Ecological determinants of algal communities of different types of ecosystems

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Abstract. The results of studies of the environmental regularities of the formation of algal communities in soils of various ecosystems in the south of Ukraine are presented. 26 forest, 11 steppe and 3 saline ecosystems were investigated. The research has established the species richness of algae in each ecosystem and produced a multidimensional ordination of algal communities based on the analysis of the main components to clarify the factors that determine the composition of algal communities. The research has established the species richness of algae in each ecosystem and produced a multidimensional ordination of algal communities based on the analysis of the main components to clarify the factors that determine the composition of algal communities. Predictors determined by edaphic conditions and phytocenotic interactions associated primarily with edificators of ecosystems were used for the analysis. The ecological space of the studied ecosystems was formed by four main factors with eigenvalues greater than one, which explained 81.4% of the total variance. PC1 (34.82% of variance) is associated with the type of ecosystem and such edaphic parameters as pH, the availability of moisture in the habitat, and soil mineralization. PC2 (21.98%) reflects changes in the gradients of trophicity (humus content) and granulometric composition of soils. PC3 and PC4 additionally explain 16.04% and 9.27% of the total data variance, respectively. Their values mainly depend on the mineralization, trophicity, and moisture supply of edaphotopes, which, at the level of the composition of algae, is obviously associated with the heterogeneity of the ecological preferences of the algal species themselves, as well as the variability of ecological niches of ecosystems, due to which there are species more typical for other types of ecosystems in the communities. The use of the factor rotation procedure by the Varimix normalized method made it possible to concretize the taxa most associated with the main components: PC1 indicates the various Cyanobacteria species, PC2 – Chlorophyta, Streptophyta and Eustigmatophyceae, PC3 – Xanthophyceae and Euglenozoa, PC4 – Bacillariophyceae.

1. Introduction
From the perspective of the general theory of systems, the internal structure of ecosystems is determined by the nature and way of interaction of elements [1]. The forest and herbaceous ecosystems have different abilities to influence the formation of their internal phytocenotic environment and the composition of the organisms that inhabit them [2–5]. The various studies have shown the specific features of algal communities in forest, steppe, desert, and other ecosystems [6–11]. This is consistent with the definition of the essence of the ecosystem,
where it is represented by a set of interconnected organisms that function in the same territory and interact with the environment in such a way that the flow of energy forms clearly defined biotic structures and the circulation of substances between the living and nonliving components. At the same time, ecological factors are not only interrelated and determine the nature of plant communities, but the latter also acts as a powerful ecological factor that forms the specificity of the ecotope [12–15]. Therefore, there is no linear relationship between vegetation and environmental conditions and their change [16]. It has a more complex character [17,18]. Even more complex nature of interactions is expected at the level of individual organisms and their communities that occupy a subordinate position relative to the edificators that determine the structure and functioning of a particular ecosystem [19,20]. This fully applies to microscopic algae inhabiting the upper soil layers. Many works have been devoted to the study of factors affecting the composition and structure of microalgal communities [21–24].

2. Research aim and objectives

However, given the contemporary understanding of the priority of the conservation and maintenance of natural diversity, there is considerable interest in microalgae, not only as organisms that provide a wide range of ecosystem services [9, 25, 26] but also sources of biotechnologically valuable compounds [14, 23, 27–30], further continuation of these studies is necessary.

The aim of this work was to identify the influence of phytocenotic and edaphic factors on the structure of algal communities in various forest, steppe, and saline ecosystems.

3. Material and methods

The analysis was carried out on the basis of material collected in 2000-2013 in the south and southeast of Ukraine in oak (5 ecosystems), alder (4), aspen-birch (3), and pine (6) forest ecosystems in the floodplains of the Samara, Severskiy Donets, Vovcha, Molochna rivers, in oak (8) forest ecosystems in gullies (ravine oak forests), in the steppe (11) and saline (3) – in flat habitats. Within each ecosystem, 5 soil samples each with a volume of 25 cm³ were randomly selected to determine the species composition of microalgae, as well as a number of physicochemical parameters of the soil: pH (water), humus (%), the sum of salts (dry residue, %), particle size distribution (content of physical clay, %). The selection of soil samples for research in each ecosystem was carried out in 3–6 fold replicates. For each ecosystem, moisture conditions (hygrotope) were determined, depending on both the climatic conditions of the study region and the location in the relief. They were ranked from “0” to “5”, respectively, from very dry habitats to wet habitats. The type of ecosystem was distinguished taking into account edificators – arboreal and herbaceous. The species composition of algae was determined based on methods of working with crops. We used soil cultures with fouling glasses, agar on BBM medium for the growth of green algae, and some Heterokontophyta (Ochrophyta), G11 – for Cyanobacteria [31], WC liquid medium – for Bacillariophyceae [32]. When setting and working with crops, standard procedures were used [31]. The cultivation was carried out at a temperature of 20°C and a light intensity of 35 mmol m⁻² s⁻¹. The alternation of light and dark periods was 12 hours / 12 hours. The determination of algae was carried out with an optical microscope “XSP–128” at a magnification × 1000, and using oil immersion. The referential system of Cyanobacteria was used in accordance with the reports of I. Komarek and A. Anagnostidis [33,34], the rest of the groups – according to “Syllabus of Plant Families” [35]. The literature used for identification included Ettl and Gartner [36,37], and other [36,38–45]. The particle size distribution of the soil was determined by the method proposed by N.A. Kaczynski, the humus content – according to I.V. Turin, pH of water extract by potentiometric method [46]. The analysis of the dependences of the composition and structure of algal communities on soil and phytocenotic parameters was carried out by the method of principal components.
4. Results and discussion

The Algae of various divisions were found within the studied ecosystems (table 1). A wide variety of Chlorophyta and Heterokontophyta species are noted in forest ecosystems. They account for 39.7–59.7% and 28.9–45.3%, respectively, of the total number of algae species in forests. The majority of Heterokontophyta is represented by species from the classes Xanthophyceae, Bacillariophyceae: 17.5–27.4% and 7.9–16.9% (respectively, of the entire diversity of species). The diversity of Eustigmatophyceae from Heterokontophyta, Streptophyta, and Euglenozoa is low and limited to a few species. Cyanobacteria in forest algal communities range from 2.7% to 15.7% of the total number of species. The data obtained are generally consistent with the results of other researchers of algae in forest ecosystems, which indicate that the main forest communities of algae are Chlorophyta and Xanthophyceae [47–49].

Table 1: The number of algal species in various ecosystems, units (%).

| Ecosystems               | Floodplain oak forests | Ravine oak forests | Alder forests | Birch and aspen-birch forests | Pine forests | Steppe ecosystems | Salt marshes |
|--------------------------|------------------------|--------------------|--------------|-------------------------------|-------------|-------------------|--------------|
| The quantity and sequence numbers of the studied ecosystems | 5 (1–5) | 8 (6–13) | 4 (14–17) | 3 (18–20) | 6 (21–26) | 11 (27–37) | 3 (38–40) |
| Cyanobacteria            | 16 (13.8%) | 13 (15.7%) | 2 (2.7%) | 12 (10.0%) | 9 (7.9%) | 40 (31.3%) | 20 (48.8%) |
| Eustigmatophyceae        | 5 (4.3%) | 3 (3.6%) | 2 (2.7%) | 5 (4.2%) | 4 (3.5%) | – | – |
| Xanthophyceae            | 25 (21.6%) | 17 (20.5%) | 20 (27.4%) | 21 (17.5%) | 20 (17.5%) | 20 (15.6%) | 7 (17.1%) |
| (Heterokontophyta)       | 10 (8.6%) | 14 (16.9%) | 11 (15.2%) | 15 (12.5%) | 9 (7.9%) | 14 (10.9%) | 3 (7.3%) |
| Bacillariophyceae        | 55 (46.6%) | 33 (39.7%) | 32 (43.9%) | 61 (50.8%) | 68 (59.7%) | 46 (36.0%) | 10 (24.4%) |
| Chlorophyta              | 5 (4.3%) | 3 (3.6%) | 4 (5.4%) | 5 (4.2%) | 4 (3.5%) | 4 (3.1%) | 1 (2.4%) |
| Streptophyta             | 1 (0.8%) | – | 2 (2.7%) | – | – | – | – |
| Euglenozoa               | 116 | 83 | 73 | 120 | 114 | 128 | 41 |

It should be noted that the role of green algae and Xanthophyceae in the formation of communities differs in various types of forest. Also among the studied forest ecosystems, there are those where pronounced participation of diatoms and cyanobacteria was observed. For example, a wide variety of diatoms was characteristic of oak forests in gullies (ravine oak forests) and alder forests growing in the lowlands of the floodplain part of river valleys. In general, Cyanobacteria, which are not numerous in forest ecosystems, were common in oak forests growing both in river floodplains and in gullies. It is believed that Cyanobacteria play an insignificant role in forest ecosystems [50]. It is also suggested that the abundance of forest litter and other decomposable biomass in forest ecosystems can provide a sufficient amount of mineral nitrogen and this leads to the absence of nitrogen-fixing Cyanobacteria [50]. Our research does not support this. There are forest ecosystems for which the development of Cyanobacteria is a
stable trait. These are deciduous and oak forests, including those growing in a temperate arid climate [51]. There is also evidence that in the composition of microorganisms of the forest litter (pine and oak forests), the number of bacteria assimilating mineral nitrogen is maximum in spring, the peak in the number of nitrogen fixers in oak forests occurs in summer, and in pine forests – in autumn [52]. Thus, these regularities still require further study, taking into account the emerging interactions between the organisms inhabiting the soil and forest litter, the processes occurring in them, the physicochemical properties of the soil, moisture conditions, phytocenotic conditions determined directly by edificators. For the studied steppe ecosystems, the predominance of Chlorophyta and Cyanobacteria algal communities was noted. In salt marshes, the role of Cyanobacteria becomes even more pronounced (table 1). A wide variety of Chlorophyta and Cyanobacteria was also noted for other xerophytic ecosystems [53–55], as well as saline soils and salt marshes [6,11,56, 57]. Thus, within each ecosystem, a specific ecological space is formed, which is assimilated by various taxa of microalgae. Using principal component analysis, four main factors with eigenvalues greater than one were identified, which explain 81.4% of the total variance (table 2).

| Factor | Eigenvalues | Percentage of total dispersion, % | Cumulative eigenvalues | Cumulative percent, % |
|--------|-------------|----------------------------------|------------------------|-----------------------|
| 1      | 4.18        | 34.82                            | 4.18                   | 34.82                 |
| 2      | 2.56        | 21.29                            | 6.73                   | 56.12                 |
| 3      | 1.92        | 16.04                            | 8.66                   | 72.16                 |
| 4      | 1.11        | 9.27                             | 9.77                   | 81.43                 |

When calculating the factor loadings matrix, the rotation of factors was used by the Varimax normalized method. It is an orthogonal rotation method that minimizes the number of high load variables per factor and simplifies the interpretation of factors [58]. In this case, the factor loadings were subjected to the normalization procedure, i.e., dividing by the square root of the corresponding dispersion. The obtained values are presented in table 3.

| Variable                        | PC1   | PC2   | PC3   | PC4   |
|---------------------------------|-------|-------|-------|-------|
| Cyanobacteria                   | 0.91  | 0.04  | -0.13 | 0.11  |
| Chlorophyta, Streptophyta       | -0.16 | -0.81 | 0.42  | -0.01 |
| Xanthophyceae                   | -0.22 | -0.32 | 0.78  | 0.16  |
| Bacillariophyceae               | 0.43  | 0.01  | 0.35  | 0.60  |
| Eustigmatophyceae               | 0.01  | -0.75 | 0.06  | 0.05  |
| Euglenozoa                      | -0.11 | 0.03  | 0.81  | 0.20  |
| Humus                           | -0.20 | 0.55  | 0.37  | 0.75  |
| Acidity                         | 0.82  | 0.29  | -0.14 | -0.29 |
| Mineralization                  | 0.56  | 0.33  | 0.17  | -0.74 |
| Granulometric composition       | 0.25  | 0.79  | 0.44  | 0.12  |
| Moisturizing                    | -0.62 | 0.29  | 0.64  | -0.08 |
| Ecosystem type                  | -0.92 | -0.15 | 0.14  | 0.12  |
The strongest connection is reflected by factor loadings above 0.7 [58]. However, taking into account the peculiarities of the studies being carried out, we took into account the values of factor loads starting from 0.5, which reflect a weaker relationship between the variable and the factor and have a meaningful interpretation. The first factor, which explains 34.82% of the dispersion, is associated with the type of ecosystem and such edaphic parameters as pH, the availability of moisture in the habitat, and soil mineralization. Along the first axis (figure 1), on one side there is a transition from swampy to xerophytic steppe ecosystems, from ecosystems without signs of salinity with weakly acidic pH to saline ones with alkaline pH values. The second factor reflects changes in the gradients of trophicity (humus content) and particle size distribution of soils. It accounts for 21.98% of the total dispersion. Along the second axis, there is a transition from ecosystems with low-humus soils of a lighter particle size composition to ecosystems with highly humified soils of a heavier particle size composition. The third and fourth factors additionally explain 16.04% and 9.27% of the total data dispersion, respectively. Their values mainly dispersion on the mineralization, trophicity, and moisture supply of edaphotopes. Among the significant factors affecting soil algae, pH, organic matter, particle size distribution, and moisture content were also indicated [50,59–63].

Figure 1: Main ecological gradients of algal communities in different ecosystems. Ecosystem numbers correspond to table 1.

In terms of the composition of microalgal communities, the first main component is indicated by the diversity of Cyanobacteria species, the second is Chlorophyta, Streptophyta, Eustigmatophyceae from Heterokontophyta, the third is Xanthophyceae and Euglenozoa, and the fourth is Bacillariophyceae. Due to the factor rotation procedure, it was possible to reduce
the number of taxa in the diagnostic groups to two. This also made it possible, despite the sufficient diversity of ecologically non-equivalent species within each large taxon, to display their preferences within the ecological space allocated by the main factors. For Cyanobacteria, the most significant characteristics of the edaphotop were found to be pH, mineralization, providing moisture, and the type of ecosystem. At the same time, Cyanobacteria are associated with negative values of the coefficients with pH and mineralization, and positive ones with providing moisture and the type of ecosystem, which indicates their multidirectional influence. Green algae (Chlorophyta, Streptophyta) and Eustigmatophyceae exhibit similar requirements for the ecological parameters of their habitat. Such edaphotop characteristics as trophicity and particle size distribution are of particular importance for them. The provision of the habitat with moisture is of particular importance for Xanthophyceae and Euglenozoa, and for Bacillariophyceae – the trophicity and mineralization of the edaphotope.

5. Conclusion

The ecological space within which communities of algae are formed in ecosystems is determined by edaphic conditions and phytocenotic interactions, determined primarily by edificators of ecosystems. In a multidimensional coordinate system describing the ecological space of algal communities, four main factors are determined that explain 81.4% of the total variance. The type of ecosystem, pH, and particle size composition of the soil has the greatest contribution to the dispersion of PC1 and PC2. A somewhat lesser relationship is observed with such characteristics of the edaphotop as mineralization, trophicity, and providing moisture of the habitat. 3 and 4 mainly depend on mineralization, trophicity and providing moisture of edaphotopes. At the level of the composition of algae, this is obviously associated with the heterogeneity of the ecological preferences of the species of algae themselves, as well as the variability of the ecological niches of ecosystems, due to which there are species more typical for other types of ecosystems in the communities. The use of the factor rotation procedure by the Varimax normalized method made it possible to concretize the taxa that are maximally associated with the main components: PC1 is indicated by a variety of Cyanobacteria species, PC2 – Chlorophyta, Streptophyta and Eustigmatophyceae, PC3 – Xanthophyceae and Euglenozoa, PC4 – Bacillariophyceae.

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