The Effects of Intertidal Mudflat Algal Cover on Benthic Invertebrates and Estuarine Birds: A Literature Review

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Key Terms: algal mat, macroalgal, *Enteromorpha*, *Ulva*, intertidal, mudflat, benthic, infauna, epifauna, estuarine, birds, wildfowl, wader, eutrophication

Contents.

1. Background

Although green algal species are a natural component of many aquatic environments there has been a worldwide increase in the prevalence and abundance of macroalgal blooms leading to the development of thick algal mats in fresh and salt water aquatic systems (Fletcher, 1996; Morand & Briand, 1996). These consist primarily of *Enteromorpha* spp. and *Ulva* spp. which increase in biomass from early spring through to late summer (Pihl *et al.*, 1996). Causes of algal blooms are several-fold but most involve anthropogenic activities including agricultural run-off, pollution, industrial or sewage effluents and increases in sea temperature (a function of global warming) (Pinckney *et al.*, 2001). These activities have the effect of causing eutrophication through enrichment of organic matter and nutrients, in particular, nitrogen and phosphorus (Nicholls, Tubbs & Haynes, 1981; Raffaelli *et al.*, 1991; Schramm & Neinhuis, 1996). One of the main responses to nutrient enrichment is the increase in the growth of ephemeral green algae, such as *Enteromorpha* and *Ulva* species, which take in excess nutrients much faster than most other aquatic plants (Pederse & Borum, 1997). Such algal species are also well adapted to the dynamic nature of estuarine environments and undergo a seasonal ‘boom and bust’ successional event. However, algal growth responses to eutrophication are hard to predict due to a variety of hydrodynamic variables (e.g. rate of flushing, wave strength, salinity, amount of suspended sediment) and geomorphological factors (e.g. substrata, slope, sediment particle size) (De Jonge, Elliot & Orive, 2002; Elliot & De Jonge, 2002).

Algal mat growth can be very rapid and represents a huge carbon stock causing major changes to biogeochemical cycles in the immediate area (Morand *et al.*, 1996; Valiela *et al.*, 1997). Eutrophication has various effects on primary producers of the benthic community. Thick algal mats reduce the water current velocity leading to increased siltation and accumulation of organic matter on the sediment (Escartín & Aubrey, 1995).This is detrimental to filtration-feeding molluscs, while conversely the abundance of benthic detrivores and more mobile opportunistic species may increase (Raffaelli, Raven & Poole, 1998).Thick algal mats will also decrease light availability to the underlying water and substrata and can act as barriers, filtering pelagic larvae from the water column thus altering the level of invertebrate larval recruitment to the sediment (Olafsson, 1988). The high oxygen requirement of developing algae causes an anoxic gradient to build up between the base of the mat and the surface sand or mud sediment while within the algal mat there may be oxygen saturation and diurnal oxygen fluctuations. This also leads to accumulation of sulphate-reducing bacteria and increases in harmful sulphide compounds within the sediment and water column beneath the algal mat causing toxic stress on the benthic fauna.

There is evidence that algal mats cause modification to the benthic assemblage with a long-term reduction of species diversity and abundance. This may impact upon higher trophic levels such as birds and fish and presents a potential threat to the continued maintenance of such populations. However, there is often a parallel increase of algal infaunal diversity and abundance as the more mobile and opportunistic benthic species seek refuge and food within the algal mat or are forced upwards due to increasing hypoxic conditions within the sediment. This represents a high level of invertebrate prey within and surrounding the algal mat but the effect may only be short lived and not all predators are adapted to be able to utilise this temporary food source. This study attempts to review and summarise the major available literature regarding the effect of macroalgal blooms on benthic ‘prey’ invertebrate fauna and their estuarine bird predators. For reviews see (Bonsdorff *et al.*, 1997a; Lambeck, Goss-Custard & Triplet, 1996; Raffaelli, 1999, 2000)

2. Objectives

The main aim of this review was to assess the literature with respect to the impact of mudflat algal cover on estuarine bird species. The primary question asks “Does an increase in algal [mat] cover affect estuarine bird abundance, diversity and/or activity?" For example, effects on the foraging behaviour or distributional preferences of estuarine waders. As a natural extension to this question the literature is also reviewed to look at the impact of algal cover on mudflat invertebrate prey species. Thus, a second question would be "Does an increase in algal [mat] cover affect the benthic invertebrate prey abundance, distribution and assemblage?" An intuitive knowledge of ecological processes tells us that the two questions may be intrinsically linked since affects to the littoral fauna and thus '*prey*' availability will potentially affect bird '*predation*' activity. However, for the purposes of this review we will treat all studies with as much objectivity and caution as is possible.

3. Methods

The methodology for this literature review followed an evidence-based framework given by recent guidelines published by the 'Centre for Evidence-Based Conservation' at Bangor University (Centre for Evidence-Based Conservation, 2010). This set of guidelines stems from earlier studies on the requirement for evidence-based approaches to conservation (Pullin & Knight, 2003; Pullin & Stewart, 2006).

3.1 Search Strategy

The two questions in the objectives section can be broken down into definable elements. These were used to drive the search strategy. They are ***subject/population:*** estuarine bird species (wildfowl and waders) OR benthic invertebrate prey species; ***intervention/exposure:*** algal mat cover; ***outcome:*** feeding behaviour, activity, abundance, diversity, assemblage; ***comparator:*** algal cover versus no algal cover. Combinations of these elements were used in electronic database searches. A number of primary search terms derived from the *intervention/exposure* element were chosen and each combined with a secondary search term derived from the *subject/population* element. Primary and secondary terms used in the literature search are presented in Table 1. For example, ***algal*** was combined with ***bird*** using the Boolean operator '**AND**' to give the search term '***algal* AND *bird***'. This was repeated for all primary and secondary terms such that a total of 105 unique search terms were used. In most cases the search terms were restricted to sources of abstract, title and/or keywords.

For searches using other sources (see below) only key terms were used (i.e. algal mat AND wildfowl OR waders OR shorebirds, eutrophication AND intertidal). As the search progressed through an iterative process there was an increase in the duplication of hits. Once these reached a reasonably high level the search was abandoned as we could be confident that all key literature and most other relevant literature had been sourced. Several terms, for example 'benthic', were rejected as they generated too many hits (over 3000 for 'algal' AND 'benthic' in ISI Web of Knowledge, for example).

Table 1. Literature search terms used in electronic database searches.

Primary Terms	**Secondary Terms**			
	Birds	**Fauna**	**Habitat**	**Wildcard**
algal algal mat macroalgal macroalgae *Enteromorpha* *Ulva* *Cyanobacteria*	bird wildfowl waders shorebirds avian estuarine birds	infauna epifauna macrofauna benthos	intertidal mudflat littoral	assemblage eutrophication

3.2 Search Sources

There were four categories of search sources. These were electronic databases, WeBS sites of relevant organisations (including statutory, advisory and non-governmental bodies), search engines (Scirus, Google, Dogpile) and hand searches of bibliographies of key articles, selected for their obvious relevance to the review objectives. Search sources are shown in Table 2.

3.3 Selection Criteria

All hits from electronic database searches were downloaded to a bibliographic software package Endnote (Thomson Reuters). Documents and other ‘grey’ literature from WeBS sites and Google searches were also downloaded. All duplicate references and documents were discarded. The selection of articles for inclusion was based upon the original two questions and their definable elements set out in the objectives. Initially, all unique article titles and/or abstracts were read for inclusion or exclusion. Exclusion criteria included studies not written in English language, unavailable literature and grey literature with minimal scientific content. For literature on birds, worldwide studies were included. For literature on benthic invertebrates, only studies carried out in Europe (plus a few other relevant studies) were included. Selected literature was then read in more detail (full text) for relevance. Thus the final tally of articles was subject to two inclusion checks. Only documents directly relevant to the effects of algal mat cover on estuarine birds and/or benthic invertebrates were included for subsequent data extraction and synthesis.

3.4 Data Extraction

To develop a data extraction and synthesis method a subset of ten relevant ‘key’ studies were scoped for both contextual and methodological information deemed to be relevant to the objectives. For literature on birds the following data was extracted: study (author), location, study length, habitat, main species studied, study type and design and summary. For literature on benthic invertebrates data extracted included: study (author) and summary.

3.5 Data Synthesis

Extracted data was incorporated into tabular format, Tables 3 and 4. The tables and associated literature was assessed for general outcomes (i.e. key results generated from multiple studies). From these results a summary of general patterns and trends could be generated.

Table 2. Search Sources.

1. Electronic databases
ISI Web of Knowledge (http://pcs.isiknowledge.com)
ISI Web of Science (access through Endnote)
Science Direct (http://www.sciencedirect.com)
Directory of Open Access Journals (DOAJ) (http://www.doaj.org/)
Copac (http://copac.ac.uk/)
Ethos (http://ethos.bl.uk)
BIOSIS (http://science.thomsonreuters.com/training/biosis/)
JSTOR (http://www.jstor.org/)

2. WeBSites
Department of Agriculture and Rural Development (http://www.dardni.gov.uk/)
Department of Environment (http://ww2.defra.gov.uk/)
Natural England – Publications catalogue (http://www.naturalengland.org.uk/)
Scottish Natural Heritage (http://www.snh.gov.uk/)
Countryside Council for Wales (http://www.ccw.gov.uk)
Joint Nature Conservation Committee - publications catalogue (http://www.jncc.gov.uk/)
The Marine Life Information network (MarLIN) (http://www.marlin.ac.uk/)
The Marine Biological Association (http://www.mba.ac.uk)
Plantlife (http://www.plantlife.org.uk/)
Botanical Society of the British Isles (http://www.bsbi.org.uk/)
The Royal Society for the Protection of Birds (http://www.rspb.org.uk/)
British Trust for Ornithology (http://www.bto.org/)
Wildlife Conservation Research Unit - publications (http://www.wildcru.org/)
National Trust (http://www.nationaltrust.org.uk/)
British Wildlife volumes 1 - 20 (http://www.britishwildlife.com/)

3. Google search Engine - 1st 50 hits for each search term used
(algal mat AND wildfowl OR waders OR shorebirds, eutrophication AND intertidal)
Scirus (http://www.scirus.com/)
Google (http://www.google.co.uk)
Dogpile (http://www.dogpile.com)

4. Bibliographies of 12 KEY articles
(Hand search of bibliographies of key/relevant articles)

4. Results

4.1 Search Strategy Results

The search method (105 search terms) generated a high degree of sensitivity to ensure capture of all or most of the relevant articles and thus reduce bias. Due to the nature of the search strategy specificity was low leading to a high level of rejection during the selection process. The majority of relevant articles were sourced from electronic databases while documents obtained from WeBS sites and other 'grey' literature consisted of reports, recommendations, educational documents or others with varying degrees of scientific content. In the search strategy 8 databases, 15 WeBS sites, 3 search engines and bibliographies of 10 key articles were searched generating approximately 400 unique references for selection screening.

This lead to approximately 50 references judged to be relevant for inclusion in the review. A number of articles were unavailable or provided only supplementary material (mostly WeBS site documents) and are listed in the Appendices (Appendix 1 and 2).

4.2 Data Extraction Results

4.2.1 Summary of studies on estuarine birds

There were few studies on the effects of algal cover on estuarine birds (Table 3). Studies varied in length with either short-term intensive surveys or analysis of long-term survey datasets from monitoring programmes. Areas covered and survey methodologies varied but with most surveys occurring in the hours before and/or during low tide. Some studies combined analysis of sediment and/or invertebrate data with bird survey data. Study locations included areas in Finland, France, Ireland, the Netherlands, Portugal and the U.K. (Scotland, England) while habitats included mainly intertidal mud and sandflats within estuaries. One study included Salinas (salt pans) while another included coastal sea areas. Species surveyed were mostly waders while one study concentrated on waterfowl. Other species included several Gull species and Shelduck.

4.2.2 Evidence on the effects on estuarine birds

Studies on the effects of algal cover on estuarine birds are outlined in Table 3. General patterns and trends of estuarine bird responses to macroalgal cover (from table 3 and associated references) are summarised below.

- Overall there was a tendency for waders to avoid areas covered by algal mats. This was mostly in response to dense algal cover (Ringed Plover, Grey Plover, Dunlin, Black-tailed Godwit, Bar-tailed Godwit, Redshank, Curlew, Knot, Oystercatcher) (Lewis, Davenport & Kelly, 2003; Lewis & Kelly, 2001; Murias *et al.*, 1996; Raffaelli, 1999; Tubbs & Tubbs, 1980)

- Low to medium patchy algal cover had little effect on bird abundance, distribution or feeding behaviour (Cabral *et al.*, 1999; Lewis *et al.*, 2003; Murias *et al.*, 1996)

- Areas which showed long-term increases in seasonal algal cover and biomass tended to support decreasing populations of waders but a causal link was inconclusive.

- Some birds showed exploitation of macroalgal mats as a food source (Kentish Plover, Redshank, Oystercatcher, Common Gull, Herring Gull) (Desprez *et al.*, 1992; Lewis *et al.*, 2001; Tubbs *et al.*, 1980)

- Areas cleared of algal cover or undergoing algal decline showed corresponding increases in wader abundance (e.g. Dunlin) (Cabral *et al.*, 1999; Lopes *et al.*, 2006)

- There was some evidence of changes in bird feeding behaviour (e.g. pecking rate – Kentish Plover) in response to algal cover (Cabral *et al.*, 1999)

- There was some evidence of alterations to bird food choice in response to algal cover (e.g. Oystercatcher)(Desprez *et al.*, 1992; Lewis *et al.*, 2001)

- In three studies (Raffaelli, Hull & Milne, 1989; Tubbs, 1977; Van Impe, 1985) there was an increase in wader and wildfowl abundance thought to result from increases in macrobenthic fauna including *Capitella capitata* (Raffaelli *et al.*, 1989)

- There were few studies regarding the effects of algal mats on wildfowl in intertidal areas (Tubbs, 1977; Tubbs *et al.*, 1980) or coastal regions (Ronka *et al.*, 2005). There were both increases and decreases of wildfowl species abundance in response to eutrophication and algal mat cover.

Table 3: Studies on the effects of algal cover on estuarine bird (wildfowl and waders) abundance, diversity and feeding activity.

(KEY: Di. – diversity; Ab. – abundance; ↑ - increase; ↓ -decrease; ↔ - no change; ha – hectares; m^2 – square metres)

Study	Location	Study length	Habitat	Main species studied	Study type and design	Summary
(Cabral *et al.*, 1999)	Mondego estuary, Portugal	8 months	Intertidal mudflats	Wader spp. including: Kentish Plover, Ringed Plover, Grey Plover, Dunlin. 62 macrobenthic spp. Polychaeta, Gastropoda, Bivalvia, Amphipoda, Decapoda, Diptera	**Survey:** monitored wader densities and behaviour (peck rate, search effort) in relation to algal mat cover. Study area: Three 1ha areas representing principal feeding microhabitats (dense eelgrass meadow, sparse eelgrass meadow, mud/sand substrate). 10 monthly wader counts in each area 2 hours before and after low tide. Fortnightly sediment samples (10 replicates) taken to assess macroalgal and macrobenthic biomass. Wader faecal analysis also performed.	↔ on wader feeding behaviour parameters caused by ↑ in macroalgal BM. ↔ to wader prey spp. in presence of macroalgal cover (maximum cover was only 36%).↓ occurrence of Ringed Plover, Grey Plover and Dunlin in areas with algal cover. ↑ peck rate of Kentish Plover in areas with algal cover. Amphipods principal prey for Grey Plover and Dunlin. *H. ulvae* principal prey for Kentish Plover and important prey species for Ringed Plover, Grey Plover and Dunlin. *Hediste diversiclor* is principle prey for Ringed Plover.
(Desprez *et al.*, 1992)	Bay of Somme, North-west coast, France.	7 years, time series	Intertidal mudflat and sand bars.	Bivalve predators: Oystercatcher, Common Gull, Prey species: *Cerastoderma edule,* *Pygospio elegans*	**Survey:** monitored changes to benthic macrofauna and to predatory birds caused by eutrophication-associated plankton/algal blooms. Respirometry measurements of water, sediment and major macrobenthic species recorded. Benthos data from fixed point every three months. Nitrate inputs supplied by third party. Macrofauna predation by birds quantified by counts and pellet analysis.	Eutrophication and high summer temperature-mediated algal blooms caused sediment anoxia and mass mortality of benthos. Algal (*Asterionella glacialis*)blooms caused ↓ Ab. of *Cerastoderma edule* and ↑ Ab. of *Pygospio elegans,* Blooms caused change in distribution and food choice of Oystercatcher and Common Gull as prey selection became more opportunistic.
(Lewis *et al.*, 2001)	Clonakilty Bay, West Cork, Ireland	5 months	Intertidal mud and sandflats	Black-tailed Godwit, Redshank	**Survey:** Wader distribution and behaviour in relation to algal cover and break down. Study area: 2 sites (5000m^2 and 10,000m^2). Bird usage monitored, 3 hours before low tide, of 3 areas (dense algal cover, thin algal cover, clear mud).	Black-tailed Godwit avoided areas with algal cover. Redshank showed no avoidance of algae and at times preferentially utilized algal areas for foraging.
(Lewis *et al.*, 2003)	Clonakilty Bay, West Cork, Ireland	2 months	Intertidal mud and sandflats	13 invertebrate spp., Oligochaetes	**Experimental:** algal removal and assessment of invertebrate re-colonization and bird usage. Study area: 12x 10m^2 plots in randomized block design. Assessed sites with algae maintained, algae	↔ Di. ↑ Ab. in all plots after 2 months. (no significant difference between treatments) Significant re-colonization of cleared sites by 2 species: *C. volutator* and *P. maculate.*

					removed and control (no intervention). Bird usage within plots, 4 hours before low tide, monitored on random days.	Few waders used plots during study. Black-headed Gulls preferentially used cleared sites while foraging.
Study	**Location**	**Study length**	**Habitat**	**Main species studied**	**Study type and design**	**Summary**
(Lopes *et al.*, 2006)	Mondego estuary, Portugal	10 years, time series	Intertidal mudflats, Salinas (salt pans)	Dunlin. Prey spp: *Hydrobia ulvae, Hediste diversicolor, Scrobicularia plana*	**Survey:** Long-term study of Dunlin abundance, macroalgal cover and macroinvertebrate biomass in relation to management activity. Study area: 227ha. Two-four weekly census of Dunlin (counts and distribution) recorded at low tide. Area of algal cover also estimated. Long-term sampling (every 2 weeks) of macroinvertebrate biomass in 3 locations.	Long-term Dunlin Ab. ↑ as macroalgal Ab. ↓. ↔ Dunlin habitat selection as macroalgal cover ↑. Short-term ↓ Ab. of Dunlin in selected plots with intermediate algal cover. ↓ biomass of *H. diversicolor* and *S. plana* in presence of algal cover.
(Murias *et al.*, 1996)	Mondego estuary, Portugal	8 months	Intertidal mudflats, Salinas (salt pans)	11 species including: Dunlin, Grey Plover	**Survey:** Wader distribution and behaviour in relation to algal cover. Study area: 134ha mudflats and 21 salt pans. Two-four weekly wader censuses (counts and distribution) recorded at low tide. Area of algal cover also estimated.	↔ in wader distribution between algal-free and algal-weeded areas or in relation temporal changes in algal Ab. Some avoidance of dense algal cover. No relocation to salt pans as algae ↑ in mudflats.
(Raffaelli *et al.*, 1999)	Ythan estuary, Aberdeenshire, Scotland.	Multiple years over 43 year period (1954-1997)	Intertidal sand and mudflats	Invertebrate groups: *Corophium, Hydrobia, Macoma, Nereis* Bird spp.: Oystercatcher, Turnstone. Knot, Dunlin, Bar-tailed Godwit, Curlew, Redshank, Shelduck.	**Survey:** assessment of invertebrate density and shorebird counts in relation to macroalgal mat distribution and biomass in upper, middle and lower sections of estuary. Study area: Ythan Estuary. Estimates of summer algal distribution by aerial photographs (1954, 1969, 1986, 1989 and 1991-97). Collection of samples and biomass analysis (1993). Invertebrate density from sediment core samples (1964, 1990 and 1997). Shorebird mean winter counts (1954, 1966, 1968, 1973, 1978 and 1989). Sediment characteristics from 57 samples (1995).	Overall long-term ↑ in macroalgal mat BM. and distribution in all sections of estuary. ↑ Ab. of *C. volutator, N. diversicolor* and *M. balthica* in upper sections of estuary. ↓ in Ab. of *C. volutator* and *M. balthica* in downstream sections (where algal mat BM is highest) ↑ Shorebird Ab. of Oystercatcher, Redshank, Dunlin, Curlew and Bar-tailed Godwit up until 1980 then ↓ Ab. between 1988-1997 as algal mats spread. Distributional shift of summer Redshank, Dunlin, Oystercatcher and Shelduck.
(Ronka *et al.*, 2005)	Island of Aasla, Rymättylä, Finland.	17 years	Bays, sounds, coastal sea areas	10 spp. waterfowl: Goldeneye, Mallard, Eider, Goosander, Red-breasted Merganser, Tufted	**Survey:** assessed impact of eutrophication on breeding waterfowl. Study area: 24.4 km^2, fringe of inner archipelago. Waterfowl censuses from 11 sites (bays, sounds and seas areas along shore). 3x during spring. Water quality data from 10	↓ Ab. of Goldeneye, Coot and Velvet Scoter as eutrophication ↑. Also modelled weather impacts and water salinity effects.

				Duck, Velvet Scoter, Mute Swan, Great Crested Grebe, Coot.	monitoring stations, 2-4x yearly (external source). Included phosphorus & chlorophyll concentration and water transparency (Secchi depth, m)	
Study	**Location**	**Study length**	**Habitat**	**Main species studied**	**Study type and design**	**Summary**
(Tubbs *et al.*, 1980)	Langstone Harbour, Hampshire, England.	6 months	Intertidal mudflat, sandflats, cord-grass marsh	9 species: Grey Plover, Redshank, Bar-tailed Godwit, Black-tailed Godwit Curlew, Dunlin, Oystercatcher, Knot, Shelduck	**Survey:** assessment of spatial and temporal use of harbour by waders in light of increasing algal cover. Used long-term data sets of bird censuses. Study area: 1320ha muds, 72ha sands and 216ha marsh. 11 bird surveys (~2 per month).	In summer/autumn 7 of 8 wader species and Shelduck avoided foraging in areas with dense algal mats. Dunlin showed no preference between algal free and algal-covered areas during the winter. Some Redshanks (and Herring and Common Gulls) observed foraging on algal fauna. ↓ in Ab. of Curlew, Redshank and Shelduck over period of algal expansion but causal link inconclusive.
(Van Impe, 1985)	Scheldt estuary, Netherlands	2 years (1982-84)	Intertidal mudflat	10 Bird spp. *Ringed Plover, Grey Plover, Bar-tailed Godwit, Redshank, Spotted Redshank, Oystercatcher Avocet, Dunlin, Shelduck, Black Headed Gull.* Invertebrate spp. *Hediste diversicolor, Corophium volutator, Macoma balthica, Hydrobia ulvae.*	**Survey:** Effect of pollution on macrofauna and estuarine birds. Study area: eight sampling stations situated at near mid-tide level. Sediment core samples taken monthly. Sediment characteristics measured: carbon content, particle size, diversity and BM of macrobenthos. Comparisons with 1952-53 data. Counts and estimates of estuarine birds: 1979-83 compared with 1947-55.	↓ in macrofauna Di compared to 1952-53 data. ↑ Ab. of *Hediste diversicolor, C. volutator*. ↓ Ab. of *M. balthica* and *H. ulvae.* General long-term ↑ in benthic faunal Ab. General long-term ↑ in intertidal bird Ab. (thought to correlate with pollution-mediated ↑ in macrobenthos Ab.

Table 3: Bird species studied: *Charadrius alexandrines* - Kentish Plover; *Charadrius hiaticula* - Ringed Plover; *Pluvialis squatarola* - Grey Plover; *Calidris alpine* – Dunlin; *Calidris canutus* - Knot; *Arenaria interpres* - Turnstone; *Limosa limosa* - Black-tailed Godwit; *Limosa laponica* - Bar-tailed Godwit; *Tringa totanus* – Redshank; *Tringa erythropus* – Spotted Redshank; *Recurvirostra avosetta* – Avocet; *Numenius arquata* - Curlew; *Haematopus ostralegus* – Oystercatcher; *Tadorna tadorna* - Shelduck.; *Mergus merganser* - Goosander; *Mergus serrator* - Red-breasted Merganser; *Podiceps cristatus* - Great Crested Grebe; *Anas platyrhynchos* - Mallard; *Bucephala clangula* - Goldeneye; *Somateria mollissima* - Eider; *Aythya fuligula* - Tufted Duck; *Fulica atra* – Coot; *Melanitta fusca* - Velvet Scoter; *Cygnus olor* - Mute Swan; *Larus canus* - Common Gull; *Larus ridibundus* – Black-headed Gull; *Larus argentatus* - Herring Gull.

4.2.3 Summary of studies on benthic invertebrates

Studies on the effects of algal cover on invertebrates were more numerous (Table 4) and included both surveys and field experiments. The study length, species studied, study design, methodology and statistical interpretation were highly varied. Table 4 summarises key findings from the major articles. This list is not exhaustive since effects of algal mat development on the benthic assemblages present are extremely complicated and diverse involving multiple hydrological and geomorphological factors as well as multiple species interactions. Literature summarised in Table 4 includes studies where clear effects to specific taxonomic groups have been identified.

4.2.4 Evidence of effects on benthic invertebrates

Studies on the effects of algal cover on benthic fauna are outlined in Table 4. General patterns and trends of benthic species responses to macroalgal cover (from Table 4 and associated references) are summarised below.

- There is an initial (short-term) increase in the macrobenthic diversity and biomass as the algal cover increases. This is followed by a long-term reduction in species richness as the algal cover thickens and subsequently decays leading to hypoxic/anoxic conditions within the sediment. This is often accompanied by an increase in the abundance of a few dominating species feeding on the algae and decaying organic matter.

- Effects of algal cover are related to temporal (seasonal) and spatial variations in algal biomass. The short term effects occur in June and July during algal development. The long-term effects from July to November when algal biomass peaks and subsequent decomposition occurs. Spatial distribution of algal cover involves numerous hydrological, geomorphological and anthropogenic factors.

- The fate of individual benthic species under algal cover is a reflection of feeding type, tolerance to hypoxia, tolerance to accumulation of hydrogen sulphide, degree of mobility and rate of re-colonization (reproductive capacity).

- There is a decrease in sediment infaunal species under developing and decaying algal mats. Groups suffering most from mortality include sedentary sediment and surface detrivores and suspension feeders.

- Some species display either increased or decreased abundance depending upon the study. This may be a function of algal density and biomass. For example, bivalves initially increase as the algal mat develops but subsequently decline during algal decomposition.

- Species decreasing in abundance in response to high algal cover include Polychaet*es* (*Amage adspersa, Pygospio elegans*, *Hediste diversicolor, Strebospio shrubsolii, Manayunkia aestuarina* and *Alkmaria romijni*), Bivalves (*Cerastoderma edule*, *Cerastoderma glaucum*, *Scrobicularia plana*, *Macoma balthica*, *Macoma nasuta*, *Macoma secta, Mya arenaria, Gemma gemma, Hydrobia spp., Lymnaea spp.*), Isopods (*Cyathura carinata*), Amphipods (*Corophium volutator*), Oligochaetes and epibenthic and infaunal Copepods.

- There is often a short-term increase in opportunistic species in the sediment underlying the algal mat including herbivorous/detrivorous Polychaet*es (Capitella capitata*, *Ophelia pulchella, Platynereis bicanaliculata*), infaunal predators (*Hediste diversicolor, Anaitides williamsi*) and Bivalves (*Macoma balthica, Hydrobia ulvae, Mactra stultorum, Venerupus senegalensis, Ruditapus decussatus, Cerastoderma edule*).

- There is an increase in benthic fauna within the developing algal mat(algal infauna) consisting primarily of vertically mobile herbivores (*Hydrobia* spp., *Theodoxus* spp., *Mytilus* spp.), mobile surface detrivores (*Corophium volutator, Gammaeidae spp., Idotea spp.*), suspension feeders (*Cerastoderma edule, Littorina tenebrosa, Venerupis senegalensis, Ruditapes decussatus, Mactra stultorum*), phytal *Copepoda* spp., *Ostacoda* spp., *Isopoda spp., Turbellaria* spp., *Nemertea* spp. and larvae (*Chironomidae* spp. *Peachia cylindrical, Cerastoderma spp.*).

- Species quick to recolonize an area previously covered in algae included *Corophium volutator*, *Capitella capitata, Phyllodoce maculate, Pygospio elegans* and *Hydrobia* species. This may reflect their high mobility and quick reproductive cycle.

- Algal filtration can prevent settlement of developing larvae (e.g. *Macoma balthica*) leading to slow re-colonization of some species.

- Some benthic species may decrease in size (e.g. *Corophium volutator* - (Hull, 1987)) or increase in size (e.g. *Hediste diversicolor* - (Norkko & Bonsdorff, 1996)) in response to algal cover.

- Long-term changes to the benthic assembly may involve decreased diversity and dominance by stress-tolerant taxa (*Macoma balthica, Chironomidae* spp.)

- Effects on benthic invertebrates may be specific to the particular algal species involved.

Table 4: Summary of major studies on the effects of algal cover on benthic invertebrate diversity, distribution, abundance and assemblage.
(KEY: Di. – diversity; Ab. – abundance; BM – biomass; ↑ - increase; ↓ -decrease; ↔ - no change)

Study	**Summary**
(Bolam *et al.*, 2000)	At 6 weeks: algal (*Enteromorpha prolifera*) BM initially ↑ then ↓ through decay. ↑ Di. / ↔ Ab. of benthic fauna. At 20 weeks: ↓ Di. / ↑ Ab. Overall dominance of *Capitella capitata* and loss of *Pygospio elegans*.
(Bolam & Fernandes, 2002)	Effects of algal species *Vaucheria subsimplex*. At 4 weeks: ↑ Di. and ↑ Ab. of macrofauna. At 20 weeks: ↓ Di. and ↑ Ab. including dominance of *Pygospio elegans* due to enhanced larval recruitment. ↑ water, organic and silt/clay content and reduced redox potential within sediment.
(Bonsdorff, 1992)	Overall ↓ in Ab. and Di. of benthic species underneath drifting algal mats. The settlement of *Macoma balthica* spat was significantly reduced by the algae (73%). No individuals of the dominating polychaetes, *Pygospio elegans* and *Manayunkia aestuarina,* were recorded under the mat. ↑ Ab. of *Corophium Volutator i*n the upper part of the algal mat. *High Ab. of Hydrobia spp.*, other molluscs (*Theodoxus, Mytilus),* mobile crustaceans (*Gammarus spp., Idotea, laera)* and chironomid larvae within algae.
(Cardoso *et al.*, 2004)	*Enteromorpha intestinalis* (green algae) had greater effect on macrofauna than *Gracilaria verrucosa* (red algae). High *Enteromorpha* algal BM caused ↓ Ab. of *Cyathura carinata*, *Scrobicularia plana*, *Alkmaria romijni* and *Cerastoderma edule*. In algal covered plots there was an ↑ in Ab. of *Hediste diversicolor*, *Hydrobia ulvae* and *Capitella capitata.*
(Everett, 1994)	Algal cover caused an ↑ in Ab. of herbivores (*Platynereis bicanaliculata*), mobile sediment-water interface feeders (*Ophelia pulchella*) and predators (*Anaitides williamsi*) but a ↓ Ab. of herbivores (*Hippolyte californiensis*), mobile sediment-water interface feeders (*Boccardia proboscidea*, *Polydora ligni, Pseudopolydora paucibranchiata, Oligochaetes, Transennella tantilla*), sedentary sediment-water interface feeders (*Phoronopsis viridis*), large bivalves (*Macoma nasuta, Macoma secta)* and predators (*Nephtys caecoides, Nermerteans*). Post-algal season samples showed ↑ herbivores (*Platynereis bicanaliculata*), mobile sediment-water interface feeders (*Capitella capitata, Cumella vulgaris, Exogone lourei, Leptochelia dubia*, *Oligochaetes, Ophelia pulchella*) and predators (*Anaitides williamsi, Turbellarians*) but a↓ in sedentary sediment-water interface feeders (*Phoronopsis viridis*).
(Fahy *et al.*, 1975)	Dense algal mat developed in vicinity of field drain inflow. Nitrate level ↓ with distance from inflow. *Hydrobia jenkinsi* epiphytic on algae. *C. volutator* only occurred outside dense algal mats. ↑*Spartina* vigour closer to nutrient discharge sites. (Long-term ↑ in Teal and Pintail may correlate with ↑*Hydrobia jenkinsi* Ab.)
(Franz & Friedman, 2002)	Assesses the effects of a macroalgal mat (*Ulva lactuca*) on intertidal sand flat copepods. *Ulva* removal resulted in overall ↑Ab. and Di. of *Copepoda* spp. but levels remained lower than at the un-vegetated site. *Ulva* addition resulted in overall ↓ of *Copepoda* Ab., ↑ in phytal Copepods and ↓ in epibenthic and infaunal Copepods. The overall effect of the *Ulva* mat was a net loss of copepod density, including the loss of nearly all infaunal species. Anoxia in sediments and within the algal mat are correlated with declines in infaunal species and with escape by some infaunal species from the sediment into the water column.
(Hull, 1987)	In July: ↓ Ab. of *Corophium volutator* and *Pygospio elegans* and ↑ Ab. of *Hydrobia ulvae, Macoma balthica, Hediste diversicolor* and *Capitella capitata*. In October: ↓ Ab. of *Pygospio elegans* at high algal density and ↑ Ab. of *Macoma balthica, Hediste diversicolor* and *Capitella capitata* at medium/high algal densities. ↓ size of *Corophium volutator.* Sediment redox potential and silt content under medium and high density algal cover revealed anoxic conditions.

Study	**Summary**
(Jones & Pinn, 2006; Pinn & Jones, 2005)	Algal cover ↑ from 5.2% (June) to 91% (August), then ↓ to 3.8% (November). Initial ↑infaunal Di. and Ab. (*Hydrobia ulvae*, *Venerupis senegalensis*, *Tapes decussatus, Cerastoderma edule, Mactra stultorum*)during mat development (June-July). Subsequent ↓ infaunal Di. (loss of *V. senegalensis, C. edule, M. stultorum, H. ulvae*) as mat thickened (Aug-Sept.) Large scale loss of infauna (*H. ulvae, C. edule, T. decussatus, Gammarus locusta, Peachia cylindrica*) during algal decay (Sept.-Nov). ↓ Ab. of *Hediste diversicolor* and mollusc spp. in sediment during study. 11 species found in algal mat sample (*H. diversicolor, Nereis pelagica, H. ulvae, T. decussatus, C. edule, Littorina tenebrosa, M. stultorum, V. senegalensis, Carcinus maenus, G. locustra, P. cylindrical)*
(Kotta & Orav, 2001)	Assessed abundance and BM structure of invertebrate assemblage in relation to environmental variables including presence of drifting algal mats of *Furcellaria lumbricalis*. Algal cover ↑ macrobenthos Ab. in areas of sediment mobility acting as refuges. Algal mats caused ↓ Ab. of sediment infauna.
(Lauringson & Kotta, 2006)	Assessed the role of algal mats on the distribution of benthic invertebrates in the sediment, water column and within the algal mats. Sediment under the drift algae hosted ↓ populations o*f Macoma balthica*, *Hediste diversicolor*, *Hydrobia ulvae* and *Cerastoderma glaucum* as compared to bare sediment. Under the drift algae the BM of *Macoma balthica* was ↑ and the BM of *Mya arenaria* and *Cerastoderma glaucum* was ↓ as compared to bare sediment. Presence of drift algae coincided with the disappearance of *Oligochaeta* and *Lymnea* spp. and appearance of *Prostoma obscurum*, *Saduria entomon, Chironomidae*, *Gammarus oceanicus*, *Marenzelleria viridis* and *Idotea baltica*. ↑ Ab. of *Hydrobia* spp. and ↑ BM of *Hydrobia* spp. and *Macoma balthica* occurred within the drift algae. ↓ BM of *Cerastoderma glaucum* in the presence of the drift algae
(Lewis *et al.*, 2003)	↔ species Di. ↑ Ab. in all plots after 2 months (no significant difference between treatments). Significant re-colonization of cleared sites by 2 species: *Corophium volutator* and *Phyllodoce maculate.* (see Table 3a for bird usage summary)
(Lopes, Pardal & Marques, 2000)	↔ in Ab. of macrofauna due to predation. Macroalgal cover ↓ Ab. of *Amage adspersa* and *Streblospio shrubsolii* and ↑ Ab. of *Capitella capitata*. Initial ↑ Ab. of *Hediste diversicolor,* then ↓ Ab. as macroalgal cover thickened.
(Lopes *et al.*, 2006)	↓ biomass of *Hediste diversicolor* and *Scrobicularia plana* in presence of algal cover.
(Nedwell, Sage & Underwood, 2002)	Determined spatial and temporal distribution of algal mats. Highest Algal Ab. during June and July. Mats particularly associated with hard substrata providing attachment points rather than nutrient status of estuary. Estuary poor in algal species, a possible negative correlation with the degree of eutrophication.
(Norkko *et al.*, 1996)	Artificial algal cover and induction of hypoxia caused structural differences in benthic assemblage. Algae rapidly colonized by mobile grazing and predatory invertebrates: *Hydrobia ulvae*, *Hydrobia ventrosa*, Gammarid amphipods, Isopods, *Hediste diversicolor*, *Prostoma obscurum* and *Turbellarian spp.* ↓ Di. and Ab. of species under algal mats - only opportunist spp. and spp. tolerant to hypoxia remained under algal mats: *Hediste diversicolor, Macoma balthica, Hydrobia ventrosa.* Benthic recovery dominated by *Hydrobia* spp.
(Norkko, Bonsdorff & Norkko, 2000)	Eutrophication-induced drifting algal mats can harbour a high Di. and Ab. of invertebrate macrofauna (26 taxa). Most Ab. included mobile surface detrivores: *Hydrobia* spp. *Chironomidae*, *Ostracoda* as well as *Cerastoderma glaucum* larvae.
(Osterling & Pihl, 2001)	↓ Ab. of total macrofauna, suspension feeders and surface detrivores (*Corophium volutator*) in sediment under algae bags and cages. ↑ Ab. of burrowing detrivores, suspension feeders and predators within algae in bags.
(Perus & Bonsdorff, 2004)	Assessed eutrophication-induced effects on Macrofauna distribution. Overall abundance and biomass declines associated with nutrient loading. In the 1990s the benthic communities become more dominated than before by stress-tolerant taxa such as *Macoma balthica* and *Chironomidae*.

Study	**Summary**
(Pounder, 1976)	↓ in *Corophium volutator* in response to nutrient pollution associated algal mat development.
(Raffaelli *et al.*, 1999)	Overall long-term ↑ in macroalgal mat BM. and distribution in all sections of estuary. ↑ Ab. of *Corophium volutator, Hediste diversicolor* and *Macoma balthica* in upper sections of estuary. ↓ Ab. of *Corophium volutator* and *Macoma balthica* in downstream sections (where algal mat BM is highest). (See table 3a for effects on Shorebirds)
(Soulsby, Lowthion & Houston, 1982)	↑ invertebrate BM under high algal cover due to dominance of *Hydrobia ulvae.*↓ Ab. of *Streblospio shrubsolii* under high algal cover. Greatest effects from Autumn (October) samples.
(Thiel, Stearns & Watling, 1998)	Examined effects of green algal mats on bivalves: *Mya arenaria ,Macoma balthica* and *Gemma gemma.* Thick algal cover resulted in ↓ Ab. of *Myaarenaria* and *Gemma gemma.* Algal addition resulted in ↓ Ab. of *Mya arenaria* but not *Macoma balthica.* Algal removal resulted in an↑ in *Mya arenaria* and *Macoma balthica* size.

4.3 Review of Data Summary

4.3.1 Birds

- There is no conclusive evidence of widespread detrimental effect of algal mats on estuarine bird abundance, diversity or feeding activity. There is some data suggestive of longer-term declines in bird abundance associated with yearly, seasonal increases in algal cover and biomass. Factors reported include direct physical effects which interfere with bird foraging or indirect (short-and long-term) effects on benthic invertebrate diversity and abundance. Detrimental effects were associated mostly with structurally dense and spatially widespread algal cover. There are several reports of an increased abundance of some species as a result of eutrophication-induced algal growth. Some of these are the result of increased eutrophication from sewage effluent and represents a limited spatial effect (i.e. in areas surrounding sewage outflow). The bulk of the literature is more than 10 years old (with some considerably older) and while providing an important scientific basis may not reflect current levels, sources or types of eutrophication.

4.3.2 Invertebrates

- Macroalgal cover has short-term effects on benthic invertebrate diversity, distribution, abundance and assemblages. Sediment species underneath algal mats generally decline (sedentary species) or are lost from the sediment layers (migrate upwards as hypoxia/anoxia and toxic sulphides increase.

- Taxa showing decline in multiple studies include Polychaetes (*P. elegans, S. shrubsolii and A. romijni*), Bivalves (*C. glaucum, S. plana, M. balthica, M. nasuta and M. secta*), Isopods (*C. carinata*) and Amphipods (*C. volutator*).

- A few opportunistic infaunal species undergo a short-term increase in abundance at the sediment surface due to increases in organic detritus (decomposing algae) related opportunism by predatory species. Species showing (short-term) increases include stress-tolerant surface detrivore species (especially *C. capitata*) and opportunistic sediment predators, (e.g. *H. diversicolor*).

- Species showing (short-term) increases in abundance within the algal layer include vertically mobile herbivores (*Hydrobia* spp.), mobile surface detrivores (*C. volutator*), larvae and algal predatory species.

- Species showing quick re-colonization ability are those with a rapid reproductive capacity (*C. capitata, P. elegans, C. volutator, Hydrobia* spp.).

5. Discussion

The relationships between algal cover and wader abundance is complex while response of estuarine birds to algal cover is species specific and depends upon multiple factors, both direct (physical effects of algal mats on foraging and prey availability) and indirect (effects on prey abundance, diversity, distribution and detectability). Few of the studies on bird abundance, distribution or foraging behaviour (in relation to algal cover) included identification of prey species consumed thus correlating these two factors is not conclusive and open to interpretation.

Although most waders eat small invertebrates (esp. *Polychaetes*) picked out of the mud or from the sediment surface there are significant differences in prey groups consumed and foraging strategies employed. Smaller waders feed on smaller Annelids of high abundance (e.g. *Nereis* and *Ceratoneries* spp.) which are distributed mostly in the upper strata while larger waders (Curlew, Godwits, Oystercatcher) will feed on larger invertebrates in the lower sediment strata as well as on crabs and molluscs. Therefore changes to specific benthic taxa may selectively affect the long-term prospects of different wader groups and/or species.

Dunlin are small waders with a medium sized bill and feed in a characteristic "sewing machine" action taking prey such as *Hydrobia ulvae*, *Hediste diversicolor* and *Scrobicularia plana* (Lopes *et al.*, 2006). They are tactile feeders, detecting prey hidden in the sediment. There appears to be little evidence of algal mat effects on Dunlin habitat selection or feeding behaviour (Cabral *et al.*, 1999; Lopes *et al.*, 2006) but decreased biomass of *H. diversicolor* and *S. plana* under algal cover has the potential to affect long-term populations (Raffaelli, 1999). As well as consuming worms, crustaceans and insects a large part of the Oystercatcher's diet consists of Bivalves including *Cerastoderma* spp. and *Mytilus edulis*. Loss of the relatively slow growing bivalves (*C. edule, C. glaucum, M. balthica, M. basuta, S. plana*) from underneath algal mats may cause a temporary dietary shift towards mobile herbivorous Gastropods (*Hydrobia* spp.) which migrate into the algae (Desprez *et al.*, 1992). Similarly, Redshank have been observed to preferentially utilise algal areas for foraging (Lewis *et al.*, 2001). However, adaptive exploitation of this food source by opportunistic species like the Oystercatcher or Redshank is not necessarily a guarantee of the maintenance of their population levels. The abundance of these two species, as well as other waders, has showed decline as algal cover has conversely increased (Raffaelli, 1999). Short-term exploitative opportunism will not apply to more specialised wader species. For example, Godwits are large long-billed waders which prey upon deeper sediment annelid worms and molluscs often probing vigorously with the head completely submerged. Curlews have a long slender down-curved bill and feed on deep worms and other invertebrates with a steady probing motion. Continuous yearly cycles of macroalgal blooms will gradually decrease the diversity of the benthic community by repeatedly increasing anoxic conditions within the sediment leading to declines in bivalve prey (*C. edule* and *M. edulis*) for these large waders. Species which commonly use visual search techniques (Redshank, Plovers, Oystercatcher) during foraging may not be able to detect prey easily under algal mat cover. This may explain, in part, the tendency of such species to avoid areas with moderate to high algal cover. Increased anoxia within the sediment will force infaunal species, such as *M. balthica* and *C. edule*, up towards more aerated sediments at the surface (Perkins & Abbott, 1972). Although this provides a temporary increase in prey abundance for many waders it is doubtful whether it will offset the longer-term impoverishment of the benthic community.

There were few studies on the effects of algal mats on wildfowl within intertidal habitats. As with waders, the effects of algal cover on wildfowl bird species will depend upon their feeding strategy and food preferences (e.g. dabbling herbivores, diving benthivores). Although one study reported a decrease in Shelduck abundance (Tubbs *et al.*, 1980) this is mainly due to their inability to exploit the temporary increase of benthic organisms (Raffaelli *et al.*, 1989; Tubbs, 1977). The herbivorous browsers (e.g. Wigeon, Wintering Geese) often include algae in their diets thus may potentially benefit from increases in algal biomass (Tubbs, 1977).

In summary, effects of algal mats on benthic fauna and their avian predators appear to depend upon the extent and abundance of algal cover. This is a function of nutrient input as well as a host of hydrodynamic and geomorphological factors. Moderate and patchy algal cover has no major effect as benthic fauna can be quick to re-colonize. Persistent, large scale algal blooms involving a high level of organic decomposition in estuaries with restricted flushing can rapidly cause significant losses to the benthic biomass thus pose a potential long-term threat to the estuarine bird population.

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Appendix 1 Studies on the effects of algal cover on estuarine birds and/or benthic fauna where full text was unavailable

Study	**Abstract Summary**
(Bonsdorff *et al.*, 1997b)	Article/Abstract unavailable.
(Bryant, 1987)	Reduction in effluents during 1970s and 1980s attributed to declining wildfowl and wader populations
(Hull, 1988)	PhD Thesis unavailable
(Meltofte *et al.*, 1994)	Reports doubling of benthic biomass between 1970 and 1990 as a result of eutrophication, benefiting species such as Eider Duck and Oystercatcher.
(Metzmacher & Reise, 1994)	Concluded that wader and gull foraging on tidal flats are influenced by benthic epistructures in their habitat choice. Suggest underlying causes are often indirect, and act by modifying prey availability or detectability. Studied Dunlin, Ringed Plover, Whimbrel, Redshank, Golden Plover, Oystercatcher and Black-headed Gull.
(Nicholls *et al.*, 1981)	Full text and abstract unavailable
(Riese, 1985)	Book/unavailable
(Raffaelli *et al.*, 1989)	Analyses long-term data sets on agricultural practice, river nutrients, biomass of macro-algal mats and numbers of shorebirds for the Ythan estuary, Aberdeenshire, Scotland. Results show that biomass of *Enteromorpha* spp. (in conjunction with a 2-3 fold increase of nitrogen in estuary river water) has increased over a 25-year period and now forms dense mats in much of the estuary. The abundance of the amphipod *Corophium volutator* is reduced under weed mats but there are sufficient clear areas between the mats to maintain an overall highly productive invertebrate community. Suggests that a general increase in mudflat invertebrate productivity accounts for increases in the numbers of six species of shorebird present over the study period.
(Raffaelli *et al.*, 1991)	Fields experiments in the Ythan estuary: under a high biomass of weed, the amphipod *Corophium volutator* disappeared almost completely from the mudflat. The physical presence of weed filaments may be as important as the effects of weed on sediment chemistry in affecting the density of *Corophium*, probably through interference with the amphipod's normal feeding behaviour. It is concluded that weed mats have a significant impact on *Corophium*, which is an important component of the diet of fish and shore-birds in the estuary.
(Raffaelli, 1992)	Review article: reviews the physical and biological characteristics of Scottish estuaries. Identifies organic enrichment by sewage, and agricultural run-off as major threats to Scottish estuaries.
(Raffaelli *et al.*, 1998)	Article/Abstract unavailable.
(Tubbs, 1977)	Effect of sewage effluent and increased macroalgae (*Enteromorpha, Ulva*) upon winter numbers of waders and wildfowl. As the algal abundance increased, winter numbers of Oystercatcher, Grey Plover, Black-tailed Godwit, Bar-tailed Godwit, Knot, Dunlin, Dark-Bellied Brent Goose, Teal and Wigeon increased. Numbers of Shelduck, Redshank and Curlew declined.

Appendix 2 Supplementary documents from WeBSite search sources

(See Table 2).

Study	**Abstract Summary**
(Langston *et al.*, 2003a)	Includes assessment of effect of eutrophication-mediated algal blooms on benthic invertebrates of the Helford Estuary. Algal bloom (primarily *Gyrodeniumaureolum)*in 2002 caused mortality of worm species *Nereis* and *Arenicola* as well as shellfish spp.
(Langston *et al.*, 2003b)	Includes description of algal communities and assessment of effect of algal blooms in the Fleet lagoon (e.g. effects of smothering on *Zostera* beds).
(Chesman, Burt & Langston, 2006)	Includes assessment of effect of eutrophication-mediated algal blooms in the Essex estuaries including Blackwater estuary.
(Taylor, 1997)	In depth study of growth parameters, nutrient uptake, response to sewage effluent and decomposition of green algae species (*Enteromorpha* and *Ulva* spp.) carried out in Langstone Harbour, Southern England.
(Verdelhos, 2010)	A case study including eutrophication effects on the bivalve. *Scrobicularia plana*.
(Holder, 2004)	Unavailable.
(MacDonald, 2006)	Includes review of effects of macroalgal mats on benthic fauna and bird predators.
(OSPAR, 2006)	Assessment of the effects of eutrophication of the coastal waters in the South Eskestuary for the period 2001-2005,
(Green, Hill & Clark, 1990)	Study on spatial association between benthic invertebrate abundance and shorebirds.

Appendix 3 Benthic invertebrate taxa listed in Table 4

Phylum>Class> Order >Family**>**Genus**>***Species* (common name)

Annelida:

Polychaeta - *Alkmaria romijni (*Tentacled lagoon worm), *Amage adspersa, Anaitides williamsi, Boccardia proboscidea, Capitella capitata* (Gallery Worm*), Exogone lourei, Hediste diversicolor (*synonym: *Neries diversicolor* – Ragworm)*, Manayunkia aestuarina, Marenzelleria viridis, Nereis pelagica* (Sandworm), *Nephtys caecoides, Ophelia pulchella, Phyllodoce maculate* (Paddleworm), *Platynereis bicanaliculata, Polydora ligni* (Polydora Mudworm), *Pseudopolydora paucibranchiata, Pygospio elegans* (Bristleworm)*, Streblospio shrubsolii*.
Clitellata - **Oligochaeta**

Nemertea:

Enopla - *Prostoma obscurum*.

Mollusca:

Bivalvia- *Cerastoderma edule* (Common Cockle)*, Cerastoderma glaucum* (Lagoon Cockle), *Gemma gemma* (amethyst gem clam), *Macoma balthica* (Baltic Tellin); *Macoma nasuta* (Bent-nosed Clam), *Macoma secta* (White-sand Macoma), *Mactra stultorum, Mya arenaria* (Soft-shell Clam), *Mytilusedulis* (Blue Mussel), *Scrobicularia plana* (Peppery Furrow Shell), *Ruditapes (Tapes) decussatus*, *Transennella tantilla* (Purple Transennella), *Venerupis senegalensis.*
Gastropoda - *Hydrobia jenkinsi (*synonym: *Potamopyrgus antipodarum* - Jenkins' Spire Snail), *Hydrobia ulvae* (Laver Spire Shell), *Hydrobia ventrosa. Littorina tenebrosa,* Lymnaea *spp.* Theodoxus *spp.*

Arthropoda (Crustacea):

Malacostraca – **Amphipoda,** *Gammerus locusta*, *Gammarus oceanicus, Carcinus maenus* (Common Shore Crab), *Corophium volutator* (Mud Shrimp), *Cumella vulgaris, Hippolyte californiensis* (California Green Shrimp), *Idothea balthica,* **Isopoda spp.** (Idotea spp., *Cyathura carinata), Leptochelia dubia. Monoporeiaaffinis, Saduria entomon.*
Ostracoda - Seed Shrimp spp.
Insecta – **Diptera** - Chironomidae spp. (Nematoceran flies).
Copepoda spp.

Platyhelminthes:

Turbellaria- *Dendrocoelum lacteum, Planaria torva.*

Phoronida:
Phoronopsis viridis

Cnidaria:
Peachia cylindrica

Appendix 4 Glossary of Terms

Algal Mat/ Macroalgal Mat - Dense mass of green or other algae (e.g. *Enteromorpha* spp., *Ulva* spp.) which blankets the substratum in a littoral or shallow-water environment, often in areas of freshwater influence or where eutrophication occurs. Other algal genera include: Cladophora, Chaetomorpha.

Algal Bloom - A massive reproduction and growth of algae, often free-floating, in response to the presence of higher than normal levels of nutrients.

Anoxic - Devoid of oxygen – an extreme decrease in level of oxygen (hypoxia). Depleted of dissolved oxygen.

Benthos - Those organisms attached to, or living on, in or near, the seabed, including that part which is exposed by tides as the littoral zone.

Benthic zone - the ecological region at the lowest level of a body of water (lake or ocean) including the sediment surface and some sub-surface layers. Organisms living in this zone are called benthos.

Eutrophication- The over-enrichment of an aquatic environment with inorganic nutrients, especially nitrates and phosphates, often anthropogenic (e.g. sewage, fertilizer run-off), which may result in stimulation of growth of algae and bacteria, and can reduce the oxygen content of the water.

Intertidal- The zone between the highest and lowest tides (from Lincoln *et al*., 1998).

Infauna - Benthic animals which live within the seabed. i.e. Within the bottom substratum rather than on its surface. Infauna usually construct tubes or burrows and are commonly found in deeper and subtidal waters. Clams, tubeworms, and burrowing crabs are infaunal animals.

Epifauna/ Epibenthos - Animals living on the surface of the seabed i.e. Aquatic animals that live on the bottom substratum as opposed to within it, that is, the benthic fauna that live on top of the sediment surface at the seafloor.

Macrofauna / Macrobenthos - Animals exceeding 1 mm in length or retained on a 1 mm or 0.5mm sieve; often applied to organisms >0.5mm. Cf. 'meiofauna', or 'microfauna', i.e. Benthic or soil organisms which are retained on a 0.5mm sieve. Studies in the deep sea define macrofauna as animals retained on a 0.3mm sieve to account for the small size of many of the taxa.