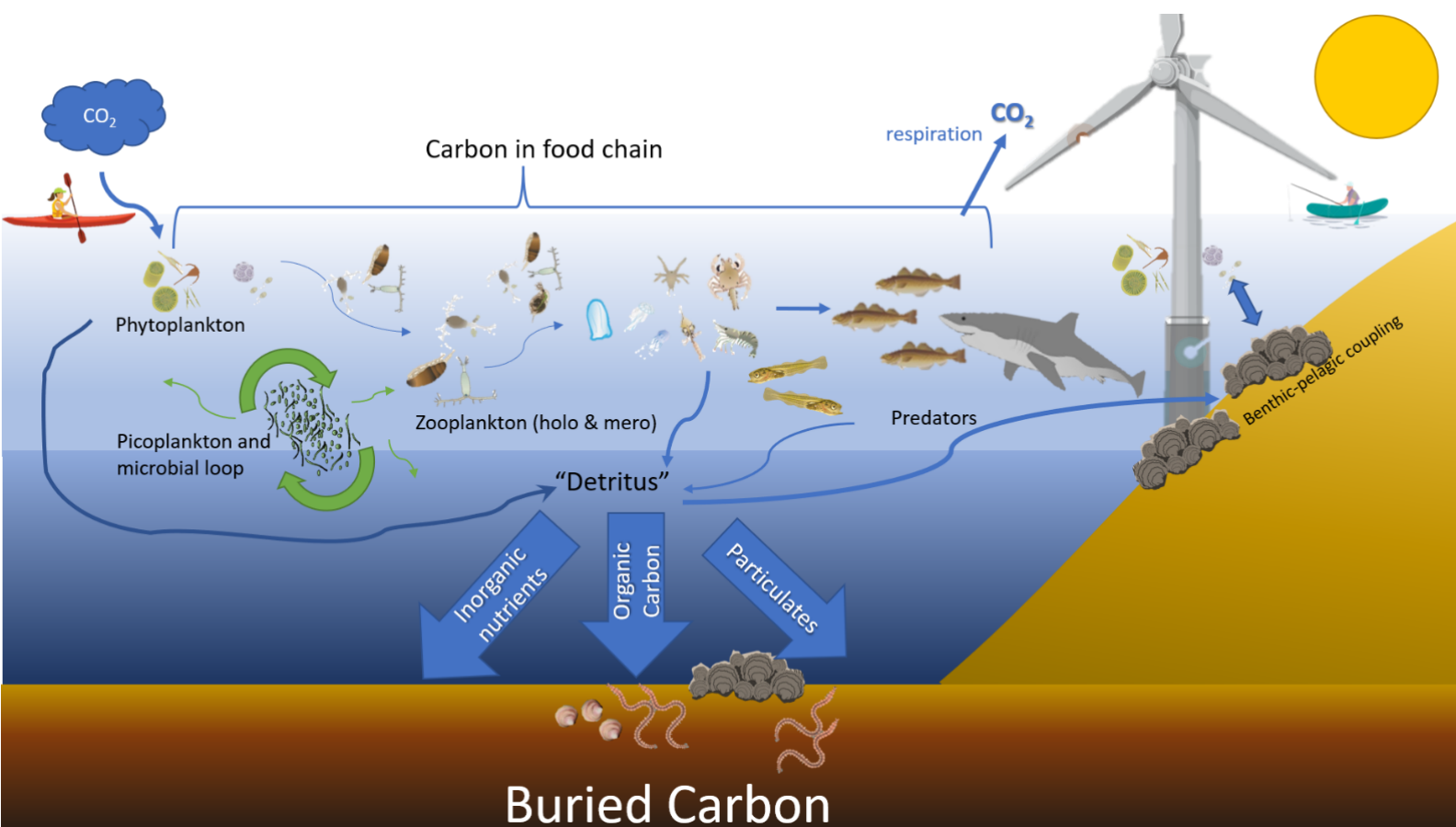# The Natural Capital Power of Plankton (Natural Capital potential and services from UK Pelagic systems)

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Contents

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The Natural Capital Power of Plankton
(Natural Capital potential and Services from UK Pelagic systems)

1. Key messages

The term 'plankton' encompasses a wide range of organisms potentially from the smallest virus and bacteria, through small and large phytoplankton (photosynthetic drifting plants), to small and large zooplankton (copepods, shrimps, jellyfish, and the larvae of bivalves, crabs, and fish), with an equally broad service provision.

The value of plankton interventions is hard to measure but roughly estimated in the region of £28-£246 **billion** per year (depending on inclusions and offsetting rates).

Natural capital concepts were developed from place based terrestrial systems and do not easily accommodate the diversity and dynamism of plankton communities.

Plankton provide a multitude of ecosystem and other services generally considered positive, but they can also have significant negative impacts (such as. harmful and nuisance algal blooms, and jelly fish swarms) which presents challenges for traditional accounting approaches. Moreover, plankton significantly influence intermediated and supporting, rather than final services traditionally used in natural capital accounts.

Plankton do not easily fit into the natural capital boxes provided but they still provide and impact on key services such as:

- the biogeochemical cycling of nutrients and carbon which can be considered as a regulating and maintenance service (as well as intermediate and supporting)
- the consideration of food webs and energy and carbon flows which is both a direct and indirect provisioning service
- many aspects cut across most categories, such as harmful and nuisance algal blooms which may impact tourism (cultural) with discoloured waters and foams on beaches, or by poisoning shellfish (provisioning), or creating loss of bottom dissolved oxygen (supporting / intermediate / biodiversity).

This perceived complexity means plankton tend to be neglected from a management (as opposed to 'incident') perspective. Management and measures currently may not be easily derived from the traditional natural capital accounting approach (which currently does not consider plankton). One solution is to provide tools and indicators to support natural capital decisions.

2. Introduction and scope

This brief report was requested to help visualise plankton through the lens of a natural capital framework; a framework which has not been historically developed to describe such a diverse and dynamic system.

This first year of the Pelagic Monitoring Programme Project (under Defra's marine Natural Capital and Ecosystem Assessment (mNCEA) Programme) concentrated on filling the sampling gaps in what will be a coordinated England (and wider UK) plankton monitoring program. There was no budget for data analysis this year, and consequently no plankton natural capital work has been undertaken thus far. However, this review is intended to highlight expected activity on this subject for years 2 and 3 of the mNCEA Pelagic Project.

UK shelf seas are 6 times the area of the UK and have been valued at £47 billion, with pelagic carbon stocks of around 2.5 Billion tonnes of carbon (Kröger *et al.,* 2018). This is mostly dissolved inorganic carbon (DIC), rather than plankton carbon. Dynamic interactions between physical, chemical, and biological processes drive net carbon uptake in the system. Observations over full annual cycles have revealed that short periods of calm can initiate phytoplankton blooms throughout the year; production in autumn can be more important than previously thought; and zooplankton grazing strongly influences phytoplankton abundance (and carbon cycling) throughout the year.

2.1 Natural capital issues when considering plankton

The term 'natural capital' was first used in 1973 by E.F. Schumacher in his book "Small Is Beautiful" and was developed further by Herman Daly, Robert Costanza, and other founders of the science of Ecological Economics, as part of a comprehensive critique on the shortcomings of conventional economics. Natural capital is a concept central to economic assessment of ecosystem services valuation which revolves around the idea, that non-human life produces goods and services that are essential to life (Figure 1). Thus, natural capital is essential to the sustainability of the economy.
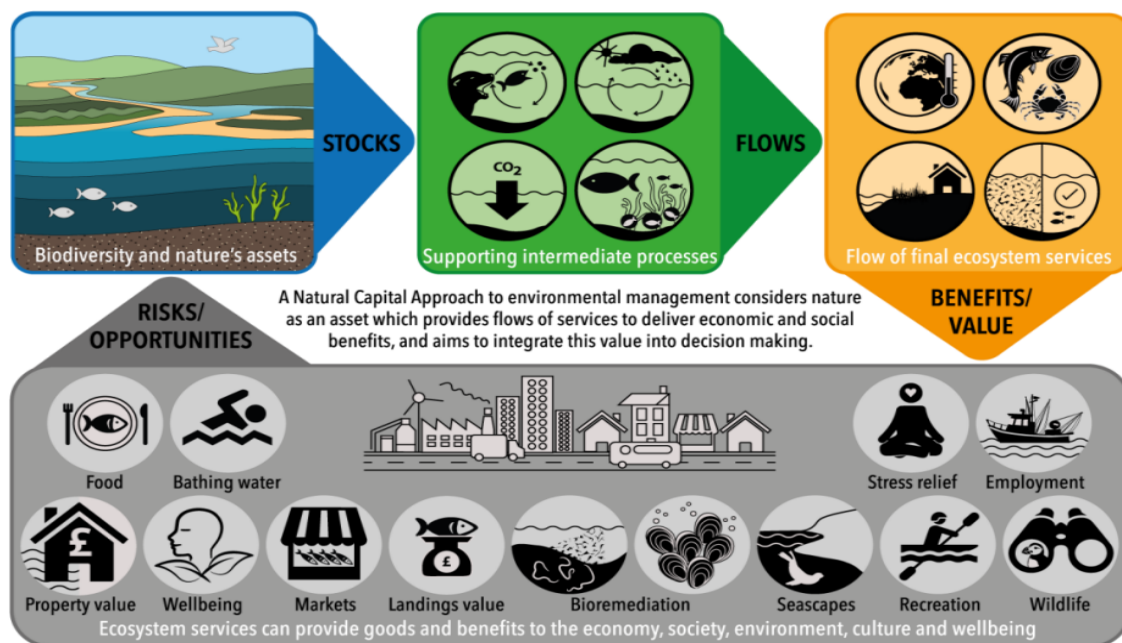
Figure 1. Overview of the natural capital approach (Credit: Illustrative Science Ltd)

Within the international community the basic principle is not controversial, although much uncertainty exists over how best to value different aspects of ecological health, natural capital, and ecosystem services. The concepts of 'assets' (or 'stocks') and 'goods and 'services' (Figure 1) however, were developed and exampled based on terrestrial ecosystems habitats (such as a forest providing lumber and fuel), or individual species (such as a commercial stock of fish). All of these can be relatively easily measured by area (of habitat) or number (of fish caught), however it is a more complex task to assess

the natural capital value of the highly dynamic (seasonal growth with large community variations) and patchy plankton community.

Another assumption of this approach is that assets are relatively homogenous (such as a saltmarsh, a herring shoal or stock) which is problematic when applying these concepts to the highly heterogenous plankton community (potentially containing everything from viruses to large jellyfish).

When considering change in plankton communities, it is important to recognise the large size ranges involved. Phytoplankton alone has a cell volume range over nine orders of magnitude (and also proportional to carbon or energy content): from less than 2 μm in equivalent spherical diameter for picoplankton; 2–20 μm for nanoplankton; 20–200 μm for microplankton, and up to 200–,2000 μm for macroplankton (see Figure 2; Sieburth *et al.,* 1978; Beardall *et al.,* 2009; Finkel *et al.,* 2010).
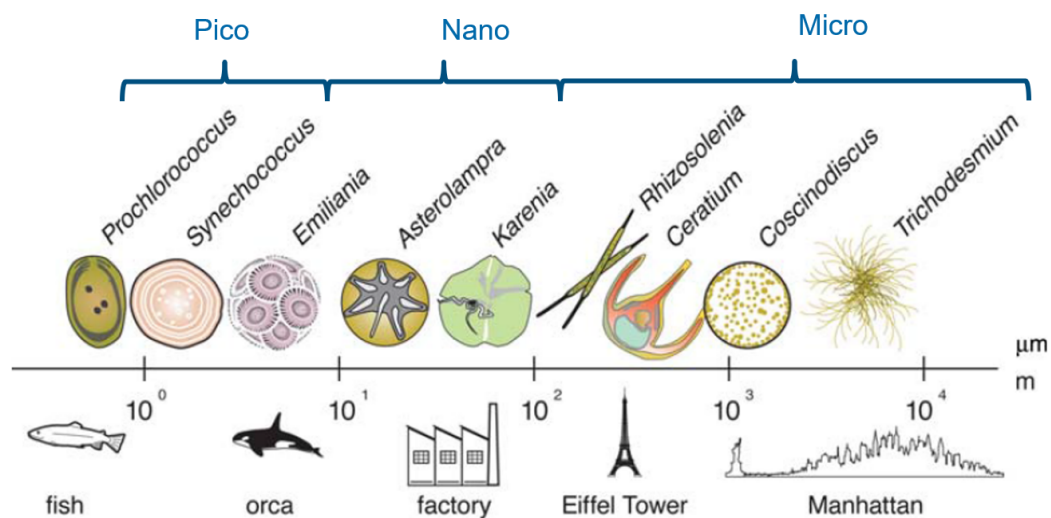
A comparison of the size range (maximum linear dimension) of phytoplankton relative to macroscopic objects.

Figure 2*: A comparison of the size range (maximum linear dimension) of phytoplankton relative to macroscopic objects (from Finkel et al., 2010)*

Although marine waters are identified as a natural capital asset (NCC 2019b, SEEA 2021), the terrestrial focus of the development of natural capital approaches has meant that some initial marine studies considered the water column as an 'enabling characteristic' of the underlying seabed (Thornton *et al.,* 2019) or, in combination with the seabed, where seabed type was used to define the spatial configuration of assets (Lusardi *et al.,* 2018). Other studies have considered the water column as an asset in its own right (Rees *et al.,* 2019) but have not applied a unified or consistent approach to defining water bodies within the broad 'water asset' category.

Because of this Le Quesne *et al.* (2022) stated that nearshore water is the natural capital asset from which natural capital services and goods are provided. But the base of all these services is driven by the plankton in the pelagic habitat which could be considered an asset itself (with quality, quantity, and location). The marine water asset was defined to include the physical and chemical attributes of the water column as well as planktonic organisms that are embedded within the water column. This includes microbes, phytoplankton, and zooplankton. The coastal, or 'nearshore', waters of England are a key part of the country's natural capital, providing a diverse range of benefits to society through supporting, provisioning, regulating and cultural services. Traditionally, these services are defined as:

- **Supporting services:** This group includes all the services that are instrumental for the functioning of ecosystems and that thus allow the release of all the other services provided by ecosystems (such as oxygen production through photosynthesis, primary production, and

nutrient cycling). Unlike other categories of services, they generally occur over a long period of time.

- **Regulating services:** These include the benefits derived from the regulation of ecosystem processes (such as climate regulation, and water depuration).

- **Provisioning services:** All the products acquired from ecosystems are grouped in this category (such as food, fuels, active ingredients and drugs, and genetic resources).

- **Cultural services:** This group include all the nonmaterial benefits that people receive from ecosystems (such as spiritual and aesthetic experiences, cognitive development, and recreational activities).

Another discrepancy is that under traditional natural capital terminology, an increase of an asset is considered a good outcome as it produces more service in a general positive direction. However, from a human perspective, plankton can be both good (such as oxygen production, carbon sequestration, and food supply) and bad (such as eutrophication, nuisance and toxic algal blooms, oxygen depletion, and hypoxic/anoxic events resulting in benthic organism or fish mortality).

A pelagic habitat can also be in a natural ecological state even when that state may be perceived to be 'negative' by societies. In some areas, the accumulation of high concentrations of algal toxins in shellfish can be driven by natural forces (prevailing conditions) but considered by society as 'negative' owing to the economic impact resulting from enforced closures of shellfish harvesting areas (Gowen *et al.,* 2012). Similarly, high biomass blooms of the dinoflagellate *Karenia mikimotoi* can result in mortalities of the benthos or farmed fish; however, these events may be driven by natural bloom formation offshore and transport in coastal currents (Davidson *et al.,* 2009; Gillibrand *et al.,* 2016) and not direct human activities.

The environmental impacts related to the negative or 'unwanted' state of plankton indicators include:

- changes in food available for higher trophic levels
- productivity impacts across trophic levels
- reduction in O_2 leading to negative change (or loss) in plankton functional groups or lifeforms (depending on location and severity)
- changes in energy flow between phytoplankton and zooplankton
- change in benthic-pelagic coupling and reproductive output
- eutrophication leading to less desirable food webs
- introduction and spreading of non-native invasive species (NNIS)
- changes to carbon cycling and sequestration
- changes to nutrient cycling and sequestration
- changes in food webs and commercial species support (such as fish and shellfish)
- interruption of life cycle closure for marine organisms
- biofouling
- Harmful (HABs) and Nuisance (NABs) algal blooms

Many of these aspects will be explored in years 2 and 3 of the mNCEA Pelagic Project. The rest of this report will discuss some of the emerging themes.

Broszeit *et al.* (2019) considered the interaction and trade-off among multiple ecosystem services key to the management of the marine environment. This approach accommodates the pelagic habitat,

processes, and services more easily than a traditional natural capital perspective. They considered a subset of 11 'services' based on Hattam *et al.*'s (2015) list of 18 services (Table 1). In this report we will both lists to assist in summarising the natural capital aspects of plankton.

Table 1. *Eleven ecosystem services and their respective definitions (from Hattam et al., 2015; Broszeit et al., 2019)*

Eleven ecosystem services and their respective definitions (from Hattam et al. (2015)) that were used in the expert workshop.

Service	Definition
Food provision[a]	The availability of marine flora and fauna for human consumption that can be caught from the wild
Climate regulation	The contribution of the marine environment to the maintenance of a favourable climate
Disturbance prevention and coastal erosion prevention	The contribution of the marine ecosystem to the dampening of the intensity of environmental disturbances such as storm floods, tsunamis and hurricanes
Bioremediation (of waste)[a]	The removal of waste input by humans from the marine environment, e.g. excess nutrients
Biological control - checks and balances[a]	The contribution of marine ecosystems to the maintenance of population dynamics, resilience through food web dynamics, disease and pest control
Feeding habitat	Provision of habitats supporting enough food for marine species to participate in the trophic web
Migratory habitat	The contribution of a particular marine habitat for migratory species populations through the provision of safe passages for migration, resting and feeding areas
Nursery habitat	The contribution of a particular marine habitat to populations through the provision of critical habitat for juvenile maturation
Gene pool protection	The contribution of marine environments to the maintenance of viable gene pools through evolution. Processes which enhance adaptability of species to environmental change, and thereby the resilience of the ecosystem
Leisure and recreation[a]	The provision of opportunities for tourism, recreation and leisure that depend on a particular state of marine ecosystems
Aesthetic experience	The contribution of the marine environment to the existence of a landscape that generates a noticeable emotional response within an individual observer

[a] Indicate the ecosystem services that the workshop focussed on.

2.2 Heterogeny in plankton

Plankton do not fit easily into traditional natural capital accounting methods as they are a highly heterogenous group of microbes, plants, and animals (from viruses, through to phytoplankton, copepods, and shrimps, to jellyfish, siphonophores, and fish larvae). They are traditionally grouped based on size, partially reflecting the ease of identification and enumeration (Figure 3).
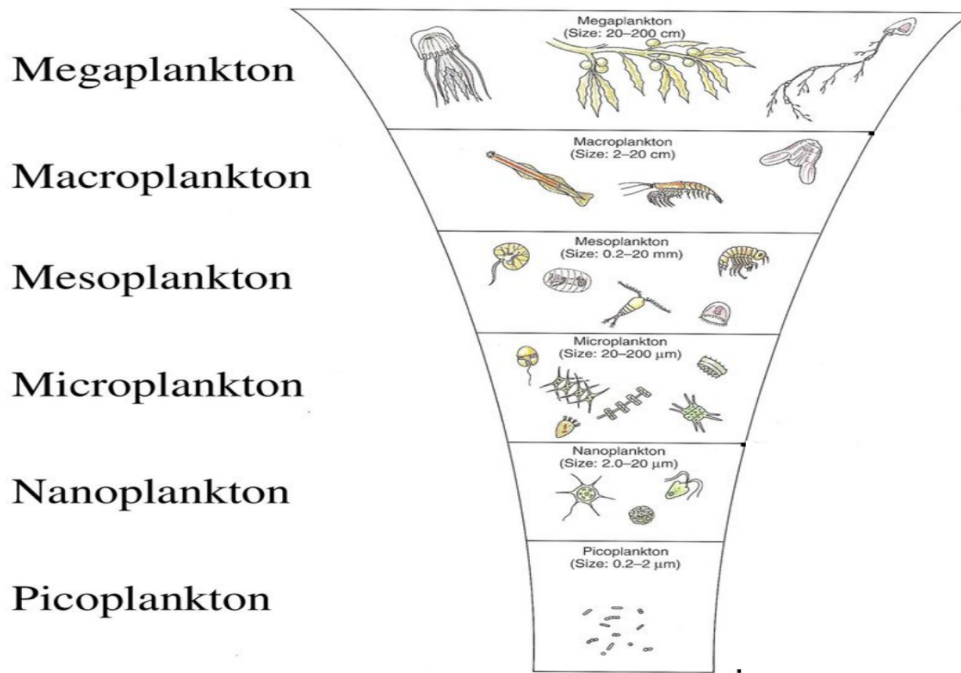
Figure 3. Plankton are traditionally grouped by size categories

The concentration of both biomass and carbon in certain groups within these sizes can be counter intuitive and, in reality, looks more like Figures 4.
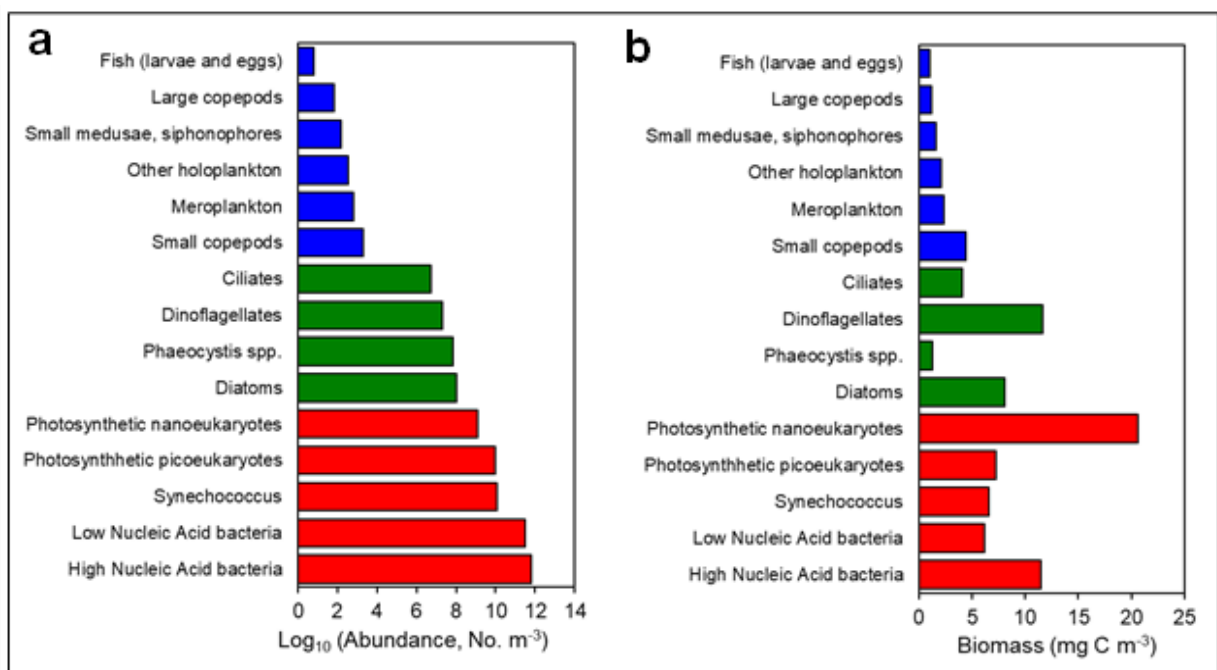
Figure 4. Plankton functional group abundance (a) and biomass (b) from 2007-2021 at station L4 in the Western Channel. Red bars represent taxa quantified consistently by flow cytometry in UK waters (Table 1), green bars by microscope analysis of settled water samples, and blue bars by microscope analysis of net catches. Only the latter taxa are visible by eye, and these comprise a negligible fraction of total numbers and biomass of the whole plankton. Data courtesy of Glen Tarran, Andrea McEvoy, Claire Widdicombe, and Amanda Beesley (PML)

2.3 Common International Classification of Ecosystem Services (CICES)

The Common International Classification of Ecosystem Services (CICES) developed from the work on environmental accounting undertaken by the European Environment Agency (EEA) supports the EEA contribution to the revision of the System of Environmental-Economic Accounting (SEEA), which is currently being led by the United Nations Statistical Division (UNSD) (Haines-Young and Potschin, 2018).

Following common usage, CICES recognises that the main categories of ecosystem outputs to be provisioning, regulating and cultural services. However, it does not cover the so-called 'supporting services' (or 'intermediate services') originally defined in the Millennium Ecosystem Assessment (MA, 2005) for describing ecosystem services. Rather these supporting services are treated as part of the underlying structures, process and functions that characterise ecosystems. Since those services are only indirectly consumed or used, and may simultaneously facilitate many 'final outputs', it was determined that they were best dealt with in environmental accounts and mapping in other ways. However, these supporting and intermediate services are an important consideration in pelagic habitats, but traditional ecosystem service classifications tend to only consider the final service (which has subsumed both the positive and negative effects of the intermediate services). This is an important consideration when relating management measures to plankton.

It is important to note that there are many reviews of the CICES system, including a Defra funded PhD that will review the CICES criteria to understand how they can be more relevant for plankton (which we expect to feed into our work by year 3).

For what are regarded as potential or putative 'final ecosystem services', CICES describes them using a five-level hierarchical structure. Each level is progressively more detailed and specific. The way the system works can be illustrated in terms of the contributions that ecosystems make to cultivated crops such as cereals:

- Section (e.g. Provisioning)
- Division (e.g. Biomass)
- Group (e.g. Cultivated terrestrial plants for nutrition, materials, or energy)
- Class (e.g. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes)
- Class type (e.g. Cereals, the ecological contribution to the growth of cultivated, land-based crops that can be harvested and used as raw material for the production of food).

Using CICES V5.1 it is possible to filter for 'Marine CICES' relevant rows which at the higher levels of classification can be collapsed; as demonstrated in Table 2.

Table 2. Entries in the marine Common International Classification of Ecosystem Services (CICES) relevant to pelagic habitats

Sectio	Division	Group
Provisi oning (Biotic)	Biomass	Cultivated aquatic plants for nutrition, materials, or energy
	Biomass	Reared aquatic animals for nutrition, materials, or energy
	Biomass	Wild plants (terrestrial and aquatic) for nutrition, materials,
	Biomass	Wild animals (terrestrial and aquatic) for nutrition, materials,
	Genetic material from all biota (including seed, spore, or gamete	Genetic material from plants, algae, or fungi
	Genetic material from all biota (including seed, spore, or gamete	Genetic material from animals
	Genetic material from all biota (including seed, spore, or gamete	Genetic material from organisms
	Other types of provisioning service from biotic sources	Other
Regula tion & Mainte nance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic
	Transformation of biochemical or physical inputs to ecosystems	Mediation of nuisances of anthropogenic origin
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events
	Regulation of physical, chemical, biological conditions	Lifecycle maintenance, habitat, and gene pool protection
	Regulation of physical, chemical, biological conditions	Pest and disease control
	Regulation of physical, chemical, biological conditions	Regulation of soil quality
	Regulation of physical, chemical, biological conditions	Water conditions
	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions
	Other types of regulation and maintenance service by living processes	Other
Cultura l (Biotic)	Direct, in-situ and outdoor interactions with living systems that depend	Physical and experiential interactions with natural
	Direct, in-situ and outdoor interactions with living systems that depend	Intellectual and representative interactions with natural
	Indirect, remote, often indoor interactions with living systems that do	Spiritual, symbolic, and other interactions with natural
	Indirect, remote, often indoor interactions with living systems that do	Other biotic characteristics that have a non-use value
	Other characteristics of living systems that have cultural significance	Other
Provisi oning (Abioti c)	Water	Surface water used for nutrition, materials, or energy
	Water	Ground water for used for nutrition, materials, or energy
	Water	Other aqueous ecosystem outputs
	Non-aqueous natural abiotic ecosystem outputs	Mineral substances used for nutrition, materials, or energy
	Non-aqueous natural abiotic ecosystem outputs	Non-mineral substances or ecosystem properties used for
	Non-aqueous natural abiotic ecosystem outputs	Other mineral or non-mineral substances or ecosystem
Regula tion & Mainte nance (Abioti c)	Transformation of biochemical or physical inputs to ecosystems	Mediation of waste, toxics, and other nuisances by non-living
	Transformation of biochemical or physical inputs to ecosystems	Mediation of nuisances of anthropogenic origin
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events
	Regulation of physical, chemical, biological conditions	Maintenance of physical, chemical, abiotic conditions
	Other type of regulation and maintenance service by abiotic processes	Other
Cultura l (Abioti c)	Direct, in-situ and outdoor interactions with natural physical systems	Physical and experiential interactions with natural abiotic
	Direct, in-situ and outdoor interactions with natural physical systems	Intellectual and representative interactions with abiotic
	Indirect, remote, often indoor interactions with physical systems that do	Spiritual, symbolic, and other interactions with the abiotic
	Indirect, remote, often indoor interactions with physical systems that do	Other abiotic characteristics that have a non-use value
	Other abiotic characteristics of nature that have cultural significance	Other

It is possible to use this classification system to score phytoplankton, however it is important to first resolve it further into both size categories and into positive and negative effects. Table 3 below is based on published and grey literature and the expert opinions of both the England and UK Pelagic Habitats Expert Groups. The scoring indicates the likelihood or intensity of the relationship.

Table 3. *Assessment of the positive (+ve) and negative (-ve) effects of different plankton on natural capital services (NCS) by Common International Classification of Ecosystem Services (CICES) class*

Section	CICES Class	Pelagic?	Picoplankto		Phytoplankto		Zooplankto	
			+ve NCS	-ve NCS	+ve NCS	-ve NCS	+ve NCS	-ve NCS
Provisioning	Plants cultivated by in- situ aquaculture grown for nutritional	y				2		
	Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)							
	Plants cultivated by in- situ aquaculture grown as an energy	y				2		
	Animals reared by in-situ aquaculture for nutritional purposes	y	1	2	2	2	3	
	Fibres and other materials from animals grown by in-situ aquaculture for direct use or processing (excluding genetic materials)							
	Animals reared by in-situ aquaculture as an energy source	y	1	2	2	3	3	
	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	y				2		
	Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)							
	Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy	y				2		
	Wild animals (terrestrial and aquatic) used for nutritional	y	1	2	2	2	3	
	Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)	?				?	?	
	Wild animals (terrestrial and aquatic) used as a source of							
	Seeds, spores, and other plant materials collected for maintaining or establishing a population							
	Higher and lower plants (whole organisms) used to breed new strains or varieties	y	?	?	?	?	?	?
	Individual genes extracted from higher and lower plants for the design and construction of new biological entities	y	?	?	?	?	?	?
	Animal material collected for the purposes of maintaining or establishing a population							
	Wild animals (whole organisms) used to breed new strains or							
	Individual genes extracted from organisms for the design and construction of new biological entities	y	?	?	?	?	?	?
	Other							
Regulation and Maintenance	Bioremediation by micro-organisms, algae, plants, and animals	y	1		3		1	
	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	y			3	1	3	1
	Smell reduction	y	?	?	?	?	?	?
	Visual screening	y				3		
	Control of erosion rates							
	Buffering and attenuation of mass movement	?	?	?	?	?	?	?
	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	?	?	?	?	?	?	?
	Pollination (or 'gamete' dispersal in a marine context)							
	Seed dispersal							
	Maintaining nursery populations and habitats (Including gene pool protection)	y	?	?	?	?	?	?
	Pest control (including invasive species)				?			
	Disease control	y		3	?	3		

Section	CICES Class	Pelagic?	Picoplankto		Phytoplankto		Zooplankto	
			+ve NCS	-ve NCS	+ve NCS	-ve NCS	+ve NCS	-ve NCS
	Decomposition and fixing processes and their effect on soil	y			1	2		
	Regulation of the chemical condition of salt waters by living	y						
	Regulation of chemical composition of atmosphere and oceans	y			3			
	Regulation of temperature and humidity, including ventilation and transpiration	?						
Cultural	Characteristics of living systems that that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	y				2		
	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through passive	y				2		
	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological	y						
	Characteristics of living systems that enable education and	y			1		3	
	Characteristics of living systems that are resonant in terms of culture or heritage							
	Characteristics of living systems that enable aesthetic	?			1	2		
	Elements of living systems that have symbolic meaning				1			
	Elements of living systems that have sacred or religious				1			
	Elements of living systems used for entertainment or							
	Characteristics or features of living systems that have an							
	Characteristics or features of living systems that have an option or bequest value							

It is also important to understand that many of these aspects have been poorly studied or may be limited to certain lifeform groups or geographic areas. Similarly, it is possible to use the Marine ecosystem capacity for service supply assessment (MECSA) system and derive a similar list (Table 4).

Table 4. Assessment of the positive (+ve) and negative (-ve) effects of different plankton on natural capital services (NCS) by Marine ecosystem capacity for service supply assessment (MECSA) groups

	MECSA biotic group	Phytoplankton	Zooplankton	Bacteria
Provisioning	Seafood and other nutritional outputs from wild animals		*	
	Raw materials from wild animals		*	
	Genetic materials from plants and algae: whole organisms	*		
	Genetic materials from plants and algae: genes	*		
	Genetic materials from animals and micro-organisms: whole		*	*
	Genetic materials from animals and micro-organisms: genes		*	*
Regulation and	Anthropogenic waste and toxicant treatment via biota	*	*	*
	Anthropogenic waste and toxicant removal and storage	*	*	*
	Erosion prevention and sediment retention			
	Maintaining nursery populations and habitats	*	*	
	Gene pool protection	*	*	*
	Pest control	*	*	*

Maintenance	Disease control	*	*	*
	Sediment nutrient cycling	*	*	*
	Chemical condition of seawater	*	*	*
	Global climate regulation	*	*	*
	Oxygen production	*		
Cultural	Recreation and leisure	*	*	*
	Scientific	*	*	*
	Educational	*	*	*
	Aesthetic	*	*	*
	Entertainment	*	*	*
	Existence	*	*	*
	Bequest	*	*	*

As can be seen in Table 4, plankton are involved in many key services, however, in many specific cases it is difficult to quantify the significance of their contribution (such as how sensitive are the services to changes in plankton abundance, composition, and timing). Defra and University of Plymouth have co-funded a PhD student (Matthew Faith) to investigate the links between UKMS/MSFD plankton indicators and the ecosystem services, and the supporting natural capital, they provide. The studentship will be carried out in collaboration with the UK and OSPAR Pelagic Habitats Expert Groups.

Some of the work packages over the next 2 years (highlighted at the end of each theme, when relevant) will help us to improve our precision on these estimates.

3. Review of themes

3.1 Plankton and biogeochemical cycles

Plankton are involved in all of the key marine biogeochemical cycles, including:

- Carbon
- Oxygen
- Nitrogen
- Phosphorus
- Silicon

And to a lesser extent:

- Sulphur
- Iron

Phytoplankton, as well as being at the bottom of the food web, perform fundamental biogeochemical cycling processes, supporting society through production of oxygen, and mitigate climate change through their absorption and dissolution of carbon dioxide (CO_2). Through the photosynthetic process marine algae (phytoplankton and seaweeds) take up CO_2 from the surrounding water and convert it into organic carbon, releasing O_2 as by-product. For this process marine algae and plants also require light and nutrients, as well as suitable water conditions (such as temperature and salinity). At the same time all organisms, including the zooplankton component, uptake O_2 and release CO_2 via respiration.

Phytoplankton are also a major contributor to the carbon fixation process and its sequestration in sediments and ocean depths, capturing CO_2 from the atmosphere (Tweddle *et al.,* 2018), and through various processes and routes locking it away in ocean sediments (the 'biological pump'). Some phytoplankton species also produce dimethylsulphoniopropionate (DMSP), a precursor to dimethyl sulphide (DMS), important for the process of cloud formation.

Plankton can perform several key functions in any biogeochemical cycle. Taking carbon as an example:

- Capture and fixing: Phytoplankton take up carbon from the atmosphere via seawater
- Storage: Short term carbon is stored in phytoplankton bodies (days to weeks turnover)
- Storage: Medium term carbon, via food webs, is stored in the food chain in the bodies of pelagic organisms from phytoplankton to zooplankton. The turnover time for this can be months to years depending on the food web, and up to centuries if we consider the carbon stored in long lived benthic bivalves or cetacean bodies.
- Sequestration: The process of storing carbon in a stabilised pool such as deep ocean sediments. This is often from the sinking of moribund and dead organisms and their waists below the photic zone.

Pressures on the pelagic community can result in fundamental changes within the community and consequentially the rates and efficiency of each of these processes. Management measure should aim to optimise these (such as medium to long term storage could be enhanced by improving benthic to pelagic coupling through bivalve restoration).

Other ecosystem services that are underpinned by the physical and biological processes taking place in the water column are water quality regulation and mediation of waste, toxins, and other nuisances by non-living processes. Under natural conditions, organic waste entering the water undergoes degradation processes including remineralisation by pelagic communities of microbes and accumulation in biomass (see Section 3.2). Impacts that may result from direct human-induced pressures, for example negative changes in plankton communities can result from local scale changes in the inputs of nutrients (such as from farming run-off, sewage, and dredging) and nutrient ratios.

Changes in plankton lifeforms can result from increases in nutrients and changes in their relative concentrations, or ratios. The onset of eutrophication leads to an increase in phytoplankton biomass. However, the composition of the phytoplankton community becomes more uneven with the disappearance of some species and the predominance of opportunistic species. This leads to a decrease in species diversity due to competitive exclusion.

However, these changes depend on the level or intensity of eutrophication; with a slight increase in eutrophication, competition loosens, resulting in greater diversity, with a further increase in eutrophication, diversity decreases again due to stress (McQuatters-Gollop *et al.,* 2009; Spatharis *et al.,* 2007). Either way, eutrophication, via its impacts on plankton and primary productivity, can lead to less desirable food web conditions. Localised changes in nutrients and plankton distribution can also result from changes to hydrological conditions following coastal development and introduction of infrastructure.

3.2 Carbon

Phytoplankton provide organic matter for the organisms that comprise most marine life. They do this by consuming carbon dioxide (CO_2) that would otherwise dissolve in seawater making it more acidic. These organisms provide organic matter which supports most of the marine food web. The removal of dissolved CO_2 from water also causes additional CO_2 to diffuse through the water surface, lowering atmospheric levels of the gas. In these ways, phytoplankton are crucial to the global carbon cycle, the

circular path by which carbon atoms travel from the atmosphere to the biosphere, to the land and then back to the ocean.

The oceans remove about ¼ to ⅓ of atmospheric CO_2 emissions generated from human activities. The world's phytoplankton incorporated a stunning 45 to 50 billion tonnes of inorganic carbon into their cells per year. Pelagic stocks represent a significant component in the carbon budget (210–230 Tmol) of the European NW Atlantic shelf, with dissolved inorganic carbon (DIC) dominating the pelagic budget (93 to 97% of total pelagic carbon). Dissolved organic carbon (DOC) occupies a further 2 to 5% with the remainder comprising a minor contribution from particulate organic carbon (POC), particulate inorganic carbon (PIC) and macrofauna (see for example, Hardman-Mountford *et al.,* 2009; and Legge *et al.,* 2020). If Plymouth Marine Laboratory's L4 site values (see Figure 4) are representative of the wider area, and carbon values are integrated down to 30m, 'back of the envelope calculations' based on the size and number of plankton and their carbon content suggest that the English Channel plankton contain *at least* 0.25 million tonnes of carbon in the food web, storing it however temporary. This is roughly equivalent to a day's worth of carbon from the CO_2 emissions of the entire UK (based on https://assets.publishing.service.gov.uk/ Angus Atkinson, PML, persona communication).

More importantly, the plankton 'sink' a significant proportion of this carbon, either through trapping in the deep ocean or through transferring it to filter and suspension feeding organisms on the seabed as part of the food web considered later. Phytoplankton and other organisms in the sunlit layer pump about 15% of the organic material produced each year to the deep sea. Once there, about 0.1% of it gets buried in the seafloor, trapped in sediment.

Continental shelf seas, including coastal and marginal seas, play a key role in the global carbon cycle, linking the terrestrial, oceanic, and atmospheric carbon pools (Omar *et al.,* 2007). Shelf seas are generally considered net sinks for CO_2, with some inner estuaries acting as net sources of CO_2 (Chen and Borges, 2009). Evidence from measurements and modelling suggests that the North-west European Shelf acts primarily as a sink for atmospheric CO_2 (Thomas *et al.,* 2004; Borges 2005; Borges *et al.,* 2005; Legge 2020). Thomas *et al.,* (2004) calculated the North Sea to be a highly efficient continental shelf pump exporting approximately 93% of atmospheric CO_2 taken up in the coastal waters off the North-west European Shelf into the deep waters of the North Atlantic.

Calcifying phytoplankton (such as coccoloithophores) may influence biological carbon cycling in two ways. Firstly, they release CO_2 from sea water into the atmosphere in proportion to the CO_2 they fix through the creation of calcium carbonate ($CaCO_3$) structures. Secondly, because the $CaCO_3$ shell material produced by marine calcifiers is much denser than the soft body parts of plankton, its presence in aggregates with organic matter may play an important role in accelerating the rate of sinking, hence contributing to carbon sequestration (Figure 5; Armstrong *et al.,* 2002).
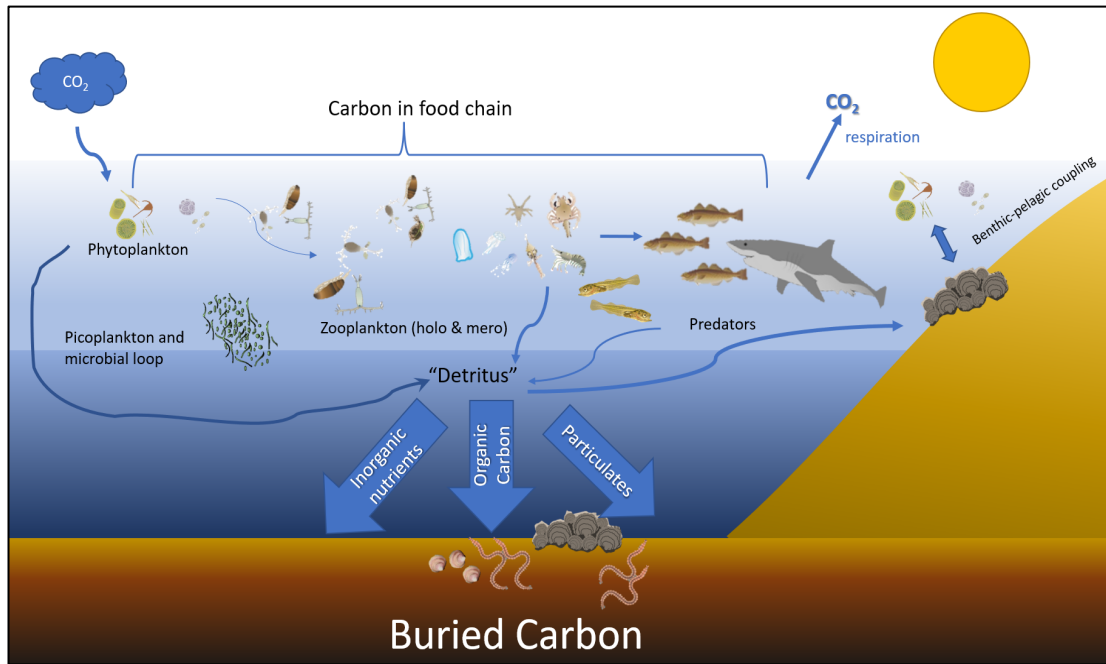
Figure 5. *Showing how plankton play a key role in cycling carbon through the food web and sequestering it long-term in the deep sea (Armstrong* et al*., 2002)*

Ocean warming due to climate change is expected to reduce the provision of the climate regulation service from the plankton.

There is ongoing research into a valuation of the oceans' storage capacity for CO_2; all current estimates are considered very preliminary. The 'goods and services' approach being used is common to socioeconomic analysis of the environment. Ocean CO_2 uptake is considered as part of the service 'gas and climate regulation'. Its economic value is estimated using 'marginal damage costs avoided', based on current carbon market values. The approach is popular in the environmental economics literature which gives it a high confidence but there are arguments regarding the discount rate to use. The application of these methods to carbon cycling in the oceans is still in its infancy, so current estimates should be treated cautiously.

An assessment by Beaumont *et al*. (2008) of the 'goods and services' provided by marine biodiversity in UK waters gave a figure for 'gas and climate regulation' of between about £0.5 billion and £9 billion per annum. However, this is considered an *underestimate* because primary production by marine phytoplankton was the only process considered and confidence in the cost estimate should be considered low. Furthermore, the current role of the biological carbon pump in shelf seas for cycling anthropogenic CO_2 is not determined, so this estimate only relates to natural cycling of CO_2 (see Appendix for 'Value of Plankton').

Aspects and issues of carbon are mainly considered in Work package 2 - Deliverable 4, of the mNCEA Pelagic Project, as highlighted in the extract below:

Work Package 2	
Purpose & objective	**Objective 2:** An improved ability to take an ecosystem approach to the management of nutrient enrichment through the development of tools, and an analysis and interpretation of links between plankton community changes and eutrophication.
Deliverable 4 (WP2) Plankton-eutrophication analysis tools and assessments	

Output & scope	First phase development of bespoke user-friendly analysis tools showing community changes and shifts due to eutrophication, nutrient imbalances, climate change, ocean acidification, particularly in waters influenced by freshwater and land-based nutrients. This will utilise riverine influenced areas as defined by plumes maps, changes in phytoplankton communities and chlorophyll concentrations with linkages to both the Land Sea Interface (EA led) and Seascapes (Cefas led) mNCEA Yr2 projects.
Activities & delivery	Delivery, with various academic delivery partners (including members of UK PHEG), will involve:
	• a reappraisal of 'eutrophication' and assessment tools under new and changing circumstances (led by Cefas and EA) including:
	• …
	• an investigation of Harmful Algal blooms (HABs) lifeforms and their potential influence on coastal 'health' (led by EA and MSS (the UK HABs lead), and University of Plymouth (UoP) including:
	o ..
	• an investigation of the change in small and large lifeforms and the impact of this change on carbon export (led by PML), including:
	o consideration of carbon biomass in different lifeforms, seasonal variation, applicability at different geographical scales
	• theory development for valuing a dynamic system with rapid turnover which typifies marine plankton (led by SAMS).
	Yr3 will include appraisal of application to policy and decision-making (led by UoP).

3.3 Nutrient cycling and eutrophication

Nutrients in coastal environments come from various sources: from rivers, atmospheric deposition, groundwater and from in situ biological fixation. Natural processes such as the weathering of rocks lead to small quantities of nutrients being released, while combustion, such as wildfires, creates oxidised nitrogen compounds which can be deposited on the sea surface. Nutrient leaching from natural soils and soil transport by erosion also introduce nutrients into the marine environment. These natural processes seldom cause eutrophication problems. However, eutrophication has occurred because of the introduction of large quantities of reactive nitrogen and phosphorus into the marine environment by human activities. The main human activities contributing nutrients to the marine environment are:

- agriculture (including forestry, and aquaculture)
- transport
- sewage and wastewater treatment
- diffuse losses
- industry
- households unconnected to sewage infrastructure
- seabed disturbance (such as dredging)

Rivers are the main transport route of nutrients to the coastal oceans. Riverine inputs of nitrogen (N) in the form of nitrate (NO_3) and ammonia (NH_3), and phosphorus (P) in the form of orthophosphate (PO_4) doubled in the period 1960-1990. Improvements under the EU Urban Wastewater Treatment Directive (UWWTD) and other initiatives have shown a steady decline in phosphorus inputs, but more limited reduction in nitrogen compounds (Figures 6 - 8) (further details in OSPAR 2023).
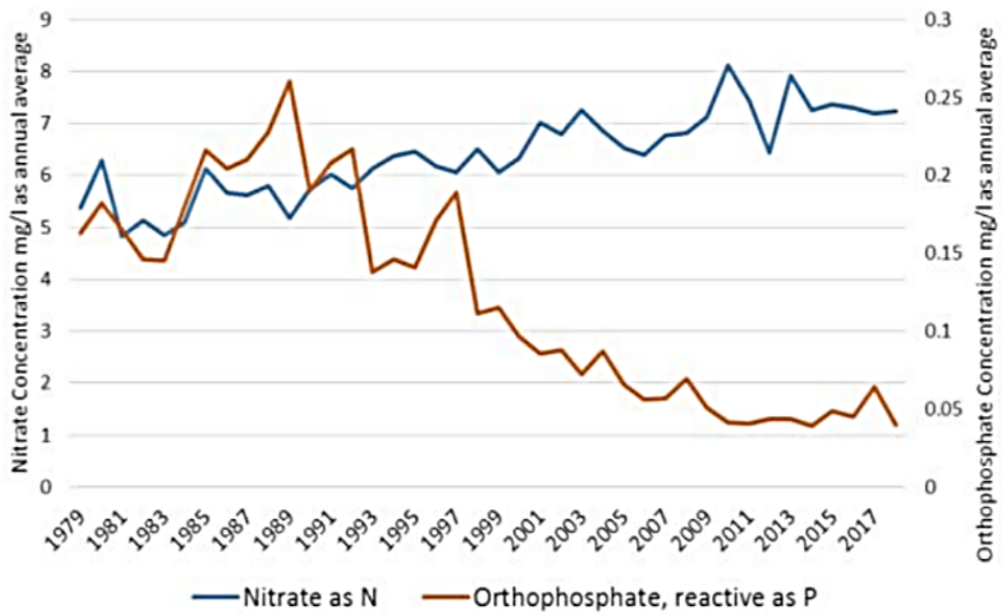
Figure 6. *Change over time in concentration of nitrate and orthophosphate riverine inputs*
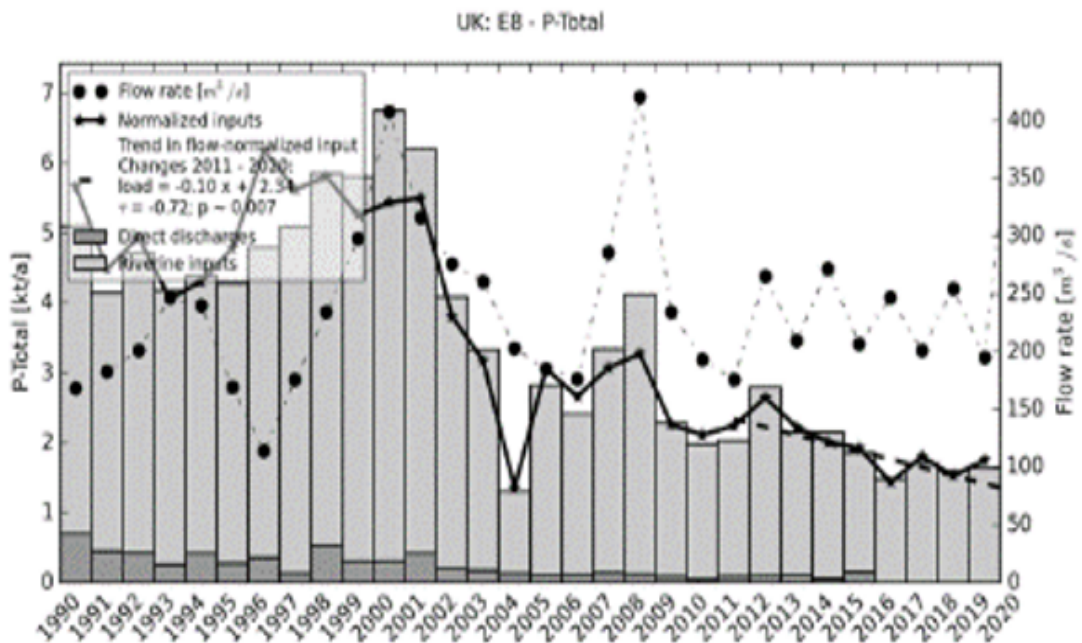

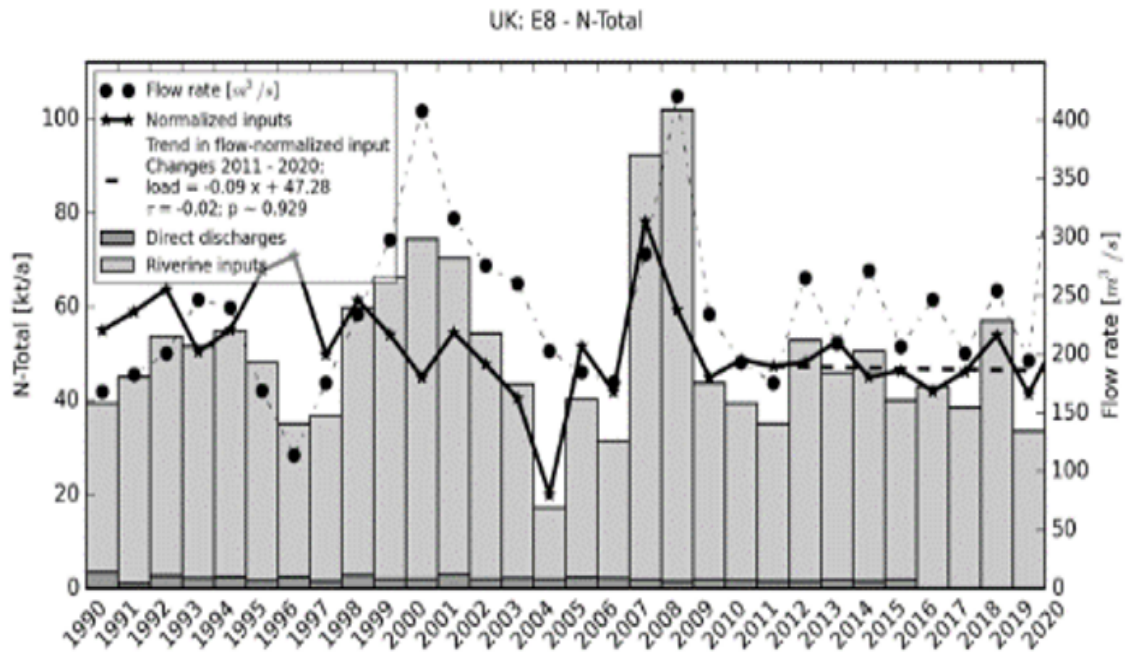**Figure 7.** *Time series of total phosphorus loads in rivers*

Figure 8. Time series of total nitrogen loads in rivers

This is especially due the strongly increased use of synthetically produced fertilisers in agriculture. Other inputs include point-source discharges of wastewater from urban sewer networks and industrial wastes. Around 2010, the worldwide discharge of N to the coastal waters was estimated to be in the order of 50 Tg N/yr (Teragrams of N per year) and the discharge of reactive (available for uptake) P in the range 5 to 8.6 Tg P/yr (Beusen *et al.,* 2015).

Groundwater discharge of nutrients is smaller, possibly no more than a few percent of the riverine discharge (see Nutrient conversion in the marine environment, and Seitzinger *et al.,* 2010).

Atmospheric deposition contributes about 8 Tg N/yr to the continental shelves and about 45 Tg/yr to the global ocean. Atmospheric deposition amounts to 30% of the total land-based nitrogen input to the North Sea, mainly as oxidized N, and 50% to the Baltic Sea (see Nutrient conversion in the marine environment, and North Sea Task Force 1993). The N:P ratio for wet deposition in the North Sea (1990) is 503:1 (Rendell *et al.,* 1993), very different from the 'expected' Redfield ratio of 16:1.

While nitrogen and phosphorus are essential nutrients for all marine primary producers, silicon (Si) is an essential nutrient only for certain organisms, in particular diatoms, silicoflagellates, rhizarians, certain radiolarians and silicious sponges. Dissolved Si (dSi), mainly as undissociated monomeric silicic acid, $Si(OH)_4$, is the only Si compound available for uptake by marine organisms. Fluvial runoff is the main dSi supplier to the marine environment. Although a relatively stable input, changing weather patterns, may change the availability of silicon.

Planktonic nutrient regeneration is a fundamental process that maintains most of the primary productivity in marine and freshwater environments. Phytoplankton are a paraphyletic group of photoautotrophs with a complex evolutionary history extending across 2.5–3.5 billion years (Olson & Blankenship 2004; Yoon *et al.,* 2004). Despite this paraphyly, they fall into evolutionarily distinct functional groups, including one major prokaryotic group (the cyanobacteria) and several eukaryotic groups (diatoms, green algae, coccolithophorids, dinoflagellates and others). The evolution of the ability to fix nitrogen is thought to be extremely ancient (Staley & Orians 1992), possibly older than oxygenic photosynthesis.

N-fixers are often thought to have high phosphorus requirements compared to other groups and thus exhibit a trade-off between N and P competitive abilities (Lenton & Klausmeier 2007). This trade-off can

lead to coexistence of N-fixers and non-fixers and can explain shifts in community composition with changing N: P ratios. Similar trade-offs between N fixation and competitive abilities for light or iron may also be important (Agawin *et al.,* 2007; de Tezanos Pinto & Litchman 2010; Ward *et al.,* 2013). Whether N-fixers occur under certain conditions has many biogeochemical consequences, because it determines how much 'new' nitrogen is being added to the ocean, because it affects the stoichiometry of organic matter exported to the deep ocean and because fixed N can be released into the environment and consumed by other primary producers and other microbes.

As previously mentioned, functional phytoplankton types are often based on size:

- Larger phytoplankton experience a lower per capita grazing rate, which allows them to become relatively more abundant if resources are not strongly limiting (Kiørboe 1993; Smetacek 1999)

- Some larger phytoplankton (e.g. diatoms) have a higher maximum growth rate, which allows them to capitalize on transiently high nutrient concentrations (Marañón 2014), especially spring Silica

- Large phytoplankton (diatoms) have greater nutrient (i.e. nitrate) storage capabilities that afford a competitive advantage under fluctuating nutrient regimes (Litchman *et al.,* 2009)

- Small and large phytoplankton are consumed by different grazer species (different size classes of grazers). Theoretically, as nutrient supply increases, small phytoplankton are controlled by their grazers, leaving sufficient remaining nutrients for larger phytoplankton to persist (Armstrong 1994)

- Larger phytoplankton are consumed by slower-growing metazoan grazers, allowing them to transiently escape grazing control when nutrients and light are sufficient (Irigoien 2005)

Major planktonic lifeforms such as diatoms, dinoflagellates, meroplankton and holoplankton have recently showed significant and alarming changes in abundance around the northwest European shelf (Bedford *et al.,* 2020; Graves *et al.,* submitted 2023). Many of these trends are downwards, but a few (such as meroplankton) are upwards.

Nutrient loads are falling in many English rivers, as are nutrient concentrations in estuaries and coasts, particularly for phosphate. The data also shows a concurrent general reduction in Chlorophyll levels; *but* phytoplankton cell counts are rising, and the fundamental *quality* of the phytoplankton community is changing. Phytoplankton cell sizes are getting *smaller* and in our inshore estuaries and coasts the proportion of diatoms to dinoflagellates is rapidly changing with potentially significant impacts on the functioning of the inshore (and maybe offshore) marine food web (Figure 9).

These changes correlate strongly with a change in the N:P ratio. These changes can be seen both in real and modelled river loads, and in concentrations in estuaries and coasts. They are a consequence of our more successful measures in reducing phosphate rather than nitrate inputs.

These plankton changes are likely to be considered as an 'undesirable disturbance', due to eutrophication pressure (N), with the corollary that English estuarine and coastal waters are unlikely to be either in Good Ecological Status (WER/WFD) or in Good Environmental Status (UKMS/MSFD), nor would achieve good status under the requirements of the 25 Year Environmental Plan (25YEP). We do not see this as clearly in sites further offshore (such as at some Smart buoys, L4, L2 and CPR and Ferry box routes) which are more strongly influenced by climate change. The effect is associated with areas that have or are being regularly influenced by freshwaters.
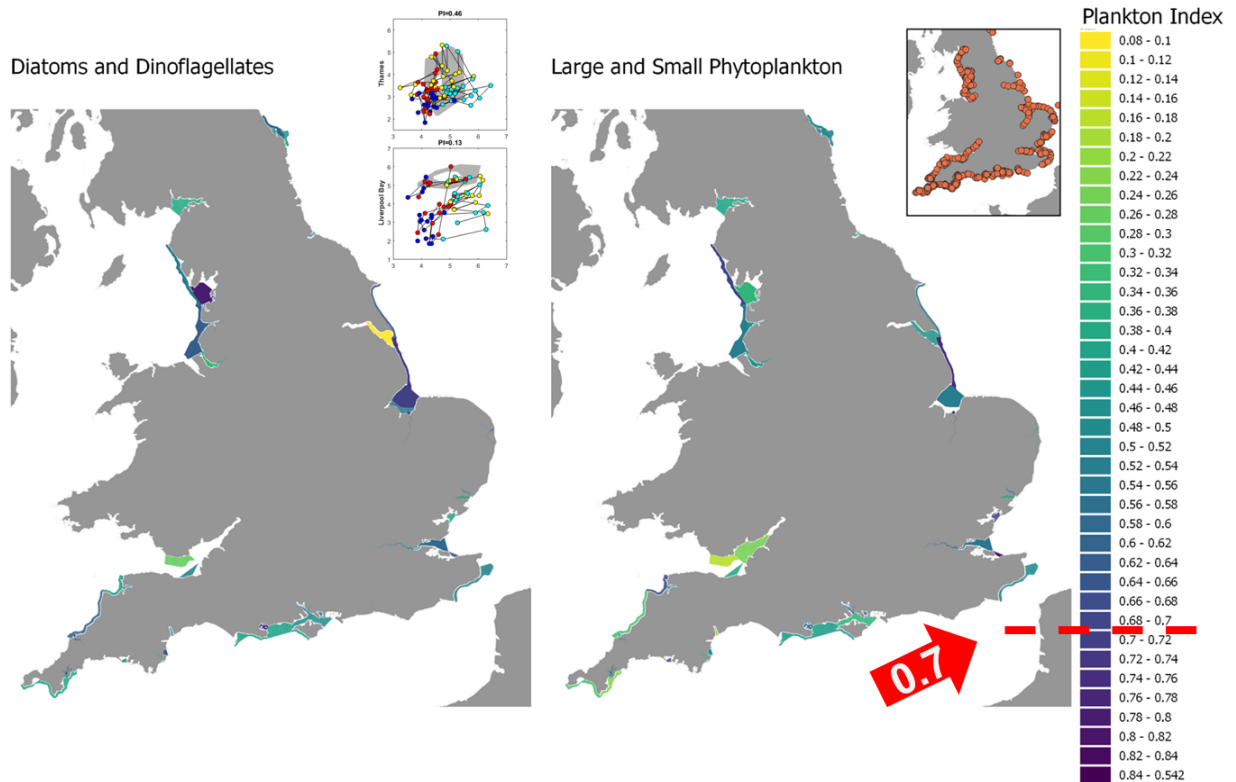
Figure 9. *Change in phytoplankton community from diatoms to dinoflagellates and from large to small cells in WER water bodies as accessed by the Plankton index (PI) tool. Any value below 0.7 is considered significant.*

Aspects and issues of eutrophication are mainly considered in Work package 2 - Deliverable 4, of the mNCEA Pelagic Project, as highlighted in the extract below:

Work Package 2	
Purpose & objective	**Objective 2:** An improved ability to take an ecosystem approach to the management of nutrient enrichment through the development of tools, and an analysis and interpretation of links between plankton community changes and eutrophication.
Deliverable 4 (WP2) Plankton-eutrophication analysis tools and assessments	
Output & scope	First phase development of bespoke user-friendly analysis tools showing community changes and shifts due to eutrophication, nutrient imbalances, climate change, ocean acidification, particularly in waters influenced by freshwater and land-based nutrients. This will utilise riverine influenced areas as defined by plumes maps, changes in phytoplankton communities and chlorophyll concentrations with linkages to both the Land Sea Interface (EA led) and Seascapes (Cefas led) mNCEA Yr2 projects.

Activities & delivery	Delivery, with various academic delivery partners (including members of UK PHEG), will involve:

	<mark>• a reappraisal of 'eutrophication' and assessment tools under new and changing circumstances (led by Cefas and EA) including:</mark>
	
	<mark> • a review of WER and UKMS results and philosophy</mark>
	
	<mark> • considerations of limiting nutrients and critical timing</mark>
	
	<mark> • identifying which techniques will give the most management and intervention potential</mark>
	
	<mark> • investigating the potential of incorporating plankton community measures (such as lifeform analysis) into eutrophication assessments</mark>
	
	• an investigation of Harmful Algal blooms (HABs) lifeforms and their potential influence on coastal 'health' (led by EA and MSS (the UK HABs lead), and UoP) including:
	
	   ○ ..
	
	• an investigation of the change in small and large lifeforms and the impact of this change on carbon export (led by PML), including:
	
	   ○ ..
	
	• theory development for valuing a dynamic system with rapid turnover which typifies marine plankton (led by SAMS).
	
	Yr3 will include appraisal of application to policy and decision-making (led by UoP).

3.4 'Harmful Algal Blooms' (HABs)

'Harmful Algal Blooms' (HABs) are a 'societal', rather than 'scientific' term that does not refer to a precise biological group of plankton. Rather this term refers to a very mixed, diverse, and unrelated group of phytoplankton that impact on human health and wealth. It includes taxa that are 'poisonous' (toxic) to humans and animals we value (either in commercial terms, or aesthetic terms), and taxa that are considered a 'nuisance' by discolouring water, creating foams and scums on beaches, fouling fishing nets and pots, or by die off creating oxygen depletion.

Occasionally the term 'Nuisance Algal Blooms' (NABs) is used but we will use HABs to cover all categories in this report.

Marine algae, although underpinning food webs, are sometimes considered a nuisance with implications for society and the economy, especially certain species of diatoms and dinoflagellates. There are approximately 300 known harmful algal species (Berdalet *et al.,* 2016) from most phytoplankton groups (Anderson *et al.,* 2015), and some cause toxicity to higher trophic level species, including fish, shellfish, marine mammals, and humans (Wells *et al.,* 2015).

There is mounting evidence of a global increase in nutrient levels of coastal waters through riverine and sewage inputs, and in both the numbers and frequency (as well as the species composition) of nuisance and toxic algae, sometimes termed 'red tides '. However, although this correlation is often cited, it is rarely the sole cause.

Phytoplankton blooms, particularly HABs, are believed to have expanded globally in coastal waters, although there are few long-term data sets available to critically evaluate this hypothesis (Smayda 1990; Hallegraeff 1993; Cloern 2001). Phytoplankton blooms are natural phenomena that were also occurring during pristine conditions (Bianchi *et al.,* 2000), but it has become a widespread belief that the increasing frequency of blooms is related to anthropogenic nutrient enrichment of coastal waters, although this has not been proven rigorously (Paerl 1988, 1997; Cloern 2001).

Undoubtedly, a relationship exists between HABs and the N and P load of coastal waters, and many nutrient enrichment experiments have shown that marine phytoplankton blooms are often nutrient limited. What is now becoming clear, however, is that although in classical terms minimum amounts can be limiting, nutrient ratios (such as N:P and Si:P) are far more important regulators.

However, Davison *et al.* (2012, 2014) assessed the evidence on:

- the level of understanding of the link between the amount, form, and ratio of anthropogenic nutrients and HABs.

- the evidence for a link between anthropogenically generated HABs and negative impacts on human health.

- the economic implications of anthropogenic nutrient/HAB interactions.

They concluded that an anthropogenic nutrient-HAB link is far from universal, and where it has been demonstrated, it is most frequently associated with high biomass (tending to algal foams and discoloured water) rather than low biomass (tending to be biotoxin producing) HABs. While organic nutrients have been shown to support the growth of a range of HAB species, insufficient evidence exists to clearly establish if these nutrients specifically promote the growth of harmful species in preference to benign ones, or if/how they influence toxicity of harmful species. They concluded that the role of anthropogenic nutrients in promoting HABs is site-specific, with hydrodynamic processes often determining whether blooms occur.

As part of the S3 Eurohabs project Best (2022, internal report) suggested that although the incidence of HAB events occurring seemed stable, the intensity of the events (in terms of biomass) was increasing.

Harmful algae can cause death in fish, shellfish, marine mammals, and humans, via their toxins, or from 'mechanical ' effects associated with their sheer quantity. There are many species, which cause a variety of problems around north-west Europe, and the frequency and distribution of algal blooms have altered in the recent past.

Phaeocystis globosa is commonly regarded as a nuisance algal species for several reasons. The species is associated with mass foam accumulations on beaches, which are a nuisance to beach recreation (Lancelot, 1995; Peperzak, 2002). Furthermore, its high biomass accumulation is associated with occasional shellfish mortality (Peperzak and Poelman, 2008), its production of dimethyl-sulphide precursors may promote acid rain (Liss *et al.,* 1994) and *Phaeocystis* blooms have been reported to cause floating slicks on the water, to clog nets and produce bad odour.

In one Dutch study (Blauw 2010) peak bloom intensity was higher at monitoring stations with higher nutrient availability, although bloom termination did not coincide with nutrient depletion. Foam events occurred on Dutch beaches during and following *Phaeocystis* blooms, when the wind direction was landward.

Bresnan *et al.* (2021) used the IOC-ICES-PICES Harmful Algal Event Database (HAEDAT) to describe the diversity and spatiotemporal distribution of harmful algal events along the Atlantic margin of Europe from 1987 – 2018 (Figure 10). They concluded that most events recorded were caused by Diarrhetic Shellfish Toxins (DSTs). The dominant causative dinoflagellates were *Dinophysis* complex.
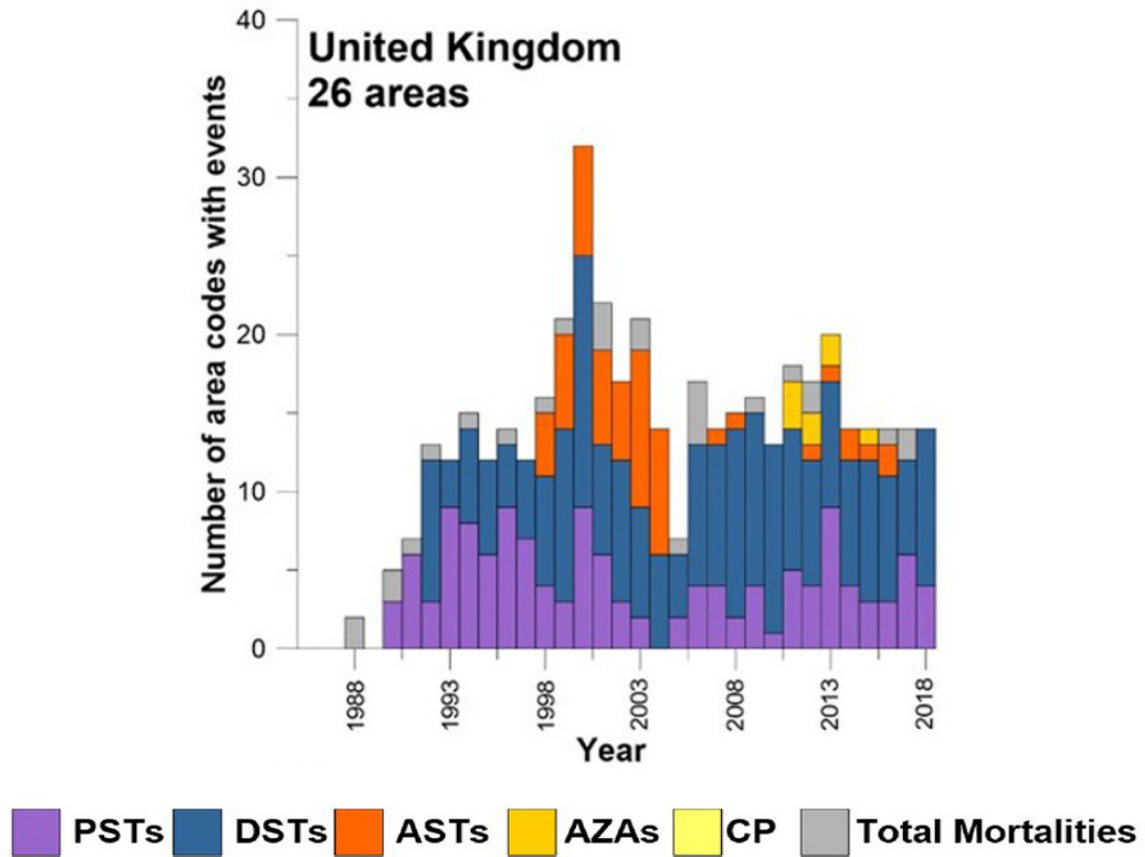
Figure 10. Bar chart of number of HAEDAT areas with events per year. HAB events tend to be classified by the phytotoxin produced rather than the organism producing it. The main categories are: PSTs (Paralytic Shellfish Toxins), DSTs (Diarrhetic Shellfish Toxins - Okadaic Acid and Dinophysistoxins), ASTs (Amnesic Shellfish Toxins), AZAs (Azaspiracid Toxins), CP (Ciguatera Poisoning). The category 'Total Mortalities' includes events of benthic mortalities as well as of dogs, birds, and aquaculture/natural fish. *[From Bresnan* et al., *2021]*

Townhill *et al.* (2018) suggest that around the north-west European shelf seas the suitable areas for the occurrence of HAB species are likely to change because of climate change in the coming century. In most cases, the suitable environmental conditions will be found further north in the shelf seas than under present day conditions.

From a marine natural capital point of view the different types of HABs impact several services (Figure 11). The 'nuisance' group tend to impact:

- provisioning services
- supporting services
- cultural services

While the 'toxic ' group are mainly seen as impacting human health (a social or supporting service) and the provisioning service when shellfish and aquaculture are impacted. Wash up of dead organisms is a relatively minor impact on cultural services in the UK.

Figure 11. *Impact of 'Harmful Algal Blooms' (HABs) on natural capital services*

From a management point of view our current legislation is quite weak. Current policy drivers can be found in the EU Shellfish Hygiene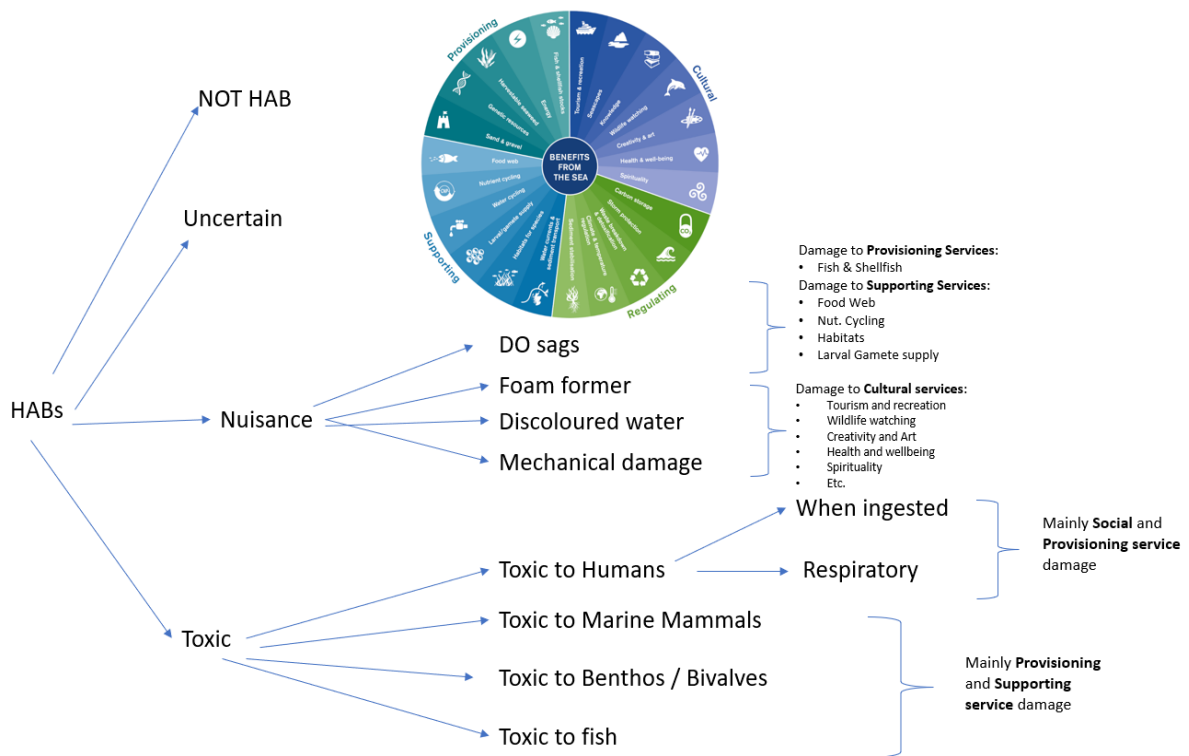 Directive (which aims to protect human health when consuming shellfish contaminated with microbes, algae, or chemicals). More generally the UK Water Environment regulations (WER, formally WFD) and UK Marine Strategy (UKMS, equivalent to the MSFD) are particularly focussed on picking up high biomass events and generally community composition. The pelagic habitats indicator within UK Marine Strategy (and OSPAR) focuses on plankton lifeforms (functional groups) which HABs do not fit into as a single group. Additionally, not all toxic taxa will produce toxins all the time, depending on genetics, physiology, and local environmental conditions. This complexity means that currently there is no policy assessment for HABs in UK waters.

HABs are picked up in Work package 2 - Deliverable 4, of the mNCEA Pelagic Project, as highlighted in the extract below:

Work Package 2	
Purpose & objective	**Objective 2:** An improved ability to take an ecosystem approach to the management of nutrient enrichment through the development of tools, and an analysis and interpretation of links between plankton community changes and eutrophication.
Deliverable 4 (WP2) Plankton-eutrophication analysis tools and assessments	
Output & scope	First phase development of bespoke user-friendly analysis tools showing community changes and shifts due to eutrophication, nutrient imbalances, climate change, ocean acidification, particularly in waters influenced by freshwater and land-based nutrients. This will utilise riverine influenced areas as defined by plumes maps, changes in phytoplankton communities and chlorophyll concentrations with linkages to both the Land Sea Interface (EA led) and Seascapes (Cefas led) mNCEA Yr2 projects.

Activities & delivery	Delivery, with various academic delivery partners (including members of UK PHEG), will involve:

	• a reappraisal of 'eutrophication' and assessment tools under new and changing circumstances (led by Cefas and EA) including:
	
	    • …
	
	• an investigation of Harmful Algal blooms (HABs) lifeforms and their potential influence on coastal 'health' (led by EA and MSS (the UK HABs lead), and UoP) including:
	
	    o investigating patterns and cycles in HABs taxa, both inshore and offshore
	
	    o relation to timeseries of factors such as nutrients, temperature, and spring blooms of non-toxic taxa (if possible)
	
	• an investigation of the change in small and large lifeforms and the impact of this change on carbon export (led by PML), including:
	
	    o ..
	
	• theory development for valuing a dynamic system with rapid turnover which typifies marine plankton (led by SAMS).
	
	Yr3 will include appraisal of application to policy and decision-making (led by UoP).

3.5 Bioremediation (of excess organic nutrients) and benthic-pelagic coupling

Waste remediation refers to the dilution, bioremediation, and burial of substances such as nutrients, sewage, contaminants, heavy metals, and plastic. Nearshore water can dilute and breakdown 'waste' while the intertidal and subtidal habitats can sequester, remineralise and bury waste in sediments.

The service of bioremediation involves many benthic organism groups because of the processes they carry out such as filter feeding or bioturbation which aid the cycling of nutrients through the ecosystem (for example, Gray and Elliott, 2009, Queirós *et al.*, 2013). Phytoplankton (and macrophytes) remove excess organic nutrients from the water column (for example, Riebesell, 1989; Heip, 1995; Diaz and Rosenberg, 2008). Filter feeders help to remove phytoplankton (and free nutrients) and also some particulates from the water column either: by using energy derived from ingested phytoplankton (and detritus) for growth and reproduction; or excreting the digested phytoplankton in faecal pellets which sink to the seabed (for example, Lindahl *et al.*, 2005, Riisgård *et al.*, 2011). Soft sediment infauna may then contribute to this service through bioirrigation and bioturbation helping to draw organic matter, such as dead plankton and faecal pellets into the sediment and this temporarily, or sometimes permanently, removes excess nutrients from the ecosystem (for example, Gray and Elliott, 2009).

Essential ecosystem functions, such as production and energy transfer in food webs, biogeochemical cycling, bioremediation, and provisioning of fish nursery areas (Granek *et al.*, 2010; Seitz *et al.*, 2014), are supported by multiple and interacting benthic-pelagic coupling processes (for example, Chauvand *et al.*, 2000).

Benthic-pelagic coupling is a concept in which sea floor processes affect pelagic ecosystems (Rowe *et al.*, 1975) and *vice versa*. It involves several oceanographic processes related to the chemistry, biology, and physics that actively link sea floor with the overlying water masses. The exchange of energy, nutrients, and organisms from one habitat to the other is a coupling of the two independent systems. The deposition of organic matter on the sea floor is derived from activities in surface waters such as photosynthesis, 'sloppy feeding ', and decomposition from dead organisms, detritus, and faeces. In the

opposite direction materials recycled or created in the sediment return to the pelagic realm to make a consequential impact on processes and organisms in the surface waters.

Coastal and estuarine ecosystem structure and function are strongly affected by anthropogenic pressures, Griffith *et al.* (2017) suggest benthic-pelagic coupling has potential sensitivity to three anthropogenic pressures: climate change; nutrient loading; and fishing (both as sediment disturbance, and removal of planktivorous fish and filter feeding bivalves). Additionally, the patchiness of water column production, the meroplankton (temporary plankton such as bivalve and crustacean larvae), sedimentation and other hydrogeomorphic factors can impact the local efficiency of transfer.

A climate change-related increase in water temperature may cause changes in the timing and decrease in the magnitude of phytoplankton blooms, which in turn may lead to a decrease in the transport of organic matter to the benthos and reduce the release of inorganic nutrients from the marine sediment. Changes in coupling between pelagic and benthic systems can in turn lead to a decrease in benthic productivity and reproduction.

Some aspects of benthic-pelagic coupling (especially meroplankton) are picked up in Work package 3 - Deliverable 6, of the mNCEA Pelagic Project, as highlighted in the extract below:

Deliverable 6 (WP3) Attributing the drivers of change in plankton assemblages	
Output & scope	We are witnessing some profound changes in plankton lifeforms, such as increases in meroplankton at the expense of the groups such as copepods which support pelagic fish. We need to understand whether these changes are due to climate, fishing, changing nutrient loads to the sea or the increase in human-made structures in the sea. We will deliver paper(s) and policy briefs / infographics outlining these various pressures and their impacts. This will lead (into Year 3) onto the development of management tools to predict behaviour of plankton groups with negative ecological and economic impacts (e.g. fouling organism, invasives, harmful algae blooms, jellyfish blooms) and recommended response measures (e.g. adjustment of harvesting times) – enabling an ecosystem approach to fisheries, shellfish, offshore structures, and recreational management.

Activities & delivery	Refining lifeform traits (mainly led by MBA and PML): An analysis of traits within some of the more diverse lifeforms which have shown evidence for large change (e.g., meroplankton and holoplankton lifeforms). We (planned lead by PML and UOP) will use long time series data on these taxa to understand which traits cause some species to be 'winners' and some to be 'losers'. As one example - within the meroplankton, which have increased significantly as a group right across the NW European shelf, they comprise a variety of taxa which can be analysed in several ways:
	• commercially exploited or not
	• spring or autumn breeders
	• soft or hard-bottom-attached adults
	• fine filter feeding or carnivorous larvae
	By assigning these higher resolution traits to taxa (compared to those already in the available) we will link the actual traits to pressures as well as linking the broader lifeform to pressures.
	So, for meroplankton at a NE Atlantic/NW European shelf scale, this will allow us to test a series of hypotheses for their increase, such as whether this is due for example to:
	• warming speeding meroplankton development times
	• increases in man-made structures in the sea
	• reduction in phytoplankton size
	• or changes in fishing activity
	Going into year 3, a similar approach will be taken to other groups and policy issues, such as climate, nutrient, and ocean acidification (OA) driven change in lifeforms (led by UOP). Our objective here is to apportion change in plankton lifeforms to pressures (SST, OA, nutrients, etc) in specific geographic areas to support decision-making and implementation of management measures.

3.6 Production, food webs, and energy flow

Half of the primary production that supports food webs is provided by photosynthetic processes carried out by microbial and phytoplankton communities in the water column. Changes in these communities can in turn affect the survival of organisms in higher levels of the food web.

As a food source for pelagic herbivores (including larval stages), phytoplankton form the basis of marine food webs ('regulation and maintenance of marine food webs'), supporting the production and supply of biomass from the upper trophic levels, including biomass produced in marine aquaculture or mariculture contexts ('wild fish and other natural aquatic biomass and related raw materials and biomass and raw materials from in-situ aquaculture'). Spatial variability in primary productivity and phytoplankton abundance can influence the distributions of upper trophic levels, including fish, birds, and marine mammals, and indirectly the local provision of ecosystem services by these organisms.

It should also be noted that shelf areas support most oceanic primary production but are, at the same time, the areas affected by most human activities and related pressures (such as offshore oil and gas, wind energy, wave and tidal renewable energy, aquaculture, aggregate dredging, and waste dumping; Tweddle *et al.*, 2018). The role played by anthropogenic pressures and their impacts in relation to food

webs and components such as phytoplankton must be kept in mind. Given the importance of pelagic environments in supporting the entire marine ecosystem, cumulative impacts resulting from human-induced pressures can alter the physical and biological dynamics governing the water column and in turn have a negative cascading effect on the provision of ecosystem services by other habitats that depend on them.

Phytoplankton primary production is at the base of the marine food web; changes in primary production have direct or indirect effects on higher trophic levels, from zooplankton organisms to marine mammals and seabirds. Capuzzo *et al.* (2017) have shown a significant decline in gross primary production in the North Sea from 1988 to 2013 (Figure 12), although the effect is patchily distributed. They correlate this with sea surface warming and reduced riverine nutrient inputs. It is predicted that there will be a trophic amplification of biomass declines (Tittensor *et al.,* 2021) and indeed there can be seen a change in the dynamics at higher trophic levels (such as small copepods and fish recruitment).
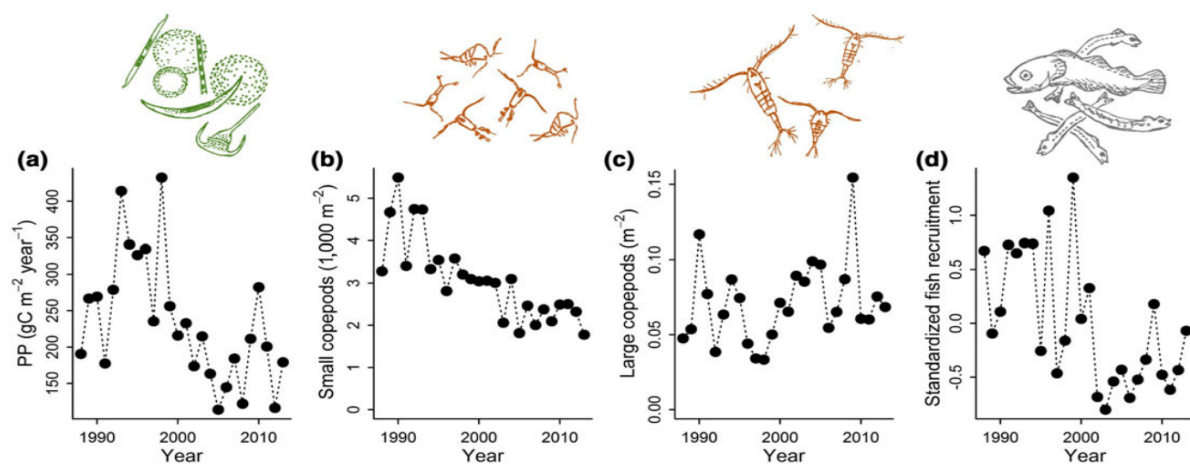

Figure 12*. Interannual variation in annual primary production (PP gC m^{-1} year^{-1}), mean abundance of small copepods (1,000 x m^{-3}), and a standardised index of fish stock recruitment (including sandeel, sprat, herring, Norway pout, cod, haddock, and whiting) in the North Sea [From Capuzzo* et al.*, 2017]*

The presence and abundance of zooplankton, and their prey-predator relationship with other trophic levels, influences fish recruitment and the production of wild biomass in higher trophic levels ('wild fish and other natural aquatic biomass and related raw materials') and the biomass produced in mariculture contexts ('biomass and raw materials from in-situ aquaculture'). Zooplankton's contribution to sustaining the balance of the food web itself ('regulation and maintenance of marine food webs') is also detectable in their role as a grazer for phytoplankton and bacteria and as a provider of nitrogen and phosphorus (nutrient cycling) that has positive effects on the primary productivity of phytoplankton.

However, it is not only the quantity but also the quality of the production that is important. For example, highly unsaturated fatty acids like eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) and arachidonic acid (AA) are essential in the development, growth, and physiological activities of aquaculture organisms (such as fish larvae oysters and mussels). Microalgae are important main sources of EPA and DHA (Galloway *et al.,* 2015, Jónasdóttir 2019). It has been noted that, as stratification events occur and change, a lot of the production is driven by nano and pico plankton during the stratification (Akinson *et al.,* 2018, Atkinson *et al.,* 2020, Schmidt 2020). These tend to be insufficient in essential fatty acids (Galloway *et al.,* 2015, Jónasdóttir 2019, Schmidt 2020).

As well as carbon we can look at the amount of biomass passing through the food web for each size class plankton. Size structure and biomass can provide a valuable index of zooplankton population dynamics and ecosystem production (Zhou and Huntley, 1997; Kerr and Dickie, 2001; Edvardsen *et al.,* 2002; Atkinson *et al.,* 2021).

The slope of the normalised biomass size spectrum (NBSS) is an emergent and measurable property of food webs and is valuable to diagnose the efficiency with which energy is transferred through the food web. At a broad (annually averaged, regional) scale, it provides a first order estimate of the mass of fish that are supported from a given mass of phytoplankton. Based on a meta-analysis, these slopes of these size spectra relate to the average chlorophyll a (chl a) concentration, which provides a proxy for nutrient
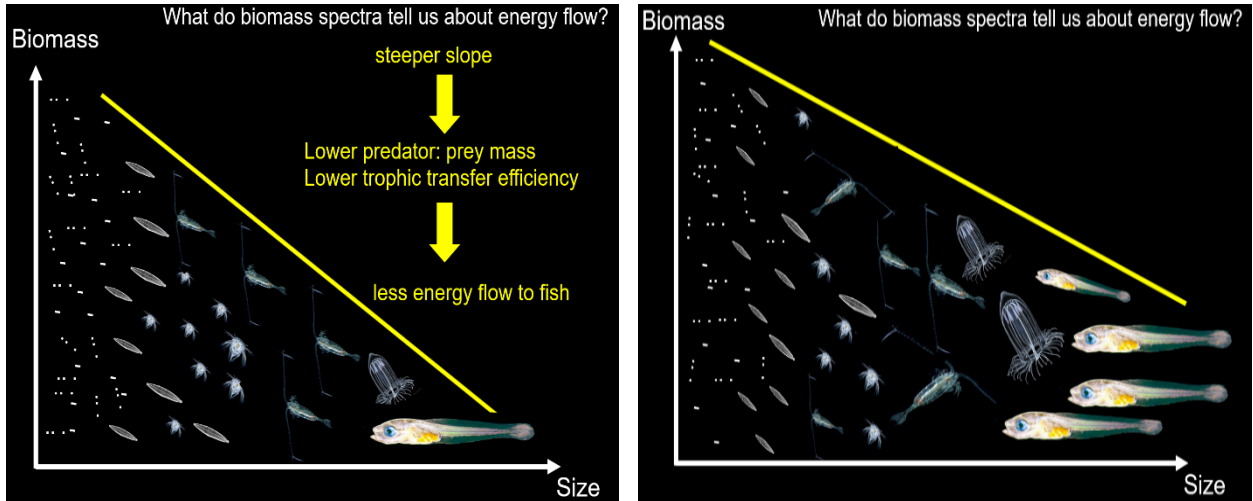
status (Atkinson *et al.,* unpublished Figure 13 and 14) and this empirical relationship (Figure 15) provides a measure of how much decline in the carrying capacity of fish will result from any given decline in chl a concentration (Figure 15, panel b). The phytoplankton of low and mid latitudes is widely projected to decline in Earth System Models (Tittensor *et al.,* 2021) due to increases in temperature and summer stratification, so this size spectrum approach, alongside modelling) provides an estimate of the implications for supportable fish biomass.

A.   **B.**

Figure 13. *Illustration of size spectra analysis and energy flow; lots of small things lead to a few big things. **A.** Steep slope is less efficient and leads to fewer fish. **B.** Shallower slope results in a higher biomass of fish*
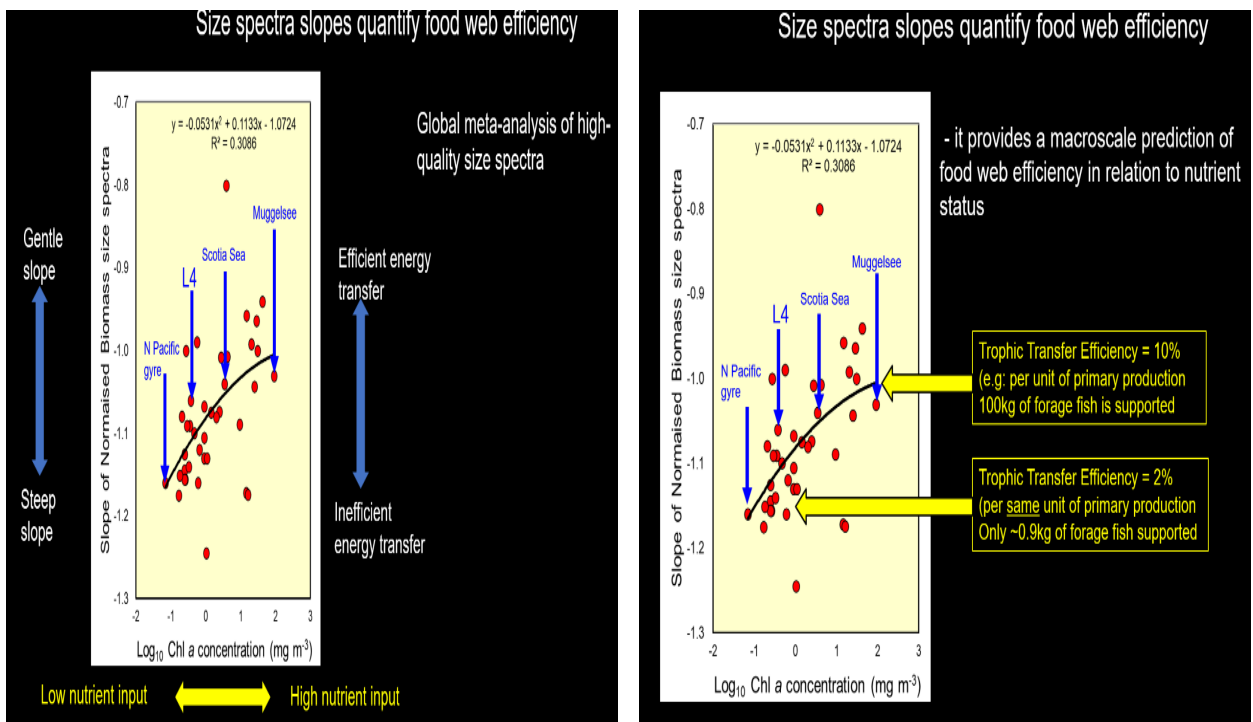
Figure 14. *'Slopes' from around the world plotted against chlorophyll as a proxy for production (and indirectly nutrient input). **A.** Steep slopes are usually found in low productivity, nutrient poor areas such as gyres, while shallow slopes are in more productive areas. Note L4 off Plymouth is approximately in the bottom third. **B.** Highlighting trophic efficiency*

Figure 15. *Size spectrum. **a.** Unpublished meta-analysis of 40 globally distributed slopes of complete normalised biomass size spectra (NBSS) of plankton size ranges spanning at least from picoplankton to macroplankton. Shown are the best fit relationship to mean* chlorophyll a (*Chl a) concentration of each ecosystem (red line), used here as a crude proxy of its nutrient status. Also shown are a linear fit to the data (blue line) and the original concept of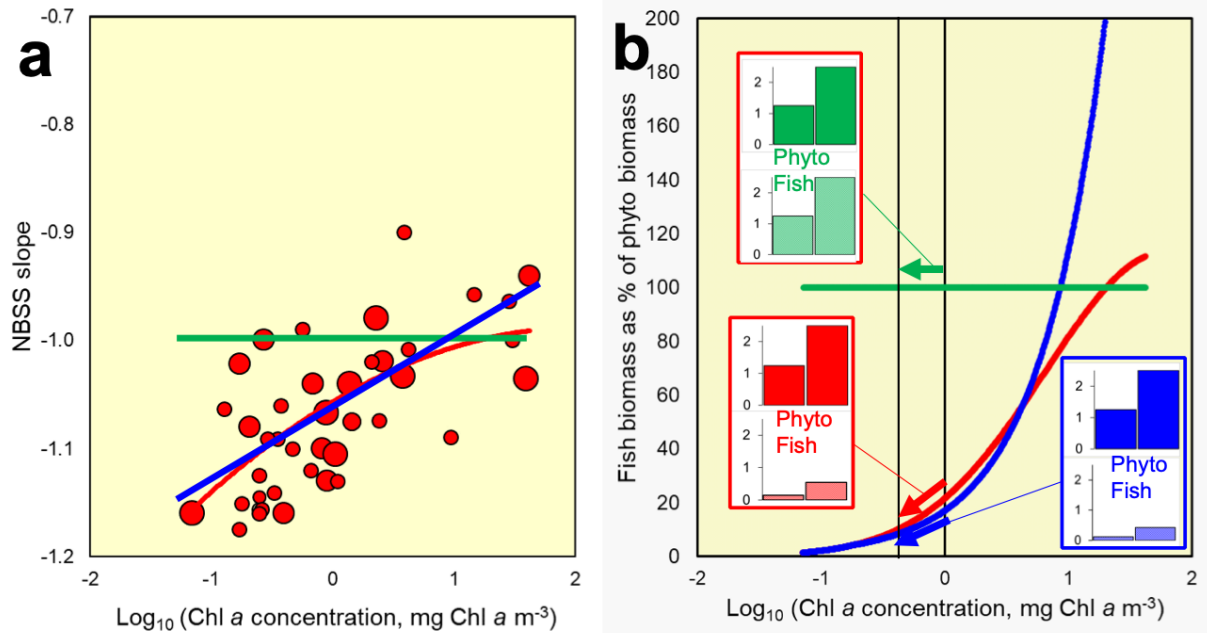 a fixed NBSS slope of -1 (Sheldon* et al., *1972, green line) based on the suggestion that there were similar biomasses in all pelagic organisms integrated within equal logarithmic mass range intervals spanning bacteria to whales. These relationships were used to estimate in **b** the respective supportable biomasses of fish as a percentage of phytoplankton. The colour coded histograms provide an indicative example of the decline in supportable fish biomass (stippled bars, in units of g C m^{-2}) that would result from Chl a (solid bars) values reducing from 1 to 0.5 mg Chl a m^{-3}, as indicated by the vertical lines on the logarithmic Chl a axis.*

Links between production, food webs, and energy flow are picked up in Work package 2 – Deliverable 6, Work package 3 – Deliverable 7, and Work package 4 – Deliverable 8, of the mNCEA Pelagic Project, as highlighted in the extract below:

Deliverable 4 (WP2) Plankton-eutrophication analysis tools and assessments	
Output & scope	First phase development of bespoke user-friendly analysis tools showing community changes and shifts due to eutrophication, nutrient imbalances, climate change, ocean acidification, particularly in waters influenced by freshwater and land-based nutrients. This will utilise riverine influenced areas as defined by plumes maps, changes in phytoplankton communities and chlorophyll concentrations with linkages to both the Land Sea Interface (EA led) and Seascapes (Cefas led) mNCEA Yr2 projects.

Activities & delivery	Delivery, with various academic delivery partners (including members of UK PHEG), will involve:
	• a reappraisal of 'eutrophication' and assessment tools under new and changing circumstances (led by Cefas and EA) including:
	• a review of Water Environment Regulations (WER) and UKMS results and philosophy
	• considerations of limiting nutrients and critical timing
	• identifying which techniques will give the most management and intervention potential
	• investigating the potential of incorporating plankton community measures (such as lifeform analysis) into eutrophication assessments
	• an investigation of Harmful Algal blooms (HABs) lifeforms and their potential influence on coastal 'health' (led by EA and MSS (the UK HABs lead), and UoP) including:
	○ investigating patterns and cycles in HABs taxa, both inshore and offshore
	○ relation to timeseries of factors such as nutrients, temperature, and spring blooms of non-toxic taxa (if possible)
	• ==an investigation of the change in small and large lifeforms and the impact of this change on carbon export (led by PML), including:==
	○ ==consideration of carbon biomass in different lifeforms, seasonal variation, applicability at different geographical scales==
	• theory development for valuing a dynamic system with rapid turnover which typifies marine plankton (led by SAMS).
	Yr3 will include appraisal of application to policy and decision-making (led by UoP).
Deliverable 7 (WP3) Investigation of plankton and pelagic fisheries food web links	
Output & scope	A report and policy brief demonstrating the value of the plankton data asset in supporting a natural capital approach for fisheries management, through an analysis of food web links between plankton and pelagic fisheries – including various data extraction and analysis steps.

Activities & delivery	Building on and complimenting the PIT-PAF (Putting It Together: linking changes in plankton and Fisheries) project there will be a workshop (led by Cefas, and SAMS, in consultation with MMO) to determine best available datasets, most appropriate lifeforms and 'fish stocks', most appropriate geographic regions, and 'ideal' policy questions or information required. From this we will produce conceptual diagrams, followed by data analysis. This information will be packaged in an accessible policy briefing (led by UOP), demonstrating clear links to current policy priorities (i.e. natural capital, ecosystem services, UKMS, 25YEP).

Running concurrently with this will be the developing size spectrum work (led by PML). The slope of the normalised biomass size spectrum (NBSS) is an emergent and measurable property of food webs and is valuable to diagnose the efficiency with which energy is transferred through the food web. At a broad (annually averaged, regional) scale, it provides a first order estimate of the mass of fish that are supported from a given mass of phytoplankton. Initially, we will conduct a global-scale meta-analysis of pelagic size structure to develop empirical relationships between the slope of the NBSS and nutrient supply (proxied by annual-average chlorophyll a) and temperature. Based on observed and modelled chlorophyll *a* distribution across the NE Atlantic/NW European shelf for the present-day and under a future climate. This will allow us to estimate the present day 'carrying capacity' of fish in an empirical way (rather than thorough uncertainties in food web modelling) and based on variables accessible from Earth Observation and modelling. These will provide 'risk maps' of fishing areas most susceptible to reduced yields. |

Deliverable 8 (WP4) Engagement tools on how plankton relates to natural capital

Output & scope	Communications and engagement products to increase understanding by policy makers of plankton and how it relates to natural capital (led by EA, UOP and PML).
Activities & delivery	We will consult with decision-making and policy colleagues (such as MMO for fisheries) to understand the most important decisions and how they link back to pelagic lifeforms. This will help shape various deliverables, but also help how to communicate them, and from which infographics and reports can be developed.

The WCO data paper (see deliverable 2.1) will be developed and simplified as an education tool (for undergrad/postgrad projects) and for understanding long-term change.

At a more detailed level, we will:

- Develop a policy briefing on links between plankton, ecosystem services, and natural capital (led by UOP)

- use outputs from the PICO project; namely a total plankton carbon mass budget for intensively sampled fixed-point time series sites, namely L4 (Plymouth) and possibly Stonehaven (Scotland)

- use these data for calculating an approximate carbon standing stock across the whole of the NW European continental shelf, by providing simple and traceable calculations for calculating their habitat volume and thenceforth total plankton carbon biomass. This value will be used alongside other existing budgetary carbon estimates (for instance the UK net carbon emissions estimates, carbon standing stock in for example seaweeds and seagrass)

- present the carbon estimates in a simple infographic extolling the high carbon biomass and high turnover of plankton in the context of other terrestrial and intertidal primary and secondary producers (whose role in carbon sequestration has been stressed).

- look at the best ways to communicate this complex information. |

3.7 Biodiversity, lifecycles, changing lifeforms and potential impacts

Life cycle maintenance service, which in the most recent CICES v.5.1 classification (Haines-Young & Potschin, 2018) are represented by the regulation service 'nursery population and habitat maintenance' (including 'the protection of natural gene pools'), is considered one of the essential ecosystem services in relation to pelagic habitats. Indeed, pelagic habitats act as breeding (including spawning and mating), nursery and feeding grounds, as well as migration and advection routes, thus contributing to the maintenance of habitats and their biodiversity, both for species that live constantly in the water column ('Holoplankton') and species that live in it only for specific stages of their life cycle ('Meroplankton') (Dickey-Collas *et al.*, 2017). The effective function and completion of lifecycle is essential for the provisioning service of 'providing genetic material from biota'.

Regarding plankton diversity, species composition and abundance are influenced by changes in physical and chemical environmental conditions. Human-induced disturbances can lead to changes in plankton diversity because only some species are able to tolerate altered habitat conditions. Consequently, plankton diversity, as well as plankton lifeform biomass and abundance, will differ between disturbed and undisturbed communities (OSPAR, 2017).

Spatial variability in primary productivity and phytoplankton abundance can influence the distributions of upper trophic levels, including fish, birds, and marine mammals, and indirectly the local provision of ecosystem services by these organisms.

The diversity of phyto- and zooplankton has been shown to be a key modulator of the biological pump (Tréguer *et al.,* 2018, Henson *et al.,* 2019). Similarly, the diversity and size structure of the zooplankton mediate the recruitment of economically important fishes (Stocker *et al.,* 2015, Brun *et al.,* 2019, Henson *et al.*2019). Most studies indicate that the diversity of phyto- and zooplankton is largely controlled by climate (e.g. Hays *et al.,* 2005, Ibarbalz *et al.,* 2019, Righetti *et al.,* 2019), with temperature being the main driver (e.g. Beaugrand *et al.,* 2013, Tittensor *et al.,* 2010, Brown *et al.,* 2004, Rutherford *et al.,* 1999). Warm temperatures promote species diversity by enhancing speciation, metabolic rates and selecting for a higher number of species (Righetti *et al.,* 2019, Beaugrand *et al.,* 2013, Tittensor *et al.,* 2010, Rutherford *et al.,* 1999). However, ocean warming forces species to shift their distribution ranges poleward to track their optimal thermal habitats (Poloczanska, E. S. *et al.,* 2013, Burrows, M. T. *et al.,* 2014), and such shifts have weakened the strength of the biological carbon pump over the past 55 years in the North Atlantic (Brun *et al.,* 2019).

Benedetti *et al.* (2020), using modelling, found that at the end of this century, under a high emission scenario, there is an overall increase in plankton species richness driven by ocean warming, and a poleward shift of the species' distributions at a median speed of 35 km/decade. Phytoplankton species richness is projected to increase by more than 16% over most regions except for the Arctic Ocean. In contrast, zooplankton richness is projected to slightly decline in the tropics, but to increase strongly in temperate to subpolar latitudes. In these latitudes, nearly 40% of the phytoplankton and zooplankton assemblages are expected to be replaced by poleward shifting species. This implies that climate change, by changing the community, threatens the contribution of plankton communities to plankton-mediated ecosystem services such as biological carbon sequestration.

Vassallo *et al.* (2022) highlighted how environmental changes, such as the increase in temperature, have led to higher costs of system functioning in the last two years. Their analyses show a clear difference between the three-year period 2003–2005 and the two-year period 2018–2019. The mesozooplankton community had changed both in terms of abundance of organisms and in terms of organisation and functionality.

Biodiversity, life cycles and lifeforms underlay all the work being done in Year 2 (2023/24) of the mNCEA Pelagic Project:

Biodiversity	Across Deliverables 1-8

3.8 Biological control

Biological control is a fuzzy concept that can be difficult to define, but as a system of checks and balances it has been defined as: 'the contribution of marine ecosystems to the maintenance of population dynamics, resilience through food web dynamics, disease, and pest control'. An example could be the occurrence, and frequency of occurrence, of jellyfish or harmful algal blooms. These groups can change the ecosystem and negatively affect services when occurring in high abundance. Harmful algal blooms (HABs) can lead to reduced water quality with consequences for bathing water quality and aquaculture, reducing both, the recreation and leisure as well as the food production services (for example, Fleming *et al.*, 2006; Anderson, 2009). In a similar way jellyfish can form blooms which also reduce bathing water quality and access to beaches (Ghermandi *et al.*, 2015). Also, they can destroy fish aquaculture if large swarms of jellyfish drift into aquaculture nets, harming fish (Baxter *et al.*, 2011). There are reports of jellyfish increasing in UK inshore waters with the risk of blockage of cooling water intakes to power stations (e.g. D'Agostino, 2021).

Filter feeding by bivalves and other benthic invertebrates can control opportunistic species such as harmful algal blooms by filtering them out of the water column. However, many of these filter feeders have a planktonic phase and recent evidence shows that UK meroplankton is increasing. If bivalve larvae are spending longer in the plankton, there is a risk to recruitment and the filtering service they provide. Predation on jellyfish by fish may reduce the abundance of such species helping to keep the ecosystem in balance. Commercial fishing may significantly reduce these predators with the result of increasing jellyfish.

This is indirectly considered in both Work Packages 2 and 3 (Deliverables 4, and 6) of the mNCEA Pelagic Project, as highlighted in the extract below:

Deliverable 4 (WP2) Plankton-eutrophication analysis tools and assessments	
Output & scope	First phase development of bespoke user-friendly analysis tools showing community changes and shifts due to eutrophication, nutrient imbalances, climate change, ocean acidification, particularly in waters influenced by freshwater and land-based nutrients. This will utilise riverine influenced areas as defined by plumes maps, changes in phytoplankton communities and chlorophyll concentrations with linkages to both the Land Sea Interface (EA led) and Seascapes (Cefas led) mNCEA Yr2 projects.

Activities & delivery	Delivery, with various academic delivery partners (including members of UK PHEG), will involve:
	
	• ..
	
	• an investigation of Harmful Algal blooms (HABs) lifeforms and their potential influence on coastal 'health' (led by EA and MSS (the UK HABs lead), and UoP) including:
	
	    ○ investigating patterns and cycles in HABs taxa, both inshore and offshore
	
	    ○ relation to timeseries of factors such as nutrients, temperature, and spring blooms of non-toxic taxa (if possible)
	
	• an investigation of the change in small and large lifeforms and the impact of this change on carbon export (led by PML), including:
	
	    ○ ..
	
	• theory development for valuing a dynamic system with rapid turnover which typifies marine plankton (led by SAMS).
	
	Yr3 will include appraisal of application to policy and decision-making (led by UoP).

Deliverable 6 (WP3) Attributing the drivers of change in plankton assemblages	
Output & scope	We are witnessing some profound changes in plankton lifeforms, such as increases in meroplankton at the expense of the groups such as copepods which support pelagic fish. We need to understand whether these changes are due to climate, fishing, changing nutrient loads to the sea or the increase in human-made structures in the sea. We will deliver paper(s) and policy briefs / infographics outlining these various pressures and their impacts. This will lead (into Year 3) onto the development of management tools to predict behaviour of plankton groups with negative ecological and economic impacts (e.g. fouling organism, invasives, harmful algae blooms, jellyfish blooms) and recommended response measures (e.g. adjustment of harvesting times) – enabling an ecosystem approach to fisheries, shellfish, offshore structures, and recreational management.

Activities & delivery	Refining lifeform traits (mainly led by MBA and PML): An analysis of traits within some of the more diverse lifeforms which have shown evidence for large change (e.g., meroplankton and holoplankton lifeforms). We (planned lead by PML and UOP) will use long time series data on these taxa to understand which traits cause some species to be 'winners' and some to be 'losers'. As one example - within the meroplankton, which have increased significantly as a group right across the NW European shelf, they comprise a variety of taxa which can be analysed in several ways:
	• commercially exploited or not
	• spring or autumn breeders
	• soft or hard-bottom-attached adults
	• fine filter feeding or carnivorous larvae
	By assigning these higher resolution traits to taxa (compared to those already in the available) we will link the actual traits to pressures as well as linking the broader lifeform to pressures.
	So, for meroplankton at a NE Atlantic/NW European shelf scale, this will allow us to test a series of hypotheses for their increase, such as whether this is due for example to:
	• warming speeding meroplankton development times
	• increases in man-made structures in the sea
	• reduction in phytoplankton size
	• or changes in fishing activity
	Going into year 3, a similar approach will be taken to other groups and policy issues, such as climate, nutrient, and ocean acidification (OA) driven change in lifeforms (led by UOP). Our objective here is to apportion change in plankton lifeforms to pressures (SST, OA, nutrients, etc) in specific geographic areas to support decision-making and implementation of management measures.

3.9 Relations to infrastructure

Shelf areas support most oceanic primary production but are, at the same time, the areas affected by most human activities and related pressures (such as offshore oil and gas, wind energy, wave and tidal renewable energy, aquaculture, aggregate dredging, and waste dumping). Developing this sustainable energy supply will require trade-offs between both direct and indirect environmental effects, as well as spatial conflicts with marine uses like shipping, fishing, and recreation.

Advances in the renewable energy sector have enabled the construction and operation of wind farms in bodies of water deep enough to present vertical temperature differences across the water column or thermal stratification. In coastal regions dominated by tidal motion, the presence of offshore wind farm (OWF) structures brings about additional turbulence and mixing of stratified waters (Shultz *et al.*, 2020). Modelling work has shown phytoplankton concentrations may be affected by the presence of offshore wind farms (van der Molen *et al.*, 2014, Tweddle *et al.*, 2018, Daewel *et al.*, 2022). These can affect local productivity.

There are some reports of changes in primary productivity recorded around wind turbines in shallow sea regions (<50 m), which are likely to have positive effects on the availability of food to higher trophic

levels and may well have knock-on effects to food provision and cultural experience of iconic species, such as birds and marine mammals (Causon and Gill 2018). Conversely, OWFs provide hard surfaces for settlement of 'fouling organisms ' which are in meroplankton. This may alter the local distribution of meroplankton. The OSPAR thematic report has shown that meroplankton is increasing (compared to Holoplankton) in our shelf seas. OWF's hard surfaces also provide a potential habitat for invasive species.

Aspects of this are covered in Work Package 3 - Deliverable 6, of the mNCEA Pelagic Project, as highlighted in the extract below:

Deliverable 6 (WP3) Attributing the drivers of change in plankton assemblages	
Output & scope	We are witnessing some profound changes in plankton lifeforms, such as increases in meroplankton at the expense of the groups such as copepods which support pelagic fish. We need to understand whether these changes are due to climate, fishing, changing nutrient loads to the sea or the increase in human-made structures in the sea. We will deliver paper(s) and policy briefs / infographics outlining these various pressures and their impacts. This will lead (into Year 3) onto the development of management tools to predict behaviour of plankton groups with negative ecological and economic impacts (e.g. fouling organism, invasives, harmful algae blooms, jellyfish blooms) and recommended response measures (e.g. adjustment of harvesting times) – enabling an ecosystem approach to fisheries, shellfish, offshore structures, and recreational management.

Activities & delivery	Refining lifeform traits (mainly led by MBA and PML): An analysis of traits within some of the more diverse lifeforms which have shown evidence for large change (e.g., meroplankton and holoplankton lifeforms). We (planned lead by PML and UOP) will use long time series data on these taxa to understand which traits cause some species to be 'winners' and some to be 'losers '. As one example - within the meroplankton, which have increased significantly as a group right across the NW European shelf, they comprise a variety of taxa which can be analysed in several ways:
	• commercially exploited or not
	• spring or autumn breeders
	• soft or hard-bottom-attached adults
	• fine filter feeding or carnivorous larvae
	By assigning these higher resolution traits to taxa (compared to those already in the available) we will link the actual traits to pressures as well as linking the broader lifeform to pressures.
	So, for meroplankton at a NE Atlantic/NW European shelf scale, this will allow us to test a series of hypotheses for their increase, such as whether this is due for example to:
	• warming speeding meroplankton development times
	• increases in man-made structures in the sea
	• reduction in phytoplankton size
	• or changes in fishing activity
	Going into year 3, a similar approach will be taken to other groups and policy issues, such as climate, nutrient, and ocean acidification (OA) driven change in lifeforms (led by UOP). Our objective here is to apportion change in plankton lifeforms to pressures (SST, OA, nutrients, etc) in specific geographic areas to support decision-making and implementation of management measures.

3.10 Biological prospecting and biologically active metabolites

Although minor in the UK, worldwide the industrial exploitation of chemicals and processes from phytoplankton is growing significantly. From an industrial perspective, phytoplankton species have been used as a feedstock for a wide range of applications, such as wastewater treatment, or production of high value compounds and commercial products, such as:

- food and feed supplements
- pharmacological compounds including complex lipids, enzymes, polymers, toxins, and pigments
- Zooplankton is commonly used as live food for larval stages of fish, shrimp, molluscs, and corals.

Remarkably, while we are overexploiting many marine resources, particularly the fisheries, the planktonic compartment composed of zooplankton, phytoplankton, bacteria, and viruses, represents 95% of marine biomass and yet the extent of its diversity remains largely unknown and underexploited (Abida *et al.,* 2013). Due to their diverse evolutionary backgrounds, planktonic organisms offer immense opportunities: new resources for medicine, cosmetics and food, renewable energy, and long-term solutions to mitigate climate change (Abida, 2013). Bioprospecting can involve the collection of organisms and subsequent screening for a specific molecule or activity of interest. An alternative to

prospecting directly for bioactive compounds is to search for DNA sequences encoding activities of interest, either from single organisms or by mining metagenomic sequencing data derived from whole plankton communities collected from the water column (e.g. Rusch *et al.,* 2007).

Typical biologically active metabolites being considered in the UK include phytoplankton-derived fatty acids, amino acids, carotenoids, vitamins, enzymes, sterols, inorganic and organic minerals, chlorophyll, and trace elements (Napiórkowska-Krzebietke, 2017).

Several phytoplankton species, both freshwater and marine (e.g. *Botryococcus braunii*, *Chlamydomonas reinhardtii, Chlorella* spp., *Dunaliella* spp., *Prymnesium parvum*, *Skeletonema costatutm*, *Picochlorum* spp.), can produce, in a fast way, large amounts of hydrocarbons, especially lipids, which are suitable for biodiesel production (Razeghifard, 2013; Mucko *et al.*, 2020).

We do not expect to be covering this further in the mNCEA Pelagic Project.

Bioprospecting	Out of scope

3.11 Cultural

The pelagic realm provides all cultural ecosystem services ranging from the scientific knowledge that can be obtained from the different pelagic environments, educational value, exploration, and related technological developments to services, including literature, entertainment, ethical considerations, tourism and spiritual health and well-being (Thurber *et al.*, 2014).

Some planktic microalgae produce pigments (such as astaxanthin, and phycoerythrin) that, in case of blooms, produce a red colouration of the surface waters. Other plankton induced colours include browns and greens. As well as being a nuisance for tourism, this phenomenon is at the origin of several myths and religious beliefs and has inspired artists over the centuries.

For example, it has been suggested that the Red Sea owes its name to the huge blooms of the cyanobacterium *Trichodesmium erythraeum* (Capone *et al.*, 1997), while others suggest a more prosaic mistranslation of the 'reedy Sea' associated with the rushes that grew along it shores (or even on local sandstone formations).

One less common version of the legend of the mythical Phoenix (or 'firebird') has it falling to its death into the sea and rising again as a shining fiery bird. It has been observed in some coastal regions with high density blooms of bioluminescent phytoplankton (notably *Noctiluca*, but also some species of *Alexandrium, Lingulodinium, Protoceratium,* and *Pyrocystis*) when water birds can be covered and if they take off will trigger the reaction and glow for some time.

While such significant cultural events are rare in the UK among the fishing industry there are cultural terms that describe the how the environment has been impacted by algae. For example, 'brown water', often indicates a poor catch or poorer flesh quality of bivalves. The brown water is often caused by *Phaeocystis*.

3.11.1 Leisure and recreation

The marine environment can be enjoyed by humans for the benefit of leisure and recreation in several ways such as swimming, angling and wildlife watching (above water through boat- or shore-based observations or in water through sub-aqua diving and snorkelling). Some processes such as excessive primary production can have a negative effect on leisure and recreation for example discoloured water, scums and foams on the beach may be as much of a nuisance as when a large biomass of opportunistic macrophytes is produced, which may wash up on beaches reducing perceived environmental quality for

beach goers; alternatively, when harmful algal blooms occur that can reduce bathing water quality to such an extent that beaches are closed to visitors.

We are not specifically looking at the impacts cultural or leisure and tourism impacts in this report (although see valuations in the appendix), although some insights may be picked up in other parts of the mNCEA Pelagic Project work (such as HABs review and impact on beaches).

Culture, leisure, and tourism	Not specifically considered.

4. Management considerations

Should plankton be a key consideration for marine management?

Because concentrations of plankton are highly patchy in both space and time, we need more consideration concerning the potential impact from human developments and activities on the service provision afforded by plankton should be accounted for in marine management processes. The multiple species of primary producers provide important provisioning and regulating services and form the basis of marine food-webs, supporting production of higher trophic levels, and act as a sink of CO_2.

However, environmental managers already face the large challenge of assimilating complex information, and subsequently reaching an understanding of the information from which they can draw suitable management actions (Lester *et al.*, 2013; Fletcher *et al.*, 2014; Holt *et al.*, 2016). Plankton are often less tangible than other assets and pressures. Keeler *et al.* (2012) linked water quality parameters to changes in water quality (for example increased nitrogen leading to algal blooms) and thence to human well-being and to improve assessment of ecosystem services. These were then connected to affected ecosystem services such as changes in recreational fishing due to abundance changes of fish.

Human maritime developments and activities are most likely to occur in, and therefore impact on, shelf seas, that is, relatively close to land.

To minimise negative impacts and secure wider environmental benefits, a marine net gain (MNG) approach, based on the value of the marine environment to people via ecosystem services and natural capital, is essential. The developing thinking on natural capital accounting is important to MNG as it provides a framework for articulating, defining, and measuring the impacts of energy related installations on environmental benefits and their relative importance in provision of wider ecosystem services. Natural capital accounting also supports the implementation of economic mechanisms, such as incentives or market-based approaches to securing MNG.

But the services provided by plankton seem nebulous and omnipresent in the marine environment making it hard to account for them using traditional natural capital accounting methods. Rather it may be necessary to have a suite of tools or indicators that quantify the natural capital service provided at different geographical and time scales. Our work here will develop and inform this suit of tools.

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Appendix 1: Summary of nearshore water value information (from Le Quesne *et al.*, 2022)

Annual value of nearshore waters to England

Wild fisheries	£59m
Aquaculture	£4.8m
Waste remediation	£573m
Atmospheric regulation	£104m
Coastal protection	£395m
Coastal visits	£13,876m
Total	£15bn

Provisioning

Wild fisheries

England under 10m fisheries value £59m for 2019 as a proxy for inshore fishery landings value. Economics of the UK Fishing Fleet 2020 — Seafish

Aquaculture

Marine aquaculture in English waters in 2017 £4.5m, with the English Aquaculture Strategy predicting 10-fold growth by 2040. English Aquaculture Strategy from Seafood 2040 — Seafish

Cost in hospital bed stays per year in Eng due to HABs in shellfish = £275,000 per year. Based on numbers in: Toxic marine microalgae and shellfish poisoning in the British isles: history, review of epidemiology, and future implications | Environmental Health | Full Text (biomedcentral.com)

Regulating

Waste remediation

Annual value of waste remediation of nitrogen and phosphorus in urban waste water in UK = £683 million in 2019, if apportioned per capita this is £573m for ENG Marine accounts, natural capital, UK - Office for National Statistics (ons.gov.uk)

Atmospheric regulation

Seagrass and intertidal sediments accumulate 147,000 tonnes CO_2 per year in SOS waters Defra, UK - Science Search at £104 per tonne CO_2 abatement value = £1.45 million per year - carbon value from https://doi.org/10.1016/j.ecoser.2018.10.013

Coastal protection

Asset value of saltmarsh for coastal flood protection £395 million (for UK) Marine accounts, natural capital, UK - Office for National Statistics (ons.gov.uk)

Cultural

Coastal visits

In England, pre-Covid there were 169m day visits and 21m overnight visits to the coast each year. This generated £13.7bn in tourism spend National Coastal Tourism Academy - overview

In addition to which the public health benefits of coastal recreation are worth £176miion per year in England in contribution to QALYs http://dx.doi.org/10.1016/j.marpol.2015.10.009

Appendix 2: An Underestimation of Plankton value in English and UK Waters (from Best, 2020)

Summary

The plankton around England represent and considerable value in natural capital stocks and services and intervention can have considerable savings (or losses).

Service		Components	Value estimate
Regulating services	O2 production	Phytoplankton	**£24 - 230 billion pa**
	Carbon Capture	Phytoplankton	**£0.5 - £9.0 billion pa**
	Benthic pelagic coupling	Phytoplankton & Zooplankton	
	Sulphate cycle	Phytoplankton	
Supporting services	Nutrient cycling	Phytoplankton	
	Food chain enhancement	Phytoplankton, zooplankton, ichthyoplankton	
Provision services	Fin fish	Zooplankton, HABS, ichthyoplankton	e.g. Copepods and English Cod stocks ≈ **£482m pa**
	Shellfish	Ocean acidification on shellfish (molluscs and crustaceans	**£3-6 billion pa** (increasing to up to **£100 billion pa** over next 50 years)
		HABs impacts on extended industry	up to **£87.5m**
		Benthic pelagic coupling / HABs	
Cultural services	Seabirds / Marine Mammals	Zooplankton, HABs, ichthyoplankton	
	Tourism	Discoloured water (phytoplankton)	Seaside tourism worth **£8 billion**. Example for Bournemouth and Poole - for each **day** of discoloured water
		HABs food poisoning	NHS costs = **£288m pa**
		Recreational fishing, bird and sea mammal	

An estimate total value of the pelagic habitat is in the range of £28 - £246 **billion** per year. This is summarised in the table below which is not complete and has used conservative estimates (e.g. only one tourism day lost; see details below table); hence the overall annual value could also be considered a conservative estimate.

Oxygen production

Every second breath we take is provided from phytoplankton. The average adult at rest inhales and exhales something like 7 or 8 litres of air per minute. That totals something like 11,000 litres of air in a day.

The air that is inhaled is about 20-percent oxygen, and the air that is exhaled is about 15-percent oxygen, so about 5-percent of the volume of air is consumed in each breath and converted to carbon dioxide. Therefore, a human being uses about **550 litres of pure oxygen** per day *if at rest*.

There are a number of ways to assess the cost of Oxygen. A BOD 600l cylinder costs £18.80 from the 2020 catalogue. So you could say single person would need this 360 days per year 18.80*360= £6768 per year. But plankton only provide 50% of this i.e. **£3384 per person per year**. The United Kingdom 2020 population is estimated at 67,886,011 people at mid-year according to UN data. Therefore, the plankton provides **£ 229,726,261,224 (£230 billion)** worth of Oxygen to the English population per year.

If you want a lower number, you could look at the cost of portable oxygen concentrators – the cheapest running costs (used by patients at home, according to the manufacturer Iconic) is about £2.00 per day, so using the same calculations you get **£24,438,963,960 (£24 billion) per year.** This is almost a tenth but does assume there is enough oxygen to concentrate!

There are several other ways of calculating this number but the one in the table is the lowest reasonable.

Carbon capture

Pelagic stocks represent a significant component in the carbon budget (210–230 Tmol) of the European NW Atlantic shelf, with DIC dominating the pelagic budget (93–97% of total pelagic carbon). DOC occupies a further 2–5% with the remainder comprising a minor contribution from POC, PIC and macrofauna.

The oceans remove about 1/3 to ¼ of atmospheric CO_2 emissions from human activities

Continental shelf seas, including coastal and marginal seas, are thought to play a key role in the global carbon cycle, linking the terrestrial, oceanic, and atmospheric carbon pools (Omar *et al*., 2007). Shelf seas are thought to be net sinks for CO_2, with some inner estuaries acting as net sources for CO_2 (Chen and Borges, 2009). Evidence from measurements and modelling suggests that the North-west European Shelf acts primarily as a sink for atmospheric CO_2 (Thomas *et al*., 2004; Borges 2005; Borges *et al*., 2005; Legge 2020). Thomas *et al*. (2004) calculated the North Sea to be a highly efficient continental shelf pump exporting approximately 93% of atmospheric CO_2 taken up in the coastal waters off the North-west European Shelf into the deep waters of the North Atlantic.

Calcifying organisms (e.g. coccoloithophores) may influence biological carbon cycling in two ways: firstly they release CO_2 from sea water into the atmosphere in proportion to the CO_2 they fix in the creation of calcium carbonate ($CaCO_3$) structures. Secondly, because the $CaCO_3$ shell material produced by marine calcifiers is much denser than the soft body parts of plankton, its presence in aggregates with organic matter may play an important role in accelerating the rate of sinking, hence carbon sequestration (Armstrong *et al*., 2002).

Only a preliminary valuation of the oceans' storage capacity for CO_2 has been undertaken. The 'goods and services' approach being used is common to socioeconomic analysis of the environment. Ocean CO_2 uptake is considered as part of the service 'gas and climate regulation'. Its economic value is estimated using *marginal damage costs avoided*, based on current carbon market values. The approach is popular in the environmental economics literature which gives it a high confidence but there are

arguments regarding the discount rate to use. The application of these methods to carbon cycling in the oceans is still in its infancy, so current estimates should be treated cautiously.

An assessment by Beaumont *et al*. (2008) of the 'goods and services' provided by marine biodiversity in UK waters gave a figure for 'gas and climate regulation' of between about **£0.5 billion and £9 billion per annum**. However, this is considered an *underestimate* because primary production by marine phytoplankton was the only process considered and confidence in the cost estimate should be considered low. Furthermore, the current role of the biological carbon pump in shelf seas for cycling anthropogenic CO2 is not determined, so this estimate only relates to natural cycling of CO2.

Legge O. *et al.* (2020) Carbon on the Northwest European Shelf: Contemporary Budget and Future Influences. Front. Mar. Sci. 7:143. doi: 10.3389/fmars.2020.00143

Hardman-Mountford, N., Litt, E., Mangi, S., Dye, S., Schuster, U., Bakker, D., Watson, A..(2009) Ocean uptake of carbon dioxide (CO2), MCCIP Briefing Notes, 9pp. www.mccip.org.uk

Finfish example for Cod

The seasonal timing of some plankton production has also altered in response to recent climate changes. This has consequences for plankton predator species, including fish, whose life cycles are timed in order to make use of seasonal production of particular prey species.

The decline of the European cod stocks due to overfishing may have been exacerbated by climate warming and climate-induced changes in plankton production (Beaugrand *et al.*, 2003). It is hypothesised that the survival of young cod in the North Sea depends on the abundance, seasonal timing, and size composition of their planktonic prey.

Climate change appears as one of the major drivers of the recent failure in cod recruitment, by acting directly on the biology of early life stages and indirectly on the quality and quantity, and timing of their zooplankton prey. The larval cod development is shaped by food availability for fish larvae and sea temperature.

Currently unfavourable changes involved a reduction in the abundance of the large calanoid copepod *C. finmarchicus*, largely being replaced by its more temperate–water affiliated co-genera, *C. helgolandicus* .While nauplii stages of *C. finmarchicus* are the preferred and often dominant prey of larval North Sea cod, the less nutritious nauplii of the autumn-spawning *C. helgolandicus* have never been found in the diet records of larval cod. In recent years, the distribution of C. finmarchicus has shifted northwards and the diet of larval cod in the North Sea tends to be more dominated by smaller copepod

The value of the Cod fishery is estimated at **£482m pa** (Statistica: Value of cod landings into the United Kingdom (UK) by UK vessels from 2014 to 2019).

Other fisheries and bird populations are also likely to be impacted (e.g. Sand eel quality and success and sea birds)

Note: the current change in phytoplankton from diatoms to dinoflagellates means that certain essential amino acids are not available to copepods, making less nutritious as food to other predators (including fish)].

(E. M. Olsen *et al.*(2018) Spawning stock and recruitment in North Sea cod shaped by food and climate. Proc. R. Soc. B. Feb 2018)

Shellfish – Ocean acidification and HaBs impacts on the extended industry

Shellfish and ocean acidification

According to Mangi *et al.* (2018) on the economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom (Environmental Science and Policy 86 (2018) 95–105). The impacts are likely to be greatest on those species that spend a developmental stage in the plankton.

Considering both crustaceans and molluscs, they used a number of economic techniques and climate change scenarios, applying *the net present value (NPV) and partial equilibrium (PE) models*, they estimated both direct and economy-wide economic losses of shellfish production currently and to 2100.

Estimates using the NPV method show that the direct potential losses due to reduced shellfish production range from 14% to 28% of fishery NPV. This equates to annual economic losses of between **£3 and £6 billion** of the UK's GDP in 2013, for medium and high emission scenarios. Results using the PE model showed the total loss to the UK economy from shellfish production and consumption ranging from £23–£88 billion.

Shellfish closures in the South West value

For the year April 2016-17 according to Food Standards Agency (FSA) reports South West production areas were closed for between 21 & 120 days with a total of 649 lost bed production days due to HABs. Most of these were mussel beds and one oyster bed. The value of the shellfish stock on these beds depends on the time of the year, size of bed and the species of shellfish - Cornish mussels have a retail value of about £6.00 per kilo, here we are assuming a wholesale value of about £2.00/kg. Mussel densities tend to be in the order of about 3.5kg/m2, with a harvestable amount of about 1.4kg/m2 (about 100-150 individuals). A small bed may 10-100's of m2 in size so could produce in the order of 14 -140kg of mussels, a large bed several tonnes. So the *minimum* losses last year due to HABS were approximately **£18,172** (£2.00*14*649) the maximum value would be at least **£181,172** (and probably much more). This could be extrapolated to the rest of the country but has NOT been calculated for the table above.

Cost savings to the extended shellfish industry

One Dutch estimate suggests HAB cause losses of up to 35% to the shellfish industry. If the shellfish industry and its associated business is valued at £250M, then understanding and eliminating the effects of HABS could save up to **£87.5M** pa.

Tourism

Consumer health and safety & the National Health Service costs

It is not easy to estimate the frequency of shellfish poisoning in the UK, it if thought to be very low as the FSA close beds as soon as toxic algae are detected. However, Hinder *et al.*(2011) reviewed the occurrence of toxic algae and epidemiology in Wales. 56 individual patients were identified with "Toxic effects of noxious substances eaten as seafood" from 1998-2009, with an age range of 5-94 years. The length of stay in hospital varied between 1 to 11 days, with the average stay length of 2.5 days (significantly related to age). The majority of incidents occurred during the summer months (June-August). Six patients were noted to have died, with a delay of between 7 months and 9 years after their incident, suggesting that there have been no deaths in Wales directly resulting from shellfish poisoning over the survey period. The population of Wales is approximately 2.9 million, hence assuming these patterns are representative, these results imply an estimated incidence of shellfish poisoning of 100

cases per year in the UK (of 16 per million per year). A night in hospital with an investigation costs about £1150 (NHS 2015: £400 bed; £250 Consultation; £500 investigations), so assuming an average stay of 2.5 days, this would equate to **£287,500 pa** (100 x 2.5 x 1150).

Tourism and discoloured water / beach closures from algal blooms

The cost of a day away from the beach

Seaside tourism is worth £8 billion in England. To use an example where the seashore is important, we consider Bournemouth and Poole council report which stated:

"the Seaside recently regained its position as highest market share for domestic overnight trips …There is no doubt that Bournemouth and Poole has a strong appeal. This is already attracting more than **10m visitors** a year spending around **£741m** including associated visitor spend." [Bournemouth and Poole Tourism strategy 2017-22]

If we assume the beach season here is 360 days a year, then a day would be worth £741m/360days = **£2.06m** per day. If we just consider the bathing season April-Aug inclusive and round that number to 150 days this figure more than doubles to almost **£5m**.