# Microfungi, algae and cyanobacteria in soils polluted with fluorine (Kola Peninsula, Russia)

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## Abstract

The analysis of algal-mycological complexes in Albic Podzolic soils affected by emissions of the Kandalaksha Aluminum Smelter (KAS) was carried out. The number and biomass of microscopic fungi in the maximum fluorine-polluted zone (fluorine-content >1000 mg/kg) more than 2 times lower than in distanced areas and amounted to 17.3 thousants colony-forming units/g and 1.33 mg/g respectively. Altogether, 31 species of soil fungi were isolated. The species *Penicillium trzebinskii* and *P. miczynskii* dominated the zone of maximum pollution. *P. glabrum*, *P. spinulosum*, and *Memnoniella echinata* prevailed in the zones of moderate pollution and background. The part of opportunistic fungi in contaminated soil increased in comparison with the background soil. The reduction of dark-colored fungi biomass in contaminated soil was noted. In total, 56 species of eukaryotic algae and 7 species of cyanobacteria were found. Among green algae, the species from families Chlorophyceae and Trebouxiophyceae dominated in all plots. In the zones of maximum and strong contamination, 53 algae species were found including xanthophytes, which were absent in unpolluted areas. The number of viable cells in the litter of the maximum contaminated soils varied from 100 thousand to 1.5 million in 1 g of absolutely dry soil. The species composition of algae and cyanobacteria in these soils showed the characteristic features of the Arctic biological soil crusts.

***Key words:*** fluorine, Kandalaksha aluminum smelter, soil contamination, biodiversity, fungi, algae, cyanobacteria

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## Introduction

The problem of environmental pollution by industrial emissions is a topical for the Kola Peninsula whereas the territory is affected by intensive aerial industrial impact from non-ferrous metallurgy plants, the Kandalaksha Aluminum Smelter (KAS) in particular (*see* Fig. 1). The KAS affiliated with the Russian Aluminum Company

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(RUSAL) is the only aluminum plant in the world located beyond the Arctic Circle. Aluminum is produced by the Soderberg technology which is widely applied in Russia and is a source of ecological risks (Barber and Tabereaux 2014, Ghosh et al. 2014, Gibbs and Labrèche 2014). The gas emissions from the KAS contain a wide variety of pollutants including fluorine compounds, polycyclic aromatic hydrocarbons, resinous substances and inorganic dust. These elements can be distributed to the long distances from the source of the contamination (up to 15–20 km). The main compounds in the aerial emissions from KAS are fluorine and aluminum (Evdokimova et al. 2013). Fluorine and its compounds belong to the group of hazardous substances for living organisms including humans (Gibbs and Labrèche 2014, Chaschin 2017, Kongerud 2007, Taiwo 2007). Fluorine is found in emissions basically in water-soluble form accessible for biota (45 kg F per 1 hectare) (Evdokimova et al. 2005).

There are about 240 aluminum plants in the world, 17 of them are located in the Russian Federation [1]. Despite this, the studies of the impact of industrial emissions of aluminum plants on soils of the adjacent territories are scarce. Thus, Norwegian scientists have studied the accumulation and transport of fluorine in soil profiles near the smelter at Årdal (Vestland county, West Norway) as well as sorption and desorption of added fluorine in representative soil and the effect of pH and ionic strength on desorption of fluorine in soil (Arnesen and Krogstad 1998). The study of prolonged fluoride pollution of soils near the aluminum smelter in Central Slovakia revealed the decreases in microbial and enzymatic activities as well as in soil microbial biomass C to organic C ratio (García-Gil et al. 2013). The most studied territories of Russia, exposed to the emissions from aluminum industry, are located in the vicinity of the Krasnoyarsk and Irkutsk aluminum smelters (Demidenko and Zhbankichov 2014, Tandelov 2012, Kozlova et al. 2011, Kirillova and Pomazkina 2014, Sokolova and Zorina 2015, Lomovatskaya et al. 2014, Pomazkina et al. 2008). The response of the microbial soil components was studied through the index of specific respiratory activity (Sokolova et al. 2011). Other researchers have shown a significant decrease in the number and species diversity of soil micromycetes, inhibition of actinomycetes and nonspore-forming bacteria affected by industrial emissions of Irkutsk Aluminum Plant (Beresneva et al. 2010, Beresneva 2015).

At present, it is known that fluorine from gas-air emissions of smelters fall into the soil with the dust particles, atmospheric precipitations. Vascular plants uptake it by root system and accumulate in aboveground organs, especially in leaves. Bioavailability of fluorine in soil depends on the concentration of its soluble forms, the type of chemical compound, and pH value. The minimum solubility occurs at pH values between 5.5 and 6.5 (Stevens et al. 2000, Larsen and Widdowson 1971). Above pH 6, the anion $F^-$ is prevailing, however, HF and the various soluble complexes with other elements are dominate at lower pHs: $SiF_6^{2-}$, $AlF_2^+$, $AlF_2^+$, $AlF_3^0$, $AlF_4^-$, and $BF_4^-$ (Stevens et al. 1998). Stevens et al. (2000) noted that the species of fluoride is most available for the plants, including HF and some of aluminum complexes. The permeability of cell membranes is much greater for these substances than for $F^-$ anion (Armstrong and Singer 1980, Gutknecht and Walter 1981, Stevens et al. 2000). Therefore, the fluorine toxicity increases in acidic soils.

Phototrophic microorganisms (algae and cyanobacteria) and microscopic fungi (micromycetes) performing diametrically opposite functions in trophic chains can reflect the effect of fluorine on microbiological processes.

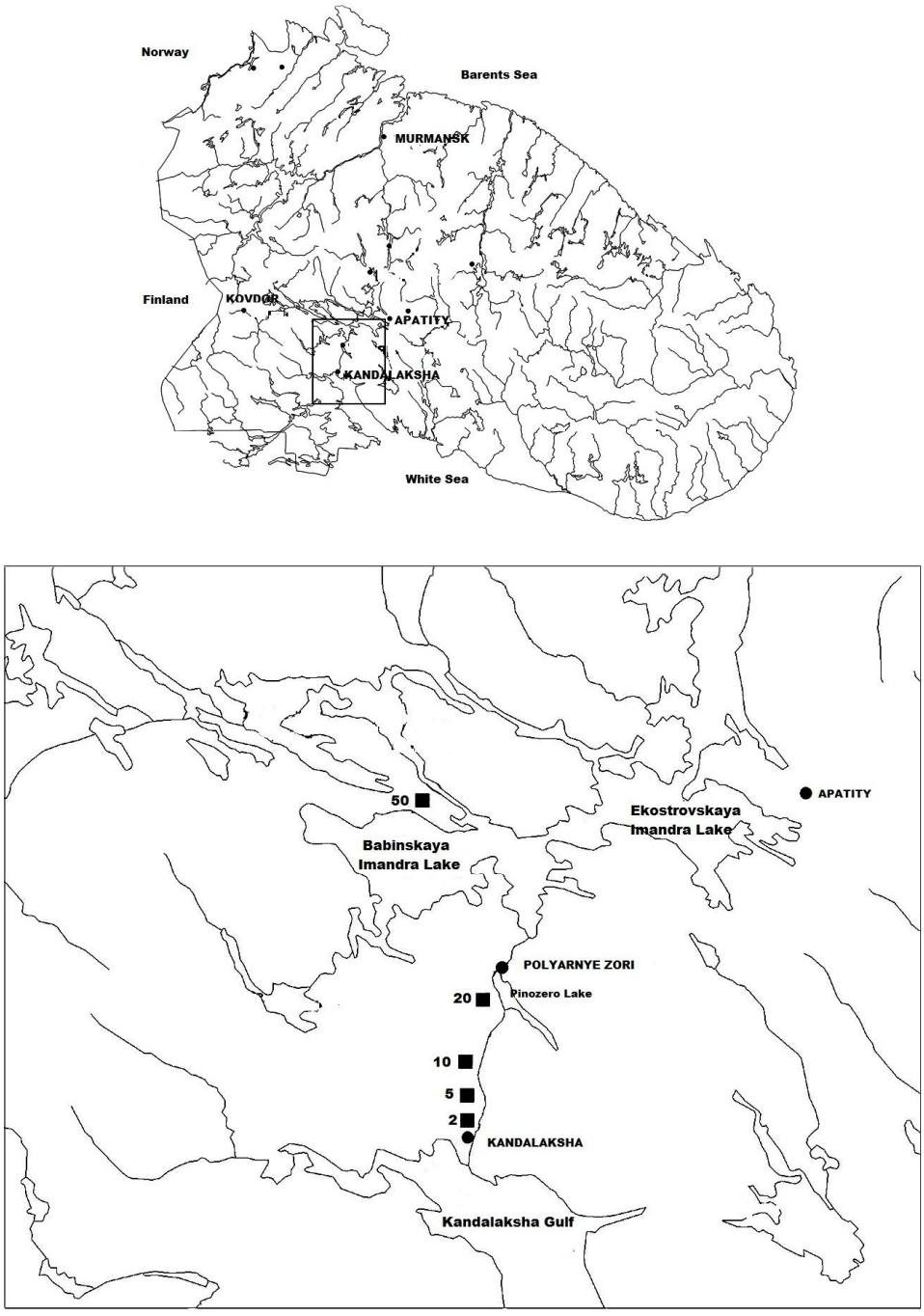


**Fig. 1.** Map showing the studied area.

The changes might be indicative of changes in production and decomposition potential in soils (Domracheva et al. 2006). A number of studies summarized in Camargo (2003) have shown the effect of fluorine and its complexes with aluminum on algae in experimental conditions. Negative effect of fluorine on cell membranes, inhibition of photosynthesis, respiration, and nitrogen fixation have been reported. However, eukaryotic algae are more resistant to the toxic effect of fluorine than cyanobacteria due to the presence of a cellulose cell wall and cell compartmentalization (Bhatnagar and Bhatnagar 2000). Fluorine can inhibit the soil fungi. This is confirmed by laboratory experiments with growing fungi on fluoride-containing media. For example, the *Verticillium lecanii* grew on a medium containing about 0.2 M NaF (Leslie and Parberry 1972), but increase of fluorine concentration has inhibited their growth. Similarly, Treshow (1965) showed inhibition of growth of some fungi at concentrations in media as low as $5 \times 10^{-4}$ M NaF (for *Pythium debaryanum*) and only one species (*Colletotrichum lindemuthianum*) was stimulated by $1 \times 10^{-3}$ M NaF at 24°C.

Since fluorine compounds are toxic to living organisms, long-term soil contamination with fluorine-containing emissions from an aluminum plant should affect the state of soil microbiota. Therefore, the aim of this study is to determine how the number and species diversity of micromycetes and algae change depending on the level of soil contamination with fluoride.

## Material and Methods

The field studies were performed on stationary monitoring plots in the aerial pollution gradient from the KAS within 0.5, 2, 5, 10, 20, and 50 km to the north of the smelter (prevailing wind direction according to wind rose diagram). The latter plot was considered as the background (control). The studied area represents the southern part of the Imandra Depression separating the Kola Peninsula from western continental Fennoscandia (60° 09′ 25″ N, 32° 24′ 42″ E). The soils of all the monitored plots are Albic Podzols developed from sandy moraine deposits with a high content of boulders. All the plots were established in pine forests with dwarf shrubs (mostly crowberry *Empetrum hermaphroditum*) and mosses in the ground cover. The thickness of the organic horizon ranged 3–5 cm.

The soil moisture was determined in weighed soil samples dried in an oven at 105°C until the constant weight. The soil acidity was determined by the potentiometric method with a Radelkis OP-300 laboratory pH meter equipped with a combined pH electrode in the 1:2.5 water soil extracts.

The number of fungi was evaluated using the plating method on the worth agar. For microbostatic effect, lactic acid (4 ml per 1 L medium) was added. Species were identified by morphological characteristics using a microscope Olympus CX 41 (Japan) with the camera Jenoptic ProgRes CT3 (Germany). A variety of identification guides were used (Raper and Thom 1968, Egorova 1986, Klich 2002, Domsh et al. 2007, Seifert et al. 2011) according to the replenished species lists in the Species Fungorum database [2]. The fungi biomass and mycelium length were calculated by Olsen' method with some modification (Olsen and Hovland 1985, Evdokimova and Mozgova 1996, Mirchink 1988). Soil suspensions after staining with acridine orange and FITC (SIGMA, Japan) were passed through Whatman® Nuclepore™Track-Etched membranes (polycarbonate, black) with 0.8 μm pore size. The hyphae length was calculated based on the number of intersections of the hy-

phae with the lines of a square grid inserted into the eyepiece.

Living algae cells were counted in dried smears of soil suspensions using fluorescence microscopy method (Treshow 1965). For the analysis of species diversity, soil samples were placed in Z8 and BBM liquid media and in Petri dishes with the same agarized culture media (Gaisina et al. 2008, Kotai 1972). Species were identified by morphological characteristics using a number of guides Andreeva (1998), Ettl and Gärtner (2014), Komárek and Anagnostidis (1998, 2005), and Komárek (2013). The species names and taxonomic affiliation were clarified by electronic database AlgaeBase [3]. Algae and cyanobacteria communities were analyzed using Sørensen-Chekanovsky coefficient and similarity measurement (for average distance) in GRAPHS clustering program (Novakovskii 2004).

The frequency of occurrence of micromycetes or algae species was calculated from the equation (Kondrat'eva and Kovalenko 1975, Kurakov 2001): $B = (a/A) \times 100$, where B is occurrence, %; a is the number of samples containing the certain species; and A is the total number of the samples. The abundance of fungi species was calculated from the equation: $C = (n/N) \times 100$, where C is abundance, %; n is a number of isolates of the certain species, and N is the total number of isolates of all species.

## Results and Discussion

According to previous studies there are four zones under anthropogenic impact that have been selected by pollution gradient (Evdokimova et al. 2013) (Table 1). The fluorine content decreases from 1000 mg/kg in the zone of maximum contamination to 200 mg/kg in the background zone. The aerial pollution has affected the soil properties. The natural litter horizons in this region are characterized by acidity due to intense leaching of the soils (Nikonov and Koptsik 1999). In the zone of the maximal contamination, the acidity of the litter is significantly lower than on the background plot (pH 5.6 against ~4).

| Contamination | Distance from KAS [km] | Concentration of F, [mg/kg] | pH | Moisture [%] |
|---|---|---|---|---|
| Maximum | 0-1.5 | > 1000 | 4.50-5.58 | 83-160 |
| Strong | 1.5–8.0 | 1000–400 | 3.75-4.31 | 87-338 |
| Moderate | 8.0–15 | 400–200 | 3.78-4.71 | 146-237 |
| Control | >15 | <200 | 3.57-3.96 | 151-350 |

**Table 1.** Zones of litter pollution with fluorine.

### Microfungi

The number and biomass of microscopic fungi in the maximum polluted zone (fluorine content > 1000 mg/kg) was more than 2 times lower than in distanced areas and amounted to 17.3 thous. CFU/g and 1.33 mg/g respectively (Fig. 2). A significant negative correlation was found between the number and biomass of micromycetes and the content of water-soluble fluorine ($r$ = -0.77 and -0.98 at $p < 0.05$ respectively).

| Species | Zones of contamination | | Control (F content <200 mg/kg) |
|---|---|---|---|
| | Maximum and Strong (F content >400 mg/kg) | Moderate (F content 400-200 mg/kg) | |
| Division ***Zygomycota*** Class ***Incertae sedis*** Order ***Mucorales*** Family ***Umbelopsidaceae*** | | | |
| *Umbelopsis isabellina* (Oudem.) W. Gams | 0.3 | 1.3 | 1.1 |
| Family ***Mucoraceae*** | | | |
| *Mucor hiemalis* Wehmer | | 4.7 | 1.7 |
| *Mucor sp.* | 0.06 | 3.2 | 1.9 |
| Order ***Mortierellales*** Family ***Mortierellaceae*** | | | |
| *Umbelopsis longicollis* (Dixon-Stew.) Y. N. Wang, X.Y.Liu et R.Y. Zheng | | 0.3 | 3.5 |
| Division ***Ascomycota*** Class ***Eurotiomycetes*** Order ***Eurotiales*** Family ***Trichocomaceae*** | | | |
| *Penicillium corylophilum* Dierckx | 0.4 | | |
| *P. implicatum* Biourge | | 0.3 | 2.8 |
| *P. jensenii* K. M. Zaleski | 0.4 | | |
| *P. glabrum* (Wehmer) Westling | 19.7 | 84.2 | 50 |
| *P. lividum* Westling | 1.8 | 1.3 | |
| *P. miczynskii* K. M. Zaleski | 25.3 | | |
| *P.nalgiovense* Laxa | 1.6 | | |
| *P. nigricans* K. M. Zaleski | | 2.5 | 1.1 |
| *P. raistrickii* G. Sm. | | 1.3 | 1.1 |
| *P.restrictum* J. C. Gilman et E.V. Abbott | 1.9 | 1.3 | 8.9 |
| *P. simplicissimum* (Oudem.) Thom | 1.4 | 0.08 | 1.1 |
| *P. spinulosum* Thom | 13.2 | 18.4 | 31.3 |
| *P. thomii* Maire | 0.6 | 0.2 | 1.1 |
| *P. trzebinskii* K. M. Zaleski | 36.5 | 2.6 | 2.1 |
| Order ***Chaetothyriales*** Family ***Herpotrichiellaceae*** | | | |
| *Exophiala jeanselmei* (Langeron) McGinnis et A. A. Padhye | 2.5 | | |
| Class ***Sordariomycetes*** Order ***Microascales*** Family ***Microascaceae*** | | | |
| *Scopulariopsis brumptii* Salv. – Duval | 3.9 | | |
| Order ***Hypocreales*** Family ***Hypocreaceae*** | | | |
| *Trichoderma koningii* Oudem | 0.6 | | |
| *T. polysporum* (Link) Rifai | | | 0.4 |
| *T. viride* Pers. | 1.8 | 1.3 | 0.5 |
| Family ***Incertae sedis*** | | | |
| *Memnoniella echinata* (Rivolta) Galloway | 6.3 | 18.7 | 26 |
| Order ***Microascales*** Family ***Microascaceae*** | | | |
| *Wardomyces anomalus* F. T. Brooks et Hansf. | | | 0.4 |
| *Wardomyces sp.* | | 0.9 | |

| | | | |
|---|---|---|---|
| Order ***Hypocreales*** Family ***Incertae sedis*** | | | |
| *Acremonium rutilum* W. Gams | | | 0.2 |
| Class ***Dothideomycetes*** Order ***Dothideales*** Family ***Dothioraceae*** | | | |
| *Aureobasidium pullulans* (De Bary et Lowenthal) Arnaud | 0.6 | 1.1 | 0.3 |
| Family ***Incertae sedis*** | | | |
| *Phoma sp.* | | | 0.2 |
| Order ***Capnodiales*** Family ***Davidiellaceae*** | | | |
| *Amorphotheca resinae* Parbery | | 2.7 | 21.3 |
| Class ***Incertae sedis*** Order ***Incertae sedis*** Family ***Incertae sedis*** | | | |
| *Sterilia mycelia* dark | 60.5 | 46.7 | 31 |
| *Torula allii* (Harz) Sacc | 11.2 | 10.7 | 21.7 |

**Table 2.** Species diversity and abundance (%) of soil microscopic fungi in the area of the Kandalaksha Aluminum Smelter.

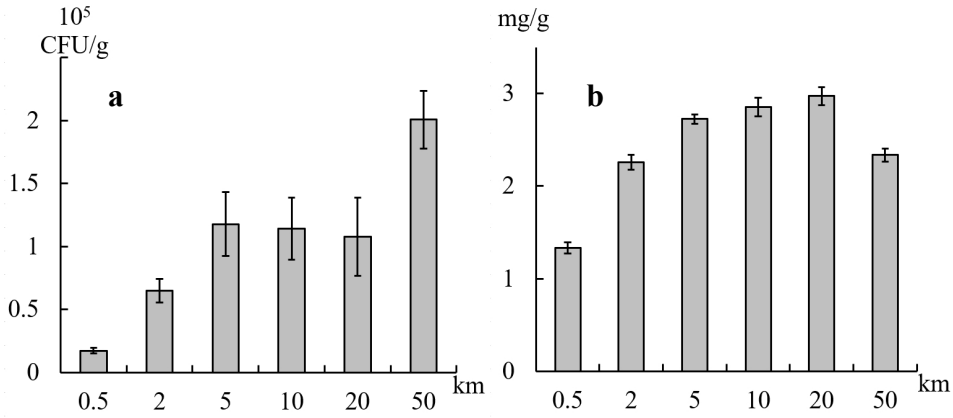


**Fig. 2.** Fungi number (a) and biomass (b) in the litter depends on pollution gradient.

The species diversity of microscopic fungi complexes in the KAS zone is represented by 31 species belonging to 14 genera, 14 families, 11 orders, 5 classes, 2 divisions and a group of fungi with sterile mycelium (Table 2).

The species *Exophiala jeanselmei, Penicillium corylophilum, P. jensenii, P. miczynskii, P. nalgiovense, Scopulariopsis brumptii, Trichoderma koningii* were isolated only 2 km from emission source. *Acremonium rutilum, T. polysporum, Wardomyces anomalus* and fungi of the genus *Torula* were found only on the background area. Species *P. trzebinskii* and *P. miczynskii* dominated in the maximum polluted zone. *P. glabrum, P. spinulosum* and *Memnoniella echinata* prevailed in the strong and moderately polluted zones. An increase of fungi diversity of genera *Aspergillus, Fusarium, Alternaria, Cladosporium* and a change of intrapartum structure of genus *Penicillium* have been found in polluted area *i.e.* the higher number of fungi from Biverticillata and Asymmetrica sections. These genera and structure of genus *Penicillium* are typical for soils of more southern regions.

Changes in the abundance, structure, and composition of fungal communities in contaminated soil occured as the result of high fluorine compounds (≥1000–1200 mg/kg) in soil, and significant decrease in its acidity (about 2 pH units), and increased competition with prokaryotes in a medium close to neutral.

In the polluted soil, the reduction of dark-colored fungi biomass was observed. In the background soil, 9% of the total biomass was presented by dark–colored fungi, in a moderately polluted area - 3%, and in a highly polluted area- only 1%. This fact is very interesting, but needs to be verified both on the basis of field studies and in laboratory experiments. Dark colored fungi, such as *Alternaria* and *Cladosporium*, were not isolated from the fluorine highly polluted soil, at the same time these fungi were random species in the moderate polluted soil. Microscopic fungi isolated from contaminated soil were often pathogenic comparing with the strains isolated from uncontaminated soil based on proteases, phospholipase activity and ability to grow at 37°C.

**Algae**

The territory near KAS (by 0.5 km) is characterized by drastically fluctuating number of algae and cyanobacteria in the litter from 100 thousand to 1.5 million cells per 1 g of absolutely dry soil (Fig. 3). Such fluctuations are explained by scarce vegetation, and therefore the soil here is very heterogeneous and sensitive to the effects of climatic environmental factors. The soil litter at a distance of 2 km from the plant was less populated by algae. Algae growth is inhibited because a high concentration of fluorine is combined with a low level of soil pH (Table 1), therefore, the toxicity of fluorine increases. The cell number was about 130 thousand per 1 g. In the 5-km zone, the number of microphototrophs increased by 4 times and remained constant moving away from the source of emissions. The abundance of algae and cyanobacteria in the upper layer of soil without vegetation at the 0.5 and 2 km from the KAS was high and reached 2 and 8 million cells/g abs. dry soil, respectively, despite the very low soil moisture (6–8%).

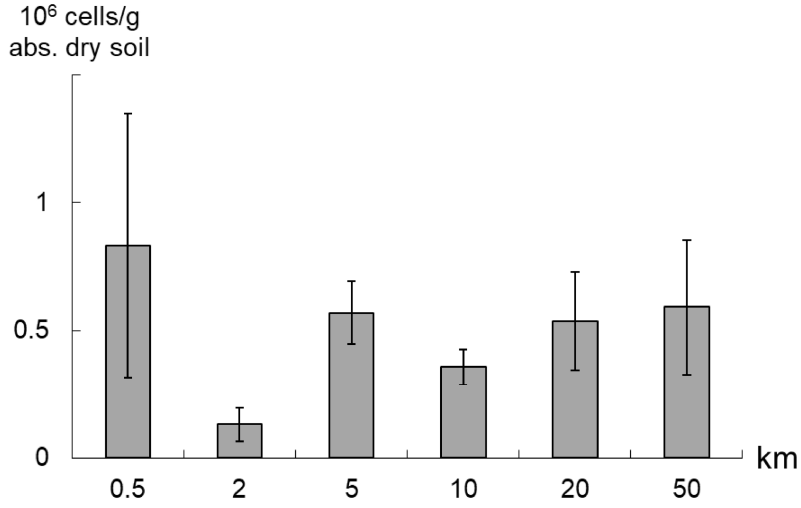


**Fig. 3.** Algae and cyanobacteria number in the litter depends on pollution gradient.

In total, 63 species of microphototrophs from the divisions Chlorophyta (41 species), Charophyta (6), Ochrophyta (9), Cyanobacteria (7) were found (Table 3). Species diversity was represented by Chlorophyceae (19) and Trebouxiophyceae (18) as the dominants. The highest occurrence (above 60%) revealed the following species: *Pseudococcomyxa simplex*, *Stichococcus bacillaris*, *Neocystis brevis*, *Parietochloris alveolaris*, *Pleurastrum terricola*, *Halochlorella rubescens*, *Klebsormidium flaccidum, Vischeria magna, and Aphanocapsa* sp. The representatives of *Nostoc*, *Chlamydomonas*, and *Chlorococcum* genera have been found in the all studied plots. The area of heavy contamination (by 5 km) differed in taxonomic composition and species diversity of algae from the distant territories (Fig.4).

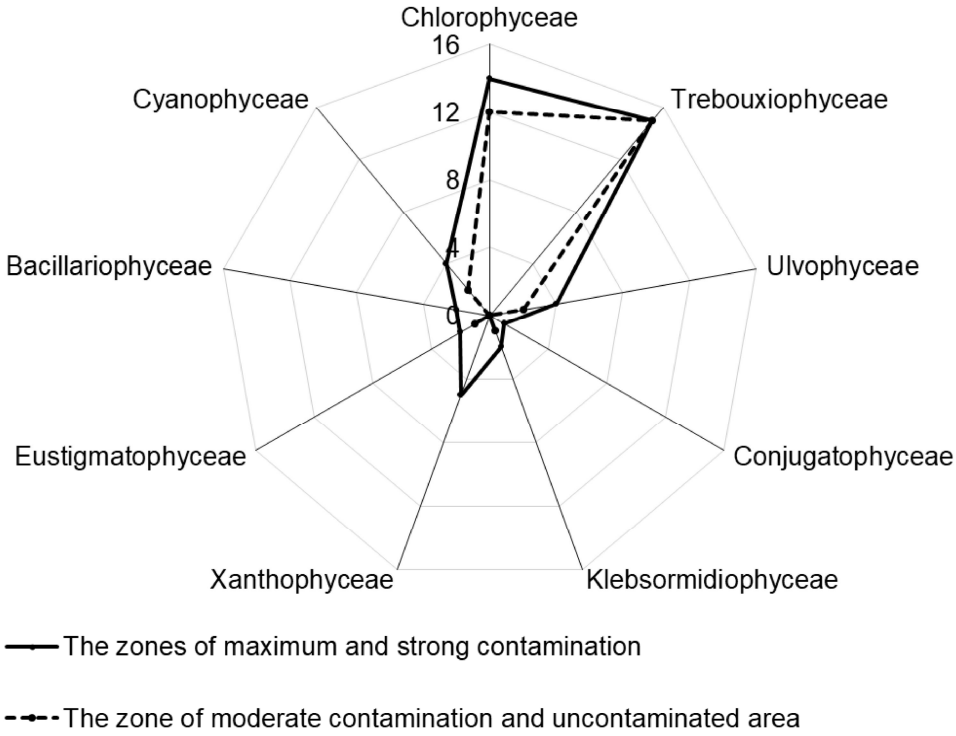


**Fig. 4.** Species diversity of algae and cyanobacterial communities at a level of classes in soils affected by KAS emissions including zones of maximum and severe pollution, as well as moderate pollution and its absence.

In the soil near the KAS, 53 species (about 80 % of total number) were found. Xanthophytes were detected among these but absent in unpolluted areas. A greater variety of filamentous algae from the genus *Klebsormidium* was noted here. It is interesting that the species *Keratococcus bicaudatus* and *Cylindrocystis brebissonii* which are typical inhabits of wet areas, were found only in this zone. Earlier, these species have been found in soil biological crusts on the technogenic substrates (Redkina et al. 2020). The likely explanation is that the accumulations of mucilaginous envelopes of cyanobacteria create a favorable water regime for these species.

| Distance from KAS, km | 0.5 | 2 | 5 | 10 | 20 | 50 |
|---|---|---|---|---|---|---|
| Phylum **Chlorophyta**, Class **Chlorophyceae** | | | | | | |
| *Borodinellopsis oleifera* K.Schwarz | | | + | | | |
| *Bracteacoccus minor* (Schmidle ex Chodat) Petrová | + | + | + | + | | + |
| *Chlamydocapsa lobata* Broady | | | + | | + | + |
| *Chlamydomonas* sp. | | | + | + | + | + |
| *Chlorococcum infusionum* (Schrank) Meneghini | | | | | + | |
| *Chloromonas reticulata* (Goroschankin) Gobi | + | + | | + | + | |
| *Coelastrella terrestris* (Reisigl) Hegewald & N.Hanagata | | | + | | + | + |
| *Coenochloris* sp. | + | | + | + | | + |
| *Dictyochloris fragrans* Vischer | | | | + | | |
| *Dictyococcus varians* Gerneck | + | + | | + | + | |
| *Ettlia minuta* (G.Arce & Bold) J.Komárek | | + | | | | |
| *Halochlorella rubescens* P.J.L.Dangeard | | | + | + | + | + |
| *Monoraphidium terrestre* (Bristol) Krienitz & Klein | | + | + | + | + | + |
| *Neocystis brevis* (W.Vischer) I.Kostikov & L.Hoffmann | + | + | + | | + | + |
| *Pleurastrum terricola* (Bristol) D.M. John | + | + | + | + | + | + |
| *Radiosphaera negevensis* Ocampo-Paus & Friedmann | + | + | + | + | + | + |
| *Sporotetras polydermatica* (Kützing) I.Kostikov, T.Darienko, A.Lukesová, & L.Hoffmann | + | + | + | + | | |
| *Tetracystis* sp. | | | + | + | | + |
| *Tetraspora gelatinosa* (Vaucher) Desvaux | | | + | | | |
| Class **Trebouxiophyceae** | | | | | | |
| *Chloroidium saccharophilum* (W.Krüger) Darienko, Gustavs, Mudimu, Menendez, Schumann, Karsten, Friedl & Proschold | + | | | + | + | + |
| *Chlorella viscosa* Chodat | | | | + | | |
| *Dictyochloropsis splendida* Geitler | | + | + | | | |
| *Diplosphaera chodatii* Bialosukniá | + | | + | | | |
| *Elliptochloris bilobata* Tschermak-Woess | | | + | | | + |
| *Elliptochloris reniformis* H.Ettl & G.Gärtner | | + | | | | |
| *Elliptochloris subsphaerica* (Reisigl) Ettl & Gärtner | | | | + | | + |
| *Keratococcus bicaudatus* (A.Braun ex Rabenhorst) J.B.Petersen | + | | + | | | |
| *Myrmecia biatorellae* J.B.Petersen | | + | | | + | + |
| *Myrmecia bisecta* Reisigl | + | + | + | + | + | + |
| *Parietochloris alveolaris* (Bold) Shin Watanabe & G.L.Floyd in Deason, Silva, Watanabe & Floyd | + | + | + | | + | + |
| *Pseudococcomyxa simplex* (Mainx) Fott | + | + | + | + | + | + |
| *Stichococcus bacillaris* Nägeli | + | | + | + | + | + |
| *Stichococcus minutus* Grintzesco & Peterfi | + | | + | + | | + |
| *Stichococcus mirabilis* Lagerheim in Wittrock & Nordstedt | | | + | | | |
| *Trochisciopsis tetraspora* Vinatzer | | | | | + | |
| *Watanabea reniformis* N.Hanagata, I.Karube, M.Chihara & P.C.Silva | | | | | | + |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Xylochloris* cf. *irregularis* Neustupa, Eliás & Skaloud | | | | + | | |
| Class **Ulvophyceae** | | | | | | |
| *Fottea stichococcoides* Hindák | + | | + | + | | |
| *Interfilum massjukiae* Mikhailyuk, Sluiman, Massalski, Mudimu, Demchenko, Friedl & Kondratyuk | | + | + | + | + | + |
| *Interfilum terricola* (J.B.Petersen) Mikhailyuk, Sluiman, Massalski, Mudimu, Demchenko, Friedl & Kondratyuk | + | + | + | + | + | + |
| *Planophila bipyrenoidosa* Reisigl | + | | | | + | + |
| Phylum **Charophyta**, Class **Klebsormidiophyceae** | | | | | | |
| *Klebsormidium dissectum* (F.Gay) H.Ettl & Gärtner | + | + | | + | | |
| *Klebsormidium flaccidum* (Kützing) P.C.Silva, K.R.Mattox & W.H.Blackwell | + | + | + | + | + | + |
| *Klebsormidium montanum* (Hansgirg) Shin Watanabe | + | | | | | |
| *Klebsormidium pseudostichococcus* (Heering) H.Ettl & Gärtner | + | | | + | + | + |
| *Klebsormidium subtile* (Kützing) Mikhailyuk, Glaser, Holzinger & Karsten | + | | | | | |
| Class **Conjugatophyceae** | | | | | | |
| *Cylindrocystis brebissonii* (Ralfs) De Bary | + | | | | | |
| Phylum **Ochrophyta,** Class **Xanthophyceae** | | | | | | |
| *Botrydiopsis eriensis* J.W.Snow | + | + | + | | | |
| *Botrydiopsis arhiza* Borzì | | | + | | | |
| *Botrydiopsis constricta* Broady | + | | | | | |
| *Characiopsis minuta* (A.Braun) Borzì | + | | | | | |
| *Xanthonema exile* (Klebs) P.C.Silva | + | | | | | |
| Class **Eustigmatophyceae** | | | | | | |
| *Pseudocharaciopsis ovalis* (Chodat) D.J.Hibberd | + | | | | + | |
| *Vischeria magna* (J.B.Petersen) Kryvenda, Rybalka, Wolf & Friedl | + | | + | + | + | + |
| Class **Bacillariophyceae** | | | | | | |
| *Pinnularia borealis* Ehrenberg | + | | | + | + | + |
| *Pinnularia viridis* (Nitzsch) Ehrenberg | | | | + | | |
| Phylum **Cyanobacteria**, Class **Cyanophyceae** | | | | | | |
| *Aphanocapsa muscicola* (Meneghini) Wille | + | + | + | + | + | + |
| *Leptolyngbya* sp. | + | + | | | + | + |
| *Microcoleus* sp. | + | | | | | |
| *Microcoleus vaginatus* Gomont ex Gomont | + | | | | | |
| *Nostoc* sp. | + | + | + | + | + | + |
| *Phormidium* sp. | + | | | | | |
| *Stigonema* sp. | | | | | + | |

**Table 3.** Species diversity of algae and cyanobacteria in the area of the Kandalaksha Aluminum Smelter.

In earlier studies of the microbial component in the KAS zone, the absence of cyanobacteria was noted. Thus, it was concluded that photosynthetic prokaryotes are sensitive to both heavy metals and fluorine compounds (Evdokimova et al. 1997). However, our studies have shown that cyanobacteria in the maximum polluted zone are represented by six species. Their presence can be explained by several reasons. Firstly, cyanobacteria are tolerant to a variety of stress conditions due to the formation of mucilaginous envelopes, which constitute a physical barrier surrounding the cell (Kehr and Dittmann 2015). Secondly, it is known that some photosynthetic prokaryotes show passive permeation of both $HF^-$ and $F^-$ across the cell membrane to reduce the toxic effects of fluorides (Nichol et al. 1987). In addition, cyanobacteria prefer a near-neutral pH level for their development (Shtina and Gollerbakh 1976) while at the closest distance from the pollution source, soil acidity decreases (Table 1). We suppose that the absence of cyanobacteria in previous studies is due to unsuccessful selection of the nutrient medium and insufficient cultivation duration.

No reliable correlation was found between the number of species in each plot and the fluorine content in the soil. However, as in the case of the number of viable cells, the species diversity in the area at a distance of 2 km from KAS is noticeably lower than in the zone of maximum contamination and in the less polluted soils.

Despite the high fluorine concentration (>1000 mg/kg), the number and diversity of microphotrophs in soils near KAS are relatively large. This may be due to a decrease in the toxicity of fluorine due to a decrease in its solubility in less acidic soils compared with the background region (Evdokimova et al. 2013). It is known that many algae and especially cyanobacteria prefer habitats with a pH close to neutral. The sparseness of the vegetation cover is also a favorable circumstance for the development of microphototrophs since it provides the sufficient illumination of the exposed areas and lack of competition between microphototrophs and higher plants for food sources.

## Conclusions

31 species of soil fungi were isolated in the zone affected by the Kandalaksha Aluminum Smelter. The number, biomass, and diversity of soil fungi decreased as the results of the accumulation of a significant amount of fluorine in the soil near the smelter. The reduction of dark-colored fungi biomass in the fluorine contaminated soils was observed. The species *P. trzebinskii* and *P. miczynskii* dominated in the maximum polluted zone. *P. glabrum*, *P. spinulosum*, and *Memnoniella echinata* species prevailed in the zones with strong and moderately soil pollution. The share of opportunistic fungi increased in the contaminated soil. Rare or atypical species for zonal soils were isolated in polluted areas: *Aspergillus niger* var. *niger*, *Paecilomyces variotii*, *P. chermesinum*, *P. variabile, Phoma medicaginis, Thielaviopsis basicola, Torula allii, Myxotrichum cancellatum*, and *Trichocladium asperum*. Among these there are activators of opportunistic mycoses.

Altogether, 63 eukaryotic algae and cyanobacteria were identified in the soil samples within the pollution gradient from aerial technogenic emission of the KAS. Green algae dominated among the algal communities of investigated soils. The species diversity of cyanobacteria–algal cenoses in soils near KAS was higher than in the soils of unpolluted areas due to the presence of xanthophytes, a greater species diversity of filamentous algae from the genus *Klebsormidium,* as well as a larger number of cyanobacteria species. The dominance of

filamentous forms in the cyanobacterial community, the abundance of coccoid green algae from the classes Chlorophyceae and Trebouxiophyceae, and the significant role of filamentous taxa (*Klebsormidium*, *Xanthonema*) are characteristic features of the Arctic biological soil crusts (Pushkareva et al. 2016). The number of algae and cyanobacteria in the litter varied from 100 thousand to 1.5 million cells per 1 gram of absolutely dry soil.

Strains of micromycetes, algae, and cyanobacteria isolated from polluted soils in the studied zones are included into the Collection of the Laboratory of Terrestrial Ecosystems of the Institute of the Industrial Ecology Problems of the North (Apatity, Russia) which is registered in the international catalogue of world herbaria (INEP Herbarium of the Institute of the Industrial Ecology Problems of the North, Kola Science Center, Russian Academy of Sciences).

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