations from the larger scale trends are not immediately obvious, but are probably several-fold. Long-term averaged satellite chlorophyll *a* concentrations may not capture all the important elements of water quality that limit macroalgae. Seasonal patterns of water column chlorophyll and sediment load may be more important than the annual averages, and these seasonal patterns may differ in a way that produces the localised reduction. Factors other than water quality may restrict macroalgal diversity in some areas. Nutrient limitation may even be a factor in areas far away from anthropogenic sources, such as the Outer Hebrides. Habitat quality and availability may also restrict species numbers, especially on soft or rapidly eroding rock such as in Lyme Bay, in areas subject to sand scour or where mixed shores of sediments and boulders and rock outcrops predominate.

Addition of further species to this indicator may improve the strength of the relationship (currently $R^2 = 0.24$) between the number of species of macroalgae present and the main drivers, but at the cost of increased time spent on the shore or reduced time available for assessing other taxa, as discussed in Section 0. The selection of 21 species was driven by the list of 57 species for which abundance was assessed by all teams during the MarClim project. The Scottish Association of Marine Science (SAMS) team did collect data on more species of algae as contextual information for the core set of MarClim species, and this was facilitated by the reduction in total intertidal diversity relative to south-west England and Ireland. It would be possible to assess the effects of including additional algae using patterns around Scotland for the 2002 to 2008 period.

Repeated assessment of the number of MarClim macroalgae from survey sites gave values of standard deviation (SD) and standard error (SE) of the mean value for each site. SD of repeated estimates were small (SD 1.39, SE 0.89, n=51 sites) relative to the mean: SD was 17% of the mean number of macroalgae recorded at these sites (8.03).

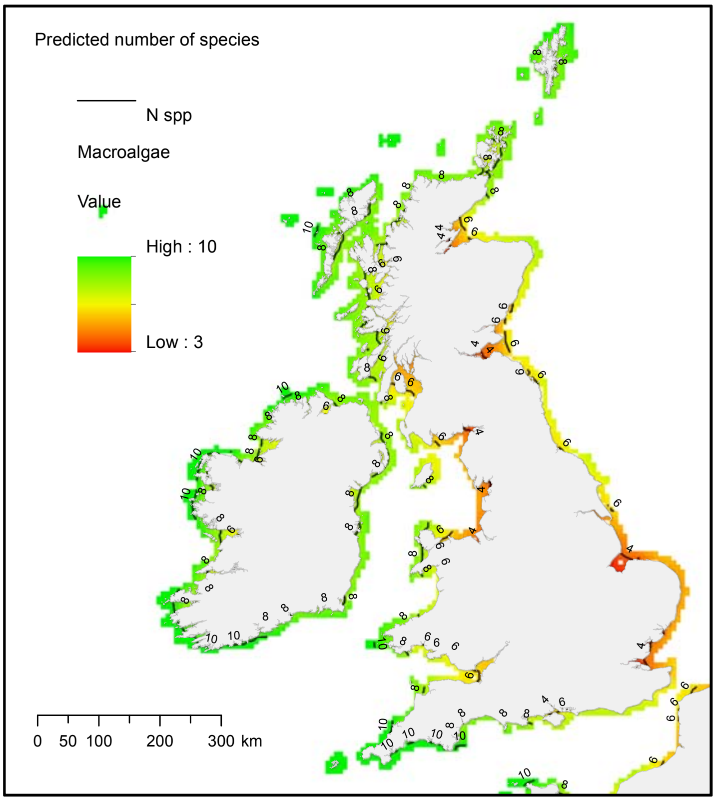


Figure 20. Predicted total number of species of rocky shore macroalgae, *N*(algae), recorded in MarClim surveys around the UK from a linear regression of species number on wave fetch, February SST and chlorophyll *a* concentration. Numbers give expected number of species for adjacent contour lines.

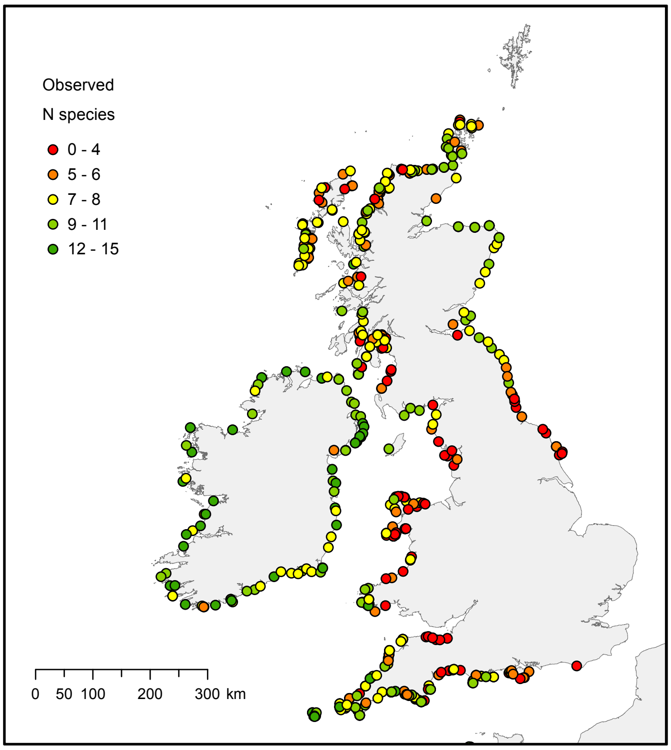


Figure 21. Observed number of macroalgae, *N*(algae), in MarClim surveys, out of the maximum possible number of 21 species.

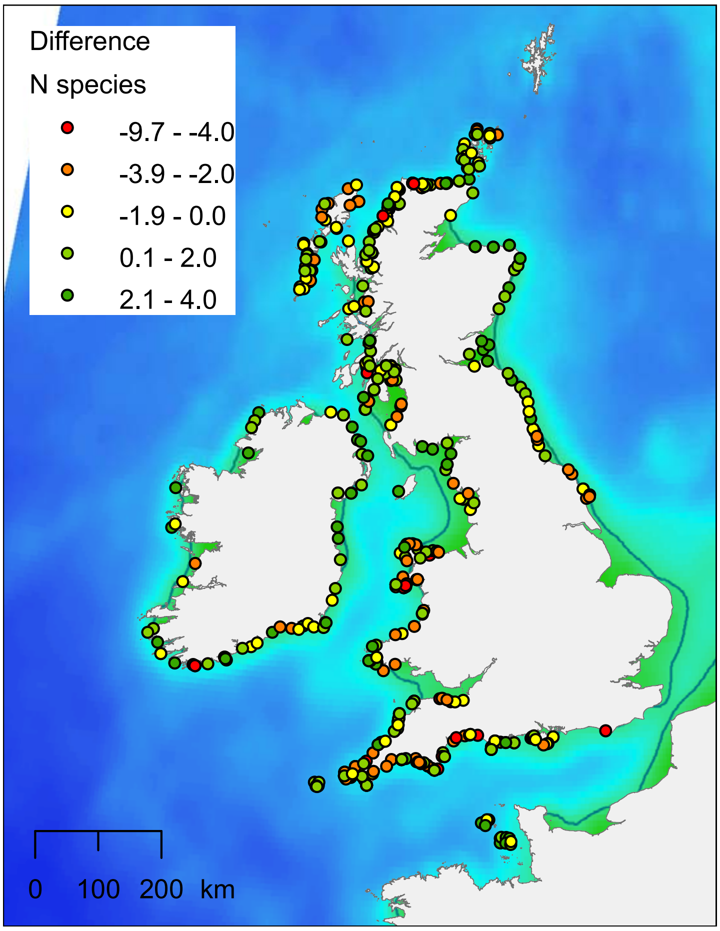


Figure 22. Difference between observed and predicted number of macroalgae, *N*(algae), from regression showing local reductions in diversity of leathery macrophytes.

i. Comparison of *N*(algae) with the Water Framework Directive Macroalgal Tool (WFDMT)

Without WFDMT data collected from the same sites at the same time as MarClim data, it is presently impossible to directly intercalibrate the two methods. However, using available WFDMT data (see Section 0), it is possible to compare the WFDMT values with those observed at the nearest MarClim site and with values predicted for the WFDMT survey locations by the relationship between *N*(algae) and the drivers of temperature, water quality and wave exposure (Table 5).

Despite the average distance from the WFDMT sites to the nearest MarClim site being only 3km (range 89m to 23km), the correspondence between the WFDMT values and *N*(algae) values at the nearest site is poor. Both indices track changes in water quality at regional scales (compare Figure 13A with Figure 10), but the two groups of species respond differently to local variation in water quality or habitat. Although the WFDMT Reduced Species List (RSL, Table 3) includes 11 of the 21 MarClim species that comprise *N*(algae), the majority of the WFDMT species are filamentous species, while the majority of MarClim species are leathery macrophytes (as defined by Steneck and Dethier 1994). These two contrasting groups may have major differences in their responses to water quality and represent different ecological functions and values. The large leathery macrophytes provide habitat for many other species and may form the bulk of the intertidal macroalgal biomass, and thereby have a greater contribution to carbon flow in algal-dominated communities as a source of detritus. The filamentous reds and greens may better represent the diversity of algae, and the sensitivity of such communities to increased sediment and chlorophyll load.

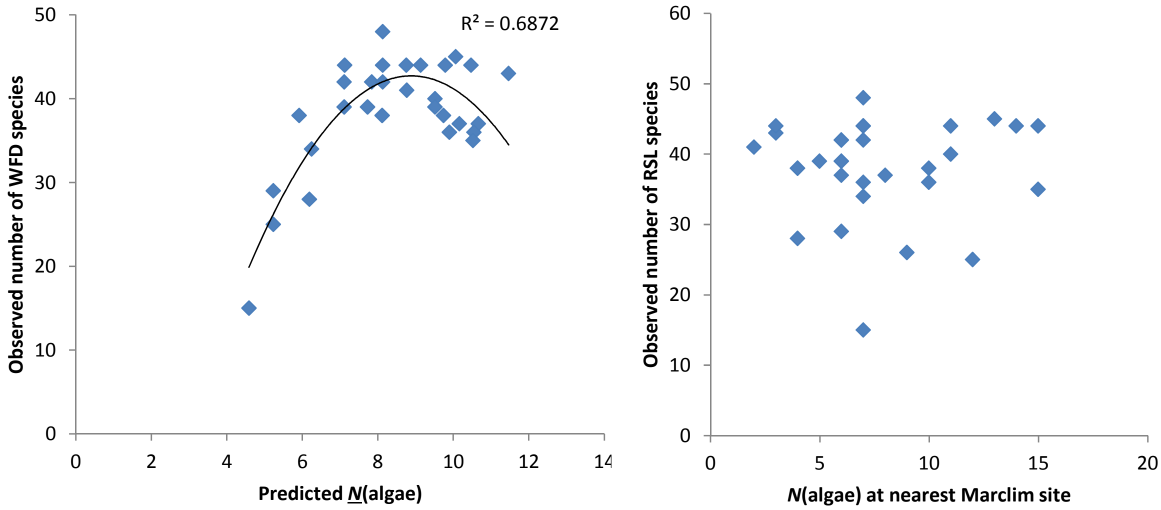


Figure 23. (A) WFDMT observed number of Reduced Species List (RSL) species plotted against predicted number of MarClim macroalgae, (B) WFDMT observed number of Reduced Species List (RSL) species plotted against number of MarClim macroalgae (*N*(algae)) for the nearest MarClim site.

The ultimate decision as to whether to use *N*(algae) or the WFDMT RSL numbers, or both, may depend on the resources available and the emphasis on maintaining diversity at local scales (use the WFDMT) or preserving ecological function at regional or larger scales (use the *N*(algae) indicator).

1.7.3 Diversity of other species: *N*(other)

The number of species other than primary producers, including grazers, suspension feeders, predators and scavengers, was derived from the total number of species less the number of macroalgae recorded as present. This gave a possible maximum of 36 species (57 total less 21 macroalgae = 36 species)

As with the total number of species, the number of consumer and predator species was negatively influenced by chlorophyll *a* concentrations and positively influenced by February SST. More of these species were predicted for wave exposed environments. Highest numbers were predicted for the west of Ireland, followed by south-west England, west Scotland, and least in eastern England and Liverpool Bay (Figure 24).

The power of the underlying drivers of temperature, chlorophyll *a* and wave fetch in predicting the diversity of animal species is good, relative to macroalgae, with an R^2 of 0.45 compared to 0.24 for macroalgae. This suggests that diversity of animals is more responsive to major environmental gradients than diversity of plants. However, the usefulness of this measure as a direct indicator of the effects of a single environmental driver is limited by the nature of a joint response to the three factors of temperature, chlorophyll and wave fetch. The combined response of animal diversity to chlorophyll *a* and temperature, indicated by the interaction term in Table 6, means that the positive response of *N*(other) to chlorophyll *a* is enhanced in areas of higher February SST.

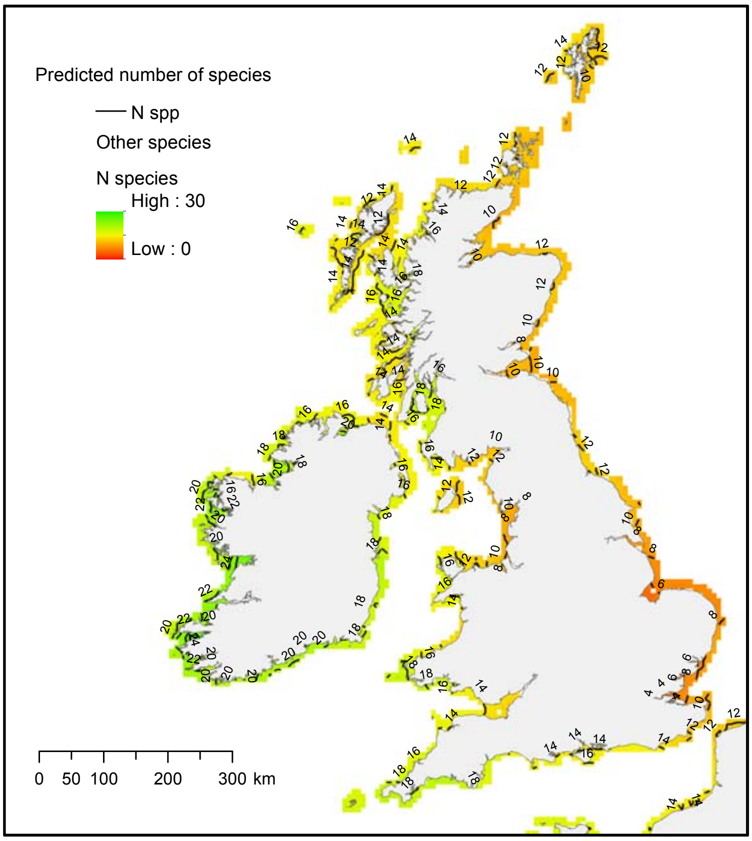


Figure 24. Predicted total number of species of rocky shore consumers and predators, *N*(other), around the UK, from a linear regression of species number on wave fetch, February SST and chlorophyll *a* concentration. Numbers give expected number of species for adjacent contour lines.

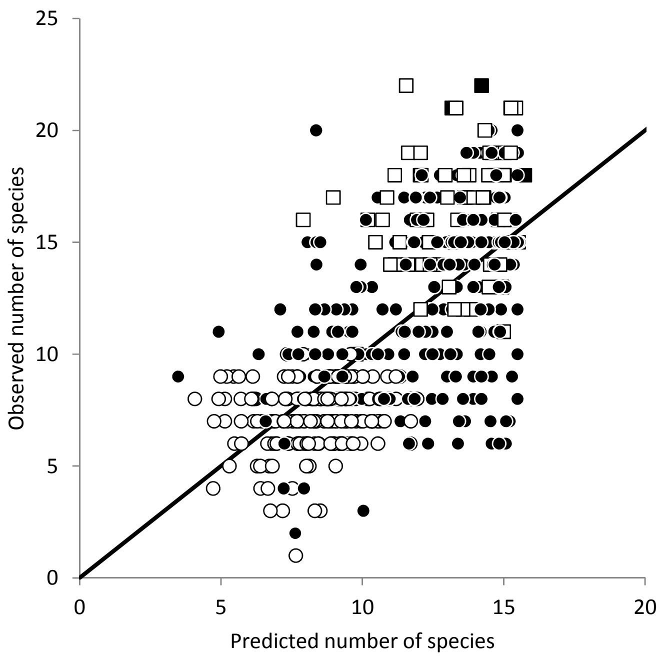


Figure 25. Observed number of species of consumers and predators, *N*(other), plotted against predicted values, with symbols for each MarClim survey team: open circles (Scottish Association for Marine Science), closed circles (Marine Biological Association), open squares (Republic Of Ireland) and closed squares (Natural Resources Wales).

Table 6. Regression parameters for number of species of consumers and predators, *N*(other), versus February SST, $\log_{10}$ chlorophyll *a* concentration and wave fetch. Regression R^2: 0.447; 557 degrees of freedom (d.f.).

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-15.903	1.709	-9.31	< 2e-16	***
February SST	2.940	0.218	13.46	< 2e-16	***
Log_{10}(chl *a* mg/m^3)	-7.440	5.066	-1.47	0.1425	
Wave fetch, Log_{10}(km)	1.136	0.217	5.23	2.40E-07	***
SST× Log_{10}(chl *a*)	2.165	0.698	3.10	0.0020	**

Significance codes: <0.001 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

1.8 Influences on species diversity – relevance for Good Environmental Status

The positive influence of February SST reflects the well-known increasing trend of species diversity of rocky shore communities from the north and east to the south and west, corresponding to a transition between Lusitanian and Boreal provinces (Forbes 1859) and the progression to beyond the poleward geographical range edges of southern and south-western species (Lewis 1964). Negative influences of increasing chlorophyll *a* concentration on both macroalgae and higher trophic levels, and thereby total diversity, result in a second marked trend of increasing diversity away from areas of high apparent concentrations of chlorophyll *a*, especially evident in numbers of macroalgal species. These diversity measures, and their known pattern of distribution along gradients of natural processes and human-related pressures, offer the greatest promise for use as indicators of Good Environmental Status (GES).

Descriptor 1 of the MSFD is couched in these terms: "*Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*." The regression equations derived and presented in this report offer a standardised expectation of the diversity of the rocky shore community for any part of the UK (and Ireland). If the observed number of species falls short of that expectation, then the unequivocal interpretation is that of a move away from GES, irrespective of whatever thresholds that are set for a 'below GES' environment. This shortfall quantifies the degree to which a site or region deviates from the Descriptor 1 condition of "*in line with prevailing […] conditions*", albeit dependent on the degree to which the major biogeographic trends have been captured. It is recommended that the comparison of observed values of the diversity and community composition indices (climate change index (CCI), water quality index (WQI) and water exposure index (WXI)) with expectations based on regression models is adopted as the foundation for judging GES, with the limits that define less than 'good' environmental status to be set in further work.

A potential drawback of this approach is the sensitivity of the number of species recorded to sources of variability other than the influence (=pressure) in question. Sampling effort is one potential source of variability, but it is reassuring that the different teams of MarClim surveyors produced data that gave similar diversity estimates for the same combinations of environmental conditions. Habitat extent and diversity will also positively influence estimates of diversity. The habitat extent/diversity effect was especially evident in the development of Wells *et al*'s (2007) WFD Macroalgal Tool. Their habitat quality index was built on the incidence of physical features such as crevices and ledges, as well as processes such as scouring and siltation, and proved very effective in predicting variation in diversity among survey sites. The geographical extent of the Wells *et al* study was too restricted to pick up the large-scale patterns evident in the UK- and Ireland-wide MarClim project. One option could be to include the incidence of habitat features in a future MarClim-based survey protocol. Alternatively, map-based estimates of the extent of rocky intertidal habitat, rock type, or even airborne-LIDAR-based estimates of habitat heterogeneity may improve the local scale predictive power and the quality of the baseline standard expectation for rocky shore diversity.

1.9 Recommendations for the use of intertidal rock indicators

1.9.1 Indicators and Good Environmental Status

In this report, a number of numerical indices have been presented that represent the status of rocky intertidal communities across the whole of the UK, based on quantitative data on presence and abundance of conspicuous and easily identifiable species, at the scale of entire shores (based on surveys that typically cover a shore line up to 200m in extent). These indices measure both present status and the amount of change in a positive or negative direction to enable an assessment of GES in numerical terms against the MSFD Descriptor 1 "*Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*" and Commission Decision Indicator 1.6.1 '*Condition of the typical species and communities'*. These indices, and their GES-relevance, are summarised in Table 7. The proposed approach to data collection for the indicators is straightforward, easy to implement, and lends itself to a rapid assessment of a larger number of sites than the approaches developed to address the WFD. Assigning abundance to distinct, definable categories such as the SACFOR scale integrates small-scale variation among microhabitats within a shore, overcoming local within-shore variability enabling broader scale comparisons appropriate for defining GES.

The authors believe that rapid and geographically extensive assessment of abundance of species through MarClim-style surveys, supplemented with additional information on habitat extent and incidence, forms the best basis for cost-effective, repeatable data collection that will deliver the indicators to assess the status of rocky shores around the UK. It has been demonstrated that this species-level data can be assembled in a variety of ways to address specific kinds of responses to particular human pressures. Community composition indicators, such as the CCI, WQI and WXI, are effective in the measurement of the change along environmental gradients in assemblage type: from cold-water to warm-water; in physical form: from robust to delicate, and ecological function: from in-situ primary producers to processors of allochthonous organic material. Expressed as ratios between abundance of species of opposing types, the composition indices may be robust in the face of variation in sampling effort as long as sampling affects the two groups of species similarly. Diversity measures, such as N(total), N(algae) and N(other), on the other hand, may be more sensitive to sampling effort, taxonomic competence and the effects of habitat extent and microhabitat availability (beta diversity).

The fact that composition and diversity of rocky shore species assemblages varies along environmental gradients in ways predictable from the basic ecology of the component species provides affirmation that the proposed indicators record responses to the pressures represented by these gradients. The pressures arising from human activities that cause change in the primary drivers of spatial variation in composition and diversity of rocky shore species are: (1) changed sea surface temperature through anthropogenic climate change induced by increased atmospheric CO_2 from the burning of fossil fuels (CCI), (2) changed phytoplankton biomass and increased light attenuation due to coastal eutrophication through runoff of nutrients and organic matter from agriculture and urban waste water into semi-enclosed seas and changes in sediment load (siltation) from increased erosion, made worse by inappropriate coastal development (WQI), and (3) physical damage to the habitat in areas of mobile boulders, through turning during collection of organisms for bait. Approaches for assessing the impact of boulder turning are not currently well developed enough to produce a working indicator.

Table 7. A summary of proposed GES indicators for UK rocky shores. All indicators address MSFD Descriptor 1 and Indicator 1.6.1 unless otherwise stated (see *italics*).

Indicator	Abbrev	Indicator value Range	Indicator basis	Primary driver	GES-relevance
Climate change indicator	CCI	0-1	Relative abundance of warm and cold water species groups (high in warmer water, low in cooler water)	Sea surface temperature (SST)	Community-level response to climate (change)
Water quality indicator	WQI	0-1	Relative abundance of high and low chlorophyll-*a* associated species (high in clear, blue water, low in nutrient rich water)	Satellite-estimated surface chlorophyll *a* concentration (may be a proxy for light attenuation). Needs validation with inshore chlorophyll and turbidity measurements.	Response to (anthropogenic) nutrient status, via effects on phytoplankton, and to sediment load
Wave exposure indicator	WXI	0-1	Relative abundance of wave-exposed and sheltered-shore species (high on wave-exposed shores, low on sheltered shores)	Wave climate, mostly driven by spatial variation in wave fetch	Context setting for survey data, but a potential indicator of long-term shifts in wave climate at site level due to climate or wave energy extraction
Non-native species indicator	NNI	0-1	Relative incidence of non-natives and native species	Proximity to and rate of spread from centres of introduction	Potential alteration of ecosystem function and service, *Descriptor 2.*
Total species diversity	N(total)	0-57	Total number of species recorded as present* in a MarClim survey, out of a checklist of 57	Combined SST (+ve), chlorophyll (-ve) and wave exposure (+ve)	Reflects regional trends, and likely local habitat diversity (the latter needs further work)
Macroalgal diversity	N(algae)	0-21	Total number of species of MarClim macroalgae present* out of 21	Combined SST (+ve), chlorophyll (strongly -ve) and wave exposure (+ve)	Evidence for potential anthropogenic diversity limitation
Consumer/ predator diversity	N(other)	0-36	Total number of higher trophic level species present* from the MarClim checklist	Combined SST (strongly +ve), chlorophyll (-ve) and wave exposure (+ve)	Most strongly indicates latitudinal trends in temperature

* at least Rare

The relationships described here for composition and diversity indices set expectations for the direction and magnitude of change. For example, a 1°C increase in February SST at any locality may be expected to result in a 0.15 (15%) increase in the Climate Change Index and an increase in diversity by four species in the MarClim set of 57. It is highly likely that any change in intertidal biota may lag behind such changes in the environment, since it may take a variable period of time for their geographical ranges to extend to match the changes in temperature, from less than a year to several years. The present-day relationships of species composition and diversity with temperature, water quality and wave exposure set a baseline against which to evaluate future change. Other groups have found this a very useful approach to set starting points against which to consider distribution shifts, in butterflies and birds in the UK, for example (Devictor *et al* 2012). Crisp and Southward did not collect their data in such a systematic a way as in the MarClim project, instead focusing entirely on climate sensitive species and only collecting information about community dominants as ancillary information. A backward look at their data in the light of these present-day relationships would be extremely enlightening, but may require inventive approaches to overcome the sparseness of the older data at assemblage level.

Species richness varies significantly across temperature, water quality and wave exposure gradients. More species tend to be found in warmer waters and wave-exposed environments, and possibly in areas of reduced water chlorophyll *a* concentrations (particularly macroalgae). The indices based on absolute numbers of species, N(total), N(algae) and N(other), may be more useful measures for judgement of GES than the community composition indicators, since they more directly address the biodiversity-related elements of the MSFD. Absence of species where the '*prevailing physiographic conditions*' (MSFD Descriptor 1) otherwise suggests their presence is indicative of a reduction in environmental status of that region of coast. The proportion of sites along a coastline where diversity drops below a threshold defined by expectations from regression analyses may be one possible avenue for the development of a candidate index that would need further exploratory analysis.

The authors recommend that:

1) The MarClim Climate Change Index (CCI) should be adopted as an indicator of the climate change status for intertidal rock communities at individual sites and regions around the UK;
2) The MarClim Water Quality Index (WQI) should be adopted as a measure of the response of rocky intertidal communities to variable conditions of chlorophyll *a* and suspended sediment in the water column as influences on water quality across the entire range of conditions present in the UK;
3) The Water Framework Directive Macroalgal Tool (WFDMT) should be used in addition to the WQI in areas of poor water quality, where the annual average concentration of chlorophyll *a* exceeds $4 mg/m^3$, given the extra sensitivity of the WFDMT in areas of high chlorophyll *a* and increased sediment load;
4) Species diversity measures from data collected in MarClim surveys should be used as proxies for total diversity of rocky intertidal communities. Diversity in these surveys is given by the total number of all species (*N*(total)), of macroalgae (*N*(algae)) and of animals separately (*N*(other)), recorded as present against a set checklist of rocky intertidal species;
5) Good Environmental Status (GES) should be measured by comparison of observed values of these proposed indicators against those expected for the prevailing conditions, obtained from statistical relationships evident in geographical patterns in existing data around the UK. This directly reflects the MSFD Descriptor 1 for GES. The degree to which the indicators can deviate from expectations before GES is judged to have been compromised remains to be defined.

1.9.2 Relationships with existing indicators for the EC Water Framework Directive

The Water Framework Directive (WFD) uses a number of tools to define 'Good Ecological Status' (GEcS) in intertidal rocky habitats: notably the WFD opportunistic macroalgal blooming tool, designed for detecting effects of eutrophication and pollution events in estuaries; the WFDMT which presents a species composition index based on the Reduced Species List (RSL) of 70 species of macroalgae; and other suggested approaches based on upstream penetration of fucoid species in estuaries (Wilkinson *et al*, 2007). Care must, however, be taken as algal abundance is often determined by grazing pressure and thus it would be possible to confound reduction in water quality with disturbance such as trampling reducing limpet density, and hence leading to more early successional ephemeral algae (Hawkins, 1981; Jenkins *et al*, 2005; Coleman *et al*, 2006).

Direct comparison of the indicators proposed in this report with the WFDMT, including: the WQI, which comprises mostly algae responding positively to increasing quality (WQI; see Section 0 iv); and the total number of species of large conspicuous macroalgae (N(algae), Section 1.7.2) indicate that the MarClim-based indicators outperform the WFDMT over broader gradients of water quality, but that the WFDMT performs better at discriminating responses in poorer water quality areas.

Aside from the effects of larger-scale gradients demonstrated in this report, work on the establishment of the WFDMT demonstrated that species richness on intertidal rocky shores is related to the presence of a range of physical habitat features, particularly the presence of ridges/outcrops and platforms, 'irregular' rocks and boulders, as well as rockpools and crevices (Wells *et al* 2007). Habitat extent, quality and complexity as a driver of species richness (Johnson *et al* 2003) is not presently well measured by the MarClim sampling protocol, and is worthy of incorporation into a revised, recommended sampling methodology.

Whilst the WFDMT is designed to detect changes in water quality at a local scale with predominantly acute impacts due to point source pollutants or localized physical impacts, the MarClim indicators are designed to detect changes in species abundance and relative dominance in response to multiple factors: climate change, water quality, wave exposure, invasive species and geographic differences in species pools across multiple spatial scales from local (within a shore and between neighbouring shores) through to regional, national and biogeographic scales (using the European MarClim dataset).

1.9.3 Suggestions for further work

i. GES targets

1) Define suitable indicator baseline(s) – identify the value of state against which ecologically meaningful targets can be set (i.e. reference conditions;
2) Define provisional indicator target(s) – define the value or range of values for the indicators which are equivalent to Good Environmental Status (GES)

The definition of the GES targets for the proposed indicators is beyond the scope of this work. Thresholds for individual indicators will likely require further data collection, the articulation of reference conditions and then identification of a suitable deviation from these conditions that can reflect '*sustainable use'* of the marine environment. There is no single agreed approach to identifying what constitutes '*good'* in Good Environmental Status (GES). For specific impacts such as fishing, the desired direction of change is not controversial; changes in stocks for example can be interpretable as indicating good status if upwards or bad if downwards (Greenstreet *et al* 2012). For other ecosystems, consensus may be less easily reached across countries and the ultimate arbiter of what is considered '*good'* depends on human values (Mee *et al* 2008). These human values will ultimately set limits for indicators below which measures of GES should not be tolerated. So, for most systems, the question as to what is 'good' remains undefined. Where exploitation is the major impact, the GES-relevant measures will likely reflect the degree of recovery from, or sustainability of continuing exploitation. For demersal fish stocks, temporal trends (Greenstreet *et al* 2012) are being used as the basis for determining GES, albeit in a rather complex fashion.

ii. Costs and recommended extent and frequency of monitoring

Options such as these will be discussed in subsequent sections of this report on monitoring protocol development. It is important to calculate the likely cost of monitoring considering the extent of monitoring required. The appropriate quality standards for indicator data collection and management are also identified.

2 Development of the MarClim methodology from classic studies

2.1 Introduction

This Section provides the context within which the MarClim approach has been developed to inform its use for indicators of several measures of MSFD Good Environmental Status (GES). In this Section the development of the MarClim approach is outlined from its origin in classic work dating back to the 1940s by Fischer-Piette, Crisp, Southward, Lewis and their colleagues to detect alterations in marine intertidal biodiversity in response to climate fluctuations and biogeographic gradients. How the MarClim approach has been applied to develop the intertidal indicators for the MSFD is also outlined before going on to explain why the continuity of the historical methods enable data collected today to be compared with surveys of distributions, population abundance and structure stretching back eight decades. The Section concludes by discussing the strengths and weaknesses of the MarClim approach.

Continuity in training, cross calibration, equipment and methodologies between past, current and future generations of scientists is essential to all time-series studies. For two decades preceding the MarClim project (2001-date) and during the initial five years of MarClim the principal scientists have been trained, communicated and worked extensively with the original data collectors including Southward, Crisp, Lewis and Kendall to ensure reproducibility of the data.

2.1.1 Broad-scale surveys

The methodologies used in the MarClim project evolved from classic work on geographic ranges on rocky shores initiated in the 1930s, plus time-series studies that commenced in the 1950s which had been prompted by the broader-scale work. Fischer-Piette (1936a) in France *et al* (1939a) made some of the groundbreaking studies of important intertidal species before World War II. Orton (1920), who had a long-standing interest in the influence of temperature on distributions and phenology (seasonal breeding cycles), encouraged further work by Southward. Collaborating with Crisp, a series of classic studies of distributions of a suite of major intertidal species around the British Isles and Ireland were made (Southward and Crisp, 1954b; Crisp and Southward, 1958). Working in parallel and jointly with Fischer-Piette, coverage from French North Africa, through Spain and Portugal to English Channel was achieved (Crisp and Fischer-Piette 1959; Fischer-Piette 1963). They also charted the spread of the non-native Australasian barnacle *Elminius (Austrominius) modestus*. These surveys were combined with laboratory and field experiments on the causes of both local and geographic distributions of these species.

Early catalogues of biodiversity used qualitative terms such as ‘rare’, ‘frequent’, ‘common’ and ‘abundant’ and the particularly unhelpful ‘not uncommon’. In terrestrial ecology the Zurich-Montpelier school of phytosociology refined such terms to aid classification of vegetation. Fischer-Piette used such terminology for mapping intertidal species. Crisp and Southward formalised these into semi-quantitative abundance scales using a semi-logarithmic progression for their biogeographic studies – in essence a scale based on the ordinal (ranked) categories of Abundant (A), Common (C), Frequent (F), Occasional (O), Rare (R), Not Found (N). This was particularly insightful given that non-parametric statistical approaches based on ranking were in early stages of development and were yet to be widely used in the late 1940s and early 1950s.

Different scales were developed for different species. In the case of algae and sessile animals the > 30% ‘Abundant’ category denoted where a discernible zone was formed.

Using a checklist of species, a 30 minute search was conducted, often aided by some quick quadrat counts (especially by Southward), where each species was placed on the five point ACFOR scale, with ‘Not Found’ also being recorded. The aim was to get a quick measure of the average abundance in the best place for a particular species on the particular shore visited to enable comparisons at a regional or UK scale (10s to 1000s of km). This approach was designed to integrate spatial patchiness on a scale of 10-100s of metres at a particular location using expert knowledge of natural history to sample in the most appropriate place for each species – it was especially important to know where to look for rare species at range edges. The scales were such that the categories ‘Frequent’ and above probably equated to individual judgement of what constituted a breeding population (e.g. in barnacles sufficient density to be within penis range for cross fertilisation). The approach enabled more than one shore to be visited on a tide often separated by 10 or more kilometres. The checklist was an *aide memoire* rather than a strict standard operating procedure. More quantitative counts would be made of barnacles and less often limpets, especially by Southward.

The abundance scales were designed for mapping and translated well to five different sizes of circles for publication of maps showing distribution and abundances of these key species. This basic methodology was then extended – in some cases perhaps beyond its original scope and applicability. Ballantine (1961) used it to derive his Biological Exposure Scale. Moyse and Nelson Smith used it in early studies of distribution in Milford Haven aimed to define baseline conditions around the oil terminal complex. Subsequently the methodology was adapted, and extended, by the Oil Pollution Research Unit of the Field Studies Council, with an additional point ‘Superabundant’ category being added to form a SACFOR scale (Superabundant (S), Abundant (A), Common (C), Frequent (F), Occasional (O), Rare (R) and the additional category: Not Found (N)). The reasoning for adding ‘Superabundant’ was that small species and in particular barnacles reached ‘Abundant’ at what were quite low densities for them. It was therefore felt that the significant ‘step-up’ in abundance needed to be reflected in the scale (K. Hiscock, pers. comm.). The MNCR SACFOR cover/density scales were derived by Hiscock (1981) and adopted from 1990 by the Nature Conservancy Council for the UK Marine Nature Conservation Review (MNCR) and the successor bodies (Joint Nature Conservation Committee and the UK country conservation agencies). The SACFOR scale provided a unified system for recording the abundance of marine benthic flora and fauna in biological surveys. MarClim switched from ACFOR to SACFOR in 2005 upon the request of JNCC to bring the time-series data into line with the JNCC standard format for recording categorical data.

2.1.2 Time–series information

Southward and Crisp noted that the warm-water barnacle *Chthamalus stellatus* was more common in the early 1950s than it had been in the 1930s (Moore 1936; Moore and Kitching 1939a) and that the cold water barnacle *Balanus balanoides* was relatively less abundant (Southward and Crisp 1954a). These early quantitative comparisons (Southward and Crisp 1954b) prompted ongoing work at a range of sites around Plymouth (Southward 1967; 1991; Southward *et al* 1995) charting fluctuations in the relative abundance of warm-water (*C.stellatus* – later on, split into *C. stellatus* and *C. montagui*, (Southward 1976; Crisp *et al* 1981) and cold-water species (*Balanus balanoides* now *Semibalanus balanoides*) in relation to temperature. Most of this work ceased in 1987 when Southward was forced to take compulsory early retirement, except for Cellar Beach (Southward 1991). The time-series study was resumed in 1997 by Hawkins and folded into MarClim related work from 2001 onwards.

There are also fewer temporally frequent counts for the warm-water and cold-water species of limpets (*Patella depressa* – warm-water, *Patella vulgata* – cold-water) at a variety of shores by both Crisp and Southward, carried forward by Hawkins since 1980 and the

MarClim team since 2001 (e.g. Southward *et al* 1995; Kendall *et al* 2004; Hawkins *et al* 2008).

2.1.3 Population studies

In parallel with the work by Crisp and Southward, Jack Lewis and the team based at the Wellcome Laboratory of Leeds University at Robin Hood's Bay also started working on fluctuations in key species. They were strongly influenced by the ground breaking work of Hutchins (1947) on geographic distributions. A key-species, fixed-site approach for intertidal monitoring or surveillance was advocated by Lewis (1976). In parallel with this Lewis and co-workers (in the NERC Coastal Surveillance Unit) pioneered work at the range-edge monitoring reproductive seasonality, settlement and recruitment for keystone habitat structuring species (limpets, barnacles and topshells). Warm-water topshells were particularly useful for monitoring the high-latitude distributional range limits, by means of replicated timed searches (Mieszkowska *et al* 2007) and the aging of *Monodonta lineata* (subsequently *Osilinus* and now *Phorcus lineatus*) (Kendall 1987).

2.2 MarClim Project

The three strands above were woven together into the MarClim project. Originally the ACFOR scale was used to enable comparability with Crisp and Southward, but in later surveys 'Superabundant' was added at the explicit request of JNCC. The 2001 checklist of species has been extended to include invasive non-native species highlighted by the UK Marine Aliens Project[12] as being of high invasion risk and also warm-water species with origins in the Mediterranean and low-latitude regions of higher environmental temperature that have, or are likely to cross the English Channel and established populations in south-west England.

Random 5cm x 5cm barnacle quadrats at high-, mid- and low-shore were used from 1997 onwards when the barnacle time–series study was re-started and transitioned to digital quadrat photographs from 2003 onwards. Random 50cm x 50cm quadrat counts of limpets are made in the midshore region in England, Wales and Scotland to quantify the relative abundance of the warm-water Lusitanian *Patella depressa* and cold-water boreal *Patella vulgata* that co-occur along much of the coastline of England and Wales. Searches were modified to replicate searches of 5 x 3 minutes for the warm-water Lusitanian topshells *P. lineatus* and *G. umbilicalis*. The SAMS team have added methodologies based on photographing quadrats to quantify cover of conspicuous species of barnacles, limpets and fucoid algae for associated work in Scotland.

The MarClim protocols in use since 2002 comprise five discrete elements:

1) Metadata collection for each survey site (date, site name and location, GPS, weather, sea conditions, names of recorders);

2) SACFOR (ACFOR pre-2005) categorical scoring of abundance for a list of climate sensitive, ecologically important (major canopy algae, space occupiers, predators) and non-native species;

3) Five replicated timed 3-minute searches of the topshells *Phorcus lineatus* and *Gibbula umbilicalis* at sites with suitable habitat for these species;

[12] http://www.marlin.ac.uk/marine_aliens/

4) Ten replicated 50cm x 50cm quadrat counts of the abundance of limpets identified to species, rock slope plus cover of barnacles, mussels, fucoids identified to species level. These quadrats are placed on the mid shore of areas without major fucoid cover or rockpools;

5) Ten replicated digital photographic 5cm x 5cm quadrats in each of the high, mid and lowshore zones. Abundance of barnacles identified to species and lifestage level determined using image analysis software.

For the purpose of the GES indicators proposed in Section 1, only elements a) and b) below will be utilized to record data for the derivation of the MSFD indicators for climate change, water quality, wave exposure and invasive species. The methodology for the SACFOR survey is explained in detail below.

2.2.1 Metadata collection

Before the survey is commenced the lead surveyor records the following parameters:
1) Site name
2) County and Country
3) Date
4) Recorders names and affiliations
5) Location using latitude/longitude in WGS84 format of the access point (e.g. car park) and the centre of survey area (e.g. midshore)
6) Score the exposure scale of the shore (using Ballantine (1961) exposure scale).
7) Weather at the time of the survey
8) Extent of lowshore accessible (i.e. full, partial due to large swell)

Digital photographs of the following elements are taken:
1) Site access
2) Overall site extent
3) Features of interest – particularly whole-shore photographs to show algal cover
4) Rare or unusual species, species of conservation interest

These metadata are collected on every site visit to ensure that subsequent surveys are always carried out at the same location and that lack of access to the lowshore due to adverse weather or sea conditions, which will affect the number of kelp and red algal species recorded, is taken into consideration during data analyses. Photographic specimen recording allows species records to be queried and taxonomically verified for rare, unusual or invasive species.

2.2.2 SACFOR categorical abundance scoring of MarClim species list

The following methodology is used to score the data:

1) Survey the whole of the sampling area to ensure all species that are present have been encountered. Using the MarClim species checklist, allocate a SACFOR category to each species (see Table 8 and Table 9) based on their maximum abundance within the area (habitat) in which they are typically found. The SACFOR category should be based on the locality in which the species is most abundant, bearing in mind that this might be a patch of habitat as small as 10m x 10m. As an example, for rockpool species such as *Sargassum muticum* the SACFOR score is based on their abundance within all suitable rockpools, not across the entire survey site. If there is only one rockpool, the species can still be Superabundant if it reaches the appropriate abundance (e.g. 80% or above for *S. muticum* within that one pool.

2) Record apparent absences in the ‘Not Seen’ category.

3) Use the notes section of the form for additional observations.

4) A MarClim site visit with records for all MarClim species should take approximately two hours for a team of two surveyors. The additional quantitative indicators (counts and digital photographs of northern and southern species of limpets and barnacles, replicated timed searches of trochids) would be worth doing if a site was visited to track climate-change responses. Thus these surveyors for two hours are required for a complete MarClim survey

Table 8. MarClim SACFOR species list; additional species are shown in **bold** typeface.

Species	Functional Group	Climate affinity	Shore Height	Habitat	SACFOR Table #
Codium spp.	Macroalgae	Warm water/ Invasive	Midshore, Lowshore	Rockpools, Open rock	1
Laminaria hyperborea	Macroalgae	Cold water	Lowshore	Rockpools, Open rock	1
Laminaria digitata	Macroalgae	Cold water	Lowshore	Rockpools, Open rock	1
Saccharina latissima	Macroalgae	Cold water	Lowshore	Rockpools, Open rock	1
Laminaria ochroleuca	Macroalgae	Warm water	Lowshore	Rockpools, Open rock	1
Alaria esculenta	Macroalgae	Cold water	Lowshore	Rockpools, Open rock	1
Himanthalia elongata	Macroalgae	Warm water	Lowshore	Rockpools, Open rock	1
Sargassum muticum	Macroalgae	Invasive	Midshore, Lowshore	Rockpools	1
Ascophyllum nodosum	Macroalgae	Cold water	Highshore, Midshore	Open rock	1
Pelvetia canaliculata	Macroalgae	Cold water	Highshore	Open rock	1
Fucus spiralis	Macroalgae	Cold water	Highshore	Open rock	1
Fucus vesiculosus	Macroalgae	Cold water	Midshore	Open rock	1
Fucus serratus	Macroalgae	Cold water	Midshore, Lowshore	Open rock, Rockpools	1
Fucus distichus	Macroalgae	Cold water	Midshore	Open rock	1
Cystoseira spp.	Macroalgae	Warm water	MIdshore, Lowshore	Rockpools	1
Halidrys siliquosa	Macroalgae	Cold water	MIdshore, Lowshore	Rockpools	1
Bifurcaria bifurcata	Macroalgae	Warm water	Highshore, Midshore, Lowshore	Rockpools	1
Mastocarpus stellatus	Macroalgae	Cosmopolitan	Lowshore	Open rock, Rockpools	1
Chondrus crispus	Macroalgae	Cosmopolitan	Midshore, Lowshore	Open rock, Rockpools	1
Lichina pygmaea	Macroalgae	Cold water	Highshore	Open rock	2
Undaria pinnatifida	Macroalgae	Invasive	Lowshore	Open rock	1
Dictyopteris polypodioides	Macroalgae	Warm water	Lowshore	Rockpools	1
Calliblepharis jubata	Macroalgae	Warm water	Midshore	Rockpools	1
Chondracanthus acicularis	Macroalgae	Warm water	Midshore, Lowshore	Open rock	1
Asparagopsis armata	Macroalgae	Invasive	Midshore, Lowshore	Rockpools	1
Colpomenia peregrina	Macroalgae	Invasive	Midshore, Lowshore	Open rock, rockpools	1
Saccorhiza polyschides	Macroalgae	Warm water	Lowshore	Open rock	1
Grateloupia turuturu	Macroalgae	Invasive	Midshore, Lowshore	Rockpools	1
Halichondria panicea	Invertebrate	Cold water	Midshore, Lowshore	Overhangs, Crevices, Underboulders	7

Species	Functional Group	Climate affinity	Shore Height	Habitat	SACFOR Table #
Hymeniacidon perleve	Invertebrate	Warm water	Midshore, Lowshore	Overhangs, Crevices, Underboulders	7
Anemonia viridis	Suspension feeder	Warm water	Midshore, Lowshore	Rockpools, Crevices, Underboulders	7
Aulactinia verrucosa	Suspension feeder	Warm water	Midshore, Lowshore	Rockpools, Crevices, Underboulders	7
Actinia fragacea	Predator	Warm water	Midshore, Lowshore	Rockpools, Crevices, Underboulders	7
Actinia equina	Predator	Cold water	Highshore, Midshore, Lowshore	Rockpools, Overhangs, Crevices, Underboulders	7
Haliplanella lineata	Invertebrate	Invasive	Midshore, Lowshore	Rockpools, Overhangs, Crevices, Underboulders	7
Sabellaria alveolata	Suspension feeder	Warm water	Midshore, Lowshore	Open rock	6
Chthamalus stellatus	Suspension feeder	Warm water	Highshore, Midshore, Lowshore	Open rock	3
Chthamalus montagui	Suspension feeder	Warm water	Highshore, Midshore, Lowshore	Open rock	3
Semibalanus balanoides	Suspension feeder	Cold water	Highshore, Midshore, Lowshore	Open rock	3
Balanus crenatus	Suspension feeder	Cold water	Lowshore	Underboulders	3
Perforatus perforatus	Suspension feeder	Warm water	Lowshore	Overhangs, Crevices, Underboulders	3
Austrominus modestus	Suspension feeder	Invasive	Highshore, Midshore, Lowshore	Open rock	3
Pollicipes pollicipes	Suspension feeder	Warm water	Midshore, Lowshore	Crevices, Open rock	3
Mytilus spp.	Suspension feeder	Cold water	Highshore, Midshore, Lowshore	Open rock, Crevices, Rockpools	6
Clibanarius erythropus	Invertebrate	Warm water	Midshore, Lowshore	Dead *Nucella lapillus* shells	5
Haliotis tuberculata	Grazer	Warm water	Midshore, Lowshore	Open rock, Underboulders	7
Testudinalia testudinalis	Grazer	Cold water	Midshore	Open rock, Underboulders	4
Patella vulgata	Grazer	Cold water	Highshore, Midshore, Lowshore	Open rock	4
Patella depressa	Grazer	Warm water	Midshore, Lowshore	Open rock	4
Patella ulyssiponensis	Grazer	Warm water	Midshore, Lowshore	Open rock, Rockpools	4
Ansates pellucida	Grazer	Cold water	Lowshore	Macroalgal stipes in Lowshore	4
Gibbula umbilicalis	Grazer	Warm water	Midshore, Lowshore	Open rock, Underboulders	5

Species	**Functional Group**	**Climate affinity**	**Shore Height**	**Habitat**	**SACFOR Table #**
Gibbula pennanti	Grazer	Warm water	Lowshore	Open rock, Underboulders	5
Gibbula cineraria	Grazer	Cold water	Lowshore	Open rock, Underboulders	5
Phorcus lineatus	Grazer	Warm water	Highshore, Midshore	Open rock, Underboulders	5
Calliostoma zizyphinum	Grazer	Warm water	Lowshore	Overhangs, Crevices, Underboulders	5
Littorina littorea	Grazer	Cold water	Highshore, Midshore	Open rock, Underboulders	4
Littorina saxatilis agg.	Grazer	Cold water	Highshore	Open rock, Crevices, Dead barnacle tests	5
Melarhaphe neritoides	Grazer	Warm water	Highshore	Crevices, Dead barnacle tests	5
Nucella lapillus	Predator	Cold water	Lowshore	Open rock, Crevices, Overhangs, Underboulders	5
Onchidella celtica	Grazer	Cold water	Midshore	Open rock, Crevices	4
Crassostrea gigas	Suspension feeder	Invasive	Midshore, Lowshore	Open rock	6
Crepidula fornicata	Suspension feeder	Invasive	Lowshore	Open rock, Underboulders	4
Botrylloides violaceus	Suspension feeder	Invasive	Lowshore	Crevices, Overhangs, Underboulders	7
Corella eumyota	Suspension feeder	Invasive	Lowshore	Overhangs, Underboulders	7
Dendrodoa grossularia	Suspension feeder	Warm water	Lowshore	Crevices, Overhangs, Underboulders	7
Asterocarpa humilis	Suspension feeder	Invasive	Lowshore	Crevices, Overhangs, Underboulders	7
Didemnum vexillum	Suspension feeder	Invasive	Lowshore	Open rock, Crevices, Overhangs, Underboulders	7
Asterias rubens	Predator	Cold water	Lowshore	Open rock	5
Leptasterias mulleri	Predator	Cold water	Lowshore	Open rock	5
Paracentrotus lividus	Grazer	Warm water	Lowshore	Rockpools	5
Strongylocentrotus droebachiensis	Grazer	Cold water	Lowshore	Open rock	5
Watersipora subtorquata	Suspension feeder	Invasive	Lowshore	Overhangs, Underboulders	7

Table 9. SACFOR categorical boundaries for functional groups within MarClim species list.

SACFOR Category / Functional Group	Table number	Super-abundant	Abundant	Common	Frequent	Occasional	Rare	Not Seen
Macroalgae	1	80%+ cover	40-79% cover	10-39% cover	5-9% cover	2-4% cover	Only 1 or 2 plants	0
Lichina pygmaea	2	80%+ cover	40-79% cover	10-39% cover	5-9% cover, Large scattered patches	Widely scattered patches all small	Only 1 or 2 patches	0
Barnacles	3	300+ individuals per 0.01 m2, 3-4 cm^2	100-299 per 0.01 m2, 1-3 per cm^2	10-99 per 0.01 m^2	1-9 per 0.01 m^2	1-99 per m^2	<1 per m^2	0
Limpets, Winkles	4	10+ individuals per 0.1 m^2	5-9 per 0.1 m^2	1-4 per 0.1 m^2	5-9 per m^2	1-4 per m^2	<1 per m^2	0
Dogwhelks, Topshells, echinoderms	5	5+ individuals per 0.1 m^2	1-4 per 0.1 m^2	5-9 per m^2, sometimes more	1-4 per m^2, locally sometimes more	Less than 1per m^2, locally sometimes more	Always less than 1 per m^2	0
Blue mussels, Sabellaria, oysters	6	80% + cover	40-79% cover	10-39% cover	5-9% cover	2-4% cover	1% or less	0
Sponges, ascidians, hydroids	7	Present on 80%+ of suitable surfaces	Present on 40-79% of suitable surfaces	Present on 10-39% of suitable surfaces	Present on 5-9% of suitable surfaces	Small patch or single sprig in 0.1 m^2	Less than 1 patch over strip; 1 small patch or sprig per 0.1 m^2	0

Over the years other algae have been recorded on an ad-hoc basis and now would be a good time to add these to the MarClim list: *Cladophora rupestris, Cladostephus spongiosus, Auduoinella (Rhodochorton)* (all indicative of sediment loading); *Ulva lactuca* and *Ulva* spp. (formerly *Entromorpha* spp., which is indicative of disturbance and nutrient loading), *Palmaria palmata* (indicative of disturbance on open rock as mid successional species), *Dilsea carnosa, Lomentaria articulata* (turf forming), *Gastroclonium ovatum* (turf forming species), *Osmundea osmunda*.

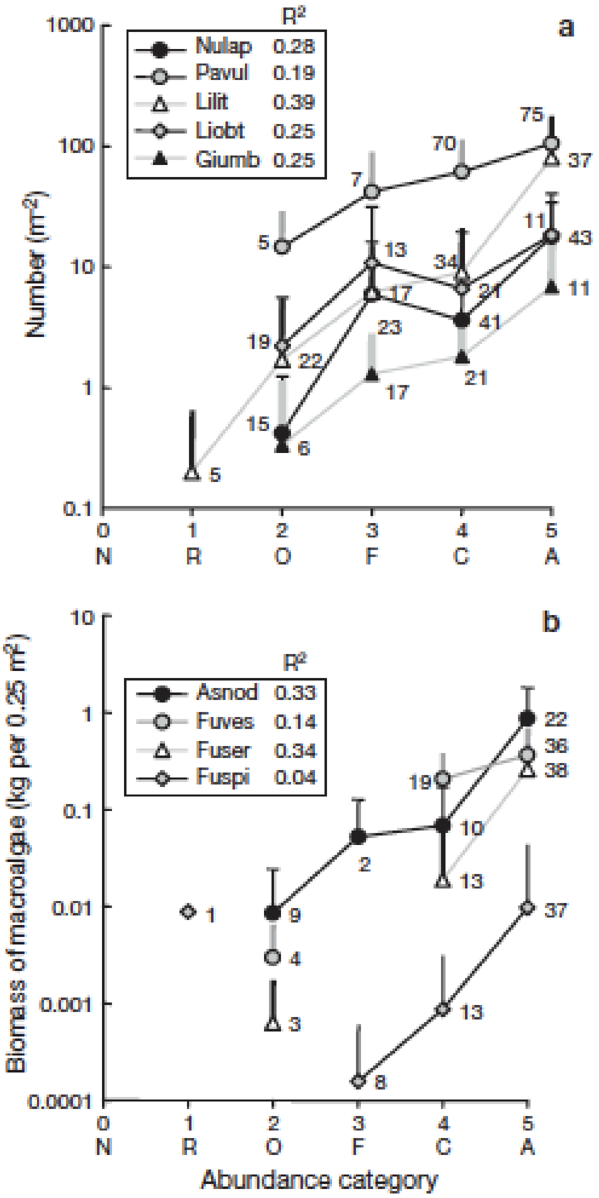


Figure 26. Independent verification of accuracy of MarClim surveyor attribution of SACFOR categories with quadrat counts of absolute abundance – i.e. the actual number of individuals within each quadrat (from Burrows *et al* 2008). (a) Average counts of 4 gastropod species from digital images of 0.25m^2 quadrats (4 quadrats at MTL +0.5m and MTL -0.5m), and (b) average wet weights of macroalgae removed from 0.25m^2 quadrats, for different abundance categories. Symbols show mean values over the number of shores indicated. Error bars show the standard deviation of the mean. Abbreviations: Nulap, *Nucella lapillus*, Pavul, *Patella vulgata*, Lilit, *Littorina littorea*, Liobt, *Littorina obtusata*, Asnod, *Ascophyllum nodosum*, Fuves, *Fucus vesiculosus*, Fuser, *Fucus serratus*. R^2 values give the proportion of variation in measured abundance explained by categorical abundance estimates.

The semi-logarithmic nature of the SACFOR scale essentially transforms non-linear data onto a linear scale on the x-axis of Figure 26. This shows that the rapid assessment method is a good predictor of abundance as measured in more labour-intensive replicate quadrats. Quadrat-based estimates of abundance for MarClim species were made independently of SACFOR assessments during MarClim surveys by the SAMS team from 2002 to 2006 (and continue in similar surveys to date). Average abundance was calculated in quadrats for five gastropod molluscs and four macroalgae, for each SACFOR abundance category. Thus, *Patella vulgata* was present at an average density of 100/m^2 at sites where SACFOR-assessed abundance was ‘Abundant’. All species examined declined in abundance in quadrats over progressively less-abundant categories. Discrimination between ‘Common’ and ‘Frequent’ for *Nucella lapillus* and *Littorina obtusata* was not reflected in quadrat-based counts, but these were based on relatively few (n=8) randomly placed 0.25m^2 areas in the mid shore, and may not have the fully integrative nature of the SACFOR whole-shore assessments. A further point to note is the lack of quadrat-estimates for species whose whole-shore SACFOR abundance was assessed as ‘Occasional’ and ‘Rare’. Plants and animals rarely occur in quadrats at such low densities and yield many zero values unamenable to formal statistical analysis by methods such as Analysis of Variance.

Highshore species:
L. pygmaea
P. canaliculata
F. spiralis
M. neritoides
L. saxatilis
C. montagui
C. stellatus
S. balanoides (N Wales & Scotland)
P. lineatus

Midshore species:
C. montagui
C. stellatus
S. balanoides
A. modestus
P. lineatus
G. umbilicalis
P. vulgata
P. depressa
P. ulysipponensis
F. vesiculosus
F. distichus
C. peregrine
M. stellatus
C. crispus
B. bifurcata
S. muticum
***Cystoseira* spp.**
H. siliquosa
D. polypodioides
C. jubata
A. armata
G. turuturu
A. equina
A. viridis
A. verrucosa
A. fragacea
H. lineata
S. alveolata
P. pollicipes
Mytilus spp.
C. erythropus
T. etstudinalis
L. littorea
O. celtica
C. gigas
P. lividus (Ireland)

Lowshore species:
C. stellatus
S. balanoides
A. modestus
G. umbilicalis
P. vulgata
P. depressa
P. ulysipponensis
C. peregrine
M. stellatus
C. crispus
B. bifurcata
S. muticum
Cystoseira spp.
H. siliquosa
L. digitata
L. hyperborea
L. ochroleucha
S. latissima
A. esculenta
S. polyschides
U. pinnatifida
H. elongata
C. acicularis
S. alveolata
A. armata
H. panacea
H. perleve
A. viridis
A. equina
A. fragacea
B. crenatus
P. perforatus
Mytilus spp.
H. tuberculata
P. pellucida
G. cineraria
G. pennant
C. formicate
B. violaceus
C. eumyota
D. grossularia
A. humilis
D. vexillum
A. rubens
L. mulleri
S. droebachiensis
W. subtorquata

Figure 27. MarClim species and their typical habitats. Species found mainly in pools shown in **bold** typeface.

2.3 Adaptation of the MarClim time-series to provide data for Marine Strategy Framework Directive (MSFD) rocky intertidal indicators for GES

The MarClim SACFOR methodology was originally designed to detect the impact of changing climate (mainly temperature, but also wave action) on rocky intertidal species present on UK coastlines. The design of the time-series protocols does not, however, preclude it from being used to address other questions, including what the impacts of other anthropogenic pressures on the distribution and abundance of species and the resultant change in community structure and function. This is due to the large number of species in the MarClim list encompassing a range of trophic levels, functional groups, thermal ranges, vertical shore heights and microhabitats and covering a range of responses to major key environmental, anthropogenic and biological drivers.

For example, the MSFD climate change index (CCI) uses a subset of the MarClim species that are sensitive to temperature, but relatively insensitive to other pressures including wave exposure and sensitivity to chlorophyll *a*. This means that any observed change can be confidently ascribed to an effect of climate, and not to some other pressure. The CCI was derived as the ratio of the SACFOR abundance (converted into a numerical scale from 0-6) of a selected subset of warm-water species to the total abundance of warm- and cold-water species combined.

2.4 Strengths and weaknesses of the MarClim approach

2.4.1 Strengths

The survey methodology allows for rapid assessment of rocky shores with no additional laboratory-based follow up or taxonomic identifications, and therefore facilitates a high number of sites and a large geographic coverage to be achieved, whilst not compromising the quality of the data. Multiple long-term sites are being monitored around most of the UK rocky shoreline, facilitating local, regional and national scale comparisons of changes and trends within the species and communities. The continuation of the original methodology developed by Crisp and Southward (1958) (with the addition of the 'Superabundant' category in 2005) has allowed the 2000s data to be placed in a far wider temporal context with data spanning both cooler (1960s, 1970s, early 1980s) and warmer (1950s, 1990s, 2000s) decades.

The species selected are predominantly conspicuous species that are relatively easy to identify by taxonomically trained scientists. They include primary producers and primary and secondary consumers, reflecting the different trophic levels of the intertidal foodweb. The species are representative of the main ecological engineer taxa that set the structure and function of rocky shore habitats and communities across the vertical and latitudinal extent of the intertidal zone around the UK. For example, barnacles and brown fucoid algae are sessile species that can occupy large amounts of rock space. The balance in abundance between these species is set by environmental, anthropogenic and/or biological factors that have been extensively researched and reviewed in the scientific literature. Limpets can alter this balance by grazing newly settled algal propagules and juveniles, thereby providing space on which more barnacles can settle (Hawkins and Hartnoll 1983). In addition there are closely related species within these taxa that have phylogeographic origins in areas of cold- or warm-water across the North-east Atlantic Ocean. Therefore two species of barnacle from different geographic evolutionary origins may perform the same function on a shore, but may respond very differently to changes in climate. Species selection also accounts for the microhabitats within a rocky shore by selecting species living on open rock, pools, overhangs and crevices.

The MarClim species list therefore encompasses the trophic levels in the rocky intertidal food web, as well as a range of functional groups, species from warm and cold temperate thermal provinces, a range of habitat niches and vertical zones within the shore and invasive species, thus collating information at both the individual species and community level. This is one of the few sustained observing programmes that is able to do this for benthic species across large geographical scales.

2.4.2 Weaknesses

The Marclim methodology was devised for measuring broad-scale and long-term responses to climate change both temporally and geographically so care must be taken in extending the approach to detecting impacts at shorter timescales and smaller spatial scales.

The surveys need to be done by trained scientists with excellent natural history and taxonomic knowledge of the shores and species concerned. Most of the species identifications are reasonably easy, but identifying barnacles and limpets – the latter non-destructively – needs training and practice. It takes about one field season to get new staff up to standard on the identification skills and basic shore-craft to apply the SACFOR methodology consistently. There are risks of differences in estimates of abundance between operators, but this can be overcome by training, joint fieldwork and intercalibration between workers.

Most of the sites originally surveyed in the 1950s and revisited during the MarClim resurveys were on more-exposed shores fully saline sites with minimal human impacts as the main response to be detected was one of climate change. Increasing the coverage of sites to more-sheltered or less-pristine areas would enable other impacts to be assessed.

The MarClim species list deliberately excluded early successional and ephemeral species because of the focus on climate change responses and to avoid seasonal variation. A selection of such species could be included to broaden the scope of the methodology, but care would need to be taken in timing of surveys.

2.5 Scientific and policy outputs of MarClim

The MarClim and related projects have generated a wealth of scientific literature and policy related documents, listed here in reverse date order.

2.5.1 Publications

MIESZKOWSKA, N., MILLIGAN, G., BURROWS, M.T., FRECKLETON, R. & SPENCER, M. 2013 Dynamic species distribution models from categorical survey data. *Journal of Animal Ecology,* **82**:1215-1226.

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2.5.2 Policy & Government Commissioned Reports and Assessments

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2.6 Suggested MarClim MSFD Sampling Protocols

The protocol below is suggested for MSFD Sampling. Further work would involve field testing by MarClim team members working with agency staff.

Before you start at each site, record:

1) Site name and grid reference
2) County/Area
3) Date
4) Recorders names and affiliations
5) Latitude and longitude of access point (e.g. car park) and lat. & long. of centre of survey area (e.g. midshore) using WGS84
6) Exposure scale of the shore (from Ballantine 1961 1-10 exposure scale)
7) Weather at the time of the survey
8) Availability of lowshore at MLWS

At each site: Photographic metadata

1) Identify area to be sampled from existing site co-ordinates and images
2) Photograph approach to site
3) Photograph general view of the sample site
4) Photograph specific features of interest and any rare organisms/new records
5) Photographs MUST be catalogued as you take them: date, site location and aspect (and zone if relevant)
6) Note major features of the shore; bedrock, cobbles, boulders, sand scouring etc.

At each site: Quantitative Data for SACFOR

1) Walk the whole of the sampling area and using the checklist find the area/habitat where each species is most abundant.
2) Place five quadrats randomly within the area/habitat in which the species is most abundant. Where multiple species occur in the quadrat record all species present. Use sensible judgement, e.g. do not count all barnacles present in a 50cm x 50cm limpet quadrat.
3) See Table 9 for quadrat sizes to be used.

Site selection and counting methods

Counting Barnacles

1) Count barnacles at *low, mid* and *high* shore levels. ‘High shore’ is defined as that area 1m below the very top of the barnacle zone, mid shore in the middle of the barnacle zone, low 1m above the bottom of the barnacle zone.
2) Take 10 digital photographs randomly within the barnacle zone using a standard camera quadrat 5x5cm frame at each shore height. Take a photographic label at the start of each set of 10 photos with the date, location and shore height. Record the slope of the rock in the recording form for each quadrat.
3) Photographs MUST be catalogued in the field so that shore levels (low, mid and high) can be separated.

Counting Limpets and Associated Fauna and Flora

1) Count limpets at both *low-* and *mid-shore* levels
2) Use a 50cm x 50cm quadrat. Where possible this should be strung at regular intervals to facilitate counting and estimation of % cover of barnacles.
3) Areas with heavy shade, with pools and those that are heavily fissured should be avoided
4) Place the quadrat and record % cover of barnacles, mussels, dominant algae and bare rock. Record the number of individuals of *Osilinus lineatus, Gibbula umbilicalis* and *Nucella lapillus* present in the quadrat.
5) Count the total number of limpets >10mm and identify to species level. Confirm the identity of *Patella depressa* through checking all features (white tentacles, black foot, shell morphology).
6) Take high resolution photographs of each quadrat and record the shore height for each image.

Counting Topshells

1) Count *Phorcus lineatus* and *Gibbula umbilicalis* in the region of the shore that they are most abundant. *Osilinus lineatus* occurs upshore of *Gibbula umbilicalis* for a large part of the year but with overlapping vertical distributions.
2) The aim is to record abundance/structure of populations. As adults and year classes 0-2 often live in slightly different habitats a detailed search is required.
3) Make 5 replicated timed counts of 3 minutes duration at each shore.
4) Select a small area in the region of the shore where the species is most abundant. Pick all individuals off visible surfaces and sample under stones and in cracks and crevices for the juveniles. Search using this method for 3 minutes and place all individuals into a sealable sample bag. Count the number of individuals.

Before leaving, have one last walk around the sample site to confirm first impressions and check that all equipment and cameras have been collected from the shore.

A: MarClim Recording Forms

<u>Site name:</u> …………………. <u>Grid reference:</u> ………………….
<u>County:</u> …………………. <u>Lat long of access point:</u> ………………….
<u>Date:</u> …………………. <u>Lat long of centre of survey area:</u> ………………….
<u>Recorder:</u> …………………. <u>Exposure</u> ………………….
<u>Weather conditions:</u> …………………. <u>Low shore availability</u> ………………….

Species	**Quadrat size / timed search**	**% Cover**	**Abundance**	**SACFOR *assigned by MarClim team**	**Comments**
Laminaria hyperborea	1m x 1m				
Laminaria digitata	1m x 1m				
Saccharina latissima (L. saccharina)	1m x 1m				
Laminaria ochroleuca	1m x 1m				
Alaria esculenta	1m x 1m				
Himanthalia elongata	1m x 1m				
Ascophyllum nodosum	1m x 1m				
Undaria pinnatifida	1m x 1m				
Codium spp.	50cm x 50cm * + voucher specimen for species id				
Sargassum (Bactrophycus) muticum	50cm x 50cm				
Pelvetia canaliculata	50cm x 50cm				
Fucus spiralis	50cm x 50cm				
Fucus vesiculosus	50cm x 50cm				
Fucus serratus	50cm x 50cm				
Fucus distichus	50cm x 50cm				
Cystoseira spp.	50cm x 50cm				
Halidrys siliquosa	50cm x 50cm				
Bifurcaria bifurcata	50cm x 50cm				
Mastocarpus stellatus	50cm x 50cm				
Chondrus crispus	50cm x 50cm				
Lichina pygmaea	50cm x 50cm				
Asparagopsis armata	50cm x 50cm				
Grateloupia turuturu	50cm x 50cm				
Halichondria panacea	50cm x 50cm				
Anemonia viridis	50cm x 50cm				
Aulactinia verrucosa	50cm x 50cm				
Actinia fragacea	50cm x 50cm				
Actinia equina	50cm x 50cm				
Sabellaria alveolata	50cm x 50cm				
Mytilus spp.	50cm x 50cm				
Clibanarius erythropus	50cm x 50cm				
Haliotis tuberculata	50cm x 50cm				
Testudinalia (Tectura) testudinalis	50cm x 50cm				
Patella vulgata	50cm x 50cm				
Patella depressa	50cm x 50cm				
Patella ulyssiponensis	50cm x 50cm				
Calliostoma zizyphinum	50cm x 50cm				
Littorina littorea	50cm x 50cm				
Nucella lapillus	50cm x 50cm				
Onchidella celtica	50cm x 50cm				
Crassostrea gigas	50cm x 50cm				
Crepidula fornicata	50cm x 50cm				
Asterias rubens	50cm x 50cm				
Leptasterias mulleri	50cm x 50cm				
Paracentrotus lividus	50cm x 50cm				
Strongylocentrotus droebachiensis	50cm x 50cm				
Chthamalus stellatus	5cm x 5cm				
Chthamalus montagui	5cm x 5cm				
Semibalanus balanoides	5cm x 5cm				
Perforatus (Balanus) perforatus	5cm x 5cm				
Austrominus (Elminius) modestus	5cm x 5cm				
Littorina saxatilis agg.	5cm x 5cm				
Melarhaphe neritoides	5cm x 5cm				
Gibbula umbilicalis	5 x 3 minute timed search				
Gibbula pennanti	5 x 3 minute timed search				
Gibbula cineraria	5 x 3 minute timed search				
Phorcus (Osilinus) lineatus	5 x 3 minute timed search				
Corella eumyota	5 x 3 minute timed search				

B: Barnacle count from photographic 5cm x 5cm images (done by MarClim team)[13]

Highshore Barnacle Count: Recorder: ………………….

Quadrat size: …………………. Lat long of centre of survey area: ………………….

Quadrat	Shore Height	% Cover barnacles	Adult count (1+)					Recruit count (O)			
			SB	CM	CS	EM	PP	SB		Total C	EM
								Cy	Sp		
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											

Midshore Barnacle Count: Recorder: ………………….

Quadrat size: …………………. Lat long of centre of survey area: ………………….

Quadrat	Shore Height	% Cover barnacles	Adult count (1+)					Recruit count (O)			
			SB	CM	CS	EM	PP	SB		Total C	EM
								Cy	Sp		
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											

Lowshore Barnacle Count: Recorder: ………………….

Quadrat size: …………………. Lat long of centre of survey area: ………………….

Quadrat	Shore Height	% Cover barnacles	Adult count (1+)					Recruit count (O)			
			SB	CM	CS	EM	PP	SB		Total C	EM
								Cy	Sp		
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											

[13] Abbreviations within the following tables: Semibalanus balanoides (SB), Chthamalus montagui (CM), Chthamalus stellatus (CS), Elminius modestus (EM), Perforatus perforatus (PP), Cyprid stage (CY), Spat stage (SP), Count (C), *Nucella lapillus* (Nl), *Gibbula umbilicalis* (Gu) and *Phorcus lineatus* (Pl).

C: Limpet Count in situ from 50cm x 50cm quadrats[14]

Shore height: Midshore Recorder: ………………….

Quadrat size: …………………. Lat long of centre of survey area: ………………….

Quadrat	x slope	% barnacles	% mussels	% algae	Nl	Pl	Gu	Count		
								P. depressa	***P. vulgata***	***P. ulysipp***
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Shore height: Lowshore Recorder: ………………….

Quadrat size: …………………. Lat long of centre of survey area: ………………….

Quadrat	x slope	% barnacles	% mussels	% algae	Nl	Pl	Gu	Count		
								P. depressa	***P. vulgata***	***P. ulysipp***
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

D: Topshell 3 minute timed counts

Recorder: ………………….

Surveyor name: …………………. Lat long of centre of survey area: ………………….

Sample	Shore Height	Total Count	
		Phorcus lineatus	*Gibbula umbilicalis*
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Notes:

[14] Abbreviations within the following tables: Semibalanus balanoides (SB), Chthamalus montagui (CM), Chthamalus stellatus (CS), Elminius modestus (EM), Perforatus perforates (PP), Cyprid stage (CY), Spat stage (SP), Count (C), *Nucella lapillus* (Nl), *Gibbula umbilicalis* (Gu) and *Phorcus lineatus* (Pl).

3 New methods for data collection and collation

3.1 Summary

Although the basic methodology for surveying rocky intertidal communities adopted by the MarClim project has remained purposefully unaltered since the 1950s, new methods for recording, storing and sharing digital images and for locating survey positions offer ways of supplementing and improving data collected during surveys. This section aims to review recent technological advances and their potential utility for rocky intertidal surveys.

Most of these advances represent ways of doing things that were previously possible but prohibitively expensive or time consuming, and are now achieved by single relatively cheap handheld devices. GPS-enabled digital cameras provide images that are automatically located, and thereby much more easily catalogued and retrieved by time and location of surveys. Smartphone ID guides can help inexperienced surveyors with uncertain species identification. Smartphone wildlife recording applications (‘apps’) can also enable non-experts to contribute species records to specific projects, such as checking for range extensions, and can help more experienced researchers confirm species records by sharing these images with a wider community.

Biotope location and extent can be more easily delineated by GPS recording systems; allowing points on the periphery of habitats to be located. Biotopes and the cover of habitat-forming species can potentially be directly recorded using unmanned aerial vehicles (UAVs – also known as remotely piloted aircraft, RPAs). There have been some experiments using low flying UAVs to get images of sufficient resolution (c. 1cm) that allow confident identification from the air. Such systems look promising but need further development and cross calibration with existing methods for routine use.

The authors recommend that handheld imaging and location-sensing devices, along with aids to species identification and quality assurance of species data (GPS cameras and Smartphone apps) be used to supplement current expert-based survey methods. Existing technology (quadrats, measuring devices), however, will be always needed. Low-level aerial photographic surveys are likely to become an important tool for intertidal surveying, but some development of these methods is still needed.

3.2 Introduction

It has been extremely important in assessments of intertidal communities to maintain as much continuity as possible with the methods of the earlier researchers of the mid-20th century. That said, existing methods of data collection have been supplemented by the onset of new technology in various ways. For example, photographic methods for recording species abundances were very expensive and slow before the advent of cheap digital photography. Counts of taxa such as barnacles from digital images are now routinely part of quantitative assessments. Regular consideration of new technologies is therefore important for continued cost-effective monitoring. This Section considers some new technological developments and their potential for inclusion in intertidal monitoring. Technology has been rapidly advancing over the last two decades, particularly in the in-situ collection of data and the storage and analysis of digital images for measuring species abundance, recording presence and absence of species, and recording the appearance of unidentified species for later identification and/or checking by experts.

Digital photography can speed up the use of quantitative surveying of quadrats for cover of major species and functional groups. As part of other studies the SAMS group have routinely done this is as an add-on when doing MarClim related surveys. Adopting such an approach would enable quantitative data on cover of major species and functional groups at various biologically defined zones on particular shores. For most locations, surveying the upper eulittoral (top barnacle, top fucoid zone), mid-eulittoral (mid fucoid or mid barnacle/ mussel) and lower eulittoral (algal turf/ *Himanthalia*/ *Fucus serratus*) zones would be sufficient; but additional zones could be added at locations of special interest (e.g. low-shore open rock *Bifurcaria* and *Cystoceira* zones in southwest England, low-shore kelp, and low-shore *Corallina* / *Patella ulyssiponensis* dominated areas). Such methodology works less well for non-destructive surveys of the under-storey of canopy dominated areas, because the canopy often completely obscures the bedrock, and only complete removal permits useful photographs to be taken; but can still be used where the overlaying plants can be pushed aside and when backed up by note-taking.

Consumer electronic devices have advanced to the stage whereby relatively affordable mobile phones are now powerful computers capable of storing and transmitting good quality images. Smartphones also tend to have embedded GPS receivers, and even traditional digital cameras are now appearing with similar GPS capabilities. GPS information combined with images removes one of the major obstacles to rapid indexing of digital images. Species ID guides and species recording apps also promise the possibility of instantly recording and communicating species identification data. In addition, GPS tagged digital images can be rapidly linked to GIS mapping products such as biotope maps to provide additional data as is currently being piloted by Natural England for the rMCZ evidence-gathering process.

However, as with conventional digital cameras, digital images from smartphones need careful curating and are only useful when accompanied by appropriate metadata. Specially designed apps may be able to tag such images in the field – ensuring that the correct sampling location, time, date and shore height/habitat are associated with each image. If this is not possible, cataloguing of images after they are downloaded into a computer can be achieved by cross reference to field notes and by the inclusion of handwritten labels or numerical tiles laid in the corner of the field of view when the image is taken. In either case, a protocol for image curation and further processing is needed for proper quality assurance and control (QA/QC).

Challenging field conditions, often at remote sites, can render complex electronics quite useless, with waterproof notebooks and survey sheets remaining as reliable recording devices. These approaches are considered and recommendations made for effective deployment of new technology in the field and more rapid integration of field data into ecological databases.

Alongside these handheld electronic devices, the technology for recording and identifying the type and extent of habitats at smaller scales has been advancing rapidly, even since 2010. Accurate GPS receivers that record location can be very useful for delineating habitats or biotopes directly by experts in the field. However, the most significant development in this area has been the advent of Unmanned Aerial Vehicles (UAV), also referred to as Remotely Piloted Aircraft (RPA) that can record centimetre-scale resolution images of habitats over the typical extent of a MarClim survey (100-200m) and much larger areas if required. The extent and scale of such surveys are interlinked, but the potential for use of UAVs to quickly map and record intertidal rock communities is considerable.

Information is also presented on commercially available, mass-market consumer products and software as available at the time of writing (August 2013). These products are presented as examples and their inclusion in this report does not imply endorsement.

3.3 New methods for biological data recording

Several new technologies offer the potential to supplement existing MarClim methods in order to allow more cost effective and accurate monitoring of intertidal rock community condition. Aerial imagery cannot replace in-situ surveyor identification or measurement of individual species, but airborne imaging vehicles are able to rapidly cover large areas of intertidal habitat and provide visual outputs of suitable resolution to detect patches of habitat dominated by, for example fucoids, kelps and barnacles. Thus it would not replace ground surveys for these MSFD indicators where individual species, often of the same Genera require identification and numerical counts to be made. The advantages of using GPS-enabled cameras and smartphones to record and help identify species during in situ surveys is considered within this Section.

3.3.1 GPS cameras

A simple and useful addition to the field recorder's equipment is a GPS-enabled digital camera. While MarClim surveyors have been using GPS and digital cameras on intertidal surveys for more than a decade, the cataloguing and geo-location of images is a time-consuming process. Image catalogues are essential for the future use of images taken on surveys. These usually take the form of databases or spreadsheets with fields that give the image file name and storage location in the file system, with other fields giving the site name and the date and time that the picture was taken. These data are then usually linked dynamically to another table with the GPS location for each study site, matched to each image in the catalogue by the name and date or some other common field.

GPS-enabled digital cameras record the GPS location in the Exchangeable Image File Format (EXIF) header of each image, and this allows the latitude and longitude of the image to be extracted, bypassing the need to manually add the survey site information to the catalogue. While each image may still require the addition of a description in the image catalogue, the automatic recording of GPS information will dramatically reduce the time needed to prepare the image catalogue. A particularly impressive feature of current models of digital cameras is the close focus (1cm macro) ability, allowing high quality images of very small organisms, such as barnacles. One potential drawback is the higher demand on battery power made by the GPS receiver, and only trials of the equipment will tell whether this is a serious problem.

An additional advantage of the use of GPS-enabled cameras is for the collection and sharing of photographs of reference specimens with taxonomic experts. Images that are precisely located can be matched with particular habitats and localities, such as low or high shore, or wave-exposed or wave-sheltered habitats. This can narrow the possibilities for species ID, and can usefully give evidence for new species records outside the currently known geographical ranges. If such cameras become one of the main vehicles for data collection, a central depository for the resulting images would be a very useful resource, preferably accessible via the internet. Protocols for recording such images during surveys would also need to be developed.

3.3.2 Smartphone apps for wildlife recording

The potential for collection of species data by the public is rapidly expanding with the wide market penetration of smartphones, reaching 50% of the UK population and 60% of mobile phone users in 2013[15]. Most of these devices have the capability for photographs and sound recording, as well as the collection of GPS location data.

[15] http://www.newmediatrendwatch.com/markets-by-country/18-uk/154-mobile-devices

There are many apps for iOS, Android and other mobile operating systems that facilitate wildlife species recording. These roughly divide into (1) those that are purely aids to identification and (2) those that allow remote recording and transmission of species data to central servers. There are several online reviews of such apps and the following draws heavily on one published by the *Daily Telegraph*[16] detailing the World Wildlife Fund's (WWF) 'top ten' apps.

A key point here is that many of the existing apps can be used immediately and directly in the context of intertidal monitoring, without further expense. Deployment by field personnel employed in intertidal surveys for assessment of environmental status would offer a quick way of returning species records to a coordinating group for collation and checking. Inclusion of GPS data in image headers, an option for most smartphone cameras, would add credibility to images collected by non-specialists and the public in general. As part of a countrywide coordinated effort to collect information, like a British Garden Birds Survey[17], these user-submitted images could supplement expert-led surveys, and significantly extend the spatial coverage of species distribution maps.

3.3.3 Smartphone species identification guides

Printed species identification guides can be expensive and cumbersome to take on field surveys, but smartphones can hold many such guides and offer novel ways of species identification, such as playing bird song. The general approach is to offer pictorial information for each species, arranged in such a way as to facilitate identification. Some of these apps are free, and the cost of the paid apps ranges from very inexpensive (£1.69) to moderately expensive (£9.99).

Potential sources of error arise from the person taking the photograph being responsible for identification of the species based on comparisons with standard images. The accuracy therefore entirely depends on every individual's taxonomic skill and ability to match features of species between images. Here are some examples:

Butterflies of Britain and Ireland (by NatureGuides Ltd.)[18]

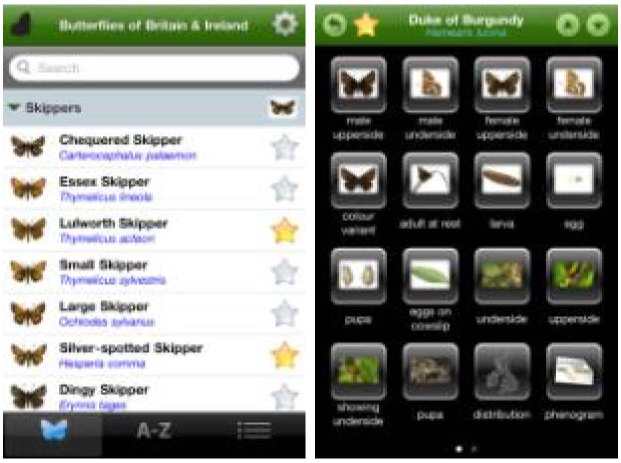

Figure 28. Screen capture from 'Butterflies of Britain and Ireland'

This app offers multiple images for each species and includes species distribution maps.

[16] http://www.telegraph.co.uk/technology/10026275/WWF-Wildlifes-Top-10-Apps.html
[17] http://www.bto.org/volunteer-surveys/gbw?gclid=CI76ms-akL8CFW3MtAodSSQAuQ
[18] https://itunes.apple.com/gb/app/butterflies-britain-ireland/id310574311?mt=8

Wild Mushrooms of North America and Europe[19] (by Roger Phillips (Lite) / Glen Byram) - Free

Figure 29. Screen capture from ‘Wild Mushrooms of North America and Europe’

The app has an interactive key, using onscreen sliders as switches for diagnostic morphological features.

Some guides offer links to online material, including recent sightings of rare species, such as the **BirdGuides** app (by NatureGuides Ltd.)[20].

Figure 30. Screen capture from ‘BirdGuides’

3.3.4 Smartphone species recording apps

Species recording apps are growing in number. The most promising and versatile of those seen is **Project Noah**. The following text is adapted from the Project Noah website.

Project Noah[21] is a species recording app that allows ‘citizen scientists’ to share their wildlife observations with each other and with science practitioners. It offers considerable promise in the way that users can join ‘missions’ that can be designed to target particular species and habitats.

[19] https://itunes.apple.com/gb/app/wild-mushrooms-north-america/id370634260?mt=8
[20] https://itunes.apple.com/gb/app/birdguides/id418131898?mt=8
[21] http://www.projectnoah.org/mobile

Figure 31. Screen images from ‘Project Noah’.

A recent BBC report on smart applications for wildlife recording mentions this app[22].

‘Project Noah is a global study that encourages nature lovers to document the wildlife they encounter, using a purpose built phone app and web community’.

Launched early last year, the developers behind the project aim to reconnect people with nature, while the Wall Street Journal commented that smartphones were the ‘butterfly nets of the 21st Century’ when it described the project.

"We‘ve helped people learn about organisms they never knew existed and we‘ve brought awareness to important work and research. We‘ve had visitors from 192 countries, nearly 94% of the world, and have photo submissions from all seven continents", says the project‘s founder Yasser Ansari. In addition to the virtual ‘collection’ of species, Project Noah encourages citizen science by linking up with existing surveys including the International Spider Survey and the Global Coral Reef Monitoring Network. By submitting time-stamped, geographically tagged photographs to the site, users can contribute data to official monitoring programmes and studies. Uptake seems relatively limited for missions, with recorders in the 100s rather than 1000s, but even with this level of participation the potential is excellent for the use of the app for intertidal species recording.

A quick search for ‘barnacle’ as a keyword within the Project Noah app gave 48 records, mostly from the west coast of the USA and Canada. Posts include generally excellent images, such as this one[23] (Figure 32) by user ‘PunkusArnett’ showing the goose barnacle *Pollicipes polymerus* on a rocky shore in the Juan de Fuca Strait. Images of similar quality would allow species identification and/or confirmation.

[22] http://www.bbc.co.uk/nature/13454621
[23] http://www.projectnoah.org/spottings/11249443

Figure 32. Smartphone-recorded image of *Pollicipes polymerus* as posted on the Project Noah website.

3.3.5 Potential disadvantages of the use of smartphone apps

Circumstances can render the use of smartphone apps impossible. Prolonged use in the field can exhaust smartphone batteries and, usually, no alternative power sources are available once the device battery is dead. While there are ways around this problem, such as spare batteries or external power sources, these involve greater planning and come at a cost of having to remember to make sure the devices are charged before setting out on a field expedition.

Use of smartphones in difficult field environments can pose problems too:

1) **Waterproofing -** Smartphones are rarely built to withstand extreme precipitation or wave splash.

2) **Readability -** Screens can become unreadable in very bright sunlight.

3) **Operation -** Wet or cold fingers can make it difficult to operate touchscreen displays. This problem may be exacerbated by adding waterproof casings and shock proofings.

The best option is to have reliable low-tech alternatives to smartphones and other sensitive equipment in circumstances where the high-tech options fail. Waterproof paper, notebooks, laminated photo ids and keys, and simple point and shoot cameras will therefore continue to be needed for field surveys. The indicators proposed in this report all derive from SACFOR data collected using MarClim methods. At present, use of new technology tends to be for the purposes of confirming and archiving images that may hold information for potential use for currently unforeseen monitoring needs.

Table 10. Uses of potential technological advances for proposed indicators.

Indicator	Parameter	Current method	Potential technological alternative	Notes
Climate change (CCI)	SACFOR abundance of climate indicator species	In-situ counting and visual assessment by trained experts	In-situ counting and visual assessment by surveyors using apps	Identification errors may occur due to surveyor ability to match species with photographic id guides. Regular confirmation of species identification by experts using voucher specimens or photographs would be needed.
Wave exposure (WXI)	SACFOR abundance of climate indicator species	In-situ counting and visual assessment by trained experts	In-situ counting and visual assessment by surveyors using apps	
Invasive Non-Native Species (NNI)	SACFOR abundance of climate indicator species	In-situ counting and visual assessment by trained experts	In-situ counting and visual assessment by surveyors using apps	
Biodiversity	SACFOR abundance of climate indicator species	In-situ counting and visual assessment by trained experts	In-situ counting and visual assessment by surveyors using apps	

3.3.6 Recommendations

The authors believe that the use of smartphone apps to supplement MarClim-type field recording will develop over the next few years. There is no currently available smartphone app equivalent to the 'Collins' pocket guide to the seashore', or more scholarly identification guides, so the smartphone cannot yet provide the necessary information to allow identification by uncertain surveyors. It is therefore recommended that the available software and hardware should be periodically reviewed and potentially suitable products regularly trialled. However, at this stage in the development of the technology and with the current practice of surveys it is not recommended to use such apps for GES monitoring.

Smartphone apps for general recording, such as Project Noah, are likely to enable a growing participation of 'citizen scientists' in the collection of additional data that will support the core sampling effort. These apps will provide information on changing species distributions, for example, and provide a quick way to share pictures for species identification by a growing community of enthusiastic people. Data collected in this fashion must be interpreted by experts (to QA the digital photographic records collected, given the wide range in taxonomic experience and skills and the high numbers of volunteers contributing records), and sites potentially revisited, before Good Environmental Status-related decisions can be made. Citizen science data may be useful in alerting the responsible agencies to potential problems or highlight areas that may be impacted or changing rapidly.

3.4 New methods for recording habitat extent

Among the limitations of the MarClim approach to intertidal surveying are that it does not explicitly define the spatial extent of a site, and that integrating abundance estimates across each site can be fairly subjective. Two important new technologies may help extend the

MarClim surveying approach and better match the biodiversity focused survey efforts with those that consider habitat extent.

3.4.1 Handheld GPS mapping solutions

Handheld GPS (Global Positioning System) units such as those made by Trimble in the UK offer varying degrees of accuracy from 10m to 5m and price ranges commensurate with accuracy. These tablet or smartphone-style electronic units facilitate the capture of submetre data with software workflows and optional VRS (Virtual Reference Station) corrections. For example, the Trimble® GeoExplorer® 6000 series is the latest in GNSS (Global Navigation Satellite System – a name for the type of system of which GPS is one). Combining submetre accuracy GNSS, high quality photo capture, wireless Internet, and connectivity options in a single product, the handheld unit is a field device for organizations mapping critical assets and infrastructure, or for those who require dependable submetre accuracy GNSS data, simple operation, and repeatable results. These units integrate all functions into a rugged, waterproof package: high-sensitivity GNSS, Windows® Embedded Handheld or Android operating system, Office applications, camera, and cellular connectivity on board. These GPS mapping tablet units use TerraSync™ and GPS Pathfinder® Office software to allow biotope, habitat and feature mapping in the field directly onto maps or aerial images, with the ability to directly email mapped products.

Data collected with Trimble field software can be post-processed at 50cm accuracy using the Trimble GPS Pathfinder® Office software or GPS Analyst™ extension for Esri ArcGIS Desktop software.

These units remove the requirement for transferring paper maps of biotopes drawn in the field to geo-referenced digital map products by a GIS (Geographical Information System) specialist. However, they only allow small areas to be mapped to the required resolution for phase 1 biotope mapping on the small screen and therefore slow down the in-field mapping process. They are also costly devices for intertidal surveys, currently retailing at around £5,000 for the handheld device and all necessary mapping and data software.

3.4.2 Remotely piloted aircraft for aerial surveys

Remote sensing is well established as the approach of choice for defining the extent and quality of land habitats but has rarely been applied for mapping marine habitats. This is not surprising given the opacity of seawater, but remote sensing and mapping from aerial platforms may be practical for very shallow waters and for intertidal areas.

Satellite images have proved effective for detecting kelp beds, either using Landsat imagery (Byrnes *et al* 2011), or high resolution visual imaging such as Spot 4 (Casal *et al* 2011). Aerial photography from aircraft has long been used to delineate kelp beds, and was notably used after the Second World War by the Scottish Seaweed Research Association to map kelp around Scotland (Walker and Richardson 1955). Use of aerial photography for mapping rocky intertidal communities is rare, though it has been useful for detecting long term change in *Ascophyllum nodosum* populations (Davies *et al* 2007). Aerial photography is expensive and difficult, and has not been generally used as a measurement or monitoring tool for habitat extent by ecologists for rocky shore habitats.

Recent developments in Unmanned Aerial Vehicle (UAV) technology have made the possibility of aerial surveys of intertidal areas a practical proposition. An experience with one such UAV (a Quest 200[24]), operated by the Marine Technology Group at the Scottish Association for Marine Science (SAMS) in June 2013 is described here. The aim of the

[24] http://www.questuav.com/

survey was to characterise the rocky shore in the immediate lee of the planned Lewis Oyster Wave Array, a planned wave power extraction device on the north coast of the island of Lewis. The work was done as part of the 'Terawatt' project, funded by the UK Engineering and Physical Sciences Research and coordinated by Heriot Watt University. The project aims to determine the environmental effects of the deployment of wave and tidal energy devices. SAMS' part in the project, coordinated by Mike Burrows, was to characterise the effects of extraction of wave- and tidal-energy on ecological communities. One of the goals of this work is to cross-validate the explicit assessment of habitat extent and abundance of large conspicuous species (such as macroalgae and barnacles) from an aerial platform, with estimates of abundance made in randomly placed quadrats at defined shore levels, and categorical techniques (SACFOR) designed to give abundance estimates integrated over a large, but not specifically measured, area of shore.

This was a first attempt to use the UAV with a digital camera to survey rocky shores, and proved to be successful. The field survey took place over four days during which the two teams did aerial overflights and MarClim-style surveys of a number of rocky shores between Borve Melbost and the Butt of Lewis. The team on the ground made SACFOR abundance estimates and used photographic quadrats (0.25m^2 and 5x8cm^2) at three shore levels at eight separate locations. The UAV team flew six flights over three of the same survey sites as the ground team. The analysis of the results of this survey is not yet complete, and remains in development as part of the Terawatt research project.

The UAV flew a pre-programmed flight path over the survey site, designed to cover the site with a large (<100) number of overlapping aerial images. The flight path was determined after discussion with the ground team, and programmed into the onboard computer of the UAV. The flightpath took the UAV in a looping track along the shoreline (below), with the camera taking images of the shore every two seconds from an altitude of 30m whenever it entered the pre-defined survey area.

Figure 33. UAV flightpath (grey line) from a single flight over a section of rocky shore near Eorapaidh, Lewis. The UAV-mounted camera took images every 2s at the locations shown by the symbols. Black lines show tidal limits in shapefiles obtained from Ordnance Survey Open Data, with the open sea to the north-west of the map, and land to the south-east.

An important element of the aerial survey process is the deployment of ‘Ground Control Points’ (GCPs). These took the form of highly visible markers. 25cm-diameter white bucket lids with a large X made of black duct tape were used. A surveyor’s level was used to determine the elevation of these control points relative to the water level and each other. These data are used to improve the alignment of images and to provide a base level for the digital elevation model built during the photogrammetry procedure. GCPs were set out and surveyed by the ground team before the start of their ground-based survey.

Each flight began with a series of checks of the UAV. Weather conditions limited the flying capability of the aircraft, and a strong breeze and rain prevented flights on one day out of three possible days. Once the UAV was airborne it followed the flight plan, logging GPS locations every two metres and collecting images every 2 seconds. The flight gave between 120 and 180 images of the study site, each image covering an area of about 45m by 60m.

Figure 34. Preflight checks for the UAV, including checking the operation of control surfaces, at the launch site at Borve Melbost.

The example image below (Figure 35) illustrates the amount of visual detail discernible at this resolution. Barnacle covered rock is clearly distinguished from bare rock, and even the 2013 settlement of *Semibalanus balanoides* is evident as a lighter coloured barnacle zone. Individual *Fucus vesiculosus* plants are visible in the mid intertidal, and *Enteromorpha* can also be seen as a bright green fringe around the rock pools to the right of the image. Kelp appears as dark brown areas at the water’s edge towards the top of the image.

Post-processing of the images, GPS data and Ground Control Point (GCP) locations using photogrammetry software (Agisoft Photoscan Professional) produced both an ortho-photo and a digital elevation model of each survey site.

Figure 35. Aerial image of a rocky shore at Eorapaidh, North Lewis, taken from an altitude of 30m with a Panasonic Lumix LX5 on a Quest 200 UAV – covering an approximate area of 45m by 60m at a resolution of 1.5cm per pixel.

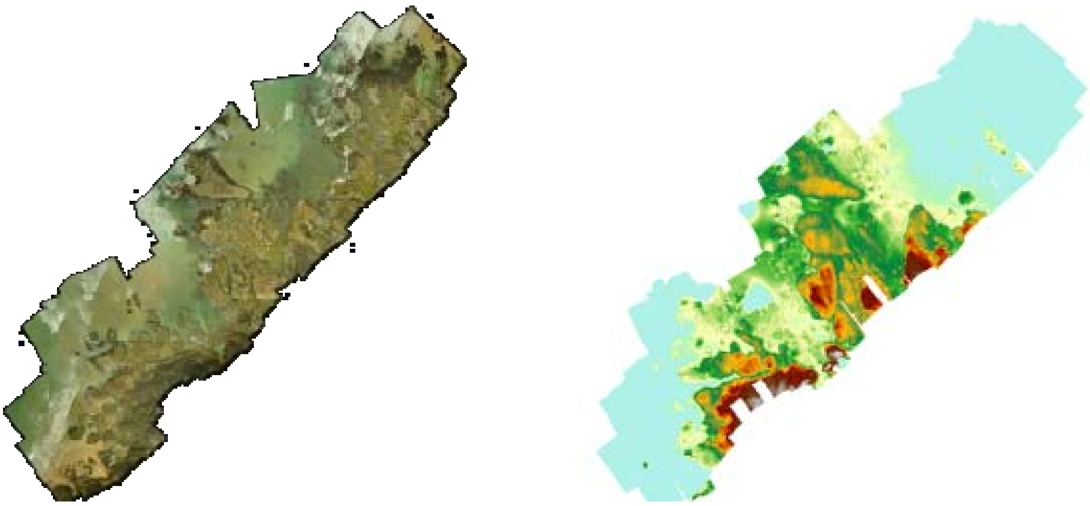

Figure 36. (left) Ortho-image of the rocky shore at Eorapaidh, (right) Digital elevation model of the same site.

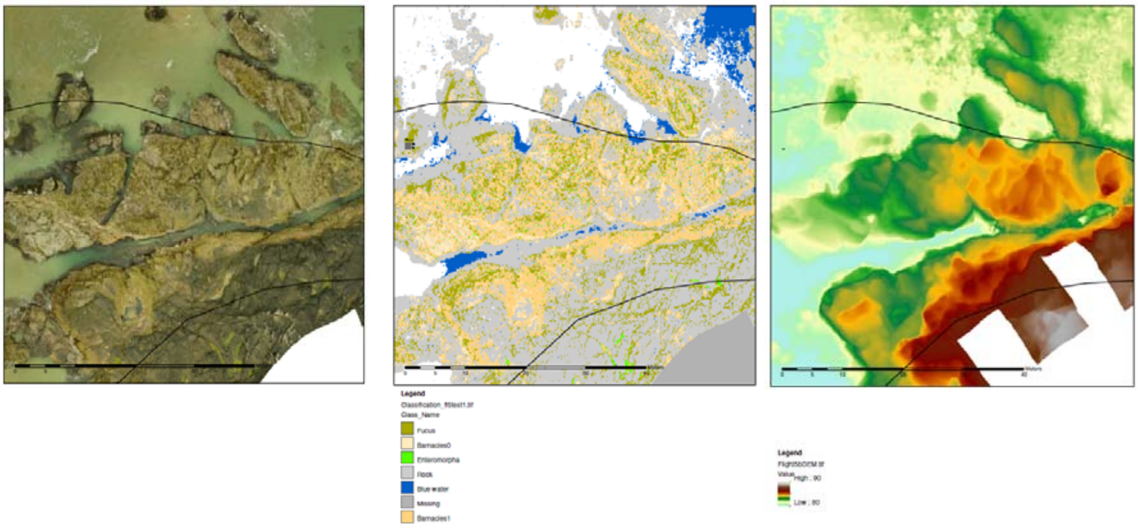

Figure 37. Processed data from the digital image: (left) Original image, (middle) Supervised pixel classification into distinct types of substratum cover, (right) Digital elevation model.

The resulting ortho-image can be processed using standard pixel classification techniques. The authors experimented with supervised pixel classification (above). This method involves identifying small areas of the image as training data for the rest of the image and was able to distinguish *Fucus,* barnacles settled in 2013 and older barnacles (mostly *Semibalanus balanoides)* and *Ulva (Enteromorpha)*, alongside bare rock and open water. Judging by the original image, the classification was moderately successful. Areas of deep shadow on the higher shore were mis-classed as *Fucus*, but most of the classes appeared plausible. The addition of a near-infrared sensor to the camera may improve the discrimination of the macroalgae from rock. This approach to monitoring intertidal areas is still in the very early stages of development, and cannot be seen as a substitute for species identification by trained surveyors on the ground. But the approach offers much for mapping biotopes and rapid quantification of the abundance of the dominant, habitat-forming species. It will not quantify the abundance of smaller mobile gastropod species, and is unlikely to be useful for tracking changes in species distribution limits. At this stage in the development of the technology, this approach will not directly contribute to the recording of data for the rocky shore indicator.

3.5 Recommendations for use of new technology

Much of the new technology assessed here remains outside of the current toolkit of expert surveyors of the rocky shore environment. The primary advances are in imaging and location systems, with new platforms such as smartphone and unmanned aerial vehicles offering most promise for the potential future collection of data to underpin the indicators proposed here. All of the technology reviewed here should be seen as a supplement to basic surveying equipment (quadrats and calipers) and expertise: the ability to recognise and identify species and habitats, and to use appropriate methods to quantify abundance and habitat extent. It is considered that this would be best done by having an expert-led survey at ground level, using the protocols outlined in Section 2. The continued development of new technology, especially for imaging and recording biodiversity data, can supplement the existing methods but are not yet sufficiently well integrated into or calibrated with monitoring approaches presently in use to replace the current protocols. Further research and development would be needed to achieve such integration and potential replacement of exisiting approaches.

The authors recommend that:

1) Digital imaging and recording technology and GIS/GPS technology should be used where possible to allow for species identification and abundance estimation after the field survey. Identification and counts for small attached species such as barnacles can be done this way therefore providing a) more time on the shore and b) digital records for quality assurance. The use of these technologies is outlined in the protocols for field data collection in Section 2 of this report.

2) New platforms for geo-located images (smartphones and UAVs) should be reviewed for their usefulness as primary surveying tools. UAVs offer considerable promise for routine assessment of intertidal habitat extent, including the status and condition of primary habitat forming species such as macroalgae, barnacles and mussels. Aerial surveys do, however, need ‘ground truthing’ to confirm the identity of these habitat formers. At this stage in the development of the data collection methods from UAVs, the platforms are not recommended as a method of collecting data to inform indicators. Over the next decade, these devices will become much more commonplace, and are likely to become a vital part of the field ecologist’s toolkit.

4 Implementing the Proposed System of Indicators

In this report a series of indicators of the status of biological communities on UK rocky shores have been developed that show how the abundance and diversity of conspicuous and easily identified species are responding to major environmental drivers. The methods outlined in Section 2 are designed to collect categorical species abundance (SACFOR) data for individual sites in a relatively rapid and repeatable way. The proposed approach is both compatible and comparable with efforts to define the biogeography of rocky shore species back to the 1950s, thereby offering the best chance of detecting significant change in a well-documented long-term context. It can also be supplemented by more quantitative studies of key climate indicators such as barnacles, limpets and trochids.

In this section, the authors briefly outline their view as to how the proposed indicators could be implemented as a coherent system of surveillance and monitoring for UK rocky shore habitats. Standard operating procedures are presented in Section 2.2 of this report.

4.1 Surveys and Data collection

The proposed indicators are based on the observed changes in species abundance and assemblage composition along environmental gradients. For example, combining the Water Quality Index (WQI, Section 1.6.3, p.19) and the macroalgal diversity index (*N*(algae), Section 1.7.2, p.35) demonstrates the change from diverse, macroalgae-dominated communities in clear-water conditions to communities with low species diversity, dominated by suspension-feeding invertebrates, in areas of poor-water quality characterised by increased phytoplankton and suspended sediment concentrations. In collecting these data during the main phase of the MarClim project (2001-2006), over 700 sites were surveyed around England, Scotland, Wales and Ireland, with 120 of these sites still surveyed on an annual basis across England and Wales. The authors recommend that these 700 sites form the basis of a network of sites where surveys (with a subset repeated annually) are repeated to assess the status of shores over broad regions. This will allow the collection of data to assess variability in indicator values at the level of individual sites. Variability in indicator values may be generated by several processes. Species occurrence and abundance in each location is strongly influenced by the availability and extent of suitable habitat, and the data collection method, like any other, is prone to some degree of measurement error. Furthermore, natural variability in populations of species, not related to the pressures that the indicators are designed to detect, results in a degree of natural variation (or ‘noise’) around the signal. For these reasons, the authors further recommend that surveys are formed into campaigns that span many sites, and that any changes in indicators are considered by comparisons across groups of sites, between different time periods and different areas, and not at the level of single sites. By taking this approach, broadscale climate-driven change in the biogeography of species can be segregated from regional and local impacts such as eutrophication, harvesting, recreational use leading to trampling, point source pollution, shifts in sediment supply and coastal development. Such an approach can also measure recovery from chronic (e.g. TriButylTin (TBT) pollution) and acute impacts such as oil-spills.

The spatial configuration of sets of survey sites should be assembled initially from the wider set of MarClim sites, but where this is not possible sites should be selected to be spatially discrete, separated by at least several kilometres. Survey sites should comprise, as far as possible, bedrock or very large stable boulders greater than 1m in diameter, over most, if not all, shore levels. Locations with only mobile boulders or with considerable sediment, such as sand or shingle over the lower or upper shore, should be avoided, since these may lack suitable habitats at some shore levels, may be prone to scouring or be unsuitable for long-lived species. For example, *Ascophyllum nodosum* (egg wrack or rockweed) is not generally found on boulders, even very large immobile ones. Such areas are likely to be highly naturally disturbed, be a mosaic of early- and mid-successional stages, have low diversity and be subject to natural disturbances. There are, however, some regions where rocky shores spanning the entire tidal range are rare, such as the eastern English Channel. In such areas, sites without the full range of habitats will have to be used with care.

Methods for data collection are comprehensively described in Section 2, with specific protocols and proforma data recording sheets given in Section 2.6. Given the taxonomic expertise required to identify many of the species and the training and cross-calibration required to ensure surveyors all select the same SACFOR category for the same abundance of each species, a period of training spanning several months is required.

The core MarClim check list of 57 species could usefully be expanded by adding some additional species such as non-native species, plus additional species that experience suggests would provide further information (i.e. species associated with sediment load *Cladostephus spongiosus, Rhodochorton*; or with disturbance *Ulva* spp., *Palmaria palmata*). The species list should still be manageable and consist mainly of ready identifiable species in the field.

4.2 Data processing and collation

Once data have been entered onto paper recording sheets, checked for obvious errors, and compared with digital camera photos for further validation or supplementary data (for making counts of barnacle densities, for example), these data should be transferred to the appropriate database entry software, using the currently recommended interfaces (Marine Recorder) and the Excel standard MarClim template spreadsheets and Access databases for quantitative barnacle and topshell counts for easy entry and editing. Data quality assurance should be performed on the electronic data before a copy is lodged with the Data Archive for Seabed Species and Habitats (DASSH).

The seven proposed numerical indices (climate change index (CCI), water quality index (WQI), water exposure index (WXI), non-native species index (NNI), total species diversity index (*N*(total)), macroalgal diversity index (*N*(algae)) and consumer/predator diversity index (*N*(other)); see Sections 1.6 and 1.7) are calculated from the integer equivalent values for the SACFOR categories (Super-abundant (S), Abundant (A), Common (C), Frequent (F), Occasional (O) and Rare (R)), such that S is represented by the number 6, A by 5, C by 4, F by 3, O by 2, R by 1 and absence (Not Seen (NS)) by zero. The community composition indices are formed by the relative abundance of contrasting groups of species responding positively and negatively to the pressure considered. Species richness indices are formed by adding the total number of species in each category whose abundance was recorded as at least rare. The calculation of these index values is easily achieved using simple spreadsheet formulae.

Many options are available for analysis once index values have been calculated, depending on the questions of interest. It is not possible to list all the possibilities exhaustively, but three major categories of treatment of data are described briefly below.

4.2.1 Comparison with past observations

A likely use of the rocky shore indicators is the comparison with historical values to judge, for example, whether rocky shore communities in a particular region or across a whole country are changing in response to increased water temperatures, in line with expectations under climate change. Where the data are obtained from single return visits to previously surveyed sites, the comparison can be based on paired data values for the past and current time periods. This approach has been taken by MarClim researchers (Simkanin *et al* 2005) to detect patterns of change on Irish shores from the 1950s to the 2000s, and permitted use of statistical methods to show which species changed significantly (with a probability of less than 5% that the change was as a result of random sampling of the same distribution), and which species changed, but by less than the operator error, as determined by repeated surveys by different teams. The teams recorded the same abundance category for each species 76% of the time, and within one category 83% of the time.

Where the survey sites are not at the same locations in each time period, for contrast, the comparison is much weaker, but statistical methods may help to separate the relative influence of differences in habitat among the sites selected in the two periods and the effect of a change in pressure. The temporal change due to the change in climate or water quality, for example, cannot be entirely separated from the effect of selecting different sites in the second period (the two effects are 'confounded' in statistical terms) and any apparent change in indicators between the two periods would need to be interpreted with care. This re-emphasises the need to revisit large numbers of previously surveyed sites as far as possible when attempting to detect change. Large numbers of sites allow simple binomial probability tests or tests comparing the cumulative frequency of occurrence of the categorical abundance of a particular species (e.g. Kolgoromov Smirnov 2-sample tests) along a stretch of coast (e.g. English Channel) or a whole country (e.g. Wales or Scotland).

4.2.2 Comparison among areas within and among regions

It may be necessary to judge a change in environmental status by comparing indicators from survey sites in different areas within a region or among regions, to detect the potential impact of a localised change in pressure, a local warming, such as in the southern North Sea, or a deterioration in water quality/change in pelagic primary productivity or suspended sediment load. In such circumstances, the ideal scenario would be to arrange surveys in areas anticipated as unaffected, or far from the localised pressure, and designate these as 'reference' sites to contrast them with those close to the local pressure as 'impact' sites. If prior data exists for all these sites then the design would conform to the requirements of a Before-After-Control-Impact (BACI) design. Ideally several surveys would exist prior to the disturbance and several after, considerably improving the chances of successfully detecting an impact that could be attributed to a particular change in pressure (the Beyond-BACI design: Underwood 1994).

A simpler approach may be just to make statements about whether one area exhibits more, or less, response to a particular pressure, and in this case simple unpaired statistical comparisons of mean values among groups of sites from different areas would suffice. It would be difficult to separate relative effects of differences in pressures from difference in habitat availability or extent among the different areas, but a straightforward comparison of values could be interpreted with care to allow judgement of more or less impacted areas.

4.2.3 Comparison with expectations from biogeographical trends

Where assessments are needed about environmental status where there is no past data from a reference area or period of time upon which to define a suitable baseline, there may be no other option than to compare observed communities with those expected for the environmental conditions – the '*prevailing physiographic conditions'* of MSFD Descriptor 1. Observed index values can be compared with expectations defined by regression models derived from the existing MarClim dataset (see Sections 1.6 and 1.7). Environmental status may be assessed by determining the difference between expected values and the observed values calculated on the basis of species abundance and presence as suggested in Section 1.9.1 and comparing this to an agreed target or limit of deviation from the expected value.

Equations for calculating expected values of the CCI (Equation 1, Figure 7 and Figure 8), WQI (Equation 2 and Figure 11), WXI (Equation 3 and Figure 14) and species richness measures: Ntotal (Table 4), Nalgae (Table 5) and Nother (Table 6) are provided.

Calculating these expected values requires the extraction of values for environmental predictors (February and November sea surface temperature (SST), wave fetch data, long-term average log10 chlorophyll *a* values) for the survey site locations. Normally this will be achieved by matching point data (the site locations) to gridded datasets of environmental variables. These datasets will be made available to practitioners who require this process.

Such an approach is equivalent to the River Invertebrate Prediction and Classification approach (RIVPACS) widely used in freshwater systems (Wright *et al* 2000); in essence deviation from a predicted expected state is used to judge whether status has been impacted in some way. This approach is more powerful if there are historical data which allow detrending of any broad-scale climate influences or the incorporation of such influences into prediction of the expected state, thereby providing a moving baseline accounting for the prevailing conditions at the time of assessment.

4.3 Interpretation and conclusions: Good Environmental Status?

Further progress is still required before these indicators can be translated into statements about achievement of, or failure to achieve, Good Environmental Status (GES) for the MSFD in Section 1.9.3. There is promise in comparisons of observed indicator values with those expected for the environmental conditions at each site, since this approach directly addresses Descriptor 1 of the MSFD (‘*Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions*’). What level of deviation or shortfall from expectations constitutes a failure to achieve GES is at present undefined, but is required to be set before further progress can be made. Whichever way this is defined, a key advantage of the entire approach outlined in this report is that the basic data can be reconfigured to suit future, and even as yet unforeseen needs for implementing conservation policies.

4.3.1 Proposed next steps

The following steps would take the proposed methodology forward.

1) Formal cross-calibration with teams experienced in the WFD methodology.
2) Trialling an expanded list of species during the 2014 routine MarClim surveys in south and south-west England and Wales.
3) Development of a list of sites for annual monitoring.
4) For those MarClim sites with repeated surveys but no known impacts, explore temporal variation.
5) The authors are currently looking to launch MarClim 2 on a multi-agency basis. Research and monitoring under MarClim 2 would complement the further development and implementation of GES indicators for rocky shores, and potentially deliver much of the information required for GES at the same time.

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Appendix 1

Table A1. Sensitivity of UK rocky shore species to three primary drivers of species abundance: temperature, wave exposure and water quality. Values presented are regression coefficients from multiple linear regression of abundance (as integer equivalents of ranked abundance categories, with satellite-derived estimates of local average February sea surface temperature (SST), wave fetch, and local average chlorophyll *a* concentration. Columns headed CCIndex, WQIndex and WXIndex shows the selection of species as contributing to the three indicators of climate change status, water quality status, and the wave exposed character of the survey. Full details of the analysis are given in Section 1.6. Data are sorted in order of decreasing association with wave-exposed conditions.

Abbreviation	Species	Intercept	b(FebSST)	b(W fetch)	b(Log chl a)	Abundance	CCindex	WQIndex	WXIndex
Pauly	*Patella ulyssiponensis*	-11.795	1.499	0.831	2.432	2.627	0	0	0
Maste	*Mastocarpus stellatus*	-3.713	0.614	0.682	0.577	2.758	0	0	1
Chste	*Chthamalus stellatus*	-9.558	1.279	0.665	0.091	1.969	0	0	0
Ladig	*Laminaria digitata*	1.461	0.113	0.625	-3.377	3.234	0	-1	1
Acequ	*Actinia equina*	-2.478	0.560	0.553	-0.527	3.133	1	0	1
Mener	*Melarhaphe neritoides*	-10.683	1.365	0.519	2.856	2.647	1	0	0
Hielo	*Himanthalia elongata*	-3.251	0.560	0.510	-3.456	1.578	1	-1	1
Alesc	*Alaria esculenta*	3.694	-0.403	0.444	-3.784	0.955	-1	-1	1
Padep	*Patella depressa*	-7.986	0.948	0.436	3.220	1.727	1	0	1
Oslin	*Osilinus lineatus*	-12.538	1.601	0.379	3.819	2.451	1	0	0
Samut	*Sargassum muticum*	-7.088	0.870	0.353	1.906	1.533	1	0	1
Bibif	*Bifurcaria bifurcata*	-6.377	0.784	0.351	0.786	1.203	1	0	1
Lisax	*Littorina saxatilis*	-7.923	1.076	0.340	4.023	3.496	0	0	0
Baper	*Balanus perforatus*	-7.235	0.894	0.327	1.780	1.458	1	0	0
Chcri	*Chondrus crispus*	-3.618	0.540	0.288	2.230	1.770	1	1	0
Hasil	*Halidrys siliquosa*	2.975	-0.258	0.237	-1.903	1.229	0	-1	0
Lahyp	*Laminaria hyperborea*	-2.046	0.274	0.216	-0.112	0.636	0	0	0
Nulap	*Nucella lapillus*	2.734	0.093	0.192	-2.051	3.589	0	-1	0
Hapan	*Halichondria panicea*	-1.071	0.313	0.187	-1.591	1.526	0	-1	0
Pavul	*Patella vulgata*	5.426	-0.177	0.185	-1.583	4.481	0	-1	0
Cospp	*Codium sp*	-2.192	0.331	0.174	-0.713	0.804	0	0	0
Anvir	*Anemonia viridis*	-6.080	0.795	0.159	2.322	1.050	1	1	0
Saalv	*Sabellaria alveolata*	-1.317	0.135	0.149	0.875	0.494	0	0	0
Acfra	*Actina fragacea*	-1.624	0.179	0.143	0.734	0.422	0	0	0
Gicin	*Gibbula cineraria*	-2.356	0.400	0.127	0.065	1.310	0	0	0
Cyspp	*Cystoseira spp.*	-2.860	0.355	0.116	0.709	0.560	0	0	0

Abbreviation	Species	Intercept	b(FebSST)	b(W fetch)	b(Log chl a)	Abundance	CCindex	WQIndex	WXIndex
Lipyg	*Lichina pygmaea*	-5.522	0.928	0.103	-0.308	1.914	1	0	0
Gipen	*Gibbula pennanti*	-0.594	0.064	0.102	-0.065	0.293	0	0	0
Fuser	*Fucus serratus*	4.167	-0.040	0.068	-1.530	3.915	0	-1	0
Bacre	*Balanus crenatus*	0.333	-0.064	0.066	1.151	0.416	0	0	0
Lasac	*Laminaria saccharina*	-2.123	0.319	0.063	0.575	0.617	0	0	0
Oncel	*Onchidella celtica*	-0.452	0.051	0.044	0.177	0.185	0	0	0
Chmon	*Chthamalus montagui*	-5.848	1.086	0.043	2.042	3.170	1	0	0
Myspp	*Mytilus edulis*	3.245	-0.148	0.039	0.255	2.427	0	0	0
Saspi	*Sabellaria spinulosa*	0.006	-0.011	0.034	0.166	0.082	0	0	0
Fuind	*Fucus inderterminate*	-1.181	0.160	0.016	0.466	0.541	0	0	0
Asrub	*Asterias rubens*	-1.065	0.163	0.013	0.371	0.384	0	0	0
Tetes	*Tectura testudinalis*	-0.040	0.004	0.011	0.098	0.079	0	0	0
Laoch	*Laminaria ochroleuca*	-0.100	0.012	0.008	0.002	0.016	0	0	0
Fudis	*Fucus distichus*	-0.069	0.008	0.002	0.048	0.011	0	0	0
Cahir	*Campecopea hirsuta*	-0.022	0.002	0.001	0.012	0.006	0	0	0
Clery	*Clibanarius erythropus*	-0.007	0.000	0.001	0.011	0.003	0	0	0
Hatub	*Haliotis tuberculata*	0.000	0.000	0.000	0.000	0.000	0	0	0
Stdro	*Strongylocentrotus droebachiensis*	0.000	0.000	0.000	0.000	0.000	0	0	0
Giumb	*Gibbula umbilicalis*	-9.909	1.519	-0.002	3.904	2.692	1	0	0
Lineg	*Littorina neglecta*	-0.738	0.096	-0.002	0.475	0.426	0	0	0
Lemue	*Leptasterias muelleri*	0.035	0.003	-0.021	-0.004	0.010	0	0	0
Paliv	*Paracentrotus lividus*	-0.576	0.100	-0.038	0.005	0.187	0	0	0
Caziz	*Calliostoma zizphinum*	-1.283	0.200	-0.042	0.134	0.379	0	0	0
Auver	*Aulactinia verrucosa*	-1.229	0.185	-0.058	0.383	0.269	0	0	0
Elmod	*Eliminius modestus*	-1.252	0.214	-0.235	4.899	1.198	0	1	0
Sebal	*Semibalanus balanoides*	10.505	-0.721	-0.245	-1.731	4.353	-1	-1	0
Lilit	*Littorina littorea*	7.322	-0.498	-0.387	1.916	3.238	-1	1	-1
Fuspi	*Fucus spiralis*	5.745	-0.256	-0.403	-0.852	3.022	0	0	-1
Fuves	*Fucus vesiculosus*	5.882	-0.300	-0.408	-0.193	2.929	0	0	-1
Asnod	*Ascophyllum nodosum*	4.500	-0.148	-0.658	0.044	2.180	0	0	-1
Pecan	*Pelvetia canaliculata*	7.418	-0.259	-0.883	-2.707	3.118	0	-1	-1

Appendix 2

Table A2. Selection criteria for inclusion as indicator species for the three community composition indices. To be considered for use as an indicator, species must have been relatively more sensitive to the target predictor variable than to the other two predictors. Thus for a species to be considered as a climate-sensitive species, its sensitivity to February sea surface temperature (SST) should exceed 0.4, and its sensitivity to wave fetch (Wave Exp) and chlorophyll *a* concentration (Log Chla) be less than 0.6 and 4 respectively. Values for each species are given in Table A1. Numbers of species selected as positive and negative contributors to each index are shown on the right hand side of the Table.

		Number of species		
	b-value	Positive contribution	Negative contribution	Total
Climate Change indicator				
Criteria		13	3	16
Abundance >	0.5			
Feb SST >	0.4			
Wave Exp <	0.6			
Log Chla <	4			
Water quality indicator				
Criteria		4	10	14
Abundance >	0.5			
Feb SST <	0.8			
Wave Exp <	1			
Log Chla >	1			
Wave exposure indicator				
Criteria		8	5	13
Abundance >	0.5			
Feb SST <	1			
Wave Exp >	0.35			
Log Chla <	5			

Appendix 3

SAS code for calculation of three indices: CCI (`ccindex` below), WQI (`wqindex`) and WXI (`wxindex`). Abbreviations for species as in Table A1.

```
data ccindex;
 set zeroreduced;
 pcold=sum(Alesc,Lilit,Sebal)/(3*5);

pwarm=sum(Acequ,Anvir,Baper,Bibif,Chcri,Chmon,Giumb,Hielo,Lipyg,Mener,Oslin
,Padep,Samut)/(13*5);
 ccindex=pwarm/(pcold+pwarm);
 cclogit=log10(ccindex /(1-ccindex));


plochla=sum(Alesc,Fuser,Hapan,Hasil,Hielo,Ladig,Nulap,Pavul,Pecan,Sebal)/(1
0*5);
 phichla=sum(Anvir,Chcri,Elmod,Lilit)/(4*5);
 wqindex=phichla/(plochla+phichla);
 wqlogit=log10(wqindex /(1-wqindex));

 pshelt=sum(Asnod,Pecan,Fuspi,Lilit,Pecan)/(8*5);
 pexpos=sum(Acequ,Alesc,Bibif,Hielo,Ladig,Maste,Padep,Samut)/(5*5);
 wxindex=pexpos/(pexpos+pshelt);
 wxlogit=log10(wxindex /(1-wxindex));

run;
```