Effect of Climate Change on Algae Valuable Source of Medicinal Natural Compounds

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Abstract The word algae represent a large group of different organisms from different phylogenetic groups, representing many taxonomic divisions. They are distributed worldwide in the sea, in freshwater and in moist situations on land. Algae grow rapidly, produce useful products, and provide environmental benefits. Algae have potential as foods, and vitamins, bioactive substances, polysaccharides and other valuable commercial products and also are useful as raw material for future biofuel production and liquid fertilizer. Algae can be classified into two main groups; first one is the microalgae, which includes blue green algae, dinoflagellates, bacillariophyta (diatoms) etc., and second one is macroalgae (seaweeds) which includes green, brown and red algae. Changes in global temperature and ocean chemistry associated with increasing greenhouse gas concentrations are forcing widespread shifts in biological systems. In response to warming, species ranges are shifting toward the poles, up mountainsides, and to deeper ocean depths. Concern for the environment and global climate change has increased in recent years, and algae can provide a number of significant environmental benefits. They remove carbon dioxide from the atmosphere, helping to reduce the harmful effects of the gas on climate change and the health of the environment. The aim of this chapter is to provide an overview of the current knowledge on these photosynthetic organisms regarding their environmental and pharmaceutical benefits.

Keywords Seaweed · Microalgae · Natural product · Greenhouse gas

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Introduction

In the last decades, the attention of the natural product researchers has been focused on the marine environment. It is a wealthy source of plants, animals and micro-organisms, which due to their adaptation to this unique habitat, produce a wide variety of bioactive molecules, which can be developed as nutraceuticals and pharmaceuticals for human nutrition supplementation and disease therapy. The specific habitat where an organism is growing has influence on the chemical nature of the marine primary and secondary metabolites. The intraspecific variation can produce differences in the chemical structures of compounds and their concentrations in different marine environments (Fan et al. 2014; Kiuru et al. 2014).

The word algae represent a large group of different organisms from different phylogenetic groups, representing many taxonomic divisions. In general algae can be referred to as plant-like organisms that are usually photosynthetic and aquatic, but do not have true roots, stems, leaves, vascular tissue and have simple reproductive structures. They are distributed worldwide in the sea, in freshwater and in moist situations on land. Most are microscopic, but some are quite large, e.g., some marine macroalgae that can exceed 50 m in length. Algae grow rapidly, produce useful products, and provide environmental benefits. Algae have potential as foods, and vitamins, bioactive substances, polysaccharides and other valuable commercial products and also are useful as raw material for future biofuel production and liquid fertilizer. Furthermore, algal products can be produced sustainably. With the great diversity of algae, there is great promise that algal features may serve to enhance a large variety of current products, and produce new ones. As the currently expanding market for algae-based goods indicates, the future is bright for the research and development of algal products. Algae also contribute to increased sustainable practices. In the last 500 years, agricultural production processes on land have advanced, and there are now new and well-developed approaches to conventional farming operations. Significant progress also stems from the production of commercial products in water. As an aquatic organism, algae can be grown to produce useful products without using very much land (Hudek et al. 2014).

Algae can be classified into two main groups; first one is the microalgae, which includes blue green algae, dinoflagellates, bacillariophyta (diatoms)… etc., and second one is macroalgae (seaweeds) which includes green, brown and red algae.

Microalgae are important sources of commercially produced high-value unique chemicals including carotenoids, antioxidants, fatty acids, enzymes, polymers, peptides, toxins and sterols. They are also the first step in the aquatic food chain. Moreover, microalgae are considered as the actual producers of some highly bioactive compounds found in marine resources. Attempts to develop commercial products from microalgae are not new, with the earliest being the proposal to use microalgae as a source of lipids, carotenoids and the extensive work done in the 1970s on microalgae as a source of single-cell protein (Borowitzka 2013).

Macroalgae are used for great number of application by man. The principal use of seaweeds as a source of human food and as a source of gums (phycocollides).

Gums like agar, alginic acid and carrageenan are primarily constituents of brown and red algal cell walls and are widely used in industry. An increasing attention to macroalgae metabolites of industries from different branches (textile, fuel, plastics, paint, varnish, cosmetics, pharmaceutical and food) was noticed in the last years. Seaweeds are being used in cosmetics, and as organic fertilizers. They have the potential to be much more widely used as a source of long- and short-chained biochemical with medicinal and industrial uses. From human health point, macroalgae rich in unique bioactive compounds not present in terrestrial food sources, including different proteins (lectins, phycobili proteins, peptides, and amino acids), polyphenols, and polysaccharides and a novel source of compounds with potential to be exploited in human health application. Macroalgae are part of the diet in different countries and constitute a source of beneficial nutrients, such as vitamins, trace minerals, lipids, amino acids and dietary fibers, its use as a low-calorie food should be investigated, as it might be important in body weight control and cardiovascular health. The metabolites found in macroalgae are described as having anti-inflammatory, antimutagenic, antitumor, antidiabetic, and antihypertensive properties. In addition, they are hepato protections, and can also inhibit the lipoxygenase, aldose reductase and cholinesterase's (Zubia et al. 2009; Lopes et al. 2012; Andrade et al. 2013).

Changes in global temperature and ocean chemistry associated with increasing greenhouse gas concentrations are forcing widespread shifts in biological systems. In response to warming, species ranges are shifting toward the poles, up mountainsides, and to deeper ocean depths. Factors including warming and ocean acidification are causing the reorganization of local communities as species are added or deleted and as interactions among species change in importance. Because greenhouse gas emission rates continue to accelerate, the climatically forced ecological changes that have been documented over the past half century will likely pale in comparison to changes in the coming decades (Harley et al. 2012).

Concern for the environment and global climate change has increased in recent years, and algae can provide a number of significant environmental benefits. They remove carbon dioxide from the atmosphere, helping to reduce the harmful effects of the gas on climate change and the health of the environment.

Climate Change and Marine Organisms

Rising atmospheric carbon dioxide (CO_2) is one of the most critical problems because its driving a number of important physical and chemical changes. The primary direct consequence of global warming is thermal expansion of water and global-scale trends ocean acidification, Climbing temperatures create a host of additional changes, such as sea level increase, increased ocean stratification, decreased sea-ice extent, and change patterns of ocean circulation, precipitation. Both warming and altered ocean circulation act to reduce subsurface oxygen (O_2) concentrations, along with regionally specific increases or decreases in wave heights, upwelling, terrigenous nutrient runoff, and coastal salinity, all of which in turn impact the health of marine species, ecosystems, and our coastal communities (Harley et al. 2012; Keeling et al. 2010; Zacharioudaki et al. 2011; Doney et al. 2012).

Studies on the global response of a wide variety of marine and terrestrial species to climate change conclude that the planet is facing drastic ecosystem shifts and numerous extinctions. Species that fail to acclimatize physiologically or evolve genetically to increasing temperatures will either move northwards into cooler habitats or become extinct (Jueterbock et al. 2013).

Marine ecosystems cover 71% of the Earth's surface, our knowledge of the effects of climate change in oceans is limited compared to terrestrial ecosystems.

Responses to climate change are particularly rapid and strong in marine ecosystems, especially in the marine intertidal where species often live at their upper temperature tolerance limits. Global warming-related range shifts of marine species exceed those of terrestrial species by an order of magnitude. Furthermore, climate-change induced range shifts are more predictable for marine than for terrestrial species, since the distributional limits of marine species are usually directly correlated with their thermal tolerance limit. Range shifts of key or foundation species are of central importance, since by definition these species play a crucial role in, and can trigger changes throughout, the entire web of interactions within an ecological community (Jueterbock et al. 2013; Sunday et al. 2012).

In recent decades, the rates of change have been rapid and may exceed the current and potential future tolerances of many organisms to adapt. Further, the rates of physical and chemical change in marine ecosystems will almost certainly accelerate over the next several decades in the absence of immediate and dramatic efforts toward climate mitigation. However, there is increasing evidence suggesting that marine plants and animals could respond as fast or faster than their terrestrial counterparts, from both observations and theory (Keeling et al. 2010; Doney et al. 2012).

Cyanobacteria in a Changing Climate

Cyanobacteria are the Earth's oldest known oxygen evolving photosynthetic microorganisms, and they have had major impacts on shaping our current atmosphere and biosphere. Their long evolutionary history has enabled cyanobacteria to develop survival strategies and persist as important primary producers during numerous geochemical and climatic changes that have taken place on Earth during the past 3.5 billion years (Paerl and Huisman 2009a, b).

Cyanobacteria are predicted to increase due to climate and land use change. biospheric environmental perturbations, including nutrient enrichment and climatic changes strongly affect cyanobacterial growth and bloom potentials in freshwater and marine ecosystems. Since the 1960s, however, there has been a dramatic global increase in the number of publications and reports of cyanobacterial blooms. While increased reports may to some extent be due to increased monitoring efforts, there is substantial evidence that blooms are increasing not only in frequency, but also in biomass, duration and distribution. Furthermore, it has been hypothesised that cyanobacteria may continue to increase in response to global climate change (Paerl et al. 2011; Carey 2012).

Cyanobacterial blooms present major challenges for the management of rivers, lakes and reservoirs. Blooms have adverse impacts on aquatic ecosystems and human health, with wide-ranging economic and ecological consequences. Toxic cyanobacterial blooms present a considerable risk to drinking water and have major public health, ecological, and economic effects. The increased frequency and intensity of blooms have been attributed to changing precipitation patterns, melting glaciers and intensifying storms result in the escalation of nutrient's input and promote eutrophication. Eutrophication is a process induced by increased nutrients, especially nitrogen and phosphorus, in water bodies resulting in growth of algae and plants. More recently, it has been predicted that a changing climate associated with rising levels of atmospheric CO_2 will increase the occurrence of blooms, or at least favour cyanobacterial dominance of phytoplankton communities (Carey 2012; Paerl and Huisman 2009a, b).

Climate change, including global warming, is causing changes to regional rainfall and hydrology, which will have cumulative effects with nutrient-over-enrichment in modulating cyanobacterial harmful algal blooms. Regional and global warming enhances the initiation, magnitude, duration, and distribution of cyanobacterial harmful algal blooms. Furthermore, increasing variability in rainfall patterns impacts nutrient and sediment delivery, sediment-water exchange and metabolism, flushing and water residence time, and vertical stratification, which, in turn, may affect cyanobacterial harmful algal blooms dominance and persistence (Paerl et al. 2016).

Temperature is an all-pervasive environmental parameter that affects the metabolism, growth, reproduction, and survival of living organisms, as well as the interactions among species. As a consequence, climate warming will result in shifts in phytoplankton community composition, including shifts between cyanobacteria. In natural systems, it has been shown that warmer water temperatures do favour cyanobacterial dominance in phytoplankton communities. Similarly, it has been proposed that warmer temperatures will mean earlier and longer potential bloom periods, as well as lead to possible range expansions. warming on cyanobacteria are increased occurrence of cyanobacterial blooms with ongoing climate warming (Carey 2012; Kingsolver 2009).

Many species of planktonic cyanobacteria produce gas vesicles, which provide buoyancy and allow access to well-lit surface waters. The regulation of buoyancy, which allows migration in stratified lakes between illuminated surface waters and nutrient rich bottom waters, occurs as cells accumulate carbohydrates when exposed to light and respire these products of photosynthesis in the dark. Changes in climate, such as increased temperatures, prolonged droughts and longer water residence times, are predicted to promote cyanobacterial bloom establishment by increasing the strength and duration of stratification. Increased stratification will favor the fast-migrating buoyant cyanobacteria. As nutrient loading and stratification increase, there will tend to be a shift towards buoyant species that can access both the well-lit surface waters and hypolimnetic nutrient pool (Carey 2012; Rinke et al. 2010).

Fundamentally, cyanobacteria are an extremely diverse group with different sets of traits, and will respond to different aspects of climate change (e.g., increased stratification, altered nutrient availability). The ability of cyanobacteria to response to environmental conditions associated to climate change has been documented since the first occurrence of cyanobacteria around 3.5 million years ago. Thus, looking into the evolutionary history, cyanobacteria has been adapted to extreme conditions such as temperature fluctuation, exposure to high UV radiation, abundance and scarcity of nutrients. cyanobacterial blooms are favored not by an individual environmental factor, but by a combination of multiple interacting physical, chemical, and biotic drivers. It is evident that although cyanobacterial blooms can be enhanced by increasing temperature, there must be sufficient phosphorus and nitrogen to sustain high populations. There will most likely also be regional differences in which cyanobacterial taxa dominate, depending on how future climate, hydrology, and nutrient loading vary geographically (Carey 2012).

In general, Climate change alters local hydrologic and biogeochemical processes, including rainfall and runoff (amount and temporal dynamics), nutrient export from watersheds, mixing regimes, internal nutrient cycling, and food web dynamics. These changes present a significant challenge to resource managers aiming to control cyanobacterial harmful algal blooms in a future favoring bloom occurrence. A research program that focuses on how extant strategies will be influenced by climate change is needed to support effective cyanobacterial harmful algal blooms control programs (Paerl et al. 2016).

Climate Change Effects on Phytoplankton

Every day, more than 100 million tons of carbon dioxide are drawn from the atmosphere into the ocean by billions of microscopic ocean plants called phytoplankton during photosynthesis. In addition to playing a big role in removing greenhouses gases from the atmosphere, phytoplankton are the foundation of the ocean food chain (Behrenfeld et al. 2006).

Phytoplankton account for <1% of the photosynthetic biomass on Earth, but are nevertheless responsible for nearly 50% of global net primary production and are the primary energy source for aquatic ecosystems. Climate modifications, such as the rise in atmospheric CO_2 and warming, affect the marine biosphere through modifications in pH, carbonate availability, water column stability, nutrient and light regimes. These changes directly impact small-sized (*ca.* <1–>100 μm) phytoplankton organisms, whose short-term life cycles make them amenable to quickly respond to subtle environmental variations. Phytoplankton response can be both directly through physiology and indirectly mediated through effects on environmental factors limiting primary production most notably light and nutrients.

Changing climatic conditions can modify these environmental factors and alter phytoplankton structure and taxonomic composition. Therefore, tracking changes in the phytoplankton community structure can be an accurate indicator of ecosystem perturbations (Winder and Sommer 2012; Guinder and Molinero 2013).

Interactions between climate and phytoplankton are complex, because other factors such as resource availability, density dependence, and predation strongly control the abundance, distribution, and size structure of the community. Despite these complexity of interacting processes, some widespread climate related responses have emerged, and the mechanisms involved in climate-related changes are becoming better understood. Impacts of climate change on plankton are mainly manifested as shifts in seasonal dynamics, species composition, and population size structure (Winder and Sommer 2012; Adrian et al. 2009).

Temperature is a key parameter that directly affects physiological rates of phytoplankton at multiple scales, e.g., enzymatic reactions, respiration, body size, generation time, ecological interactions, community metabolism. Phytoplankton experience an increase in enzymatic activity and growth rates over a moderate range of temperature rise with an average $Q_{10} = 1.88$ (photosynthesis and respiration rate increase resulting from a 10 °C rise in temperature). As a result, a temperature increase should lead to greater phytoplankton growth rates and biomass accumulation under adequate resource supply. Enhanced growth of primary producers is expected under future trends of temperature increase. The projected scenario, however, becomes complex when considering indirect effects of warming, such as grazing acceleration, which play key modulating roles of phytoplankton biomass accumulation. However, compared to photosynthesis rates, the metabolism of heterotrophic organisms is more sensitive to temperature Consequently, warming should increase consumption by herbivores more strongly than primary production. This can strengthen top-down control over primary production by increasing grazing rates and thus affect phytoplankton production and taxonomic composition (Winder and Sommer 2012; Guinder and Molinero 2013; Sommer and Lewandowska 2011). Salinity closely co-varies with temperature and also has important implications in plankton physiology, affecting germination of resting stages, growth rates and development of blooms in coastal waters (Guinder and Molinero 2013).

The most significant climatic effects on phytoplankton species composition will very likely be mediated through changes in thermal stratification patterns such as the extent of the growing season and vertical mixing processes. Vertical mixing is one of the key variables that conditions the growth performance of phytoplankton within the water column. because mixing processes are usually accompanied by changes in resource availability of light and nutrients (Winder and Sommer 2012).

Increasing evidence of changes in plankton size structure has been reported worldwide in relation to global warming. Temperature effects on the size structure of the phytoplankton community composition toward a dominance of small species The reduction in cell/body size of planktonic organisms and displacements of species ranging to higher latitudes have been mainly ascribed to global warming. Phytoplankton cell size follows biophysical rules (e.g., nutrient uptake, motion, sinking rates, kinetics of metabolism) that affect growth rates, the biogeochemical cycling and trophodynamics. The replacement of large cells by smaller ones under warming conditions is likely related to shifts of the species' environmental optimum growth and the higher competitive skills of small cells (Winder and Sommer 2012; Beaugrand et al. 2010).

Finally, Climate-driven modifications in marine water physics and chemistry impact phytoplankton from the individual to ecosystem levels through alterations in both bottom-up and top-down controls, namely resources availability-light and nutrients- and zooplankton grazing pressure and selectivity. At the individual level phytoplankton is affected via changes in physiology, morphology and behavior and the community level is affected by changes in structure (size, composition, diversity), phenology and the biogeographical distribution of species that derive in new interspecific interactions and trophodynamics. Among the most common direct and indirect universal responses of phytoplankton to climate change are alterations in growth and photosynthesis rates and in calcification processes related to CO_2 rise and ocean acidification, dominance of smaller species under warmer conditions (related to both water stability and/or grazing pressure) and changes in the phenology, magnitude and species composition of phytoplankton spring bloom due to earlier thermal stratification, overwintering and/or enhanced zooplankton activity (Guinder and Molinero 2013).

Effects of Climate Change on Seaweed

Seaweeds are ecologically important primary producers, competitors, and ecosystem engineers that play a central role in coastal habitats ranging from kelp dforests to coral reefs. Although seaweeds are known tobe vulnerable to physical and chemical changes in the marine environment, Less attention has been paid to seaweed even though they constitute some of the most significant biogenic producers of calcium carbonate ($CaCO_3$) and contribute to deep-sea productivity. Seaweeds are key habitat structuring agents that harbor incredible biodiversity. Seaweeds form the base of productive food webs that include economically valuable species and extend well beyond the shallow waters in which seaweeds dwell. Seaweeds are intimately linked to human cultural and economic systems via the provision of ecosystem goods and services ranging from food to medicine to storm protection (Harley et al. 2012; Christie et al. 2009; Koch et al. 2012).

Seaweed survival, growth, and reproduction are known to vary with numerous climatically sensitive environmental variables including temperature, desiccation, salinity, wave heights, nutrient supply via upwelling and run-off, pH, and carbon dioxide concentration itself (Harley et al. 2012; Chu et al. 2012).

Temperature determines the performance of seaweeds, and indeed all organisms, at the fundamental levels of enzymatic processes and metabolic function. Seaweeds have evolved biochemical and physiological adaptations, including variation in the identity and concentration of proteins and the properties of cell membranes, that enable them to optimize their performance with respect to the temperatures they encounter. In response to increase temperature, seaweeds can produce heat shock proteins that repair or remove damaged proteins However, protein thermal physiology is not well understood in macroalgae. and the upregulation of heat shock protein production is only one of many transcriptional changes that occur in seaweeds during periods of thermal stress. As a result of non-stressful conditions at intermediate temperatures and stress at the extremes, the relationship between temperature and most subcellular, tissue-level, or whole-organism processes is described by a hump-shaped thermal performancecurve. From colder to warmer, these curves generally rise exponentially as rates of biochemical reactions increase, peak at some optimum temperature, and then fall rapidly as the biological components of the system become less efficient or damaged. The effect of a small increase in thallus temperature will be beneficial when the initial temperature is cooler than optimal and detrimental when it is warmer than optimal, and the precise change in performance can be predicted from the starting and ending temperature values along the curve. Unfortunately, the shapes of thermal performance curves and the positions of their optima are poorly described in most seaweeds (Harley et al. 2012; Kordas et al. 2011; Kim et al. 2011; Eggert 2012).

Increased temperature is generally thought to have negative effects on spore production, germination, recruitment, and sporophyte growth and context-specific effects on gametogenesis depending on the source population and degree of warming has also been linked to mortality of spores, gametophytes, eggs, and sporophytes. Much less is known about the effects of increasing CO_2 concentrations. On the basis of current knowledge, we can expect positive effects on gametogenesis and variable effects (e.g., positive effect of increasing CO2, but negative effect of decreasing pH) on germination (Harley et al. 2012; Buschmann et al. 2004).

Carbon dioxide concentrations in seaweed habitats are increasing with anthropogenic emissions and, in some regions, with intensified upwelling of CO_2-enriched water. As with terrestrial plants, it is tempting to predict that sea weedswill benefit from the increase in inorganic carbonconcentration. Because CO_2 diffusion rates are much higher in air than in water, seaweeds that are exposed at low tide and those with floating canopies at the sea-air interface have greater access to CO_2. However, aerial exposure does not necessarily reduce the probability of carbon limitation, as exposure at low tide can dramatically reduce rates of carbon acquisition and even immersed seaweeds can benefit from increasing atmospheric CO_2 concentrations. Most green and brown algae (and many red algae) can also utilize bicarbonate by converting it to CO_2 intracellularly Just as terrestrial C_3 plants are more likely to be CO_2 limited and therefore more likely to benefit from elevated CO_2 than C_4 plants, seaweeds lacking CCMs are more likely to be carbon-limited and thus more likely to benefit from additional CO_2 (Harley et al. 2012; Long et al. 2004; Williams and Dethier 2005).

In addition to providing carbon for photosynthesis, anthropogenic CO_2 emissions reduce seawater pH and the saturation state of calcium carbonate. As this increases the cost of calcification and the likelihood of dissolution, calcifying organisms are particularly sensitive to elevated CO_2 in seawater. Ocean acidification is consistently related to reduced growth rates in calcified macroalgae (Harley et al. 2012; Kroeker et al. 2010).

All of the anthropogenically forced changes in the physical and chemical environment are occurring simultaneously, and in many cases, the impact of any particular stressor on the physiology and performance of marine macrophytes will depend upon the presence and magnitude of additional limiting or disruptivestressors. the enhancement of photosynthesis by elevated CO_2 varying with nutrient availability. The percent cover of algal turfs decreased with increasing CO_2 under ambient nutrients, but the reverse was true under elevated nutrients. There are also many interactions among disruptive stressors, including temperature, desiccation, pH, salinity, and ultraviolet radiation. For example, in tropical and warm-temperate crustose coralline algae, the negative effect of warmer temperatures on bleaching, growth rates, calcification rates, and survival were significantly greater under conditions of elevated CO_2/reduced pH. As of yet, it is difficult to predict when one stressor will increase or decrease the effect of another. There are also no known biases toward synergistic or antagonistic effects; in a meta-analysis of multi-stressor studies on Fucus spp., synergistic, additive, and antagonistic outcomes were all equally prevalent. We desperately need to incorporate more ecophysiological research into a multi-stressor framework to improve our understanding of when, where, and why important context-dependent outcomes emerge (Harley et al. 2012).

Linkages Between Harmful Algal Blooms and Climate Change

Increasing human settlements in the near-shore modify the environment through eutrophication and pollution processes, and significantly affect the marine biota and human health. The synergistic effects of anthropogenically driven temperature rise and eutrophication can enhance the occurrence of harmful algae blooms (HABs) in the coasts. HABs have significant negative implications for the marine ecosystem functioning, as they can cause detriment to biodiversity and eventual death of predators, causing severe impacts on fisheries and resource availability with serious repercussion for human health and economy (Guinder and Molinero 2013).

Temperature is one of the main environmental factors affecting physiological processes in phytoplankton, acting at many different stages of growth and bloom development. It not only is one of the most important environmental drivers expected to change with climate, but also is the least contentious, since there already has been measurable warming of the surface mixed layer and the upper several hundred meters of the oceans (Wells et al. 2015).

The link between increasing water temperatures and phytoplankton growth rates has long been recognized, and it is expected that increased potential growth rates will accompany warming. Temperature influences motility, germination, nutrient uptake, photosynthesis, and other physiological processes. Optimal and inhibitory threshold temperatures differ among metabolic processes. The optimal temperature for photosynthesis is generally greater than the optimum for growth. Indeed, the biogeography of phytoplankton species boundaries is determined in large part by temperature regimes, as is almost certainly is true for HAB species. But phytoplankton, including HAB species, can show strong intraspecific differences in temperature tolerance and responses. The chemical composition of a species' (e.g., lipids, fatty acids, and toxicity) also is a function of temperature. While higher toxicity (i.e., toxin accumulation) of some species can occur with slowing growth, temperature and toxin production appear to be directly linked in some species but not others. Much of the basic information needed to generate a preliminary forecast of which regions or habitats (poles vs. tropics, estuaries vs. coasts) HAB species will be the most resilient or susceptible to temperature change likely is available (Wells et al. 2015; Bissenger et al. 2008; De Boer 2005).

Temperature is a keystone parameter differentially affecting a range of metabolic processes, and thus is anticipated to have a strong influence on phytoplankton community compositions and trajectories. While increasing annual temperatures should broaden the windows of some HAB activity it will not affect others or even lessen other harmful algal blooms. Ecosystem interactions, strain variability within HAB and non-HAB species, and concurrent hydrographic or oceanographic changes all complicate even this seemingly straightforward expectation. It is logical that HAB habitats should expand to higher latitudes, but there is little clear evidence that this has happened and the time series observation systems needed to verify this change currently are lacking. There is little evidence to date that changing temperatures directly affect toxin production in HAB species although these findings are by no means comprehensive. It is unlikely that temperature alone will drive competitive selection of HAB species over non-HAB species, but it is probable that temperature effects on metabolic rates will magnify or lessen the influence of other climatic pressures on HAB prevalence (Wells et al. 2015).

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