Environment Agency

Evidence

The potential risks to human health posed by living, attached seaweeds and dead, beach-cast material associated with sandy beaches: a preliminary report

Integrated catchment science programme

Evidence Directorate

University of London Marine Biological Station Millport,
Isle of Cumbrae, Scotland. 2009

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This report is the result of research commissioned and funded by the Environment Agency

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84911-133-1

Further copies of this summary are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506
E: enquiries@environment-agency.gov.uk.

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Dissemination Status:
Released to all regions
Publicly available

Keywords:
marine, seaweed, health, risk, bathing waters, UK

Environment Agency's Project Manager:
Andrew Wither, Evidence Directorate

Product Code:
SCHO1009BRGB-E-P

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Miranda Kavanagh

Director of Evidence

Executive Summary

The key question(s) of whether a) the survival time of faecal bacteria in the environment is extended when associated with macro-algae (seaweed) and b) if, in fact, it is possible for these bacteria to grow in association with seaweed remain unresolved. As these points have obvious health implications, the aim of this report was to investigate these questions as extensively as possible via the literature currently available. The main conclusions of this review were:

- The interaction between seaweeds and bacteria is poorly understood and very complex. From the literature it is known that seaweeds can support a biofilm containing substantial numbers of bacteria, although the majority of these appear to be naturally occurring marine bacteria and non-faecal in origin. However some studies have shown that the presence of faecal bacteria on this substrate cannot be excluded and more research is required in areas where there is the potential for high levels of faecal contamination (e.g. due to storm water runoff).
- There appears to be strong evidence of the association of enterococci with *Cladophora glomerata* particularly in the Great Lakes. *C. glomerata* is unlikely to be encountered on UK marine bathing beaches but this example highlights the possibility, particularly in the case of enterococci which can tolerate a wider range of temperature and salinity than *E. coli*, that conditions associated with particular types of macro-algae may be advantageous to the survival and even possible growth of faecal indicators in the marine environment under certain conditions.
- There are suggestions in the literature that beachcast seaweeds may be a contributing factor to elevated levels of faecal indicator organisms in the sand.
- The lack of real, detailed scientific evidence on the relationship between faecal bacteria and marine seaweeds (both living and dead) make it impossible to offer an informed judgement on whether in fact seaweeds do pose a health risk and if so the extent of this risk.

While the human health aspect of beach–cast seaweed is of the utmost importance, it is also important to consider the possible effects of seaweed removal from beaches. In coastal ecosystems beach-cast seaweed plays an important role in helping to maintain the diversity of species within this sandy shore habitat and also in helping to provide sand stability to the beaches. The implications to the overall health of a beach ecosystem of the removal of macro-algae have therefore also to be considered. Information is provided which shows that deposited strandline material is a potentially important habitat to a variety of species and that some beach management regimes may have an impact on the organisms associated with this habitat and on the beach ecosystem as a whole.

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Legislative Context of Report (Scotland)

(Scotland was used here as an example; similar legislation is in place for England, Wales and Northern Ireland)

The purpose of this report is to review in as wide a sense as possible the impact of proliferation (or accumulation) of macro-algae on bathing beaches in accordance with the requirements of Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality.

The need to take into consideration macro-algal impact is specified under Article 9 of the above directive under ‘other parameters’ item 2:

> When the bathing water profile indicates a tendency for proliferation of macro-algae and/or marine phytoplankton, investigations shall be undertaken to determine their acceptability and health risks and adequate management measures shall be taken, including information to the public.

The Bathing Waters (Scotland) Regulation 2008 will require SEPA to consider the impact of macro-algae on Scottish bathing beaches from 2010 with the other environmental agencies in England, Wales and Northern Ireland following this lead in 2011.

Within The Bathing Waters (Scotland) Regulation 2008, Schedule 2, Part 4 requires that where any bathing water profile indicates a tendency for proliferation of macro-algae and phytoplankton, SEPA must carry out such investigations at that bathing water as are necessary to:

a) determine whether such proliferation constitutes a health risk to bathers and
b) all adequate management measures to be put in place in accordance with regulation 15 of Schedule 1

Within regulation 15, item 4 refers to determination of whether proliferation poses a health risk (due to threat of disease or to direct physical injury) while 15.5 determines what parameters are used to assess if proliferation is considered to be unacceptable.

(5) In determining whether the proliferation is unacceptable, the interested parties must have regard to–

(a) whether the extent or volume of the proliferation is unusual;
(b) whether the proliferation is unsightly;
(c) any effluence or effluvia arising from the proliferation;
(d) the impact upon the ecosystem of that bathing water which would result from the removal of the proliferation;
(e) the amount of waste or litter which is contained in the proliferation; and
(f) where the bathing water or any part of it forms part of a European site or of land which is a SSSI, the views of SNH upon the criteria set out in sub-paragraphs (a) to (e).

(In the following report, *Enterococcus* spp and *Streptococcus* spp (as was the name used in older literature) are collectively referred to as Intestinal Enterococci (IE) (or enterococci), unless specific species are mentioned in literature and are relevant to discussion. Also macroalgae are often commonly referred to as seaweeds and the terms are used interchangeably within this report).

1 Introduction

Are seaweeds an issue on bathing beaches?

Figure 1 Example of amount of beach-cast weed blown ashore on small popular beach after strong winds, Foul Port, Great Cumbrae, May 2009.

Clean beaches are one of the prime parameters that are sought after by recreational users. Local economies may depend on the aesthetic quality of recreational water areas, and the environmental degradation of beaches is known to lead to loss of income from tourism (WHO, 1). In this context beach-cast seaweed, and associated litter, is considered a problem. The smell of decaying seaweed can also have a negative impact on beach use.

Management options for dealing with this seaweed together with debris/litter include manual or mechanical beach cleaning. This then avoids the issue of whether the seaweed could in itself be considered a potential health hazard, which is the one of the main questions to be covered in this review.

Beach-cast seaweed does, however, form an integral part of a beach ecosystem, providing food and stability to the sand structure. As mentioned in criteria for the blue flag award scheme (section 10): 'Seaweed is a natural component of the littoral ecosystem. The coastal zone must also be considered as a living and natural environment and not only as a recreational asset to be kept tidy. Thus the management of seaweed on the beach should be sensitive to both visitor needs and littoral biodiversity' (2). In some instances the strandline is therefore handpicked to remove litter while the seaweed remains.

As with micro-algae, blooms of macro-algae appear to be becoming more frequent around the coastline in temperate waters due to increased nutrient loading. These 'nuisance' species tend to be mainly filamentous, often unattached or loosely attached forms, mainly green algae (e.g. *Ulva* spp., *Cladophora* spp.) with occasional examples of brown algae such as *Pilayella littoralis* (Valiela et al., 1997; Raffaelli et al., 1998) and

Ectocarpus siliquosus (Jeffrey et al., 1993). Unlike micro-algae, macro-algal blooms generally lack direct chemical toxicity and therefore the damage or nuisance value of these blooms is more likely to be due to biomass decomposition and anoxia (Valiela et al., 1997).

In the UK, a 'red macroalgal tide' was reported to SEPA on the shore at Castletown Beach near Thurso in 2007. This consisted of a swathe of the red algae, *Spermothamnion repens,* which forms small balls of filamentous algae. It appears to occur commonly in this region (although not usually to the extent seen in 2007) but it has also been reported in the US, where it now causes an annual problem on beaches in Rhode Island (Salit, 2005). There the blooms are linked to sewage input and beaches failing to comply with bathing water standards (3), on which more later.

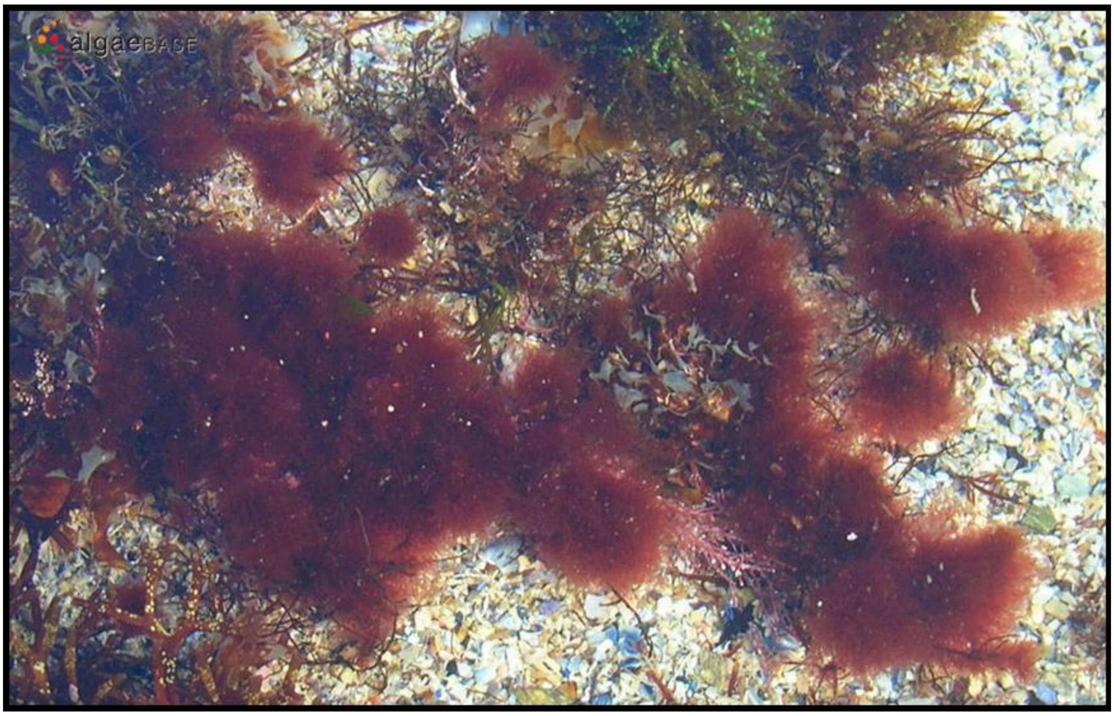

Figure 2 'Redtide macroalga', *Spermothamnion repens* showing filamentous 'ball-like' tufts (Guiry, M.D. & Guiry, G.M., 2007).

The coastline of the British Isles harbours a large array of seaweed species. Broadly speaking, seaweed can be found in three different states: attached to the substrate, free-floating or beach cast. Bathing beaches within the United Kingdom encompass a broad range of beaches of different sizes, shapes and composed of a variety of different substrates. Beaches with extensive (several miles) of sandy beach and comparatively little rocky substrate present such as Pendine Sands, (Carmarthenshire, Wales), Woolacombe Beach (North Devon, England) and St Andrews West Sands (Fife, Scotland), whilst the ideal of many tourists are relatively atypical/unrepresentative of the majority of bathing beaches in the United Kingdom. Such beaches are potentially affected by seaweed deposited on the shore either from offshore stands of macroalgae adjacent to the beach or seaweed rafted to the beach from many miles away (deposition on beaches is discussed further in Section 5). Many other UK designated bathing beaches are typically heterogeneous in composition and composed of areas of sandy beach, with rocky substrata present either in the form of base-rock intrusions or other stable substrate such as rock, boulder, cobble, pebble and gravel. Many beaches (in bays or embayments etc.) are also surrounded by base-rock, either intertidally or subtidally.

On soft-sediment shores (e.g. mudflats) macroalgae can also be present due either to the presence of gravel or larger stones and shells, which form an attachment point for some algal species or through species that can attach to the sediment itself. In many UK coastal areas the production of marine macrophytes in offshore beds is extremely high. The composition, extent and productivity of these communities are influenced by a variety of biotic and abiotic factors including substrate availability, light, nutrients, water motion, salinity and temperature. In high salinity waters this production consists mainly of large brown algae, commonly referred to as kelps. The dominant orders of the algae belong to the Laminariales (technically kelps) and fucales. While the intertidal zone is inhabited primarily by the fucoids (e.g. *Fucus vesiculosus*, *Fucus serratus*, *Fucus spiralis and Fucus cerenoides*), the subtidal is dominated by the laminarians (*Laminaria hyperborea*, *Laminaria digitata*, *Laminaria saccharina*, *Sacchorhiza polyschides* and *Himanthalia elongata*).

Proliferation of macro-algae is unlikely to occur on a bathing beach *per se* due to lack of points of attachment for seaweed holdfasts but on adjoining rocky shores and sublittoral areas or boulder areas on beaches. It is the growth and subsequent detachment of growth in these areas by storm events that cause the macro-algae to become washed up on bathing beaches. Here it generally accumulates on the strandline of bathing beaches and it is this aspect of seaweed 'proliferation' that will be the main subject of this review.

The key question(s) of whether the survival time of faecal bacteria in the environment is extended when associated with macro-algae and if, in fact, it is possible for these bacteria to grow in association with seaweed is uncertain. As this has obvious health implications, the aim of this report was to investigate this as extensively as possible via the literature currently available.

The 1976 Bathing Waters Directive as revised in 2006 was introduced to safeguard the health and well being of swimmers and beachgoers on designated bathing beaches. In relation to the build-up of macro-algae on the beach, therefore, the potential risks associated with this have to be assessed, together with what is considered the 'nuisance value' of the build-up of seaweed on the beaches.

The health risks can be broken down as follows:

- direct contact with growing seaweed (attached or recently detached)
- direct contact with dead, beach-cast weed (or products released during the decomposition process)
- possible indirect effects while bathing as a result of faecal bacteria associated with seaweed being re-suspended into the water column

Leftley and Hannah (2008) cover the first two points in a report commissioned by the Environment Agency on the potential health risks posed by exposure of bathers to marine macro-algae and/or phytoplankton blooms on beaches. Briefly summarized, this report states that there is the possibility of an allergic contact response to some seaweed found in UK waters such as Japanese Wireweed (S*argassum muticum)* but the risk is considered low other than for particularly sensitive or sensitised individuals. The problem of direct contact with beach-cast dead seaweed is more likely to be from associated debris in the strandline piles, some of which could potentially be harmful (syringe needles, discarded sanitary towel, condoms, broken glass and rusty cans etc). Often in late summer stranded dying jellyfish are also part of the strandline and one or two species of these if touched could cause irritation or in the worst case scenario a full allergic response. Food or nutrients released as a result of decomposing seaweed attracts various organisms such as flies and small crustaceans to the strandline. These are considered to be 'undesirable' or 'annoying' to beachgoers, particularly the kelp flies even though these are non-biting.

Another aspect of decaying seaweed not addressed in the report by Leftley and Hannah (2008) was that of levels of hydrogen sulphide (H_2S) released by anaerobic sulphate reducing bacteria found in decomposing mounds of seaweed.

H_2S is a health concern because it can affect several systems in the body. Exposure to episodic low levels can cause eye irritation, sore throat, and cough. Long-term, low level exposure can result in fatigue, loss of appetite, headaches, dizziness, and nausea. Consequently, H_2S is listed by the US EPA and other federal agencies, as well as the State of Washington, as a hazardous air pollutant (Washington State Department of Health, 2001).

The main aspect of the potential health risk of seaweeds to be considered in this report, however, is whether macro-algae can potentially extend the survival time of faecal indicators and act as a reservoir for these and faecal pathogens, releasing them back into the water column and thus influencing the bathing water sampling results and by implication increase the risk from bathing.

While the health aspect of beach–cast seaweed is of the utmost importance, it is also important to consider the possible effects of seaweed removal from beaches. In coastal ecosystems sandy beaches play an important role in energy flow and in the transfer of nutrients and help to maintain diversity of species within the habitat. The implications to the overall health of a beach ecosystem of the removal of macro-algae have therefore also to be considered.

2 Macro-algae as reservoirs for faecal indicator organisms and potential pathogens

Any solid in an aqueous environment will develop a biofilm and become covered in fouling organisms and this is the case with seaweeds. Whether it is therefore possible that bacteria of faecal origin may become part of the normal macroalgal biofilm or rather are loosely associated with seaweed, if at all, was investigated through the literature.

This section sets out to cover as many possible aspects of seaweed/bacterial interactions which may be relevant to the survival or growth of faecal microorganisms.

2.1 Faecal and other bacteria associated with seaweeds surfaces

Studies of bacteria associated with a range of macroalgal species in various parts of the world including UK are briefly summarised in Table 1. Most of these were 'ecological studies' investigating the diversity and role of bacteria on surfaces. From Table 1 it can be seen that a) bacteria are present in large numbers on seaweed surfaces, b) there were a few reports of potentially harmful bacterial genera present and c) results on whether bacteria tend to be associated with healthy undamaged tissue or damaged/senescent tissue are conflicting (this was considered to try and assess whether bacteria were more likely to be associated with living growing algae or with decaying beach-cast weed).

More recent work on bacterial/macroalgal associations relates to biofouling and antimicrobials and has used molecular techniques (e.g. Longford et al. 2007). This was the first study to compare the bacterial diversity of three co-occurring host surfaces, one of which was the green alga, *Ulva australis* (which had 25 associated bacterial species), the second was the red algae, *Dilsea pulchra* (with 62 bacterial species) while the third host was a species of sponge. The study showed a strong host-specificity for each of the surfaces, all of which were exposed to the same overlying water and its associated microbes.

Country	Temperature Range	Macro-algal species	Nos. of Bacteria (& method)	Main Groups of possible interest to this study found	Comments	Reference
Japan, Dec 1973 – June 1974	20.6 – 11.4°C	*Enteromorpha linza* *Monostroma nitidum* *Porphyra suborbiculata* *Eisenia bicyclis*	$10^4 – 10^6$ cm^{-2} $10^4 – 10^6$ cm^{-2} $10^3 – 10^4$ cm^{-2} $10^1 – 10^4$ cm^{-2} (CFU *)	Vibrios found in surrounding seawater but did not appear to dominate on any of the macro-algae. *Flavobacterium-cytophaga* group more common in greens than in SW - beneficial	Greens >reds> brown in terms of bacterial numbers/cm2 (browns possibly release antimicrobial substances ?)	Shiba & Taga, 1980
Nova Scotia, Canada, March 1972 – March 1973	~ 0 – 15°C	*Laminaria longicruris*	~10^3 -10^4 cm^{-2} (CFU)	Of 4200 isolates characterised, no enterococci found, predominance of vibrios and pseudoalteromonas	Differences in growth patterns and species composition found on part of frond (growing or decaying)	Laycock, 1974
Canada May – September 1964		*Ascophyllum nodosum* *Polysiphonia lanosa*	$10^4 – 10^7$ g^{-1} (CFU)	25 isolates characterized – 8 *Vibrio* spp, 8 *Flavobacteria*, 3 of '*Escherichia* group', 2 *Pseudomonas* sp and 1 each of *Sarcina*, *Staphylococcus*, *Achromobacter* (or *Alkaligenes*), and a pink yeast (*Rhodotorula* sp)	Specifically looking at seaweed from unpolluted area 22/25 isolates required a supplement of amino acids in the growth medium. Although '*Escherichia* group' mentioned, given the lack of sewage pollution in area authors suggest that they are related to Serratia or Proteus, non-faecal members of Enterobacteriaceae found in the sea . High proportion of H_sS producers relative to that in sea water found.	Chan & McManus, 1969
Firth of Clyde	6 - 15 °C	*Fucus spiralis* *Fucus serratus*	3 x 10^7 - 15 x 10^7 cm^{-2} (direct	No attempt made to characterize	Bacteria were more abundant on undamaged than damaged tissue in	Armstrong et al., 2000

		Laminaria digitata *Palmaria palmata*	counting using SEM)	bacteria enumerated	*F.spiralis* and *F.serratus*	
Firth of Clyde	7 - 15 ^{o}C	*Fucus serratus* *Porphyra umbilicus* *Ulva lactuca*	47.0 x 10^{6} cm^{-2} (I) 41.7x 10^{6} cm^{-2} (D) 16.0 x 10^{6} cm^{-2} (I) 95.3x 10^{6} cm^{-2} (D) 38.4 x 10^{6} cm^{-2} (I) 84.6x 10^{6} cm^{-2} (D) (SEM method)	No attempt made to characterize bacteria enumerated	In this study, as above in *Fucus* sp., no. of bacteria on intact and damaged tissue similar but more seen on damaged red and green algal tissue	Rogerson , 1991

Table 1 Summary of information in the literature on the occurrence, abundance and types of bacteria associated with various seaweeds.
(Techniques for counting and characterising bacteria have changed with time as new methodologies have been developed. * CFU = Colony forming units, SEM method = numbers estimated with aid of a scanning electron microscope.

Given the historic and current interest in seaweed as a food source throughout the world and including the UK, (details on this can be found at: http://www.seaweed.ie/uses_general/humanfood.lasso), there appears to be little published information available in scientific literature concerning the associated microbial epiflora of harvested seaweeds or the safety of consumption of this in terms of faecal pathogens. Studies may have been commissioned by the Food Standard Agency (FSA) to address this issue but the authors were unable to source any possible information on this other than that published in literature.

Moore et al. (2002) examined the epiflora of dried dulce (*Palmaria palmata*) collected from the coast of Northern Ireland and found no evidence of intestinal pathogens using conventional microbiological techniques. Included was testing for *E.coli* 0157:H7 together with *Camplyobacter spp., Salmonella spp, Staphlococcus aureus, Listeria monocytogenes* as well yeasts and moulds.

'This is the first preliminary report on the microbial diversity of edible seaweed and demonstrated the presence of several halophilic genera and species in fresh ready-to-eat edible seaweed from Northern Ireland. Although no gastrointestinal pathogens were cultured from this material, a larger study requiring examination of seasonal effects, quality of marine water and effect of drying on faecal pathogens, is required to support a functional HACCP- (Hazard Analysis and Critical Control Points-) based approach to ensuring safety of this product'*

These authors highlight here the need for a more detailed investigation of the possible association of faecal pathogenic bacteria with seaweeds, particularly those used as a food source.

*The specimens for analysis were 'obtained within 1 week of collection' implying testing of the dried product as it is normally sold rather than freshly collected seaweed.

In coastal waters of Malaysia where conditions of temperature and nutrient input differ considerably from those of Northern Ireland, a disease outbreak in a red alga, *Gracilaria changii,* which caused loss of pigment, withering of stalks and death of the seaweed was investigated (Musa & Wei, 2008). Fresh seaweed samples were collected, washed in sterile saline water to remove loosely associated bacteria, homogenized and homogenate tested. In both diseased and healthy (control) samples *Escherichia coli, Enterobacter cloaca, Klebsiella oxytoca, Pasteurella haemolytica, Vibrio alginolyticus* and *Vibrio chlorea* (all potentially pathogenic to humans) were positively identified. No significant difference in total bacteria count (~ 3.2×10^8 CFU g^{-1}), *Vibrio* count (~1.65×10^8 CFU g^{-1}) or *E.coli* count (~ 2.0×10^8 CFU g^{-1}) was found between the diseased and healthy plants implying that these microorganisms were normally found in association with this red seaweed. It was suggested that the contamination of the seaweed with faecal organisms was likely to have been due to growth in polluted waters.

In another study in Malaysia by Vairappan and Suzuki (2000), algal fronds of *Ulva reticulata* were subjected to desiccation for 31 days and total surface bacteria and bacterial species counts were monitored together with moisture content and water activity index (aw). Total bacterial counts peaked at 7 days (rising from 1500 CFU cm^{-2} to 8300 CFU cm^{-2} decreasing thereafter to 5200 CFU cm^{-2} on day 14) with *Azomonas sp., Aeromonas hydrophila, Vibrio alginolyticus, Escherichia coli**, Proteus vulgaris* and *Vibrio parahaemolyticus* being isolated throughout the drying process. *V. alginolyticus* was the most commonly occurring characterized micro-organism followed by *E.coli.*

** Before the bacteria were characterized they were grown on a 3% NaCl 'HIMEDIA' agar suggesting that *E.coli* was able to grow at this salt concentration.

2.2 Macro-algal products that may enhance faecal bacterial growth

Macroalgae may play a possible role in the survival of faecal indicator organisms by providing them with nutrients and/or osmoprotectants (as a means of coping with salinity stress) in the marine environment.

2.2.1 Macro-algae as a possible nutrient source

Carbon fixed by seaweeds is released into the surrounding water as dissolved organic carbon during photosynthesis, the amount released is a matter of debate but may range from 1% up to 40% of the net fixed carbon depending on method of estimating this (Sieburth, 1969; Kailov & Burlakova, 1969; Johnston et al*.,* 1977; Hatcher et al*.,* 1977; Pregnall, 1983). Biofilm bacteria are advantageously placed to take up this dissolved organic carbon but some will be released into the surrounding water.

Chan and McManus (1969) discovered a requirement of amino acids for the majority of bacteria isolated from *Ascophyllum* and *Polysiphonia*. Algae are known to produce a number of extracellular organic substances containing peptide-, amide- and free amino-nitrogen (Allen, 1956; Fogg & Boalch, 1958) and it is likely that marine bacteria are adapted to utilizing these sources. An additional intracellular source of amino acids may become available when cells at tips of seaweed fronds (or other points) become damaged and release cell contents as suggested by Laycock (1974). Fronds of seaweed recently cast up on the beach are also likely to be a source of these.

Whether bacteria of faecal origin are merely adsorbed onto seaweed surfaces in perhaps a viable but non-culturable stage (VBNC) or are able to utilize the nutrients and carbon surrounding the seaweed for growth and replication is somewhat unclear (for further information on this see: *E.coli* - Winfield & Groisman, 2003; enterococci - Lleò et al. 2006; Signoretto & Canepari, 2008).

2.2.2 Macro-algae providing osmoprotectants

Osmotic stress is one factor, which has been implicated, in the apparent death of *E. coli* in seawater (Bogosian et al., 1996). Bacteria can respond to osmotic shock initially accumulating K^+ but also by the synthesis and/or accumulation of organic osmotic solutes. These osmolytes include sugars, free amino acids and their derivatives such as betaine and glycine betaine. For full details of the possible osmoadaptive systems available to *E.coli* strains, see Kempf and Bremer (1998).

Widespread distribution of glycine betaine or related compounds have been found in marine algae (Blunden & Gordon, 1986, Blunden et al., 1992) and also of dimethylsulphoniopropionate (DMSP), which may have a possible role in their osmotic balance (Dickson et al. 1980, Edwards et al., 1987). Both in turn can be utilised by bacteria for osmoprotection.

Ghoul et al. (1990) showed that *E.coli* was able to grow in autoclaved marine sediment faster than in seawater alone due to high content of organic matter in the sediment but also due to the fact that the cells accumulated glycine betaine from the sediment. Ghoul et al. (1995) subsequently showed that algal extracts provided appreciable osmoprotectants for *E.coli* as well as nutrient sources for growth.

It is likely that these osmoprotectants, are released from algal cells due to physical damage or on cell death when the seaweeds are physically removed by wave action from their habitat and cast up on the beach. There they could percolate into the sediment being adsorbed on to sand grains if not immediately taken up and utilized. All the research on this has so far been based on laboratory experiments and extrapolations made into the field situation.

2.3 Antimicrobials from macro-algal or epiphytic bacteria

2.3.1 Seaweeds may themselves produce antimicrobial substances

Seaweeds have different strategies to avoid being settled on and overgrown by other organisms. Examples of antifouling mechanisms are physical, such as sloughing off surface layers of host algae (e.g. Filion-Myklebust & Norton, 1981; Keats et al. 1993), and chemical, whereby secondary metabolites that prevent settlement and growth of fouling organisms are produced. Seaweeds are rich in secondary metabolites (e.g. Tringali, 1997; Faulkner, 2002) to protect themselves from bacterial colonization or biofilm formation and many macroalgal secondary metabolites are currently being assessed in terms of their antimicrobial activities (Lindequist & Schweder, 2001; Newman et al., 2003).

Production of antimicrobials by seaweeds was found to be variable; between species and seasonally within species e.g. Hornsey and Hide (1974, 1976, 1985) demonstrated that crude extracts from various UK species of marine algae showed inhibitory activity against pathogenic bacteria (*Staphlococcus aureus* and *E.coli*) and that some species such as *Ascophyllum nodosum* produced antimicrobial substances over the summer months while others e.g. *Ulva lactuca* and *Laminaria saccharina* showed no antimicrobial activity over this period.

The literature on the topic of antimicrobials from seaweeds is extensive due to the applied biotechnological potential of these products and various review articles are now available (e.g. Steinberg, 1998; Egan et al., 2008).

2.3.2 Antimicrobials produced by epiphytic bacteria attached to seaweeds

Bacteria isolated from the surface of seaweeds have also been shown to release compounds that repel other fouling bacteria, suggesting that they may protect the seaweed from fouling by other organisms (Boyd et al., 1998; 1999a; 1999b; Burgess et al., 1999). In a survey of antibiotic activity of epiphytic marine bacteria (Lemos et al., 1985) *Ulva intestinalis* was found to be the source of the highest number of species with antimicrobial activity. It was also found in this and other studies that antibiotic producing bacteria were always pigmented (Gauthier & Flatau, 1976; Gautier, 1977) and *Ulva* spp in general have a higher percentage of pigmented culturable bacteria than other genera of macroalgae. There is also a correlation between pigmentation and antifouling compounds (Egan et al., 2002).

2.4 Literature suggesting that macro-algae on beaches may explain unaccountable elevated faecal counts

The possibility that beach-cast macroalgae may be the cause of higher than expected faecal indicator counts in water column has been suggested in several water quality reports in various parts of the world for example:

Scotland - Rosehearty Beach on 20th July 2008 exceeded mandatory faecal coliform count (3000 CFU 100 mL^{-1}) with IE count of 1130 CFU 100 mL^{-1}. Possible cause of failure on this occasion was suggested to be a build up of seaweed in the area, which could harbour bacteria and prolong their survival (SEPA, 2008).

Australia - water quality at Barfleur Beach, NSW, was extremely variable in 2004 with enterococci exceeding guideline levels. Elevated levels of enterococci did not appear to be correlated with rainfall and one of hypotheses proposed to explain the high enterococci levels was 'bacterial regrowth amongst the seaweed that accumulates in this area. However '….one off samples taken amongst seaweed clumps showed higher bacterial levels than samples taken away from seaweed. DAL testing (antibiotic resistance testing) confirmed enterococci identified are species of faecal origin and unlikely to regrow or regrow in association with seaweed' (4).

(This tends to imply that on checking, it was assumed that given the faecal origin of the enterococci that they were unlikely to have been able to grow on the seaweed but other studies to be discussed later suggest that this might be possible.)

New Zealand – At each of the 77 coastal sites monitored for enterococci within the Wellington region over 2007/08, observations of weather and the state of the tide, and visual estimates of seaweed cover, were made at each site to assist with the interpretation of the monitoring results. It is suggested that in some cases, an increase in enterococci counts may be due to the presence of seaweed. Under warm conditions when seaweed is excessively photosynthesizing or decaying, enterococci may feed off the increased carbonaceous material produced during photosynthesis or off the decaying seaweed (4, Milne & Warr, 2007)

United States – Easton's beach, Rhode Island mentioned earlier has been subject to large amounts of a small red filamentous algae, *Spermothamnion repens*, being washed ashore. In recent years this beach has also been closed due to sewage pollution on several occasions. It was reported that "during periods when runoff from heavy rains carried coliforms to the beach, the areas with no seaweed would have no bacteria, but on the other side we would be getting this reading through the roof and have to close the beach". (No link with sewage pollution was associated or made with blooms of this species in Caithness (Scanlan & Holt, 2009)).

All of the above examples are somewhat anecdotal and appear not to have been rigorously tested. Milne and Warr, 2007 (above) although quoting no reference source is possibly referring to work by Anderson et al. (1997, see below) with regard to decaying seaweed but no literature could be found to explain the 'excessively photosynthesising' hypothesis – in warm weather if nutrients are available growing algae will release substantial amounts of dissolved organic carbon which could potentially be taken up by the enterococci for growth (but study by Anderson, 2000, showed that high levels of enterococci were not associated with fresh seaweed).

The above examples are just a small selection of many found in the grey literature but it has to be emphasised that these are, in the main, anecdotal.

2.5 More direct evidence of a link between macro-algal and faecal counts in the water column

A study on the environmental occurrence of faecal enteroccoci in New Zealand as a compliment to epidemiological studies of bathing water quality found that enterococci on degrading drift seaweed at recreational beaches exceeded seawater levels by 2-4 orders of magnitude (see Table 3), suggesting that 'expansion' had occurred in this permissive environment with resultant potential to contaminate adjacent sand and water (Anderson et al. 1997).

The term ‘expansion’ was perhaps purposely chosen to be rather vague because research as such did not offer proof of definitive growth. The results found could be interpreted to show this or alternatively it is possible that the seaweeds were acting as ‘sponges’, soaking up the bacteria which would be adsorbed on to their surface where it appears their survival time increases.

Site	Enterococci			Faecal coliforms		
	Wenderholm		Mission Bay	Wenderholm		Mission Bay
	Summer (Feb 1995)	Winter (July 1995)	Summer (Feb 1995)	Summer (Feb 1995)	Winter (July 1995)	Summer (Feb 1995)
1	22:1:14	3:1:6	26:1:1	164:1:15	2:1:9	3,467:1:13
2	ND:1:125	ND:2:ND	130:1:6	ND:1:367	14:1:1	104:1:16
3	9:1:1	1:8:ND	967:12:1	ND:ND:10	90:16:1	31:1:1

ND - not detected; [1]seaweed from within decaying mass, generally moist and decaying; [2]sand from areas adjacent to degrading seaweed, the top 2-5cm of sand sampled; [3]seawater at knee depth in direct line with each beach site; presented as ratios e.g. 22:1:14 = seaweed, sand, seawater ratio. (Anderson *et al*, 1996)

Table 2 Results of monitoring on two recreational beaches in New Zealand (seawater, sand and seaweed were sampled), taken from Anderson et al. (1997).

In this New Zealand study the species of enterococci isolated from degrading seaweed were types usually associated with faecal sources i.e. *E. faecalis* and *E. faecium*.

In a further study by Anderson (2000), enumeration of enterococci from bathing beaches in Auckland, indicated occasionally high levels from seaweed and sand, where levels of up to 660 CFU/100 g (wet weight) were recorded from aged and degrading seaweed but not from fresh seaweed samples. Restriction enzyme analysis (REA) of isolates from degraded seaweed indicated a dominance of clonal populations (i.e. populations of enterococci of same species or sub-species) on these, which supported the notion of either replication or survival of strains within the decaying seaweeds.

Following up the above, laboratory studies were conducted to investigate enterococci persistence and growth on seaweed but these were not conclusive, although there was some evidence to suggest enterococci replication was occurring. This was indicated by molecular fingerprinting (REA analysis), which showed that the inoculated strain persisted for the full duration of experiments - up to 28 days. The isolation of non-inoculum strains from seaweed treatments, combined with increased abundance of these strains with incubation, suggested the persistence or replication of enterococci that were naturally occurring on seaweed

This appears to be one of the strongest pieces of work in the marine environment that has recorded an association of enterococci on seaweeds but it also alludes to the possibility of growth on seaweeds. Temperatures in this study were likely to have been above those found in UK waters.

Further ‘marine examples’ were found in the literature from Florida (where conditions are tropical/subtropical). A study of beaches by Shibata et al. (2004) found that on average the highest numbers of faecal indicators (TC, FC, *E.coli*, enterococci and *C. perfringens*) in the sand were found in sand under seaweed or in submerged sand (covered by incoming tide). The largest concentrations of *C. perfringens* and total coliform were obtained from below seaweed. Results are shown in Figure 3 (a, b). It was hypothesized that the seaweed provided nutrients, protection from UV light, and helped to maintain moist conditions so that microbes could flourish or survive longer. Many of the total coliforms recorded could, however, have been of non-faecal origin.

Figure 3a Total Coliform count on Beaches in Florida

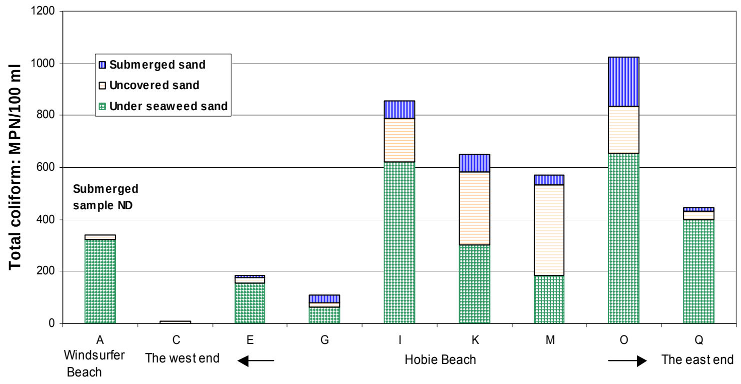

Figure 3b *C.perfringens* count on Beaches in Florida

(Taken from Shibbata et al., 2002 ASM meeting. Ref **02-GM-A-1307-ASM: Q-51**

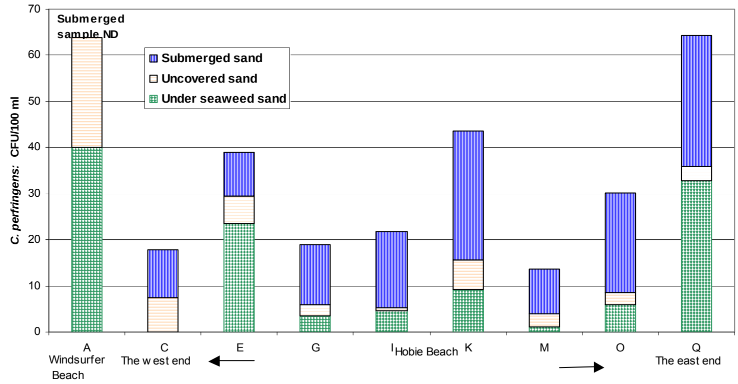

Figure 3a Total coliform count on beaches in Florida 3b) *C. perfringens* count on beaches in Florida.

A separate study by Bonillo et al. (2006) in approximately the same area of Florida found that seaweed sampled on the beach was likely to be one of the possible sources (together with the other obvious culprits of stormwater runoff and bird faeces) of the enterococci found in the sand. This conclusion was based on the fact that there was a similar prevalence of *E. faecalis* and *E. hirae* in stormwater runoff, bird faeces, **and seaweed** as were found in sand samples**.** This study found that nearly half the enterococci isolated from seaweed sampled were *E. faecalis* (*E.saccharolyticus* made up the majority of rest of enterococci found on the seaweed).

A study in southern California of faecal indicators in the wrack line (strandline consisting of marine vegetation, typically kelp, as well as eelgrass and other debris deposited at the high tide mark) showed that these strandlines could act as a bacterial reservoir releasing faecal indicators back into the water column on high tides. Dog fouling on the strandline was considered a possible reason for enhanced levels of faecal bacteria on the wrack but when areas of strandline with and without fouling were compared there was no significant difference (Martin & Gruber, 2005). Elevated levels of indicator organisms were found on strandline wrack but not on freshly deposited vegetation. Ribotyping of *E.coli* from wrack confirmed that a large percentage (67-80%) of these were of avian origin and the remaining 20-33% originated from mammals (including dogs) and other unknown sources.

2.5.1 High Faecal Indicator Counts associated with *Cladophora glomerata*

The problem caused by *Cladophora* mats which are regularly washed up on the shores of the Great Lakes in North America has provided what appears to be the most comprehensive block of research into the extended survival and growth potential of faecal bacteria attached to living or decaying seaweed, albeit at warmer temperatures than occur in UK waters but more specifically in a freshwater system.

Cladophora glomerata (L.) Kütz. is widely distributed throughout the world's freshwater systems such as the Great Lakes. The species is found in both fresh water and brackish waters throughout temperate regions of the world (Dodds & Gudder, 1992) and usually grows in dense belts close to the water surface. It occurs widely throughout Europe, causing macroalgal blooms and problems in the Baltic Sea (Paalme et al., 2007; Berezina & Golubkov, 2008). In the U.K., it is recorded as widespread in freshwater habitats and locally in brackish waters (Brodie et al., 2007).

Blooms of this filamentous green algae are often associated with high nutrient levels but, within the Great Lakes, reoccurrence of blooms of *C. glomerata* have been coincident with the establishment of dense communities of invasive zebra and quagga mussels (*Dreissena polymorpha* and *Dreissena bugensis*, respectively), which occurred during the early to mid-1990s (Vanderploeg et al., 2002). This macroalgae is considered of high nuisance value in this area as rotting algal material on the beaches produces a foul odour which is off-putting to people using the lakes and at times has been so offensive in sight and smell that is has been confused with raw sewage (Higgins et al., 2008).

A more direct potential health risk is associated with this macroalgae as bacteria such as *E. coli* and human pathogenic organisms (Shiga toxin producing *E. coli*, *Salmonella, Shigella, Campylobacter*) have been found adhered to both living and decomposing filaments of *Cladophora* along the shorelines of Lake Michigan (Byappanahalli et al., 2003; Whitman et al., 2003; Ishii et al., 2006; Olapade et al., 2006).

E. coli and enterococci were present on 97% of *Cladophora* samples collected from 10 beaches on the Wisconsin, Illinois, Indiana, and Michigan shorelines of Lake Michigan (Whitman et al.,. 2003). *E. coli* densities on *Cladophora* for the 10 beaches surveyed were generally high but highly variable; the overall log mean *E. coli* density was 5.3 +/- 4.8 CFU/g. Concentrations of enterococci on *Cladophora* averaged 4.8 +/-4.5 log CFU/g. Transect sampling in two separate beach areas found that *E. coli* counts in floating algae were significantly higher than in stranded algae, sand, or water, and that stranded algae had more *E. coli* than either sand or water. *E. coli* was also found on attached macroalgae. Furthermore, *E. coli* and enterococci survived for >6 months in sun-dried *Cladophora* mats stored at 4^{o}C and grew readily after rehydration (Whitman et al., 2003).

The primary objective of the study by Byappanahalli et al. (2003) was to examine growth potential of *E. coli* and enterococci in *Cladophora*. Several laboratory-based experiments were conducted using algae or leachate preparations from *Cladophora* as the principal growth medium.

Results showed that *E. coli* growth in *Cladophora* leachate was directly proportional to leachate concentration, indicating that undetermined substances in the leachate were responsible for *E. coli* growth. *E. coli* strains associated with *Cladophora* were highly related yet in most instances were genetically distinct from each other. This suggested that the relationship between *E. coli* and *Cladophora* might not be interdependent. It is possible that water-borne *E. coli* are able to populate newly emerging algal filaments.

Growth requirements for *E. coli* are relatively simple whereas enterococci require more complex growth media but leachate from *Cladophora* was also found to support enterococcal growth in this study. Samples were however incubated at 35°C to optimize potential growth although growth was evident at 25°C (ambient temperature in lake with warmer temperatures on land).

Olapade et al., (2006), investigated the occurrence of faecal indicator organisms on *Cladophora* mats on beaches on the shores of Lake Michigan. They found that *E. coli* was detected in all 63 samples obtained from 11 sites, and the average levels at most beaches ranged from 2,700 CFU/100 g (wet weight) of *Cladophora* to 7,500 CFU/100 g of *Cladophora* but three beaches were found with more elevated numbers, the highest being 27,950 CFU/100 g of *Cladophora*. *E. coli* levels in the lake water collected at the same time from these three sites were less than the recommended U.S. Environmental Protection Agency limit, 235 CFU/100 ml. It was also shown that *E. coli* persisted on *Cladophora* mats in microcosms at room temperature (not specified) for more than 7 days, and in some experiments it persisted for as long as 28 days.

Cladophora glomerata is not likely to be encountered on UK marine bathing beaches but the above example highlights the possibility, particularly in the case of enterococci which can tolerate a wider range of temperature and salinity than *E.coli*, that conditions associated with particular types of macroalgae may be advantageous to the survival and even possible growth of these faecal indicators in the marine environment under certain conditions.

2.6 Association of potentially pathogenic *Vibrio* micro-organisms with seaweeds

Several studies such as that by Musa & Wei (2008) have highlighted the association of several *Vibrio* spp. With seaweeds, in that particular case, *V. alginolyticus* and *V. cholerae* were found on healthy as well as diseased plants of *Gracilaria changii.* An incident of cholera reported in California, US was associated with consumption of seaweed imported illegally from the Philippines (Vugia et al., 1997).

The use of seaweed as a source of food and dietary fibre has a long tradition in Japan and here several studies have investigated the role of seaweeds as a reservoir for several of these potential human pathogens e.g. *V. parahaemolyticus* (Mahmud et al., 2006, 2007) and *V. vulnificus* (Mahmud et al., 2008). The seaweeds sampled (mainly *Porphyra, Undaria, Laminaria* and *Fucus* species) supported a diverse *V. parahaemolyticus* population throughout the year and were therefore considered a reservoir for this organism in Japanese waters. Its occurrence however was positively correlated with water temperature and its abundance on seaweeds was at least 50 times higher during summer (20-29°C) than in winter (10-18°C). A similar pattern was seen for *V. vulnificus* with highest counts observed in summer and autumn samples. During the winter months, no *Vibrio* spp. could be detected from water samples while the seaweed samples still harbored a population of 10^3–10^4 CFU g^{-1}. Over the course of study, total *Vibrio* counts were 0–10^4 CFU mL^{-1} and 10^2–10^6 CFU g^{-1} in water and seaweeds, respectively.

V. vulnificus appears to be an emerging pathogen and this has been linked to rising sea temperatures allowing it to spread more globally.

2.7 Summary

In terms of association of seaweeds and faecal bacteria the literature provides, in general, a mixed message. The carbon and other nutrients available during active growth or on decomposition can encourage growth of bacteria in general and of interest is the possible role of osmoprotective substances released from macroalgae which could extend the survival time and possible growth of faecal organisms in the hostile marine environment. However the seaweeds themselves and their 'natural' bacterial biofilm community are known to actively discourage settlement and growth of bacteria. Grazing pressure on microbes associated with seaweed surfaces is also an important potentially limiting factor.

There is clear evidence of association, and potentially growth, of *E.coli* and enterococci with *Cladophora* in freshwater systems Similarly there is evidence of enterococci associated with marine macroalgae in New Zealand and US (Florida and CA). *E. coli* were observed to survive for up to 28 days on *Cladophora* in freshwater systems while in the marine environment, enterococci were able to survive for this length of time on decaying seaweed .

Seaweed harvesting for food goes on around the coast of the UK; this seaweed and surrounding water quality will obviously be checked by the FSA for any potential problems. Few if any investigations on seaweeds, however, appear to have been undertaken specifically in sewage polluted temperate coastal waters to test whether there is any uptake of faecally derived bacteria and if this 'contaminated weed' could therefore pose a potential risk on bathing beaches when washed up, or if bacteria could be resuspended from this back into the water column. Numerous questions remain unanswered such as:

- Can FIOs be found on attached, living seaweeds in UK?
- If so are specific types of seaweed more likely to be associated with FIOs?
- If FIOs are found associated with seaweed does this extend their survival time in seawater?
- Alternatively, is it the case that FIOs only become associated with strandline seaweeds?

3 Macroalgae and sand - possible crossover of contamination

A large percentage of gross carbon production in algae is released as dissolved organic material (approximately 39% in brown algae, about 38% in red algae, and about 23% in green algae). The rest of the organic matter is released during decomposition of that part of the standing stock not consumed by herbivorous animals. About 30% of gross production may be released in this way. Thus, the total flow of dissolved organic matter from seaweeds during growth and after death may be as much as 70% of their gross production (Khailov & Burlakova, 1969). The proportion of carbon being processed by detrivores/herbivores and microbial decomposers varies according to the type of macroalgae as well as other environmental factors.

Microbial decomposition of beach-cast kelp was found to follow a basic pattern of bacterial colonization (Koop et al. 1982). Initial colonisation by cocci along the junctions of epidermal cell walls led to lysis and release of cell contents. This phase was followed by shedding of much of the epidermal layer of the kelp, revealing honeycomb- like cells of the underlying parenchyma1 tissues. At this stage the major release of dissolved and particulate organic matter from the cell contents that are known to contain high concentrations of mannitol, laminarin, alginates and other carbohydrates (Jensen and Stein, 1978; Newell et al., 1980) occurred. The lysed cells were then colonised by bacterial rods and occasionally yeasts and fungi.

Thermophilic fungi have been isolated from large (one to two metres high) self-heating mounds of seaweeds from a beach in California which were also causing H_sS odour problems (Nonomura, 1978). Seaweed drift piles can provide good habitats for thermophilic fungi: they are openly exposed to solar heating (see Jack and Tansey, 1977 for the requirements of solar heating for thermophilic fungi) and the piles are usually fairly aerobic, well insulated, and moist. Conditions in seaweed piles, which may however limit the growth of these fungi, include high salinity and low nitrogen content. Little work other than this was found on conditions, specifically growth conditions for microbial decomposition, within large piles of beach-cast seaweed.

The sand of a marine beach can be regarded as a gigantic cleaning filter because of the large amounts of water (10 – 91 m^3 m^{-1} d^{-1}) passing over and through it as the tide floods and ebbs (McLachlan, 1989; Heymans & McLachlan, 1996). While the seawater is being filtered, large amounts of dissolved organic matter (DOM) and particulate organic matter (POM) are adsorbed on the surface of the sand grains. This organic matter consists mainly of phytobenthos assimilates, products washed and leached out of seaweeds, animal faeces produced mainly by meio- and macrofauna and seabirds, and remains of marine plants and animals (Koop et al., 1982, Brown & McLachlan 1990, Jędrzejczak 1999)

3.1 Leachate of soluble compounds

In a study of microbial breakdown of *Ecklonia* in South Africa, very high concentrations (up to 5640 mg L^{-1}) of leachate were found immediately beneath the decomposing kelp debris and that this material was mainly utilised during passage through a I m sand layer (only 3-10% remained to drain into receiving area below this) (Koop et al., 1982).

3.2 Finely degraded particulate material

Koop et al. (1982) described that part of the process of microbial decomposition of kelp was the release of particulate as well as dissolved organic material and that this material passes into interstitial spaces in sand. There is little additional published information on this subject.

3.3 Burial of whole seaweed (intentionally or otherwise)

Mats of algae are frequently washed inshore along sandy beaches on the Kattegat shores of Denmark after storms and subsequently buried by sand deposition. Areas of quicksand in shallow subtidal water in these areas were found by Dando et al. (1993) to be organic rich layers of decomposing algae, which were producing substantial quantities of gas (hydrogen, methane and hydrogen sulphide). High hydrogen concentrations are produced as a by-product of carbohydrate and protein digestion by anaerobic bacteria under high organic loading (Wohlin, 1982). Under these conditions, the low pH, due to rapid acid production (Foree & McCarty, 1970), inhibits the activity of hydrogen-utilising methanogens. How enterococci, *E.coli* and possible pathogens would fare in these conditions has not been investigated but Dando et al. (1993) considered this habitat to be equivalent to that in an anaerobic digestor or a cow rumen (Pavlostathis & Giraldo-Gomez, 1991) so it is presumed that survival if not growth is possible assuming the saline conditions can also be accommodated.

Since the first-order decay constant for anaerobic decomposition of the biodegradable fraction of algae is of the order of 0.01 to 0.03 d^{-1} (Foree & McCarty, 1970) and stranded kelp mats can decompose in 8 d (Koop et al., 1982), such habitats are ephemeral, although recurring several times a year in the Kattegat, leaving the sand enriched in iron sulphide.

Neira and Rackemann (1995) reported similar processes occurring on intertidal sands in the Wadden Sea, Germany as a result of *Enteromorpha* (now *Ulva*) growth where burial of weed gave rise to black spots in the intertidal sediment. A long and dramatic impact on meiofauna in these anaerobic ‘hot spots’ was noted.

It has, however, been suggested, by Whitman et al. (2003) that algal mats of *Cladophora* washed onto beach sand in the Great Lakes area may get buried in the sand by wave action or human activities, where they are protected from sunlight and desiccation. Here it is possible that indicator bacteria may multiply due to available nutrients from the decomposing mats and in turn, the beach sand can serve as a source of indicator bacteria for the nearshore water, especially when waves resuspend buried mats.

4 Sand as a reservoir for faecal indicator organisms and potential pathogens

Around the world where bathing beaches are monitored for water quality, failure of a beach to reach minimum standards may require closure of the beach or in the case of the European Union, posting of notices to advise bathers on the risk of swimming, both of which have financial implications for the local tourist area. In cases of regular failure, sources of this pollution are sought and in many investigations the beach sand itself has being studied as a possible source.

4.1 Freshwater beaches (Great Lakes example)

A study by Alm et al. (2003) around Lake Huron (range of air temperature from 16 - 24 ^{o}C and water from 14 - 24.5^{o}C over course of study) found that enterococci counts in sand were 4 -38 times higher than those found in water and *E.coli* counts were 3-17 times higher. In the water column over summer months counts of *E.coli* were 4 times higher than enterococci. This study found that relative to both enterococci in water and to *E.coli* in sand, the sand seemed to differentially accumulate enterococci.

Beversdorf et al. (2006) surveying faecal indicators in approximately the same region concluded that sand MAY act as a resevoir for *E.coli* and that replication of cells appeared to be a possible contributing factor (as indicated in both field and laboratory studies) but that this warranted further study.

4.2 Marine Beaches

Laboratory and field studies have demonstrated long-term survival of indicator bacteria such as *E. coli* and other faecal coliforms in sediments (Gerba & McLeod, 1976). More recently it has been shown that faecal indicator bacteria can persist and potentially multiply in tropical soil and sand (Davies et al., 1995; Oshiro & Fujioka, 1995; Solo-Gabriele et al., 2000; Craig et al., 2004; Desmarais et al. 2004; Anderson et al., 2005) It has also been shown that these can be released back into water column during high tides.

The ability of *E.coli* to increase in soil was negatively correlated with the soil's moisture content and it was suggested that this was due to the ability of *E.coli* to outcompete predators in relatively dry soil (Solo-Gabriele et al., 2000). A similar conclusion, i.e. lack of predation, was given by Bonillo et al. (2007) to explain the highest indicator densities being found in upper beach sand (5 m above the intertidal zone) on three South Florida beaches when compared with wet (intertidal sand) and water column. Similar findings of high densities of enterococci in sand above the high water mark with low moisture content have also been reported in California (Yamahara et al. 2007) and in Hawaii (Oshiro & Fujioka, 1995)

Lack of predation is likely to be an important factor in the survival of faecal indicators in these conditions. Enterococci species may in general be resistant to desiccation but it has also been recently shown in non-sterile sand mesocosm experiments that naturally occurring enterococci in dry sand can replicate when sand is periodically wetted as would happen on high spring tides (Yamahara et al., 2009).

It is possible that the above papers could be relevant when considering the survival of *E.coli* and enterococci on beach-cast seaweed as it dries on the strandline, as a lack of predation combined with protection from sunlight could be important factors affecting their survival. Vairappan and Suzuki (2000) in Malaysia found increasing numbers of *E.coli* initially on *Ulva* sp. as the seaweed was dried.

4.3 Brief summary of possible sources of enhanced FIO levels in sand:

a) Runoff from rivers/sewage outfall/stormwater drains – sand near outfall sources have been found to contain higher levels of faecal indicators than sand further from the source (Rheinloo, 2008).

b) Animal sources i.e. birds, dogs on beach (e.g. Anderson et al., 2005; Bonillo *et al*. 2007) .

c) Seaweed/seaweed products – indirect evidence here – high organic content of sand/sediment shown to enhance survival of *E.coli* (Craig et al.*,* 2004). Seaweed breakdown could contribute to this organic carbon (section 3) but there are few if any published reports specifically testing enhancement by seaweed enrichment (again preliminary results obtained by Rheinloo, 2008).

A recurring theme emerging in the literature is the tidal influence on bathing water quality. High enterococci counts in the water column have been associated with spring and in particular spring-ebb tides in surveys of marine recreational beaches in California (Boehm & Weisberg, 2005). The proximity to a terrestrial runoff source had minimal influence on the tidal effect thus suggesting other tidally forced sources such as contaminated groundwater (fresh or saline) from beach aquifers, enterococci enriched sand, bird faeces or decaying seaweed near the high tide mark.

4.4 Key Summary Points regarding FIOs and Seaweeds

- The interaction between seaweeds and bacteria is poorly understood and very complex. From the literature it is known that seaweeds can support a biofilm containing substantial numbers of bacteria, although the majority of these appear to be naturally occurring marine bacteria and non-faecal in origin. However some studies have shown that the presence of faecal bacteria on this substrate cannot be excluded and more research is required in areas where there is the potential for high levels of faecal contamination (e.g. due to storm water runoff).
- There appears to be strong evidence of the association of enterococci with *Cladophora* spp., particularly in the Great Lakes. *Cladophora glomerata* is not likely to be encountered on UK marine bathing beaches but this example highlights the possibility, particularly in the case of enterococci which can tolerate a wider range of temperature and salinity than *E. coli*, that conditions associated with particular types of macroalgae may be advantageous to the survival and even possible growth of faecal indicators in the marine environment under certain conditions.
- There are suggestions in the literature that beachcast seaweeds may be a contributing factor to elevated levels of faecal indicator organisms in the sand.
- The lack of real, detailed evidence on the relationship between faecal bacteria and marine seaweeds (both living and dead) make it impossible to

offer an informed judgement on whether in fact seaweeds do pose a health risk and if so the extent of this risk.

5 Nuisance assessment of beach-cast seaweed and methods of dealing with this

5.1 Beach-cast Material

Macroalgal material attached to sediments or hard substrata in subtidal and intertidal habitats can become detached through normal cyclical processes (e.g. the seasonal shedding of fronds, plant death etc.) and through physical detachment caused by tides, waves and stormy weather. Detached macroalgal material can be deposited throughout the intertidal range of habitats such as beaches (sand, cobble and gravel), sand-flats and salt-marshes (e.g. Valiela & Reitsma, 1995). Beach-cast phytodetritus (hereafter collectively termed "wrack") along with associated carrion e.g dead birds and man-made debris form strandlines on beaches, which define the high water mark of the latest tide. Strandlines are mobile, being shifted by wind and tidal action, and are occasionally swept away in stormy weather conditions.

The species composition and extent of deposited beachcast material will depend on the dominant species present in the locality (both intertidally and offshore) although 'rafted' seaweed material may come from several miles away due to the presence of buoyant tissue or gas-filled bladders (Vandendriessche et al., 2007). In the United Kingdom, major contributors to strandline deposited material, in terms of biomass, are the intertidal brown fucoid algae (e.g. *Fucus vesiculosus*, *Fucus serratus*, *Fucus spiralis*) and fronds/whole plants of the large subtidally growing seaweeds e.g. *Laminaria hyperborea*, *Laminaria digitata*, *Laminaria saccharina*, *Sacchorhiza polyschides* and *Himanthalia elongata*. On southern beaches the invasive brown species *Sargassum muticans* may also contribute significantly to beach-cast material and this has now extended its range substantially both west and northwards (5). This species has fronds which are easily detached as part of their reproductive strategy (Andrew & Viejo, 2005). Kelp forests are very productive communities, turning over their biomass many times per year. Much of this produced biomass breaks up on the shore in response to storm events, seasonal mortality or senescence (Polis & Hurd, 1996, Zemke-White et al., 2005). It has been estimated that up to 25% of annual kelp production may end up in the surf zone of the beach environment.

In some localities, ephemeral green and red algae are comparatively minor contributors to the strandline. However, in other locations, (typically associated with eutrophication and habitat change) there is an increasing prevalance of large quantities of ephemeral seaweeds which may grow in-situ (fine, particulate shores in transitional waters) or be deposited in large quantities on the shore in so-called 'green' or 'red' macroalgal tides (Fletcher, 1996). These blooms are typically dominated by a few out of several co-occurring opportunistic species, which are all favored by increased nutrient loads (Runca et al., 1996; Nelson, 2001). Most blooms consist of green algae such as *Enteromorpha*, *Cladophora*, *Chaetomorpha* and *Ulva* (Bolam et al., 2000). Algae such as *Ectocarpus* sp. and *Pilayella* sp. may sometimes occur in large quantities, particularly in cold temperate areas (Jeffrey et al., 1993; Kiirikki and Blomster, 1996). In the Archipelago Sea, SW Finland, thick, loose-laying mats of *Cladophora glomerata*, *Pilayella littoralis* and *Ceramium tenuicorne* cover shallow, flat bottoms during the summer months (Bonsdorff, 1992; Malm et al., 2004). Winds and currents may move the masses towards the shore, and huge drift walls accumulate on the beaches (Vahteri et al., 2000). In other parts of the Baltic Sea large quantities of red seaweeds

(*Polysiphonia fucoides* and *Furcellaria lumbricalis*) may also be deposited on beaches in southeast Sweden (Malm et al., 2004). In tropical to warm temperate areas, such macroalgal blooms mostly occur during the cold season (Hernandez et al., 1997), while cold temperate areas are affected during the summer (Hull, 1998; Kolbe et al., 1995; Tyler et al., 2001). The forcing factors which determine the extent and longevity of macroalgal blooms include nutrient supply, temperature, turbidity, bed stability, hydrography and type of substratum (Scanlan et al., 2007). The importance of nuisance blooms as potentially important indicators of nutrient enrichment and habitat change and their potentially deleterious impact on sensitive marine communities is recognized in the Water Framework Directive (WFD, 2000) and in the development of monitoring tools and classification systems (Scanlan et al., 2007). The Environment Agency for England and Wales has also developed internal guidance (Wither, 2003) for assessing the risk to Natura 2000 sites for the Habitats Directive. No detailed surveys have been undertaken to estimate the amounts of naturally beach cast material around the U.K. coastline, due to the transient and inconsistent nature of this habitat. However, detailed studies have been conducted in various other parts of the world – some of this information is summarized in Table 3.

Table 3 Quantities of Beach cast materials recorded on coastal shores.

Location	Year of study	Quantity /dimensions	Composition/Dominant Species	Beach Type	Environmental conditions	Reference
Barkley Sound, British Columbia	-	Max. 140 mg (dry wt.) km^{-1} shoreline	*Fucus* spp., *Macrocystis integrifolia*, *Nereocystis luetkeana*, *Enteromorpha* sp.	Sand, cobble, gravel	Fully saline	Orr et al., 2005
Nuevo Gulf (South Patagonia)	1992-1999	Spring/summer maxima: 45,000 – 215,000 kg (dry wt.) km^{-1} yr^{-1} shoreline	8 species of chlorophyta 13 species of phaeophyta 19 species of rhodophyta	Sand	Fully saline, potentially elevated nutrient levels	Piriz et al., 2003
Puck Bay, southern Baltic Sea	2002	Mean: 17,000 kg (dry wt.) km^{-1} yr^{-1}	*Cladophora* sp., *Fucus* spp., *Furcellaria* sp., *Pilayella* sp., *Chara* sp. *Enteromorpha* spp., *Zostera* spp. (eelgrass)	Sand	Brackish (3-8 psu). Microtidal & eutrophic	Kotwicki et al., 2005
Cape Peninsula, South Africa	1979	20000 – 30000 kg (wet weight) m^{-1} yr^{-1}	Kelps – *Ecklonia maxima* *Laminaria pallida*	Sand	Fully saline	Griffiths & Stenton-Dozey, 1981
Perth, Western Australia	1985	222 – 85544 g m^{-2}	*Ecklonia maxima* Red algae species Seagrasses of the genera *Amphibolis* & *Posidonia*	Sand	Fully saline	McLachlan, 1985
Algoa Bay, west coast of South Africa	1988	600 – 508,000 kg km^{-1} yr^{-1}	*Hypnea rosea*, *Plocamium corrallorhiza* & 15 other species	Narrow sandy beach	Fully saline	McGwynne et al., 1988
Padre Island, Texas, U.S.A.	1997	0 to c.a. 650 g m^{-2}	*Sargassum fluitans* and *S. natans*	Sand	Fully saline	Engelhard & Withers, 1997
Roscoff Aber Bay, France	Summer 1997	5000000 kg (wet weight)	*Enteromorpha spp.*	Various	-	Merceron, 1999

The amounts of beachcast materials recorded in the above studies vary greatly and the upper end of the values should be viewed as extremes. Typically, the quantities of the beachcast material recorded as being deposited on many American and South African beaches would not be seen on UK beaches.

Predicating the quantity of macrophyte materials which may be deposited on any one specific U.K. beach is extremely difficult as a variety of different factors influence coastal deposition. Kirkman & Kendrick (1997) found no direct link between offshore annual production on a 16 km stretch of Australian coast and the amount of unattached, subtidal and beach-cast seaweeds found in the immediate vicinity. This was because the direction, distance and time over which detached seaweeds travel is unknown. Surface drifting seaweeds may be affected by winds, while bottom-drifting seaweeds may be more affected by currents. Seasonality of different algal species also plays a role in their abundance as a component of beach-cast wrack (Rodil et al., 2008). Weather plays a primary role in determining the abundance of beach-cast seaweeds. Winter storms may be responsible for tearing loose a large biomass of seaweed and wind direction may determine whether dislodged, rafting material is deposited on any particular shore. Seasonal, lunar, tidal and spatial fluctuations in beach wrack accumulations have been reported by many authors (Orr et al., 2005; Olabarria et al., 2007; Ince et al., 2007).

Once cast ashore, seaweeds can become resuspended, either floating in the water column or on the surface near the sea floor. This is because a significant proportion of beach-cast seaweed may be cast up during the neap tidal cycles. Spring tides or wave action can provide a medium through which this material is resuspended, thus removing it from the beach environment (Zemke-White et al., 2005). The aspect and slope of the beach, wind direction and strength and the tidal cycle will all play a part in the residence time of seaweeds on a specific beach.

5.2 Strandline Degradation

Once deposited and retained on a beach, wrack beds are subjected to different processes such as dehydration, ageing, fragmentation, burial by sand, and decomposition. These processes are highly variable and influenced by both site- and time-specific environmental conditions and in most cases depend on the composition of the wrack itself (Colombini and Chelazzi, 2003; Olabarria et al., 2007). The wet weight of beach cast material rapidly decreases – probably due to the leaching of carbohydrates and non-structural proteins which may account for much of their loss in mass following death (Rice and Tenore, 1981). Freshly cast beach wrack is rapidly colonised by a variety of invertebates which vary depending on the geographical location. However, typical strandline inhabitants in the U.K. include detritivores of marine and terrestrial origin (such as isopods, talitrid amphipods and dipteran larvae, (Llewellyn & Shackley, 1996). The grazing of amphipods and other detritivores accelerates the decomposition of vascular material not only by the mechanical action of fragmenting material but also by selectively grazing the microbiota, leading to a general increase in community metabolism. Despite the potential importance of herbivorous invertebrates in macrophyte degradation, bacteria and fungi constitute the primary decomposers of buried wrack and physical leaching and fragmentation are also important (Griffiths et al., 1983; Inglis, 1989). Usually less than 10% of the biomass of marine macrophytes is consumed by herbivores. The remainder dies and decays, forming detritus that contains a high proportion of structural carbohydrate, which most animals cannot digest. The detritus is colonized by fungi and bacteria that take nitrogen and other nutrients from the water while using the plant tissue as their carbon source (Mann, 2000).

The degradation rate of stranded macrophytes is highly variable and is influenced by a variety of factors including air temperature, salinity, moisture, thickness of the wrack deposits and oxygen levels. Studies have indicated that temperature may be ranked among the most crucial factors regulating the decomposition process in the field with faster decomposition rates occurring at higher temperatures (Carpenter & Adam, 1979; Birch et al., 1983; Paalme et al., 2002). The thickness of wrack deposits, which have insulating properties (Kirkman & Kendrick, 1997) can also affect the temperature and moisture of the materials, which can in turn affect metabolic rates and carbon processing. Coupland et al. (2007) showed that in *Sargassum* spp. and *Ecklonia radiata* dominated wrack the temperature inside was buffered by the insulation properties of the wrack material, particularly where the thickness of the deposits exceeded 5 cm. Comparisons between the wrack temperature and that of the overlying air showed that wrack temperature changed only 0.28°C for each degree the overlying air temperature changed, with wrack temperature being warmer than air at the lowest air temperatures and cooler than air at the higher temperatures. The speed of wrack degradation may also vary for individual species depending on whether the material is lying on the sediment surface or buried within the sand. Paalme et al. (2002) found that the brown algae *Pilayella littoralis* had a faster decomposition rate, compared with *Cladophora glomerata*, in aerobic conditions, whereas the species was found to be very resistant to decay in anaerobic conditions. Where anaerobic decomposition of algal material occurs – either at the base of strandlines in contact with sediment or where algal material is incorporated into the sediment itself, sulphate reduction by anaerobic bacteria will occur, with the formation of hydrogen sulphide (Vahteri et al., 2000). Neira and Rackemann (1996) buried 50 kg of *Enteromorpha* spp. to a depth of 16 cm in intertidal sediment. Sulphide in the pore water of the algae-loaded area increased strongly after one and a half weeks, up to14 $mmol.dm^{-3}$ in the algal biomass layer. After three weeks the maximum concentration reached 18 $mmol.dm^{-3}$, with a mean of 7.2 $mmol.dm^{-3}$ for the sediment column. Elevated sulphide levels persisted in the porewater in the vicinity of the decaying algae for several months.

Hydrogen sulphide is frequently produced during the degradation process of seaweeds. Hydrogen sulfide (H_2S) is a toxic gas with an offensive odour reminiscent of rotten eggs. Exposure is via inhalation; there is negligible absorption via the skin (Costigan, 2003). The odour is detectable at very low concentrations; the threshold for perception is between 0.02–0.13 ppm. Short-term, single exposures to concentrations of 500 ppm and above may be fatal to humans. However, hydrogen sulphide levels this high are typically only encountered in enclosed environments associated with industrial processes, such acute levels would not be able to develop in exposed, coastal sites. H_2S is an irritant of mucous membranes of the eyes and respiratory tract. Chronic eye effects in response to lower concentrations of hydrogen sulphide include: irritation, tearing, and inflammation with distorted vision. Respiratory effects can occur at these same levels or lower, resulting in feelings of nose and throat irritation, cough and signs of inflammation. Asthma can be exacerbated by exposure to H_2S at lower levels. Nervous system effects such as headache, nausea (with or without vomiting), inability to concentrate on simple tasks, sleep disturbance and loss of reasoning ability can occur at low levels (perhaps at less than 1,000 ppb) (Washington State Department of Health, 2001).

New U.K. occupational health limits set for inhalation exposure to H_2S in the workplace must comply with occupational exposure standards of 5 ppm (8 hour TWA) and 10 ppm (STEL). Few studies have monitored the environmental levels of hydrogen sulphide associated with the degradation of large quantities of macroalgae. Aside from the nuisance value to holiday makers from the smell of low H_2S levels it is unlikely that under normal conditions high enough levels of H_2S would be liberated to induce acute symptoms or chronic effects. However, under extreme conditions where large quantities of algae are deposited on a frequent basis, without any effective management regime there is the potential for significant quantities to be liberated. In Busselton, Western Australia, a marina development resulted in an unnatural accumulation of beachcast material over a period of years (6). Hot-spots of hydrogen sulphide were recorded with levels peaking at 17.17 parts per million (ppm) - well above the World Health Organisation guidelines.

During the degradation process a variety of other organic substances are also released. The composition and quantity of these leachates will vary according to the extent and composition of the strandline (Hunter, 1976; Kristensen & Hansen, 1995).

5.3 Management techniques

On U.K. beaches where the deposition of seaweeds and associated anthropogenic waste is perceived to be a physical risk to health, or a nuisance – in terms of extent or volume of the beachcast material and the amount and type of anthropogenic waste associated with it, various regimes/policies are in place for its removal.
Municipal authorities have beach management policies in place to clean beaches during the bathing season to make them attractive to tourists, to fulfil bathing water legislations and to meet the cleanliness criteria required to obtain awards such as the Blue flag awards. There are currently 71 beaches with this designation in the United Kingdom (7).

Approaches to beach cleaning by local authorities can vary greatly. These range from manual picking up of large and obvious pieces of man-made material in the strandline to the raking and removal of all material (both natural and man-made) using beach-cleaning machinery. The basic ends of mechanised cleaning machines are improvised agricultural machinery comprised of a tractor and some form of agricultural rake trailed behind the tractor. However, there is an increasing trend for local authorities to use purpose-built beach-cleaning machinery which include those produced by the Barber, Rockland and Beachtech companies. Machines produced by these companies vary greatly but they typically rake the beach, remove and sieve surface sand taking out all objects down to the size of cigarette stubs (including stones and pebbles) before depositing the cleaned sand and smoothing it to give the beach a visual 'pristine look.'
In addition to the different types of methods used to clean beaches, the extent and frequency of cleaning can also vary greatly from beach to beach. These regimes can range from a one-off cleaning event in response to a mass, unusual deposition event (e.g. after storms), cleaning the strandline only once a month using manual picking to cleaning the entire beach from high to low-water every day using mechanical equipment.

Depending on the beach cleaning method employed, councils have to dispose of the materials collected as a consequence of their beach management regimes. In the case of litter handpicked from the strandline this may be a simple matter of bagging the waste and sending it to landfill. However, the disposal of aggregated algae may be more difficult, especially where very large quantities of such beachcast material occur. The techniques used for dealing with this material can be broadly placed under 2 categories - A) in-situ natural techniques for disposal or B) removal of the material from the immediate vicinity of the beach. In-situ regimes involve a variety of methods including the raking/depositing of the strandline material to a location far below the current high-water line on the beach. This action is performed in the hope that the collected material will be re-floated and dispersed away from the beach during the next high tide. The success of this as a dispersal technique on any particular beach depends on the weather conditions, current strength and the quantities of material involved. Under calm weather conditions, rather than being dispersed by incoming tides, the majority of this material may be naturally buried by sand (over the course of several tides) leading to significant anaerobic 'patches' on beaches (Cowie & Hannah, Pers. Obs. Figure 4). Other regimes may call for the deliberate burial of this material into the beach. Another in-situ technique utilized is where the algal material is deliberately aggregated into large mounds on the beach with subsequent reliance on natural degradation processes to reduce the beachcast material (Wither, Pers Comm.).

Figure 4 Algal 'hot-spot' on a sandy beach formed by sand being deposited on the small algal mound with gradual incorporation into the beach.

5.3.1 Removal and utilisation

Where local councils elect to remove seaweed from the beach because of the large quantities deposited and high nuisance value there are currently 3 main traditional options open to them – incineration of the seaweed, depositing it as landfill or placement of the material back into the sea either in an adjacent area to the cleaned beach or some distance away. Where eutrophic conditions exist there is an indication that the removal and disposal of wrack somewhere apart from the marine environment can remove some of the excess nutrient from eutrophic waters (Schramm, 1991). However, the practice of removal and remote disposal, i.e. to landfill, is becoming less of an option because of the expense associated with the removal and disposal of large quantities of seaweed (landfill tax has recently increased by £8 a tonne) and the United Kingdom's E.U. obligations to reduce the amount of landfill it produces. Additionally, these are potentially detrimental environmental consequences associated with such actions (outlined in section 6). These problems have led to the idea that the nuisance to humans associated with beachcast material could be partially remedied by using the beached algae in a variety of useful applications. Historically, small quantities of strandline material have been removed from beaches by local populations to use as a soil conditioner and beachcast material has been utilized for decades in the production of agar and alginates (Tseng, 1947). The recognition that macroalgal proliferation is occurring in some parts of the world has led to new technologies being developed to try and commercially utilize the increasing amounts of beach-cast material. These include using processed seaweed as a partial replacement for cellulose fibres in paper-making (8), using it as a raw material for the production of compost, biogas (Wosnitza & Barrantes, 2005; Morand et al. 1990; Schramm 1991; Mazé et al. 1993; Habic & Ryther, 1983), compound feedstuffs, green manure and poultry fodder (Briand, 1991).

Attractive as these mechanisms for utilizing beachcast seaweeds seem, many of these technologies are at the trial stage and are still being developed. Typically, the success of a particular process depends on reliable quantities of seaweed of a certain species being deposited – something that does not usually occur around the U.K. coastline.

Summary of the main points and gaps in knowledge:

1. Whilst anecdotal accounts about the quantities of wrack deposited on U.K. shores exist, the lack of published scientific information, either historical or recent, make it impossible to determine an indication of the proliferation of macroalgae around the U.K. coastline, whether there are increases in beach-cast material, and any potential increase in risks associated with such depositions.
2. There is a lack of information regarding the potential health impacts of large quantities of hydrogen sulphide being liberated by the degradation of mass strandings of macroalgae.
3. Information is lacking regarding the potential for degrading wrack and associated leachates, either on the surface of sandy beaches or incorporated into the sand, to either harbour FIOs or to enable their proliferation in the environment.

6 Ecological importance of macro-algae to beach ecosystems and impacts of various removal methods

6.1 Strandline ecology (summary of knowledge including that from UK)

Strandlines provide a unique, fringe habitat, neither exclusively marine nor terrestrial and are colonised by invertebrates from both systems (Gheskiere et al., 2005). Detached macrophytes, that have been transported from other regions and accumulate as strandlines on sandy beaches, can play a major role in fuelling secondary production, particularly for sandy beaches with little in situ production (Brown and McLachlan, 1985). Detached macrophytes generally support a rich and diverse invertebrate fauna (Colombini and Chelazzi, 2003). Amphipods, isopods, Sea slater (*Ligia oceanica*) and dipterans are the major primary consumers of beach-cast wrack, with amphipods usually being the most numerically dominant (Colombini and Chelazzi 2003). Amphipods have been shown to comprise 50–90% of the total macroinvertebrate fauna in beach-cast wrack (e.g. Behbehani & Croker 1982; Robertson and Lucas 1983). Since amphipods can provide food for other invertebrates, birds and fish (Robertson & Lenanton, 1984; Dugan et al., 2003; Dugan, 2006), they potentially provide an important link in the food chain in intertidal environments. Other invertebrates found in strandlines include beetles (Coleoptera); in some southern regions these include the nationally scarce ground bug *Scoplostethus pictus* (Dumfries County Council, 2007). Wrack and wrack-inhabiting organisms can provide food and nesting habitats for shorebirds including turnstones, plover, sanderling, knot, dunlin and gulls (Bradley & Bradley, 1993; Schulz; 1992; Dugan, 2006).

Strand-lines may also enhance the stabilization of the foreshore by supplementing the organic and moisture content of the substratum so that pioneering plants such as sea sandwort, *Honkenya peploides*, sea rocket, *Cakile maritima*, and saltwort, *Salsola kali* may eventually establish (Budd, 2004). Some rare and scarce species may are also be found associated with strandlines such as the oysterplant. These species can withstand periodic disturbance and are tolerant of seawater inundation. They are of great ecological importance in sand dune formation, where they can act as precursors to sand dunes, enabling the formation of embryonic dunes and subsequently fore-dunes (Davidson et al., 1991).

Although there is no current UK wide Habitat action plan for strandlines, they are encompassed in associated UKBAP listings which include a broad habitat statement for supralittoral habitats (those habitats above the extreme high water spring tide level) and littoral sediments, and within that, priority habitat action plans for coastal sand dunes, saltmarsh and mudflats, which are all of relevance to strandlines. Individual beaches may have specific designations such as SSSI (Site of Special Scientific Interest) status and have specific beach management policies in place to address their commitments to this designation.

The importance of ‘naturalness’ is also appreciated in some beach awards. In the Seaside award rural beach criteria it states that…

'The existence of seaweed is a vital part of the beach ecology on some rural beaches. The raking of sandy areas closest to fore dunes and the removal of seaweed should be treated sensitively as the removal of pioneer species, such as sea rocket and sea stock which grow in front of the dunes, prevents them establishing roots and stabilising the dune structures. It is recommended that the cleaning regime for each beach be examined. It may be more effective & economical to hand pick litter at some sites'

The importance of strandline habitats are also being recognised by U.K. County councils and they are increasingly being built into Local Biodiversity Action Plans (e.g. Davies & Gillham, 2004). Many of these LBAPS include action points aimed at altering the public's perception that strandlines are merely a nuisance to be disposed of by using information boards/posters at beaches and supplying information sheets about the importance of strandlines as a habitat.

6.2 Environmental impacts of different beach management regimes

Councils have a sensitive balancing act in trying to meet the expectations of people (both locals and visitors), providing cost effective beach management and sustaining the needs of wildlife. There are diverse views regarding beach management, including the clearance of litter and seaweed. There is however, a growing concern internationally about the use of beach-cleaning machines and their damaging impact on the overall strandline-related species diversity and abundance (Belpaeme et al., 2004). If the cleaning is mechanical e.g. big tractor-driven rakes followed by the removal of all drift-line material (both man-made and dead seaweed) this can have important impacts on nutrient re-cycling within the beach. Most sandy beaches are relatively nutrient poor – by their nature they occur in regions of increased wave action, which prevent high levels of particulate organic material occurring – unlike muddy shores high in organic matter. Consequently, the annual deposition and break down of seaweed by microbial communities can represent an extremely important source of nutrient input to the beach microbial and larger faunal communities. On many beaches cleaning is highly seasonal and only occurs during the summer season; it is during this period that the maximum breakdown of seaweeds would occur due to the warmer temperatures – bacterial decomposition is more efficient in warm temperatures. The maximal deposition of seaweed occurs during the winter (due to storms). If cleaning occurs through this period then the impacts on the beach may be even greater. Adverse impacts of the removal of strand-line material can also be species specific. Many invertebrate species occupy or utilise the decaying strand material to feed – e.g. isopods and amphipod 'sand-hoppers'. Removal of this material can cause great problems to populations of these groups this has already been documented extensively (e.g. Davidson et al., 1991; Kirby, 1992, Llewellyn & Shackley, 1996; Weslawski et al., 2000; Dugan et al., 2003; Gheskiere et al., 2006). Direct correlations have also been made in different parts of the world between the removal of beachcast material and declines in several bird species which utilise this habitat (Bradley & Bradley, 1993).

In addition to the impacts on organisms there is some evidence (both scientific and anecodatal) that aggressive beach cleaning practises have the potential to accelerate beach erosion and change the topography of beaches (e.g. Piriz et al., 2003). Dramatic differences in beach topography were noted between raked and unraked beaches in New Jersey, USA (Nordstrom et al., 2000). Where seaweed is removed from a beach in large amounts, large quantities of sand may also be removed along with the debris (although some modern machines are designed to avoid this). Aggressive raking may also influence beach sediment stability by disrupting the integrity of discrete beach sand layers. On some sandy shores the cohesiveness of sediments is enhanced by particles being bound together by microbial extracellular polymeric substances (eps) a kind of ‘glue’ which is secreted by diatoms and bacteria and can bind mud and fine sand particles. Persistent disruption of these communities through mechanical beach cleaning may influence the cohesiveness of sediments and possibly adversely affect the sediment dynamics of these shores. Changes to sand structure may be most notable where beaches are composed of a thin layer of sand covering an underlying level of pebbles/cobbles. Raking can bring these to the surface altering the composition of the beach.

However, studies have shown that the impact of beach raking on invertebrate biodiversity and beach morphodynamics is variable and a reflection of these typically complex habitats. For example, Feagin and Williams (2008) compared raked and unraked beaches on Galveston Island, Texas over a two-year period and found that raking did not significantly change the elevation of the beaches. Engelhard & Withers (1997) found that both invertebrate macrofauna and organisms associated with wrack were affected by the sporadic mechanical raking of *Sargassum* to some extent but they recorded a recovery of both groups after 14 days.

Only one study has been conducted examining the effects of beach cleaning on community structure in the UK (Swansea Bay, Wales). Llewellyn and Shackley (1996) concluded that mechanical beach cleaning had a serious deleterious effect on strandline related species diversity and population abundance. When not subjected to cleaning a fully balanced, representative selection of strandline invertebrates was present, where mechanical cleaning had occurred, there was a very poor selection of strandline invertebrates. When material was left on the beach for 5 months, amphipods and other associated strandline fauna appeared to recover (Llewellyn & Shackley, 1996).

Most studies agree that aggressive beach cleaning can reduce/prevent the establishment of seedlings in the upper beach and prevent the formation of embryo sand dunes. Sand dune systems are now accepted internationally as playing a vital part in the defense of coastal areas, particularly now as the effects of global warming are becoming apparent. Provided they are properly maintained they are relatively cheap and are self sustaining (Defend the dunes trust, 2002). In the United States (on appropriate shores), beach-cast material is typically collected and placed at the face and botttom of sand dunes to increase dune stability and artifically enhance the process of foredune creation to mitigate its removal from other areas. These measures are now being proposed for certain beaches in the UK (Defend the Dunes Trust, 2002).

From the studies available it is obvious that the extent of detrimental impacts associated with beach cleaning will depend on the cleaning regime employed, the frequency of cleaning and type of shore being cleaned. There is the potential to mitigate some of these impacts through the avoidance of mechanically cleaning areas where ground-nesting bird are present, use of ‘strandline islands’ where areas of strandline are left in place in-between cleaned areas to fuel natural processes and support invertebrate populations and a reduction in the number of times individual beaches are mechanically raked – lowering the level of environmental impacts.

Summary of the main points and gaps in knowledge:

1. Strandlines are ephemeral habitats at the interface of the land and sea and are important habitats for a variety of invertebrates and their predators including different bird species.
2. There are a variety of potentially detrimental environmental impacts associated with beach-cleaning activities; the extent of these impacts will depend on the cleaning regime employed, the frequency of cleaning and type of shore being cleaned.

3. There is a lack of information about the short and long-term environmental impacts of different beach cleaning practises on UK beaches.
4. The least damaging practice is the hand-picking of anthropogenic waste from the strandline, the most damaging to invertebrate communities and their predators is perceived to be the daily cleaning of beaches with custom-built devices which rake the beach, extract all material (both anthropogenic waste and organics) and deposit the collected seaweed in landfill or incineration.
5. There is negligible information available about the different types of beach cleaning practise in the United Kingdom. There is currently no UK wide policy on beach cleaning practises and a lack of information available to councils to formulate informed decisions.

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