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The role of Phytoplankton and climate change in marine ecosystems: from a biologist's point of view.

El papel del Fitoplancton y el cambio climático en los ecosistemas marinos: desde el punto de vista de un biólogo.

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ABSTRACT

The purpose of the present manuscript is pointing out the current state of knowledge of role of Phytoplankton and affections by climatic change. In this review we describe the ecological, biological and chemical importance of phytoplankton and its key role on trophodynamics in food webs. Thus, the manuscript abords some effects on phytoplankton by climatic change: Phytoplankton composition, Biomass reduction, migration of phytoplankton to poles, Acidification of oceans and proliferation of certain species and finally the proliferation of harmful algal blooms. Some mitigation and remediation actions are: use of clean and renewable energy, reduction of CO_2 emissions, reduction of nutrient runoffs to basin and recycling are some actually strategies in use to reduce the impact of human activities to climatic change.

Keywords: phytoplankton, climatic change, CO_2 emissions, Ocean Acidification, harmful algal blooms

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RESUMEN

El propósito del presente manuscrito es puntualizar el estado de conocimiento de la función del Fitoplancton y sus afecciones por el cambio climático. En esta revisión, describimos la importancia ecológica, biológica y química del fitoplancton y su rol en la trofodinámica en las cadenas alimenticias. Así también se aborda los efectos del cambio climático sobre el fitoplancton: composición del fitoplancton, la reducción en biomasa, migración del fitoplancton hacia los polos, acidificación de los océanos y la aparición de ciertas especies y la proliferación de los florecimientos algales nocivos. Algunas medidas de mitigación y remediación son: el uso el uso de energía limpia y renovable, la reducción de las emisiones de CO_2, reducción de efluentes con nutrientes en las cuencas y el reciclado son algunas de las estrategias actuales para reducir el impacto de las actividades humanas sobre el cambio climático.

***Palabras Clave**:* Fitoplancton, Cambio climático, Emisiones de CO_2, Acidificación del Océano, Florecimientos algales nocivos.

INTRODUCTIÓN

Sea water contain several dissolved species including small cells called plankton. Plankton consists of two different taxa: phytoplankton and zooplankton. Phytoplankton is well represented by diatoms and dinoflagellates as calcarean microalgae (coccolithophores), green and yellow microalgae: pelagophytes and prasinophytes. And also, zooplankton species, which feed on phytoplankton Zooplankton is another component of ecological and biological importance for food webs (Field et al., 1998).They are found in superficial layer of the water column wherein the solar radiation is common until it reaches 200 m. These conditions include the production of oxygen, recycling from several nutrients, removal of CO_2 from the atmosphere and producing organic biomass through primary production (Winder & Sommer, 2012).

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Zooplankton are animals (i.e. Krill), and phytoplankton are plants. As most plants do, phytoplankton can produce oxygen by photosynthesis when sufficient light is available, i.e.., in the photic layer of the ocean during the daytime. The oxygen first comes to the water and eventually into the air through the sea surface, thus contributing to the total oxygen budget in the atmosphere. This contribution appears to be massive: It is estimated that about 70% of the Earth atmospheric oxygen is produced by the ocean phytoplankton (Harris, 1986; Moss, 2010).

Plankton not only is a key element of the marine food web, but also have a significant effect on the climate (Charlson et al., 1987; Williamson & Gribbin, 1991) and the composition of the atmosphere, in particular on the amount of oxygen (Harris, 1986; Moss, 2009). Comparing the phytoplankton biomass to land and wet plants, phytoplankton represent just a few 1% which corresponds to global biomass of the world. However, is more efficient in the production of O_2 and the best in capture atmospheric CO_2.

This biological carbon pump exports approximately 5–12 gigatonnes of carbon per year, from the surface to the mesopelagic layer, from which approximately 0.2 Gigatonnes is stored in sediment for millennia (Ciais et al., 2013), thus contributing to the vertical gradient of carbon in the ocean.

Correspondingly, one can expect that a decrease in the rate of the oxygen production by phytoplankton may have catastrophic consequences for life on Earth, possibly resulting in mass extinction of animal species, including the mankind. Therefore, identification of potential threats to the oxygen production is literally an issue of vital importance.

For these reasons phytoplankton in our world is a keystone to limnetic, marine, and brackish water are supported in and provides food source to all living organisms including to human beings.

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1.- Phytoplankton in oceans

1.1 Base of Food Web

In nature, phytoplankton are composed by chlorophyll cells and are responsible for the photosynthesis process, in order to produce organic compound since inorganic compounds (Equation 1). According to Pimm & Cohen (1991), phytoplankton is considered as the first step of food chain and plays a key role in the transferring of nutrients and energy helping to support ecological ecosystems.

Hypothetically a food chain is compound by several steps as primary producers, primary consumers, secondary consumers, tertiary consumers, omnivorous and apex predators. Primary producers are phytoplankton, green plants, seaweeds and phytobenthos, they are capable of transferring nutrients to upper steps e.g. primary consumers: Zooplankton, Filtering feeders: bivalves, detritivores biota: crabs and snails, small fishes until enormous whales (Pershing & Stamieszkin, 2020). Trying to figure it out the number of plankton required to keep in good health to these giants of oceans, practically is impossible to quantify the budget of organic matter to consume by these big whales. Indicating unequivocally the importance of phytoplankton in aquatic ecosystems. In Figure 1, different type of phytoplankton and Zooplankton located in nearly coast of Mazatlan Bay are showed.

Also is known about the scarcity of plankton and the negative impact of food webs, inclusive provoking a cascading effect wherein some trophic nodes are dissolved by the absent of plankton capable of supporting the food webs (Murphy et al., 2019). Therefore, is vital to monitoring the level of nutrients (carbon, nitrogen and phosphorous) in order to reduce the excess of nutrients and diminishing presence of toxic phytoplankton that may produce deleterious effects in biota and death even.

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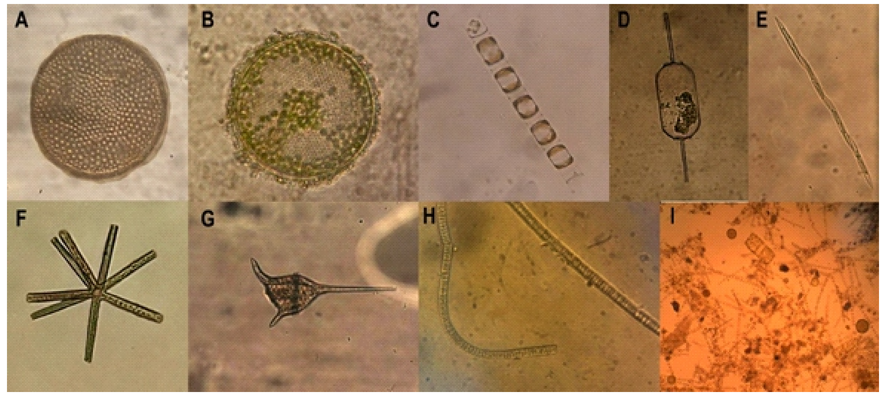
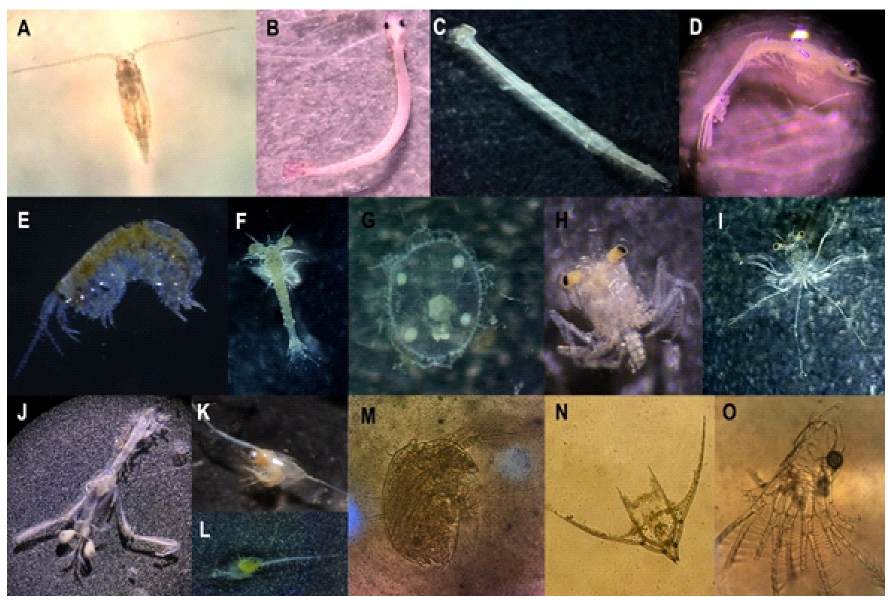


Fig. 1. Phytoplankton: A. *Coscinodiscus sp,* B. *Coscinodiscus granii*, C. *Skeletonema costatum,* D. *Ditylum brightwelli,* E. *Pseudo-nitzschia pungens*, F. *Thalassionema nitzschioides*, G. *Ceratium sp*, H. Filamentous cyanobacteria, I. Mix of phytoplankton 10X objective.



A. Copepode, B Fish larva, C. Chaetognatha, D Shrimp postlarvae, E. Amphipods, F. Shrimp zoea, G. Jellyfish larva, H. Megalopa of brachiura, I. Lobster Phyllosoma J. Stomatopod, K. Zoeae of brachiura, L. Zoea of brachiura, M. nauplius, N. Equinoderm larvae, O. Barnacle exuvium.

1.1 Oxygen production

Due to physiological condition as primary producers; phytoplankton, macroalgae and cyanobacteria are capable of produce oxygen as a waste subproduct in the following reaction:

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$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{Sun light}} \underset{\text{Sugar}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6\ O_2} \quad \text{(Equation 1)}$$

The photosynthesis reaction starts with two keys reactive: 6 molecules of CO_2 and 6 molecules of H_2O molecules in presence of light (400-700 nm), as a result the formation of sugar (glucose: energy) and a sub product six molecules of appreciated oxygen. In this way, primary producers transform the old and toxic atmosphere to an oxidative atmosphere capable to support life in both: terrestrial crust and oceans.

In the global oxygen production, oceans apport to atmosphere about 50 and 85 % of oxygen per year to earth planet. The O_2 annual budget is at least 27.000 million of tons per year. In other words: six of seven oxygen molecules come from oceans. The "responsible" of these productions are microalgae and cyanobacteria (Dwivedi & Ahmad, 2023).

On June 6th 2024, Sweetman et al. (2024) reported evidence of "dark oxygen production" at abyssal sea floor using chamber experiments and polymetallic nodules-covered abyssal seafloor, in which O_2 increased over two days more than 3 times the background concentrations, which from *ex situ* incubations, attributing to polymetallic nodules. They hypothesized the sea water electrolysis may contribute to this dark oxygen production.

2.- Key factors which affect the phytoplanktonic composition:

Phytoplankton dynamics are linked to several factors as annual fluctuations of temperature, water column stratification, light availability, and consumption by predation: grazing (Sommer et al., 1989; Cloern, 1996).

Temperature directly affects plant metabolism, which consists of both photosynthetic and respiratory activity, while metabolic rates of primary producers are primarily limited by photosynthesis (Dewar et al., 1999).

Vertical mixing is one of the key variables that conditions the growth performance of phytoplankton within the water column (Diehl et al., 2002; Salmaso, 2005), because mixing processes are usually

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accompanied by changes in resource availability of light and nutrients. Vertical mixing of natural waters is largely determined by meteorological variables. Heat exchange processes and wind action create two opposing tendencies—the tendency to stratify and suppress mixing, and the tendency for inputs of turbulent kinetic energy to promote mixing (Wetzel, 2001). The seasonal cycle of summer stratification and winter mixing is a product of the time varying nature of these two tendencies.

2.1 Effects of global warming on phytoplankton composition

As mention in previous paragraphs, water mixing also affects nutrient availability for phytoplankton growth. Enhanced water column stratification suppresses the upward flux nutrients from deep-waters layer trough vertical mixing resulting in more nutrient-depleted conditions in surface water (Livingstone, 2003; Schnittner et al., 2005). Also altering mixing regimens affects the competitive advantage of specifical algal cell type, that are better competitor for nutrients (Falkowski & Oliver, 2007) and are able to maintain their vertical position in the water column (Huisman et al., 2004) (Fig. 2).

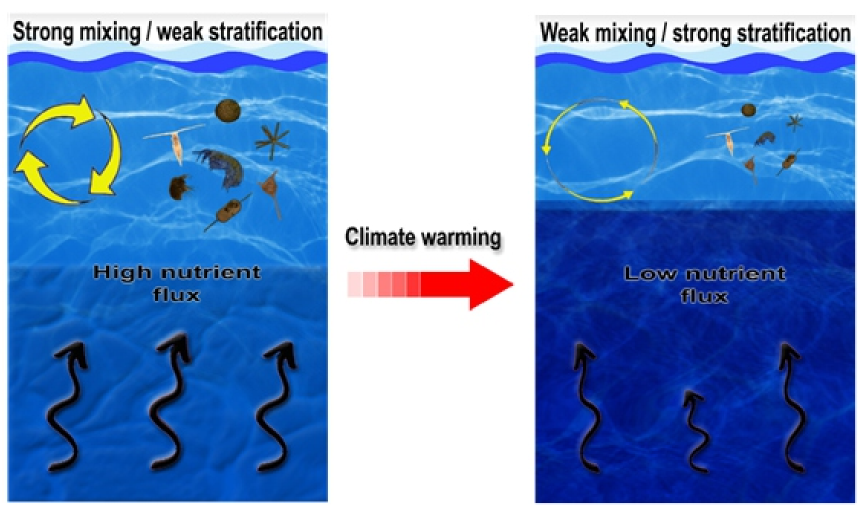

Fig. 2. Global warming effect on water column stratification (yellow arrows), associated nutrient distribution (black arrows) and plankton communities, modified from Winder & Sommer (2012).

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In eutrophic ecosystems, there is a reduction of vertical mixing will shift the competitive advantage between buoyant cyanobacteria and sinking phytoplankton species (Huisman et al., 2004). Intense stratification can also increase hypolimnetic oxygen with oxygen depletion which has increased consequences for internal nutrient loading both for lake and oceans. Also, climatic change may increase the phosphorous natural budget due to anoxic conditions resulting from the eutrophication process.

Climatic change effect is observed in the frequent of plentiful rains and droughts since 1970´s. provoking changes in the nutrient profiles in runoffs to aquatic environments (IPCC, 2007). Increasing the runoff, also may modify the nutrient ratios in certain type of systems depending on some factors: biogeochemical cycles, adaptation and type of phytoplankton.

For example, phytoplankton and cyanobacteria biomass is related to air temperature that controls the export of nitrogen and dissolved organic carbon from basin. Indicating that climatic change affects the balance between phytoplankton and bacterial production (Jansson et al., 2010).

For coastal region, like Mazatlan city, enhanced upwelling due to increasing temperature gradient between land and sea which will increase nutrient availability and stimulate the phytoplankton production (Rabalais et al., 2002). The main factors that commonly cause hypoxia are stratification and excess nutrient supply. Strong density stratification isolates deeper layers from the surface, where the most important inputs (gas exchange and photosynthesis) occur. A large nutrient supply induces high primary production and algal blooms in the surface and causes hypoxia in two ways: the resulting turbidity limits light penetration and inhibits primary production in deeper layers, and the organic matter excess depletes the available oxygen when it is consumed and oxidated (Fennel & Testa, 2019). This phenomenon is seen particularly in estuarine and costal lagoon, wherein high mortalities of fish occurred by depletion of oxygen in the aquatic systems.

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2.2 Climate effects on phytoplankton profile

The abundance of phytoplankton, distribution, size and structure of phytoplankton depends on some factors as resource availability, density dependence and predation that shape the phytoplankton profile.

Despite this complexity of interacting processes, some widespread climate- related responses have emerged, and the mechanisms involved in climate-related changes are becoming better understood (Richardson, 2008; Adrian et al., 2009). Impacts of climate change on plankton are mainly manifested as shifts in seasonal dynamics, species composition, and population size structure.

2.3 Global warming and phytoplankton biomass reduction

Global warming affects on phytoplankton proliferation and biomass by the stratification of the water column, this implicates an unadequate flux of nutrients and posteriorly the mix of those nutrients reducing the availability of nutrients and the proliferation of phytoplankton.

Behrenfeld et al. (2009) by using satellite data pointed out a significant decrease in phytoplankton and primary production in tropical and subtropical oceans due an ocean stratification caused by warmer surface water, which prevents nutrient-rich water from mixing upwards.

2.4 Global warming and changes in size and phytoplankton structure

Daufresne et al. (2009) found that global warming benefits smaller organisms in aquatic ecosystems by causing a general reduction in the body size of aquatic life. This change in body size occurs across multiple levels of biological organization, from individuals to entire communities. The researchers concluded that this trend is a universal ecological response to global warming, along with shifts in species ranges and seasonal shifts in life cycle event

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3. Phytoplankton and migrations to poles

There is evidence of restricting of marine plankton assemblages under global warming. Beneditti et al. (2021) use an ensemble of species distribution models for a total of 336 phytoplankton and 524 zooplankton species to determine their present and future habitat suitability patterns. For the end of this century, under a high emission scenario, they pointing out an overall increase in plankton species driven by ocean warming, and a poleward shift of the species distributions at a median speed of 35 km/decade.

Phytoplankton species richness is projected to increase by more than 16% over most regions except for the Arctic Ocean. In contrast, zooplankton richness is projected to slightly decline in the tropics, but to increase strongly in temperate to subpolar latitudes. In these latitudes, nearly 40% of the phytoplankton and zooplankton assemblages are replaced by poleward shifting species. This implies that climate change threatens the contribution of plankton communities to plankton-mediated ecosystem services such as biological carbon sequestration.

Furthermore, Agarwal et al. (2024), detected a change in the color in the oceans. From tropical regions related to the increase or diminish of diverse types of phytoplankton. This change of color in chlorophyl indicates a structural change in phytoplanktonic composition.

Also, Cael et al. (2023) analyzed more than 20 years of continuous data were thought to be needed to detect a trend driven by climate change. They show that climate-change trends emerge more rapidly in ocean color (remote-sensing reflectance, R_{rs}). The focus in a 20-year time series from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite, and find significant trends in R_{rs} for 56% of the global surface ocean, mainly equatorward of 40°.

The climate-change signal in R_{rs} emerges after 20 years in similar regions covering a similar fraction of the ocean in a state-of-the-art ecosystem model, which suggests that observed trends indicate shifts in ocean colour-and, by extension, in surface-ocean ecosystems-that are driven by climate change. On the whole, low-latitude oceans have become greener in the past 20 years.

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4. Acidification of oceans and phytoplankton:

The constant and increasing levels of CO_2 provokes the acidification in oceans. Furthermore, being the habitat for many species, oceans are like carbon sinkers dumpers absorbing 30% of the CO_2 that human release to atmosphere. Some chemical compounds are involving CO_2, H_2O and $HCO_{3,}$ the chemical volatility of HCO_3 produce an excess of H^+ which reacts with CO_3 becoming acid conditions to oceans. Since the Industrial Revolution, the average pH of surface ocean waters has fallen by approximately 0.1 pH units, which represents a roughly 30% increase in acidity (Middelburg et al., 2020).

Dutkiewicz et al., (2015) used a numeric method in order to show the impact of oceanic acidification and global warming in the structure of phytoplankton, resulting effects for the next 2100 years. 96 species were tested under future adverse conditions instead a single reaction by specie. They found a global phytoplankton restructure by acidification. Some species non calcareous like cyanobacteria will be benefit by increasing of CO_2 and but no good prognostic was shown for calcarous cells.

Calcarous phytoplankton (called cocolitophores) they will be detrimental by decreasing the pH scale. Provoking acid conditions, affecting to this kind of phytoplankton, its growth and consequently survival. Therefore, migration of phytoplankton to avoid adverse conditions forcing to them to look for better locations for its proliferation (poles) (Middelburg et al., 2020).

Finally, the acidification and global warming provoke an alteration in high scale, resulting in alterations and breaking down of some trophic relationship (prey-predator), occasioning a trophic collapse in sensitive food webs and alteration in biogeochemical process.

5. Harmful algal bloom (HABs)

The harmful algal blooms occurs when microscopic algal colonies (phytoplankton, diatoms, dinoflagellates and cyanobacterias) growth so fast and uncontrolled way until reach high concentration (thousands or millions of cellules per mililiter (Well et al., 2021).

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They are not harmful for its fast growing (often coloring the surface water of red or green colors), is because the provoke:

1.- Toxins: toxic compounds (phycotoxines) occasioning deleterious effect in biota and humans.

2.- Hypoxia environments: As soon as harmful phytoplankton died, cyanobacteria readily consume high level of dissolved oxygen to digest them, provoking "death or anoxic zones" where in oxygen levels are depleted.

Considering of HABs as a unique factor that allow the hyper production of this cells is not enough, is required to considers some factors as: increasing CO_2 in sea waters, increasing of temperature, high volumes of nitrogen, iron and phosphorous and acidification of sea. All together provoke the proliferation of these blooms of algae with the consequences previously mentioned.

Its is important to mention that Well et al. (2021) provide a good approach and show the interaction of climatic change and HABs. This material is basic to immersed into HABs and climatic change.

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