Трансформация экосистем
Ecosystem Transformation

ISSN 2619-0931 Online
www.ecosysttrans.com

DOI 10.23859/estr-220927
EDN ZFXKDL
UDC 582.261.1:574.64 (262.5)

Article

Comparison of benthic diatoms diversity (Bacillariophyta) in the Special Protected Area Cape Sarych and other water areas of the Crimea (the Black Sea)

Elena L. Nevrova

A.O. Kovalevsky Institute of Biology of the Southern Seas, Russian Academy of Sciences, pr. Nakhimova 2, Sevastopol, 299011 Russia

el_nevrova@mail.ru

Abstract. The structure of diatom taxocenes in the Special Protected Area "Coastal Aquatic Complex Cape Sarych" and the previously studied areas of the Crimea (conditionally clean Cape Fiolent, Novy Svet settl., Bay Dvuyakornaya and heavily polluted bays Balaklavskaya, Karantinnaya, Inkerman, and Sevastopolskaya) were analyzed with the use of the index TaxDI. At Cape Sarych, we identified 82 species and intraspecific taxa of diatoms belonging to 35 genera, 25 families, 15 orders, 3 classes of Bacillariophyta, among which 18 species were new to the flora of the Black Sea. The structure of diatom taxocenes in pristine water areas was formed by branches of different hierarchy and predominance of close at the genus level polyspecies taxa. Diatom taxocenes of polluted waters were characterized by a high proportion of mono- and oligospecies branches closing at the family or order levels that brought to reduced diatom taxonomic diversity, increased evenness and decreased variability of their hierarchical structure. The impact of technogenic pollutants caused a transformation of the primary link of the marine sublittoral ecosystem which is expressed in the reduced structure of diatom taxocenes and disappearance of diatom species with low resistance to negative factors.

Keywords: taxonomic distinctness index, TaxDI, AvTD, VarTD, hierarchical diversity, taxocene structure, Crimean coast

Funding. The study was carried out as a part of State Task of the FRC IBSS (registration No. 121030100028-0).

Acknowledgements. The author would thank Petrov A.N (PhD) for assistance in collecting benthic samples and calculating TaxDI indices; Lishaev V.N., a leading engineer (FRC IBSS) for SEM microphotography; Professor A. Witkowski (University of Szczecin, Szczecin, Poland) for sharing the equipment for LM microphotography and consultations on identification; Professor H. Lange-Bertalot and master engineer M. Ruppel (University Frankfurt am Main, Germany) for SEM microphotographs and consultations on Bacillariophyta taxonomy.

ORCID:
E.L. Nevrova, https://orcid.org/0000-0001-9963-4967

To cite this article: Nevrova, E.L., 2023. Comparison of benthic diatoms diversity (Bacillariophyta) in the Special Protected Area Cape Sarych and other water areas of the Crimea (the Black Sea). *Ecosystem Transformation* **6** (5), 43–64. https://doi.org/10.23859/estr-220927

Received: 27.09.2022
Accepted: 21.10.2022
Published online: 08.12.2023

DOI 10.23859/estr-220927
EDN ZFXKDL
УДК 582.261.1:574.64 (262.5)

Научная статья

Анализ разнообразия бентосных диатомовых водорослей (Bacillariophyta) в районе ООПТ мыс Сарыч и других акваториях Крыма (Черное море)

Е.Л. Неврова

Федеральный исследовательский центр "Институт биологии южных морей им. А.О. Ковалевского РАН", 299011, г. Севастополь, пр. Нахимова, д. 2

el_nevrova@mail.ru

Аннотация. С помощью индекса TaxDI проанализирована структура таксоценов диатомовых акватории ООПТ «Прибрежный аквальный комплекс у м. Сарыч» и ранее изученных районов Крыма (условно чистые м. Фиолент, п. Новый Свет, б. Двуякорная и сильно загрязненные б. Балаклавская, б. Карантинная, б. Инкерман, б. Севастопольская). У м. Сарыч выявлены 82 вида и внутривидовых таксона диатомовых, принадлежащих к 35 родам, 25 семействам, 15 порядкам, 3 классам Bacillariophyta, среди которых 18 видов, новых для флоры Черного моря. Структура таксоцена диатомовых чистых акваторий сформирована ветвями разной иерархии с доминированием поливидовых таксонов, замыкающихся на уровне рода. Таксоцены диатомовых загрязненных акваторий характеризуются высокой долей моно- и олиговидовых ветвей, замыкающихся на уровнях семейства или порядка, что приводит к снижению таксономического разнообразия, повышению выравненности и уменьшению вариабельности их иерархической структуры. Воздействие техногенных поллютантов вызывает трансформацию первичного звена экосистемы морской сублиторали, выраженную в редуцировании структуры таксоцена диатомовых и исчезновении низкорезистентных видов.

Ключевые слова: индекс таксономической отличительности, TaxDI, AvTD, VarTD, иерархическое разнообразие, структура таксоценов, прибрежье Крыма

Финансирование. Работа осуществлена по теме № 121030100028-0 Госзадания ФИЦ ИнБЮМ.

Благодарности. Автор благодарит к.б.н. А.Н. Петрова (ФИЦ ИнБЮМ) за помощь при отборе бентосных проб и расчетах индексов TaxDI, ведущего инженера В.Н. Лишаева (ФИЦ ИнБЮМ) за микрофотосъемки на СЭМ, профессора А. Витковски (Щецинский университет, г. Щецин, Польша) за оборудование для микрофотосъемок на СМ и консультации при идентификации, профессора Х. Ланге-Берталот и инженер-магистра М. Руппель (университет г. Франкфурт-на-Майне, Германия) за микрофотосъемки на СЭМ и консультации по таксономии Bacillariophyta.

ORCID:
Е.Л. Неврова, https://orcid.org/0000-0001-9963-4967

Для цитирования: Неврова, Е.Л., 2023. Анализ разнообразия бентосных диатомовых водорослей (Bacillariophyta) в районе ООПТ мыс Сарыч и других акваториях Крыма (Черное море). *Трансформация экосистем* **6** (5), 43–64. https://doi.org/10.23859/estr-220927

Поступила в редакцию: 27.09.2022
Принята к печати: 21.10.2022
Опубликована онлайн: 08.12.2023

Introduction

In the Russian Federation, the concept of creating the special protected natural areas (SPNA) makes provision both for the establishment of new protected areas and the expansion of the existing ones. In the program "Biodiversity conservation needs assessment in the Crimea", among fifteen areas of the highest priority for protection is the site "Cape Aya – Cape Sarych"|, the southwestern coast of the Crimea (Vyrabotka prioritetov..., 1999). The natural object "Coastal Aquatic Complex Cape Sarych" was founded in 1972, its boundaries were approved in 2005, and the status of the special protected area was designated by the governmental regulation of Sevastopol in 2015 (Milchakova et al., 2015).

This hydrological Local Nature Phenomenon distinguished by abundant unique habitats of various groups of hydrobionts has a high environmental value. The primary tasks for preserving its biodiversity involve the strengthened control over the coastal ecosystem state, certification and thorough biodiversity assessment.

A key link in the functioning of the coastal ecosystems of the Black Sea are benthic diatoms (Bacillariophyta). The evaluation of their species richness is relevant to setting the priority in species protection and solving the problems related with monitoring and bioindication of the marine environment state (Blanco et al., 2012; Borja et al., 2013; Keck et al., 2016; Nevrova, 2022; Stenger-Kovács et al., 2014; Tokatli et al., 2020). In hydroecological researches of the Black Sea shelf, the study of benthic diatoms diversity is of particular importance because of the presence of highly contaminated coastal waters causing the transformation of taxocenes structures, as well as changes in species and taxonomic richness of Bacillariophyta (Nevrova et al., 2015; Petrov et al., 2005; Petrov and Nevrova, 2004, 2007). To reveal various aspects of biodiversity and to develop recommendations for Bacillariophyta protection, a comprehensive analysis and synthesis of the results obtained both from the traditional floristic studies and modern formalized application is required. The comparative analysis of parameters of the species structure and taxonomic diversity of diatom taxocenes in the ecologically heterogeneous biotopes remains a challenging and poorly developed problem (Heino et al., 2007; Petrov and Nevrova, 2007, 2014; Petrov et al., 2010; Stenger-Kovács et al., 2014).

This work is focused on analyzing the species composition of benthic diatoms in the previously unexplored and undisturbed biotope of the aquatic complex of the special protected area Cape Sarych in Sevastopol. Also it deals with the comparison of the features of taxonomic diversity in this water areas with the already investigated coastal areas of the Crimea exposed to different anthropogenic loads. For this purpose, a quantitative assessment of the structure of Bacillariophyta taxocenes in the waters of Cape Sarych and other biotopes was performed using the taxonomic distinctness index TaxDI (Warwick and Clarke, 1998, 2001). Besides, we revealed the causes of the detected differences affecting diversity of benthic Bacillariophyta.

Materials and methods

Cape Sarych is located between Bay Laspi and Foros settlement in the south of the Crimea Peninsula (Fig. 1). The rocky coastline is formed by blocks of hard marbled limestone. The bottom is represented by rocky boulders covered with macrophytes; in places, pebbles, fine gravel and coarse sand are present.

In August 2007, the biomaterial for studying benthic diatoms was collected at a depth of 3–5 m using a meiobenthic tube ($S = 15.9$ cm^2) at 4 stations at Cape Sarych, the protected natural area of regional importance in the city of Sevastopol (N 44.38728° E 33.73833°). A total of eight samples (two at each

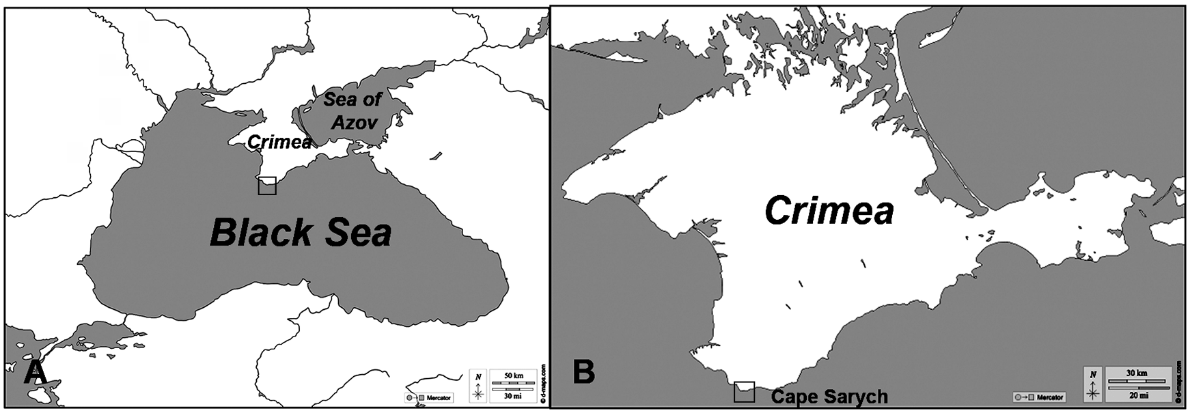

Fig. 1. Map of study sites in the special protected water area Cape Sarych (southern coast of the Crimea, the Black Sea): **A** – Crimea Peninsula; **B** – study site.

station) of soft substrate consisting of fine crushed stone and coarse sand were taken from the upper 2–3 cm layer of the bottom sediments and exposed to ultrasound bath treatment to separate epipelon and epipsammon properly. Diatom valves were purified by means of acids (Diatomovyye vodorosli SSSR, 1974), placed in Naphrax® medium and examined using a Nikon Eclipse E600 light microscope (LM) with a PlanAPO 100×1.45 lens and a Nikon DS-Fi1 digital camera, Japan (Institute of Marine Sciences at the University of Szczecin, Poland), as well as scanning electron microscopes (SEM) Hitachi S4500, Japan (Goethe University, Frankfurt am Main, Germany) and Hitachi SU3500, Japan (FRC IBSS). Diatom valves were measured in ImageJ v 1.53e (https://imagej.nih.gov/ij/). The classification (Bacillariophyta) was based on the system by F.E. Round et al. (Round et al., 1990) further developed by other scientists (AlgaeBase; Catalog of Diatom Names[1]; Guiry and Guiry, 2023; Guslyakov et al., 1992; Levkov, 2009, Witkowski et al., 2000, etc.). Nomenclature names of taxa correspond to the International Plant Names Index[2]. For the construction of the map (Fig. 1), we used the d-maps website (https://d-maps.com) and edited it in Adobe Photoshop©v 21.2.10.

A comparative assessment of taxonomic diversity of diatom taxocenes in the special protected natural area (SPNA) Cape Sarych and other previously studied areas of the coastal Crimea (the Black Sea) was made using the PRIMER v6 program (Clarke and Gorley, 2006) and taxonomic distinctness indices (TaxDI). The algorithm for calculating the Average Taxonomic Distinctness Index AvTD (Δ^+) and its variability VarTD (Λ^+) was described by E.L. Nevrova (2022), R.M. Warwick and K.R. Clarke (Warwick and Clarke, 1998, 2001).

Results and discussion

The study on species richness of benthic diatoms in Cape Sarych was carried out for the first time. The obtained results should encourage further investigations. Note that in accordance with our previous prognostic assessment of the taxonomic composition of Bacillariophyta in the coastal areas of Crimea, when considering any one station on the site, 35% of the total species composition can be revealed and while analyzing any four stations – about 70%. High reliability of differences between the diatoms species composition at the neighboring stations of the test site was statistically confirmed (Petrov and Nevrova, 2013, 2014). Thus, from all the above and the analysis of 8 stations of Cape Sarych the total species composition would exceed 80%.

During our investigation implemented in the SPNA Cape Sarych, 82 species and intraspecific taxa of benthic diatoms were marked on the soft bottom belonging to 35 genera, 25 families, 15 orders, 3 classes of division Bacillariophyta (Table 1). The list contains 18 species described earlier as new to the diatom flora of the Black Sea, as well as 1 species (previously found in the Crimea coast) as new to science (Witkowski et al., 2010). Some taxa were not identified to the species level; they were

[1] Catalogue of Diatom Names. California Academy of Sciences, USA. Web page. URL: http://researcharchive.calacademy.org/research/diatoms/names/index.asp (accessed: 10.09.2022).

[2] International Plant Names Index. Web page. URL: http://www.ipni.org (accessed: 10.09.2022).

documented as microphotographs and included in the master list for subsequent analysis because of their morphological difference. To date, the description of new species cannot be completed because of insufficient biomaterial of various Black Sea diatom populations.

Abundance of benthic diatom species found in the SPNA confirms Cape Sarych high priority in diatoms biodiversity preservation. Due to remoteness of this area from various pollution sources, it is expected to replenish the master list (Bacillariophyta), discover floristic finds and describe the new to science taxa during further studying the southern coast of the Crimea. Numerous rare unidentified and new to the Black Sea flora species found at Cape Sarych are presented in Fig. 2–7.

The growing anthropogenic impact on the Crimean shelf is responsible for deterioration of species richness of benthic diatoms and, as a consequence, transformation of the marine sublittoral as a whole. Therefore, Bacillariophyta biodiversity evaluation in order to develop the protection measures is among the relevant problems of preserving the algal flora of the Black Sea. The saturated structure of taxocenes of benthic diatoms and their species richness in the conventionally clean water areas may promptly reduce in case of water contamination. The latter can be induced by disappearance of numerous intolerant species and their replacement by few pollutant-resistant ones. Assessing the taxocene structure of benthic diatoms in the relatively pristine coastal and technogenically polluted biotopes allows to reveal the aspects of biodiversity in various environmental conditions (Facca and Sfriso, 2007; Izsak et al., 2002; Leira et al., 2009; Nevrova, 2022; Stenger-Kovács et al., 2016).

Literary sources on benthic diatoms of the Black Sea are mainly focused on identification of the species composition and revealing of trends in seasonal changes of dominant species dwelling on solid natural and artificial substrates. Diatom taxocenes on soft bottom have been less studied. Moreover, the problem of Bacillariophyta diversity evaluation has not been developed at all. Most often, the publications present the lists of diatom species. However, the lack of quantitative parameters of abundance or biomass makes the traditional indices application (Shannon, Margalef, Pielou, etc.) in biodiversity assessment impossible. A similar situation arises when biotope types or the number of samples differ greatly, or when taxocenes with similar parameters of species richness are compared (Nevrova, 2022; Warwick and Clarke, 1998, 2001). The mentioned taxocenes can include the species both phylogenetically close (belonging to the same genus) and distant (belonging to different families, orders and classes). In this case, the taxonomic aspects of diversity are different even when comparing

Table 1. Benthic diatoms at Cape Sarych. * – species new to the Black Sea diatom flora; ** – species previously described as new to science; *** – rare species.

Taxon	Species
Class Coscinodiscophyceae Orders: 2 Families: 3 Genera: 4 Species: 5	*Cyclotella operculata* (C. Agardh) Kütz.
	Pantocsekiella ocellata (Pant.) K.T. Kiss & Ács
	Thalassiosira eccentrica (Ehrenb.) Cleve, *T. parva* Proshk.-Lavr.
	Triceratium antediluvianum (Ehrenb.) Grunow***
Class Fragilariophyceae Orders: 5 Families: 5 Genera: 7 Species: 7	*Ardissonea baculus* (W. Greg.) Grunow
	Grammatophora marina (Lyngb.) Kütz.
	Licmophora gracilis (Ehrenb.) Grunow
	Microtabella delicatula (Kütz.) Round
	Opephora marina (W. Greg.) P. Petit
	Tabularia tabulata (C. Agardh) P.J.M. Snoeijs
	Thalassionema nitzschioides (Grunow) Mereschk.

Таксон	Виды
Class Bacillariophyceae Orders: 8 Families: 17 Genera: 24 Species: 69 Species and intraspecific taxa: 70	*Achnanthes brevipes* var. *intermedia* (Kütz.) Cleve *Achnanthidium minutissimum* (Kütz.) Czarn.*** *Amphora exilitata* Giffen*, *A. helenensis* Giffen*, *A. pediculus* (Kütz.) Grunow, *A. proteus* W. Greg., *Amphora* sp. S1 *Bacillaria paxillifera* (O.F. Müll.) T. Marsson *Berkeleya scopulorum* (Bréb.) E.J. Cox *Caloneis densestriata* (Proshk.-Lavr.) Gusl., *C. liber* (W. Sm.) Cleve, *Caloneis* sp. 3 *Campylodiscus thuretii* Bréb. *Cocconeis britannica* Naegeli*, *C. diminuta* Pant.*, *C. costata* W. Greg., *C. euglypta* Ehrenb., *C. pediculus* Ehrenb., *C. placentula* Ehrenb., *C. pseudocostata* O.E. Romero*, *C. scutellum* Ehrenb., *C. scutellum* var. *parva* (Grunow) Cleve, *Cocconeis* sp. G2, *Cocconeis* sp. 5W *Diploneis chersonensis* (Grunow) Cleve***, *D. smithii* (Bréb. ex W. Sm.) Cleve, *D. vacillans* (A.W.F. Schmidt) Cleve, *Diploneis* sp. 5 *Encyonopsis microcephala* (Grunow) Krammer* *Fallacia pulchella* Sabbe et Muylaert*, *Fallacia* sp. 10S *Halamphora angularis* (W. Greg.) Levkov, *H. coffeaeformis* (C. Agardh) Levkov, *H.* cf. *exigua* (W. Greg.) Levkov, *H. subacutiuscula* (Schoemann) Levkov***, *H. tenerrima* (Aleem et Hust.) Levkov* *Haslea subagnita* (Proschk.-Lavr.) I.V. Makarova et Karayeva, *H.* cf. *howeana* (Hagelstein) Giffen* *Hippodonta* sp. 7 *Mastogloia cuneata* (Meister) Simonsen* *Navicula* cf. *duerrenbergiana* Hust., *N.* cf. *phylleptosoma* Lange-Bert.*, *N. hamiltonii* Witkowski, Lange-Bert. et Metzeltin*, *N. palpebrulum* Cholnoky*, *N. parapontica* Witkowski, Kulikovskiy, Nevrova et Lange-Bert.**, *N. perminuta* Grunow ex Van Heurck, *N. ramosissima* (C. Agardh) Cleve, *N. salinicola* Hust., *N. viminoides* var. *cosmomarina* Lange-Bert.*, Witkowski, Bogaczewicz-Adamchak et Zgrundo*, *Navicula* sp. B1 *Nitzschia aequorea* Hust.*, *N. agnita* Hust.*, *N. angularis* var. *affinis* (Grunow) Grunow, *N. capitellata* Hust.***, *N. coarctata* Grunow, *N.* cf. *coarctata* Grunow, *N. dissipata* (Kütz.) Grunow, *N. fonticola* Grunow, *N. frustulum* (Kütz.) Grunow, *N. inconspicua* Grunow, *N. perindistincta* Cholnoky* *Parlibellus hendeyi* Witkowski, Lange-Bert. et Metzeltin* *Plagiotropis lepidoptera* (W. Greg.) Kuntze *Planothidium* cf.1 *delicatulum* (Kütz.) Round et Bukht., *P.* cf. *delicatulum* (Kütz.) Round et Bukht., *Planothidium* sp. 3F *Pleurosigma rigidum* W. Sm. *Rhoicosphenia abbreviata* (C. Agardh) Lange-Bert. *Seminavis* sp. 2 *Trachyneis aspera* (Ehrenb.) Cleve

two taxocenes with the same species richness. Previous classifications of Bacillariophyta relied entirely on the morphology of diatom valves. Modern studies take into account the findings of phylogenetics and sexual reproduction. Clearly, a taxocene composed of closely related species is less taxonomically diverse than that containing the same number of species but belonging to different taxonomic levels (Warwick and Clarke, 1998, 2001).

Based on hierarchical relationships, the assessment of the taxonomic structure of diatom taxocenes differs from traditional diversity indices. The index TaxDI is applied to assess taxonomic diversity of different animal groups (Arvanitidis et al., 2005; Campbell et al., 2007; Ceschia et al., 2007; Ellingsen et al., 2005; Heino et al., 2007; Leonard et al. , 2006; Mouliott et al., 2005; Munari et al., 2009; Warwick et al., 2002) and plant (Izsak et al., 2002; Leira et al., 2009; Yang et al., 2016) aquatic organisms of freshwater bodies and the World Ocean. Note that we were the first who had estimated taxonomic diversity of marine benthic diatoms (Nevrova, 2013a, b, 2014, 2015, 2016, 2022; Nevrova and Petrov, 2019b; Nevrova et al., 2015; Petrov et al., 2010).

To do this the analysis of diversity of benthic diatoms taxocenes of the Crimea coastal biotopes with different anthropogenic disturbance and various parameters of Bacillariophyta species richness required. As a result, the protected areas of capes Sarych (82 species and intraspecific taxa) and Fiolent (290), Novy Svet settl. (93), and Dvuyakornaya Bay (304) were referred to the areas with conditionally clean waters, whereas bays Sevastopolskaya (186), Karantinnaya (135), Balaklavskaya (191), and Inkerman (116) – to heavily polluted ones. The data on the average value of heavy metal content and three classes of organic pollutants in soft bottom of the Crimean coast were reported earlier (Nevrova, 2015).

Maximal similarity in species richness of diatoms was revealed from the pairwise comparison of taxocenes in the most polluted bays: Karantinnaya – Sevastopolskaya (Bray-Curtis similarity coefficient = 64.8), Balaklavskaya – Sevastopolskaya (57.8) and Balaklavskaya – Karantinnaya (54.0). Obviously, it was due to the reduced structure of diatom taxocenes in the anthropogenically disturbed biotopes. High similarity was also noted for Bacillariophyta taxocenes in the pristine areas, i.e. Bay Dvuyakornaya – Cape Fiolent (55.9), Cape Sarych – Novy Svet settl. (39.01). This indicator was also high for diatom taxocenes of Cape Sarych – Bay Karantinnaya (28.7), Cape Sarych – Bay Inkerman (27.4) and Cape Sarych – Bay Sevastopolskaya (20.2). The use of traditional Margalef and Shannon indices turned out to be uninformative in assessing species diversity of benthic diatoms in the studied biotopes. The indices were the highest in Bay Dvuyakornaya and Cape Fiolent and the lowest – in Cape Sarych and the coast of Novy Svet settl. because of the corresponding maximum and minimum numbers of the found species (Table 2).

Since the obtained results do not allow to estimate the real diatoms diversity and clarify the reasons causing its formation, we analyzed taxonomic diversity of diatoms using the TaxDI index: the average taxonomic distinctness index (AvTD, Δ^+) and its variability (VarTD, Λ^+) (Nevrova, 2013a, b, 2014, 2015, 2016, 2022; Nevrova and Petrov, 2019a, b; Warwick and Clarke, 1998, 2001) (Table 2). The master list of benthic Bacillariophyta of the Black Sea (1100 species and intraspecific taxa) was aggregated into 7 hierarchical levels (from intraspecific taxa to division) used to construct bivariant ellipses with 95% probability contours of distribution of points of Δ^+ and Λ^+ values calculated via thousandfold random combinations for a number of subsets from different species number (S) of the compared water areas (Fig. 8). The location of a point characterises the average vertical evenness of taxa distribution along the hierarchical tree (Δ^+) and their horizontal variability (Λ^+). A simultaneous presentation of these two characteristics is required in order to estimate taxocene diversity and identify probable impact of heterogeneous biotope conditions on its formation. The values of indices Δ^+ and Λ^+ for diatom taxocenes in the relatively clean water areas (capes Fiolent, Sarych, Dvuyakornaya Bay and Novy Svet settl.) are given in the upper left corner of the graph (Fig. 8). AvTD for these locations is lower, while VarTD higher than the average for the Black Sea (Δ^+ = 82.09 and Λ^+ = 316.83). It means that the taxocene structure of the studied sites is formed by branches of various species saturation and hierarchy; it greatly differs from the architectonics of the Black Sea Bacillariophyta flora. Low values of Δ^+ (minimum for capes Fiolent and Sarych) are due to dominance of polyspecies taxa closing at the general genus level. Maximum Λ^+ values for capes Sarych and Fiolent demonstrate high variability and unevenness of the hierarchical structure of diatom taxocenes (Nevrova, 2014, 2016, Nevrova and Petrov, 2019b).

As for points of Δ^+ and Λ^+ values of diatom taxocenes from the heavily polluted water areas (bays Balaklavskaya, Karantinnaya, Inkerman, and Sevastopolskaya), they are located in the low right corner of the graph; values of AvTD, VarTD are higher and lower, respectively, than the average for the

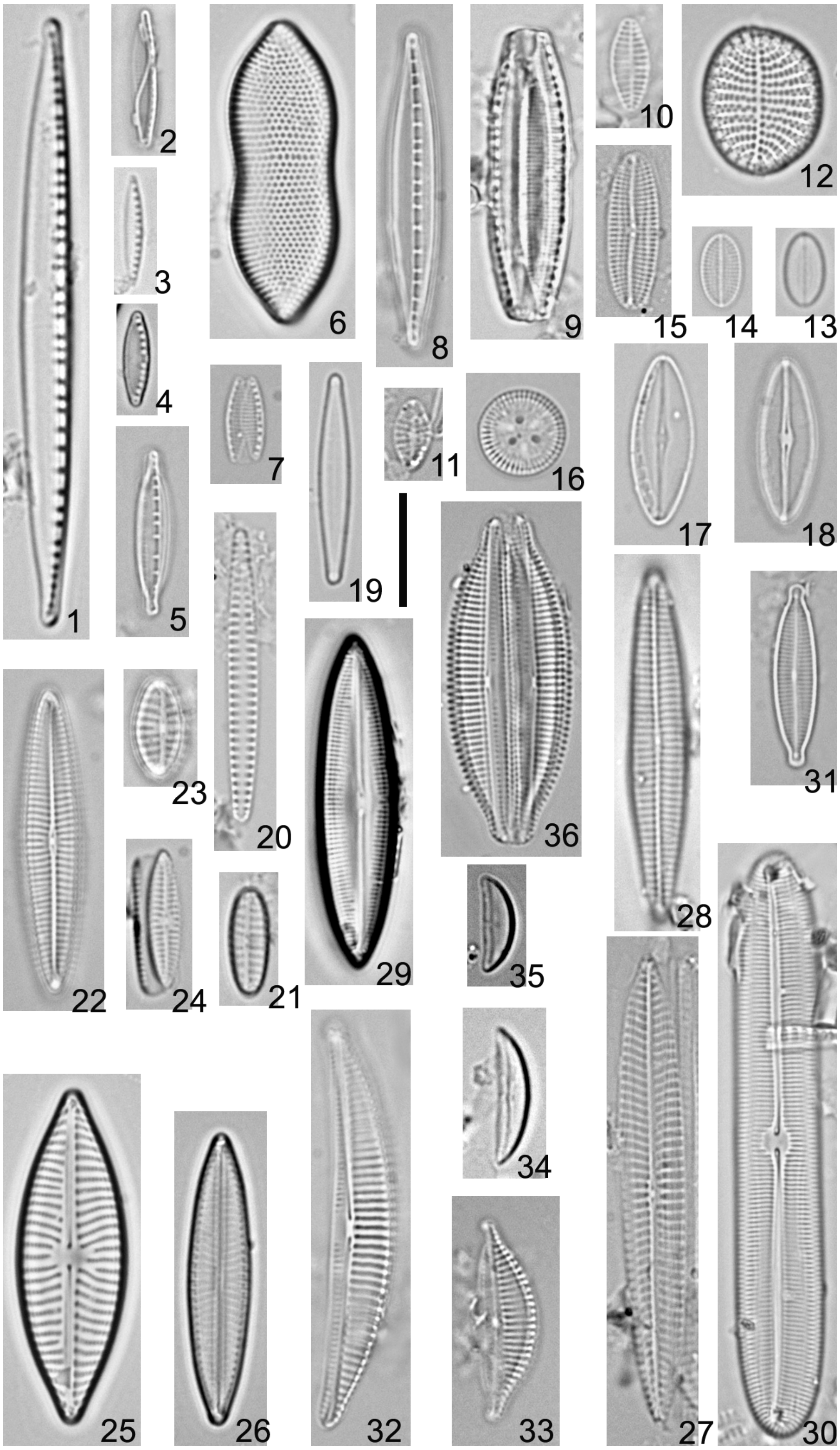

Fig. 2. Benthic diatoms found near Cape Sarych (LM). 1 – *Nitzschia capitellata;* 2 – *N. aequorea*; 3 – *N. inconspicua*; 4 – *N. perindistincta; 5 – N. dissipata; 6 – Nitzschia* cf. *coarctata; 7 – N. frustulum;* 8 – *N. angularis* var. *affinis;* 9 – *N. fonticola;* 10 – *Planothidium* cf. *delicatulum*; 11 – *Planothidium* cf. 1 *delicatulum*; 12 – *Cocconeis britannica;* 13, 14 – *Cocconeis* sp. 5W (raphe valve and rapheless valve)*;* 15 – *Fallacia* sp. 10S; 16 – *Pantocsekiella ocellata;* 17, 18 – *Mastogloia cuneata* (different focus); 19 – *Hyalosira delicatula;* 20 – *Opephora marina;* 21 – *Hippodonta* sp.7; 22 – *Navicula parapontica;* 23 – *N. viminoides* var. *cosmomarina;* 24 – *N. salinicola;* 25 – *Navicula* cf. *phylleptosoma;* 26 – *Haslea subagnita;* 27 – *Haslea* cf. *howeana;* 28 – *Navicula duerrenbergiana;* 29 – *Caloneis densestriata;* 30 – *C. liber;* 31 – *Encyonopsis microcephala;* 32 – *Halamphora* cf. *exigua;* 33 – *Halamphora subacutiuscula*; 34 – *Amphora helenensis;* 35 – *A. exilitata;* 36 – *Halamphora angularis.* Scale bar 10 µm.

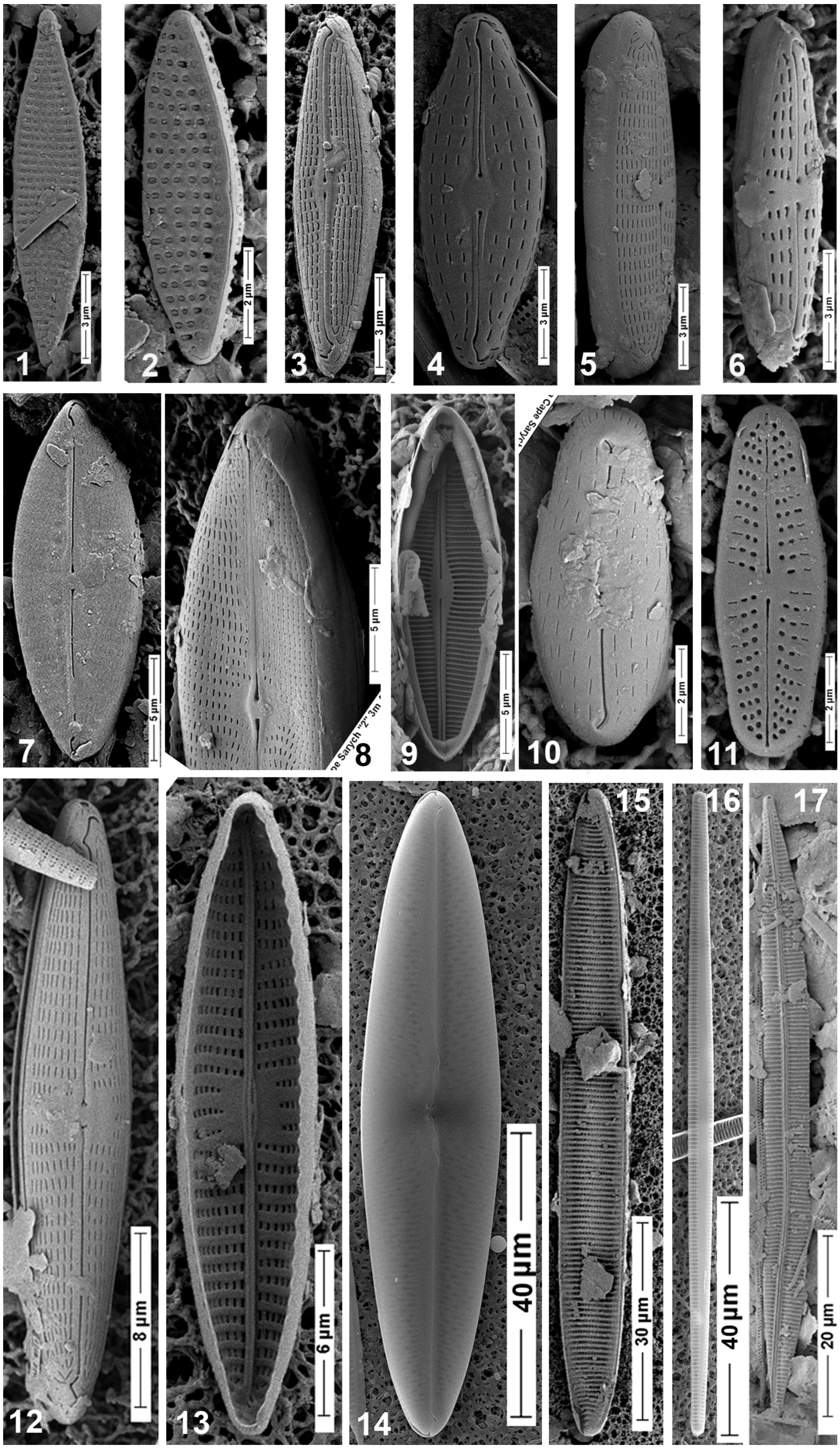

Fig. 3. Benthic diatoms found near Cape Sarych (SEM): 1 – *Nitzschia aequorea;* 2 – *Nitzschia frustulum;* 3 – *Navicula salinicola*; 4 – *Navicula viminoides* var. *cosmomarina;* 5 – *Navicula* sp. B1; 6 – *Navicula perminuta;* 7 – *Navicula palpebrulum;* 8 – *Navicula hamiltonii;* 9 – *Mastogloia cuneata* (internal view); 10 – *Hippodonta* sp.7; 11 – *Achnanthidium minutissimum;* 12, 13 – *Navicula parapontica* (external and internal views, respectively); 14 – *Trachyneis aspera*; 15 – *Ardissonea baculus*; 16 – *Tabularia tabulata*; 17 – *Bacillaria paxillifera*. Scale bar: 1, 3, 4, 5, 6 – 3 µm; 2, 10, 11 – 2 µm; 7, 8, 9 – 5 µm; 12 – 8 µm; 13 – 6 µm; 14, 16 – 40 µm; 15 – 30 µm; 17 – 20 µm.

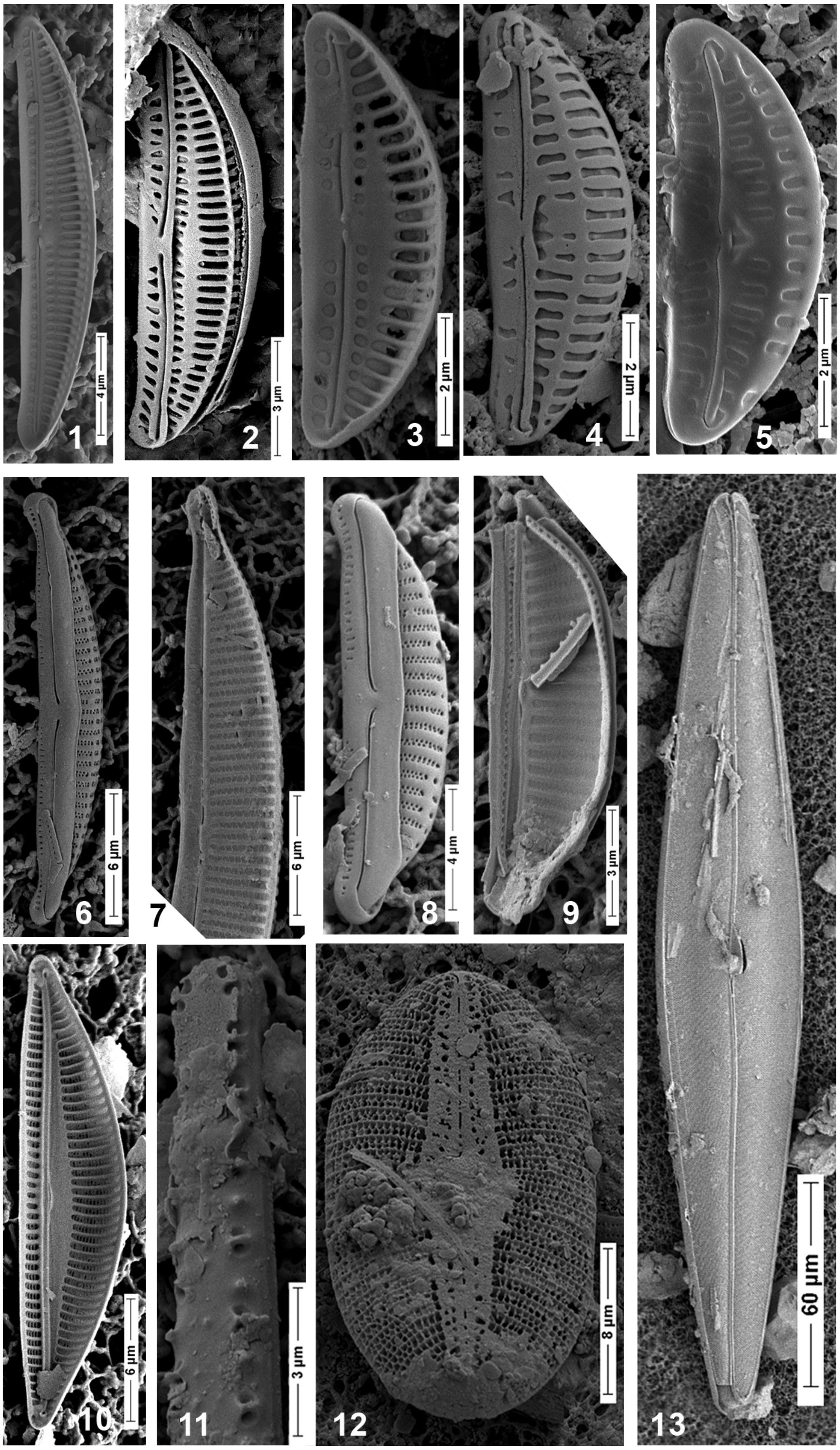

Fig. 4. Benthic diatoms found near Cape Sarych (SEM): 1 – *Amphora* sp. S1; 2, 3 – *Amphora helenensis* (external and internal views, respectively); 4, 5 – *Amphora exilitata*; 6, 7 – *Halamphora coffeaeformis* (external view, internal view, correspondingly); 8, 9 – *Halamphora tenerrima* (external and internal views, respectively); 10 – *Seminavis* sp. 2 (internal view); 11 – *Thalassionema pseudonitzschioides;* 12 – *Diploneis smithii*; 13 – *Pleurosigma rigidum.* Scale bar: 1 – 4 µm; 2, 9, 11 – 3 µm; 3, 4, 5 – 2 µm; 6, 7, 10 – 6 µm; 8 – 4 µm; 6 – 8 µm; 9, 10 – 6 µm; 13 – 60 µm.

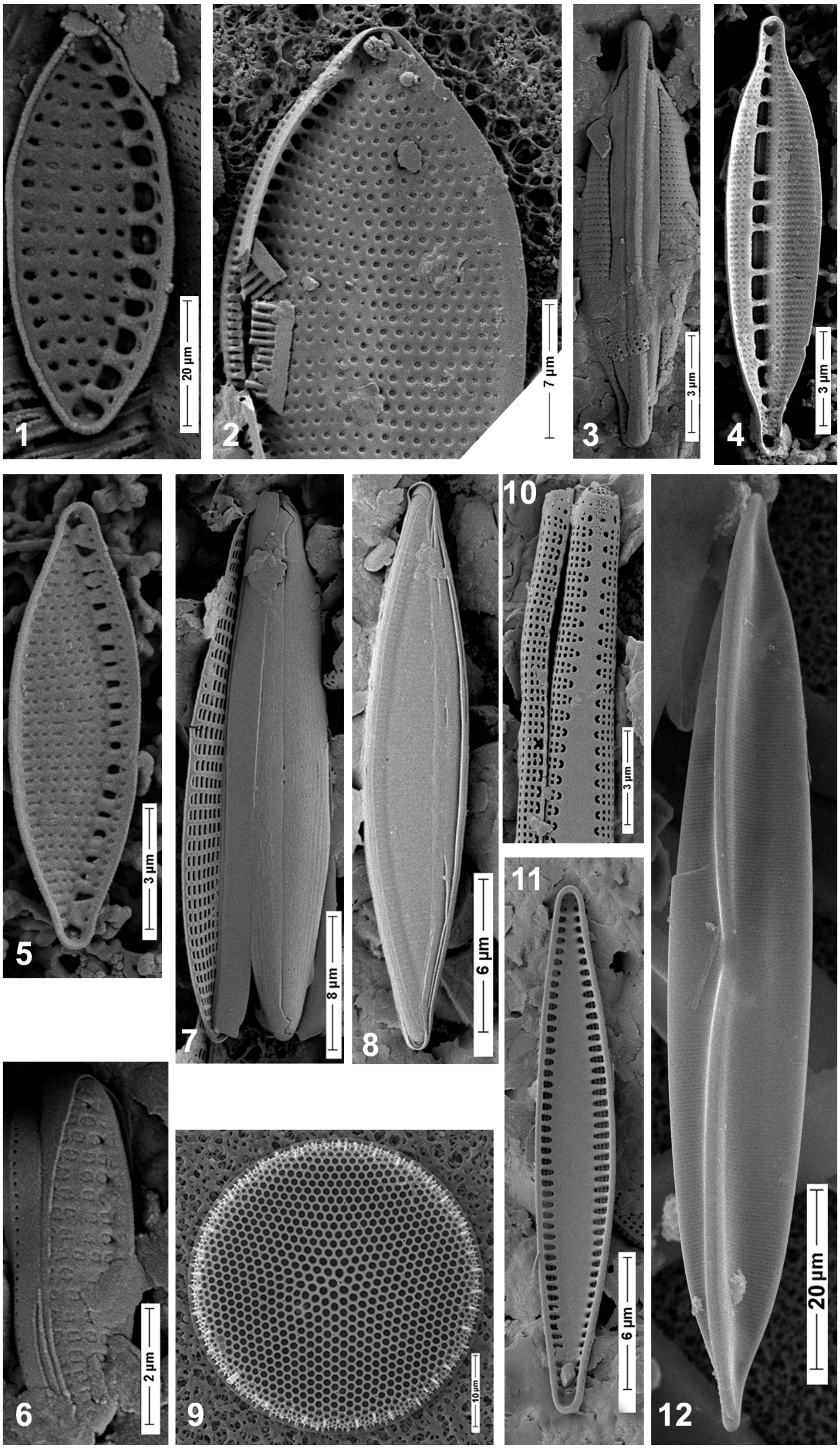

Fig. 5. Benthic diatoms found near Cape Sarych (SEM). 1 – *Nitzschia inconspicua;* 2 – *Nitzschia* cf. *coarctata;* 3, 4 – *Nitzschia dissipata*; 5, 6 – *Nitzschia perindistincta* (external view, internal view, correspondingly); 7 – *Haslea* cf. *howeana*; 8 – *Nitzschia agnita*; 9 – *Thalassiosira excentrica*; 10, 11 – *Tabularia tabulate* (external and internal views, respectively); 12 – *Plagiotropis lepidoptera.* Scale bar: 1, 6 – 2 µm; 2 – 7 µm; 3, 4, 5, 10 – 3 µm; 7 – 8 µm; 8, 11 – 6 µm; 9 – 10 µm; 12 – 20 µm.

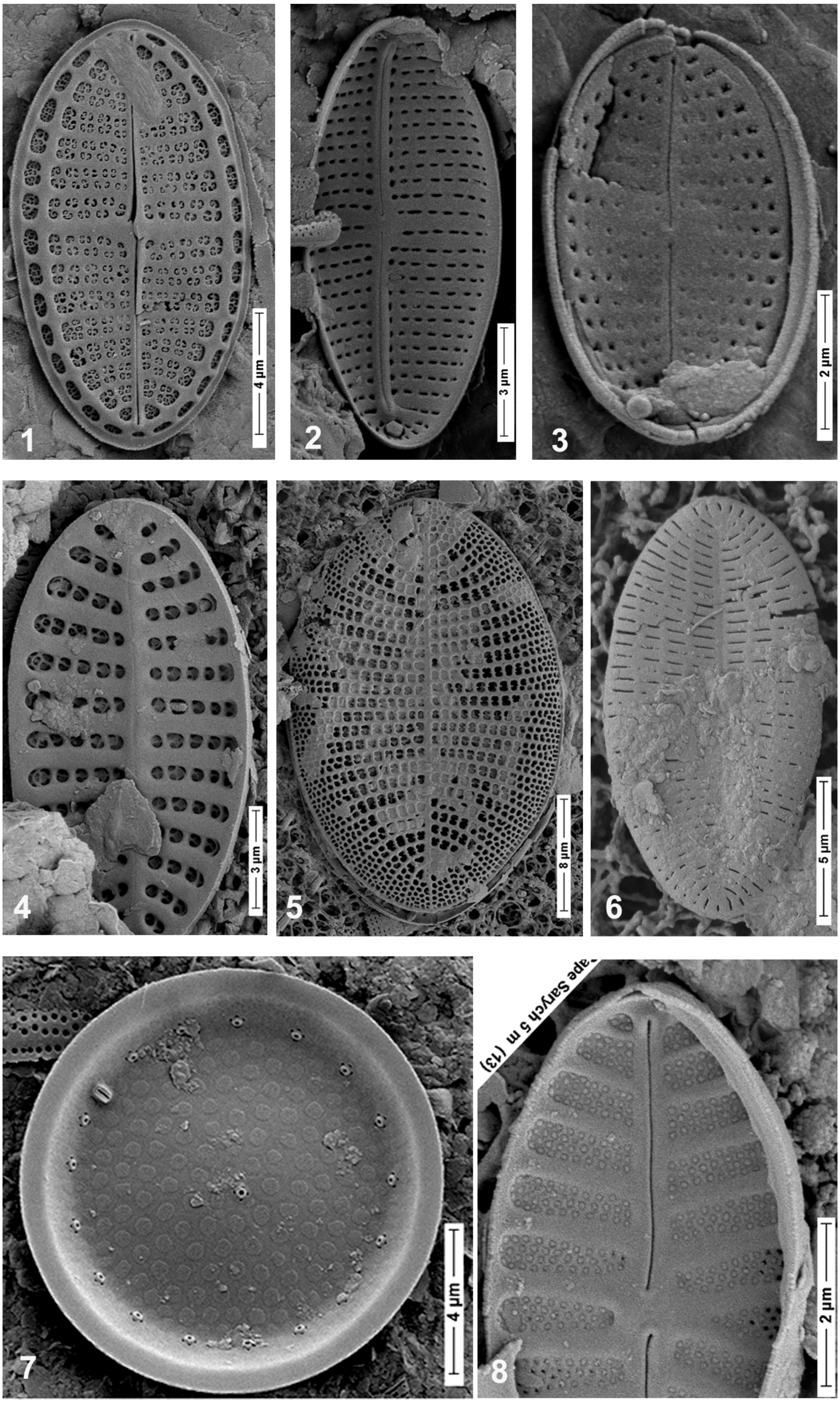

Fig. 6. Benthic diatoms found near Cape Sarych (SEM). 1 – *Cocconeis pseudocostata;* 2 – *Cocconeis* sp. G2 (internal view)*;* 3 – *Cocconeis diminuta*; 4 – *Cocconeis costata; 5 – Cocconeis scutellum; 6 – Cocconeis placentula; 7 – Thalassiosira parva* (internal view); 8 – *Planothidium* cf. *delicatulum.* Scale bar: 1, 7 – 4 µm; 2, 4 – 3 µm; 3, 8 – 2 µm; 6 – 5 µm; 5 – 8 µm.

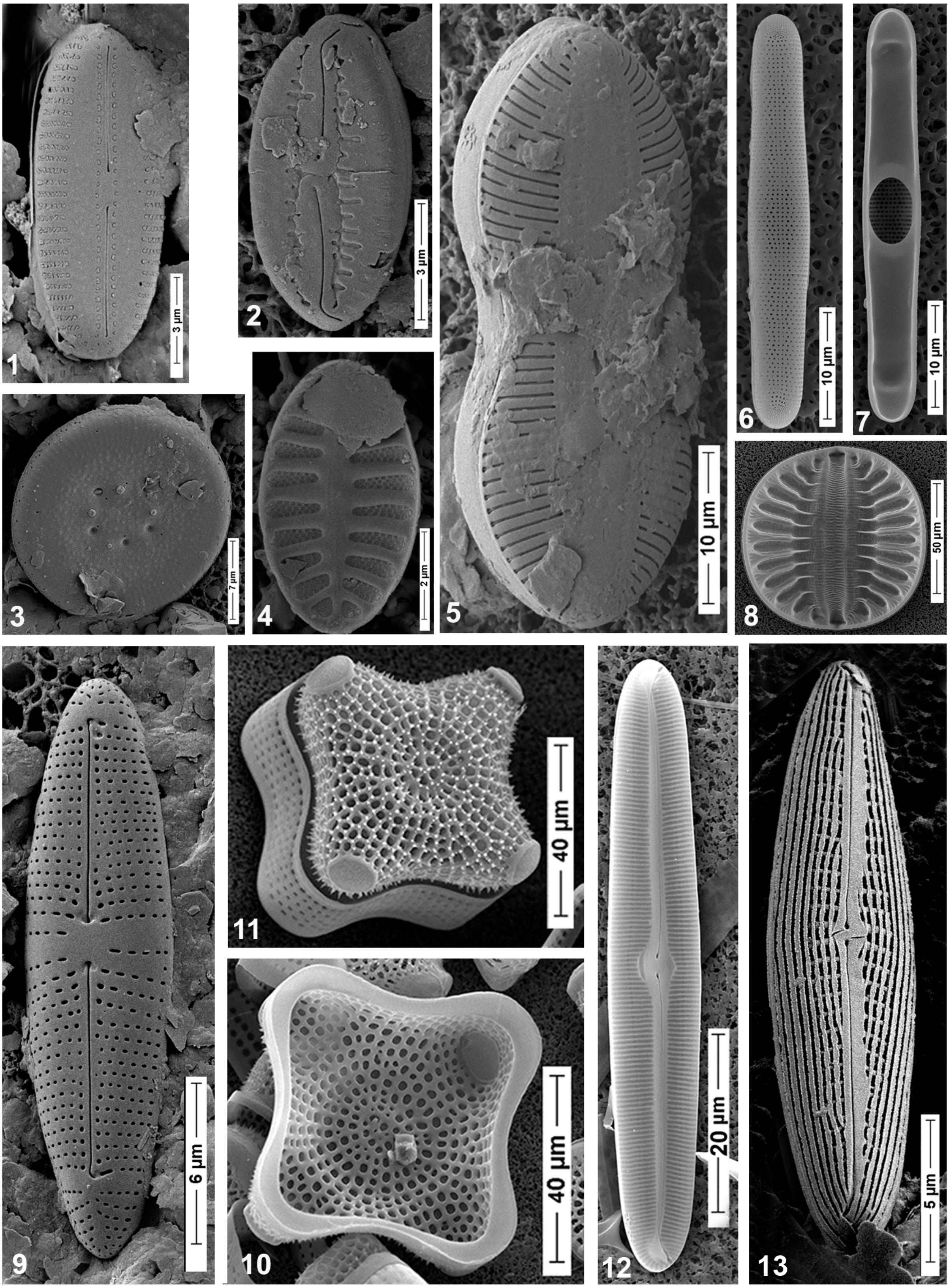

Fig. 7. Benthic diatoms found near Cape Sarych (SEM). 1 – *Diploneis* sp. 5*;* 2 – *Fallacia pulchella;* 3 – *Cyclotella operculata*; 4 – *Planothidium* sp. 3F*; 5 – Diploneis chersonensis;* 6, 7 – *Grammatophora marina* (external and internal views, respectively); 8 – *Campylodiscus thuretii*; 9 – *Parlibellus hendeyi;* 10, 11 – *Triceratium antediluvianum*; 12 – *Caloneis liber;* 13 – *Haslea subagnita*. Scale bar: 1, 2 – 3 µm; 3 – 7 µm; 4 – 2 µm; 5, 6, 7 – 10 µm; 8 – 50 µm; 9 – 6 µm; 10, 11 – 40 µm; 12 – 20 µm; 13 – 5 µm.

Table 2. Indices of species diversity (S, d, H') and taxonomic distinctness (AvTD and VarTD) of benthic diatom taxocenes of the Crimea studied water areas.

Biotope	Number of species (S)	Margalef index (d)	Shannon index (H', ln)	AvTD (Δ^+)	VarTD (Λ^+)
Bay Karantinnaya	135	27.32	4.91	73.08	172.20
Bay Sevastopolskaya	186	35.40	5.23	73.42	147.09
Cape Sarych	82	18.20	4.39	70.11	202.84
Novy Svet settlement	93	20.30	4.53	70.37	175.57
Bay Inkerman	116	24.19	4.75	74.17	157.18
М. Фиолент	290	50.97	5.67	68.45	195.71
Cape Fiolent	304	53.00	5.72	70.31	188.57
Bay Balaklavskaya	191	36.17	5.25	73.72	186.01

Black Sea (Fig. 8). The observed differences are due to the relatively high proportion of monospecies and oligospecies branches in the hierarchical structure of diatom taxocenes as compared to that of the Bacillariophyta flora of the Black Sea.

The dominance in the taxocene architectonics of diatom monospecies branches closing at high levels of family or order results in the increased Δ^+ and decreased Λ^+. In the heavily polluted areas, a decline in taxonomic diversity and a reduction in the taxonomic tree structure may be a consequence of permanent impact of pollutants (heavy metals salts, petroleum hydrocarbons, pesticides, etc.). It brings to disappearance (from polyspecies branches) of certain species with low tolerance to external negative factors and oligospecies branches predominance (Leira et al., 2009; Leonard et al., 2006; Warwick et al., 2002).

Thus, the use of TaxDI provides statistically reliable information about taxonomic diversity and diatom taxocene structure formed under the influence of various anthropogenic factors. This index is recommended to apply in comparative assessments of biota diversity of the protected and other water areas.

Conclusion

High species richness of benthic diatoms and numerous new floristic finds were revealed in the previously unstudied Special Protected Area “Coastal Aquatic Complex at Cape Sarych”. A total of 82 species and intraspecific taxa of benthic diatoms belonging to 35 genera, 25 families, 15 orders, 3 classes of Bacillariophyta division, including 18 new to the Black Sea floristic finds and 1species recently described as new to science were identified.

We compared hierarchical diversity of diatom taxocenes in the coastal biotopes of the Crimea with different anthropogenic impact. For instance, these are conventionally clean water areas near capes Sarych and Fiolent, Bay Dvuyakornaya, Novy Svet settl. and heavily polluted bays Balaklavskaya, Karantinnaya, Inkerman, and Sevastopolskaya. It was determined that the least values of Δ^+ in the relatively pristine areas were due to the predominance of diatom polyspecies taxa closing at the general genus level, while the maximal values of Λ^+ were evidence of a high variability and unevenness of the hierarchical structure of diatom taxocenes. Heavily polluted areas were characterized by maximum Δ^+ values exceeding the average for the Bacillariophyta flora of the Black Sea because of a high proportion of monospecies branches in the hierarchical structure of diatom taxocenes and a decline in taxonomic diversity. Technogenic pollutants cause a transformation of the primary link of the marine sublittoral ecosystem as expressed in the reduced structure of diatom taxocenes and low-resistant species elimination.

Our findings suggest that further studies of benthic diatoms of the undisturbed SPNA Cape Sarych should be continued and expanded due to high importance for nature conservation of this site. It is recommended to use TaxDI in analyzing the structure of benthic Bacillariophyta taxocenes of the protected and other water areas that will allow to obtain reliable data on taxonomic diversity of diatoms.

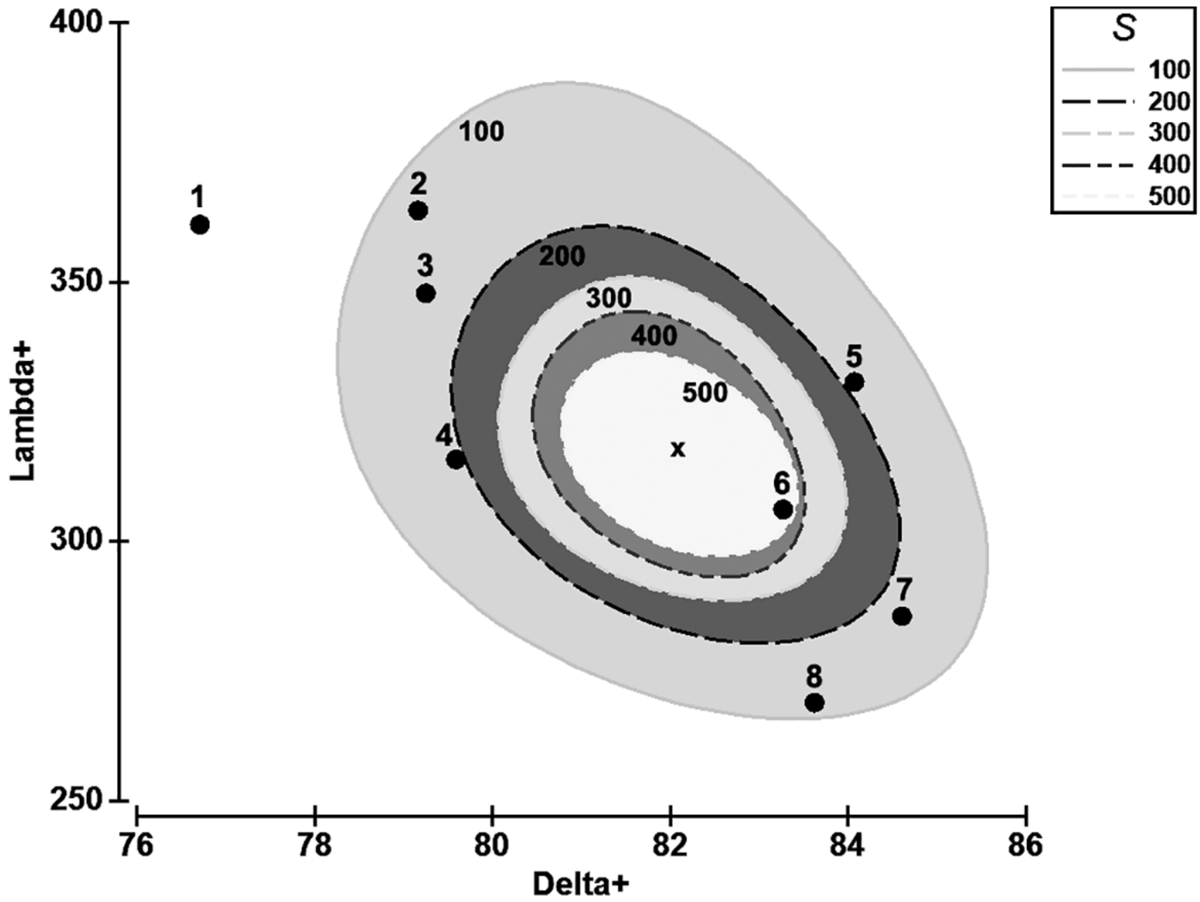

Fig. 8. Location on an ellipse (95% probability) of TaxDI index values (Δ^+ and Λ^+) for benthic diatom taxocenes in Crimea water areas: 1 – Cape Fiolent, 2 – Cape Sarych, 3 – Dvuyakornaya Bay, 4 – Novy Svet, 5 – Balaklava Bay, 6 – Karantinnaya Bay, 7 – Inkerman, 8 – Sevastopol Bay, **×** – expected mean value calculated from the master list of Bacillariophyta of the Black Sea (Δ^+ = 82.09, Λ^+ = 316.83).

References

Arvanitidis, C., Atzigeorgiu, G., Koutsoubas, D., Kevrekidis, T., Dounas, A. et al., 2005. Estimating lagoonal biodiversity comparison of rapid assessment techniques. *Helgoland Marine Research* **59**, 177–186. https://doi.org/10.1007/s10152-005-0216-8

Blanco, S., Cejudo-Figueiras, C., Tudesque, L., Bécares, E., Hoffmann, L., Ector, L., 2012. Are diatom diversity indices reliable monitoring metrics? *Hydrobiologia* **695**, 199–206. https://doi.org/10.1007/s10750-012-1113-1

Borja, A., Elliott, M., Andersen, J.H., Cardoso, A.C., Carstensen, J. et al., 2013. Good Environmental Status of marine ecosystems: What is it and how do we know when we have attained it? *Marine Pollution Bulletin* **76** (1–2), 16–27. https://doi.org/10.1016/j.marpolbul.2013.08.042

Campbell, W.B., Novelo-Gutierrez, R., 2007. Reduction in odonate phylogenetic diversity associated with dam impoundment is revealed using taxonomic distinctness. *Fundamental and Applied Limnology* **168** (1), 83–92. https://doi.org/10.1127/1863-9135/2007/0168-0083

Ceschia, C., Falace, A., Warwick, R., 2007. Biodiversity evaluation of the macroalgal flora of the Gulf of Trieste (Northern Adriatic Sea) using taxonomic distinctness indices. *Hydrobiologia* **580** (1), 43–56. http://dx.doi.org/10.1007/s10750-006-0466-8

Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual. Tutorial. PRIMER-E, Plymouth, UK, 126 p.

Diatomovyye vodorosli SSSR. Iskopayemyye i sovremennyye [Diatoms of the USSR. Fossil and modern]. Vol. 1, 1974. Proshkina-Lavrenko, A.I. (ed.). Nauka, Leningrad, USSR, 403 p. (In Russian).

Ellingsen, K.E., Clarke, K.R., Somerfield, P.J., Warwick, R.M., 2005. Taxonomic distinctness as a measure of diversity applied over a large scale: the benthos of the Norwegian continental shelf. *Journal of Animal Ecology* **74** (6), 1069–1079. https://doi.org/10.1111/j.1365-2656.2005.01004.x

Facca, C., Sfriso, A., 2007. Epipelic diatom spatial and temporal distribution and relationship with the main environmental parameters in coastal waters. *Estuarine, Coast and Shelf Science* **75,** 35–49. https://doi.org/10.1016/j.ecss.2007.03.033

Guiry, M.D., Guiry, G.M., 2023. AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. URL: https://www.algaebase.org (accessed: 17.06.2023).

Guslyakov, N.E., Zakordonets, O.A., Gerasimyuk, V.P., 1992. Atlas diatomovykh vodorosley bentosa severo-zapadnoy chasti Chornogo morya i prilegayushchikh vodoyemov [Atlas of diatom algae of the benthos of the northwestern part of the Black Sea and adjacent reservoirs]. Naukova Dumka, Kiev, Ukraine, 115 p. (In Russian).

Heino, J., Mykra, H., Hamalainen, H., Aroviita, J., Muotka, T., 2007. Responses of taxonomic distinctness and species diversity indices to anthropogenic impacts and natural environmental gradients in stream macroinvertebrates. *Freshwater Biology* **52** (9), 1846–1861. https://doi.org/10.1111/j.1365-2427.2007.01801.x

Izsak, C., Price, A.R.G., Hardy, J.T., Basson, P.W., 2002. Biodiversity of periphyton (diatoms) and echinoderms around a refinery effluent, and possible associations with stability. *Aquatic Ecosystem Health* **5** (1), 61–70.

Keck, F., Rimet, F., Franc, A., 2016. Phylogenetic signal in diatom ecology: perspectives for aquatic ecosystems biomonitoring. *Ecological Application* **26** (3), 861–872. https://doi.org/10.1890/14-1966

Leira, M., Chen, G., Dalton, C., Irvine, K., Taylor, D., 2009. Patterns in freshwater diatom taxonomic distinctness along an eutrophication gradient. *Freshwater Biology* **54** (1), 1–14. https://doi.org/10.1111/j.1365-2427.2008.02086.x

Leonard, D., Clarke, K., Somerfield, P., Warwick, R., 2006. The application of an indicator based on taxonomic distinctness for UK marine biodiversity *assessment*. *Journal of Environmental Management* **78** (1), 52–62. https://doi.org/10.1016/j.jenvman.2005.04.008

Levkov, Z., 2009. *Amphora* sensu lato. Diatoms of Europe. A.R.G. Gantner Verlag K.G, Ruggell, Liechtenstein, 916 p.

Milchakova, N.A., Aleksandrov, V.V., Bondareva, L.V., Pankeeva, T.V., Chernysheva, E.B., 2015. Morskiye okhranyayemyye akvatorii Kryma: nauchnyy spravochnik [Marine protected areas of Crimea. Scientific Handbook]. N. Orianda, Simferopol, Russia, 312 p. (In Russian).

Mouliott, D., Gaillard, S., Aliaume, C., Veriaque, M., Belsher, T., Troussellier, M., Chi, T., 2005. Ability of taxonomic diversity indices to discriminate coastal lagoon environmental based on macrophyte communities. *Ecological Indicator* **5** (1), 1–17. https://doi.org/10.1016/j.ecolind.2004.04.004

Munari, C., Warwick, R.M., Mistri, M., 2009. Monitoring with benthic fauna in Italian coastal lagoons: new tools for new prospects. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19**, 575–587. https://doi.org/10.1002/aqc.1005

Nevrova, E.L., 2013a. Struktura i taksonomicheskoye raznoobraziye donnykh diatomovykh v priust'yevykh zonakh rek Bel’bek i Chernaya (Yugo-Zapadnyy Krym, Ukraina) [Structure and taxonomic diversity of benthic diatom at estuarines of rivers Belbek and Chernaya (Southwestern Crimea, Ukraine)]. *Algologia [Algology]* **23** (4), 471–492. (In Russian).

Nevrova, E.L., 2013b. Taksonomicheskoye raznoobraziye i struktura taksotsena bentosnykh diatomovykh v Sevastopol’skoy bukhte (Chernoye more) [Taxonomic diversity and structure of benthic diatom taxocene (Bacillariophyta) at Sevastopol Bay (the Black Sea)]. *Morskoy ekologicheskiy zhurnal [Marine Ecological journal]* **3** (12), 55–67. (In Russian).

Nevrova, E.L., 2014. Ekologo-taksonomicheskaya otsenka donnykh diatomovykh v Balaklavskoy bukhte (Yugo-Zapadnyy Krym, Chernoye more) [Taxonomic diversity and environmental assessment of benthic diatoms at Balaklava Bay (Southwestern Southwestern Crimea, the Black Sea, Ukraine)]. *Algologia [Algology]* **24** (1), 47–66. (In Russian).

Nevrova, E.L., 2015. Donnyye diatomovyye vodorosli (Bacillariophyta) Chornogo morya: raznoobraziye i struktura taksotsenov razlichnykh biotopov [Benthic diatoms (Bacillariophyta) in the Black Sea: diversity and structure of taxocenes of various biotopes]. *Doctor of Biological Sciences thesis.* Moscow, Russia. 442 p. (In Russian).

Nevrova, E.L., 2016. The composition and structure of the benthic diatom taxocene (Bacillariophyta) near Cape Fiolent (the Black Sea, the Crimea). *Russian Journal of Marine Biology* **42** (5), 392–401. https://doi.org/10.1134/S1063074016050072

Nevrova, E.L., 2022. Raznoobraziye i struktura taksotsenov bentosnykh diatomovykh vodorosley (Bacillariophyta) Chernogo morya [Diversity and structure of benthic diatom taxocenes (Bacillariophyta) of the Black Sea]. Institute of Biology of the Southern Seas, Sevastopol, Russia, 329 p. (In Russian). https://doi.org/10.21072/978-5-6048081-0-8

Nevrova, E., Petrov, A., 2019a. Benthic diatoms species richness at Dvuyakornaya Bay and other coastal sites of Crimea (the Black Sea) under various environments. *Mediterranean Marine Science* **20** (3), 506–520. http://dx.doi.org/10.12681/mms.20319

Nevrova, E., Petrov, A., 2019b. Assessment of benthic diatoms taxonomic diversity at coastal biotopes with different anthropogenic impact (Crimea, the Black Sea). *Turkish Journal of Botany* **43** (5), 608–618. https://doi.org/10.3906/bot-1903-43

Nevrova, E.L., Snigireva, A.A., Petrov, A.N., Kovaleva, G.V., 2015. Rukovodstvo po izucheniyu morskogo mikrofitobentosa i yego primeneniyu dlya kontrolya kachestva sredy [Guidelines for quality control of the Black Sea. Microphytobenthos]. N. Orianda, Simferopol, Russia, 175 p. (In Russian).

Petrov, A., Nevrova, E., 2007. Database on Black Sea benthic diatoms (Bacillariophyta): its use for a comparative study of diversity pecularities under technogenic pollution impacts. *Proceedings of an International Conference of Marine Biodiversity Data Management.* Hamburg, Germany, 153–165.

Petrov, A., Nevrova, E., Terletskaya, A., Milyukin, M., Demchenko, V., 2010. Structure and taxonomic diversity of benthic diatoms assemblage in a polluted marine environment (Balaklava Bay, Black Sea). *Polish Botanical Journal* **55** (1), 183–197.

Petrov, A.N., Nevrova, E.L., 2004. Sravnitel’nyy analiz struktury taksotsena donnykh diatomovykh (Bacillariophyta) v rayonakh s razlichnym urovnem tekhnogennogo zagryazneniya (Chernoye more, Krym) [Comparative analysis of taxocene structure of benthic diatoms (Bacillariophyta) in regions with different level of technogenic pollution (the Black Sea, the Crimea)]. *Morskoy ekologicheskiy zhurnal [Marine Ecological journal]* **3** (2), 72–83. (In Russian).

Petrov, A.N., Nevrova, E.L., 2013. Prognostic estimation of species richness of benthic Bacillariophyta. *International Journal on Algae* **15** (1) 5–25. https://doi.org/10.1615/InterJAlgae.v15.i1.10

Petrov, A.N., Nevrova, E.L., 2014. Numerical analysis of the structure of benthic diatom assemblages in replicate samples (Crimea, the Black Sea). *Nova Hedwigia*. *Beiheft* **143**, 245–253.

Petrov, A.N., Nevrova, E.L., Malakhova, L.V., 2005. Mnogomernyy analiz raspredeleniya bentosnykh diatomovykh (Bacillariophyta) v pole gradiyentov abioticheskikh faktorov v Sevastopol'skoy bukhte (Chernoye more, Krym) [Multivariate analysis of benthic diatoms distribution across the multidimensional space of the environmental factors gradient in Sevastopol Bay (the Black Sea, the Crimea)]. *Morskoy ekologicheskiy zhurnal [Marine Ecological journal]* **4** (3), 65–78. (In Russian).

Round, F.E., Crawford, R.M., Mann, D.G., 1990. The diatoms. Biology and morphology of the genera. Cambridge University press, Cambridge, UK, 747 p.

Stenger-Kovács, C., Tóth, L., Tóth, F., Hajnal, E., Padisák, J., 2014. Stream order-dependent diversity metrics of epilithic diatom assemblages. *Hydrobiologia* **721,** 67–75. https://doi.org/10.1007/s10750-013-1649-8

Stenger-Kovács, C., Hajnal, É., Lengyel, E., Buczkó, K., Padisák, J., 2016. A test of traditional diversity measures and taxonomic distinctness indices on benthic diatoms of soda pans in the Carpathian basin. *Ecological Indicators* **64,** 1–8. https://doi.org/10.1016/j.ecolind.2015.12.018

Tokatlı, C., Solak, C.N., Yılmaz, E., 2020. Water quality assessment by means of bio-indication: A case study of Ergene river using biological diatom index. *Aquatic Sciences and Engineering* **35** (2), 43–51. https://doi.org/10.26650/ASE2020646725

Vyrabotka prioritetov: novyy podkhod k sokhraneniyu bioraznoobraziya v Krymu: rezul’taty programmy “Otsenka neobkhodimosti sokhraneniya bioraznoobraziya v Krymu”, osushchestvlennoy pri sodeystvii Programmy podderzhki bioraznoobraziya BSP [Developing Priorities: A New Approach to Biodiversity Conservation in the Crimea: results of the program "Biodiversity Conservation Needs Assessment in the Crimea" implemented with the assistance of the Biodiversity Support Program BSP], 1999. BSP, Washington, USA, 257 p. (In Russian).

Warwick, R.M., Clarke, K.R., 1998. Taxonomic distinctness and environmental assessment. *Journal of Applied Ecology* **35**, 532–543.

Warwick, R.M., Ashman, C.M., Brown, A.R., Clarke, K.R., Dowell, B. et al., 2002. Inter-annual changes in the biodiversity and commuity structure of the macrobenthos in Tees Bay and the Tees estuary, UK, associated with local and regional environmental events. *Marine Ecology Progress Series* **234**, 1–13. https://doi.org/10.3354/meps234001

Warwick, R.M., Clarke, K.R., 2001. Practical measures of marine biodiversity based on relatedness of species. *Oceanography and Marine Biology: an annual review* **39**, 207–231.

Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. Diatom flora of Marine coast 1. Iconographia Diatomologica. Vol. 7. A.R.G. Gantner Verlag K.G., Ruggell, Liechtenstein, 926 p.

Witkowski, A., Kulikovskiy, M., Nevrova, E., Lange-Bertalot, H., Gogorev, R., 2010. The genus *Navicula* in ancient basins. I. Two novelties from the Black Sea. *Plant Ecology and Evolution* **143** (3), 307–317.

Yang, Zh., Xu, Yu., Xu, G., Xu, H. 2016. Temporal variation in taxonomic distinctness of biofilm-associated diatoms within the colonization process in coastal ecosystems. *Journal of the Marine Biological Association of the United Kingdom* **96** (5), 1119–1125. https://doi.org/10.1017/S002531541600028X

Список литературы

Выработка приоритетов: новый подход к сохранению биоразнообразия в Крыму: результаты программы «Оценка необходимости сохранения биоразнообразия в Крыму», осуществленной при содействии Программы поддержки биоразнообразия BSP, 1999. BSP, Вашингтон, США, 257 с.

Гусляков, Н.Е., Закордонец, О.А., Герасимюк, В.П., 1992. Атлас диатомовых водорослей бентоса северо-западной части Черного моря и прилегающих водоемов. Наукова думка, Киев, Украина, 115 с.

Диатомовые водоросли СССР. Ископаемые и современные. Т. 1, 1974. Прошкина-Лавренко, А.И. (ред.). Наука, Ленинград, СССР, 403 с.

Мильчакова, Н.А., Александров, В.В., Бондарева, Л.В., Панкеева, Т.В., Чернышева, Е.Б., 2015. Морские охраняемые акватории Крыма: научный справочник. Н. Оріанда, Симферополь, Россия, 312 с.

Неврова, Е.Л., 2013a. Структура и таксономическое разнообразие донных диатомовых в приустьевых зонах рек Бельбек и Черная (Юго-Западный Крым, Украина). *Альгология* **23** (4), 471–492.

Неврова, Е.Л., 2013b. Таксономическое разнообразие и структура таксоцена бентосных диатомовых в Севастопольской бухте (Черное море). *Морской экологический журнал* **3** (12), 55–67.

Неврова, Е.Л., 2014. Эколого-таксономическая оценка донных диатомовых в Балаклавской бухте (Юго-Западный Крым, Черное море). *Альгология* **24** (1), 47–66.

Неврова, Е.Л., 2015. Донные диатомовые водоросли (Bacillariophyta) Черного моря: разнообразие и структура таксоценов различных биотопов. *Диссертация на соискание ученой степени доктора биологических наук.* Москва, Россия, 445 с.

Неврова, Е.Л., 2016. Состав и структура таксоцена бентосных диатомовых водорослей (Bacillariophyta) у мыса Фиолент (Крым, Черное море). *Биология моря* **42** (5), 334–342.

Неврова, Е.Л., 2022. Разнообразие и структура таксоценов бентосных диатомовых водорослей (Bacillariophyta) Черного моря. ФИЦ ИнБЮМ, Севастополь, Россия, 329 с. https://doi.org/10.21072/978-5-6048081-0-8

Неврова, Е.Л., Снигирева, А.А., Петров, А.Н., Ковалева, Г.В., 2015. Руководство по изучению морского микрофитобентоса и его применению для контроля качества среды. Н. Оріанда, Симферополь, Россия, 175 с.

Петров, А.Н., Неврова, Е.Л., 2004. Сравнительный анализ структуры таксоцена донных диатомовых (Bacillariophyta) в районах с различным уровнем техногенного загрязнения (Черное море, Крым). *Морской экологический журнал* **3** (2), 72–83.

Петров, А.Н., Неврова, Е.Л., Малахова, Л.В., 2005. Многомерный анализ распределения бентосных диатомовых (Bacillariophyta) в поле градиентов абиотических факторов в Севастопольской бухте (Черное море, Крым). *Морской экологический журнал* **4** (3), 65–77.

Arvanitidis, C., Atzigeorgiu, G., Koutsoubas, D., Kevrekidis, T., Dounas, A. et al., 2005. Estimating lagoonal biodiversity comparison of rapid assessment techniques. *Helgoland Marine Research* **59**, 177–186. https://doi.org/10.1007/s10152-005-0216-8

Blanco, S., Cejudo-Figueiras, C., Tudesque, L., Bécares, E., Hoffmann, L., Ector, L., 2012. Are diatom diversity indices reliable monitoring metrics? *Hydrobiologia* **695**, 199–206. https://doi.org/10.1007/s10750-012-1113-1

Borja, A., Elliott, M., Andersen, J.H., Cardoso, A.C., Carstensen, J. et al., 2013. Good Environmental Status of marine ecosystems: What is it and how do we know when we have attained it? *Marine Pollution Bulletin* **76** (1–2), 16–27. https://doi.org/10.1016/j.marpolbul.2013.08.042

Campbell, W.B., Novelo-Gutierrez, R., 2007. Reduction in odonate phylogenetic diversity associated with dam impoundment is revealed using taxonomic distinctness. *Fundamental and Applied Limnology* **168** (1), 83–92. https://doi.org/10.1127/1863-9135/2007/0168-0083

Ceschia, C., Falace, A., Warwick, R., 2007. Biodiversity evaluation of the macroalgal flora of the Gulf of Trieste (Northern Adriatic Sea) using taxonomic distinctness indices. *Hydrobiologia* **580** (1), 43–56. http://dx.doi.org/10.1007/s10750-006-0466-8

Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual. Tutorial. PRIMER-E, Plymouth, UK, 126 p.

Ellingsen, K.E., Clarke, K.R., Somerfield, P.J., Warwick, R.M., 2005. Taxonomic distinctness as a measure of diversity applied over a large scale: the benthos of the Norwegian continental shelf. *Journal of Animal Ecology* **74** (6), 1069–1079. https://doi.org/10.1111/j.1365-2656.2005.01004.x

Facca, C., Sfriso, A., 2007. Epipelic diatom spatial and temporal distribution and relationship with the main environmental parameters in coastal waters. *Estuarine, Coast and Shelf Science* **75,** 35–49. https://doi.org/10.1016/j.ecss.2007.03.033

Guiry, M.D., Guiry, G.M., 2023. AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. URL: https://www.algaebase.org (accessed: 17.06.2023).

Heino, J., Mykra, H., Hamalainen, H., Aroviita, J., Muotka, T., 2007. Responses of taxonomic distinctness and species diversity indices to anthropogenic impacts and natural environmental gradients in stream macroinvertebrates. *Freshwater Biology* **52** (9), 1846–1861. https://doi.org/10.1111/j.1365-2427.2007.01801.x

Izsak, C., Price, A.R.G., Hardy, J.T., Basson, P.W., 2002. Biodiversity of periphyton (diatoms) and echinoderms around a refinery effluent, and possible associations with stability. *Aquatic Ecosystem Health* **5** (1), 61–70.

Keck, F., Rimet, F., Franc, A., 2016. Phylogenetic signal in diatom ecology: perspectives for aquatic ecosystems biomonitoring. *Ecological Application* **26** (3), 861–872. https://doi.org/10.1890/14-1966

Leira, M., Chen, G., Dalton, C., Irvine, K., Taylor, D., 2009. Patterns in freshwater diatom taxonomic distinctness along an eutrophication gradient. *Freshwater Biology* **54** (1), 1–14. https://doi.org/10.1111/j.1365-2427.2008.02086.x

Leonard, D., Clarke, K., Somerfield, P., Warwick, R., 2006. The application of an indicator based on taxonomic distinctness for UK marine biodiversity *assessment. Journal of Environmental Management* **78** (1), 52–62. https://doi.org/10.1016/j.jenvman.2005.04.008

Levkov, Z., 2009. *Amphora* sensu lato. Diatoms of Europe. A.R.G. Gantner Verlag K.G, Ruggell, Liechtenstein, 916 p.

Mouliott, D., Gaillard, S., Aliaume, C., Veriaque, M., Belsher, T., Troussellier, M., Chi, T., 2005. Ability of taxonomic diversity indices to discriminate coastal lagoon environmental based on macrophyte communities. *Ecological Indicator* **5** (1), 1–17. https://doi.org/10.1016/j.ecolind.2004.04.004

Munari, C., Warwick, R.M., Mistri, M., 2009. Monitoring with benthic fauna in Italian coastal lagoons: new tools for new prospects. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19**, 575–587. https://doi.org/10.1002/aqc.1005

Nevrova, E., Petrov, A., 2019a. Benthic diatoms species richness at Dvuyakornaya Bay and other coastal sites of Crimea (the Black Sea) under various environments. *Mediterranean Marine Science* **20** (3), 506–520. http://dx.doi.org/10.12681/mms.20319

Nevrova, E., Petrov, A., 2019b. Assessment of benthic diatoms taxonomic diversity at coastal biotopes with different anthropogenic impact (Crimea, the Black Sea). *Turkish Journal of Botany* **43** (5), 608–618. https://doi.org/10.3906/bot-1903-43

Petrov, A., Nevrova, E., 2007. Database on Black Sea benthic diatoms (Bacillariophyta): its use for a comparative study of diversity pecularities under technogenic pollution impacts. *Proceedings of an International Conference of Marine Biodiversity Data Management.* Hamburg, Germany, 153–165.

Petrov, A., Nevrova, E., Terletskaya, A., Milyukin, M., Demchenko, V., 2010. Structure and taxonomic diversity of benthic diatoms assemblage in a polluted marine environment (Balaklava Bay, Black Sea). *Polish Botanical Journal* **55** (1), 183–197.

Petrov, A.N., Nevrova, E.L., 2013. Prognostic estimation of species richness of benthic Bacillariophyta. *International Journal on Algae* **15** (1) 5–25. https://doi.org/10.1615/InterJAlgae.v15.i1.10

Petrov, A.N., Nevrova, E.L., 2014. Numerical analysis of the structure of benthic diatom assemblages in replicate samples (Crimea, the Black Sea). *Nova Hedwigia*. *Beiheft* **143**, 245–253.

Round, F.E., Crawford, R.M., Mann, D.G., 1990. The diatoms. Biology and morphology of the genera. Cambridge University press, Cambridge, UK, 747 p.

Stenger-Kovács, C., Tóth, L., Tóth, F., Hajnal, E., Padisák, J., 2014. Stream order-dependent diversity metrics of epilithic diatom assemblages. *Hydrobiologia* **721,** 67–75. https://doi.org/10.1007/s10750-013-1649-8

Stenger-Kovács, C., Hajnal, É., Lengyel, E., Buczkó, K., Padisák, J., 2016. A test of traditional diversity measures and taxonomic distinctness indices on benthic diatoms of soda pans in the Carpathian basin. *Ecological Indicators* **64,** 1–8. https://doi.org/10.1016/j.ecolind.2015.12.018

Tokatlı, C., Solak, C.N., Yılmaz, E., 2020. Water quality assessment by means of bio-indication: A case study of Ergene river using biological diatom index. *Aquatic Sciences and Engineering* **35** (2), 43–51. https://doi.org/10.26650/ASE2020646725

Warwick, R.M., Clarke, K.R., 1998. Taxonomic distinctness and environmental assessment. *Journal of Applied Ecology* **35**, 532–543.

Warwick, R.M., Ashman, C.M., Brown, A.R., Clarke, K.R., Dowell, B. et al., 2002. Inter-annual changes in the biodiversity and commuity structure of the macrobenthos in Tees Bay and the Tees estuary, UK, associated with local and regional environmental events. *Marine Ecology Progress Series* **234**, 1–13. https://doi.org/10.3354/meps234001

Warwick, R.M., Clarke, K.R., 2001. Practical measures of marine biodiversity based on relatedness of species. *Oceanography and Marine Biology: an annual review* **39**, 207–231.

Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. Diatom flora of Marine coast 1. Iconographia Diatomologica. Vol. 7. A.R.G. Gantner Verlag K.G., Ruggell, Liechtenstein, 926 p.

Witkowski, A., Kulikovskiy, M., Nevrova, E., Lange-Bertalot, H., Gogorev, R., 2010. The genus *Navicula* in ancient basins. I. Two novelties from the Black Sea. *Plant Ecology and Evolution* **143** (3), 307–317.

Yang, Zh., Xu, Yu., Xu, G., Xu, H. 2016. Temporal variation in taxonomic distinctness of biofilm-associated diatoms within the colonization process in coastal ecosystems. *Journal of the Marine Biological Association of the United Kingdom* **96** (5), 1119–1125. https://doi.org/10.1017/S002531541600028X