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Dependence between the quantum yield of chlorophyll *a* fluorescence in marine phytoplankton and trophicity in low irradiance level

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The paper presents the dependence of relative fluorescence quantum yield of marine phytoplankton on trophicity (as a measure of trophicity the chlorophyll *a* concentration was assumed). The dependence was worked out using the following empirical data from different regions of Southern Baltic: artificially excited phytoplankton fluorescence measured with BBE Moldaenke FluoroProbe and phytoplankton light absorption coefficient measured with spectrophotometer. The statistical analyzes allow establishing mathematical expression describing relation between fluorescence quantum yield and chlorophyll *a* concentration in sea water. This result can be useful in the future in the modeling of fluorescence quantum yield as a function of environmental factors.

Keywords: marine optics, optical measurements in the photobiology, quantum yield, chlorophyll fluorescence, bio-optical modeling.

1. Introduction

Investigation of different characteristics (photosynthetical and others) describing state and functioning of marine phytoplankton using fluorescence measurements is popular and widely applied in today's oceanology. The natural sun induced chlorophyll fluorescence (SICF) as well as fluorescence induced with artificial light in various kinds of fluorometers can provide useful information about many natural marine phytocoenosis characteristics from chlorophyll concentration in phytoplankton to its taxonomic composition, *e.g.* [1–12]. For all fluorometric methods the information concerning fluorescence quantum yield is crucial.

Quantum yield of fluorescence, like quantum yield of photosynthesis, depends on different environmental factors, first of all on trophicity, light and temperature (see, for example, [13–18]). It was a subject of investigation of many authors in reference to both sun induced chlorophyll fluorescence (SICF) and artificially induced fluorescence *e.g.* [3, 10, 11, 19, 20]. The authors presented valuable information about relationships between quantum yield of fluorescence and environmental factors. However,

the mathematical models describing fluorescence quantum yield as a function of temperature, light and trophicity have not been worked out yet. Therefore my goal is to find the relationship between fluorescence quantum yield and these factors. What is more, a far-reaching goal is to work out mathematical description of fluorescence quantum yield which allows us to apply this relationship in fluorometric methods of marine phytoplankton investigations, like the one we did for photosynthesis quantum yield [21]. This paper is the first step to this aim and is going to clarify whether and how fluorescence quantum yield in the low irradiance (usually employed in fluorometers) depends on trophicity. As an indicator of trophicity we assume the chlorophyll *a* concentration*.

To reach this aim we use empirical data measured with FluoroProbe produced by BBE Moldaenke. This instrument measures artificial chlorophyll fluorescence in 680 nm induced for five wavelengths (470, 525, 570, 590, 610 nm) and by using internal algorithm invented by the producer determines main algae taxons in sea water. The instrument measures additional parameters in order to eliminate possible contribution of the dissolved fluorophores and the particulate non-fluorescent scatter to fluorescence signal. Details of this method can be found in [22]. In this work, we use the data of fluorescence intensity induced in this way and light absorption coefficient for phytoplankton measured spectrophotometrically to determine the quantum yield of chlorophyll fluorescence in phytoplankton (in arbitrary units). The method is described in detail below.

The light that induces fluorescence in FluoroProbe has relatively low intensity. As we know, in low irradiances the quantum yield of photosynthesis depends mainly on trophicity and to a lesser extent on light and temperature [21, 23–25]. Therefore, as first approximation we assumed that fluorescence quantum yield determined with FluoroProbe is a function of trophicity only.

2. Theoretical background

Quantum yield of phytoplankton fluorescence Φ_{fl} is the ratio of the number of quanta emitted as chlorophyll fluorescence and the number of quanta absorbed by photosynthetic pigments of algae. For phytoplankton in natural communities, under natural light conditions or illuminated by artificial light with wide spectral range it equals:

$$\Phi_{\mathrm{fl}} = \frac{\mathrm{Fl}}{\mathrm{PUR}} \tag{1}$$

where: Fl is the intensity of fluorescence light with maximum for living phytoplankton at 680 nm expressed in quanta $\mathrm{m^{-3}\,s^{-1}}$, *i.e.*, measured as a number of quanta emitted

*According to convention proposed in [26], the chlorophyll *a* concentrations (C_a [mg $\mathrm{m^{-3}}$]) in different trophic types of sea are: oligotrophic (O): O1 0.02–0.05, O2 0.05–0.10, O3 0.10–0.20; mesotrophic (M): 0.2–0.5; intermediate meso-eutrophic (I): 0.5–1.0; eutrophic (E): E1; 1.0–2.0 E2 2–5, E3 5–10, E4 10–20, E5 > 20.

in the unit of time by chlorophyll *a* in marine phytoplankton contained in the unit of volume of marine water. PUR (photosynthetically used radiation) [quanta $m^{-3} s^{-1}$] – a number of quanta absorbed in the unit of time by phytoplankton pigments contained in the unit of volume of marine water:

$$\mathrm{PUR} = \int_{400}^{700} I(\lambda) a_{\mathrm{pl}}(\lambda) \mathrm{d}\lambda \tag{1a}$$

where: $I(\lambda)$ [quanta $m^{-3} s^{-1}$] is a scalar irradiance of exciting light expressed as the number of quanta; $a_{\mathrm{pl}}(\lambda)$ [m^{-1}] is a phytoplankton light absorption coefficient for λ.

While phytoplankton fluorescence is excited with monochromatic radiation (or in the spectral range it narrows enough, as in the case of FluoroProbe), the spectral values of quantum yield of fluorescence $\Phi_{\mathrm{fl},\lambda}$ can be determined from the following equation:

$$\Phi_{\mathrm{fl},\lambda} = \frac{\mathrm{Fl}}{a_{\mathrm{pl},\lambda} I_{\lambda}} \tag{2}$$

where $a_{\mathrm{pl},\lambda}$ and I_{λ} are respectively: light absorption coefficient for λ and scalar irradiation, which is constant for each of the five wavelengths.

One should notice that there is a close relation between fluorescence quantum yields Φ_{fl} and $\Phi_{\mathrm{fl},\lambda}$ defined above. The quantum yield Φ_{fl} is a weighted average using a spectral distribution of light exciting fluorescence of spectral values of $\Phi_{\mathrm{fl},\lambda}$. It can be expressed as:

$$\Phi_{\mathrm{fl}} = \frac{1}{\mathrm{PAR}} \int_{400}^{700} I_{\lambda}(\lambda) \Phi_{\mathrm{fl},\lambda}(\lambda) \mathrm{d}\lambda \tag{3}$$

where: PAR (photosynthetically available radiation) is the total irradiance in spectral range 400–700 nm:

$$\mathrm{PAR} = \int_{400}^{700} I_{\lambda}(\lambda) \mathrm{d}\lambda \tag{3a}$$

Using the FluoroProbe measurements we can directly determine spectral quantum yield of fluorescence, $\Phi_{\mathrm{fl},\lambda}$ defined by Eq. (2), for five wavelengths mentioned above. Unfortunately, there is no information about the absolute values (in number of quanta or in energetic units) of exciting (I_{λ}) and emitted (Fl) light, so we can express $\Phi_{\mathrm{fl},\lambda}$ only in arbitrary units which are different for each spectral channel of FluoroProbe.

3. Material and methods

To achieve the goal of the paper, 181 sets of empirical data were collected in cruises r/v Oceania to different regions of Southern Baltic and in coastal experiments near the pier in Sopot. Each of the 181 sets of data includes:

– The values of chlorophyll *a* concentration, C_a [mg m^{-3}] (*i.e.*, the water trophicity) determined spectrophotometrically in water samples [27, 28];

– The values of spectral phytoplankton light absorption coefficient *in vivo* $a_{\mathrm{pl},\,470}$, $a_{\mathrm{pl},\,525}$, $a_{\mathrm{pl},\,570}$, $a_{\mathrm{pl},\,590}$, $a_{\mathrm{pl},\,610}$ [m^{-1}] determined for five wavelengths using non-extraction method [29, 30] in the same water samples as chlorophyll concentration;

– Intensity of fluorescence, Fl [rel.unit] measured *in situ* after excitation at fives selected wavelengths with FluoroProbe fluorometer. The influence of the "yellow substance" (that is colored dissolved organic matter which absorbs and emits light in UV and VIS region in marine water [31]), transmission of the water, internal instrument temperature and the led brightness and offset were eliminated from fluorescence signal.

The next step was to determine the spectral value of fluorescence quantum yield $\Phi_{\mathrm{fl},\,\lambda}$ for five wavelengths, by using collected empirical data, according to simplified Eq. (2):

$$\Phi_{\mathrm{fl},\,\lambda}\,[\mathrm{a.\,u.}] \;=\; \frac{\mathrm{Fl}}{a_{\mathrm{pl},\,\lambda}} \tag{4}$$

Next, using statistical analysis, the relations between quantum yield of fluorescence $\Phi_{\mathrm{fl},\,\lambda}$ and trophicity C_a were established. The results are presented in Sections 4 and 5.

To be precise, it has to be mentioned that the results refer to chosen trophic types of Baltic water. Chlorophyll *a* concentrations, registered during cruises and coastal experiments, vary from 0.4 to 15 $\mathrm{mg\,m}^{-3}$. The results of analysis presented below refer mainly to eutrophic and, to a lesser degree, mesotrophic waters and are not representative of oligotrophic waters.

4. Results

The dependence of the fluorescence quantum yield $\Phi_{\mathrm{fl},\,\lambda}$ (in arbitrary units) on chlorophyll *a* concentration for five selected wavelengths is presented in Fig. 1. The left column of graphs in Fig. 1 presents empirical points, in the right column one can find the proper mean values and standard deviation determined for different trophic types of water. It is clearly noticeable that in each region of the spectrum examined the quantum yield of fluorescence $\Phi_{\mathrm{fl},\,\lambda}$ decreases with the water trophicity. Therefore, the positions of experimental points $\Phi_{\mathrm{fl},\,\lambda}$ versus C_a have been approximated using expression (see continuous curves in Fig. 1):

$$\Phi_{\mathrm{fl}}\,[\mathrm{a.\,u.}] \;=\; \frac{A + BC_a^D}{E + C_a^D} \tag{5}$$

where: C_a is a chlorophyll *a* concentration expressed in [$\mathrm{mg\,m}^{-3}$]; parameters A, B, D and E were determined by using a nonlinear regression methods and their values for each wavelength are given in Tab. 1.

As we can see from Fig. 1, the values of fluorescence quantum yield slightly increase as the excitation wavelength increases from 470 to 610 nm. This shows that

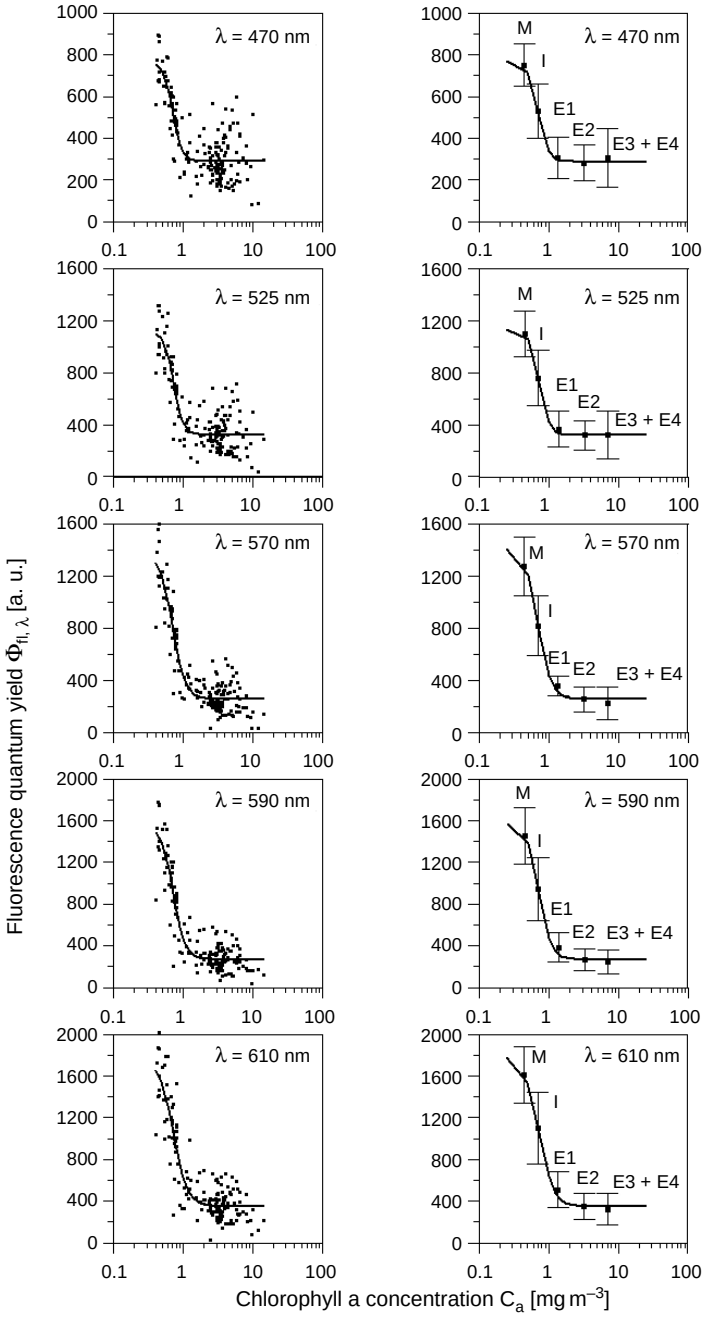

Fig. 1. Spectral dependence of a relative quantum yield of fluorescence $\Phi_{fl,\lambda}$ on chlorophyll *a* concentration for selected wavelengths. Left column of the graph – position of experimental points, right column – mean and standard deviation calculated from experimental data $\Phi_{fl,\lambda}$ for different trophic types of sea water (*i.e.*, for selected ranges of chlorophyll *a* concentration). Continuous curves – approximation using Eq. (5).

T a b l e 1. Values of parameters in Eq. (5) determined by using a nonlinear regression methods for quantum yield of fluorescence excited with five selected wavelengths.

	λ = 470 [nm]	λ = 525 [nm]	λ = 570 [nm]	λ = 590 [nm]	λ = 610 [nm]
A	87.7	158	270	299	450
B	287	320	252	268	347
D	6.17	6.14	4.53	4.97	4.16
E	0.114	0.140	0.194	0.192	0.254

the wavelength of exciting light affects the action spectra of photosynthesis, and, in turn, fluorescence. This influence of wavelength seems to be rather weak, so it is not considered in the paper, but in the future should be the subject of more detailed analysis. It may allow us to understand intricacies passed over in this paper.

It is easy to notice that the quantum yield of fluorescence in each wavelength of exciting light asymptotically approaches the value of *B* in Eq. (5) for high values of chlorophyll *a* concentrations. This makes it possible to normalize $\Phi_{\mathrm{fl},\lambda}$ for each

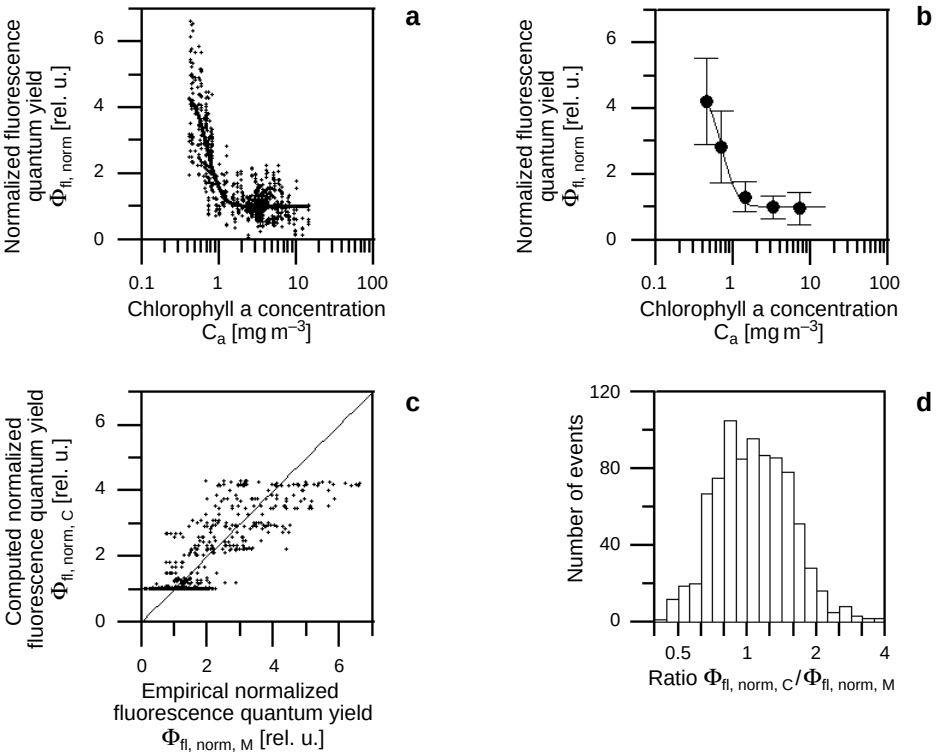

Fig. 2. Dependence of normalized quantum yield of fluorescence excited in different regions of visible spectrum on chlorophyll *a* concentration; empirical points (dots) and approximation using Eq. (6) (curve) (**a**); mean values (dots) and standard deviation (bars) for different trophic types (**b**); comparison of values computed using Eq. (6) – $\Phi_{\mathrm{fl,\,norm},\,C}$ with empirical values – $\Phi_{\mathrm{fl,\,norm},\,M}$ (**c**); histogram of the $\Phi_{\mathrm{fl,\,norm},\,C}/\Phi_{\mathrm{fl,\,norm},\,M}$ ratio (**d**).

T a b l e 2. Errors of the estimation of normalized fluorescence quantum yield using Eq. (6).

Arithmetic statistics		Logarithmic statistics			
Systematic error $\langle\varepsilon\rangle$ [%]	Statistical error σ_ε [%]	Systematic error $\langle\varepsilon\rangle_g$ [%]	Standard error factor x	Statistical error	
				σ_- [%]	σ_+ [%]
19.90	82.63	7.92	1.51	–33.88	51.23

Relative mean error (systematic): $\langle\varepsilon\rangle = N^{-1}\sum_i \varepsilon_i$ (where $\varepsilon_i = \frac{X_{i,C} - X_{i,M}}{X_{i,M}}$, while $X_{i,M}$ – measured values, $X_{i,C}$ – estimated values (subscript M means "measured", subscript C means "calculated").

Standard deviation (statistical error) of ε: $\sigma_\varepsilon = \sqrt{\frac{1}{N}\left[\sum(\varepsilon_i - \langle\varepsilon\rangle)\right]^2}$.

Mean logarithmic error: $\langle\varepsilon\rangle_g = 10^{\langle\log(X_{i,C}/X_{i,M})\rangle} - 1$, where $\langle\log\left(\frac{X_{i,C}}{X_{i,M}}\right)\rangle$ – mean of $\log\left(\frac{X_{i,C}}{X_{i,M}}\right)$.

Standard error factor: $x = 10^{\sigma_{\log}}$, where $\sigma_{\log}$ – standard deviation of the set $\log\left(\frac{X_{i,C}}{X_{i,M}}\right)$.

Statistical logarithmic errors: $\sigma_+ = x - 1$, $\sigma_- = \frac{1}{x} - 1$.

wavelength and present the normalized values of $\Phi_{\mathrm{fl},\lambda}$ in Fig. 2**a**, apart from the differences in absolute values of energy of light exciting fluorescence. This can be reached by dividing the values of $\Phi_{\mathrm{fl},\lambda}$ by the values of B for each wavelength, respectively.

The dependence of the normalized quantum yield of fluorescence on chlorophyll *a* concentration is presented in Fig. 2**a**. The mean for different trophic type values and standard deviations can be found in Fig. 2**b**. The empirical points were approximated by using hyperbolic expressions analogous to Eq. (5):

$$\Phi_{\mathrm{fl,\,norm}} = \frac{0.838 + C_a^{5.02}}{0.187 + C_a^{5.02}} \tag{6}$$

The diagram of this function can be found in Figs. 2**a** and 2**b** as a curve. The accuracy of $\Phi_{\mathrm{fl,\,norm}}$ estimation using Eq. (6) was also assessed by a comparison of empirical values of fluorescence quantum yield $\Phi_{\mathrm{fl,\,norm},M}$ with $\Phi_{\mathrm{fl,\,norm},C}$ determined by using Eq. (6) from known chlorophyll *a* concentration (see Fig. 2**c**). The errors of this estimation are presented in Tab. 2, while histogram of the $\Phi_{\mathrm{fl,\,norm},C}/\Phi_{\mathrm{fl,\,norm},M}$ ratio can be found in Fig. 2**d**.

5. Conclusions

The results of analysis presented above confirm the assumption of close relation between the quantum yield of fluorescence and chlorophyll *a* concentration as trophicity of sea water indicator. The statistical analyzes of experimental data allow establishing the approximate mathematical expressions describing this dependence for low irradiances (see Eqs. (5) and (6) and Tab. 1). These equations describe dependence

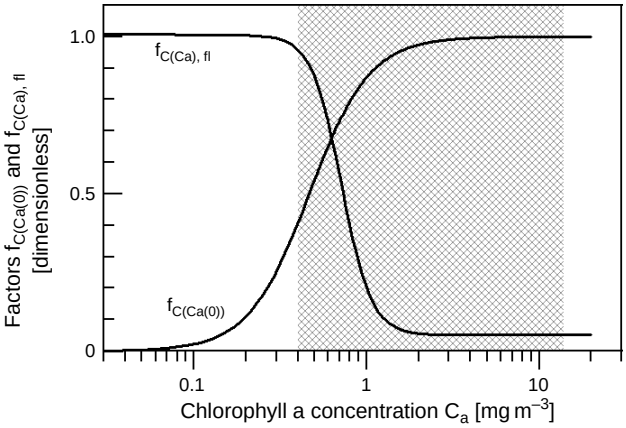

Fig. 3. Factors describing the dependence of quantum yields of fluorescence ($f_{c(Ca),\,fl}$ − Eq. (8)) and photosynthesis ($f_{c(Ca(0))}$ − Eq. (7)) on chlorophyll *a* concentration in Southern Baltic. The gray shading on the plot indicates the areas of empirical investigation.

of fluorescence quantum yield on chlorophyll *a* concentration with satisfactory accuracy (see relatively small values of errors of estimation in Tab. 2).

The dependence of the quantum yield of fluorescence on trophicity (where the concentration of chlorophyll *a* in sea water was also assumed as the indicator of trophicity) shows decreasing tendency with increasing trophicity (see Figs. 1 and 2). This means that the quantum yield of fluorescence values decreases until a relatively small boundary while concentration of chlorophyll *a* increases. On the other hand, the quantum yield of photosynthesis increases with increasing water trophicity. This was examined earlier by our team and described in detail in WOŹNIAK *et al.* [21].

Figure 3 illustrates a kind of comparison of both dependences of photosynthesis and fluorescence quantum yields on water trophicity. The curve describing factor $f_{c(Ca(0))}$ according to expression (after [21]):

$$f_{c(C_a(0))} = \frac{C_a(0)^{2.48}}{0.15 + C_a(0)^{2.48}} \tag{7}$$

demonstrates relative (from 0 to 1) changes of quantum yield of photosynthesis in Baltic due to relation between the number of functional PS2 reaction centers and the surface concentration of chlorophyll *a*, $C_a(0)$, *i.e.*, the trophic index of the sea. This problem was described in detail in paper [21] mentioned above. The second curve describes factor $f_{c(Ca),\,fl}$, that is, relative changes of fluorescence quantum yield with water trophicity (*i.e.*, with chlorophyll *a* concentration at different depths, $C_a(z)$, not at the surface $C_a(0)$). It was determined from dependence $\Phi_{fl,\,norm} = f(C_a)$ (Eq. (6)) by dividing both sides of equation by the value of $\Phi_{fl,\,norm}$ for chlorophyll concentration

equal zero (*i.e.*, $\Phi_{\text{fl, norm}}(C_a = 0) = 0.838/0.187 = 4.48$). As a result, an expression describing factor $f_{c(Ca),\,\text{fl}}$ takes the form:

$$f_{c(C_a),\,\text{fl}} = \frac{\Phi_{\text{f l, norm}}}{4.48} = \frac{0.187 + 0.223 C_a^{5.02}}{0.187 + C_a^{5.02}} \tag{8}$$

As we can see in Fig. 3 both processes of energy deactivation of excited chlorophyll *a* molecules in phytoplankton (*i.e.*, photosynthesis and fluorescence) are in close inversed relation and the sum of their relative values is close to 1 ($f_{c(Ca(0))} + f_{c(Ca),\,\text{fl}} \approx 1$)

Coming to the end we should point out that all of the relations between phytoplankton fluorescence quantum yield and trophicity discussed here are related mainly to eutrophic regions of the Baltic Sea and fluorescence excited with low irradiation. The relation between quantum yield of fluorescence and other environmental factors like see water temperature have not been analyzed in this work. It will be the topic of our investigations in the future. In particular, as the continuation of these analyzes, we are going to work out more universal mathematical model of fluorescence quantum yield describing its relation to three main factors that exert influence on phytoplankton vegetation, *i.e.*, trophicity, temperature and light conditions in a wide range of their variability.

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