

Quantification of Phytoplankton Primary Habitability in the Gulf of Ana María, Cuba



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Abstract The Gulf of Ana Maria is located in the southeast Cuban platform and is one of the most important regions for fisheries in the country. Taking into account that marine primary production defines the areas and yields of fishery production, we develop a habitability index that quantifies the environmental suitability for phytoplankton assemblage development. The index considers light and limiting nutrient as the main environmental factors governing the phytoplankton primary production in the Gulf of Ana María. We considered a function of radiation described by a photosynthesis model and function of nutrient described by a eutrophication index. Quantitative estimates of habitability were made in nine stations at 1:00 PM and 4:00 PM for a typical day of October, in order to match with the available field data. Solar irradiation at sea surface was calculated by using the tropospheric ultraviolet and visible computational code TUV4.6, and we derived the data of attenuation coefficient of light from Secchi depth data. Besides, we used nutrient concentration of soluble reactive phosphorus (limiting nutrient). We obtained the first optical classification of the waters of the Gulf of Ana María, with a dominance of coastal water C5. It was found an intermediate potential (~50%) for phytoplankton development in the Gulf of Ana María, which is mainly limited by nutrients rather than by light. Further refinements in both the index and data collection are expected to reach more accurate conclusions.

Keywords Habitability index · Nutrients · Light

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1 Introduction

Coastal environments are one of the most ecologically and socioeconomically important on the planet. Despite their relatively small coverage (occupying only $\sim 8\%$ of the ocean's surface area), they contribute to 15–30% of global primary production, $>40\%$ of seabed carbon sequestration, and 80% of world fishing capture [1–3]. Coastal ecosystems have an important role in the global biogeochemical cycles of carbon and macronutrients [4], and they are considered buffering systems between the continents and the open ocean. The coastal ocean provides nutrients to the open ocean, and much of these nutrients come from rivers runoff [5]. Some quantitative studies have shown that when the coastal nutrient supply is enhanced, both the coastal ocean and the open ocean primary production and chlorophyll-a (chl-a) concentration increase in comparable amounts [6]. However, in general, coastal phytoplankton assemblages are more sensitive to environmental changes than the oceanic ones [1, 2].

The coastal waters of Cuba are very important for the biogeographic processes affecting the biodiversity of the so-called Great Caribbean Region and for conservation and sustainable use of natural resources in this region [7]. Moreover, it has been reported that several regions of the Cuban coasts fertilized the oligotrophic waters of the Caribbean Sea [8]. However, coastal waters of Cuba are threatened by fishing, tourism, as well as other economic activities associated with the marine platform [7]. Especially, phytoplankton is very vulnerable in some regions of the country due to both natural variability and anthropogenic activity [9].

The main flux of nutrients into the Cuban coastal waters comes from hydrographic basins; thus, damming of rivers has recently caused a reduction of nutrient loading to coastal waters [10, 11]. This situation has affected the Gulf of Ana María (located in southeastern Cuban shelf), whose hydrochemical conditions are characteristics of a coastal zone with excellent interchange of nutrients with the adjacent Caribbean Sea [12]. On the other hand, this region is one of the main fishing areas of the country, so that the productivity of various fisheries resources has declined, such as the shrimp species *Farfantepenaeus notialis* [11, 13–15]. A reduced flow of freshwater into the coastal waters causes a large variability of nutrients concentrations in the area which can affect the phytoplankton photosynthesis rate and the distribution and abundance of organisms of higher levels of the trophic webs. In this way, the potential for life in the ecosystem (i.e., its habitability) could change.

The Quantitative Habitability Theory (QHT) has been developed as a standard framework to quantify changes in the living conditions of a natural environment and to explain the distribution, abundance, and productivity of life [16, 17]. For instance, the Standard Primary Habitability (SPH) is a climatological measure of habitability of a region for most primary producers. It is a normalized scale, where values close to one represent the best environmental conditions for the metabolic activity of most organisms, while values close to zero are unfavorable [16].

The abundance and distribution of phytoplankton can be determined by several variables such as nutrients, salinity, weather conditions (light, temperature, rainfall,

etc.), and the shape of aquatic system (depth, volume, surface area, etc.) [18]. However, [19] considered that solar radiation is a factor of first-order driving photosynthetic activity in marine ecosystems, while nutrient concentration is a second-order factor. Given the estuarine conditions of the Gulf of Ana María, it could be thought that salinity has an important role in influencing primary productivity of phytoplankton assemblages. However, spatiotemporal variability of salinity in this area has been reported to be limited. For instance, it has been demonstrated that salinity was rather homogenous in 38 stations of the Ana María Gulf, during the raining season (October of 2011) with values in the range 36.0–37.3 ups [12]. Besides, in [20], it is reported similar values of salinity (i.e., 36.46–38.31 ups) along the coastal line of the Gulf of Ana María during the transition between dry and raining seasons and during rainy months.

Taking into account the situation previously described, this work aims to determine the habitability potential of phytoplankton in the Gulf of Ana María, through the construction of an Aquatic Primary Habitability Index (APHI), considering light and nutrients as possible environmental regulatory factors of photosynthetic activity.

2 Materials and Methods

2.1 Study Area

The Gulf of Ana María is a big macro-lagoon located in the southern-central shelf of Cuba. It is limited to the north by the provinces of Sancti Spiritus, Ciego de Avila, and Camagüey and to the south by “Jardines de la Reina” archipelago, which regulates the water flows with the adjacent Caribbean Sea. The Gulf of Ana María has a surface area of 9398 km² and an average (maximum) depth of 15 m (30 m) [21]. One of the most relevant characteristics of this geographic basin is determined by rivers, which periodically (although unevenly) contribute to the increase of dissolved nutrients and suspended particles concentration in its waters. The rivers that flow into the Gulf of Ana María are Zaza, Agabama, southern Jatibonico, and San Pedro [12].

2.2 Aquatic Primary Habitability Index

One of the main postulates of QHT is related to the formulation of habitability indexes (HI) as the product of simple functions (f) of a set of environmental variables ($\{x_j\}$) (Eq. 1) that limits the primary productivity of life at any environment [16]:

$$HI = \prod_{i=1}^n f_i(\{x_j\}). \tag{1}$$

Thus, we propose an APHI of the form:

$$APHI = f(R)f(N) \tag{2}$$

where $f(R)$ is a function of solar radiation and $f(N)$ is a function of nutrients.

Radiation function $f(R)$ The photosynthetic potential of phytoplankton in nine stations in the Gulf of Ana María (Fig. 1) was quantified, and the sampling activities were developed in October of 2011. The stations were selected taking into account that the depth of the station was higher than the Secchi depth. The spectral irradiances ($W\ m^{-2}\ nm^{-1}$) of the photosynthetically active radiation (PAR, 400–700 nm) and ultraviolet (UV, 280–399 nm) at the sea surface were determined using the tropospheric ultraviolet and visible computational code TUV 4.6 [22] at 1:00 PM and 4:00 PM and considering solar zenith angles of incidence of 35° and 76°, respectively. These conditions match the sampling campaign.

The spectral irradiances just below the surface ($z = 0^-$), denoted by $E(\lambda, 0^-)$, were obtained from those just above the surface ($z = 0^+$) through the following equation:

$$E(\lambda, 0^-) = [1 - R]E(\lambda, 0^+), \tag{3}$$

where R is the reflection coefficient calculated with Fresnel formulae [23] applied to the interface air–water. The spectral irradiances $E(\lambda, z)$ at depth z were determined using Lambert–Beer’s law of optics as:

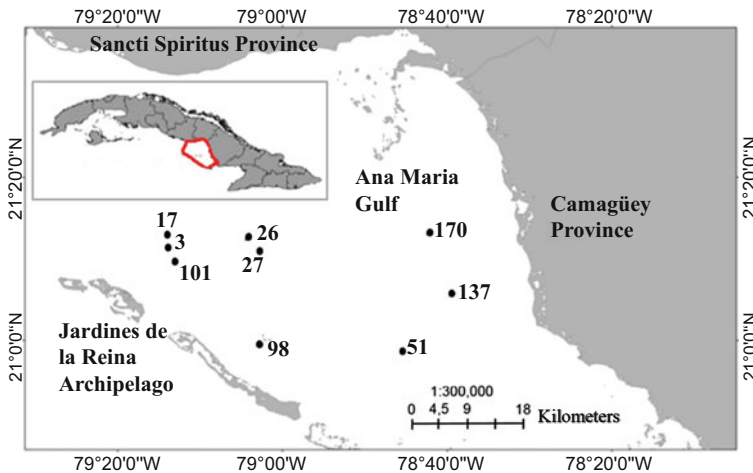


Fig. 1 Study area and sampling stations

$$E(\lambda, z) = E(\lambda, 0^-)e^{-K(\lambda)z}, \tag{4}$$

where $K(\lambda)$ is the light extinction coefficient or so-called attenuation coefficient for the wavelength λ . This parameter is a measure of the vertical light attenuation through the water column [18]. Given to the scarce published studies for the Gulf of Ana María ([12] and references therein), there is not an optical characterization of its marine waters, and consequently, there are not data of attenuation coefficients. In order to determine the optical type of water at each station (and therefore the set of values of $K(\lambda)$), the following empirical relation [24] was used:

$$K = \frac{k}{z_s}, \tag{5}$$

where K is the average attenuation coefficient of water for visible light (PAR), k is a dimensionless constant, which is considered here equal to 2 [24], and z_s is the Secchi depth. z_s together with nutrient concentration were obtained from a field campaign conducted during October 2011 [12]. Once the average attenuation coefficients were obtained through Eq. (5), they were compared with the coefficients of Jerlov [25] (Table 1). The optical water type assigned to each station was the one closer to Jerlov’s value.

Beside the Secchi depth, another way to evaluate the underwater light penetration is to determine the euphotic depth (z_{EU}), which is relatively easy and accurate to estimate [26] by determining the depth at which 1% of the PAR entering the water remains. Making the assumption that K of PAR is approximately constant with depth [23], the euphotic depth is given by the following equation, which was obtained from the Lambert–Beer equation.

$$z_{EU} = \frac{4.6}{K} \tag{6}$$

Equations (7) and (8) were used to determine the irradiances of the photosynthetically usable radiation (PUR) and UV, respectively. The asterisks indicate that

Table 1 Average attenuation coefficients and optical classification of Jerlov for marine waters [25]

Waveband	Coastal waters					Oceanic waters		
	C1	C3	C5	C7	C9	I	II	III
UV	1.35	1.84	2.65	3.18	4.12	0.09	0.30	0.50
PAR	0.29	0.38	0.51	0.71	1.04	0.15	0.19	0.25
UV + PAR	0.59	0.79	1.12	1.41	1.92	0.14	0.21	0.31

both are photometric functions (i.e., they contain biological information through the inclusion of a biological action spectrum):

$$E_{\text{PUR}}^*(z) = \sum_{\lambda=400\text{nm}}^{700\text{nm}} A(\lambda)E(\lambda, z)\Delta\lambda \quad (7)$$

$$E_{\text{UV}}^*(z) = \sum_{\lambda=280\text{nm}}^{399\text{nm}} \varepsilon(\lambda)E(\lambda, z)\Delta\lambda. \quad (8)$$

In the first one, $A(\lambda)$ is the absorptance, the fraction of light absorbed by the cell [23] and $\Delta\lambda = 1$ nm. Considering that in general there are very few studies of phytoplankton assemblages in the Gulf of Ana María, we used the absorption spectrum of the chl-a. This one constitutes most of the chlorophyll present in primary producers [23]. Measurements of this photopigment historically have provided an estimate of algal biomass and its spatial and temporal variability [27]. Chl-a has two main absorption bands in the red and in the blue regions of the spectrum (Fig. 2).

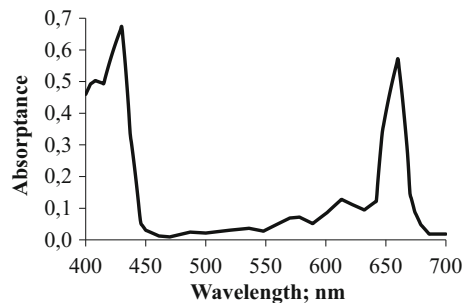
To evaluate the inhibitory effects of UV on photosynthesis, we used the same biological weighting function ($\varepsilon(\lambda)$) used in [29] which is representative of phytoplankton species living in tropical and subtropical latitudes. This function takes into account the photosynthetic apparatus and DNA damages, since both contribute to the inhibition of photosynthesis.

To determine photosynthesis rates ($P(z)$) at depth z normalized with respect to the saturation rate P_S , the photosynthesis E model of [30] was used:

$$\frac{P(z)}{P_S} = \frac{1 - \exp[-E_{\text{PAR}}(z)/E_S]}{1 + E_{\text{UV}}^*(z)}. \quad (10)$$

The parameter E_S accounts for the efficiency with which a species uses PUR; the smaller its value, the greater its efficiency. Taking into account the limited number of studies on phytoplankton in the study area, we assumed, as our first approach, the values $E_S = 2 \text{ W m}^{-2}$ and $E_S = 100 \text{ W m}^{-2}$, which represent a very wide range of this parameter in nature [31, 32].

Fig. 2 Absorptance of the chl-a molecule [28]



The exact value of $f(R)$ was determined through Eq. (11), which represents the total photosynthetic potential $(P/P_S)_T$, but normalized to the station depth z_{\max} . $(P/P_S)_T$ was calculated by splitting the water column into N layers of thickness $\Delta z = 1$ m:

$$f(R) = \left(\frac{P}{P_S} \right)_T = \frac{1}{z_{\max}} \sum_{i=1}^N \left(\frac{P}{P_S} \right)_i \Delta z, \quad (11)$$

where $(P/P_S)_i$ is the photosynthetic rate inside the i th layer of the water column.

Nutrient function $f(N)$ As the function of (limiting) nutrient, we used the Eutrophication index proposed by [33]:

$$EI = \frac{C}{C - \log x_i} + \log A, \quad (12)$$

where EI is the eutrophication by the limiting nutrient in each sampling station for the sampling campaign, A is the number of sampling stations, C is the logarithm of the total concentration of limiting nutrient per campaign, and x_i is the total nutrient concentration in the sampled station. The grading scale is as follows: $EI < 3$ indicates *oligotrophic* conditions, $\leq 3 EI \leq 5$ *mesotrophic*, and $EI > 5$ *eutrophic*.

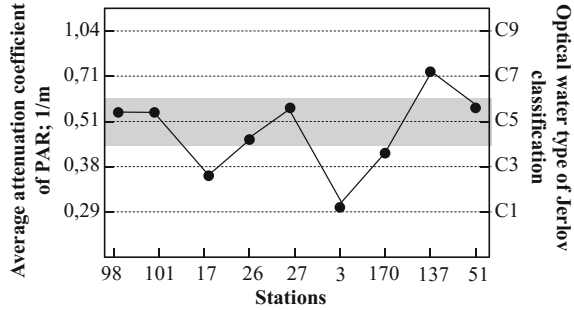
Taking into account the findings of [12], we considered the soluble reactive phosphorus (SRP) as the limiting nutrient in the waters of the Gulf of Ana María. The *APHI* was normalized with respect to the maximum value obtained at 1:00 PM and 4:00 PM, for each case. The spatial distribution of normalized *APHI* was interpolated by SURFER 9 package.

3 Results

3.1 Optical Water Classification

The values of the light attenuation coefficient for the waters of the Gulf of Ana María ranged from 0.31 to 0.73 m^{-1} , with an average value of 0.50 m^{-1} . The lowest (highest) attenuation coefficient value was found in the southwestern (southeastern) area of the gulf at station 3 (137) (Fig. 3). According to the modeling framework developed in this study, the marine waters of the Gulf of Ana María are categorized as coastal waters according to the marine water classification of Jerlov [25]. The clearest water type found was C1 (station 3), and the more turbid water type was C7 (station 137) (Fig. 3). There was not a representation of the darkest coastal waters (C9), while the most abundant optical water type was the intermediate turbidity (C5) (Fig. 3). Seawaters showed spatial variability in their optical properties. We identified three optical subregions in the Gulf of Ana María. The first one was located near the coastline, showing the darkest waters found in this study; the second subregion was located in the central gulf and is characterized by an intermediate turbidity, while the third subregion was at the western gulf and shows the clearest water types.

Fig. 3 Average attenuation coefficient of light and optical classification of the waters of the Gulf of Ana María. The gray band indicates stations with intermediate turbidity (C5 waters)



The average depth of the study area was 11 m, while the maximum and minimum depths were 21 m (station 101) and 5 m (station 137), respectively. The calculated extension of the euphotic layer, at most stations, was deeper than the station depth (Table 2), while the Secchi depths were relatively shallow (Table 2). For what concerns the trophic conditions, we found that all stations presented oligotrophic conditions, except the station 101 which showed eutrophic conditions (Table 2). However, we can observe that the values of the EI for SRP are relatively close to the lower limit of the mesotrophic classification according to [33] (see Sect. 2). This result could be related to the dominance of waters with intermediate turbidity (C5). However, the interactions of the variables nutrients and light in aquatic ecosystem are not totally understood and will be the focus of future work in our group.

Table 2 Hydrographic variables determined in the Gulf of Ana María

Station	Depth (m)	Secchi depth (m)	K (m^{-1})	Euphotic depth (m)	EI (SRP)	Trophic status
98	17	3.75	0.53	8.68	2.48	Oligotrophic
101	21	3.75	0.53	8.68	5.33	Eutrophic
17	6	5.5	0.36	12.77	2.39	Oligotrophic
26	9	4.25	0.47	9.78	2.31	Oligotrophic
27	9	3.5	0.57	8.07	2.07	Oligotrophic
3	12	6.5	0.31	14.84	2.15	Oligotrophic
170	18	4.5	0.44	10.45	2.64	Oligotrophic
137	5	2.75	0.73	6.30	2.32	Oligotrophic
51	6	3.5	0.57	8.07	2.14	Oligotrophic

3.2 Aquatic Primary Habitability Index

Figures 4 and 5 show the photosynthetic potential of phytoplankton assemblages in the waters of the Gulf of Ana María. Given that stations 26, 27, 51, 98, and 101 showed the same optical water type, their photosynthetic potential curves overlap and similarly occur for the stations 17 and 170. It can be observed that the maximum photosynthetic potential at station 137 is reached shallowest as compared with other stations. This result can be related to the fact that station 137 has the darkest optical water type (C7), which leads to a strong attenuation of UV radiation and consequently reduces the deleterious effects of this waveband. In contrast, the maximum photosynthetic potential at station 3 is reached deepest in the water column since in this station we found the clearest optical water type (C1).

Photosynthetic potential appears to have been affected by UV radiation at the ocean surface, which is indicated by the observed photoinhibition ($P/P_s \approx 0$). Because UV radiation is strongly attenuated in the first meters of the waters column, it is logic to obtain low values of the photosynthetic potential near the surface. Then, from 6 m depth approximately (except station 137) to the bottom of the water column, the photosynthetic potential showed the maximum value in all cases analyzed. Thus, the highest variability of the photosynthetic potential is observed in the first meters of the water column which is determined by the UV radiation fluxes, while the high photosynthetic activity at the bottom of the waters column is maintained due to the high PAR intensity reaching these depths. On the other hand, we did not find differences of the photosynthetic potential between the most and less efficient species using PAR (i.e., $E_S = 2 \text{ W m}^{-2}$ and $E_S = 100 \text{ W m}^{-2}$), while a small difference was only observed at different times of the days (at 1:00 PM and 4:00 PM). In general, photosynthetic curves at 1:00 PM showed the maximum values in shallower water than the ones at 4:00 PM. In general, the obtained results indicate that there is no limitation by solar radiation to perform the photosynthetic process in the waters of the Gulf of Ana María.

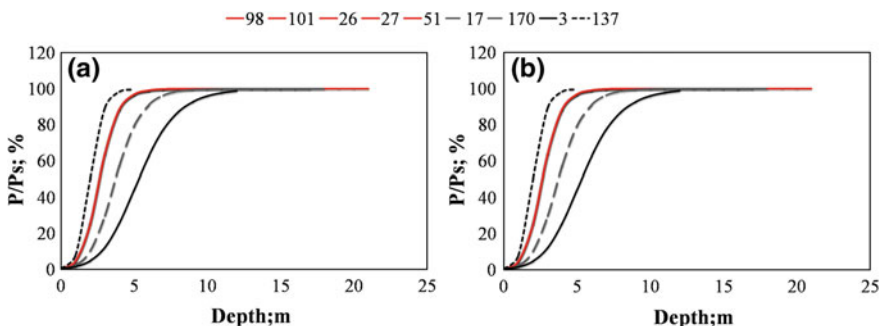


Fig. 4 Photosynthetic potential at 1:00 PM (35°) for **a** most and **b** less efficient species using PAR. Stations with the same color indicate that their photosynthetic curves overlap

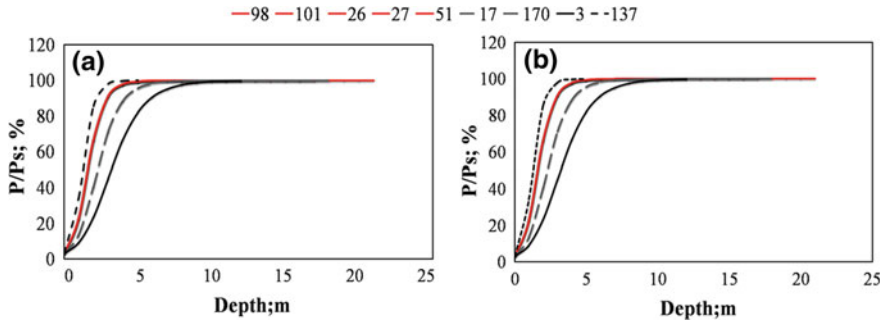


Fig. 5 Photosynthetic potential at 4:00 PM (76°) for **a** most and **b** less efficient species using PAR. Stations with the same color indicate that their photosynthetic curves overlap

Given there were no differences between the photosynthetic potential between the phytoplankton species (i.e., $E_S = 2 \text{ W m}^{-2}$ and $E_S = 100 \text{ W m}^{-2}$), we did not find considerable differences either in the habitability maps of those species. Thus, in Fig. 6, we only show the spatial distribution of the *APHI* values for the species $E_S = 2 \text{ W m}^{-2}$, which largely agree with the one for species $E_S = 100 \text{ W m}^{-2}$. *APHI* values were normalized with respect to its maximum value at station 101. In general, the potential to support the primary productivity of phytoplankton is similar for the times of the day analyzed, being highest in the southwestern gulf and lowest in the central basin. The *APHI* values indicate, in average, an intermediate potential for primary production of phytoplankton (~50%). The differences of the *APHI* values between stations were determined by the differences in nutrient concentration, which suggest that the latter govern the potential of the waters of the Gulf of Ana María to support phytoplankton productivity.

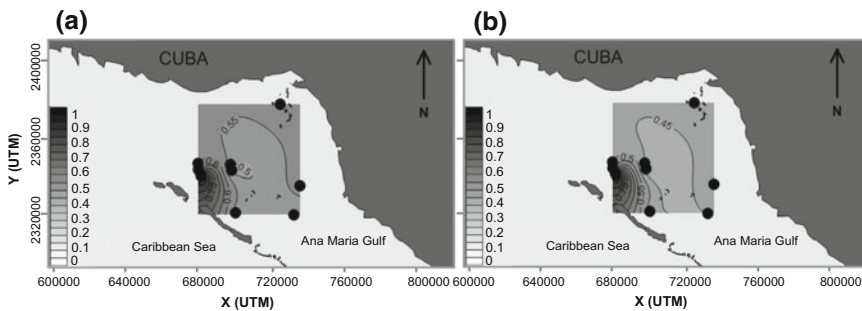


Fig. 6 Spatial distribution of the values of the aquatic primary habitability index primary in the Gulf of Ana María at **a** 1:00 PM and **b** 4:00 PM for the most efficient species using PAR ($E_S = 2 \text{ W m}^{-2}$)

4 Discussion

The coastal waters are less transparent than the open ocean waters, which is determined by the high concentration of sediments and colored dissolved organic matter (CDOM) [34]. In general, three major components contribute to light attenuation in aquatic ecosystems, i.e., the water itself, the dissolved yellow substances (CDOM) and the suspended particulate fraction including phytoplankton (chl-a as a measure of phytoplankton abundance) and tripton (inanimate particulate matter) [23]. The simplest approach to determine the contribution of each of these elements on the light attenuation in the marine water column assumes that their effects are additive in nature [35]. In this case, the total light attenuation coefficient, K_t , is partitioned as follows:

$$K_t = K_{SW} + K_{CDOM} + K_{chl} + K_{tripton} \quad (13)$$

where K_{sw} , K_{CDOM} , $K_{tripton}$ are the partial attenuation coefficients for seawater, CDOM, chl-a, and tripton, respectively.

We suggest that tripton (specifically suspended particulate matter (SPM)) might be present in high concentrations in the water column of the Gulf of Ana María. SPM is an important distinction between estuaries and the open ocean, where SPM concentration is low and attenuation coefficient is more strongly correlated with phytoplankton biomass [36]. It has been reported that the benthic habitat of the stations studied is dominated by mud with some patches of seagrass and corals [37]. Besides, during the studied period, it was reported a high number of atmospheric phenomena such as storms and rainfalls [38], which may lead vertical mixing and therefore resuspension of particulate matter present in high concentrations at the seabed.

The relative shallow Secchi depth obtained in our study can be related to above-mentioned ideas. It has been reported that the Secchi depth can be greater than that observed if only plankton cells are responsible for the light extinction [39]. This observation means that particles other than plankton cells may be the most important factors for determining the Secchi depth in many coastal areas. In many coastal environments, light attenuation by suspended sediments confines the euphotic zone to a small fraction of the surface water column [36]. However, in our case, the euphotic depth was—in almost all stations—higher than the depth of the station (Table 2) which indicates that independent of the existing moderate turbidity (waters C5), still high radiation intensity can penetrate until the bottom given to some extent to the shallowness of the analyzed stations.

In shallow coastal waters, the euphotic zone extent regulates the occurrence and depth distribution of seafloor habitats [40] and therefore the distribution and abundance of photosynthetic organisms. In the Gulf of Ana María, it has been reported a high number of macroalgae, corals, and gorgonians inhabiting the seafloor [41, 42]. Corals live in symbiosis with a dinoflagellate microalga (the so-called zooxanthellae), which need solar radiation and nutrients to develop

photosynthesis in the same way that macroalgae and phytoplankton cells do. Thus, it could be considered that intensity of solar radiation reaching the benthic habitats of the Gulf of Ana María is suitable to fuel photosynthesis, including the phytoplankton photosynthesis which has shown the maximum values at the bottom of the studied stations (Figs. 4 and 5).

The temporal variability of photosynthetic rates and depth-normalized total photosynthetic potential is mainly determined by the flux of irradiance (PAR + UV) that penetrates the water column at different times of the day as well as the depth of the station. The flux of radiation at 1:00 PM is greater than at 4:00 PM. The solar angle of incidence at 1:00 PM (35°) allows very little reflection of radiation (i.e., high penetration into the water column) at the air–water interface as compared to the angle of incidence at 4:00 PM which is 76° .

Stations with the highest and smallest *APHI* were 101 and 27, respectively. They showed the same optical water type (C5), but different trophic status (Fig. 3 and Table 2). The station 101 had eutrophic waters for phosphorous, and this type of water body is characterized by a high biological activity, introducing high concentrations of nutrients and primary production rate [18]. On the other hand, the station 27 showed oligotrophic conditions, with very low biological activity, low nutrient concentration and primary productivity, and limited biomass [18]. Thus, we can infer that SRP is the environmental variable limiting primary production in the Gulf of Ana María and not light. This result disagrees with earlier findings for other aquatic systems, for which light availability was reported as the critical environmental factor governing estuarine phytoplankton productivity. In estuaries, nutrient availability is generally adequate to support production [43]; hence, light availability is the most important factor controlling biomass-specific productivity, and consequently, primary productivity is strongly correlated with light availability. The reported oligotrophication in the waters of the Gulf of Ana María could be associated with the damming of the rivers that flow into the gulf. However, more studies are needed to corroborate this suggestion.

5 Conclusions

In this study, we have proposed an optical classification of the waters of the Gulf of Ana María as well as a quantitative index to measure its phytoplankton habitability. It was found a dominance of waters with moderated turbidity (C5) and oligotrophic condition for phosphorus (SRP). The latter appears to be the most important variable influencing the primary habitability of phytoplankton. We obtained that the Gulf of Ana María has an intermediate environmental potential ($\sim 50\%$) to support phytoplankton productivity. However, it should be noticed that this is a preliminary work. Both the theoretical (*APHI*) and experimental (sampling in time and space) tools should be refined to reach more accurate conclusions. The *APHI* can be refined by considering the interactions between the variables, while a more

extensive data collection should be done to properly evaluate the spatiotemporal evolution of habitability in the Gulf. This will be addressed in the near future.

References

1. Yool A, Fashman MJR (2001) An examination of the ‘continental shelf pump’ in an open ocean general circulation model. *Global Biogeochem Cycles* 15(4):831–844
2. Muller-Karger FE, Varela R, Thunell R, Luerssen R, Hu C, Walsh JJ (2005) The importance of continental margins in the global carbon cycle. *Geophys Res Lett* 32(1):L01602
3. Flores VFJ, Agraz HC, Benitez DP (2007) Ecosistemas acuáticos costeros: importancia, retos y prioridades para su conservación. In: Sánchez O, Herzog M, Peters RE, Márquez-Huitzil R, Zambrano L (eds) *Perspectivas sobre conservación de ecosistemas acuáticos en México*, pp 147–167
4. Arndt S, Geneviève L, Nathalie G, Pierre R, Christiane L (2011) Nutrient dynamics and phytoplankton development along an estuary–coastal zone continuum: a model study. *J Mar Syst* 84:49–66
5. Agboola JI, Kudo I (2014) Different contributions of riverine and oceanic nutrient fluxes supporting primary production in Ishikari Bay. *Cont Shelf Res* 88:140–150
6. Giraud X, Le Quéré C, Da Cunha LC (2008) Importance of coastal nutrient supply for global ocean biogeochemistry. *Glob Biogeochem Cycles* 22:GB2025. <https://doi.org/10.1029/2006gb002717>
7. Alcolado PM, García EE, Arellano-Acosta M (eds) *Ecosistema Sabana-Camagüey. Estado actual, avances y desafíos en la protección y uso sostenible de la biodiversidad. Proyecto PNUD/GEF Sabana-Camagüey CUB/98/G32; CUB/99/G81*. Editorial Academia, Habana (2007)
8. Kondratiova T, Sosa M (1966) Productividad primaria de las aguas cubanas. *Estudios Instituto de Oceanología, Academia de Ciencias de Cuba* 2, 21–24
9. V National report to the convention on biological diversity, Republic of Cuba, 2014. Instituto de Ecología y Sistemática y Centro Nacional de Biodiversidad. Ministerio de Ciencia, Tecnología y Medio Ambiente. La Habana (2014)
10. Piñeiro R (2006) Influencia del aporte fluvial en la zona marino costera suroccidental del Golfo de Batabanó, Cuba. *Rev Cuba Investig Pesq* 24(1):28–31
11. Baisre JA, Arboleya Z (2006) Going against the flow: the effect of river damming in Cuban fisheries. *Fish Res* 81:283–292
12. González-De Zayas R, Lestayo González JA, Merino-Ibarra M, Castillo Sandoval FS (2012) Condiciones hidroquímicas recientes de la zona central del golfo de Ana María, Cuba. *Rev Investig Mar* 32(2):9–14
13. Piñeiro R, Puga R, González-Sansón G (2006) Bases para el manejo integrado del recurso langosta (*Panulirus argus*) en la zona costera sur de Pinar del Río. I. Factores ambientales. *Rev Investig Mar* 27(3):245–251
14. Baisre JA (2006) Assessment of nitro-gen flows into the Cuban landscape. *Biogeochemistry* 79:91–108
15. Puga R, Piñeiro R, Cobas S, De León ME, Capetillo N, Alzugaray R (2010) La pesquería de la langosta espinosa, conectividad y cambio climático en Cuba. In: Hernández-Zanuy AC, Alcolado PM (eds) *La Biodiversidad en ecosistemas marinos y costeros del litoral de Iberoamérica y el cambio climático. Proceedings of the First Workshop of the network CYTED BIO-DIVMAR*. La Habana, Cuba, Instituto de Oceanología, pp 112–131
16. Mendez A (2010) Evolution of the global terrestrial habitability during the last century. In: *Sixth astrobiology science conference*, pp 26–29, Houston, TX, USA

17. Cardenas R, Perez N, Martinez-Frias J, Martin O (2014) On the habitability of aquaplanets. *Challenges* 5:284–293
18. Ji ZG (2008) *Hydrodynamics and water quality: modeling rivers, lakes, and estuaries*. Wiley
19. Platt T, Sathyendranath S (1988) Oceanic primary production: estimation by remote sensing at local and regional scales. *Science* 241:613–1620
20. Betanzos VA, Garcés RY, Delgado MG, Pis RMA (2012) Variación espacio-temporal y grado de eutrofia de sustancias nutrientes en aguas de los Golfos de Ana María y Guacanayabo, Cuba. *Rev Cienc Mar Costeras* 4:117–130
21. Sosa BM (2006) Las pesquerías de camarón en Cuba. FAO project report
22. Madronich S (2009) Tropospheric ultraviolet and visible (TUV) radiation model 4.6
23. Kirk JTO (2011) *Light and photosynthesis in aquatic ecosystems*. Cambridge University Press
24. Shifrin KS (1988) *Physical optics of ocean water*. American Institute of Physics Translation Series. Springer Science & Business Media
25. Jerlov NG (1976) *Optical oceanography*. Elsevier Publications Company, Amsterdam
26. Lee Z, Weidemann A, Kindle J, Arnone R, Carder KL, Davis C (2007) Euphotic zone depth: its derivation and implication to ocean-color remote sensing. *J Geophys Res* 112:C03009:1–C03009:11
27. Strickland JDH, Parsons TR (1972) *A practical handbook of seawater analysis*. Fisheries Research Board of Canada, Canada
28. Comar CL, Zscheile FP (1941) Spectroscopic analysis of plant extracts for chlorophyll a and b. *Am Soc Plant Biol (ASPB)* 16(3):651–653
29. Avila-Alonso D, Baetens JM, Cardenas R, De Baets B (2017) Assessing the effects of ultraviolet radiation on the photosynthetic potential in Archean marine environments. *Int J Astrobiol* 16(3):271–279
30. Cullen JJ, Neale PJ, Lesser MP (1992) Biological weighting function for the inhibition of phytoplankton photosynthesis by ultraviolet radiation. *Science* 258:646–650
31. Rodríguez L, Cardenas R, Avila-Alonso D (2014) On the photosynthetic potential in the open oceans. *Rev Cuba Fis* 30(1):15–17
32. Avila-Alonso D, Cardenas R, Rodríguez L, Alvarez-Salgueiro J (2016) Phytoplankton photosynthetic potential in coastal zones around the world. *Rev Cuba Fis* 33:62–63
33. Karydis M, Ignatiades L, Moschopoulou N (1983) An index associated with nutrient eutrophication in the marine environment. *Estuar Coast Shelf Sci* 16:339–344
34. Häder DP, Kumar HD, Smith RC, Worrest RC (2007) Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. *Photochem Photobiol Sci* 6:267–285
35. Vant WN (1990) Causes of light attenuation in nine New Zealand estuaries: estuarine Coastal and Shelf. *Science* 31:125–137
36. Cloern JE (1987) Turbidity as a control on phytoplankton biomass and productivity in estuaries. *Cont Shelf Res* 7:1367–1381
37. Ventura-Díaz Y, Rodríguez-Cueto Y (2012) Hábitats del Golfo de Ana María identificados mediante el empleo de procesamiento digital de imágenes. *Rev Investig Mar* 32(2):1–8
38. Matos F, Batista LM, Sánchez-Hernández A (2012) Condiciones hidrometeorológicas en la porción central del golfo de Ana María, Cuba. *Rev Investig Mar* 32(2):15–19
39. Wallin M, Håkanson L, Persson J (1992) Load models for nutrients in coastal areas, especially from fish farms (in Swedish with English summary). Nordiska ministerrådet, Copenhagen
40. Luhtala H, Tolvanen H (2013) Optimizing the use of Secchi depth as a proxy for euphotic depth in coastal waters: an empirical study from the Baltic Sea. *ISPRS Int J Geo-Inf* 2:1153–1168
41. Suárez AM, Martínez-Daranas B, Guimaraes-Bermejo M, Volta R (2013) Macroalgas del golfo de Ana María, SE de Cuba. *Rev Investig Mar* 33(2):1–6

42. González-Díaz P, Perera-Pérez O, Pérez-García JA, Hernández-Fernández L (2012) Biodiversidad de corales, gorgonias y esponjas en un sector del golfo de Ana María. *Rev Investig Mar* 32(2):20–29
43. Nixon SW (1981) Freshwater inputs and estuarine productivity. In: Cross R, Williams D (eds) National symposium on freshwater inflow to estuaries, U.S.