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The importance of climate change on Algal Blooms: Causes, Impacts, and Mitigation Strategies

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Abstract

Algal blooms have emerged as a significant environmental concern, impacting marine ecosystems, fisheries, and tourism. Algal blooms refer to the swift proliferation of algal populations in aquatic environments, frequently triggered by the enrichment of nutrients. The marine region of Denmark is especially susceptible due to its distinct environmental conditions and human-induced pressures. Grasping the dynamics of these blooms is essential for safeguarding marine biodiversity and bolstering local economies. The specific manner in which climate change should be integrated into the execution of the directives is not clearly defined. This is particularly evident in the habitats directive and the marine strategy directive, which contain vague and broad statements. The same ambiguity is found in the water framework instruction; however, EU guidelines indicate that the second and third generation river basin management plans are required to consider the impact of climate change on the aquatic environment. This paper examines the causes of these blooms, their ecological and economic impacts, and proposes strategies for mitigation.

Keywords: Algal; Safeguarding; Bloom; Biodiversity.

1. Introduction

A number of special circumstances apply in Denmark, which means that the sea plays a greater role in the population's awareness and in terms of management than in most other

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countries. Educating local communities about the impacts of pollution and sustainable practices is very essential issue. Denmark has a coastline of approximately 7,300 km, which is very much in comparison with the country's total area of 43,000 km^2. In Denmark, there is no place further than approximately 50 km from the nearest coast. This means that the vast majority of Danes regularly experience and relate to the sea, and that the sea therefore constitutes an important part of the national identity. Denmark is historically a maritime country, as the sea has always played an important role in relation to resources, transport, trade and recreational activities.

The Danish coastal areas are characterized by an extraordinarily large variation in terms of both physical, chemical and biological conditions. There are bays, broads and inlets, but also more open water, straits, belts and sound.

The salinity ranges from low-saline to high-saline, which, together with the variation in the physical conditions and the degree of nutrient load, provides the basis for a very different species composition of plant and animal life between the areas. There is also great dynamics in the coastal areas as a result of the influence of changing wind conditions, tides, currents, freshwater impact and a large variation between seasons and between years. Furthermore, Denmark is characterized by a significant load on the marine environment as a result of a high population density, intensive agriculture and by being a welfare society with a large consumption of resources. However, Danish waters are also affected by load from other countries, which is supplied via air, water and shipping. These conditions mean that human activity causes significant pressure on coastal areas in particular through the supply of nutrients, environmentally hazardous substances and alien species as well as physical disturbance in connection with commercial fishing, transport, construction and recreational activities. As a consequence, Danish marine areas in general and coastal areas in particular are vulnerable to further impacts from ongoing and future climate change (Krause-Jensen and Rasmussen, 2009).

Algal blooms are rapid increases in algal populations in aquatic systems, often resulting from nutrient enrichment. The Danish marine area is particularly vulnerable due to its unique environmental conditions and anthropogenic pressures. Understanding the dynamics of these blooms is crucial for preserving marine biodiversity and supporting local economies.

Climate change has significantly altered aquatic ecosystems, leading to an increase in the frequency and severity of algal blooms. These blooms, particularly harmful algal blooms (HABs), disrupt ecological balance, threaten biodiversity, and pose risks to human health. Understanding the relationship between climate change and algal blooms is crucial for developing effective mitigation strategies.

Algal blooms arise when specific environmental conditions promote the rapid proliferation of phytoplankton, resulting in a noticeable change in the color of ocean waters. For a bloom to take place, a precise combination of environmental factors is necessary:

- Abundant and bright sunlight

- Elevated nutrient concentrations
- Calm water conditions (minimal wind and circulation)
- A reduced presence of grazers or predators

Additionally, other environmental elements such as temperature and salinity can affect HABs in various ways and may assist in identifying the origins of these blooms.

1.1. Causes of Algal Blooms

Algal blooms develop as a result of rapid algal proliferation in freshwater or marine environments, driven by a combination of physical and chemical influences (Sengupta *et al*., 2017). These blooms typically arise when conditions are favorable, including ample sunlight, elevated water temperatures, minimal wind activity, and increased nutrient availability (Dale *et al*., 2006; Gobler, 2020).

- Nutrient Enrichment: Increased runoff from agriculture and urban areas introduces excess nitrogen and phosphorus into the sea.
- Climate Change: Rising sea temperatures promote algal growth. Warmer temperatures favor the growth of certain algae, particularly cyanobacteria, which thrive in slow-moving, warm waters.
- Overfishing: Disruption of food webs can lead to imbalances favoring certain algal species.
- Coastal Development: Habitat destruction alters natural nutrient cycling.
- Changes in Salinity – Altered freshwater runoff patterns due to climate change can increase salinity in inland waters, promoting the spread of salt-tolerant algae.
- Higher Carbon Dioxide Levels – Elevated CO_2 concentrations enhance algal photosynthesis, accelerating bloom formation.
- Shifts in Rainfall Patterns– Increased precipitation can lead to nutrient-rich runoff entering water bodies, fueling excessive algal growth.

1.2. Impacts of Algal Blooms

Algal blooms can have devastating effects on aquatic ecosystems, disrupting the delicate balance that supports marine and freshwater life. When excessive nutrient pollution—often from agricultural runoff or wastewater discharge—triggers rapid algae growth, it can deplete oxygen levels, leading to dead zones where fish and other organisms struggle to survive. Some algal blooms produce harmful toxins, posing risks to wildlife and even human health through contaminated drinking water or seafood. Additionally, blooms can block sunlight from reaching underwater plants, hindering photosynthesis and reducing biodiversity. Their impact extends beyond the water, affecting industries like fishing and tourism, as degraded ecosystems lead to economic losses. Understanding the causes and implementing mitigation strategies is crucial for preserving ecological stability. The most important effects in this issue are:

- Ecological Effects: HABs can produce toxins that affect marine life and disrupt food chains.
- Economic Consequences: Fisheries suffer from reduced catches; tourism declines due to unsightly waters and health risks.
- Oxygen Depletion: Decomposition of algal biomass leads to hypoxic conditions, threatening marine organisms.
- Ecosystem Disruption – Blooms block sunlight, deplete oxygen, and harm aquatic organisms.
- Human Health Risks – Some algae produce toxins that can affect the liver and nervous system.
- Economic Consequences – HABs impact fisheries, tourism, and water treatment costs (Tewari, 2022)
- Algal blooms impact marine ecosystems in distinct ways compared to freshwater environments as the following subjects:

  Unique Effects on Marine Ecosystems

  - Toxic Blooms and Food Chain Disruption – Some marine algal blooms, like dinoflagellate blooms (red tides), produce neurotoxins that accumulate in shellfish, leading to paralytic shellfish poisoning in humans and marine animals (Schleyer and Vardi, 2020).
  - Hypoxia and Dead Zones– Marine algal blooms can lead to oxygen depletion, creating hypoxic zones where marine life struggles to survive (Lan *et al*., 2024).
  - Economic and Ecological Damage – Blooms affect fisheries, aquaculture, and tourism, causing financial losses and ecosystem imbalances (Neves and Rodrigues, 2020).
  - Altered Marine Biodiversity – Unlike freshwater blooms, marine blooms can shift entire oceanic food webs, affecting plankton, fish populations, and coral reefs (Sarkar, 2018).

2. Materials and methods

This paper provides a number of assessments of the impact that future climate change may have on the biological conditions in watercourses, lakes and coastal parts of the sea. The study focuses on the biological elements that are included in the objectives of the river basin management plans, which are generally algae, higher plants, small animal fauna and fish. The significant climate changes included in the analyses are variations in temperature, precipitation, and salinity. However, some of the assessments will also include other climate elements such as and wind.

The paper reviews the effect of climate change on the ecological quality elements (fauna, fish, plants). Overall, the report states that the climate changes that have already occurred affect the ecological quality elements that are used to assess the ecological status, in comparison with the Water Framework Directive.

3. Results and Discussion

3.1. Coastal areas

Nutrient salt concentrations in inland Danish waters are closely linked to runoff from land and thus precipitation. Increased precipitation will therefore mean more eutrophic conditions, especially in coastal areas that are closest to the freshwater source.

Oxygen conditions will worsen in a future warmer climate, even without increased primary production (eutrophication). This is because temperature has both a direct physical effect on the solubility of oxygen in water and an indirect effect via the effect of temperature on the metabolism in the ecosystem and thus oxygen dynamics.

Phytoplankton species composition, biomass and distribution will probably be affected by future climate change. Furthermore, increased stratification together with higher summer temperatures can form the basis for algal blooms, which in many cases can consist of toxic and otherwise harmful algae, including blue-green algae from the Baltic Sea area and furrow algae.

Macroalgal vegetation will be pressured towards lower productivity and lower biodiversity as a result of the expected climate changes with increased wind energy, warmer sea water, possibly lower salinity, rising water levels and increased nutrient input. Examples show that climate change will affect the macroalgal indicators that are used or expected to be used in the marine directives.

Seagrasses, including eelgrass, are expected to be further stressed by climate change, which may mean that the assessment of the environmental status of Danish waters based on eelgrass may shift in a predominantly negative direction.

The diversity of the benthic fauna can be affected both negatively and positively by the expected climate changes. The overall effect is assumed to be negative because data indicate that oxygen is more important for the distribution of benthic fauna diversity than food supply. However, these assessments are uncertain, as they are based on the distribution of the fauna under the current climate and not on how the fauna will be composed in a future climate. Enforcing stricter regulations on coastal development and fishing practices to protect vulnerable ecosystems.

Phytoplankton species composition, biomass and distribution will likely be affected by future climate change. Furthermore, increased stratification together with higher summer temperatures may form the basis for algal blooms, which in many cases may consist of toxic and otherwise harmful algae, including blue-green algae from the Baltic Sea area and furrow algae.

3.2. Plankton

Phytoplankton is a broad term for single-celled algae. Algae basically function like plants without possessing specialized tissue types such as roots and wood, as is known from land plants. Instead, phytoplankton distribute themselves in the water column, subject to the prevailing physical conditions, such as wind, current, sunlight and nutrients. Phytoplankton utilize the sun's energy to fix carbon dioxide (CO_2) via photosynthesis using a number of specialized pigments that retain sunlight and convert this into energy and new carbon biomass. The most important pigment found in all plants, including algae, is called chlorophyll a. In addition to CO_2 and light, a number of nutrients are required, which, depending on the season, are supplied to the marine environment to a greater or lesser extent from land. Nitrogen, silicon and phosphorus are considered by far the most important nutrients.

Since nitrogen is the dominant growth-limiting factor in the marine environment around Denmark (Carstensen *et al*. 2006), it is necessary to address the supply of nitrogen in relation to climate change. Phytoplankton is removed from the water column via several processes. During the seasonal algal blooms in spring and to a lesser extent in autumn, phytoplankton settles onto the seabed in larger quantities, which in certain situations can supply enough organic material to provide a basis for oxygen depletion due to oxygen consumption during the metabolism of the organic material. The part of the organic material that is not metabolized is permanently buried in the seabed. Outside of algal bloom periods, the majority of the phytoplankton in the water column is metabolized by microorganisms in a process called the microbial loop. In this process, the majority of the carbon biomass is released as CO_2 into the water column, while only a smaller proportion is metabolized on the seabed, and an even smaller proportion is deposited on the seabed. When the turnover in the water column is dominant, the nutrients remain in the water column's material cycle to a much greater extent.

Phytoplankton is a central biological indicator of the state of the environment in relation to both the Water Framework Directive and the Marine Strategy Directive. In order to meet the directives' requirements for monitoring the most important indicators, the species composition and biomass of phytoplankton are continuously identified in the national monitoring programme, NOVANA. Since the pigment chlorophyll a is universal for all phytoplankton, there is continuous monitoring of the concentration of this pigment in the NOVANA programme as a proxy for the total biomass of phytoplankton. It should be noted that the relationship between the biomass of phytoplankton and chlorophyll a is not linear and highly variable, as the relationship is determined, among other things, by the growth conditions and light conditions (Taylor *et al*. 1997).

3.3. Climate change and Plankton

It is highly likely that future climate change will lead to further changes in phytoplankton species composition, biomass and distribution. Furthermore, the shift in the occurrence of individual species will probably shift the timing in relation to the upper links of the food webs, if these are unable to adapt to the changes quickly enough. This will change the flow through the food chains from primary producer algae to fish.

Similarly, an increased frequency of storms during the phytoplankton growing season can be a contributing factor to algal blooms. Increased stratification together with higher summer temperatures can form the basis for algal blooms, which in many cases can consist of toxic and otherwise harmful algae, including blue-green algae and furrow algae. In combination, these changes can negatively affect the assessment of the environmental status under the Water Framework Directive and the Marine Strategy Directive.

3.3.1 Temperature

Temperature has only a small direct effect on algal growth, as phytoplankton growth is mainly determined by the availability of nutrients and light. It is not certain that climate change, such as increased nutrient concentrations and temperature, will lead to increased growth of the dominant phytoplankton species. A more likely scenario is rather a shift between groups and species.

Rising sea temperatures over the entire growing season have, since the beginning of the 20th century, advanced the spring bloom by two to three weeks (Henriksen, 2009). In addition, higher temperatures in winter cause microbial turnover to increase, and thus the available carbon in the water column to be converted earlier in the year. When both the spring bloom is advanced and an increasing part of the microbial turnover takes place in winter and early spring, a mismatch arises in the energy flow from the primary producers to the other trophic levels of the food web, if these are unable to adapt to the relatively faster shifts in seasonal variation.

This is confirmed by both global time series and local observations from the North Sea, where a number of food web size fractions ranging from furrow algae to water fleas and benthic larvae have had their season of maximum occurrence shifted (Burthe *et al*., 2012; Edwards and Richardson, 2004).

The consequence of the shift between food items and their predators is assumed to be the main reason for the weak recruitment of, for example, cod, observed in the North Sea (Beaugrand *et al*., 2003). In the Baltic Sea, rising temperatures are expected to lead to a decrease in growth efficiency and increasing mortality for the water flea Pseudocalanus sp. (Isla *et al.*, 2008). The consequence is that the current structure of the planktonic food chain is shifting in relation to the timing of algal blooms, water fleas and fish spawning times in the Baltic Sea, with negative consequences for parts of the fish stocks, as has been seen for cod in the North Sea.

3.4. Climate scenarios

The consequences of several different climate scenarios have been established and calculated internationally – in the tables referred to as A1B, A2, B2 and 2C. The Danish government has used scenario A1B as the official Danish climate scenario with a time horizon until 2050. Tables 1 and 2 show the climate effects in relation to precipitation and temperature, respectively. As can be seen from the Tables, the expected average change in climate until 2050 is an increase in precipitation on an annual basis of 7% with an annual variation from 4% in spring and summer to 11% in winter and an increase in temperature on an annual basis of 1.2 °C with an annual variation of an increase of 0.9 °C in summer and 1.5 °C in winter, respectively.

The official climate scenario in Denmark (A1B, cf. Table 1 and Table 2) has the climate normal for the period 1961-90 as a starting point. If one compares the expected climate changes in 2050 in the A1B scenario (Table 1 and Table 2) with the actual changes in the period 2001-10 – where the reference period is also 1961-90 – it is seen that the expected change in the climate parameters in 2050 has largely already occurred, as precipitation has increased by 7% and temperature by 1.1 °C. The analyses in this report therefore primarily focus on the general effects of climate change on both biological and physical/chemical parameters rather than a relationship to a specific climate scenario.

Table 1 represents precipitation changes are given as percentage changes compared to the reference period 1961-1990. The 2050 projection covers the average for the period 2021-2050, and similarly 2100 covers the average for the period 2071-2100. The figures for 2050 are for the A1B scenario, while the figures for 2100 are given for each of the four scenarios A1B, A2, B2 and 2C. The figures in parentheses indicate the uncertainty (standard deviation) of the ensemble mean in percentage points, which is obtained by averaging the ensemble of 14 climate model runs for 2050 and 8 climate model runs for 2100 (Beaumont *et al.*, 2011).

Table 1. Precipitation changes during the years

Season	2050 A1B Precipitation	2100 A1B Precipitation	A2 Precipitation	B2 Precipitation	2C Precipitation
Annual average	+ 7 % (± 3 %)	+ 14 % (± 6 %)	+ 15 % (± 7 %)	+ 11 % (± 6 %)	+ 9 % (± 4 %)
Spring	+ 4 % (± 3 %)	+ 14 % (± 6 %)	+ 16 % (± 7 %)	+ 12 % (± 5 %)	+ 9 % (± 4 %)
Summer	+ 4 % (± 4 %)	+ 5 % (± 8 %)	+ 5 % (± 9 %)	+ 3 % (± 7 %)	+ 2 % (± 5 %)
Autumn	+ 7 % (± 3 %)	+ 9 % (± 5 %)	+ 10 % (± 6 %)	+ 8 % (± 5 %)	+ 7 % (± 4 %)
Winter	+ 11 % (± 3 %)	+ 25 % (± 6 %)	+ 27 % (± 7 %)	+ 21 % (± 5 %)	+ 17 % (± 4 %)

In Table 2 the temperature data are changes in degrees Celsius compared to the reference period 1961-1990. The 2050 projection covers the average for the period 2021-2050, and similarly 2100 covers the average for the period 2071-2100. The figures for 2050 are for the A1B scenario, while the figures for 2100 are given for each of the four scenarios A1B, A2, B2 and 2C. The figures in parentheses indicate the uncertainty (standard deviation) on the ensemble mean, which is obtained by averaging the ensemble of 14 climate model runs for 2050 and 8 climate model runs for 2100 (Beaumont *et al.*, 2011).

Table 2. Temperature changes during the years

Season	2050 A1B Temperature	2100 A1B Temperature	A2 Temperature	B2 Temperature	2C Temperature
Annual average	1,2 ºC (± 0,2 ºC)	2,9 ºC (± 0,3 ºC)	3,2 ºC (± 0,3 ºC)	2,5 ºC (± 0,2 ºC)	1,9 ºC (± 0,2 ºC)
Spring	1,1 ºC (± 0,2 ºC)	2,7 ºC (± 0,3 ºC)	2,9 ºC (± 0,3 ºC)	2,3 ºC (± 0,3 ºC)	1,8 ºC (± 0,2 ºC)
Summer	0,9 ºC (± 0,1 ºC)	2,2 ºC (± 0,2 ºC)	2,6 ºC (± 0,2 ºC)	2,0 ºC (± 0,2 ºC)	1,5 ºC (± 0,1 ºC)
Autumn	1,4 ºC (± 0,1 ºC)	3,1 ºC (± 0,3 ºC)	3,4 ºC (± 0,3 ºC)	2,7 ºC (± 0,2 ºC)	2,1 ºC (± 0,2 ºC)
Winter	1,5 ºC (± 0,2 ºC)	3,5 ºC (± 0,3 ºC)	3,8 ºC (± 0,3 ºC)	3,0 ºC (± 0,3 ºC)	2,3 ºC (± 0,2 ºC)

3.5. Consequences in relation to future water management plans

According to the project description, one of the purposes of this report is to point out the issues that should be addressed in the future in relation to climate and water management plans. The climate changes that are primarily described in this report are increased temperature and increased precipitation. The fundamental effort to address these changes (i.e. ensuring that temperature and precipitation do not increase or only to a lesser extent) lies in the international agreements on the reduction of greenhouse gas (GHG) emissions and as such cannot be addressed in the water management plans.

One of the significant issues in future water management plans will be to describe as precisely as possible the effect that climate change will have on the biological quality elements. This report provides a more general input to this, but without relating it to a specific climate scenario or year.

There are still significant “gaps” in the knowledge base that need to be filled before it is possible to describe more precisely the direct impact of climate change on the quality elements and how these changes affect the overall ecosystem.

Another significant issue will be how the effects on the biological quality elements of climate change can best be mitigated. The report below provides some examples of mitigation measures, but it is not possible to provide a comprehensive overview of the opportunities/challenges in this context. Partly because there is a lack of sufficient knowledge in the area, and partly because that is not the task.

It is expected that some of the models that are being developed for use in water planning will also be able to be used for more detailed estimates of some of the effects of climate change, such as increased nutrient input and lower oxygen content.

Marine

3.6. Effects of climate change on macroalgal communities in Danish waters

The expected climate change is expected to affect marine algae at both the species and community level. Since algal communities in Danish waters unfold in a complex three-dimensional “world”, governed by an interaction between different vertical and horizontal gradients of natural and human-made factors, it is difficult to predict exactly what we can expect about future life on rocky reefs. However, a number of studies have been conducted on specific relationships between species and climate-relevant variables, which are presented in this chapter.

3.6.1 Effects of increased wind on algal communities

The different climate scenarios indicate that Danish waters will be affected by more wind and more frequent and stronger wind events. The wind scenarios are relatively uncertain, especially with regard to changes in the strength of the wind events. More frequent and especially increased wind forces will affect the species composition of algal communities at shallower water depths. No studies have been conducted in Danish waters that can document whether this will lead to lower productivity on the reefs overall, but this cannot be ruled out.

3.6.2 Effect of increased water temperatures on algal community diversity

Over the past 30-40 years, a temperature increase of 1-1½ °C has been observed in surface and bottom waters in inland Danish waters (Hansen, 2015). The temperature is expected to continue to increase as the air temperature increases according to climate scenarios. Climate scenarios predict a significant decrease in the ice cover in the northeastern Baltic Sea and a consequent significant warming of the Baltic Sea due to reduced back-radiation of solar energy from the ice cover (Kjellström and Christensen, 2013). Outflowing excess Baltic Sea water can therefore be expected to provide additional heat energy to the Danish sea areas, especially in the upper water layer.

Rising sea temperatures are expected to have an impact on the biogeographical distribution of macroalgae, especially in habitats where the species live close to their upper limit of heat tolerance.

In Northwestern Europe, there has been concern about the effects of rising sea temperatures on the large brown alga, Saccharina latissima (Figure 1). The species is very productive and can be found in such large numbers that it is referred to as a habitat structuring organism. The species also has a rapidly growing commercial interest as a culture species in Danish waters.

Sugar kelp is found in all Danish waters and has been recorded down to about 20 m water depth under good growth conditions. Sugar kelp has a life cycle with a large leaf-shaped stage called the sporophyte and very small male and female plants called gametophytes. The large leaf-shaped stage has a lifespan of 3–5 years. The growth of the sporophyte stage is generally inhibited at temperatures above 17 to 20 °C, and the gametophyte stage and young individuals of the sporophyte stage cannot survive temperatures above 22–23 °C (Ae Lee and Brinkhuis, 1988).

A Norwegian study concluded that long-term water temperatures above 19 °C in 1997 along the coast of southwest Norway were one of several reasons for a structural shift from a community dominated by sugar kelp to a community dominated by filamentous algae

(Moy *et al*., 2008). High temperatures were also recorded along the southwest Norwegian coast in 2002 and 2006, and field studies in the same area also indicated a decline in sugar kelp in the area.

Figure 1. Sugar kelp on the rocky bottom of the Hatter Barn reef in the Natura 2000 site of the same name. The large leaf-shaped alga is the sporophyte stage. Photo: Peter Bondo Christensen.

A Danish study has looked at whether there was a statistical relationship between the occurrence of five selected species in June and warm sea temperatures the previous year (Dahl *et al*., 2013). Data were analyzed for a 20-year period up to and including 2010. The five species, of which sugar kelp was one, are all common and important components of algal communities in both open areas and fjords.

The species were selected based on a literature study that indicated that Danish waters could be close to their southern distribution range in terms of temperature. However, the collapse occurred before unusually high temperatures, which were harmful to sugar kelp, were measured in the surface water in the central, deeper parts of the fjord areas. Diver observations indicated that heavy snail grazing, mass mortality of blue mussels and very poor water quality were the reasons for the decline of the kelp (Dahl *et al*., 1995). Sugar kelp is known for its rapid recolonization (Kain, 1979), but critically high temperatures for sugar kelp were subsequently measured repeatedly in 1995, 2003 and 2006 in Danish fjord areas. It cannot therefore be ruled out that elevated temperatures were a contributing factor in the fact that the sugar kelp population in some areas, such as Flensborg Fjord, has not or only partially recovered compared to its previous level.

However, the collapse occurred before unusually high and harmful temperatures for sugar kelp were measured in the surface water in the central deeper parts of the fjord areas. Diver observations indicated that heavy snail grazing, mass mortality of blue mussels and very poor water quality were the reasons for the decline of the kelp (Dahl *et al*. 1995). Sugar kelp is known for its rapid recolonization (Kain, 1979), but critically high temperatures for sugar kelp were subsequently measured repeatedly in 1995, 2003 and 2006 in Danish fjord areas. It cannot therefore be ruled out that elevated temperatures were a contributing factor in the fact that the sugar kelp population in some areas such as Flensborg Fjord has not or only partially recovered compared to the beginning of the 1990s (Figure 2). No comparable changes in the distribution of sugar kelp on rocky reefs in open waters have been observed over the entire 20-year period, but in these areas the temperature at 5-15 meters' depth has also always been below the critical limit. There is thus reason to be concerned about the future of sugar kelp as a productive and habitat-creating macroalgae on rocky reefs in fjord areas, as rising temperatures will increase the likelihood of critically high temperatures in shallow rocky reef areas.

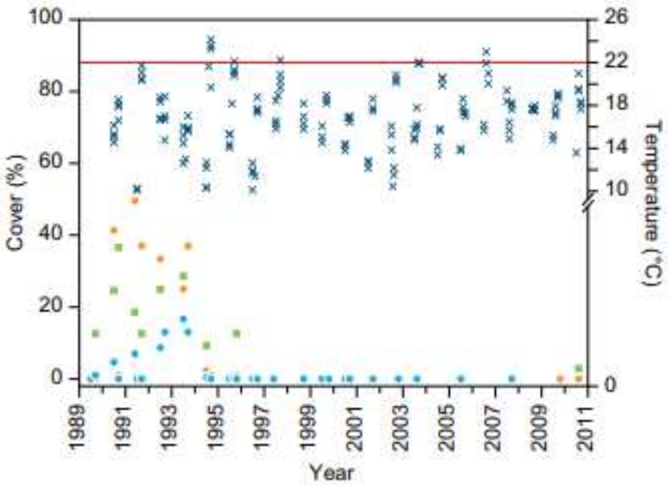

Figure 2. The coverage of sugar kelp on hard substrate at three depths in Flensborg Fjord presented together with the water temperature measured at the water chemistry station in the fjord. The upper critical temperature for sugar kelp is indicated (Figure from Dahl *et al*. 2013).

3.6.3 Effects of increased precipitation and nutrients on the diversity and productivity of algal communities

Future climate change is expected to lead to a further increase in precipitation over the Baltic Sea region, and in that case the salinity in the Baltic Sea will decrease quite significantly (Meier *et al*., 2011). In particular, more winter precipitation and more frequent cloudburst events are expected in summer compared to today. Increased precipitation will cause an increase in freshwater runoff from land and thus a greater leaching of nutrients from agricultural areas, especially in winter. This could also reduce salinity, especially in the more closed Fjord inlet systems, just as a greater outflow of fresher Baltic Sea water through Danish waters will lower the salinity of the water surface in the inner Danish waters.

The input of more fresh surface water will also strengthen the stratification in the Danish waters, which may, however, be compensated by increasing winds, which will increase mixing and possibly water exchange. Overall, climate change is assumed to lead to a loss of marine species, as the expectation of decreasing salinity in the Baltic Sea in particular is considered reasonably certain.

Monitoring algal blooms in marine ecosystems involves a combination of advanced technologies and traditional sampling methods. Here are some key approaches:

- Remote Sensing and Satellite Imaging

- Satellites equipped with ocean-color sensors detect chlorophyll concentrations, helping scientists track bloom formation and movement over large areas (Sebastiá-Frasquet *et al*., 2020).
- Automated In-Situ Sensors
- Buoys and underwater sensors continuously measure water quality parameters like temperature, salinity, and nutrient levels, providing real-time data (Lan *et al*., 2024).
- Molecular and Genetic Techniques
- DNA-based methods identify harmful algal species and track their genetic markers, improving early detection (Smith *et al*., 2024).
- Modeling and Forecasting
- Predictive models use historical data and environmental variables to anticipate bloom occurrences, aiding in proactive management (Lan *et al*., 2024).

3.7. Mitigation Strategies

The Marine Strategy Framework Directive is implemented through marine strategies. There is little mention of climate change in the Marine Strategy Framework Directives other than that climate change must be appropriately integrated and adaptation to expected climate change must be incorporated.

The supplementary criteria document (Anon. 2010) states:

"Climate change is already having consequences for the marine environment, including ecosystem processes and functions. When preparing their marine strategies, Member States should, where relevant, specify any indication of the effects of climate change."

Climate change is thus not mentioned at all or only mentioned in very vague terms in the directives. It is therefore necessary to consult various supplementary EU documents such as strategy papers, white papers and guidance documents (Anon, 2008; Anon, 2009a; Anon, 2009b) for a more detailed explanation of how Member States should address climate change in relation to the directives.

The emergence of HABs in both coastal and inland waters poses a considerable threat to communities. This intricate biogeophysical phenomenon is further exacerbated by the effects of climate change. This review consolidates recent research focused on the influence of climate change on three key lake parameters: lake temperature, precipitation, runoff, and lake ice, all of which affect lake ecology and subsequently influence the occurrence of HABs (Tewari, 2022). Some important process should be done to manage the related environment and address the issues:

- Nutrient Management – Reducing agricultural runoff and wastewater discharge can limit excess nutrients that fuel algal blooms.
- Implementing best agricultural practices to reduce runoff.

- Establishing wastewater treatment facilities to limit nutrient discharge.
- Monitoring and early detection – Advanced prediction models and monitoring systems can help detect blooms before they become severe. Developing real-time monitoring systems for water quality and algal populations using satellite imagery and buoys.
- Climate adaptation measures – Addressing climate change through emission reductions and sustainable water management can mitigate long-term risks.

Conclusion

Addressing the issue of algal blooms in the Danish marine area requires a multifaceted approach involving scientific research, community engagement, regulatory measures, and international cooperation. By implementing these strategies, we can mitigate the adverse effects of algal blooms while promoting a sustainable marine environment. Research Initiatives supporting studies on algal bloom dynamics to inform management strategies effectively.

As stated above, it is not stated very precisely how climate change is to be incorporated into the implementation of the directives. In particular, for the Habitats Directive and the Marine Strategy Directive, there are some very general and loose formulations. This also applies to the Water Framework Directive - however, it is clear from the EU guidelines that for 2nd and 3rd generation river basin management plans, the plans are expected to address the extent to which climate change affects the aquatic environment.

The overall purpose of this report is to provide an updated overview of the expected ecological effects as a result of climate change in the perspective of the Water Framework Directive. The focus will therefore be on how climate change affects the biological quality elements of the Water Framework Directive.

Although, research is ongoing on the possible effects of climate change on both quality elements and at ecosystem level, more reliable knowledge is lacking about the impact of climate change on the ecological status and on the quality elements in watercourses, lakes and marine areas. Lack of knowledge about the impact of climate change on biological quality elements in particular is also mentioned in the water management plans of many other countries.

Knowledge about the effects of climate change on ecological systems is available and is being continuously built up, but there are often significant uncertainties in the assessment of the impact on biological quality elements. The challenge in future water management plans will therefore be whether the existing knowledge is sufficient to determine appropriate measures.

However, there are some fundamental relationships that must be described as well-known and well-documented, and which can therefore be addressed in future water management plans. The increased precipitation, which all climate scenarios predict, will lead to an increased nutrient input to water bodies, and the effects of such an input on both lakes and coastal areas are thus well-known.

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