SOIL BIOLOGY

Organic Constituents and Biota in the Urban Atmospheric Solid Aerosol: Potential Effects on Urban Soils

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Abstract—The main components of solid atmospheric aerosol are soil and rock particles raised from the earth's surface by wind erosion, and primary biological aerosol particles. In the composition of atmospheric aerosol, many pollutants, both mineral and organic, appear in areas with intensive human activity. Summer dust (solid atmospheric fallouts) that fell out of atmosphere was collected at two sites in Moscow (the territory of the Leo Tolstoy Museum-Estate in Khamovniki and the Botanical Garden of the Biological Faculty of Moscow State University). Morphological and microbiological studies were carried out in order to characterize the composition of the organic part of urban solid atmospheric fallouts and its possible impact on soils and the urban ecosystem as a whole. It has been found that the composition of the organic part of the samples was identical and included: the representatives of aeroplankton and other particles of biological origin, and also fragments of oil films, plastic fibers, carbon particles, etc., which indicated the hydrocarbon and microplastic pollution brought from the atmosphere. The composition of the studied groups of microorganisms in atmospheric fallouts and in urban soils was similar and indicated close ecological links between urban dust aerosol and soils. The biomass of the studied groups of microorganisms of atmospheric solids was dominated by fungi, many of which are potentially pathogenic and allergenic organisms. Apparently, atmospheric solid aerosols are carriers of microbiological pollution associated with animal feces in the city. The presence of such particles in the air indicates insufficient soil activity as a “bacterial filter”.

Keywords: primary biological aerosol particles, allergenic and opportunistic fungi, sanitary-indicative microorganisms, microplastic, urban ecosystems

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INTRODUCTION

Solid atmospheric particles or dust circulate in the ground layers of atmosphere and connect the components within ecosystems and different ecosystems among them. Raising from one sites and settling on the other ones, dust particles perform linkage between habitats [28, 33]. Hence, substrates are transported between cities not only locally, but also for long distances [3, 50]. If inorganic part of atmospheric dust is composed mostly of soil and rock particles on natural territories, so microfragments of artificial materials, including those from road constructions and buildings, are added to it in urban territories [20, 54].

Additionally to mineral particles, living organisms—aeroplankton and their residues (“primary biological aerosol particles”) are also transferred [34]. The diameter of particles of bioaerosol varies from 0.3 to 100 μm [32, 39]. The air flows transfer every year

with water-dust suspension approximately 10¹⁸ living cells of microorganisms, endotoxins, mycotoxins and plant pollen from one continent to another, expanding their geography [37]. For example, fungal spores can be found in all parts of the earth's sphere all over the year [30, 42, 51], even under the extreme conditions of Antarctica [49]. Cultured forms of bacteria and fungi are found high in stratosphere, so their contribution into total carbon content in the atmosphere requires further study [29]. Additionally to bacteria and fungi, a vast number of living cells of algae, lichens, mosses, and protists are found in the atmosphere [52]. Favorable ‘mild’ conditions of urban microclimate provide the survival of many adventitious species in urban environment.

It is known that the dust content in the atmosphere in urban territories near roadways is ten–hundred times higher than that in natural territories [1]. The

intensity of aerial pollution and local transfer of solid particles between the sites are greater.

To forecast the development of soil and community of soil organisms, it is important to know either the amount and concentrations of pollutants in dust fallout, or the total composition of urban dust, and especially of its organic part. It was found out earlier that urban dust is characterized by high content of organic carbon. Many components of hydrocarbonic composition, typical for molecules of organic substances, are identified during microscopic study. Our data suggest that organic carbon concentration in the samples from different parts of Moscow city accounts for up to 10% of the fallout material [20, 54], and this agrees with other studies [57].

Dust can be the source of new substrates to provide nutriment of soil microorganisms, the source of new species diversity, can form new soil properties and ecological niches due to the input of matter not typical for natural environment substrates, and change living conditions of soil microorganisms. Despite the control of parameters of total dustiness of the atmosphere (indices PM_{2.5} and PM₁₀), ecological importance of solid particles migrating in the atmosphere and their effects on soils are poorly known.

The goal of our study is to characterize the composition of organic component and particular groups of organisms in urban solid atmospheric depositions in the samples collected in the territory of Moscow as potential source of influence on soil properties and the diversity of soil organisms.

OBJECTS AND METHODS

The study was carried out in the territory of Moscow. Moscow is situated in the center of the East European Plain, which is composed of unconsolidated fine-disperse deposits mostly of glacial and glaciofluvial origin. Climate is moderately continental with cold snowy winter and moderately warm summer. Formation of a “heat island” above the city was recorded in XX century. Mean annual air and soil temperatures in the city is steadily rising [10, 47, 48]. The second half of July and August in Moscow are usually most favorable for collecting the dry dust. The weather was as usually in August 2019 in the period of material collecting for the study: mean temperature was +17.6°C, accumulated precipitation 42 mm, mean wind velocity 1.2 m/s ([https://gr5.ru/Архив_погоды_в_Москве_\(центр,_Балчуг\)](https://gr5.ru/Архив_погоды_в_Москве_(центр,_Балчуг))).

Atmospheric depositions were collected at the height 80 cm above the soil surface. Dust load was calculated per year.

Studied plots. Both plots for collecting solid atmospheric depositions were situated in green territories with a limited recreational load at different distance from the city center (Fig. 1), in the immediate vicinity of streets with vehicle traffic. Because heat island

formed above the city extends beyond city limits, meteorological observatories recorded significant increase of air and soil temperatures during the past century, and we can consider that both plots are situated in the central zone of the heat island [10, 47, 48].

First plot is the memorial garden of the Leo Tolstoy Museum-Estate in Khamovniki, the branch of the Leo Tolstoy State Museum, it is situated in Central Administrative Okrug of Moscow. The altitude of the plot above sea level is 140 m.

The territory of the estate occupies the area approximately 1 ha and is surrounded recently by residential quarter and office buildings in the places of former industrial enterprises (weaving mill, brewery works, etc.). Only museum visitors have access to the garden. There are several memorial trees in the garden, and plants, which were grown in gardens in mid-to-late XIX century are now planted there.

Second plot is the Botanical Garden of Biological Faculty of Lomonosov Moscow State University (BG MSU) on Vorob'evy Gory (the territory of the university campus). The altitude of the plot above sea level is 195 m. It was the city outskirts in mid-XX century. Nowadays, the territory can be considered as a part of core city. The object is situated in the South-western Administrative Okrug of Moscow. Botanical Garden occupies the area of more than 30 ha. The employees and students of Moscow University and small group tours have access to the Garden, and this provides a rather low recreational load.

Collecting of atmospheric depositions. The material for the study was collected by direct settling of aerosol particles from the atmosphere into exposed containers. We used authorized method for collecting dry atmospheric fallouts, similar methods were tested earlier and described by other researches for open as well as for forest natural territories [25, 26]. Eight preliminary weighed plastic containers 11 × 13.5 cm were placed on every folding table. The containers were covered by deep household trays, in the side walls of which the perforations were made for free air circulation. Solid atmospheric depositions were accumulated in containers. The containers were exposed during 46 days from late July to mid-September 2019. Small quantities of moisture got into containers evaporated in a natural way. The collectors were placed in open on possible windswept places.

After completing the experiments, dust load in the studied plots was calculated according to the formula: $P = P_a / (ST)$, where P_a is the weight of settled down dust, g; S is projective area of settling, m²; T is time length of experiment, days. The result was multiplied by 365.

Laboratory methods. Morphological diagnostics of sample composition was carried out with the help of binocular magnifying glass directly on the surface of containers (magnification ×4...×56) and under scan-

Fig. 1. Studied key sites in the city map (a): (1) Memorial Garden of Leo Tolstoy Museum-Estate in Khamovniki and (2) Botanical Garden of the Biological Faculty of Moscow State University; (b) photo of units for collecting atmospheric depositions on the plots.

ning election microscope JEOL 6610 LV with energy dispersive spectrometer INCA XACT.

Three containers from every plot were used for electron microscopic examination. The content of fungi was analyzed in triplicate from three containers in every point, the content of bacteria was determined in duplicate from the remaining containers.

Isolation of biological components of aerosols from dust samples. Dust from every container was washed with sterile water (volume 10 mL), into which one drop (0.025 mL) of Twin-80 was added to decrease electrostatic properties of plastic (the container material). Wash water was shaken accurately on the surface within container and transferred into sterile tube.

Evaluation of fungal biomass and population density of bacteria was carried out with the method of direct microscopy: fungi were accounted, when staining with calcofluor white (Fluorescent brightener 28, Sigma), bacteria—with staining with acridine orange [17]. To desorb fungal structures, washed portions of dust were treated preliminary in Vortex device (3000 rpm, 2 min). To desorb bacteria from the surface of dust particles, water suspension was treated by ultrasound in the device UDZN (22 kHz, 0.44 A, 2 min). The number of fungal propagules and bacterial cells per 1 g of substrate was calculated according to the standard procedure [19]. Fungal biomass (mg/g of soil) was calculated, taking into account that spore density is equal to 0.837 g/cm³, and mycelium density is 0.628 g/cm³ [19].

Cultured microscopic fungi were isolated from dust water wipes via inoculation of serial dilutions by S. Waksman in modification of D.G. Zvyagintsev [17]. Deep inoculation was made into solid nutritional Czapek's medium [31]. Taxonomic identification of pure cultures was carried out on the basis of cultural-morphologic characters on Czapek's medium and on media recommended for particular groups of fungi with the help of modern manuals for corresponding genera and groups [31, 35]. The species were classified as allergenic and potentially pathogenic on the basis of known literature data [16, 43].

Cultured saprotrophic bacteria were isolated from the dust water wipes by inoculation into the universal glucose-peptone-yeast extract agar, which allows isolating from soil up to 50 genera of the block of aerobic and facultative anaerobic bacteria [17]. Taxonomic identification of bacteria to a genus level was carried out on the basis of phenotypic characters [11, 18].

The content of sanitary-indicatory microorganisms in the samples was studied according to the guidelines of Russian Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing, Ministry of Healthcare of the Russian Federation (MU 2.1.7.730-99. Hygienic Assessment of Soil Quality in Settlements). The number of coliform bacteria was determined in the samples of soil dust according to the procedural guidelines (MR FC/4022 Methods for Microbiological Control of Soil). The number of

Table 1. Dust load in studied key sites, g/m² per year

Studied site	Load				Standard deviation (σ)
	min	max	med	average (μ)	
Museum-Estate Garden in Khamovniki (<i>n</i> = 7)	10.69	64.12	21.37	26.72	17.99
BG MSU (<i>n</i> = 8)	10.69	42.75	21.93	23.38	12.93

total coliform bacteria and thermotolerant coliform bacteria (TTCB) per 1 g of soil dust were calculated in CFU/g. The colonies of TTCB were isolated into pure culture for subsequent genetical identification of strains (belonging to sanitary-indicatory species *Escherichia coli*). For this purpose, variable region V3–V4 of gene 16S rRNA was studied using BLAST program [13]. DNA was isolated according to earlier described procedure [5]. Analysis of sequences in gene 16S rRNA was carried out at Syntol Co. (Moscow, Russia).

Statistical treatment of data was carried out using the MS Excel program.

RESULTS

Generally, dust load in both studied plots was low during the period of observation. It was higher in the plot situated in central part of the city as expected (Table 1).

Diversity of objects of organic ingredients in the samples of atmospheric depositions. Despite different positions of plots, the major properties of samples were similar. All objects of solid atmospheric depositions were subdivided provisionally to inorganic and organic. All studied samples contained mineral grains and aggregates of relatively large size (from tens of μm to 1 mm), composed of quartz and other silicate grains. These particles dominated the composition of mineral components of the samples. Fragments of carbonate mortar of cement, road pavement, and solid magnetic particle were present in the mineral part of solid depositions.

The number of separate fragments of dead plant and animal tissues in the samples of depositions was much smaller in comparison with the number of units of their mineral component, although they occupied a great volume due to their size. It was found under the binocular magnifying glass at low magnification that the abundance of primary biological aerosol particles accounted for about 40–50% of the volume of samples studied (Table 2, Fig. 2a). Fragments of leaf plates and bodies of insects, seeds, fungal hyphae and spores, algae, organic residues, and manufactured fibers and spills-films of petrochemicals were found in summer dust.

Fragments of plant tissues in solid atmospheric depositions as well as large mineral grains adsorb on their surfaces the fine grains and crystals, and on the contrary, the surface of mineral aggregates retain the bioaerosol ingredients (Figs. 2b–2e).

When doing primary description of the samples under the binocular magnifying glass, greenish-yellow and brownish spots-films, covering about 3% of the total area of container, were observed. Their hydrocarbon composition was determined later under the electron microscope. An assumption was made, that this is a condensate of vehicle emission. The material was taken and analyzed from the exhaust pipe to confirm the assumption about the origin of these films. Its elemental composition was identical to that of hydrocarbon films (Fig. 3).

Dried fragments of fecal matter were found in the samples of both objects. The fragments were identified by high content of carbon and phosphorus, the portion of the latter accounted for more than 5% of the mass of substrate (Fig. 4a).

Small (average size of single alga was about 10 μm) red algae were found in experimental containers of both plots covering about 40% of container surface (Fig. 2c).

Separate fragments of artificial fibers which composition dominated by carbon, most probable plastic materials, were found in the samples. This component of atmospheric depositions was found just during visual examination of the sample: by bright colors and shape (1–10 μm). When oxygen was found in the fibers, and its ratio to carbon was 1 : 5, and the typical “frayed” fibrous structure was recorded, it was possible to suppose that they originated of cellulose or polyethylene terephthalate (chemical formula (C₁₀H₈O₄)_{*n*}) (Fig. 4b). Plastic fibers of mostly carbonic composition were found either.

Fungal biomass content in atmospheric depositions. Fungi are the most significant biological component of aeroplankton, present in all studied samples. It was determined with the method of direct microscopy that fungal biomass in dust depositions can account for up to 0.3% (Fig. 5). Fungal biomass in dust depositions is dominated (according the biomorphological structure) by fungal spores, their biomass was 7–12 times greater than the biomass of fungal mycelium. One gram of dust depositions contained hundreds of millions of fungal propagules. Average density of spores was greater in the site in Botanical Garden, Moscow State University, and reached billions per 1 g of dust depositions. The density of fungal spores was approximately 30% lower in the Museum-Estate site. Analysis of size structure of fungal propagules demonstrated absolute domination of fine spores (diameter <3 μm)

Table 2. Approximate proportions between components in dust depositions: results of examination of samples at magnification up to $\times 50$

Sample content	Museum-Estate Garden in Khamovniki	BG MSU
	fraction in total volume, %	
Mineral component		
Dull, light ungrounded carbonate particles (fragments of building mortars)	5	10
Transparent, fawn and pinkish dull particles, sometimes with sharp edges (silicate grains)	10	20
Dark-gray to black particles and aggregates of different size, not rounded (up to 1 mm, some are very small <0.1 mm)	10	20
Large dark pieces (asphaltconcrete)	<3	<3
Rounded dark particles (magnetic)	<3	<3
Reddish crumbs (bricks, red asphaltconcrete)	—	<3
Organic component		
Fragments of leaf blades	10	—
Plant seeds (mostly birch)	5	5
Thin, smooth, transparent, threadlike structures (probably roots, hyphae, etc.)	5	5
Small insects and their fragments (wings and extremities)	5	10
Thin colored (red and blue) and colorless threads, separate or several tangled	<3	<3
Rounded red particles (dried algae)	40	25
Brown aggregates (organic residues?) partly associated with threadlike structures	5	<3
Yellowish-green and brown brownish spots-films (hydrocarbonic films)	<3	<3

in the samples from both plots, such spores are the component of the fraction of dust depositions PM_{2.5}. Slightly greater (15%) portion of spores of medium size (3–10 μm) from the fraction PM₁₀, but with lower total number, was found in the memorial garden of the Leo Tolstoy Museum-Estate in Khamovniki.

Additionally to fungal spores, fragments of fungal mycelium were found in solid atmospheric depositions (Fig. 5). Total length of mycelium was not very great and accounted for 67 ± 93 and 122 ± 92 m, respectively, in dust depositions in Khamovniki and BG MSU. The depositions were dominated by thin mycelium with diameter <4 μm in the second site and by thick mycelium >4 μm in the first site.

Number of propagules of cultured fungi. The total number of colony-forming units (CFU) of cultured fungi was almost two times greater in the plot in BG MSU in comparison with the Leo Tolstoy Museum-Estate in Khamovniki (Table 3), and this agreed with the data of direct microscopy.

Taxonomic composition of cultured fungi. More than 30 species belonging to 21 genera of microscopic fungi, representatives of Mucoromycota, Ascomycota, Basidiomycota phyla, were found in samples, several forms without sporulation were also recorded (Table 3). Representatives of *Alternaria* (*A. alternata*, *A. tenuissima*), *Aureobasidium pullulans*, *Cladosporium* (*C. cladosporioides*, *C. macrocarpon* and others) genera, and *Penicillium* spp. dominated in dust atmospheric depo-

sitions in both plots. Species of *Trichoderma* genus were found as frequent and abundant.

The total species diversity of fungal assemblages in two plots was similar. In general, high similarity was observed between fungal aerosols in two key sites, the Sorensen-Chekanovsky similarity coefficient was 0.63. This indicated approximately similar initial substrates, which are primary sources of the input of fungal propagules to the air. The similarity could be explained first by the presence of tree and herbaceous plants in both plots.

However, some differences could be noted between species compositions and structures of fungal component of dust in studied territories. Dust depositions in the garden in Khamovniki were dominated by the representatives of *Penicillium* (*P. chrysogenum* Thom, *P. citrinum* Thom, *P. glabrum* (Wehmer) Westling, *P. janczewskii* K.W. Zaleski, etc.) genus. These are typical soil-inhabiting species, they can get into dust depositions with soil particles. Additionally, abundant presence was recorded here of fungi, typically developing in phylloplane and on tree bark: these are ekkrisotrophs and phytopathogens from *Alternaria*, *Aureobasidium*, *Botrytis*, *Cladosporium*, *Fusarium*, and *Epicoccum* genera [35]. They usually form spores of medium and large size, and this agrees with obtained data about greater fraction and biomass of such spores in total fungal biomass in the territory of park.

Fig. 2. Primary biological particles within aerosol: (a) general view of dust at magnification $\times 45$ (Museum-Estate Garden in Khamovniki), (b) chitin cover of animals with stuck mineral particles (Museum-Estate Garden in Khamovniki), (c) overgrowing of dust microaggregate by unicellular algae (BG MSU), (d) trichome with stuck mineral particles (BG MSU), and (e) fungal conidia adsorbed on rounded mineral aggregate of dust (Museum-Estate Garden in Khamovniki).

Significant population was recorded in dust depositions in BG MSU of small-spore species from *Acremonium*, *Cephalótrichum*, *Paecilomyces*, and *Phoma* genera, which develop on living and dead plant substrates [35]. Some typical components of phylloplane,

which are usually found in the case of accumulation of plant exudates, were very abundant; these are fungi from *Botrytis*, *Epicoccum*, *Mucor*, *Rhizopus*, and *Trichoderma* genera. Taxonomical composition of isolated fungi in this site correlated with the data about domi-

Fig. 3. The comparison of composition of hydrocarbonic films determined semiquantitatively with the help of energy dispersive microanalyzer (hydrogen was excluded from the spectrum): (a) scraping out of exhaust pipe; (b) clot of films in dust depositions (Museum-Estate Garden in Khamovniki).

nation of small and big part of large spores in fungal biomass.

Total number of bacteria in studied samples. Population density of bacteria in samples of atmospheric depositions collected accounted for 8.4 billion cells/g in the territory of Museum-Estate Garden and 5.2 billion cells/g in the territory of BG MSU. The total number of bacteria in the territory of Museum-Estate Garden was almost two times greater than in the territory of BG MSU (Table 4). Obtained data were close to the values of total number of bacteria, recorded in the samples of upper soil horizon in BG MSU, which accounted for 1 to 10 billion cells/g of soil [21].

Population density and taxonomic composition of cultured saprotrophic bacterial complex. Population densities of cultured saprotrophic complex of bacteria (SBC) differed insignificantly. This index accounted for 2.3 million CFU/g in the territory of BG MSU and 2.5 million CFU/g in the territory of Museum-Estate Garden.

Taxonomic composition of bacterial complex was analyzed. Significant numbers of bacteria from *Arthrobacter*, *Micrococcus*, and *Pseudomonas* genera were present in samples from both experimental sites. The

contents were lower for *Erwinia* genus and Enterobacteriaceae family. Bacteria from *Cytophaga* and *Rhodococcus* genera were found in the samples taken in the territory of BG MSU.

Assessment of sanitary-indicatory microorganisms content. Determination of sanitary-indicatory microorganisms and their high relative abundance is an important evidence of anthropogenic load on soil, and the presence of these organisms in atmospheric depositions suggests the presence of fecal contamination.

Coliform bacteria were isolated from dust depositions on both studied key sites. Their content accounted for 9% of population density of SBC in BG MSU and 15% in Museum-Estate Garden (Table 5). Relative abundance of thermotolerant coliform bacteria in the number of total coliform bacteria accounted for 2.2% in BG MSU and 10.6% in Museum-Estate Garden.

The strains of sanitary-indicatory *Escherichia coli* species were found in the group of TTCB identified with the help of analysis of nucleotide sequences of the region of 16S rRNA (similarity 99.99%). The strains of *E. coli* were found in dust depositions in both sites. The content of *E. coli* was higher in studied dust sam-

Fig. 4. Components of dust and their composition (hydrogen was excluded from the spectrum): (a), dried fragments of fecal matter (the sample from the plot in BG MSU); (b), fibers of cellulose origin in solid atmospheric depositions (Museum-Estate Garden in Khamovniki).

ples collected in the territory of Museum-Estate Garden than in the samples from the territory of BG MSU. In accordance with sanitation regulations developed for soils, the samples of atmospheric depositions should be considered as heavily polluted (MR FC/4022. Methods for Microbiological Control of Soil).

DISCUSSION

More intense dust load in Central Okrug of the city was expected. Total low levels of dust load in both plots were connected with the construction of dust collectors and with regular atmospheric washing by rains. The total rainfall was low, the rains were regular

although of low intensity. This forced us to use semi-closed construction, instead of placing the containers in the open air.

Separation of aerosol particles to organic and inorganic components was conventional, because there were aggregates of mixed composition. Fragments of biological origin and those with hydrocarbons often were closely associated with the mineral part of atmospheric depositions.

Organic components in studied samples of solid atmospheric depositions were very diverse. Fragments and residues of living organisms, and their propagules—the components of aeroplankton (seeds, fungal spores, and plant pollen), as well as fragments of fecal materi-

Fig. 5. The content and structure of fungal biomass in dust depositions in studied sites.

als and detritus were found here. Fungal hyphae and algae expanding in their growth in the moist environment of containers accounted for significant part in the samples.

According to the obtained data, fungal biomass reached 2.5–3.5 mg/g in dust depositions. Such significant fungal biomass was recorded due to selected season for collecting dust depositions. It was shown earlier that maximal sedimentation of fungal propagules (up to hundreds of thousands per m^2 per day) was observed just in August [14].

The total lower number of fungal propagules in the Garden in Khamovniki was due to the decrease of small and large spores number. However, similar concentrations of medium-size spores (3–10 μm) were observed (Fig. 5). This fraction usually is composed of yeasts and fungal spores, inhabiting surfaces of plants and the ground layer. Probably, such distribution was caused by the peculiarities of the soil cover and time of plot use. The presence of spores of different size fractions in aerial dust depended not only on colonizing the surfaces in ground and above-ground layers by fungi, but also on the composition of soil fungal community, spores of which can get to the air with dust. Small spores are most often common to many typical soil saprotrophs, and the fraction of large spores usually includes ascospores, some basidiospores, and dormant fungal structures. The decrease in different-sized fungal spores in the Museum-Estate Garden plot can suggest indirectly the less diverse soil fungal community and lower saturation of soil in this plot with diverse organic substrates. However, this is just an assumption, until soil were not yet analyzed.

Fungal dust depositions are absolutely dominated by pigmented forms, these are melanin-containing mycelial fungi from *Alternaria*, *Aureobasidium*, *Cladosporium*,

Epicoecum genera, etc., and carotene-containing yeasts of *Cystofilobasidium capitatum* and *Rhodotorula mucilaginosa* living on plants. The presence of pigments accounts for the resistance of these fungi to different factors of aerial environment [4]. Accumulation of pigmented fungi is one of specific features of soil mycobiota in urban environment [9, 15]. Such fungi apparently get to soil with urban dust.

Some information has been accumulated recently about taxonomic and size compositions of fungal propagules being components of bioaerosols, as well as about the proportion between colorless basidial spores and pigmented ascospores in the air of different regions of the world, though some researchers consider this information insufficient [38, 46, 56]. Our data on the species composition and biomorphological structure of fungal aerosols confirm the described regularity of domination of propagules of epiphytic fungi and xylophages with spores of medium size and phytopathogenic fungi with large, often melanized, spores, which usually live on plants in the air. These are representatives of *Cladosporium*, *Alternaria*, *Fusarium*, and *Epicoecum* genera, and small-spore soil-inhabiting species from *Penicillium*, *Aspergillus* genera, etc. The proportion between dominants and subdominants can slightly vary in different regions, but in general the composition of the nucleus of dominants of fungal aeroplankton is stable in different continents and regions [16]. The domination of spores of PM10 size fraction is constantly observed in fungal aerosols [58]. Favorable conditions for fungal development and sporulation are formed in forest sites due to the abundance of exudates on the surface of bark and leaves; and phytopathogenic fungi with large spores can develop on tree surface [45]. Monitoring of presence in dust of fungal spores was carried out earlier in the BG MSU (in the territory of weather station). It demonstrated the predominance of basidiospores and conidia of ascomycetes in late summer and early autumn [8]. Our data correlate with available literature data. However, it should be noted that analysis of fungal aeroplankton is usually carried out in urban territories, and the interest of researchers is focused to a less degree on undisturbed forest territories. That makes sense. High population density of fungal spores in the PM10 fraction is observed in cities. Hence, the intensity of risks for population's health increases in urban ecosystems [53, 55].

Representatives of *Alternaria* and *Cladosporium* genera, being among the mostly common agents of human allergic diseases of fungal etiology, compose a significant part in dust fungal depositions in the studied sites [15, 16, 42, 43]. Representatives of *Absidia*, *Aspergillus*, *Candida*, and *Fusarium* genera, some species of which are known as potentially pathogenic for humans, were recorded among isolated fungi [16, 43]. The diversity and abundance of such fungi were higher in the Garden in Khamovniki than in BG MSU. This

Table 3. Taxonomic composition and structure of fungal assemblages in dust depositions in the studied territories (frequency (%)/relative and species (%))

Composition	Museum-Estate Garden in Khamovniki	BG MSU
Mucoromycota Phylum		
<i>Absidia spinosa</i> Lendn.	11/0.2	—
<i>Mucor</i> spp.	11/2.8	22/6.0
<i>Rhizopus oryzae</i> Went & Prins. Geerl.	—	11/0.2
Ascomycota Phylum		
<i>Acremonium</i> spp.	11/1.4	22/17.5
<i>Alternaria alternata</i> (Fr.) Keissl.	67/7.1	44/4.9
<i>Alternaria tenuissima</i> (Kunze) Wiltshire	33/3.6	22/2.1
<i>Aspergillus ustus</i> (Bainier) Thom & Church	—	11/0.1
<i>Aspergillus niger</i> Tiegh.	22/2.0	—
<i>Aspergillus terreus</i> Thom	—	11/0.2
<i>Aspergillus fumigatus</i> Fresen.	11/0.5	—
<i>Aureobasidium pullulans</i> (De Bary) G. Arnaud ex Cif., Ribaldi & Corte	44/14.9	56/14.0
<i>Botrytis cinerea</i> Pers.	—	44/2.2
<i>Candida</i> spp.	11/2.1	—
<i>Cephalótrichum stemonitis</i> (Pers.) Nees	—	44/5.3
<i>Cladosporium cladosporioides</i> (Fresen.) G.A. de Vries	67/8.6	33/1.5
<i>Cladosporium macrocarpum</i> Preuss	22/8.7	—
<i>Epicoccum nigrum</i> Link	11/0.4	44/5.8
<i>Fusarium</i> spp.	33/2.1	33/3.1
<i>Penicillium</i> spp.	100/30.1	44/8.4
<i>Phoma</i> sp.	11/0.9	33/4.1
<i>Purpureocillium lilacinum</i> (Thom) Luangsa-ard, Houbraken, Hywel-Jones & Samson	—	11/0.7
<i>Trichoderma</i> spp.	44/9.4	44/12.2
Basidiomycota Phylum		
<i>Rhodotorula mucilaginosa</i> (A. Jörg.) F.C. Harrison	11/0.3	11/0.7
<i>Cystofilobasidium capitatum</i> (Fell, I.L. Hunter & Tallman) Oberw. & Bandoni	11/1.4	11/0.7
Sterile mycelium	33/3.5	44/10.1
Number of isolated species, <i>n</i>	26	25
Number of CFU/g of dust	$(0.567 \pm 0.351) \times 10^6$	$(1.008 \pm 0.872) \times 10^6$

may be related to the position in the center of the city and intensity of recreational activity in the Garden.

Red one-cell algae (Rhodophyta) were found, which form films on the surface of mineral aggregates in the samples subjected to moistening, or in the form of rounded conglomerates in dry samples. These apparently were aerophilous algae that lived under conditions of sufficient atmospheric moistening with permanent alteration of moistening–drying cycles. The species of *Rhodospira*, *Phragmonema*, and *Porphyridium* genera were found among well-known aerophilous algae. Mass development of the latter is

connected with the presence in soil of great amounts of organic nitrogen compounds [2]. In the containers they abundantly reproduced in moist environment and slightly increased total weight of samples, so one sample had been excluded, when calculating dust load. It can be noted that mass development of reddish algal incrustations was observed on tree trunks in summer 2019.

The particles—carriers of organic soil contaminants were found in the samples of solid dust depositions additionally to primary aerosol particles of biological origin (microorganisms, fragments of biological mate-

Table 4. Total number of bacteria, number and taxonomic composition of cultured saprotrophic bacteria in studied samples

Key site	Total number of bacteria, billion cells/g	Number of saprotrophic cultured bacteria, million CFU/g	Taxonomic composition of saprotrophic cultured bacteria (at generic level)
Museum-Estate Garden in Khamovniki	8.45 ± 0.85	2.50 ± 0.25	<i>Arthrobacter</i> , <i>Micrococcus</i> , <i>Pseudomonas</i> , <i>Erwinia</i> , family Enterobacteriaceae, <i>Cytophaga</i> , <i>Rhodococcus</i>
BG MSU	5.20 ± 0.54	2.30 ± 0.24	<i>Arthrobacter</i> , <i>Micrococcus</i> , <i>Pseudomonas</i> , <i>Erwinia</i> , family Enterobacteriaceae

Table 5. Number (above the line, thousand CFU/g) and fraction (under the line, %) of bacteria from Enterobacteriaceae family (TCB) and thermotolerant coliform bacteria (TTCB) in studied samples

Plot	TCB	TTCB	Presence of <i>Escherichia coli</i>
Museum-Estate Garden in Khamovniki	$\frac{240 \pm 26}{15}$	$\frac{25.6 \pm 2.5}{10.6}$	+
BG MSU	$\frac{210 \pm 24}{9}$	$\frac{4.4 \pm 0.5}{2.2}$	+

rial, plant residues, fragments of animal hair fibers) [34]. These were inclusions of hydrocarbonic ingredients as clearly visible even by naked eye, but difficultly identified objects: fibers of plastic materials and cloths, pigment scales, and hydrocarbonic films. Energy dispersive microanalyzer does not allow determining the exact concentrations of elements in the particles and aggregates or their restricted areas, but provides insight into the composition and proportions between the main components of the studied material. In combination with characteristic forms of micro-objects, this allows their identification [20, 24, 27, 28].

The values of total population density of bacteria in the samples of soil dust were similar to that in surface horizons of urban soils [5, 12, 22]. Greater values recorded in the samples taken in the Garden in Khamovniki in comparison with BG MSU were connected with intense traffic and less intense air exchange, because the territory is situated at lower altitude. Taxonomic composition of saprotrophic cultured bacteria (at generic level) also corresponded to the composition of dominating genera in urban soils [12, 23]. High content of *Enterobacteriaceae* in studied samples attracts someone's attention. It is known that many representatives of Enterobacteriaceae cause enteric and allergic diseases and *E. coli* is an indicator of fecal contamination of soil. Representatives of this family are not found in significant amounts in soils of natural biogeocenoses, but if they are there, they are presented by saprotrophic species and genera of Enterobacteriaceae [6, 7].

It is known that accumulation of potentially pathogenic (representatives of family Enterobacteriaceae) and of potentially allergic bacteria of *Rhodococcus* and *Micrococcus* genera in urban contaminated soil, indicates serious disturbance of ecological

function of soil as "bacterial filter" and can be dangerous for humans [44]. The presence of these bacteria in studied samples indicates significant bacterial pollution of the air in the city.

Determined fraction of **TTCB** in dust depositions attests to intense susceptibility of urban environment (including air) to fecal contamination, which is dangerous to human health. This is confirmed by the presence of microfragments of fecal matter in dust (Fig. 4). Fecal contamination was greater in Khamovniki site than in BG MSU. This was apparently caused by the presence of significant fecal contamination of soils of residential territories, which are subject to high anthropogenic load owing to the residential activity of humans and the intrusion to soil of excrements of synanthropic animals. They can be found in both territories, although in Khamovniki around the Museum-Estate Garden there are small patches of open soils and planted land. People walk their dogs in courtyards. Dog walking near the Lomonosov Moscow University is less intense, because the density of residents is lower there.

Urban soils in studied locations apparently cannot be considered as epidemically clean, if follow the Government regulatory documents (MU 2.1.7.730-99. Hygienic Assessment of Soil Quality in Settlements. Clause 8.1). Sanitary-and-hygienic functions of soil are very important. They are connected with extermination of pathogenic microorganisms and stimulation of organic residues decomposition including products of exchange of different living organisms by the bacteria of saprotrophic complex. It can be assumed that serious disturbance and degradation of the whole natural complex, including soil cover, occur in the downtown because of greater anthropogenic load in comparison with the territory of Moscow University [41].

Soil less well copes with its sanitary functions, and the part of potentially pathogenic, pathogenic, and allergenic microorganisms in it increases. This is reflected in the taxonomic status of cultured saprotrophic bacteria present in solid dust depositions.

Dust depositions in megapolis can serve not only the source of new, not typical for natural undisturbed ecosystems substrates for microorganisms, but can also affect the structure of microbial complex, increasing its species diversity due to introduction of synanthropic species [9]. Monitoring of dust depositions in megapolis allows revealing the trends of qualitative and quantitative changes in the state of microbial complexes in natural environment in urboecosystem, which affects directly human health [36, 40].

CONCLUSIONS

Contamination with solid atmospheric particles in experimental plots corresponded to low level of dust load in the year of observation. Summer dust load in Museum-Estate Garden in Khamovniki was higher than in the BG MSU.

Organic materials of different genesis: representatives of aeroplankton, algae, fungal spores, seeds and pollen, as well as plant and animal tissues of different degree of decomposition, were found in the samples of summer atmospheric depositions in both studied key sites.

The presence of microfragments of artificial materials of hydrocarbonic composition: accumulations of films of petrochemicals, plastic fibers, carbonaceous particles, etc., was recorded in all samples, and this suggests atmospheric hydrocarbonic contamination and contamination by microplastics.

The composition of the studied groups of microorganisms in dust and urban soils was similar, and this attested to their close ecological relationships. Allergic and potentially pathogenic species from phylloplane, which are the largest source of fungal spores, get into urban soils and accumulate there by means of atmospheric transfer.

Taxonomic structures of studied groups of microorganisms in solid atmospheric depositions are dominated by fungi from *Alternaria*, *Acremonium*, *Cladosporium*, and *Penicillium* genera and by bacteria from *Arthrobacter*, *Micrococcus*, and *Pseudomonas* genera; some of them are potentially pathogenic and allergenic microorganisms.

Atmospheric solids perform in the city the function of carriers of microbiological contamination connected with animal dung. Significant exceedance of MAC for soils of sanitary-indicator group of **TTCB** was found in both objects (3.5×10^5 and 3.7×10^4 CFU/g). Fecal contamination was higher in Khamovniki site. Apparently, urban soils in both sites should not be considered as epidemically clean, if be governed by regula-

tory documents of hygienic evaluation of soil quality in populated areas.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests.

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