Impacts of Climate Change on plankton and pelagic habitats in UK waters around the UK and Ireland

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KEY FACTS

What is already happening?

- Climate change is driving major shifts in plankton communities and pelagic habitat conditions across UK waters.
- Long-term monitoring shows declines in large phyto- and zooplankton in oceanic waters beyond the continental shelf, while smaller plankton and microbial species are dominating in warmer, stratified shelf waters. Smaller species transfer energy less efficiently, reducing food availability for predators.
- Warming and changes in stratification and currents are impacting phyto- and zooplankton species distribution, with some warm-water species spreading northward and contracting their southward distributions, while others are declining in southern areas.
- The timing of the spring plankton bloom has advanced in many parts of the North Sea, creating risks of mismatch with fish spawning.
- Gelatinous organisms such as jellyfish are increasing in some regions, likely due to warming as well as changes in predator and prey availability; however, in most regions they remain poorly monitored.
- Marine heatwaves and other extreme events may impose increasing stresses on plankton communities although their effects are still in early stages of being explored.

- These climate driven pressures on plankton communities are amplified by eutrophication, changing nutrient ratios, coastal darkening (reduction in water clarity caused by land runoff and climate-driven sediment resuspension), fishing impacts, and offshore energy infrastructure.

What could happen in the future?

- Future warming is expected to result in earlier and longer lasting spring blooms in some regions, farther northward shifts in phyto- and zooplankton, as well as fish species, reduced overall primary productivity by intensifying water-column stratification and depleting surface nutrients, and increased dominance of smaller phytoplankton and protist species (single-celled eukaryotic organisms) adapted to nutrient-poor conditions.
- Climate-driven changes in primary productivity and phyto- and zooplankton community composition are expected to adversely impact marine food-web functioning and efficiency, reducing the maximum sustainable yield for key fish species in some regions. Fish larvae are also likely to need more prey to survive as warmer water increases metabolic demands.
- Carbon export to the seafloor is expected to be weakened with declining primary productivity and phytoplankton community shifts towards smaller and slower sinking plankton, reducing the rate at which UK seas remove anthropogenic carbon from the atmosphere.
- Reduced food web productivity from changes in plankton will have wider impacts to the functioning of the UK marine environment and alter the provision of future ecosystem services, including key fisheries.

SUPPORTING EVIDENCE

Executive Summary

Pelagic habitats, and the plankton they support, form the foundation of marine ecosystems in UK waters, underpinning fisheries, food webs, biodiversity, and climate regulation. Plankton are sensitive to environmental change, making them useful early warning indicators of climate impacts. This review updates the 2020 MCCIP assessment by synthesising over 100 recent studies on plankton and climate change in UK seas (2019–2026), with a more-detailed focus on predicted future change under different emissions scenarios as well as key challenges and emerging issues that impact our ability to understand and predict these impacts.

Introduction

Pelagic habitats occupying the water column of the North-East Atlantic, North Sea, Celtic Seas, Irish Sea, English Channel, and adjacent shelf waters (i.e. waters over the continental shelf, generally <200 m depth), are fundamental to the health and productivity of UK seas. These habitats support

marine biodiversity, fisheries, and climate-regulating processes, making them essential for UK marine ecosystem functioning (Faith *et al.*, 2025).

Plankton, ranging in size from microscopic phytoplankton and zooplankton to metre-long jellyfish, form the foundation of pelagic food webs. Phytoplankton drive primary production and carbon uptake, while zooplankton transfer energy to higher trophic levels, supporting fish, seabirds, and marine mammals.

Plankton communities are highly sensitive to physical and chemical changes in their environment, making them useful early-warning indicators of environmental impacts (McQuatters-Gollop *et al.*, 2019). In UK waters, warming, changes in stratification, ocean acidification, and shifts in nutrients are already affecting plankton communities and dynamics (Holland *et al.*, 2024; OSPAR Commission, 2023). Understanding current and projected changes in plankton and pelagic habitats is essential for achieving UK Marine Strategy objectives and informing climate adaptation policy.

What is already happening?

Observed large scale trends

UK-relevant plankton time-series data can very broadly fall into two categories:

(1) In-situ data sources: first, a series of inshore, weekly- to quarterly-resolution, fixed-point time-series that often include multiple depths from the surface to the seafloor with coverage of the full plankton community; and second more offshore (~20 km) coverage over much greater time-space scales with the Continuous Plankton Recorder (CPR) Survey, which samples a portion of the plankton community in the upper mixed layer (Figure 1), and

(2) Remote sensing data sources: optical techniques are used to extract time-series information on phytoplankton total biomass, and composition of functional types using optical data from Earth-orbiting satellites.

Together, these datasets show clear long-term shifts in plankton abundance and composition across UK seas.

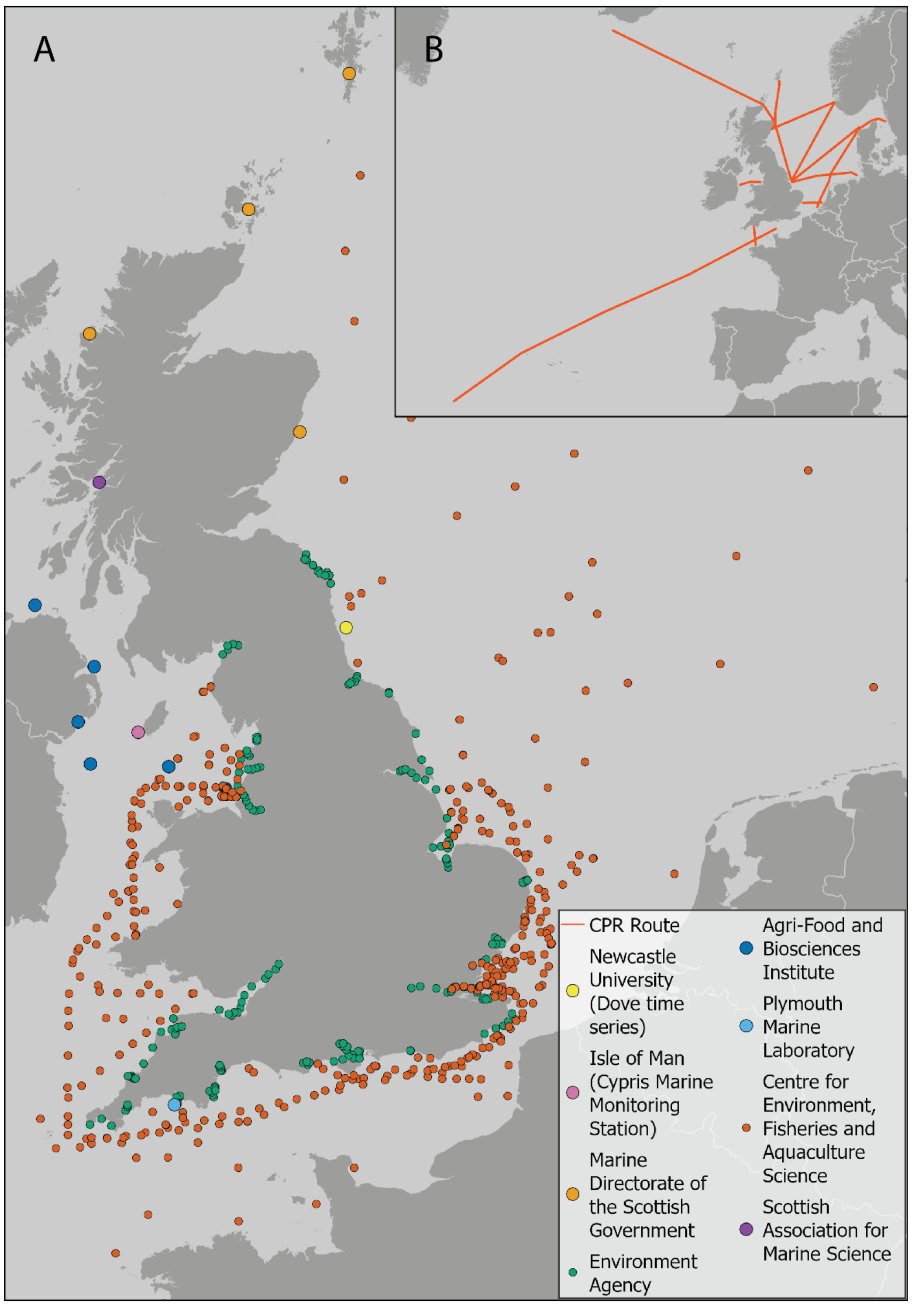


Figure 1. *In-situ plankton sampling stations and routes from the UK monitoring network, including fixed-point stations (A) and the Continuous Plankton Recorder (CPR) Survey (B). Points are coloured according to the institution responsible for sampling. Please note that panel A contains both routine time-series monitoring stations and stations visited much less regularly. Figure adapted from Holland et al. (2025) and provided by Robert Brookes (Cefas).*

Across UK shelf seas and the adjacent North-East Atlantic, long-term monitoring studies have shown consistent changes in the abundances of important plankton lifeforms, or groups of plankton with shared functional traits (e.g. diatoms, large copepods; Figure 2), including, for some UK shelf seas, declines in large taxa and increases in meroplankton (Bedford *et al.*, 2020; Holland *et al.*, 2023). These observed large-scale trends have been attributed to changes in distribution and abundance (Section 2.2), as well as changes in phenology (Section 2.3).

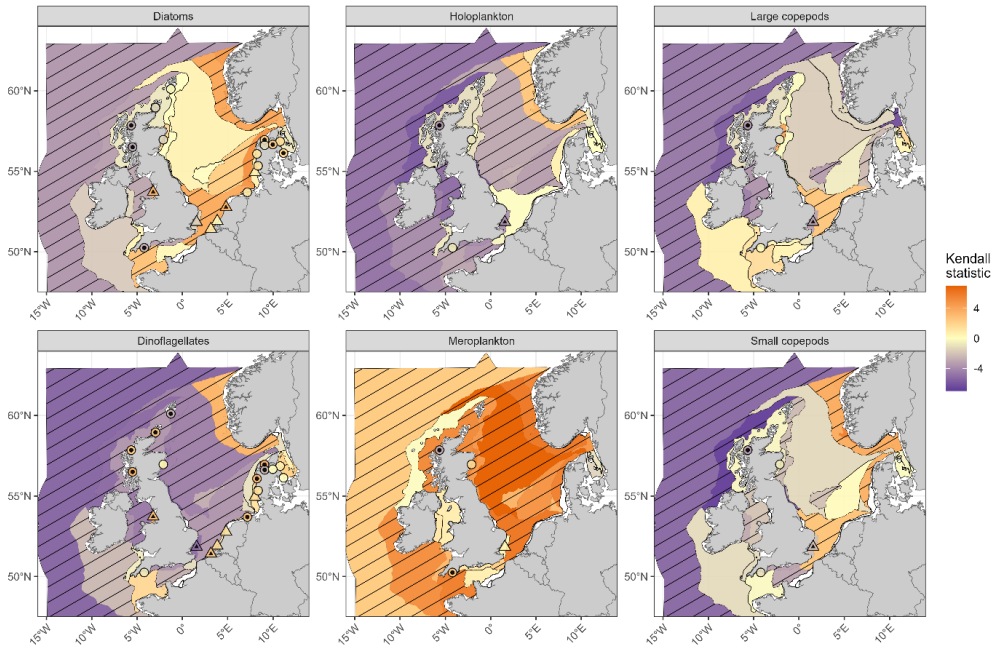


Figure 2. *Kendall trend test results for six plankton lifeforms, with polygons based on offshore (> ~20 km from land) data from Continuous Plankton Recorder (CPR) Survey and points based on data from fixed-point monitoring stations. Polygons and points are coloured by the results of the Kendall trend test, indicating the consistency of long-term increase (orange, > 0) or decrease (purple, < 0) in abundance over the duration of the time-series study (1960-2019). Polygons with hatching or points with an internal symbol indicate statistically significant change ($p \leq 0.05$). Figure adapted from Holland et al. (2023).*

Changes in basin-scale ocean current circulation, including changes in the subpolar gyre and a weakened, warmer European Slope Current, are changing the characteristics of water masses flowing into the North Sea, with implications for plankton communities and ecosystem structure (Clark *et al.*, 2022; Kléparski *et al.*, 2024). These large-scale changes contribute to reduced food web efficiency and carbon export (Atkinson *et al*., 2024) associated with a shift towards smaller plankton body sizes (Desmit *et al.*, 2020), as well as weakening of the spring bloom (Alvera-Azcárate *et al.*, 2021). The 2025 MCCIP report on ocean circulation highlighted that variability in North Atlantic circulation, including shifts in the subpolar gyre and changes in the origin, temperature, and nutrient content associated with Atlantic inflows, directly alters both physical and biogeochemical properties of UK shelf seas, with implications for productivity, plankton community structure, and ecosystem functioning (McCarthy *et al*., 2025).

Observed changes in distribution

Long-term observations indicate northward shifts of warm-water plankton taxa and range contractions of cold-water taxa, alongside contrasting responses among plankton groups. For example, diatom taxa (e.g. *Pseudo-nitzschia seriata* complex and *Rhizosolenia* spp.) show increasing abundance in northern regions but decline in more southerly regions (Edwards *et al*., 2022; Holland *et al.*, 2026), whereas euphausiids (e.g., *Thysanoessa* spp.) have experienced declines across the North Atlantic without poleward

redistribution (Edwards *et al.*, 2021). Zooplankton groups, including Calanoid copepods, are becoming more abundant in northern parts of the North Sea, with declines in prey availability observed in other regions, potentially reducing food availability for sandeels (Olin *et al*., 2022).

There has been a clear divergence in trends between shelf and oceanic (beyond shelf) waters as well as between coastal fixed-point sites and CPR data (Bedford *et al*., 2020; Holland *et al*., 2023). In the North Sea, trends in the abundance of several plankton lifeforms, particularly meroplankton, and in some cases diatoms and small copepods, have increased or remained stable, in contrast to the predominantly declining trends observed across most lifeforms in the North-East Atlantic (Figure 2). Around south-west England, euphausiid zooplankton, key prey for fish and marine mammals, have declined (Edwards *et al*., 2021) under increasingly thermally stratified conditions (Schmidt *et al*., 2020).There has also been evidence of shifts in plankton communities around the south-west of England, including declines in chlorophyll (an indicator of phytoplankton biomass) and some crustacean groups, alongside increases in meroplankton (the pelagic larvae of benthic invertebrates) and gelatinous or semi-gelatinous taxa, including a recent large increase in salps (McEvoy *et al*., 2023; Sanders *et al*., 2025). Trait-based analyses also indicate replacement of large diatoms with smaller cells and dinoflagellates (Di Pane *et al*., 2022; Kléparski *et al*., 2023). Shifts toward smaller plankton cells are associated with less efficient energy transfer between trophic levels and subsequent declines in copepod numbers in UK shelf seas (McQuatters-Gollop *et al*., 2024; Schmidt *et al*., 2020).

Observed changes in phenology

Climate change is altering the timing and magnitude of regular seasonal plankton cycles. A basin-scale remote sensing study of chlorophyll in the North Sea has shown that the spring bloom now occurs up to one month earlier than in the late 1990s (Alvera-Azcárate *et al.*, 2021), although regional variability can exist alongside more-regional evidence of shifts in phenology in the south (Liu *et al.*, 2025). These changes affect both the nutritional quality and timing of food available to support higher trophic levels. Increased stratification and associated nutrient limitation favour smaller phytoplankton and microbial food web pathways, which are typically associated with reduced efficiency of energy transfer to zooplankton, particularly during summer, when the energetic demands of zooplankton are greatest (Atkinson *et al.*, 2024; Bedford *et al.*, 2020).

In the eastern English Channel, nearshore areas have warmed faster than offshore, with larger changes in the timing of seasonal biomass peaks inshore (Hubert *et al.*, 2025; Huguet *et al.*, 2024). Long-term CPR records indicate that seasonal peak abundance for some dinoflagellates is now occurring several weeks earlier, while bloom timing for diatoms has remained more stable, altering the traditional patterns of seasonal succession and resulting in a more prolonged and continuous period of high phytoplankton abundance (Chivers *et al.*, 2020; Kléparski *et al.*, 2023). Complex and region-specific changes in zooplankton phenology have been detected in some areas. In the

western English Channel, copepod egg production now peaks later in summer and into autumn, coinciding with reduced availability of phytoplankton prey in spring and increased predation, while Scottish stations have shifted to earlier seasonal peaks in zooplankton (Corona *et al.*, 2024; Uriarte *et al.*, 2021).

These phenological shifts are complex and taxon-specific, driven by predation and reproduction which can provide resilience to the bottom-up effects of climate change for some taxa (Cornwell *et al.*, 2020). Meroplankton in the North Sea now remain abundant for a longer seasonal window, linked to warming-driven strengthening of benthic-pelagic coupling (Bedford *et al.*, 2020). Phenological shifts can disrupt fish stocks due to mismatches between key planktonic stages and the early life stages of fishery species that prey on them (i.e., match-mismatch hypothesis; Cushing, 1990), affecting recruitment of fish such as herring and sandeel (Akimova *et al.*, 2023; Marchal *et al.*, 2025; Régnier *et al.*, 2019), and with potential effects for higher trophic levels (Régnier *et al.*, 2024). While the strength of evidence for plankton timing mismatches in the marine environment is debated (Samplonius *et al.*, 2021), Régnier *et al.* (2019) provide clear evidence linking disparate temperature mechanisms to timing mismatch for fish and zooplankton prey. These changes in phenology are shifting the seasonal structure of pelagic food webs, with implications for fisheries productivity and carbon cycling under future warming scenarios.

Observed changes in gelatinous zooplankton

Monitoring for gelatinous zooplankton remains sparse, however, recent studies indicate their increased influence in UK waters under climate-driven changes. In the western English Channel, abundances of gelatinous and semi-gelatinous predators have increased in recent decades, co-occurring with shifts to smaller phytoplankton, and declines in copepods linked to summer nutrient stress (McEvoy *et al.*, 2023). These conditions reduce energy transfer efficiency to crustacean zooplankton, creating opportunities for gelatinous taxa to proliferate. Marine heatwaves, which have intensified in the English Channel and North Sea (Berthou *et al.*, 2024), can further contribute to these trends by stressing copepod populations and altering their prey fields, indirectly benefiting gelatinous zooplankton (Mortelmans *et al.*, 2021; Simon *et al.*, 2023). These changes also have implications for benthic-pelagic coupling and carbon cycling, since gelatinous zooplankton contribute differently to carbon sequestration versus crustacean zooplankton (Marques *et al.*, 2024; McMonagle *et al.*, 2024).

The increased prevalence of gelatinous zooplankton is likely facilitated by several interacting processes, including warming-induced stratification, shifts in nutrient concentrations and balances, and top-down controls by fish and other predators. Increased presence of gelatinous zooplankton can impact fisheries by preying on eggs and by competing with fish larvae for prey (Marques *et al.*, 2023). They can also disrupt aquaculture through causing

damage to fish gills and through generating hypoxia events associated with bloom decay (Båmstedt, 2022). Uncertainties remain regarding the magnitude and persistence of these changes, as well as their cumulative effects on ecosystem services.

Observed changes in microbial plankton

McQuatters-Gollop *et al*. (2024) concluded that small microbial plankton (pico- and nanoplankton, comprising bacteria, protists, and phytoplankton), below 0.02 mm in size can dominate UK shelf communities, especially in summer, although this study was based on relatively limited observations. Plankton <20 µm constitute >70% of biomass and >99% of abundance in the western English Channel, where variation in their abundance is linked to changes in water temperature, nutrient concentration, and stratification (McQuatters-Gollop *et al*., 2024). Flow-cytometry data from the eastern English Channel indicates decadal increases in the bacterioplankton genus Synechococcus, co-occurring with declines in larger phytoplankton in nearshore areas (Hubert *et al*., 2025; Schmidt *et al*., 2020). These observations from the English Channel provide evidence that warming and nutrient changes promote shifts towards smaller cells and microbial trophic pathways (Figure 3).

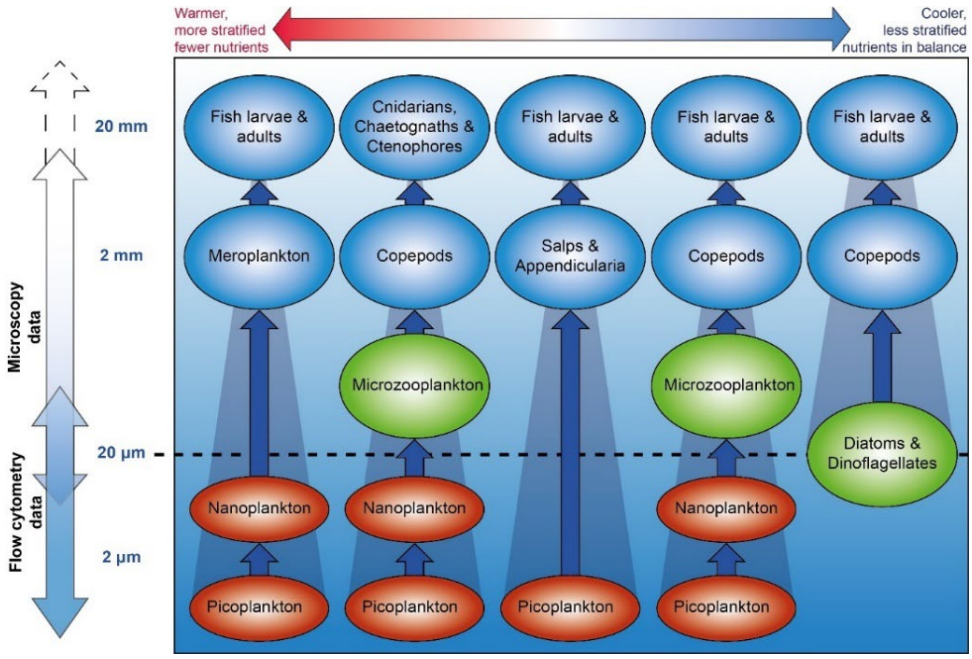


Figure 3. *Simplified schematic illustrating some examples of food chains from primary producers to fish that may emerge from warming, increase in stratification, and nutrient stress/imbalance. This schematic purposefully simplifies the complexity of real food webs which may involve, for example, varying predator and prey sizes, mixotrophy and multiple alternative pathways. The classic 'textbook' food chain from diatoms to copepods to fish is illustrated on the right, and multiple recent studies suggest that we are moving away from this to alternative pathways towards the left of the figure. The grey funnels signify that in these alternative food chains, the larger number of trophic steps and/or the base of the food web being smaller sized, sometimes lower quality food would yield lower efficiencies of energy transfer to higher trophic levels. Figure adapted from McQuatters-Gollop et al. (2024).*

Climate-driven warming is expected to further increase upper ocean stratification and cause shoaling (i.e. shallowing) of the mixed layer,

particularly in summer, reducing nutrient supply to surface waters, although regional and seasonal variability in wind and mixing processes may locally deepen the mixed layer or moderate this shoaling (McCarthy *et al*., 2025). Shoaling of the mixed-layer, combined with increasing temperatures, is altering phytoplankton communities, favouring smaller cells, mixoplankton (protists exhibiting both autotrophy and heterotrophy; Mitra and Flynn, 2023), and microbial pathways that retain and recycle limited nutrients in the stratified surface layer (Aardema *et al*., 2024). Warming experiments have shown increasing dominance of small plankton (Ahme *et al*., 2024; Cabrerizo *et al*., 2024) alongside declines in larger phytoplankton biodiversity *(King et al*., 2023). Finally, a recent analysis concluded that indirect effects of warming, through enhanced stratification and reduced nutrient supply, were more important than direct thermal effects in driving the increasing dominance of small plankton (Atkinson *et al*., 2024). These climate-driven changes at the base of the food web strengthen the microbial loop and favour smaller cells, reducing energy transfer to zooplankton and fish larvae, and altering carbon export.

Observed UK ecoregion patterns

The CP2 Reporting Regions (https://jncc.gov.uk/resources/86a761a7-8564-4c22-9ddb-ee1d0aa50003), originally developed for the 2010 Charting Progress 2 assessment to evaluate human and environmental pressures on UK seas (UKMMAS, 2010), were used here to present regional summaries based on recent research examining climate change impacts on plankton in UK waters (Figure 4). These regions have informed marine assessments, MPA designations, and ecological indicators, as well as the previous version of this report (Edwards *et al.*, 2020), and were updated by JNCC in 2025 to align with UK EEZ, UKCS, and Isle of Man boundaries. These regions differ from the COMP4 assessment units currently used for OSPAR and UKMS assessment (Enserink *et al.*, 2019; OSPAR Commission, 2023), but were maintained for consistency with the previous report. While these regions align with UK management boundaries, many plankton processes operate at broader, transboundary scales. Where UK-specific evidence is limited, studies from adjacent regions have been included to characterise ecoregional responses, reflecting the connectivity of UK waters with neighbouring systems through physical and biogeochemical processes (e.g. currents, nutrient inputs, and advection).

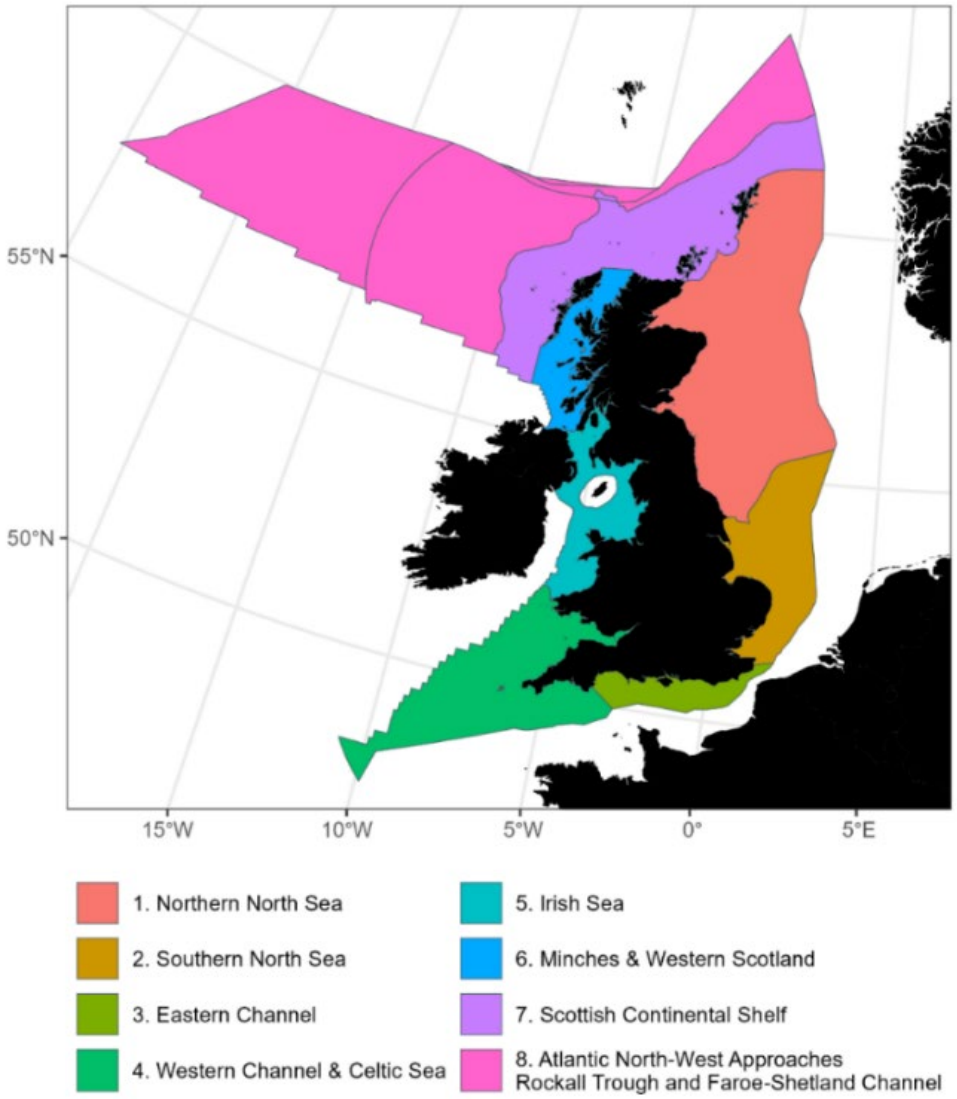


Figure 4. *The CP2 Reporting Regions, updated by JNCC in 2025, used to categorise studies to facilitate and to align with UK EEZ, UKCS, and Isle of Man boundaries.*

1. Northern North Sea

Recent studies show that warming-driven changes in stratification and shelf-edge inflows are restructuring pelagic habitats in the Northern North Sea. Variability in the strength of the European Slope Current can alter the exchange of Atlantic-origin waters at the shelf edge (Clark *et al.*, 2022) However, observations indicate that since ~2014 offshore waters have experienced a period of reduced salinity (Holliday *et al.*, 2018), highlighting substantial interannual variability in inflow. Data since 1997 from the Scottish Coastal Observatory monitoring site at Stonehaven, off the north-east coast of Scotland, indicate altered copepod phenology and significant decreases in abundance for a few species during certain times of the year (mainly *Pseudocalanus elongatus* during the coldest months and in September) (Corona *et al.*, 2024). These bottom-up changes have impacted higher trophic levels, with variation in sandeel availability and phenology

strongly influencing seabird breeding success through trophic mismatch and prey limitation (Régnier *et al.*, 2024). Plankton lifeform analyses indicate that warming, stratification changes, and nutrient imbalance are restructuring offshore plankton communities with increases in diatoms and declines in dinoflagellates (Holland *et al.*, 2024). Further warming is expected to contribute to declines in euphausiids, with implications for fish prey consumption and recruitment (Edwards *et al.*, 2021).

Evidence of shell dissolution in pteropods and larval gastropods at Stonehaven indicates emerging impacts of ocean acidification (León *et al.*, 2020). Region-specific modelling of ecosystem indicators show that that pelagic ecosystems around Shetland and Orkney have stronger bottom-up regulation compared to other North Sea regions, highlighting the need for understanding region-specific climate change impacts (Trifonova and Scott, 2024). Food web changes observed for sandeel, a forage fish predator, in various North Sea sites include decreases in their daily food total available energy (as represented by their zooplankton prey), as well as phenological shifts moving peak prey availability outside the main sandeel feeding period, with consequences for higher trophic levels (Olin *et al.*, 2022).

2. Southern North Sea

Earlier phytoplankton blooms in the Southern Bight have been linked to short-term variability in nutrient inputs and salinity, with higher phosphate and reduced salinity preceding bloom onset; these patterns were interpreted as bottom-up controls linked to climate variability but were based on a limited coastal time-series data and should be treated with caution (Liu *et al.*, 2025). Satellite observations also show progressively earlier spring blooms in this region (Alvera-Azcárate *et al.*, 2021). Here, the spring peak in chlorophyll rose during 1998-2008, declined slightly through 2017, and stabilised by 2020 (Alvera-Azcárate *et al.*, 2021). Despite a 50% reduction in riverine nutrients and declining chlorophyll in the Dutch North Sea since 2002, reversing earlier eutrophication trends, one study has shown that bloom frequency for *Phaeocystis globosa* and toxin-producing taxa (*Pseudo-nitzschia, Prorocentrum, Dinophysis* spp.) increased between 2000 and 2018, potentially reflecting shifts in nutrient stoichiometry and seasonal dynamics (Brandenburg *et al.*, 2025), however, there have been no reports of this occurring within UK waters of the Southern North Sea.

These observations are consistent with additional studies of climate-driven plankton community restructuring, including shifts in functional composition and increasing dominance of meroplankton and smaller taxa across the North Sea (Djeghri *et al.*, 2023). Long-term weekly phytoplankton monitoring from the Cefas SmartBuoy network demonstrates high variability in biomass and community composition at Southern North Sea stations, linked to changes in nutrient inputs and hydrographic conditions (Mace and the Phytoplankton Taxonomy Team, 2024).

Regarding zooplankton, hydrozoans have declined while decapod crustacean larvae increased, influenced by changes in predation and temperature-driven shifts in water clarity (Marques *et al.*, 2024). Bioenergetic modelling and field data indicate winter food limitation for herring larvae, compounded by increasing metabolic demand under warming (Akimova *et al.*, 2023). Multiple long-term time-series, including VLIZ LifeWatch (Mortelmans *et al.*, 2019) and Ghent University surveys (Van Ginderdeuren, 2013), show warming and more frequent marine heatwaves coinciding with abrupt collapses in dominant copepods (e.g. *Temora*, *Acartia*, *Centropages*, *Calanus helgolandicus*), likely from exposure to thermal tolerance limits (Mortelmans *et al.*, 2021; Semmouri *et al.*, 2023).

3. Eastern Channel

Across the Eastern Channel, multiple French time-series studies, including REPHY (REPHY, 2017) and SRN (Lefebvre and Devreker, 2022), have shown declines in chlorophyll since the late 1990s (Huguet *et al.*, 2024). Declines were strongest nearshore, likely from reduced nutrient inputs, while offshore decreases were more influenced by warming and stratification (Huguet *et al.*, 2024). A 24-year Normandy shellfish hygiene dataset (HYDRONOR Observatory) also recorded increasing winter temperatures, gradual acidification, and altered nutrient regimes alongside decreasing chlorophyll and reduced diatom productivity since the early 2010s (Sosinski *et al.*, 2025). Warming and altered nutrient ratios have increased picoplankton, including photosynthetic bacterioplankton, and reduced microphytoplankton, especially nearshore, with implications for fisheries and carbon export (Hubert *et al.*, 2025). The Downs herring stock, which spawn in autumn in the Eastern Channel and Southern North Sea, have shifted to later spawning since ~2010, driven more by declines in zooplankton prey availability, particularly *Calanus finmarchicus*, rather than direct warming effects (Marchal *et al.*, 2025).

4. Western Channel & Celtic Sea

The Western Channel & Celtic Sea is among the best studied UK regions, with long-term high-frequency monitoring from the Western Channel Observatory, including Station L4 near Plymouth (McEvoy *et al.*, 2023). Warming and strengthening summer stratification have coincided with declining summer chlorophyll and crustacean zooplankton, alongside increases in meroplankton and gelatinous zooplankton (McEvoy *et al.*, 2023; McQuatters-Gollop *et al.*, 2024). Recent studies also show changes in microbial plankton, with pico- and nanoplankton now dominating summer biomass and abundance (McQuatters-Gollop *et al.*, 2024). Since 2019, salps have become established along southern Cornwall and Devon, forming dense summer blooms (Sanders *et al.*, 2025), albeit with a return to much lower numbers in 2025. Their efficient feeding on pico- and nanoplankton bypasses traditional food webs that supply nutritious zooplankton for fish larvae (Atkinson *et al.*, 2021; Schmidt *et al.*, 2020). Bioenergetic modelling for sardine and anchovy links recent declines in growth and condition to reduced

zooplankton abundance and size (Menu *et al.*, 2023), consistent with a shift toward smaller prey and a less efficient food web (McQuatters-Gollop *et al.*, 2024).

5. Irish Sea

In the Irish Sea, warming and intensifying seasonal stratification have reorganised plankton communities. Molecular studies based on relative abundance of genetic sequence material indicate that bacterioplankton in warm, nutrient-poor stratified surface waters have become less diverse, with *Synechococcus* spp. making up a larger share of the community, particularly in late summer (Costello *et al.*, 2023; King *et al.*, 2023). An experimental study in north Wales found that warmer temperatures heighten food-limitation sensitivity in native *Semibalanus balanoides* barnacle larvae, favouring less temperature-sensitive species including the non-native barnacle *Austrominius modestus* (Griffith *et al.*, 2021). In the western Irish Sea, warming has advanced egg hatching for *Nephrops norvegicus* (langoustine) by ~17-19 days between the 1980s-1990s and the 2000s-2010s, with little change in pelagic larval duration, potentially affecting recruitment to this important fishery (McGeady *et al.*, 2021).

6. Minches & Western Scotland

This is a data-poor region, with in-situ plankton monitoring limited to the Scottish Coastal Observatory station at Loch Ewe and the Lorn Pelagic Observatory operated by the Scottish Association for Marine Science. Since the late 1990s, the European Slope Current supplying the Hebridean shelf and continental margin has weakened and warmed as cooler subpolar inflow was partly replaced by warmer, saltier subtropical waters, with potential consequences for nutrient supply and plankton productivity in northern UK seas (Clark *et al.*, 2022). Long-term monitoring at Loch Ewe shows that changes in salinity driven by freshwater input and variability in offshore water masses affect zooplankton community structure, often to a greater degree than temperature effects (Wells *et al.*, 2022). Loch Ewe has also experienced increases in dinoflagellates, with blooms of *Ceratium* (now *Tripos)* spp. recorded in recent years (Bedford *et al*., 2020).

7. Scottish Continental Shelf

Direct observational studies of plankton change on the Scottish Continental Shelf remain limited. However, warming, changes in stratification, and variability in Atlantic inflow are altering physical conditions that influence plankton habitats and productivity (Clark *et al.*, 2022). Since the late 1990s, reduced inflow and warmer water along the continental slope have reduced nutrient supply and shifted Hebridean and shelf-edge waters toward more subtropical conditions, with implications for plankton community structure (Clark *et al.*, 2022). In addition, episodic freshening events linked to changes in subpolar circulation (e.g. 2012–2016) have altered stratification and nutrient dynamics in upstream source waters (Holliday *et al.*, 2020). These hydrographic changes interact with warming to influence plankton phenology

and size structure, with implications for trophic pathways and carbon cycling. Indicators reveal increasing meroplankton and decreasing holoplankton and small copepods, suggesting stronger benthic-pelagic coupling under warming and stratification (Bedford *et al.*, 2020). Early evidence from Orkney, Shetland, and east Scotland also suggests that up to 5% of adult harbour seal diets of sandeel, pelagic fish, flatfish, and cod, may have exceeded neurotoxic doses of domoic acid from *Pseudo-nitzschia* spp. between 2010–2023 (Hall *et al.*, 2024).

8. Atlantic North-West Approaches, Rockall Trough and Faroe-Shetland Channel

Pelagic habitats in the Atlantic North-West Approaches are influenced by shelf-edge circulation and advection through the Rockall Trough. In particular, variability in Atlantic inflow and the weakening of the European Slope Current since the late 1990s have altered water-mass properties and nutrient supply, with implications for plankton communities in this region (Clark *et al.*, 2022; Fraser *et al.*, 2022). Long-term bivalve records show repeat instability in the subpolar North Atlantic, increasing since the late 20th century as temperature-salinity patterns shifted with a weakening subpolar gyre (Arellano-Nava *et al.*, 2025). Between 2012 and 2016, anomalous freshening in the Iceland Basin and Rockall Trough has influenced stratification and nutrient supply, with likely consequences for the timing and development of plankton blooms in downstream shelf and slope waters (Holliday *et al.*, 2020). Phytoplankton data are limited here, but satellite chlorophyll has increased with rising temperatures in oceanic waters (Casal *et al.*, 2022). CPR data link multi-decadal changes in dinoflagellates to warming-driven northward advection during subpolar gyre contraction (1996–2012), followed by biodiversity collapse during gyre re-expansion, when a low-salinity anomaly blocked this advection (2013–2020) (Kléparski *et al.*, 2024). These basin-scale changes primarily reflect open-ocean dynamics but may also influence shelf-edge and adjacent shelf regions. Strong plankton-fish connectivity was observed along the Porcupine Bank and Rockall margins; blue whiting (*Micromesistius poutassou*) recruitment, including a larger than usual recruitment in 2020, has been driven by elevated chlorophyll under stable, stratified, conditions with low mixing (Laiz *et al.*, 2025).

What climate change impacts could happen?

Predicted changes in distribution

Future climate change is predicted to further alter the regional distribution of plankton across UK seas, driven by changes in relative abundance rather than physical advection, largely extending observed trends (see Section 2.2). In the North Sea, warming under high-emission scenarios (SSP5-8.5) is projected to increase subsurface (100 m) water temperatures by ~0.5–1.2°C by 2100, with the strongest warming occurring after mid-century (Sando *et*

al., 2024). This warming is associated with shifts in the copepod community, including reductions in the cold-water species *Calanus finmarchicus*, particularly through further contraction of its southern distribution, alongside increases in the more temperate *C. helgolandicus*. These changes reflect broader community re-organisation rather than simple replacement between two species, as they form part of a wider assemblage with differing ecological roles (Bonnet *et al.*, 2005; Sando *et al.*, 2024).

One modelling study concluded that *Calanus finmarchicus* and cod are projected to decline further under strong warming, while hake and mackerel expand northwards to track thermal niches and due to reduced zooplankton prey in southern parts of the North Sea (Sandø *et al.*, 2024). Climate change scenario studies consistently project poleward shifts in suitable spawning habitat for small pelagic fish such as sardine under RCP8.5, a similarly high emissions scenario to SSP5-8.5, with gains around the UK and losses in southern areas, driven by changes in plankton productivity and temperature-dependent spawning windows (Lima *et al.*, 2022). These shifts may provide some regional benefits to UK fisheries, although the extent to which they offset declines in other stocks remains uncertain. These distributional shifts reflect climate-driven changes in circulation, stratification, nutrient supply, interacting with species-specific thermal limits. Under future warming, taxa at the warm edge of their thermal range are likely to decline, while those adapted to warmer conditions are likely to increase in relative abundance. In many cases, redistribution is driven not by active northward shifts, but rather by regional changes in relative abundance of different taxa.

Predicted changes in phenology

Future climate change is projected to significantly impact plankton phenology in UK waters, although responses vary by region. Earlier and more-prolonged blooms are more likely in southern areas such as the Southern North Sea (Alvera-Azcárate *et al.*, 2021), whereas in more-northern regions, including Scottish waters, timing and magnitude of the spring bloom remain strongly limited by seasonal light availability (Chivers *et al.*, 2020) (see Section 3.2). Models and long-term analyses project earlier phytoplankton blooms and longer growing seasons in the Southern North Sea and English Channel, driven by warming and earlier onset stratification (Mészáros *et al.*, 2021; Thewes *et al.*, 2022). However, ecosystem model experiments show that reductions in underwater light (e.g. increased suspended particulate matter and coloured dissolved organic matter) could delay or suppress blooms, highlighting how interacting physical drivers complicate phenology predictions (Thewes *et al.*, 2022). In the North-East Atlantic and North Sea, species-based modelling under CMIP6 scenarios (SSP2-4.5 and SSP5-8.5) predicts changes in the seasonal duration and abundance of large flattened (oblate) diatoms, whereas elongated (prolate) diatoms and dinoflagellates are expected to expand their seasonal windows and shift the timing of peak abundance (Kléparski *et al.*, 2023). Observational and modelling evidence indicates that these shifts in primary producer phenology will cascade to

zooplankton, altering seasonal peaks for copepods and key prey taxa, increasing risk of timing mismatch for fish such as herring and sandeel (Olin *et al.*, 2022). These results suggest predicted phenological changes will likely impact food web dynamics and carbon cycling in UK seas.

Predicted changes in food web dynamics

Future climate change is projected to restructure trophic pathways in UK seas, further reducing energy transfer efficiency and amplifying biomass decline from the base of the food web (Figure 5) (Atkinson *et al.*, 2024; Faith *et al.*, In review). Projected food-web changes largely extend current trends toward smaller plankton, reduced crustacean zooplankton, and increased dominance of microbial pathways (see Section 2.5). Increasing dominance of small plankton is expected to further disrupt nutrient cycling and traditional food webs (Atkinson *et al.*, 2021; McQuatters-Gollop *et al.*, 2024; Schmidt *et al.*, 2020). Species-based modelling suggests shifts from large, fast-sinking diatoms to elongated diatoms and dinoflagellates may reduce carbon export and weaken pelagic food webs in offshore areas by reducing prey quality for herbivorous zooplankton (Kléparski *et al.*, 2023). Mesocosm experiments show warming produces less productive food webs with reduced energy transfer to higher trophic levels (Cabrerizo *et al.*, 2024). Model simulations reinforce these predictions. Simulations from the end-to-end model StrathE2E2 predict that warming could reduce omnivorous zooplankton, triggering trophic cascades that disadvantage pelagic fish and instead favour demersal species (Thorpe *et al.*, 2022). Ecopath ecosystem modelling for the Southern North Sea indicates that a 30% reduction in primary production would require substantial reductions in fishing effort (up to ~50%) to maintain maximum sustainable yield for several demersal fish and crustaceans (Stäbler *et al.*, 2019). Bottom-up changes are likely to affect fish; physiological models predict herring larvae may require up to 35% more prey under warming, increasing recruitment risk if prey fields decline or shift (Akimova *et al.*, 2023). Collectively, these results suggest future food webs being increasingly reliant on benthic pathways and microbial recycling loops, with reduced carbon export and energy transfer to pelagic fish.

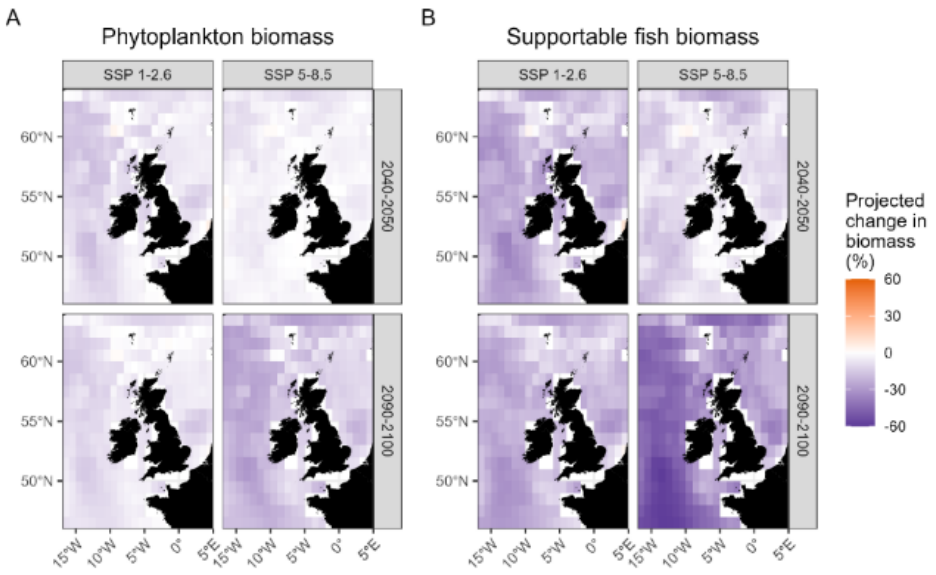


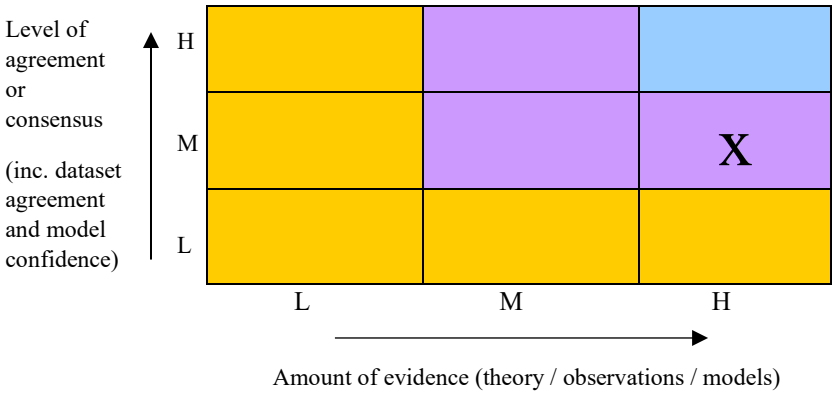
Figure 5. *Projections of future phytoplankton biomass and supportable fish biomass relative to 1990–1999, adapted from Faith et al. (In review). (A) Projections of phytoplankton biomass taken from the Earth System Models GFDL-ESM4 and IPSL-CM6A-LR (see Faith et al. (In review) and Tittensor et al. (2021) for methods); and (B) Projections of supportable fish biomass derived from normalised biomass size spectra approaches (see Faith et al. (In review) and Atkinson et al. (2024) for methods), demonstrating the trophic amplification of projected phytoplankton biomass declines to more substantial declines in the supportable biomass of pelagic fish.*

Predicted consequences for society

Projected climate-driven changes to plankton in UK seas could cause major societal impacts by disrupting key ecosystem services, such as fisheries productivity, carbon sequestration (Brun *et al.*, 2019), and the stability of marine food webs (Faith *et al.*, 2025; Grigoratou *et al.*, 2025). Fisheries are of particular concern: reduced carrying capacity (Atkinson *et al.*, 2024; Faith *et al.*, In review; Tittensor *et al.*, 2021) and direct climate change effects on fish larvae (Régnier *et al.*, 2019) are projected to reduce maximum sustainable yields under continued warming, based on size-spectrum and ecosystem modelling studies, although the magnitude of these changes remains uncertain (see Section 4.2). In addition, trophic amplification of biomass losses (Figure 5B), supported by broader ecosystem model projections (du Pontavice *et al.*, 2021; Tittensor *et al.*, 2021), suggests potential declines in fish biomass. Some changes have global relevance; the North-East Atlantic's biological carbon pump is important to global climate regulation (Brown *et al.*, 2021). Projected reductions in primary productivity (Tittensor *et al.*, 2021) (Figure 5A) and shifts toward smaller plankton (Atkinson *et al.*, 2024) suggest a reduced capacity for carbon sequestration, weakening the region's ability to offset future carbon emissions. These projections are primarily derived from modelling studies and should be interpreted in the context of the uncertainty discussed in Section 4.2.

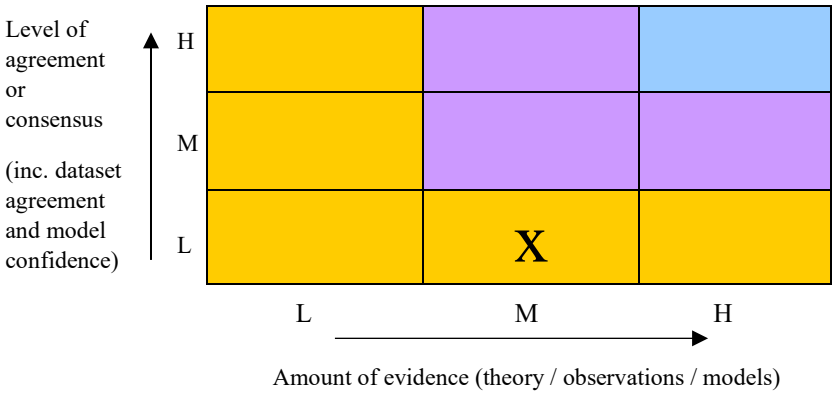
CONFIDENCE ASSESSMENT

What is already happening?



Long-term monitoring programmes, including the Continuous Plankton Recorder Survey, Western Channel Observatory, Scottish Coastal Observatory, Lorn Pelagic Observatory, inshore Environment Agency monitoring, and Earth observation data, provide extensive temporal and spatial coverage. Although these datasets vary in duration, resolution, and spatial extent, together they present a clear pattern of change, including consistent shifts in phenology, size structure, and trophic pathways, as well as changes in zooplankton communities and an increasing influence of gelatinous taxa. Observational evidence is further supported by mesocosm experiments, trait-based analyses, and multi-trophic studies, which reinforce the mechanisms driving these changes. However, agreement among studies was more moderate, as contrasting patterns between offshore declining trends off the shelf and more variable or increasing trends in coastal and North Sea regions, alongside differences among plankton groups and lifeforms, reduce consensus in the direction and magnitude of change. In addition, while key drivers such as warming, stratification, nutrient stoichiometry, circulation, and light availability are widely understood, their relative importance varies across regions and seasons, limiting agreement on the dominant processes responsible for observed changes.

What could happen in the future?



The evidence base supporting projections of plankton change is moderate, but overall confidence is limited by low agreement among studies. A wide range of modelling and experimental studies have explored future scenarios, including trait- and species-based phenology models, end-to-end ecosystem frameworks, coupled physical-biogeochemical models, and mesocosm experiments examining warming, heatwaves, and nutrient dynamics. These approaches generally agree on broad patterns, such as earlier bloom timing, extended growing seasons, and poleward shifts in species distributions. However, there is considerable variation in the magnitude, timing, and regional expression of these changes, reflecting differences in model structure and how key processes are represented. In particular, major disagreement among models remains for bulk ecosystem properties, such as consumer biomass (Heneghan *et al.*, 2019), and some projections diverge substantially from observed trends (Burrows *et al.*, 2014), highlighting ongoing challenges in model reliability. Agreement is also restricted by the complexity of multiple interacting pressures, including warming, stratification, nutrient stoichiometry, light availability, and circulation, which are inconsistent across modelling frameworks. Additionally, important components of the plankton community, such as microbial and gelatinous taxa, are often underrepresented in both observations and models, and responses to ocean acidification and combined stressors remain poorly understood outside experimental settings. Overall, these limitations lead to lower confidence in the direction and magnitude of predicted changes, although modelling capability is improving and the evidence base is growing.

KEY CHALLENGES AND EMERGING ISSUES

Attributing multiple interacting pressures and model uncertainty

Attributing changes in plankton communities to specific drivers (e.g. warming/heatwaves, stratification, underwater light, nutrient balance, advection/circulation, and top-down controls) remains challenging. Similar datasets can present contrasting interpretations of mechanisms driving change (e.g. Beaugrand *et al.*, 2019; Schmidt *et al.*, 2020; Zhao *et al.*, 2023). Although this MCCIP report benefits from longer time-series studies and improved mechanistic understanding compared with Edwards *et al.* (2020), major gaps remain in our ability to model future changes in pelagic food webs with confidence. Long-term indicator and trait-based studies show clear ecosystem shifts, but causality often involves multiple interacting drivers, non-linear responses, and critical tipping points (Holland *et al.*, 2024). Even where mechanisms are well understood, such as the influence of underwater light and suspended particulate matter on blooms, projections can differ widely depending on model assumptions (e.g., Thewes *et al.*, 2021; Thewes *et al.*, 2022). Uncertainty in projecting future production, distribution, and food webs remains high, as many projections are based on model simulations that are subject to limitations and internal variability, including coarse representation of lower trophic levels and limited understanding of multi-stressor interactions (Horn *et al.*, 2021; Sandø *et al.*, 2024). Reductions in long-term monitoring programmes further weaken our ability to detect and interpret change, affecting the policy relevance of OSPAR and UK pelagic habitats indicators (Holland *et al.*, 2025). Large uncertainties also persist in carbon sequestration pathways; for example, estimates of carbon flux to the mesopelagic zone vary by an order of magnitude (McMonagle *et al.*, 2024). Without clearer attribution of plankton responses to environmental change, setting realistic management targets and assessing risk for fisheries and carbon flux remain challenging (Di Pane *et al.*, 2022).

Monitoring blind spots and data integration issues for policy indicators

Major UK monitoring programmes, including the CPR Survey, under-sample small or fragile taxa (Bedford *et al.*, 2020; Holland *et al.*, 2023), including small and gelatinous zooplankton, both expected to become more influential in future food webs. The CPR also misses unarmoured dinoflagellates, limiting understanding of offshore dinoflagellate dynamics (Bedford *et al.*, 2020; Holland *et al.*, 2023). A recent UK synthesis shows pico- and nanoplankton dominate summer biomass and respond strongly to warming and stratification, yet they are absent from OSPAR or UKMS indicators (McQuatters-Gollop *et al.*, 2024), despite including pathogenic microbes relevant to food security (Harrison *et al.*, 2022). Gelatinous taxa are also increasing in some regions but are still included inconsistently in these policy frameworks (McEvoy *et al.*, 2023; Ndah *et al.*, 2022; Sagarminaga *et al.*,

2024). Key geographic blind spots also persist, particularly in western and offshore Scottish waters where important fisheries are concentrated.

While newer monitoring tools have emerged, including flow cytometry, eDNA, metabarcoding, transcriptomics, and automated imaging, they remain patchy in coverage and lack standardised QA/QC protocols (Hubert *et al.*, 2025; Lombard *et al.*, 2019; Payton *et al.*, 2022), although they remain useful for filling gaps in traditional long-term time-series data and providing additional taxonomic- or size-based information (Holland *et al.*, 2025). Expanding monitoring coverage alone is insufficient; targeted mechanistic studies are also needed to identify processes controlling plankton populations, community structure, and ecosystem function. Without this understanding, predicting responses to warming, stratification, multi-stressor interactions, or altered nutrient regimes remains challenging. Recent work on plankton size spectra (Atkinson *et al.*, 2021; Atkinson *et al.*, 2024), trait- and energy-based analyses (Schmidt *et al.*, 2020), and pico-/nanoplankton dynamics (McQuatters-Gollop *et al.*, 2024), demonstrates how mechanistic research improves attribution to drivers and confidence in future projections.

Increase in extreme events, shifting circulation regimes, and tipping-points risk

In line with IPCC terminology, climate pressures can be grouped into sudden-onset extreme events, slow-onset changes, and low-probability high-impact tipping points (Pörtner *et al.*, 2023; Seneviratne *et al.*, 2021). Marine heatwaves, periods of abnormally warm water lasting days to months, have become more frequent, intense, and prolonged since the 1980s (Semmouri *et al.*, 2023). They are already disrupting plankton phenology and pushing key zooplankton toward thermal limits, with collapses observed in warm years (Semmouri *et al.*, 2023; Simon *et al.*, 2023). Experimental studies show that multiple stressors (e.g.warming, acidification, nutrient imbalance) can compound these impacts and slow recovery (Ahme *et al.*, 2025; Cabrerizo *et al.*, 2024).

Other extreme events, droughts, floodwater discharge, storms, and storm surges, are also projected to intensify (Pörtner *et al.*, 2019). These events can resuspend toxins, darken coastal waters (Davies and Smyth, 2025), decrease salinity, deliver pulsed nutrient loads, and cause plankton mortality through turbulence or abrasion (Maud *et al.*, 2018). A series of extreme UK storms in 2014/15 caused disproportionate losses of larger and gelatinous taxa, though recovery occurred within months (Atkinson *et al.*, 2021). Short duration and sporadic nature of these events make sampling challenging, thus, impacts on plankton remain poorly understood. More field research at finer scales using developing imaging technologies (Giering *et al.*, 2022; Holland *et al.*, 2025) will likely improve mechanistic understanding.

Slow-onset hydrographic changes are also reshaping plankton communities. A weakening, warming European Slope Current and shifts in shelf-edge

inflow are modifying the supply and composition of plankton advected into the North Sea (Clark *et al.*, 2022; Kléparski *et al.*, 2024). These circulation changes influence nutrient availability and primary productivity (Holt *et al.*, 2018), as well as prey fields and recruitment windows for forage fish such as herring and sandeel, increasing risk of mismatched phenology with their zooplankton prey and making fisheries harder to manage and predict (Akimova *et al.*, 2023; Alvera-Azcárate *et al.*, 2021).

Low-probability but high-impact tipping points are also important to consider. The Atlantic Meridional Overturning Circulation (AMOC) (Boot *et al.*, 2025), an important component of North Atlantic heat transport, is very likely to weaken this century; while imminent collapse is unlikely, major weakening would still have severe climatic and ecological consequences (Seneviratne *et al.*, 2021). However, recent studies suggest models may underestimate collapse risk (Ditlevsen and Ditlevsen, 2023; Vanderborght *et al.*, 2025). Strong AMOC weakening could substantially reduce phytoplankton biomass and lead to declines in total marine biomass, with the greatest impacts experienced by higher trophic levels. Biomass reductions of up to ~30% are projected for some regions and functional groups (Boot *et al.*, 2025). However, responses of commercially important fish are expected to vary regionally (Figure 6), with some areas showing increases in projected biomass. Even without full collapse, major weakening would reduce primary production, impact commercial fish stocks, and reshape the UK's climate.

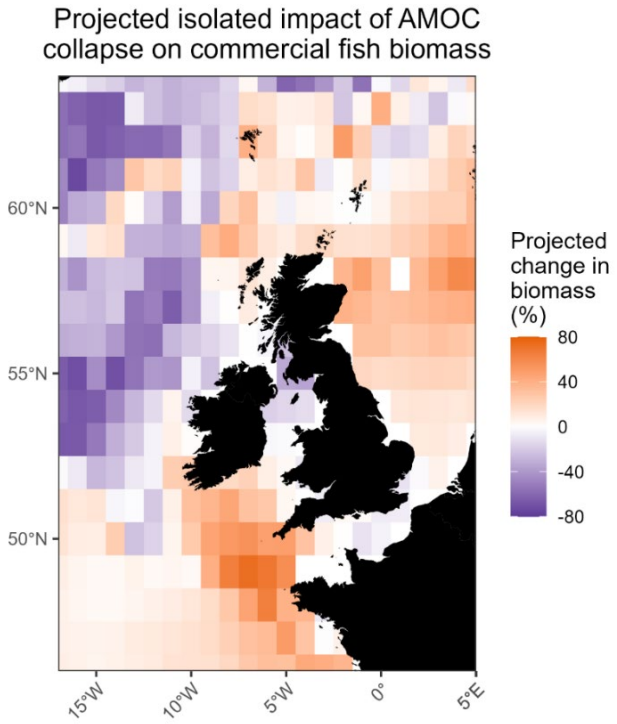


Figure 6. *Projected change in biomass of commercially important fishes caused by a simulated AMOC collapse. Projected future biomass of commercially important fishes sourced from Boot et al. (2025) for scenarios of no AMOC collapse (control) and AMOC collapses simulated from hosing experiments (see methods in Boot et al. (2025)). Percentage change in commercial fish biomass under control and hosing experiments were reprocessed here to show the percentage difference in commercial fish biomass and thus isolate the projected impact of AMOC collapse on biomass changes.*

CONCLUSIONS

Climate change is driving major shifts in plankton communities and pelagic habitat conditions across UK waters. Warming, increased stratification, and altered nutrient regimes are consistently identified as dominant pressures, occurring alongside eutrophication, changing nutrient ratios, coastal darkening, and fishing impacts. These drivers are reshaping community composition, phenology, and distribution, with a growing dominance of smaller plankton and microbial pathways. Additionally, the rapid expansion of offshore energy infrastructure represents an emerging pressure on plankton communities. Introduction of artificial hard substrate from wind infrastructure provides new habitat for filter feeders, increasing their associated grazing pressure on plankton (Degraer *et al.*, 2020), while installation-scale turbulence and mixing may affect local stratification and nutrient supply (Daewel *et al.*, 2022; Dorrell *et al.*, 2022), with potential consequences for plankton productivity and community structure.

Long-term evidence shows earlier phytoplankton spring blooms in more-southern UK waters, more-frequent trophic mismatches, and summer declines in nutritious crustacean zooplankton, partially replaced by meroplankton. These changes reduce food web efficiency and carbon export, with implications for fisheries recruitment, biodiversity indicators, and ecosystem services.

Although the evidence base to support these conclusions is strong, key gaps remain, particularly for microbial and gelatinous plankton and for some UK marine regions. Future projections generally indicate negative impacts on fish stocks and carbon cycling, although most of this evidence is derived from modelling studies and is subject to considerable uncertainty in magnitude and regional variation. In addition, responses are expected to vary among species, with some potentially benefiting from climate-driven redistribution and creating new fisheries opportunities (e.g. Townhill *et al.*, 2019; Townhill *et al.*, 2023), even where overall impacts on currently important UK fisheries are projected to be predominantly negative. Ongoing model development will increase confidence in the magnitude and location of these impacts so policy decisions can be better targeted. Overall, these findings highlight the need for improved integration of plankton indicators into UK marine policy, broader taxonomic monitoring coverage, increased monitoring frequency, and better consideration of lower trophic levels in predictive models. Addressing these gaps is essential for achieving Good Environmental Status under the UK Marine Strategy and ensuring that climate adaptation measures are informed by sound and relevant ecological evidence.

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