SAND COLONIZATION AND INITIATION OF SOIL DEVELOPMENT BY CYANOBACTERIA AND ALGAE

OIMAHMAD RAHMONOV[1,3], JOLANTA PIĄTEK[2]

[1] Department of Physical Geography, University of Silesia, Będzińska 60, PL-41-200 Sosnowiec, Poland; e-mail: ojmahmad@wnoz.us.edu.pl (corresponding author)
[2] Department of Phycology, W. Szafer Institute of Botany, Polish Academy of Sciences, Lubicz 46, PL-31-512 Kraków, Poland; e-mail: cabala@ib-pan.krakow.pl
[3] Faculty of Biology, Tajik State National University, Rudaki 17, 734025 Dushanbe, Tajikistan

Abstract

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There are no stages of soil cover development in which cyanobacteria and algae do not participate. The degree of algae distribution on the ground and in the soil profile varies. As a result, the role of algae at particular stages of soil development and in different soils is differentiated. The most obvious and significant role of algae is connected with the process of rock weathering and primary humus formation on purely mineral substrata. The research work consisted in determining the species composition of soil cyanobacteria and algae and their role in sand colonisation and soil development. Occurrence of 11 species of cyanobacteria and algae was recorded in the Pustynia Błędowska desert area (six Cyanophyta; one Bacillariophyceae; four Chlorophyta (3 taxa, 1 sp.) in 2001 and 2002. The physico-chemical properties of the soil varied under different communities of cyanobacteria and algae. The highest contents of Nt, Corg, available P and exchangeable cations such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} were observed under *Cylindrocapsa* sp. cover. Microscopic examinations revealed the existence of intricate filament nets composed of cyanobacteria and algae, which connect mobile sands and intercept the finest mineral fractions carried by the wind. Sand stabilisation by algae contributed to the initiation of soil forming processes.

Key words: soil nutrients, sand stabilization, soil development, cyanobacterial-algal crust, Pustynia Błędowska desert, South Poland

Introduction

The cyanobacterial and algal flora in the soil is composed of different ecological groups. These are: (i) ground algae, which develop on large scale in favourable conditions on the soil surface in the form of a coating or cyanobacterial-algal crust, (ii) semiaquatic algae occupying constantly humid surfaces, (iii) algae developing in the soil profile (Hollerbakh, Shtina, 1969; Shtina, Hollerbakh, 1976; Belnap, 1993).

The composition of cyanobacterial and algal floras occurring on sands and soils is still poorly studied in Poland (Starmach, 1972; Żurek, 1981; Picińska-Fałtynowicz, 1997; Pankratova et al., 1999). Only a few data on the occurrence and the role of algae in the Pustynia Błędowska desert have recently been published by Rahmonov (1999, 2001) and Szczypek et al. (2001), but these authors did not identify the algae. Taxonomic studies on the cyanobacterial and algal flora in this area were made for the first time by Cabała and Rahmonov (2004). The taxonomy and ecology of soil algae and their role in the processes of soil formation have frequently been object of research, e.g. Hollerbakh et al. (1956); Starks, Shubert (1982); Lukešová, Komárek (1987). Lukešová (2001) studied ground or semiaquatic algae and Shtina (2000) studied algae developing in the soil profile. In the vast majority of Western research work soil algae and cyanobacteria have been identified with the biological soil crust (Kleiner, Harper, 1972) or microbiotic soil crusts (Belnap, 1993). These are composed of lichens, cyanobacteria, algae, mosses, liverworts and microfungi growing on/or just below the soil surface. These type of crusts have also been known as cryptogamic, microphitic, microfloral or cryptobiotic (Williams, 1994). Because both cyanobacteria and algae were investigated in the present study, the authors are using the term 'cyanobacterial-algal crust' proposed by Williams (1994).

One of the chief factors involved in regulating photosynthesis of the cyanobacterial-algal crust is moisture content (Shields, Durrell, 1964). It is widely known that bacteria and algae are the first organisms that colonize weathering rocks and initiate primary humus formation on the mineral substratum. The research work of Hollerbakh et al. (1956) very convincingly exhibits the algae's participation in primitive soil formation, particularly on desert soils. The scale of algal participation in organic matter formation in the soil is shown in the results of cyanobacterial-algal crust analyses from different climatic zones (Starks et al., 1981). According to Hollerbakh et al. (1956) and his team the only algal dry matter biomass in the algal crust on takyrs (soils characteristic for arid and semiarid areas) amounts to about 500 kg/ha. In favourable weather conditions formation of about 6 tons of organic matter on an acre was observed (Bolyshev, 1967) in the algal crust in the soils of Arizona.

The aim of the present studies was to recognize the composition of cyanobacteria and algae in the colonization of soil under low pH conditions, and their participation in soil-forming processes.

Study area

Investigations were carried out in sandy areas of the eastern part of the Silesian Upland, Southern Poland (50°20'18.8'' N and 19°28'57.8'' E) (Fig. 1a). The genesis of this area is connected with the medieval mining and metallurgical activity of man, associated with the deforestation of vast territories. Since the middle of the 19^{th} century this area of mobile sand has been described as the largest in Poland – area about 30 km^2 – (and one of the largest in Europe). Because of sandy hummocks covered with plants, frequent sandstorms, and the occurrence of the mirage phenomenon, this area has been referred to as a desert.

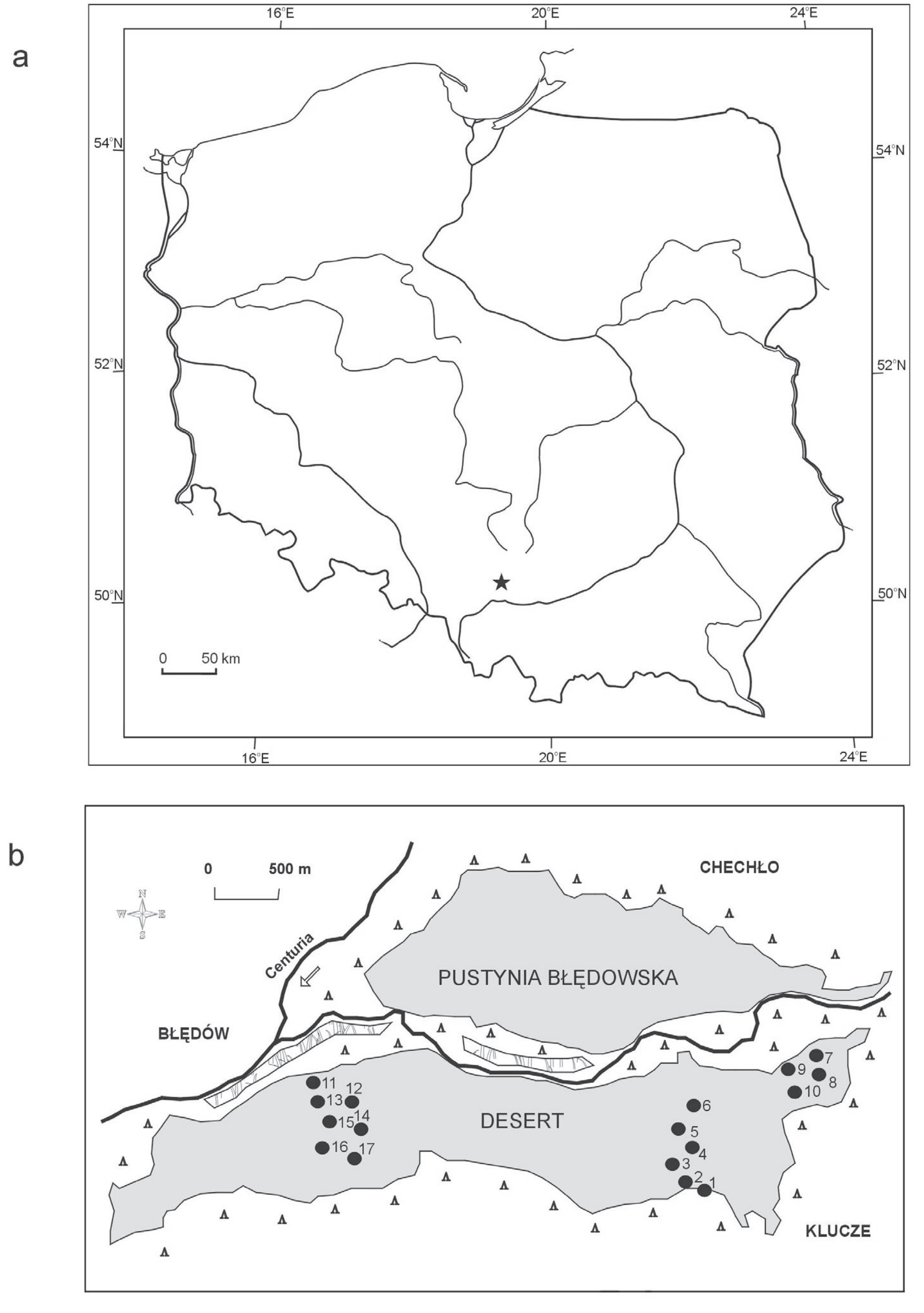

Fig. 1. a) The localization of study area in Poland; b) 1–17 the collecting sites.

However, in terms of climate this area has nothing to do with desert, it is of anthropogenic origin. The Pustynia Błędowska desert area is situated at heights ranging from 302 to 332 m above sea level.

The geological substratum here is built of fluvial and fluvio-glacial sands. Their thickness in some places reaches a depth of 80 m (Tyc, 1997). In this area aeolian processes of development still occur to different degrees, and as a result different landforms are created (Tyc et al., 1999). The average annual precipitation ranges here from 676 to 726 mm, and the average annual temperatures range from 7.1 to 7.7 °C. The vegetation season lasts about 210 days and begins in March. In the study area slightly alkaline precipitation dominates. Chemical reaction and composition of the precipitation depend on weather conditions. The Ca^{2+} content can vary during the year from 7 to 11 mg/l, SO^{2-} from 18 to 39 mg/l, NO_3^- from 9 to 12 mg/l, Cl^- from 7 to 11 mg/l (Leśniok, 1996).

Material and methods

The material was collected at 17 consecutive localities in the southern part of Pustynia Błędowska desert (Fig. 1b) in June and October 2001 and in April and May 2002, and was taken to the laboratory in Petri dishes. All measurements, descriptions, illustrations, photographs and observations of cyanobacteria and algae were made from live material. An Amplival Carl Zeiss Jena light microscope was used for the studies. A detailed taxonomic characterization of the species of cyanobacteriae and algae recorded is presented in a separate publication (Cabała, Rahmonov, 2004). Soil samples were collected from 11 of the localities. Arabic numbers on the map (Fig. 1b) correspond with Roman numbers in Tables 1 and 2.

Physico-chemical properties of the soil were determined by common geochemical methods. Soil pH was measured in a 1:5 soil:water suspension, using a Radiometer model PHM62 pH meter with a radiometer combined glass electrode. Organic carbon (Corg) in soil samples was determined by means of Tiurin's method and

T a b l e 1. The soil proprieties under algae community.

Number of point	Thickness of horizons	Loss ignition	Corg	pH		Hydrolitic acid	P	Nt	C/N
				H_2O	KCl				
	[mm]	[%]			me/100	me/100	[%]		
I	8	0.95	0.73	4.5	4.3	0.67	0.19	0.012	61
II	9	1.62	0.93	4.4	4.3	0.62	0.17	0.021	44
III	4	0.94	0.49	5.1	4.7	0.65	0.32	0.021	23
IV	8	0.60	0.41	4.7	4.4	0.45	0.31	0.011	37
V	9	1.08	0.62	4.5	4.5	0.41	0.21	0.023	27
VI	7	1.17	0.59	4.4	4.3	0.53	0.31	0.041	14
VII	13	2.51	1.32	4.4	4.4	0.60	0.40	0.044	30
VIII	10	1.58	0.88	4.9	4.6	0.62	0.28	0.043	20
IX	11	4.58	2.41	4.4	4.3	0.54	0.27	0.041	20
X	7	1.14	0.65	4.7	4.3	0.56	0.38	0.031	21
XI	15	6.53	3.43	4.8	4.6	0.84	0.41	0.084	40

T a b l e 2. The soil proprieties under algae community.

Number of point	Thickness of horizons	Exchangeable cations				Exchange acidity		Sorption capacity		
		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Al^{3+}	H^{+}	S	T	V = S/Tx100
	[mm]	[cmol$^{(+)}$kg]								[%]
I	8	0.10	0.02	0.04	0.02	0.01	0.12	0.18	0.31	58
II	9	0.18	0.03	0.04	0.02	0.02	0.13	0.27	0.42	64
III	4	0.08	0.1	002	0.01	0.01	0.14	0.12	0.27	44
IV	8	0.23	0.02	0.02	0.02	0.03	0.09	0.26	0.38	68
V	9	0.22	0.02	0.02	0.02	0.02	0.08	0.28	0.38	74
VI	7	0.12	0.01	0.01	0.01	0.02	0.11	0.15	0.28	54
VII	13	0.09	0.01	0.02	0.01	0.06	0.14	0.13	0.33	39
VIII	10	0.10	0.02	0.02	0.02	0.03	0.10	0.16	0.29	55
IX	11	0.14	0.02	0.01	0.02	0.06	0.10	0.19	0.35	54
X	7	0.09	0.01	0.01	0.01	0.04	0.11	0.12	0.27	44
XI	15	0.31	0.03	0.04	0.04	0.03	0.26	0.42	0.71	59

total nitrogen (Ntot.) by means of Kjeldahl`s method (Binkley, Vitousek, 1989). In soil material the contents of acid exchangeable (H^{+}, Al^{3+}) and alkaline (Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}) cations were also determined. Exchangeable acid cations were determined by means of the method used by Sokolow, whereas alkaline cations were determined in a solution of 1M CH_3COONH_4 of pH 7. Element contents were determined by means of atomic absorption spectrometry AAS (firm Solaar).

Observations of the soil surface were performed using a Scanning Electron Microscope (SEM) Philips XL 30 ESEM. Samples were coated with gold-palladium and then observed using secondary electron emission.

Results

Six species of cyanobacteria (*Chroococcus minor, Ch. minutus, Ch. varius, Synechococcus aeruginosus, Gloeocapsa atrata, Merismopedia glauca*) and five species of algae (*Cylindrocapsa* sp., *Klebsormidium crenulatum, Pinnularia borealis, Stichococcus chlorelloides, S.* cf. *fragilis*) were identified. Among the 11 identified taxa, 5 species form small gelatinous colonies (*Chroococcus minor, Ch. minutus, Ch. varius, Gloeocapsa atrata, Merismopedia glauca*), 4 taxa are unicellular forms (single cells) (*Synechococcus aeruginosus, Pinnularia borealis, Stichococcus chlorelloides, S.* cf. *fragilis*), the remaining 2 are filamentous taxa (*Cylindrocapsa* sp., *Klebsormidium crenualtum*), which were in the majority in terms of domination, especially the unidentified species of the *Cylindrocapsa* genus. At localities 9, 11 and 7 *Cylindrocapsa* sp. formed characteristic woolly clusters of intertwined threads 0.5–1.0 cm thick on the sand surface (Fig. 1b, Tables 1 and 2). Among long filaments of *Cylindrocapsa* sp. there were frequently single individuals of other algae, especially

Chroococcus minor, Ch. minutus, Gloeocapsa atrata, Merismopedia glauca, Synechococcus aeruginosus, Stichococcus chlorelloides and *S.* cf. *fragilis*.

Cyanobacteriae and algae, especially filamentous ones, form a network that surrounds single sand grains (Figs 2, 3a) or a few grains at a time (Fig. 4). In this way they form a cyanobacterial-algal crust on the ground surface, which plays an important role in the process of biogeocenosis formation in sandy ecosystems poor in nutrient compounds (Fig. 4). Point microanalysis was made to determine the chemical composition (qualitative analysis) of selected fine mineral fractions trapped by the cyanobacterial-algal crust (Fig. 3a). The fine fractions trapped by cyanobacterial-algal networks consist of various minerals of different chemical composition, which can become available (Fig. 3b) as nutrient components for plants in the subsequent stage of succession. Cyanobacteria and algae inhabit the surface layers of sands (Fig. 4). They can be easily observed on the sand surface in early spring, in the period of high humidity.

Soil initiation processes occur directly on deflation field surfaces. This surface is colonized by ground soil algae and cyanobacteria (Fig. 4). During their growth and after they die, these organisms significantly influence the physico-chemical properties of the substratum. As a result, the initiation of soil forming processes, particularly humification, begins.

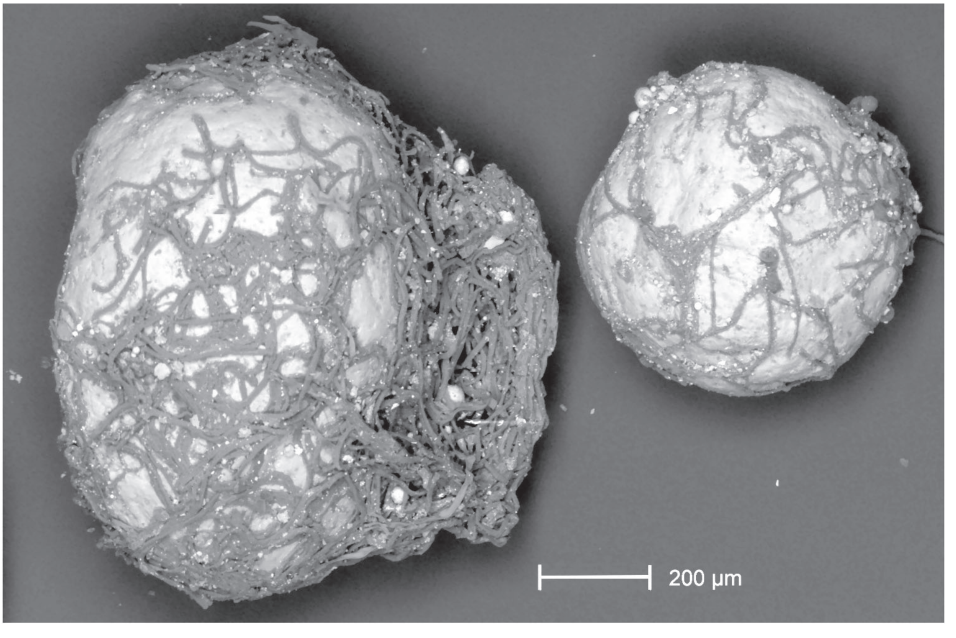

Fig. 2. Single sand grains entangled by filamentous algae.

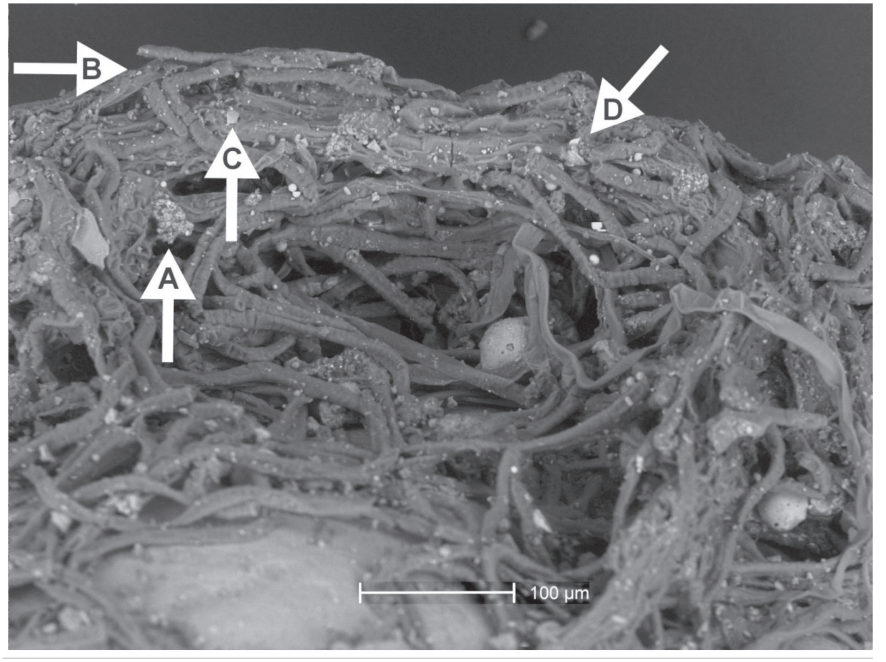

Fig. 3a. The minerals absorbed by net of filamentous algae.

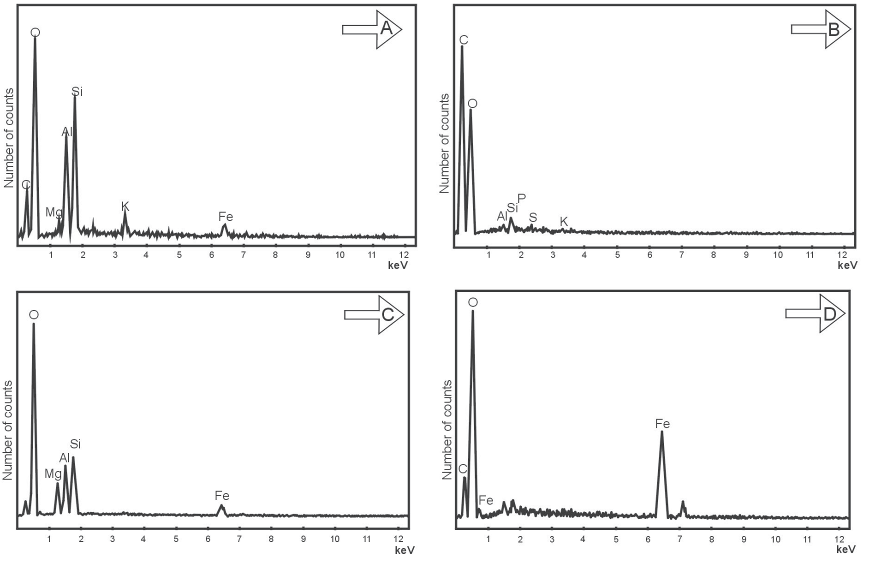

Fig. 3b. The chemical composition of selected fine mineral fraction: A – biotite, B – muscovite, C – amphibole from gedrite groups, D – hematite.

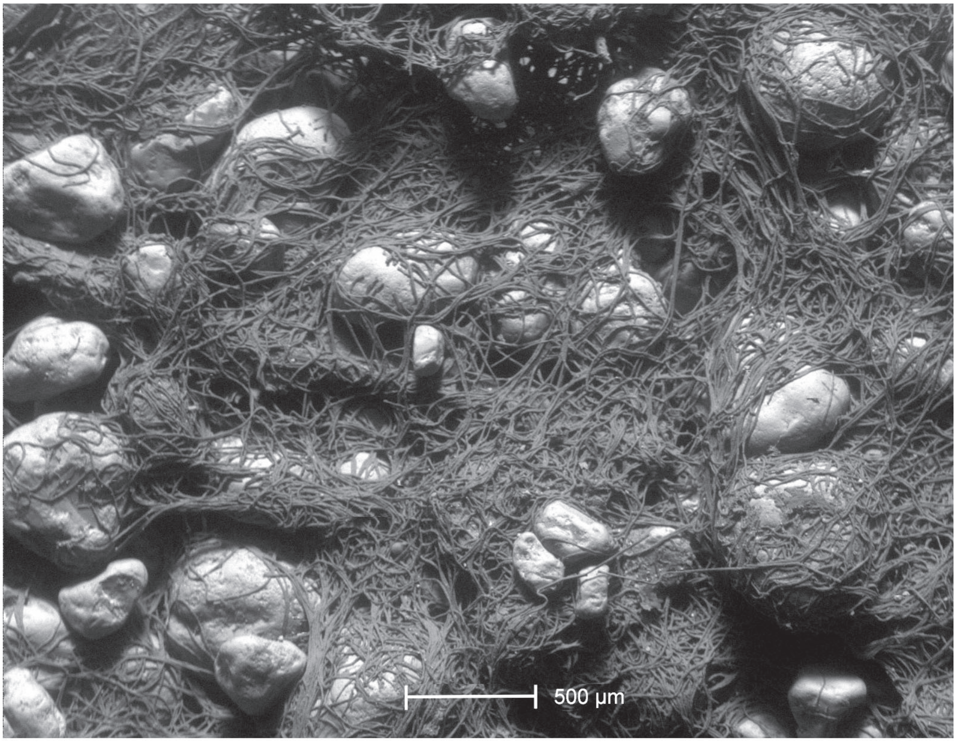

Fig. 4. The net of algae which inhibits sand erosion.

Selected soil properties on surfaces under the cyanobacterial-algal crust are presented in Tables 1 and 2.

In terms of soil pH there was little variation within the study areas (Table 1). Standard deviation of the soil pH in the study areas was 0.22 (in H_2O) and 0.13 (in KCl). In both cases the variation coefficient (Vs) is very low and amounts to 4.82 and 3.03% respectively. On the other hand, the hydrolytic acidity shows slightly higher variability and amounts to 19.5%. The average ($\overline{x}$) pH value is 4.64 in water and 4.42 in acid.

Corg content at the localities under examination shows high differentiation, the variation coefficient (Vs) is 89.21%. Standard deviation for organic carbon content in the samples is 0.95% and the average 1.13%. The highest organic carbon content was recorded at locality XI, and the lowest at IV. Organic carbon content shows a positive correlation with the organic-humus horizon thickness, where the correlation coefficient is R = 0.98. The ratio of carbon to nitrogen ranges from minimum 14:1 to maximum 61:1; the average being 31:1. This testifies to a weak process of mineralization and release of available nutrient compounds for plants. Available phosphorus (Pavail.) content at particular localities is weakly differentiated and shows a positive correlation (R = 0.376) with organic carbon content. On the other hand, total nitrogen (Ntot.) content shows a high degree of variability (Vs = 61%) and a positive correlation coefficient (R = 0.836) with organic carbon content.

Alkaline cations contents (Ca^{2+}, Mg^{2+}, K^+, Na^+) are differentiated and the variation coefficient for them is Vs = 0.518 (Ca^{2+}), 0.369 (Mg^{2+}), 0.613 (K^+), 0.318 (Na^+) respectively. Exchangeable cations show positive correlations with organic carbon. The highest are recorded in the following order: sodium (R = 0.613), calcium (R = 0.524), for magnesium and potassium R = 0.335. In terms of content, alkaline exchangeable cations can be ordered as: $Ca^{2+}>Mg^{2+}>K^+>Na^+$ (Table 2). Sorption capacity is weakly developed. This is related to the lack of, or trace quantities of, clay minerals and also to weak weathering processes, and consequently the soil formation processes. The degree of the sorption complex saturation with alkaline cations is weakly differentiated (Table 2).

Cyanobacteria and algae dried out during periods of deficient humidity and decomposed, leading to the formation of an organic-humus horizon (O/A). This process is long-drawn-out. By its properties the O/A horizon resembles an *ochric* horizon. The thickness of this layer on particular study localities ranged from 4 to 15 mm (Table 1). Directly under the O/A horizon is the parent rock, on which were built quartz sands. It is an initial sandy soil that can be classified as an Aeolian Regosol according to the Systematics of Polish Soils (1989) or as Protic Arenosole according to WRB (1998). The organic-humus horizon (O/A) is very wind-erosion resistant. Such surfaces with cyanobacteria and algae are subsequently colonized by bryophytes and lichens, which form the biological soil crust (Rahmonov, 1999).

Discussion and conclusion

A cyanobacterial-algal crust develops most often under harsh conditions that include extremes in temperature and light and at least a periodic lack of water. They occur in almost all arid and semiarid ecoregions worldwide, and in local arid microenvironments in some climates e.g., temperate regions (Büdel, 2003). An example of this is the Pustynia Błędowska desert, which is characterized by a specific microclimate that is conducive to soil crust formation. The different growth types of algal crusts and their relation to edaphic factors were investigated by Komáromy (1976) in Hungarian forests and grass steppe ecosystems, where the occurrence of *Klebsormidium crenulatum* was also recorded. This species, like all others recorded in the investigation area, develops directly on poor quartz sands with no organic matter. Dying tissues contribute to the formation of primary organic matter, necessary for the process of humus formation.

According to Büdel's (2003) classification of crust formation types, some Pustynia Błędowska desert species belong to the mucose growth type of crust formation (*Chroococcus minor, Ch. minitus*) and to the glutinose growth type of algal crust formation (*Pinnularia borealis*). The species that belonged to the muscose growth type adhere to the soil surface. At least part of the life cycle of the algae occurs inside the soil. Some algae migrate to the soil surface under favourable conditions. The glutinose growth type mainly occurred in the grass ecosystem, where they prefer permanently wet soil, but in the study area they occurred in dry sandy soil without a good humus horizon. As stated above, the organic-humus horizon (O/A) formation is only at an early stage in the study area. A similar situation is also to be seen in the Toruń Basin (Jankowski, Bednarek, 2000).

The critical role of cyanobacterial-algal soil crusts in biogeocoenosis formation processes of arid and semiarid areas has long been recognized (West, 1990; Johansen, 1993). These crusts (also known as cyanobacterial-algal crusts, biological soil crusts, cryptogamic, microphitic, microfloral, desert algal crusts or cryptobiotic crusts) reduce wind and water erosion (Hollerbakh, Shtina, 1969; Shtina, Hollerbakh, 1976; West, 1990; Rahmonov, 1999), increase nitrogen available to the ecosystems through fixation and carbon dynamics (Evans, Belnap, 1999; Belnap, 2003; Evans, Lange, 2003), inhibit or promote seed germination depending on the circumstance (Rahmonov, 2001), and stabilize soil moisture and improve water conditions (Yair, 2003; Eldridge, 2003). Cyanobacteria and soil algae directly participate in most biogeochemical processes occurring in soil and influence its physico-chemical properties. The main biochemical processes that algae participate in are: organic matter and nitrogen accumulation, decomposition of minerals, and migration of elements (Shtina, Hollerbakh, 1976). There is information also about calcium, magnesium and sulphur (Tikhomirov, 1957), phosphorus and nitrogen accumulation in the algal crust (Belnap, 2003). Diatoms decompose aluminosilicates and absorb from them the aluminium necessary for their development (Melnikova, 1955). The extracellular substance secreted by algae contains organic compounds able to fix exchangeable cations and enrich the soil in this way. Thus there is a positive correlation between the organic substance content and the alkaline cations content (Table 2). In experiments carried out by Glazovskaya (1950) algae actively decomposed muscovite, biotite and other minerals. The influence of algae on the physico-chemical properties of soil was studied on the cyanobacterial-algal soil crust on the surface layer of soil, which usually constitutes the initial humus horizon (Table 2). According to the character of the substratum (stable or loose), the extent of its colonization by algae is different. The species of algae and cyanobacteria on loose sand consists only of single specimens or colonies of individuals of the same species. Only at a later stage of soil succession is a compact and hard algal cover formed, consisting usually of filamentous algae such as *Cylindrocapsa* sp. The cyanobacterial-algal crust formed with participation of *Cylindrocapsa* sp. inhibits water and wind erosion and stabilizes the substratum in the Pustynia Błędowska desert. This in turn facilitates the entry of other organisms (e.g. vascular plants), for which the ecological conditions in loose sand were not favourable for their development. Algae participate in the sand fixation process by secreting extracellular gelatinous substances containing fats and saccharides (Nierop et al., 2001; Malam et al., 2001), and also by creating dense cyanobacterial-algal filaments (Fig. 4). Algal and cyanobacterial tissues absorb and store moisture, change the infiltration and evaporation rate, thereby improving water conditions in the rhizosphere zone, and facilitate the encroachment of organisms with high ecological requirements in the later stages of succession.

There are no stages of soil cover development in which cyanobacteria and algae do not participate. At different stages of soil formation ecologically different groups of cyanobacteria and algae take part; not only ground and soil species, but also rock algae (lithophytes). The degree of algae distribution on the ground and in the soil profile varies. As a result, the role of algae at particular stages of soil development and in different soils is differentiated. The most obvious and significant role of algae is connected with the process of rock weathering and primary humus formation on purely mineral substrata. Biological rock weathering processes depend to a great extent on the life cycle of algae, connected with epilithic and endolithic associations.

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