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Assessing The Environmental and Anthropogenic Factors Affecting Algae and How They Can Be Used as Indicator Species in Different Aquatic Ecosystems

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Assessing The Environmental and Anthropogenic Factors Affecting Algae and How They Can Be Used as Indicator Species in Different Aquatic Ecosystems

By

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CERTIFICATE OF APPROVAL

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Absract

Within Earth’s waters resides microscopic photosynthetic creatures known as algae that supply the world with about half of the entire oxygen supply. These algae consist of diatoms, dinoflagellates, cyanobacteria, and coccolithophores, all of which can be found in the Earth’s bodies of water. Their distribution depends on many environmental factors such as temperature, nutrient availability, light availability, and also on anthropogenic factors such as dams, sewage, and agriculture. Many of these algal species and groups can be used as indicator species, as they can appear when conditions are outside normal ranges. Those that are considered indicator species can be studied and documented over the years to monitor conditions in certain areas and ensure that the water quality remains in a good and healthy range. They have been used to find evidence of eutrophication in waters and to assess the trophic status of the water. Additionally, they have been used to find patterns in sea surface conditions and oceanographic changes. By understanding the different ways algae are affected and how they respond to different variables, we can gain a better idea of the health of the surrounding aquatic ecosystems.

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1. Introduction

All around the globe lies a universal current called the global conveyor belt, a combination of surface currents and deep-water currents that cycles on a 1000-year loop, mixing warmer and colder waters while swirling nutrients throughout the water column (Barnes and Tarling, 2017). Within these currents resides tiny microscopic algae of all different species and groups, such as dinoflagellates, coccolithophores, cyanobacteria, and diatoms. They can be found in all the Earth's bodies of water including oceans, lakes, rivers, and even in small ponds. Each of these different organisms contributes to the production of oxygen world-wide, together responsible for roughly half of the entire oxygen supply (Liu et al., 2019). These organism's distribution and growth, however, are at the mercy of the world's environmental and anthropogenic factors.

There are certain groups and species of algae that are considered indicator species, exhibiting strong reactions to changes in the surrounding environment (Järvinen et al., 2013). When light availability, salinity, or currents shift, some algae will become highly noticeable in an area where they might generally be present in low numbers or absent in an area in which they were typically dominant. Since these species and groups can reveal changes in these factors, scientists learned to watch for the arrival of them in certain areas they know are changing due to environmental or anthropogenic factors. By identifying what changes occurred to cause the bloom of particular species or groups, the underlying cause can be traced to see if it is due to human influence on the environment or if the bloom resulted simply due to the natural environmental changes (Järvinen et al., 2013). Environmental influences can be documented in this way and the observations can be used to determine cause and effect in a similar type of bloom. Indicator species have been used in experiments to predict what would happen if a particular change occurred in nature. By studying how these indicator species react in certain situations, scientists gain a better understanding of the environment and any possible effects the humans have on them (Mosleh et al., 2012). Studies of these indicator species have allowed researchers to develop ideas of how to make changes in the future to better manage and protect our aquatic surroundings instead of harming them, such as creating sewage treatment plants in areas that need them or implementing management plans to ensure our waters do not become overpolluted.

The objective of this paper is to describe how different types of algae have been used as envrionmental indicator species. Through the examination of studies grouped by different freshwater and saltwater ecosystems, we see how algal indicator species can give us insights into the health and wellbeing of our aquatic ecosystems. Indicator species have been used to track trophic levels in lakes, water flow and seasonality in rivers, pollution in bays, and even warming conditions in pelagic waters. By continuing to follow these insights and monitoring the waters, sustainable management plans, as well as early warning systems, can be put in place so that the water sources we rely on remain healthy and reliable.

2. Characterization of indicator species

The general rule of thumb for algae is that the location of different species' distributions throughout aquatic ecosystems depends on each species' ability to survive the conditions those areas possess. The ideal temperature, salinity, depth, light availability, and nutrients must be present as each group has different requirements for survival. When proper conditions for survival are present in an area, blooms can happen rapidly while those requirements remain. If the requirements are not met, or the requirements shift in any way, the presence of algal species can noticeably change.

Some algal species and divisions are categorized as "indicator species," meaning they appear in different places when the right conditions for them to thrive occur. As such, they can be considered a sort of warning signal for specific conditions caused by anthropogenic or environmental changes (Zhu et al., 2016). These changes can include the presence of nutrient pollution, changes in salinity due to runoff from terrestrial areas, shifts in the position of currents causing temperature changes, or even higher concentrations of some nutrients that might contribute to seasonal variations. They can be used to assess the health of the water environment in addition to any changes that might occur (Parmar et al., 2016). Knowing this information is essential for the health of organisms that live there as well as our day to day life. While we rely on the bodies of water closest to us for drinking water, cleaning water, fishing, and even for recreation, the organisms that live there rely on the availability of food and clean water to survive in.

Each algae species and group have what is referred to as their basis of range and their expatriation area (Semina, 1997). A species' basis of range is where they can survive indefinitely despite any outward conditions. It serves as the algae's home base, where they will always thrive. Reproduction usually occurs in this area and populates outside ranges. Their expatriation area is that space where they cannot survive indefinitely, given the current conditions. In these areas, the nutrient concentrations, water temperature, and light availability is not right for successful reproduction and growth. The species or taxa will often die out unless they can become replenished from the basis of range. For example, a study done in Lake Kinneret observed that the disappearance of the species *Peridinium gatunense* from where it had previously regularly bloomed was due to restrictions of freshwater usage being placed in the surrounding area (Salmaso et al., 2012). These areas are where the algae can spread and potentially expand their range, but doing so causes them to be challenged by the current environmental and anthropogenic conditions, which may not always be favorable. The only reason the species and groups manage to spread outside their basis of range is due to the temporary presence of favorable environmental conditions at that specific time. Reproduction usually cannot occur in these expatriation areas, as the anthropogenic or environmental conditions are not considered ideal for such successful growth.

3. Environmental variables affecting algal growth

There are many different physical and chemical characteristics that can cause algal groups to have different distribution and growth patterns. Whether it be the distribution of individual species and taxonomic groups or the longitudinal distribution within the water column, each of these variables contributes to the survivability of the algae. Each species and group possess their own balance of requirements that is necessary for their continued growth and reproduction. As the following key environmental variables place limitations on their distribution, each species and group are restricted to some regions of the world.

3.1. Temperature

Temperature is the environmental factor that most often limits the range of growth and distribution. As temperatures rise, algae metabolism also increases, causing a direct effect on their productivity levels (Miao and Yang, 2009). Algae might react to these changes in temperature by increasing or decreasing their cell division rate. When an ideal temperature range is reached for that group or species, the cell division rate can increase anywhere from 1 to 3 times the normal amount for every 10-degree change (Miao and Yang, 2009). This increase in division and production will continue until temperatures become too high for the algae to survive. At this point, they proceed to die off, as metabolism and division cannot be supported. One other way that temperature affects algae is by changing the viscosity in the water. Low viscosity causes the algae to sink faster and remain at deeper depths. As temperature decreases, viscosity increases, causing the algae to sink slower (Miao and Yang, 2009). This promotes more division and primary production as they remain at ideal depths for this. Since temperature changes tend to be slow in many aquatic environments, this promotion of growth can happen over an even longer period (Miao and Yang, 2009).

Temperature can also have an effect on the latitiudinal distribution of algae. Certain taxa cannot survive in warm temperatures, but dominate in cold temperatures. This is true of diatoms (Bacillariophyta), which thrive in cold climates (Chen, 2015). They are most often found in the polar regions of the world and are very rarely found closer to the equator. During a batch experiment, it was found that diatoms exhibited higher growth rates in temperatures at or below 25 °C and lower growth rates at temperatures above 30 °C (Mesquita et al., 2020). Dinoflagellates (Dinoflagelleta), however, are dominant in the warm, tropical climates near the equator (Chen, 2015). Much like dinoflagellates, the optimal climate for cyanobacteria is also warmer waters. In the same batch experiment referenced above, cyanobacteria were found to have increased growth rates at temperatures around 30 °C (Mesquita et al., 2020). Despite these effects that temperature can have, it is not always the most crucial factor in algal growth.

3.2. Light availability

It's been thought that light has a considerable effect on the distribution and growth of different algae, especially within the water column. It seems evident that light would have a part to play with algal species, as their ability to photosynthesize depends on the availability of light. Considering this fact, scientists believed some of these species or groups could only be found within a certain depth of water, as sunlight and light penetration disappears throughout the water column with increased depth. One group of algae that does not generally adhere to this idea are the diatoms (Bacillariophyta), which need less light exposure. This allows them to survive at deeper depths (Capone et al., 2008). For example, at the surface waters, diatoms only need a fraction of the light that is available to grow and have been found to reproduce and photosynthesize in dim or dark areas (Capone et al., 2008). These species and groups tend to dwell and dominate at lower depths rather than just at the surface due to this fact. In fact, many algae species tend not to need much light exposure to photosynthesize at all, as they can adjust the photosynthetic pigment in their cells to allow for survival in depths beneath the euphotic zone (Miao and Yang, 2009). In addition to this, algae that possess flagella or cilia can also move up and down in diurnal migration-like patterns in response to the changing light availability and intensity, allowing for higher productivity levels than initially believed (Miao and Yang, 2009).

3.3. Seasonality

As the seasons change, algal communities can be profoundly affected. Winter seasons bring cooler surface waters and winds that begin to mix the waters. Then, spring and summer months bring sunlight and nutrients, allowing the algae to reproduce and grow rapidly. Algal blooms can be heavily promoted during the spring and summer months as this continued mixing of the waters brings in new nutrients and allows the algae found in deeper depths to be pushed towards the surface, giving them access to the sunlight they’d been limited to (Venrick, 1993). Populations of algae are primarily influenced during these warmer months as species composition and diversity are affected. Rainy seasons tend to occur during these spring and summer months, in some areas of the world, and there is generally an increase in productivity (Nankabirwa et al., 2019). One of the main supplements of seasonality is that of El Niño**.** El Niño is an anomalous event that primarily occurs every few years during December and pushes unusually warm, nutrient-poor surface waters towards the coast of South America near Chile and Peru (Racault et al., 2017). As these waters are pushed to the coast, primary production is limited due to the poor nutrient availability (Racault et al., 2017).

3.4. Nutrient availability

A handful of nutrients are vital for the development of some algae. Specifically, nitrogen, silicon, and phosphorus are essential nutrients for algal growth in certain taxa. A lack of any of these nutrients can cause detrimental damage to algae. Nitrogen deficiency results in the algae's photosynthesis productivity to be reduced (Capone et al., 2008). Phosphorus deficiency causes a decline in the cell protein, weakening of photosynthesis capabilities, and intensified internal respiration (Miao and Yang, 2009). A silicon deficiency results in the cell wall thinning, which can throw the other nutrients out of balance (Ittekkot et al., 2012). Silicon availability seems to be the most vital nutrient when it comes to the growth and formation of diatom assemblages. Diatoms tend to primarily compose many of the algal blooms that arise and they rely heavily on silicon (Ittekkot et al., 2012). Diatoms use silicon to form the outer crust of their cell and for their development in general (Capone et al., 2008). When algal blooms occur, the nutrients in the surrounding waters are quickly depleted, usually within one week (Miao and Yang, 2009). Silicon tends to be the most limiting factor and can be the difference between a diatom algal bloom or a non-diatom algal bloom. Due to this, nutrient availability is the most important environmental variable in terms of limitations.

4. Anthropogenic variables affecting algal growth

Anthropogenic pressures have adverse effects on algae communities that can be both detrimental and beneficial. Factors that have been accelerated by human interaction have had impacts on these communities that have primarily gone unnoticed. These communities need a delicate balance of salinities, temperature, and nutrient availability that can easily be tampered with due to anthropogenic stressors. The overall biomass and composition of algae in our waters are directly affected by water quality. They can have a direct effect on us, as we use many of these water sources for things such as drinking water (Salmaso et al., 20120).

For example, dams that have been erected to provide water for drinking and agriculture can cause salinity imbalances when freshwater rushes into saltwater due to the sluice gates being opened (Sin and Jeong, 2015). However, these low-salinity waters being introduced cause vertical stratification in the water, allowing the algae to have more sunlight as they hover in shallower depths for longer (Bharathi et al., 2018). This promotes their growth, allowing them to use up the available nutrients in the surrounding waters. In addition to this stratification, the freshwater input can bring an influx of nutrients to either promote reproduction or limit nutrient availability. If the ratios are thrown out of proportion, the phytoplankton community structure is affected (Bharathi et al., 2018). Rising turbidity levels due to the flow, however, can cause primary production levels to decrease (Sin and Jeong, 2015).

A study was conducted in the Mississippi River delta during a period of water discharge to examine what effects this anthropogenic event had on algal communities in the Gulf of Mexico. In this study, the water was sampled every two hours via the ship's flow-through system directly after discharge for a total of fifty-two hours (Dagg et al., 2008). During the two days after the discharge event, macronutrients that had been put into the water dissolved rapidly and the algae population increased dramatically. The discharge caused a low-salinity area to form at the surface of the water with a possible phosphorus limitation despite levels of phosphorus and nitrogen being high (Dagg et al., 2008). The algae that exhibited higher population levels consisted of freshwater dinoflagellates and small-celled cyanobacteria while diatom levels remained at a similar level to before the discharge took place (Dagg et al., 2008). These increased growth levels only remained for 1 to 2 days as salinity levels became too high when mixed with the Gulf waters.

In other areas of the world, some rivers carry sewage and wastewater away from riverbank cities that cannot afford a sewage treatment plan. Due to this, terrigenous materials, or dissolved organic matter (DOM), have become more present causing increased turbidity levels and limiting the amount of sunlight that can penetrate the water column (Häder et al., 2020). Intense agricultural land use in the surrounding areas cause more nutrients to enter the community as well. In addition to this, mines that are further upstream cause clay to enter into the river system and mix in with the terrigenous materials already polluting the waters (Häder et al., 2020). However, these additions to the waters can also promote primary production in some areas. The DOM present in these waters can provide the necessary nutrients for algal growth that might have otherwise been lacking (Häder et al., 2020).

The effect that anthropogenic pressures have on the algal community can be positive or negative. On the one hand, they can cause detrimental harm to the community, making it almost impossible for growth and primary production to occur as turbidity levels rise which limits the number of nutrients and sunlight available to the community (Häder et al., 2020). On the other hand, however, an influx of nutrients into the community and incoming freshwater causing stratification in the water column can allow the algal communities ample amounts of sunlight and the necessary nutrients to bloom at alarming rates (Sin and Jeong, 2015). Increased research into what effects these different factors have on algal communities, both long-term and short-term, could provide the information necessary to predict what may happen in the future.

5. Freshwater examples of algal indicator species

Algal indicator species are monitored in studies of freshwater systems primarily pertaining to the water quality of that area. Some freshwater systems are mainly influenced by anthropogenic factors rather than environmental factors and monitoring these ecosystems is vital to the formation of sustainable management plans so they can continue to be used resourcefully.

5.1. Riverine indicator species

Rivers worldwide are facing increased disturbances due to anthropogenic stressors and human interactions. The algal composition in rivers can give us a look into what kind of effect these stressors are having on the rivers. In addition to this, river water flow already has a specific influence on algal growth and reproduction, which could also influence the stressors impacting river systems. Monitoring these types of changes and hydrological effects gives us an idea of what kind of impact humans are having on these ecosystems.

Qu et al. (2019) looked into the types of effects riverine phytoplankton and algae were facing due to some increasing anthropogenic and environmental stressors. Specifically, they looked at hydrological effects on the groups and anthropogenic land-use effects. They grouped the 396 taxa studied into 21 groups based on similarities in function (Qu et al., 2019). Qu et al. (2019) found that water flow has a profound effect on the phytoplankton community structure, a factor that can be heavily influenced by anthropogenic stressors. In those areas that can be flooded and turbulent during wet seasons, it was found that the group able to withstand turbulence, made up of benthic diatoms (specifically of genus *Navicula*, *Nitschia*, *Gomphonama*, *Fragilaria*), was more dominant than the others (Qu et al., 2019). Another area exhibited that agricultural land use had a more positive effect on the growth and sustainability of some algal groups (of genus *Microcystis*) than urbanized land use did. As agricultural land-use caused nutrient runoff into the river, cyanobacteria were able to bloom and reproduce due to the necessary nutrients being in surplus (Qu et al., 2019).

An earlier study done in 2013 found a similar result to the study above. In this study, water flow was deemed to be the driving force behind the algal growth and reproduction (Devercelli and O'Farrell, 2013). As freshwater discharge flowed into the river system, there was a decline in algal growth levels when the waters became diluted. Devercelli and O'Farrell (2013) also found that salinity, temperature, and trophic status did not prove to be driving factors despite affecting species composition in the rivers. The Salado rivers were found to have high turbidity levels before the study was conducted, with the low velocities being just enough to keep the particles suspended (Devercelli and O'Farrell, 2013). In addition to this, the waters were found to have high conductivities when evidence of the species *Entomoneis paludosa*, *Chaetoceros* cf. *whigamii* and *Chaetoceros muelleri* were present, each of which is categorized as being present in highly conductive waters (Devercelli and O'Farrell, 2013). During periods of low water flow, algal growth was not restricted and phytoplankton species were dominant. High water flow periods were more restrictive on algal growth as light, nutrient, and turbidity levels were thrown out of balance (Devercelli and O'Farrell, 2013).

Algal indicator species in rivers can allow us to monitor the changing conditions as seasons change, water flow changes, and water levels rise and lower. Water flow changes tend to be the driving force behind algal growth and reproduction levels when influenced by outside anthropogenic and environmental effects. In the two studies above, algal indicators were used to show how these changes affected the river ecosystems. Gaining a visual representation of how the river systems are being affected allows for management systems and plans to be put in place in the areas that need it the most.

5.2. Lake indicator species

Algal distribution in lakes around the world can tell us a lot about the lake's water quality, nutrient distribution in the lake, and even information about the trophic levels in the water. As these factors are being monitored, discoveries are being made on ways aquatic indicator species can be used to assess how lakes are vulnerable to anthropogenic impacts. Monitoring these factors allows the lakes to be sustainably protected and managed (El-Serehy et al., 2018).

One study conducted in Ugandan lakes explored the different algae present and tested which ones could be used as indicators for the different trophic levels. They selected 26 out of 75 of the freshwater crater lakes in the area ranging from depths of 2 m and 220 m and recorded the number of phytoplankton cells counted, as well as the number of different phytoplankton taxa.

The lakes were selected to cover the "full regional gradient of aquatic productivity" and the amount of human impact on them (Nankabirwa et al., 2019). Cyanobacteria were documented to occupy the majority of the lakes in this area. One cyanobacteria species, *Planktolyngbya limnetica,* was dominant when productivity levels were low (6.1 µg/L) while another species, *Microcystis aeruginosa*, was dominant when productivity levels were high (134.7 µg/L) (Nankabirwa et al., 2019). When productivity levels were a bit higher, around 24.6 µg/L, the cyanobacteria species that were typically found included *Cylindrospermopsis raciborskii* and *Synechococcus elongates.* The third level identified in this study was dominated by *Merismopedia tenuissima* and *Synechococcus* sp. 1 with the productivity levels around 29.9 µg/L (Nankabirwa et al., 2019). The study showed that 12 out of 25 phytoplankton species studied could be considered significant indicators of different trophic levels and that four trophic levels could be identified present in these lakes (Nankabirwa et al., 2019).

Another study conducted in a lake explored the water quality and trophic state present in five of the deep lakes near the Alps. To collect the data, monthly samples were taken from each of the five lakes at depth ranges between 251 m and 410 m, then analyzed in the lab using comparative methods. The data showed that certain phytoplankton species and groups were regularly found throughout different seasons as the ecosystem changed. Some of the algal groups documented were highly dominant in those lakes that were considered more eutrophic than the others and were found to be on the higher end of the alkalinity gradient they created (Salmaso et al., 2006). However, the data also showed that the trophic status of the southern lakes was worsening (Salmaso et al., 2006). In one lake, specifically Lake Garda, the phytoplankton species *Tribonema* of division Chrysophyta has made more of an appearance over the years (Salmaso et al., 2006). Their presence indicates that the trophic level in this lake is worsening, which is supported by the increase of total phosphorous they documented (Salmaso et al., 2006).

A study in Poland also explored the trophic status of lakes using algae as indicators. In this study, they collected samples once a month at the deepest depths and a northern point in Lake Kortowskie, then analyzed the samples quantitatively. Like the other two studies reviewed above, the samples showed seasonal changes that were expected in the phytoplankton biomass. The values collected indicated high levels of eutrophication were present, aligning with the status of Lake Kortowskie as eutrophic (Jaworska et al., 2014). The previous studies conducted showed the group Dinophyceae was the dominant phytoplankton group. In this study, however, it shows blue-green algae as being dominant over the Dinophyceae group and even possibly resulting in blooms of them (Jaworska et al., 2014). These findings indicated a high trophic level in this lake, qualifying its' ecological status as bad (Jaworska et al., 2014).

The use of algal indicators can be highly valuable when assessing things such as water quality in lake waters. It is especially useful in lakes that are highly susceptible to anthropogenic impacts, such as the ones studied above. In each of these studies, the indicator species gave a picture of the trophic levels within the lakes, allowing the researchers to conduct the studies to determine if the lake was experiencing eutrophication and whether it's ecological status could be considered good or bad. From there, the management plans and sustainable protection plans can be implemented.

6. Saltwater examples of algal indicator species

In recent years, scientists have been paying closer attention to the saltwater algae and phytoplankton indicator species. The monitoring of these algal groups or species has proved important for the overall health of coastal waters. Pollution and eutrophication from freshwater flowing into coastal waters from rivers could cause nutrients to increase or decrease, effectively throwing the balance of algal species out of the normal ranges.

6.1. Coastal and bay indicator species

Coastal and bay indicator species can be used to inform us of the health of the waters in terms of pollution, runoff, or eutrophication. These factors cause changes in nutrient levels, specifically nitrogen and phosphorus. As nutrient levels increase or decrease due to these factors, algal biomass can be monitored and a connection can be inferred. Changing nutrient concentrations is the driving force behind increased primary production and the growth of coastal algae (Jaanus et al., 2009). In coastal waters, the primary source for this increase is from total nitrogen and total phosphorous concentrations. By monitoring the responses in phytoplankton, the levels can also be tracked, and the source for the nutrient changes can be found.

A study done in the Baltic coastal waters was aimed to identify species and groups of algae that could be used to monitor eutrophication by connecting them to changing nutrient levels (Jaanus et al., 2009). The researchers in this study used “ships of opportunity” where they would board ferry vessels weekly and conduct the analysis onboard over eight years, from 1997 to 2005. They found that the mean of total phosphorous and total nitrogen levels in the coastal waters were higher near the Finnish coast and only slightly higher near the Estonia coast (Jaanus et al., 2009).

Three diatom species exhibited strong relationships with the observed nutrients near the Finnish coast. Two of these observed diatom species, *Cyclotella choctawhatcheeana* and *Cylindrotheca closterium*, were present with differing total phosphorous concentrations. In contrast, the third diatom species, *Skeletonema costatum*, showed correlations with nitrogen and dissolved inorganic matter levels (Jaanus et al., 2009). The authors concluded that the most highly notable changes in biomass were during June and July, with July being the popular growth month for cyanobacteria followed by a slow down in August. With this type of information, researchers can identify which months are most important for monitoring and which species will allow them to asses the water quality in the coastal waters (Jaanus et al., 2009).

Some researchers have discovered that algae indicator species can be used to determine the origin point of algal blooms. In Willapa Bay, Washington, scientists have utilized this method of identification to find where species-specific phytoplankton blooms originated. According to this study, previous papers had shown an oceanic influence within the estuary, causing part of the bay to receive direct ocean water influx (Newton and Horner, 2003). Some of this inflow has recently been found to be caused by wind-induced currents. The endemic phytoplankton populations exhibited nitrogenous nutrient limitation, meaning the blooms could only happen when nitrogen concentrations were sustainable. This prompted the question of whether the algae in the area were being imported from the ocean influx or if the flow was causing nutrient changes in the bay, allowing the endemic populations to bloom (Newton and Horner, 2003). The results from this study indicated that Willapa Bay experiences strong seasonality with high salinity and low water temperatures, indicating the oceanic inflow into the bay (Newton and Horner, 2003). In analyzing the primary production levels between oceanic phytoplankton and endemic bay populations, it was deemed that the blooms were due to oceanic phytoplankton, specifically *Pseudonitzschia* spp., drifting into the bay on the oceanic inflow rather than endemic populations blooming due to nitrogen concentration increases, as primary production was higher when oceanic species were present (Newton and Horner, 2003).

A study conducted in Discovery Bay, Jamaica utilized phytoplankton indicator species to assess the water quality and see if the negative impacts to the bay were enough to affect it. The authors observed roughly 120 species of phytoplankton, consisting mostly of diatoms and marginally of dinoflagellates (Webber et al., 2005). The eastern and southwestern areas of the bay exhibited low salinities, high light and high nitrates present, allowing Webber et al. to conclude that these areas were likely the more “eutrophic” zones of the bay. Despite this, however, the dominance of diatoms deemed the bay as not eutrophic, since most eutrophic areas are characterized by dinoflagellates being dominant (Webber et al., 2005). After reviewing each of the species found at the different test stations with past data, it was found that Discovery Bay could not be considered polluted, but pristine, providing a baseline for phytoplankton communities and conditions (Webber et al., 2005).

The use of indicator species in bays and coastal waters allows us to identify outstanding effects on the water quality and find the source behind them. The study done in Willapa Bay similarly used them by identifying the different species in the bay and the ocean, then determining which ones were present when the algal blooms occurred. In Discovery Bay, researchers used them to identify whether the bay was undergoing eutrophication. Jaanus et al. conducted a similar experiment concerning eutrophication. These studies show just how helpful algal indicator species can be in monitoring water quality, especially in areas where freshwater input is located.

6.2. Pelagic indicator species

Algal indicator species in pelagic waters have not been studied as carefully as those in other bodies of water. Since most of the pelagic waters do not necessarily have a direct effect on the human population, they are not given as much attention as those that can offer us much-needed information about the health of our vital waters. Researchers, however, have conducted a few studies on them to observe seasonal and oceanographic changes. These factors can show us how and if ocean acidification or climate change is taking place in these different areas.

Silva et al. (2013) conducted an experiment in the pelagic waters in the vicinity of the Azores islands to describe patterns and processes by looking at oceanographic changes at the surface. The authors primarily looked at coccolithophores, as they've been known to have a possible sensitivity to climate change and ocean acidification (Silva et al., 2013). Coccolithophores, dinoflagellates, and diatoms accounted for the majority of the documented biomass, with coccolithophores dominating during the spring in some areas and dinoflagellates dominating in the summer in other areas. Spatial and temporal distributions changed with the seasons as surface circulation brings southern warmer waters and northern colder waters together. The diatom biomass served to indicate nutrient enrichment, while dinoflagellates showed physical stability in the surface waters (Silva et al., 2013). Coccolithophore presence indicates summer conditions of reduced nutrient availability and reduced mixing of waters (Silva et al., 2013). The authors concluded that, with the gathered data, coccolithophores could be used to monitor surface conditions and oceanographic changes.

A study on pelagic indicator species was also conducted in the Southern Ocean in 2016. In this study, the authors observed the interaction of these algae with varying nutrients to study the Southern ocean's ecosystem function and cycles. The indicator species observed consisted mainly of diatoms with a few dinoflagellates mixed in (Zhu et al., 2016). The waters of Antarctica were so rich in nutrients that even when there was high biomass of the algae, nutrients were still available for even more growth. In areas with less abundance of nutrients, there was evidence of their necessity, as blooms resulted in the heavy absences of nutrients, such as in the waters near the Davis area of Antarctica (Zhu et al., 2016). The authors found that the algal blooms and nutrient availability were negatively correlated and could be used to monitor when new nutrients are available in some areas of the Southern Ocean.

One of the few instances where pelagic waters do have an effect on human populations along the coastlines is during red tide blooms. Red tide, caused by the dinoflagellate *Karenia brevis*, has been known to cause respiratory issues in humans and kill sea life in the surrounding areas (Weisberg et al., 2019). The worst of these blooms was in 2018, when the event lasted an extended period of time from September 2017 to January 2019. Researchers conducted a study using an underwater glider to observe the water during these events to explain why this event was so long. They concluded that the bloom was actually due to the 2017 event being supported further by the event hypothesized to occur in 2018, causing it to remain an issue for an extended period of time (Weisberg et al., 2019). This occurred due to the Loop Current persisting in the Gulf of Mexico but remaining distant from the Dry Tortugas, which caused an upwelling to bring nutrient-rich waters from the deep ocean to the continental shelf on the coast (Weisberg et al., 2019). This data allows us to continue to monitor the blooms, more readily predicting when the next one will occur and how long it will last.

Pelagic waters do not usually directly affect human populations on the coast or along other water sources, as the algae located in these waters do not necessarily make it into any of these critical areas. Few studies have been conducted in these areas as a result of this. Some of the ones that have been conducted, however, show how studying these algae can be beneficial to us. By looking at the indicator species located in pelagic waters as the studies above do, we can document oceanographic changes, nutrient enrichment, and surface conditions over time.

7. Conclusion

Many of the experiments reviewed above observed algal indicator species in their natural habitat and documented how they can be used to monitor specific changes in the environment. In the coastal Baltic Sea, the months of June and July were observed to be the most critical months for increases in algal biomass with July being dominated by cyanobacteria (Jaanus et al., 2009). The trophic status in the lakes south of the Alps was found to be worsening, as an increase in the Chrysophyta taxa *Tribonema* has been more noticeable (Salmaso et al., 2006). Qu et al. found that agricultural land use was improving the algae population while urbanized land use had detrimental effects on the algal biomass in the rivers around these areas. Coccolithophores were documented to be ideal for the monitoring of ocean acidification and sea surface patterns (Silva et al., 2013). Each of these experiments exhibits how algae not only reacts to changes in the environment but can be used to study those changes. The monitoring of these changes could prove to allow us the ability to predict how future changes to the environment, whether natural or anthropogenically-driven, could affect our ecosystem.

Algae play an essential role in our ecosystem. While they are responsible for about half of the world’s oxygen supply, they also play a part in consuming part of the carbon dioxide present in the Earth’s atmosphere via an air-sea interface. They are, therefore, an important, vital piece in the delicate balance of our ecosystem. While many of the species of algae may be invisible to the naked eye, their impact on our surrounding world is immense. As stated in some of the studies above, the algal indicator species have allowed us to learn vast amounts of information about the water around us. From being able to document the patterns in oceanographic conditions to monitoring pollution levels in water with certain species, many algal species and groups serve as indicators of change in the natural balance. As temperatures shift, nutrient concentrations increase or decrease, and light availability shifts with the seasons, scientists have learned to interpret the appearances or disappearances of algae in different areas. Based on the results of findings like the studies above, we can gain a better understanding of how we are affecting our world and how the natural order of things works.

References

Barnes, D. K., & Tarling, G. A. (2017). Polar oceans in a changing climate. *Current Biology*, *27*(11), R454-R460.

Capone, D. G., Bronk, D. A., Mulholland, M. R., & Carpenter, E. J. (Eds.). (2008). *Nitrogen in the marine environment*. Elsevier.

Chen, B. (2015). Patterns of thermal limits of phytoplankton. *Journal of Plankton Research*, *37*(2), 285-292.

Dagg, M. J., Bianchi, T., McKee, B., & Powell, R. (2008). Fates of dissolved and particulate materials from the Mississippi river immediately after discharge into the northern Gulf of Mexico, USA, during a period of low wind stress. *Continental Shelf Research*, *28*(12), 1443-1450.

Devercelli, M., & O’Farrell, I. (2013). Factors affecting the structure and maintenance of phytoplankton functional groups in a nutrient rich lowland river. *Limnologica*, *43*(2), 67-78.

El-Serehy, H. A., Abdallah, H. S., Al-Misned, F. A., Al-Farraj, S. A., & Al-Rasheid, K. A. (2018). Assessing water quality and classifying trophic status for scientifically based managing the water resources of the Lake Timsah, the lake with salinity stratification along the Suez Canal. *Saudi Journal of Biological Sciences*, *25*(7), 1247-1256.

Häder, D. P., Banaszak, A. T., Villafañe, V. E., Narvarte, M. A., González, R. A., & Helbling, E. W. (2020). Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Science of The Total Environment*, 136586.

Ittekkot, V., Unger, D., Humborg, C., & An, N. T. (Eds.). (2012). *The silicon cycle: human perturbations and impacts on aquatic systems* (Vol. 66). Island Press.

Jaanus, A., Toming, K., Hällfors, S., Kaljurand, K., & Lips, I. (2009). Potential phytoplankton indicator species for monitoring Baltic coastal waters in the summer period. In *Eutrophication in Coastal Ecosystems* (pp. 157-168). Springer, Dordrecht.

Järvinen, M., Drakare, S., Free, G., Lyche-Solheim, A., Phillips, G., Skjelbred, B., ... & Pasztaleniec, A. (2013). Phytoplankton indicator taxa for reference conditions in Northern and Central European lowland lakes. *Hydrobiologia*, *704*(1), 97-113.

Jaworska, B., Dunalska, J., Górniak, D., & Bowszys, M. (2014). Phytoplankton dominance structure and abundance as indicators of the trophic state and ecological status of Lake

Kortowskie (northeast Poland) restored with selective hypolimnetic withdrawal. *Archives of Polish Fisheries*, *22*(1), 7-15.

Liu, C., Sun, Q., Xing, Q., Wang, S., Tang, D., Zhu, D., & Xing, X. (2019). Variability in phytoplankton biomass and effects of sea surface temperature based on satellite data from the Yellow Sea, China. *PloS one*, *14*(8).

Mesquita, M. C., Prestes, A. C. C., Gomes, A. M., & Marinho, M. M. (2020). Direct Effects of Temperature on Growth of Different Tropical Phytoplankton Species. *Microbial ecology*, *79*(1), 1-11.

Miao, Z., & Yang, D. (2009). Solar light, seawater temperature, and nutrients, which one is more important in affecting phytoplankton growth?. *Chinese Journal of Oceanology and Limnology*, *27*(4), 825-831.

Mosleh, M. A., Manssor, H., Malek, S., Milow, P., & Salleh, A. (2012, December). A preliminary study on automated freshwater algae recognition and classification system. In *BMC bioinformatics* (Vol. 13, No. S17, p. S25). BioMed Central.

Nankabirwa, A., De Crop, W., Van der Meeren, T., Cocquyt, C., Plisnier, P. D., Balirwa, J., & Verschuren, D. (2019). Phytoplankton communities in the crater lakes of western Uganda, and their indicator species in relation to lake trophic status. *Ecological Indicators*, *107*, 105563.

Newton, J. A., & Horner, R. A. (2003). Use of phytoplankton species indicators to track the origin of phytoplankton blooms in Willapa Bay, Washington. *Estuaries*, *267*(4), 1071-1078.

Parmar, T. K., Rawtani, D., & Agrawal, Y. K. (2016). Bioindicators: the natural indicator of environmental pollution. *Frontiers in life science*, *9*(2), 110-118.

Qu, Y., Wu, N., Guse, B., Makarevičiūtė, K., Sun, X., & Fohrer, N. (2019). Riverine phytoplankton functional groups response to multiple stressors variously depending on hydrological periods. *Ecological indicators*, *101,* 41-49.

Racault, M. F., Sathyendranath, S., Brewin, R. J., Raitsos, D. E., Jackson, T., & Platt, T. (2017). Impact of El Niño variability on oceanic phytoplankton. *Frontiers in Marine Science*, *4*, 133.

Salmaso, N., Morabito, G., Buzzi, F., Garibaldi, L., Simona, M., & Mosello, R. (2006). Phytoplankton as an indicator of the water quality of the deep lakes south of the Alps. Hydrobiologia, 563(1), 167-187.

Salmaso, N., Naselli-Flores, L., & Padisák, J. (2012). Impairing the largest and most productive forest on our planet: how do human activities impact phytoplankton?. In *Phytoplankton responses to human impacts at different scales* (pp. 375-384). Springer, Dordrecht.

Semina, H. J. (1997). An outline of the geographical distribution of oceanic phytoplankton. In *Advances in marine biology* (Vol. 32, pp. 527-563). Academic Press.

Silva, A., Brotas, V., Valente, A., Sá, C., Diniz, T., Patarra, R. F., ... & Neto, A. I. (2013). Coccolithophore species as indicators of surface oceanographic conditions in the vicinity of Azores islands. *Estuarine, Coastal and Shelf Science*, *118,* 50-59.

Sin, Y., & Jeong, B. (2015). Short-term variations of phytoplankton communities in response to anthropogenic stressors in a highly altered temperate estuary. *Estuarine, Coastal and Shelf Science*, *156*, 83-91.

Venrick, E. L. (1993). Phytoplankton seasonality in the central North Pacific: the endless summer reconsidered. *Limnology and Oceanography*, *38*(6), 1135-114.

Webber, M., Edwards-Myers, E., Campbell, C., & Webber, D. (2005). Phytoplankton and zooplankton as indicators of water quality in Discovery Bay, Jamaica. *Hydrobiologia*, *545*(1), 177-193.

Weisberg, R. H., Liu, Y., Lembke, C., Hu, C., Hubbard, K., & Garrett, M. (2019). The coastal ocean circulation influence on the 2018 West Florida Shelf *K. brevis* red tide bloom. *Journal of Geophysical Research: Oceans*, *124.*

Zhu, G. H., Jin, M., Feng, W. H., Liu, Z. L., Han, Z. B., & Hu, C. Y. (2016). Study On The Relationship Between Phytoplankton Indicator Species With Nutrient Contents In The Southern Ocean. *International Journal of Simulation--Systems, Science & Technology*, *17*(20).