Spectral analysis of the limitation of different taxonomic groups of phototrophic organisms in the semi-isolated lake Skurcha on the Black Sea Coast

• INTERNET BIOPHOTONICS XVIII" of the ANNUAL INTERNATIONAL CONFERENCE "SARATOV FALL MEETINGS XXIX"

• Anastasia S. Nagaeva[1], Elena A. Labunskaya[1], Irina G. Radchenko[1], Victor A. Lomov[2,4,5], Sevastiana S. Soloveva[2], Aleksandr N. Vasilenko[2], Valentin I Lobyshev[3], Elena D. Krasnova[1].

[1] Biological faculty Lomonosov Moscow State University, Leninskie Gory, Moscow, Russia
[2] Geographical faculty Lomonosov Moscow State University, Leninskie Gory, Moscow, Russia
[3] Physical faculty Lomonosov Moscow State University, Leninskie Gory, Moscow, Russia
[4] Computing Center Lomonosov Moscow State University, Leninskie Gory, Moscow, Russia
[5] Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences

1. Introduction

Solar radiation is the source of energy for all organisms on Earth. The evolution of phototrophic organisms has led to the formation of antenna complexes capable of absorbing different spectral ranges available in specific habitats. Light penetrating the water undergoes significant quantitative and qualitative changes, resulting in the formation of distinct spectral niches at various depths of a water body. Stratified lakes are water bodies in which water masses do not mix for extended periods due to differences in density. This phenomenon allows the study of the relationship between the quality and quantity of light and the species composition of phytoplankton, which develop within a specific water mass with boundaries that are difficult to cross. Therefore, in such water bodies, the structure of phytoplankton is influenced by the spectral characteristics of light as well as by the overall intensity of solar radiation. In this study, we present results on the structure (species and phylum composition, as well as carbon biomass) of phytoplankton in relation to the light-climate conditions at various depths of Lake Skurcha (Republic of Abkhazia). This lake is of anthropogenic origin: it originated as a quarry for sand and gravel extraction, was initially filled with fresh water, and was later connected to the sea by a channel. An anaerobic, hydrogen-sulfide–rich zone has formed in the bottom area. The presence of this hydrogen-sulfide zone makes monitoring ecological succession in the lake particularly relevant, and the potential for harmful algal blooms calls for special attention to the dynamics of phytoplankton communities.

2. Materials and methods

The study was carried out in Lake Skurcha (Black Sea, 42°47'47.5" N, 41°09'54.0" E) at the station above the deepest part of the lake bottom. Sampling and measurements were performed at the end of January 2025. Water for phytoplankton identification was sampled from horizons starting at 0 m and extending to the chemocline; samples were collected in 50-cm increments using a Whale Premium Submersible Pump GP1352 (Whale Marine, USA). In total, ten 1.5-L samples were taken from the lake. The samples were fixed with Lugol's solution and concentrated by sedimentation. Light parameters were measured using an Ocean Optics USB4000 spectrometer with a fiber-optic probe and a WindLiner LMI 20 submersible luxmeter. Water temperature at different depths was measured with a Multi 3620 IDS submersible probe (WTW, Germany), and salinity was determined in the samples using an RHS-10ATS refractometer (Kelilong Electron, China). Algae were counted and identified in a Nageotte chamber (volume 0.05 mL) under a MICMED-6 light microscope (LOMO, Russia) at 400× magnification. For the identification of diatoms, a Camscan S-2 Cambridge scanning electron microscope (UK) was used. Carbon biomass was calculated using cell volume-to-carbon relationships. Statistical analysis was performed using the PRIMER (v.6) and PERMANOVA+ software packages. To analyze the effects of environmental parameters on the structure of phytoplankton, distance-based linear modeling (DistLM) was performed. A marginal test shows the effect of a parameter when it acts alone; a sequential test shows the effect of a parameter when it acts together with other parameters.

3. Results

Analysis of hydrological characteristics. Analysis of spectral niches (Fig 1) shows that blue light suitable for fucoxanthin-containing antennae, characteristic of diatoms and golden algae, reaches up to 3 m at about 1% of the surface light intensity at the same wavelengths. Specifically, 1% of the light intensity at the 450 nm wavelength, corresponding to the in vivo absorption maximum of the FCP antenna, reaches only 2 m depth. Peridinin-containing antennae of dinoflagellates, capable of assimilating light at around 475 nm, have available light at 1% of the incident light down to 2.5 m. For antennae containing chlorophylls a and b, typical of green algae and euglenoids, the 1% threshold for red light at 677 nm (the in vivo absorption maximum of chlorophyll a) occurs between 2.5 and 3 m, and at 660 nm (chlorophyll b) at 3.5 m. For phycobilins, 1% of light in the 550–660 nm range reaches 3.5 m. Formally, this light is suitable for both phycoerythrin and phycocyanin, but the middle of this range corresponds to the in vivo spectral maximum of phycocyanin. The short-wavelength phycoerythrin 545 (PE 545), characteristic of cryptophyte algae Rhodomonas sp., does not fall within this range.

A light intensity threshold of 0.1% was determined for analyzing light niches suitable for phototrophic prokaryotes. At 4 m depth, 0.1% of light in the 527–660 nm range is present. Green sulfur bacteria (GSB) with antennae containing isorenieratene can utilize light in this range, whereas GSB with chlorobactene cannot. Purple sulfur bacteria with okenone, spirilloxanthin, and other carotenoids can also use light in this spectral range. Significant attenuation of violet and blue light occurs below the freshwater layer at 1.5 m, with blue light penetrating only to 3 m due to absorption by CDOM and, possibly, phytoplankton blooms. Light at a depth of 3.5 m, with an intensity of about 1% of the surface light, contains 28% and 29% of green and red light, respectively, 22% orange, 18% yellow, and less than 1.5% blue light (Fig 2). The half-width spectral range of solar radiation at this depth ranges from 535 to 632 nm, with a spectral maximum at 585 nm. (Fig 2).

The vertical light intensity profile is characterized by a decrease in illuminance within the first meter of the water column, a gradual decline of light between 1 and 3 meters, and the steepest drop in light intensity occurring between 3 and 4 meters (Fig 3a). Approximately 1% of the surface light intensity in the 400-700 nm range reaches a depth of about 3.5 meters. The sharp decrease in illuminance between 3 and 4 meters may be associated with the intense development of phototrophic organisms in this layer, which attenuate the light through absorption by photosynthetic pigments. The surface layer of water in the lake (0-1 m) was fresh (mixolymnion), a halocline was located in the 1.5-3 m zone, and from a depth of 3.5 m to the bottom, the water had a salinity of 14-16% (monimolymnion) (Fig. 3b). The thermocline coincided with the halocline (Fig. 3 b, c). During the research period, mesothermy was observed in the lake: the warmest water (more than 21 °C) was in the middle of the water column under the halocline. Below the depth of 11 m, the temperature dropped and near the bottom was 17 °C.

Spectra of solar radiation (Fig. 4) show a shift of the spectral maximum towards the long-wavelength region, associated with the absorption of the short-wavelength range of visible light by the colored fraction of dissolved organic matter (CDOM) or due to increased turbidity and light scattering, and a narrowing of the spectrum in the long-wavelength part due to absorption of far-red light by water molecules.

5. Acknowledgements

The research was supported by Russian Science Foundation, project № 24-24-00008 (https://rscf.ru/en/project/24-24-00008/).

The authors acknowledge the support of Centre of microscopy MSU. The scientific team also expresses its gratitude to Roman Zhiba, Head of the Department of Water Resources and Dynamics of Coastal Processes at the Institute of Ecology of the Academy of Sciences, and Ivan Neshenko, Researcher at the Department of Water Resources and Dynamics of Coastal Processes at the Institute of Ecology of the Academy of Sciences.

Figure 1. Limits of light propagation of different wavelengths in the lake Skurcha

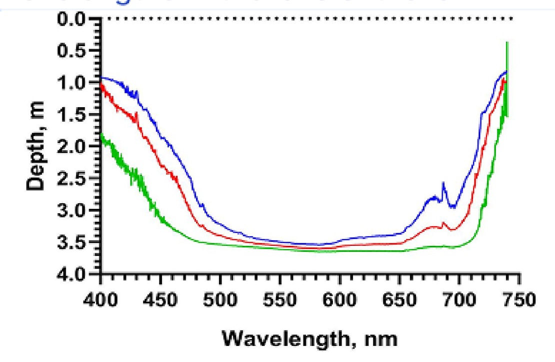


Figure 2. The percentage of different spectral ranges relative to the total light at depths

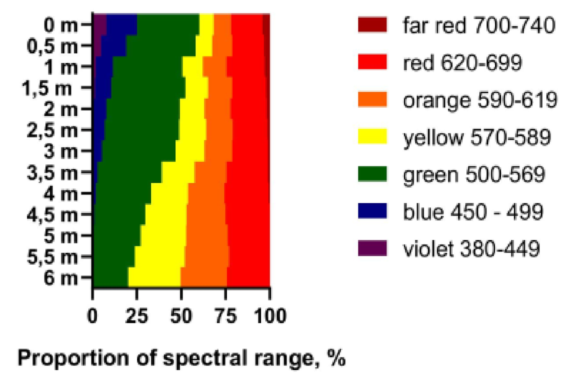


Figure 3. vertical profiles of hydrological characteristics. a - total illumination, b - salinity, c - temperature

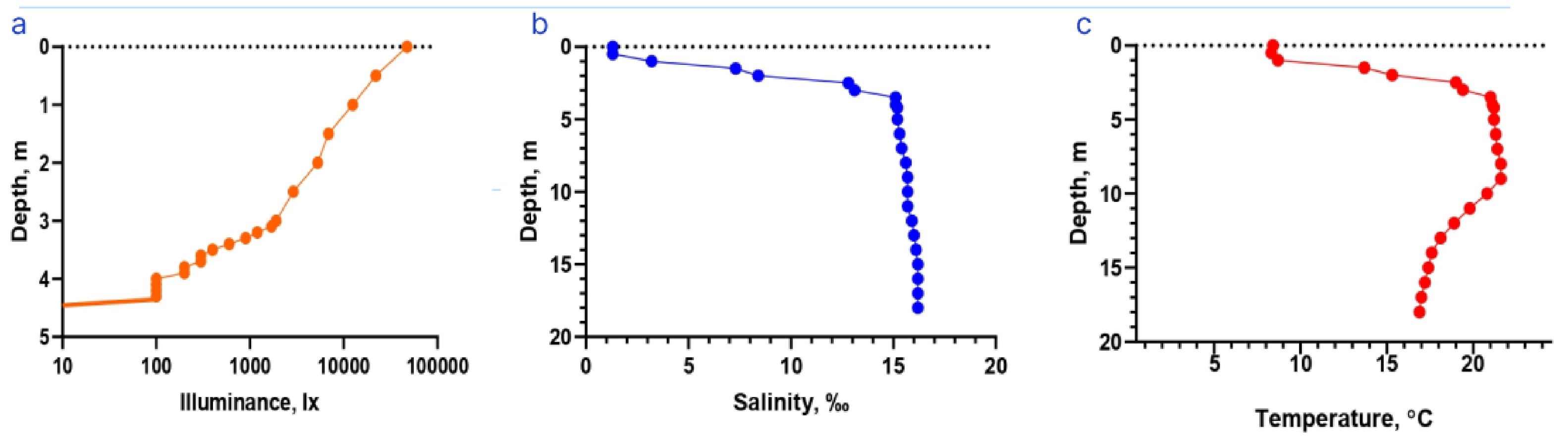


Figure 4. Underwater specrta of solar irradiance in the lake Skurcha

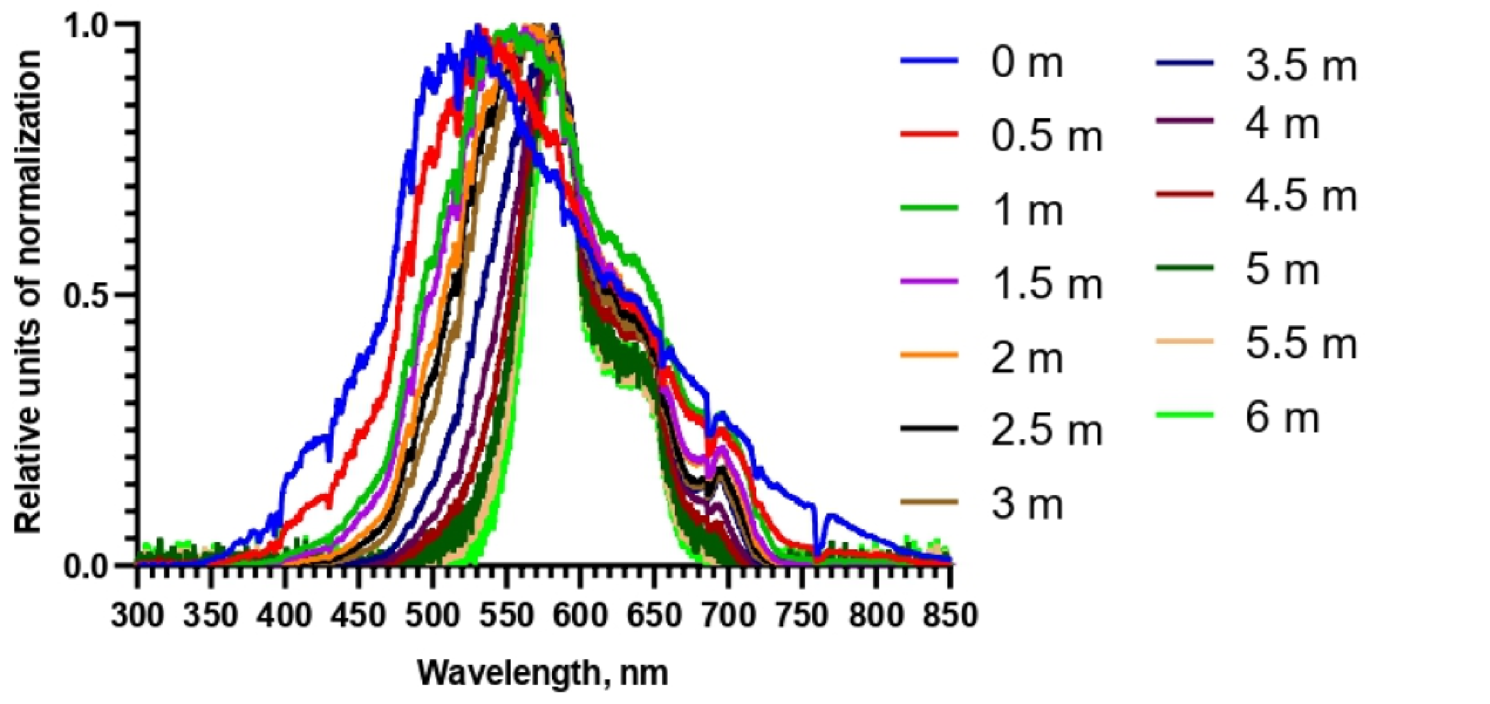


Figure 5. Effect of distribution of several several wavelengths (% of incident light) and species composition and biomass (Marginal test, DistLM)

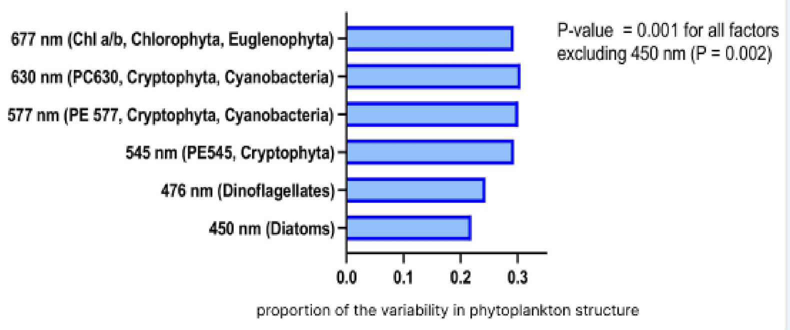


Figure 6. Effect of distribution of several several wavelengths (% of incident light) and phylum composition and biomass (Marginal test, DistLM)

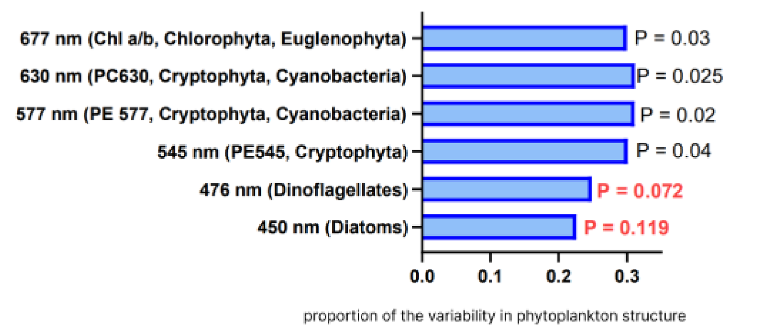


Figure 7. DbRDA (Distance-based redundancy analysis) ordination describing the relationship between distribution several wavelengths (% of incident light) and species composition and biomass (Sequential test)

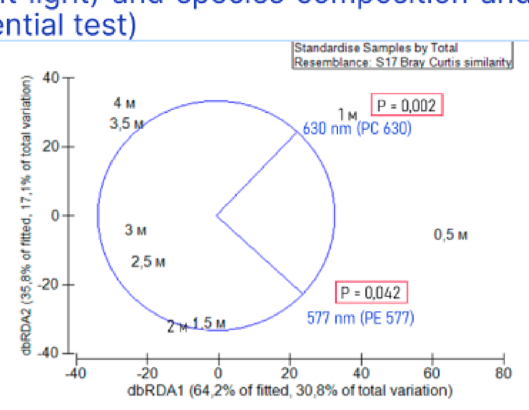
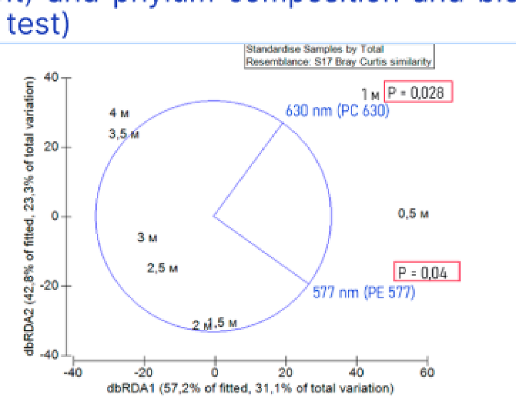


Figure 8. DbRDA (Distance-based redundancy analysis) ordination describing the relationship between distribution several wavelengths (% of incident light) and phylum composition and biomass (Sequential test)



Results (continuation)

Analysis of the effect of the amount of light in a given range (in % of the light on the surface). According to the DistLM marginal test on variation in structure of algal community (Fig 5), the following wavelengths provide the highest percentage of explanations of species composition and biomass in descending order: 630, 577, 545, 677, 476 and 450 nm. The P-value for all specified wavelengths is not more than 0.002. The effect on phylum composition and biomass has been reliably proven for four wavelengths: 677, 530, 577 and 545 nm (Fig 6). In the Sequential Test analysis on variation species composition and biomass (Fig 7), only two wavelengths turned out to be significant: 630 and 577, which explain a total of 48% of the variation in phytoplankton structure. 630, 577, and 545 nm correspond to the absorption maxima of phycobilins of cryptophyte algae. The same waves, with the exception of 545 nm, explain the observed ratios in phylum composition and biomass (Fig 8).

4. Conclusion

Analysis of the spectral composition and light distribution at different depths showed that blue light is present at depths up to 2 m in amounts no less than 1% of the incident light, and it is suitable for fucoxanthin-containing antennae of diatoms and golden algae, which corresponds to their presence in this zone. Light from the yellow-orange part of the spectrum, corresponding to antennae of cryptophytes containing long-wavelength phycoerythrins and phycocyanins, reaches depths of up to 3.5 m.Analysis of phytoplankton distribution in relation to the character of light transmission at specific wavelengths and spectral ranges demonstrated that a significant proportion of the variation in phytoplankton distribution can be explained by components of the light climate. For the studied water body, the propagation of light at wavelengths corresponding to the absorption by phycobilin antennae of cryptophytes and cyanobacteria —namely 577 nm and 630 nm — was found to be significant. These wavelengths account for approximately half (48%) of the variation in phytoplankton structure. In the analysis of spectral ranges, the greatest influence was observed within the regions encompassing the aforementioned wavelengths: 560–580 nm and 600–650 nm. These ranges correspond to the antennae absorption spectra of a broad group of cryptophyte algae, as well as to the phycobilisomes of cyanobacteria. Thus, the spectral composition of light, as well as the quantity of light within specified wavelengths and ranges, exerts a substantial effect on the vertical distribution of phytoplankton in Lake Skurcha