Folia Forestalia Polonica, Series A – Forestry, 2022, Vol. 64 (1), 15–37

ORIGINAL ARTICLE

DOI: 10.2478/ffp-2022-0003

Bioindication of megalopolis park ecosystems under aerotechnogenic loading

Nataliia Miroshnyk[1] ✉ ORCID: 0000-0003-3507-6585, *Tetiana Grabovska*[2] ORCID: 0000-0001-6995-9314, *Marina Mazura*[1] ORCID: 0000-0001-5260-1893, *Igor Teslenko*[1] ORCID: 0000-0002-4184-4774

[1] Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine, Lebedeva str., 03143 Kyiv, Ukraine, e-mail: miroshnik_n_v@mail.ru

[2] Bila Tserkva National Agrarian University, Department of General Ecology and Ecotrophology, pl. 8/1 Soborna, Bila Tserkva, Kyivska oblast, 09117 Ukraine

Abstract

This study focuses on the influence of motor transport on various indicators of park ecosystems and *Taraxacum officinale* Web., as well as on their applicability to the bioindication of the urban environments in the largest megalopolis of Ukraine, namely, Kyiv. Our investigations were carried out in 14 park ecosystems exposed to different levels of aerotechnogenic loading: low pollution level in Pushcha-Vodytsya (park) and outskirts, average pollution level alongseven roads with medium traffic and high pollution level along eight highways. Pollen indication, integration and statistical methods were used to identify the most sensitive indicators of the impact of air pollutants. The aim is to assess the impact of vehicle emissions on the state of park ecosystems in the metropolis using bioindication and GIS technologies. The effects of air pollution on green infrastructure at the level of cells, organisms, groups and ecosystems in time and space are revealed. Under the influence of aerotechnogenic pollution, there is a deterioration of trees, their drying, defoliation of crowns and deterioration of integral indicators of park ecosystems. Using QGIS (Free open source geographic information system, version 3.12.3 „București", May 15, 2020), we have created maps for the spread of air pollutants. The highest levels of air pollution and damage to parks were concentrated in the central part of the city with dense buildings and near heavy traffic roads. The average daily maximum allowable concentration (MAC) of phytotoxicants exceeded 1.5 MACa.d. and depended on the terrain and directions of the prevailing winds. We registered degradation of the megalopolis ecological state by 19.3% for 7 years.

Key words

air pollution, green infrastructure, hazard index, pollen indication, traffic, Ukraine

Introduction

In cities, air pollution is one of the main problems that affect the biological systems and the quality of residents' life (Lavrov et al. 2019; Jaung et al. 2020; Lavrov et al. 2021a). Aerotechnogenic pollution of the environment through rapid urbanisation that has led to increase in the number of vehicles is one of the strongest factors inhibiting the development of green infrastructure in the city (Fuller and Quine 2016; Ferreira et al. 2016; Çelebi and

Received 23 June 2021 / Accepted 28 January 2022

Gök 2018; Grodzinskaya et al. 2019; Vacek et al. 2020). The negative human impact is manifested in changes in physiological processes, restructuring of links and food chains, destruction of biotic groups, changes in functioning, degradation of natural biotopes and global changes in landscapes and climate (Cuinica et al. 2014; Azzazy 2016; Livesley et al. 2016; Pietras-Couffignal and Robakowski 2019). The area of contact and intensive gas exchange with the environment cause high sensitivity of plants to various pollutants (Cuinica et al. 2015; Livesley et al. 2016; Vieira et al. 2018). The most dangerous for the green areas of cities are excessive concentrations of aerophytotoxicants NH_3, NO_x (mixture of gases NO, NO_2, NO_3), SO_2, formaldehyde, phenol, soot and heavy metals. Their sources of entry into the environment are industrial enterprises and motor transport (Nikolaevsky 1998; Miroshnyk 2018; Rao et al. 2014; Nowak et al. 2014; Vacek et al. 2020). Air phytotoxicants cause leaf burns, disruption of physiological processes in plants, toxic and teratogenic effects. Emissions from vehicles make up the bulk of all emissions into the atmosphere of megacities (especially NO_x, CO). They enter the air in the surface layer, which reduces their scattering by winds and poisons most living organisms. The presence of narrow streets and tall buildings is an obstacle to scattering and also contributes to the accumulation of harmful air pollutants in urban air in the breathing zone of pedestrians and greenery (Pietras-Couffignal and Robakowski 2019; Voordeckers et al. 2021). Accumulating in the surface layer of the atmosphere, some components of exhaust gases are involved in photochemical reactions (Kiptenko and Kozlenko 2016; Livesley et al. 2016; Vieira et al. 2018; Vacek et al. 2020) and cause significant damage to plants and humans. Air in cities is characterised by high dynamism due to the movement of air masses in the horizontal and vertical directions. Low car operation indicators, fuel quality, road density and throughput also contribute to increase in air pollution, which leads to reduced speed, congestion and increased emissions of pollutants (Klebanova and Klebanov 2011; Van Wittenberghe et al. 2012). Air pollutants settle on the surface of soils and plants, and thus enter the trophic chains (soil–plant–animal–human) (Cuinica et al. 2014, 2015; Livesley et al. 2016; Leghari et al. 2018; Grodzinskaya et al. 2019).

In Europe, North America and China, tree species, herbaceous, including *Taraxacum officinale* Web., are used as indicators of the state of urban environment (Leghari et al. 2018; Martines 2018; Zajecka and Świercz 2021). In studies of the impact of air pollutants and heavy metals on the environment, various plant indicators are used, in particular, palynoindication (Cuinica et al. 2014, 2015; Ivanchenko and Bessonova 2016; Leghari et al. 2018; Petrushkevych and Korshykov 2020; Mazura et al. 2020; Bessonova and Sklyarenko 2020), life status of plantations (Nock et al. 2013; Vieira et al. 2018; Rybakova and Glazunov 2020; Vacek et al. 2020; Jaung et al. 2020), the level of defoliation of the crown (Vacek et al. 2020; Miroshnyk 2018), leaf damage (chlorosis–necrosis) (Miroshnyk 2018; Pietras-Couffignal and Robakowski 2019), changes in anatomy, content and ratio of photosynthetic pigments (Ivanchenko and Bessonova 2016; Suskalo 2018), enzymes (Suskalo 2018) and other physiological processes. The correlation between the concentrations of NO_x, SO_2 and the number of passing cars and defoliation of trees (Vacek et al. 2020) have been established. The relationship between the impact of distance to the highway, damage to the leaves of woody plants and the degree of defoliation of crowns (Miroshnyk 2018; Rybakova and Glazunov 2020; Vieira et al. 2018; Vacek et al. 2020) have been established too. An increase in the impact of motor transport with the approach from rural areas to large cities has been identified (Monok et al. 2020; Ferreira et al. 2016). Impact of soil pollution by heavy metals on vegetation in parks have been associate with the number of cars on the roads (Kijewska et al. 2016; Khan et al. 2016; Ali et al. 2017; Gąsiorek et al. 2017; Mazura et al. 2020). Air pollutants in the concentration from 1 maximum allowable concentration (MAC) and above cause necrosis on the leaves, reduce the linear growth of shoots, reduce the age of needles in conifers, shorten the life of trees (Nikolaevsky 1998; Polyakova and Gutnikov 2000; Vieira et al. 2018; Rybakova and Glazunov 2020) and destroy the pigment complex of plants (Ivanchenko and Bessonova 2016; Mazura et al. 2020; Pietras-Couffignal and Robakowski 2019). Therefore, for plants, normalisation of the content of air pollutants is lower than for humans (Nikolaevsky 1998; Furdychko et al. 2008).

Hazard indexes (HIs) of pollutants have been studied in 11 parks in Pakistan (Khan et al. 2016) and in Kyiv, where the concentration of heavy metals in soils increases with increasing traffic intensity (Grodzinskaya et al. 2019). The quality and characteristics of tree seeds have significantly deteriorated with the increase in the number of vehicles (Aliyar et al. 2020; Vacek et al. 2020). Results of 18-year monitoring of *Larix decidua* Mill. and *Picea abies* (L.) Karst. in the zone of influence of the highway with a load of 9000 cars per hour showed a significant inhibition of growth of stands in height, trunk diameter and crown parameters (Rybakova and Glazunov 2020; Vacek et al. 2020).

Possibilities of using a geographic information system (GIS) for the analysis of pollutant emissions into the atmosphere from transport are considered (Lee et al. 2006; Khan et al. 2016; Żak 2017). The high level of air pollution in Kyiv as one of the consequences of urbanisation poses a threat to public health and the natural environment. The main source of air pollution in Kyiv is motor transport – 86% of emissions or 144.3 thousand tons per year (Kiptenko and Kozlenko 2016; Ecological passport 2020). In 2019, 22.3 thousand tons of pollutants and greenhouse gases or 26.7 tons per 1 km^2 were released into the atmosphere of Kyiv. Also, 7.5 kg of pollutants were emitted per person in the city. The highest level of air pollution (2.0 MAC and above) with phytotoxicants NO_x, SO_2, formaldehyde, and heavy metals causes a catastrophic state of street greenery (necrosis, leaf dechromation, significant defoliation of the crown, drying of trees). The total emissions of the most dangerous substances for park plantings in the air of Kyiv in 2019 were: dioxide and other sulphur compounds – 12.6 thousand tons, nitrogen oxides – 31.9 thousand tons and dust – 7.5 thousand tons. The general level of air pollution in Kyiv is estimated to be more (Ecological passport, 2020). Soils with heavy metal content are highly contaminated (Grodzinskaya et al. 2019). Thus, air pollution in the metropolis has become one of the most important problems, as the man-made load on the city's ecosystems has a dangerous rate and form. The climate of the metropolis contributes to the negative impact of air pollution on urban ecosystems, biodiversity, comfort and public health. Ecological and microclimatic zoning of Kyiv urban area indicates climate change (decrease in humidity, increase in temperature inside the city compared to its surroundings [about 5°C]) and the formation of temperature inversions and prevailing winds, typical for megacities – dominated by southern (17.4%), northern (16.8%) and western (16.7%) winds. Northwest and southwest winds have an average of 11% (Shevchenko and Snizhko 2008; Weather archive). Annual amount of precipitation decreased by ~10%. Due to the effect of climate decontinentalisation in the 20th century on the territory of Ukraine, in particular, significant warming in the summer months (July–August) has been proved, and over the last 45 years, there has been a significant decrease in precipitation by ~15% in April–May and July (Boychenko et al. 2017). Bioindication studies in the anthropogenic load gradient of Kyiv were performed (Rabosh and Kofanova 2019; Miroshnyk 2018; Mazura et al. 2020). Because greenery is important for maintaining air quality and microclimate in cities (Jaung et al. 2020; Jin et al. 2021; Wei et al. 2021), it is important and necessary to comprehensively study the viability of park ecosystems (PEs) under anthropogenic pressure. That is why we chose Kyiv city – as a landmark – because it is the largest city in the country with a population of 3 million people. However, there have been no comprehensive studies using a variety of integrative bioindicators and reflecting the impact of air pollution from motor transport. Therefore, the purpose of the study was to assess the impact of vehicle emissions on the state of PEs in the metropolis (Kyiv) using bioindication and GIS technologies.

Material and methods

PE was investigated in 2018–2020 on the Kyiv territory. The state of PE was assessed with the principles of comparative ecology (Anuchin 1982). The spatial structure, species composition and sanitary condition of the stand by tiers were studied on temporary trial plots (TPs) (not less than three TPs in each ecosystem, area 0.2–0.6 ha) in the middle-aged and ripening plantations (Anuchin 1982; Monitoring and increasing the resilience of anthropogenically disturbed forests 2011; Sanitary rules in the forests of Ukraine 2016). The degree of damage for mixed stands was assessed by the weighted index of stand state (I_s) of the first tier (Monitoring… 2011):

$$Is = \frac{\begin{array}{c} k_1\,(n_a + n_b + \ldots + n_i) + \\ + k_2\,(n_a + n_b + \ldots + n_i) + \ldots + \\ + k_6\,(n_a + n_b + \ldots + n_i) \end{array}}{N} \qquad (1)$$

where:

I_s – the stand state index,

k_1–k_6 – the category of trees state (from I to VI) (Sanitary rules in the forests of Ukraine 2016),

n_a, n_b, ..., n_i – the number of different tree species in one state category, individuals,
N – the total number of evaluated trees in the TP, individuals.

Stands with an index of 1.00–1.50 were considered healthy (no damage), 1.51–2.50 (weak damage) weakened, 2.51–3.50 (average damage) severely weakened, 3.51–4.50 (severe damage) wilting and 4.51–6.00 (the damage is very strong) dead (Monitoring and increasing the resilience of anthropogenically disturbed forests 2011).

The names of the families are given according to the system of Takhtajan (2009). The grass tier non-native plant index (I_{nn}) was established as a share of alien plants from the total number of species on the TP. To assess the α-diversity of plants, we used index of Shannon's diversity (Magurran 2004):

$$H' = -\sum(P_i \times \mathrm{Ln}P_i) \quad (2)$$

where:
the relative number of species or guilds $P_i = N_i/N$,
N_i – the number of each species,
N – id the total number of individuals (number of individuals per hectare).

Pollen indication was performed according to *T. officinale* (L.) Weber ex F.H. Wigg because it is an unpretentious plant that grows in many habitats of the city. For the study, *T. officinale* pollen was taken at the stage of mass flowering. Considering that fertile and sterile cells of pollen differ in starch content, the quality of pollen was determined by the iodine method (Gram staining) (Pausheva 1980). All pollen grains without typical signs of morphological structure (i.e. everything except normally developed ones) were considered teratomorphic (Dzyuba 2006). Laboratory studies were carried out using a Nikon ECLIPSE E100 microscope and a Canon DS 126291 camera. Biometric sizing of *T. officinale* pollen grains was made in the AxioVision program at a magnification of 40× in micrometres.

Pollen sterility (S) was calculated using equation (3):

$$S = \frac{G}{N} \times 100\% \quad (3)$$

where:
G – the amount of sterile pollen (pieces),
N – the amount of pollen being examined (pieces).

The mean error was calculated as:

$$m = \pm\sqrt{\frac{S \times (100 - S)}{N}} \quad (4)$$

The sterility index (S, %) was translated into a single dimensionless system of conditional indicators of damage (CIDs) of biosystems according to Kudryavska and Dychko (2013).

$$\mathrm{CID} = \frac{|S_{\mathrm{real}} - S_{\mathrm{comf}}|}{|S_{\mathrm{crit}} - S_{\mathrm{comf}}|} \quad (5)$$

where:
CID – a conditional indicator of damage caused by adverse environmental conditions for each PE,
S_{comf}, S_{crit} – the experimentally established values of sterility (S, %) in comfortable and critical conditions for the organism, respectively,
S_{real} – the value in the studied PE.

This approach makes it possible to perform an integrated assessment of the environment and determine the levels of environmental hazards to humans and biota (Kudryavska, Dychko, 2013). If the sterility of *T. officinale* pollen is less than 30% (CID ≤ 0.30), the level of damage is characterised as below average and the category of territory on a toxic–mutagenic background is 'safe', with possible self-healing of biological systems after exposure to adverse factors. At CID = 0.31–0.69, the level of damage of the phytoindicator is above average and the category of ecological safety of the territory is 'Dangerous'; at CID ≥ 0.70, the state of damage of the bioindicator is defined as high and the category of ecological safety of the territory on a toxic–mutagenic background is 'Extremely dangerous' (Kudryavska, Dychko, 2013).

The indicator of teratomorphism ($T \pm m$, %) was used as an additional criterion for assessing the state of the atmosphere:

$$T = t/N \times 100\% \quad (6)$$

where t is the number of teratomorphic pollen grains (pieces).

The average values of the characteristic (M) and the coefficient of variation (V) were calculated. Variation of the trait was considered weak at $V < 11\%$, medium at $V = 11\%–25\%$ and strong at $V > 25\%$ (Zaitsev, 1990).

We proposed an integral indicator of the impact significance (W), which reflects the state of PE depending on the type of anthropogenic impact and trends in changes (eq. 7):

$$W = \frac{\left(\sum_{i=1}^{n} R_i S_i\right)\left(\sum_{j=1}^{m} R_i C_j\right)}{n \times m} \tag{7}$$

where:

R – the score of the state by a single dynamic indicator,

S – the score of trends in changes by a single indicator,

C_j – the score of other environmental indicators,

$n = 8$ – the number of estimated dynamic indicators,

$m = 2$ – the number of other indicators (Lavrov et al. 2021b).

The following environmental indicators (C_j) were assessed:

1) in the presence of visual signs of grass tier digression, to characterise the integrity of the ecosystem and tiers – projective grass cover (C_1): up to 30% of the test area – 1 point, 30–50% – 2 points, more than 50% – 3 points;
2) in the presence of seedlings of major and associated tree species, to assess the ability of the stand to natural regeneration (C_2): the number of reliable seedlings and undergrowth plants: up to 10,000 pieces per 1 ha – good (3 points), to 5000 pieces per 1 ha – satisfactory (2 points), up to 3000 pieces per 1 ha – weak (1 point), absent (0 points).

The index of structural diversity of PE (H_{str}) was calculated according to Lavrov et al. (2021b). To obtain a complete picture of the natural value of an individual PE, we aggregated these estimates of the PE state through the integral natural value index (Inv) (eq. 8):

$$\text{Inv} = W \times H_{str} \times 1/I_s, \tag{8}$$

where:

W – the integral indicator of the impact significance,

I_s – the index of the stand state,

H_{str} – the index of structural diversity in PE.

We calculated the size of the class interval for the indices by equation (9) (Zaitsev, 1990):

$$W = \frac{(X_{max} - X_{min}) \times \lg 2}{\lg N} \tag{9}$$

where:

X_{max} – the maximum value of the index,

X_{min} – the minimum value,

N – the sample size corresponding to the number of index values within the interval (min –max).

The level of air pollution of the metropolis from vehicles was determined on the basis of the calculation presented in Methods for determining vehicle emissions for summary calculations of urban air pollution (1999) using the service videoprobki.ua and own videos of traffic. The road load (number of cars per hour) and the average daily amount of emissions of harmful substances (NO_x, hydrocarbons [C_nH_m], soot (C_nH), SO_2, lead compounds and formaldehyde, mg/m^3) were calculated. On the territory of Kyiv, 14 monitoring points of the main highways near PEs were selected, taking into account the distance from the roadside to the beginning of the park, road width, number of lanes, car speed and prevailing wind directions (Weather archive). Also, two points were calculated for better coverage and modelling – 19k, 20k ($\sum n = 16$) (Fig. 1).

The hazard factors of air pollutants were determined by equation (10):

$$\text{HQ} = Ci/Si, \tag{10}$$

where:

HQ – the hazard quotient,

Ci – the average concentration of the i-th pollutant (mg/m^3),

Si – the MAC of the i-th pollutant in mg/m^3 (Environmental Protection 2005).

MACs of air pollutants were established by Ukrainian legislation as the reference value for the national criteria (Order of the Ukraine ministry 2020). Cumulative risk, that is, the probability of developing a harmful effect due to the simultaneous entry of chemicals with a similar mechanism of action into living organisms by all possible routes (Environmental Protection 2005), was determined using the HI; for conditions of simultaneous entry of several substances in the same way (e.g. from air pollution),

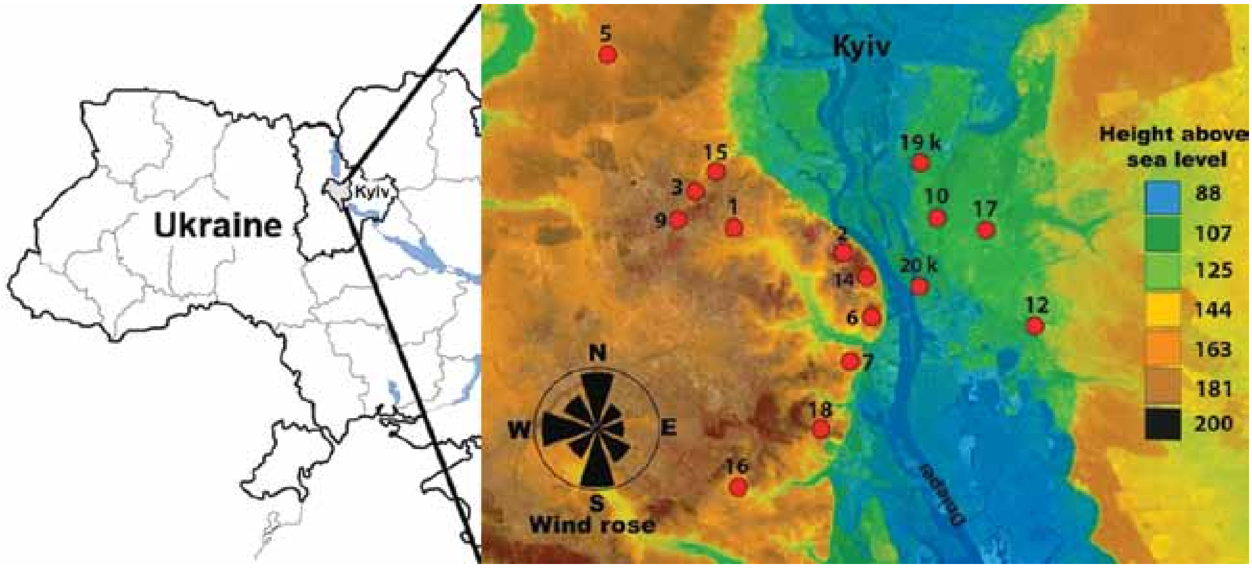

Figure 1. Location of observation and measurement points, relief and altitude, where: 1 – park named after Pushkin, 2 – Mariinsky park, 3 – Syretsky park, 5 – Pushcha-Vodytsya (park), 6 – NBG named after Hrishko, 7 – Lysa Mountain, 9 – Nyvky park, 10 – Peremoha park, 12 – park of Partisan Glory; 14 – Park of Eternal Glory, 15 – Babyn Yar, 16 – Feofania park, 17 – park DSHK, 18 – Holosiivskyi NNP, 19c – Camera 19, 20c – Camera 20. 4, 8, 11, 13, points did not have cameras; NNP – national nature park

$$\mathrm{HI} = \sum HQ_i, \qquad (11)$$

where HQ_i is the hazard quotient for individual pollutants.

The data were statistically evaluated following the method of Zaitsev (1990) and using Statistica 10, Microsoft Excel. To build a map of the city, we used a GIS package Golden Software Surfer 19.2.213 with the method of kriging and QGIS 3.16.3. The data were examined for normality using the Student's *t*-test (*P*-value 0.95).

Results

Kyiv is the largest city, capital, industrial, scientific and cultural centre of Ukraine, located in the centre of Eastern Europe, in the north of Ukraine and on the border of Polissya and forest-steppe zone on both sides of the Dnipro River. The area of the city is 836 km^2, including the green zone (460 km^2 or 55%), water areas (62 km^2, 7%), artificial urban ecosystems (314 km^2, 38%) and built-up lands of the city (364.0 km^2, 43.5%) (A regional report…, 2016). The territory of Kyiv is characterised by a complex relief, in the conditions of which air masses with a high concentration of pollutants are formed (Fig. 1). Most of the city lies on the high right bank of the Dnipro, and the Kyiv plateau is cut by a net of ravines (Babyn, Voznesensky, Protasov and others). Characteristic forms of the relief on the right bank are mountains-remnants. The smallest part is on the lower left bank of the Dnipro. The lower parts of Kyiv (left bank) correspond to the water level in the Dnipro and make up about 92 m of the altitude (Ecological passport, 2020). On the right bank of Kyiv, the height above the sea level is about 144–181 m and above (Fig. 1). The city has a powerful system of green infrastructure and objects of the natural reserve fund.

The system of ecological indicators of the PE state is built on the basis of indicators of the state of PE (I_s) and biodiversity characteristics ($H_{\mathrm{str}} + W$), which takes into account the presence and dynamics of natural regeneration of the main tier of the stand as an indicator of natural ecosystem stability. The structural biodiversity index (H_{str}) takes into account the presence of forest and protected species in PE, the presence of old trees, the density of undergrowth, understorey and so on. The following values of class intervals were obtained for the studied PEs (Tab. 1). The ranges of experimentally de-

Table 1. The value of integrated indices (environmental indicators) of the PE state

Index	H_{str}	W	Ic	Inv	Concentration NO_x, mg/m^3	HI
Very good	>2.47	9.26–12.00	1.00–1.50	>8.67	<0.020	<1.060
Good	2.21–2.46	6.51–9.25	1.51–2.50	5.79–8.67	0.021–0.040	1.061–2.121
Satisfactory	1.97–2.20	3.76–6.50	2.51–3.50	2.90–5.78	0.041–0.060	2.122–3.181
Bad	<1.96	1.0–3.75	3.51–4.50	<2.89	0.061–0.08	3.182–4.242
Very bad	–	–	4.51–6.00	–	>0.081	>4.242

termined concentrations of air pollutants NO_x in the air of Kyiv coincide with those for the urban ecosystem of Moscow (Bednova et al. 2015) (Tab. 1).

The studied PEs and suburban forests of Kyiv are formed mainly by deciduous species, less often by *Pinus sylvestris* L. In all studied parks with 100% in the main tent, there are the following species: *Fraxinus excelsior* L., *Tilia cordata* Mill., *Quercus robur* L., *Quercus rubra* L., *Aesculus hippocastanum* L., *Carpinus betulus* L., *Ulmus laevis* Pall., *Acer platanoides* L., *Acer pseudoplatanus* L., *Acer negundo* L., *Acer campestre* L., *Acer tataricum* L., *Populus tremula* L., *Robinia pseudoacacia* L., *Juglans regia* L. and *Juglans cinerea* L. The frequency of occurrence of the species *Tilia platyphyllos* Scop., *Pyrus communis* L., *Malus sylvestris* Mill. and *Prunus cerasus* L was 60%–80%. The frequency of occurrence 31%–59% was *Populus nigra* L., *Morus* L., *Betula pendula* Roth., *Salix alba* L., *Salix caprea* L., *Acer saccharum* Marshall, *Gleditsia triacanthos* L., *Ulmus laevis* Pall., *Ulmus glabra* Huds., *Populus alba* L., *Platanus* × *acerifolia* (Aiton) Willd., *Fagus* L., *Picea* L. The frequency of occurrence 10–20% was *Thuja* L., *Juniperus* L. in the studied PEs.

The *undergrowth* is most often formed by *C. betulus* L., *R. pseudoacacia* L., *Juglans L.*, *T. cordata* Mill., *Acer* L., *P. cerasus* L., *Cerasus avium* Moench, *Padus avium* Mill., *Q. rubra* L. and less often by *P. sylvestris* L., *Q. robur* L., *A. hippocastanum* L. The understorey most often consists of *Rosa canina* L., *Sambucus nigra* L., *Sambucus racemosa* L., *Frangula alnus* Mill., *Corylus avellana* L., *Sorbus* L., *Rubus idaeus* L., *Rubus caesius* L., *Rhamnus cathartica* L. *Euonymus europaeus* L., *Forsythia* Vahl, *Crataegus monogyna* Jacq., *Viburnum opulus* L., *Prunus divaricata* Ledeb., *Prunus spinos*a L. and *Swida sanguinea* (L.) Opiz. Less common in the understorey were the following: *Eriphia verrucosa* Scop., *Berberis vulgaris* L., *Syringa vulgaris* L. and *Lonicera xylosteum* L.; rare species were *Spiraea japonica* L. f., *Ptelea trifoliata* L., *Philadelphus coronarius* L., *Crataegus pentagyna* Waldst. & Kit. ex Willd. and *Symphoricarpos* Blake. Trees affected by mistletoe (*Viscum album* L.) were found in 66.3% of the studied PEs.

Species saturation of the grass tier was 3.0–202.3 pieces/ha (most common were *Chelidonium majus* L., *Urtica dioica* L., *Urtica urens* L., *Erodium cicutarium* (L.) L'Her., *T. officinale* (L.*)*, *Erigeron annuus* (L.) Pers., *Chenopodium album* L., *Impatiens parviflora* DC., *Galium aparine* L., *Stellaria media* (L.) Vill., *Poa* L.; *Trifolium* L., *Polygonum aviculare* L., *Lamium* L., *Xanthium strumarium* L., *Plantago* L., *Capsella bursa-pastoris* (L.) Medikus, *Senecio* L., *Ambrosia artemisiifolia* L. and *Calamagrostis epigeios* (L.) Roth. (Table 3). The share of nitrophils in the grass tier was 42%–64%. Less than 50% of nitrophils were in PE 5, 9, 10 and 12 (Pushcha-Vodytsya, Nyvky, Peremoha, Partisan Glory parks); in all other parks, more than 50% of species consisted of nitrophilous stenobionts (most common were *Melandrium album* (Mill.), *Garcke, S. media* (L.) Vill., *T. officinale* Wigg*., Asarum europaeum* L., *Torilis japonica (*Houtt.) DC., *Lamium album* L., *Geum urbanum* L., *Chelidonium majus* L., *Poa annua* L., *I. parviflora* DC*., U. urens* L., *U. dioica* L., *Bidens tripartita* L. and *C. epigeios* (L.) Roth). The non-native plant index (I_{nn}) was 9%–40%, and it does not depend on aerotechnogenic pollution. The most common alien plants were *L. album* L., *A. artemisiifolia* L., *E. annuus* (L.) Pers., *I. parviflora* DC. and *S. media* (L.) Vill. Trees' mortality rate was 9.5%–40% of the PE plantations. The largest share of dead trees (30%–40%) was in PE 5, 6, 10 and 16 (Tab. 2). The maximum value of the Shannon index (*H'*), more than 3.0, as a generalised measure of phytodiversity was in PE Pushcha-Vodytsya park, Victory, Partisan Glory, Feofania park and DSHK

Table 2. Integral assessment of the studied park ecosystems state in Kyiv

Assessment indicators/No. PE	1	2	3	5	6	7	9	10	12	14	15	16	17	18	19c	20c
Park area [ha]	19.5	8.9	6.5	11.7	130.0	137.0	120.0	66.1	112.0	18.4	11.7	150.0	13.9	4525.5	–	–
Canopy density (*P*)	0.70	0.50	0.82	0.53	0.90	0.70	0.64	0.52	0.50	0.81	0.80	0.77	0.41	0.95	–	–
Index of stand state (I_s)	2.2	2.03	1.9	2.5	1.96	2.4	1.95	2.4	2.3	1.7	2.37	2.25	2.19	1.99	–	–
Sanitary condition of plantations	weakened	weakened	weakened	severely weakened	weakened	weakened	weakened	weakened	weakened	weakened	weakened	weakened	weakened	weakened	–	–
Mortality of trees (*Mt*) [%]	19.84	20.83	10.81	35.80	40.20	18.59	11.90	30.70	10.53	25.00	9.77	35.71	9.46	10.7	–	–
Species saturation of grass tier, pieces/ha (*L*)	92.86	42.50	67.57	202.27	55.88	34.62	117.86	171.05	126.32	42.31	39.66	80.43	3.24	30.3	–	–
Nitrophils in grass tier (*Nt*) [%]	51.43	56.25	65.22	41.46	64.71	50.00	42.86	43.28	46.81	52.38	63.64	58.97	53.49	50.00	–	–
H′	2.86	1.97	2.51	3.60	2.01	2.23	2.15	3.30	3.11	2.37	2.46	3.07	3.65	2.22	–	–
W	2.6	2.3	3.1	4.25	6.5	4.8	4.8	3.5	3.8	1.5	7.19	5.63	1.25	5.50	–	–
State of ecosystems by *W*	CD	CD	CD	TC	vulnerable	TC	TC	CD	CD	CD	vulnerable	TC	CD	TC	–	–
H_{str}	1.94	1.75	1.93	1.93	2.07	1.94	1.72	1.93	2.06	1.98	2.02	1.96	1.46	1.81	–	–
Characteristic by H_{str}	bad	STF	bad	bad	STF	bad	STF	bad	STF	STF	STF	bad	bad	bad	–	–
Inv	2.29	1.98	3.15	3.28	6.86	3.88	4.23	2.81	3.40	1.75	6.13	4.90	5.00	5.00	–	–
Characteristic by Inv	bad	bad	STF	STF	good	STF	STF	good	STF	bad	good	STF	STF	STF		
Distance to the road, m	10.0	0.5	393.0	1.0	50.0	0.2	0.2	0.2	330.0	0.2	0.2	540.0	150.0	238.0	0.2	0.2
Number of lanes in one direction (*D*)	4	2	4	1	3	3	4	3	3	2	3	3	3	3	3	3.5
Number of cars per hour	7161.0	2010.0	4605.0	859.5	6058.5	6058.5	7122.0	2356.5	1956.0	2314.5	4989.0	5085.0	3243.0	6058.5	3312.0	4315.0
Transport speed, km/h (Q_{av})	51.43	39.89	63.01	34.62	72.40	73.50	61.71	42.92	37.89	39.89	49.50	62.61	36.00	73.50	36.29	54.88
C [mg/m^3]	0.2155	0.0861	0.0966	0.0513	0.2109	0.2109	0.1343	0.1161	0.1042	0.0970	0.1763	0.1137	0.2074	0.2109	0.1130	0.1330

Notes: PE numbers as in Fig. 1. Characteristics for H_{str}, *W*, Inv are according to Table 1. *C* – the total number of pollutants MACa.d. concentrations, mg/m^3; CD – ecosystem in critical danger; TC – ecosystem in a threatening condition; STF – ecosystem in a satisfactory condition.

park. All other values of *H'* were less than 3.0 (64.3% of the studied PE) and showed a small degree of phytodiversity of the grass tier. The sanitary condition of the main tent trees was weakened and severely weakened (Tab. 2). According to the integral indicator of the impact significance (W*)*, 50.0% of PEs were in critical danger and 35.7% were in a threatening condition. Only two PEs (14.3%) were in the group of 'vulnerable' (NBG named after Grishko, Babyn Yar), which, due to the large area and sufficient closure of the plantation tent, had more than three tiers and a high biodiversity. The structural diversity index (H_{str}) was the largest, that is, the best condition, in the NBG named after Grishko, park of Partisan Glory and Babyn Yar. According to H_{str}, satisfactory conditions were found in 42.9% (six parks) and bad conditions in 57.1% (eight parks) of the parks. The category 'very good' was absent among the studied PEs. The state of the stand (I_s) was the largest, that is, the worst condition of plantations, in PEs Pushcha-Vodytsya park, park named after Pushkin, Lysa Hora tract, Victory park, Partisan Glory park and Babyn Yar. Inv, *W* and tent closure had the same dynamics in the studied PEs. According to Inv, it was 'bad' in four PEs (28.6%), 'satisfactory' in 57.1% of the studied parks (eight parks) and 'good' in 14.3% of the parks (two parks; NBG named after Grishko and Babyn Yar). By the gradient of Inv, growth and increase in the natural values of parks were PE 14, 2, 1, 10, 3, 5, 12, 7, 9, 16, 17, 18, 15 and 6 (Tab. 2). The last three PEs were large forests with partial recreational human impact and a large buffer capacity of ecosystems, which explains their high coefficient of natural value. The load of highways was significant (maximum 7161.0 cars per hour in the city centre near the park named after Pushkin and Nyvky park). Sums of average daily concentrations of aerial emissions from cars were in the range 0.053–0.216 mg/m^3 (Tab. 2). The difference in concentrations between the most and the least polluted areas of the city reached four times by the amount of air pollutants from vehicles, mg/m^3 – 0.051 (Pushcha-Vodytsya park)/0.216 (park named after Pushkin) – and 8.3 times by the number of cars – 859.5 (Pushcha-Vodytsya park)/7161.0 cars per hour (park named after Pushkin).

According to Rybakova and Glazunov (2020), on one of the largest highways in the European part of Russia, the load is about 9000 cars per hour (Moscow Ring Road, Moscow). In the centre of Kyiv, the load

Table 3. Average daily content of air pollutants in the Kyiv park ecosystems

Contents [mg/m^3/No. PE]	5	10	2	3	12	14	16	19c	9	20c	15	1	6	7	17	18	Average	HQ_i aver.	Share from MACa.d.
NO_x	0.0210	0.0475	0.0367	0.0378	0.0413	0.0420	0.0466	0.0468	0.0588	0.0550	0.0687	0.0901	0.08657	0.0866	0.0900	0.0866	0.0589	**1.47**	**1.47**
Load characteristics by N_Ox	good	STF	good	good	STF	STF	STF	STF	STF	STF	bad	very bad	very bad	very bad	very bad	very bad	–	–	–
C_nH_m	0.0283	0.0644	0.0469	0.0555	0.0591	0.0523	0.0621	0.0617	0.0699	0.0739	0.1017	0.1189	0.11454	0.1145	0.1066	0.1145	0.0778	0.08	**1.560**
Soot (C_nH)	0.0002	0.0003	0.0001	0.0002	0.0003	0.0001	0.0005	0.0004	0.0005	0.0002	0.0004	0.0003	0.00110	0.0011	0.0012	0.0011	0.0005	0.01	0.010
SO_2	0.0014	0.0030	0.0018	0.0024	0.0028	0.0020	0.0036	0.0032	0.0040	0.0030	0.0043	0.0047	0.00705	0.0071	0.0077	0.0071	0.0041	0.08	0.081
Formaldehyde	0.0002	0.0004	0.0002	0.0003	0.0004	0.0002	0.0005	0.0005	0.0006	0.0004	0.0006	0.0006	0.00103	0.0010	0.0013	0.0010	0.0006	0.20	0.192
Lead compounds	0.0002	0.0004	0.0004	0.0003	0.0003	0.0004	0.0003	0.0004	0.0005	0.0005	0.0006	0.0008	0.00060	0.0006	0.0006	0.0006	0.0005	**1.58**	**1.560**
Sum	0.0513	0.1161	0.0861	0.0966	0.1042	0.0970	0.1137	0.1130	0.1343	0.1330	0.1763	0.2155	0.21090	0.2109	0.2074	0.2109	0.1423	–	–
HI	1.243	2.838	2.261	2.247	2.422	2.591	2.620	2.732	3.446	3.347	4.072	5.490	4.787	4.787	5.010	4.787	–	–	–
Characteristic by HI	good	STF	STF	STF	STF	STF	STF	STF	bad	bad	bad	very bad	very bad	very bad	very bad	very bad	–	–	–

Notes: denotement as in Fig. 1. PEs are arranged in order of increasing HI. STF denotes satisfactory condition; characteristics of air load (NOx, HI) are according to Table 1. Exceeding MACa.d. for humans and high load characteristics by NOx was in bold.

was 21.1% less than on the Moscow Ring Road. Number of lanes in one direction was one to four. The average speed of cars was 51.9 km/h and the speed range was 34.6–73.5 km/h. Frequent traffic jams in the city centre (Mariinsky, named after Pushkin parks), near the Holosiivskyi NNP, the NBG named after Grishko and Lysa Hora cause a decrease in the average speed of traffic, especially at traffic lights, which increases the number of emissions. For example, near heavily loaded highways, the numbers of points 2, 19c, the average traffic speed was 36.3–39.9 km/h.

HI of vehicle emissions was good only in Pusha-Vodytsya park, satisfactory in seven observation points (43.8% of all points), bad in three points (18.8%) and very bad in five points – range of value of HI 4.787–5.490 (31.3% of PEs; these are named after Pushkin, DSHK park, NBG named after Grishko, Lysa Hora tract and Holosiivskyi NNP), which corresponds to the total concentration of air pollutants of 0.207–0.216 mg/m^3. Exceedance of MAC concentrations of NOx, C_nH_m and lead compounds for humans was determined (Tab 3). HQ_i aver. was more than 1.0 in the city for aerial emissions of NOx and lead compounds. NOx load characteristic was very bad and bad (six PEs, i.e. 37.5% of all Pes). These are parks 1, 6, 7, 15, 17 and 18.

The phytotoxicant NOx had the largest share of vehicle emissions, which was 1.5 MACa.d. near PEs 1, 6, 7, 17 and 18. Since MACa.d. is two times lower for green plantations, the concentration of this pollutant in the air is 2.9 MACa.d. for plants (Tab. 4). Such concentrations of air pollutants pose a direct threat to green infrastructure. The highest concentrations of hydrocarbons (C_nH_m) nears PE 1, 6, 17 and 18 were 1.56 MACa.d. for humans and 0.56 MACa.d. for plants. The highest concentrations were near the following observation points: for soot (C_nH) – at points 9, 15, 16, 19c; for SO_2 – points 6, 7, 17 and 18; for formaldehyde –at points 1, 15, 16 and 19c; and for lead compounds – near points 1, 6, 7, 15, 17 and 18. The lowest amount of NOx emissions was near PEs 2, 3, 5, 12, 14, 16 and 19c, although at some of these points, this concentration still exceeded the MACa.d. for humans and plants. The lowest amount of emissions of lead compounds was near the points 5, 12 and 16 – 0.0002–0.0003 mg/m^3, which is equal to the MACa.d. for humans. Presence of constant concentrations of air pollutants at the level of MACa.d. is also harmful. MACa.d. for plants differs according to different authors: for vegetation of parks (Polyakova, Gutnikov, 2000): NO_x – 0.03 mg/m^3, SO_2 – 0.04 mg/m^3 (Tab. 4).

According to our data, exceeding the MAC a.d. for humans and plants for formaldehyde, hydrocarbons, NO_x has been obtained. Average annual concentrations of NO_x (3.5 MACa.d.), SO_2 (1.5 MACa.d.) and formaldehyde (1.9 MACa.d.) exceeded the MACa.d. for humans and plants (Tab. 4).

With HQ ≤ 1, there is no risk of adverse effects on human health. With an increase in HQ > 1, the probability of adverse effects increases in proportion to the increase in HQ (Environmental Protection, 2005). Since air pollution standards are lower for plants (Tab. 4), they can be applied to PEs. HQ for NO_x and lead compounds significantly exceeded 1 and posed a threat to human health and the condition of green infrastructure. Values of phytotoxicant concentrations by HQ were in the following range: HQ (NO_x) – 0.526–2.251, HQ (C_nH_m) – 0.028–0.119 (outskirts of Pushcha-Vodytsya/park named after Push-

Table 4. Assessment of air quality in Kyiv

Air pollutants	Actual average annual concentrations for 2019[1] [mg/m^3]	The average daily concentration, our calculations [mg/m^3]	MACa.d. [mg/m^3] for humans[2]	MACa.d.[3] for plants
NO_x converted to NO_2	0.14400	0.0570	0.0400	0.020
SO_2	0.07500	0.0039	0.0500	0.015
Formaldehyde	0.00560	0.0006	0.0030	0.003
Saturated hydrocarbons (C_nH_m)	–	0.0754	0.0500	0.140
Soot (C_nH)	0.03500	0.0005	0.0500	0.050
Inorganic lead compounds	0.00003	0.0005	0.0003	–

Notes: [1] Ecological passport (2020), [2] Order of the Ukraine ministry (2020), [3] according to Furdychko et al. (2008).

kin, city centre), HQ (C_nH) – 0.003–0.007, HQ (SO_2) – 0.029–0.094, HQ (formaldehyde) – 0.075–0.201 and HQ (lead compounds) – 0.582–2.818. It was found that in comparison with the control in PE 5, Pushcha-Vodytsya (park) PE state (W), Shannon biodiversity index, part of dead trees in the plantations, Hstr, species saturation of the grass tier decrease; and the number of nitrophils in the grass tier was increase. Thus, with increasing air pollution level, the state of plantations and PEs deteriorates. An increase in the number of nitrophils occurs in the grass tier as a result of significant pollution by NO_x emissions (Fig. 2). With the liquefaction of the main tent, the condition of the plantations deteriorates ($r = -0.46$); with the deterioration of the plantations' condition, species saturation of the grass tier increases ($r = 0.46$). With an increase in the main canopy density and a decrease in the number of species of grass tier, the proportion of nitrophils increases ($r = 0.52$ and $r = -0.62$, respectively). W and H_{str} have a strong relationship with canopy density ($r = 0.54$ and $r = 0.46$, respectively). H_{str} and *Inv* have a strong relationship with *W* ($r = 0.48$ and $r = 0.75$, respectively). There is no reliable correlation with the distance to the highways.

Correlations between air pollution and the state of PE are presented in Table 5.

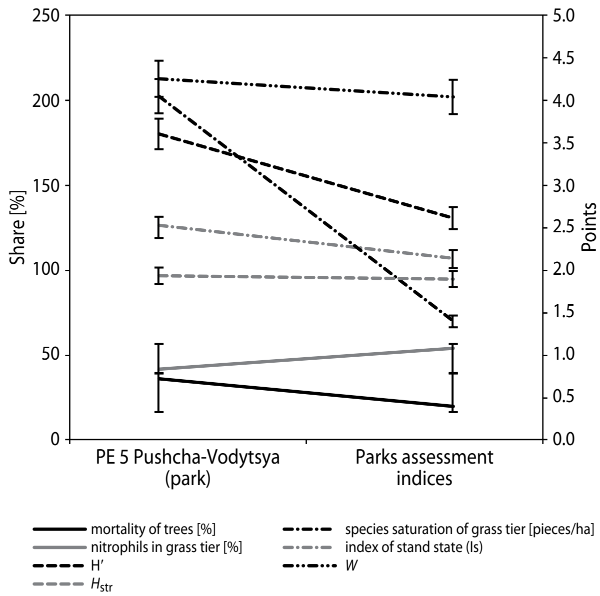

Figure 2. Assessment of the PE state compared to control (PE 5 – Pushcha-Vodytsya park)

As the number of cars increases, *W* ($r = 0.45$) and *Inv* ($r = 0.44$) increase. With increasing concentration of air pollutants and the number of lanes, species saturation of the grass tier decreases ($r = -0.58$) and Inv increases ($r = 0.54$). With increasing HI and the num-

Table 5. Correlation of the investigated PE parameters

	P	I_s	*Mt*	*L*	*Nt*	*W*	H_{str}	*Inv*	*D*	Number of cars per hour	*C* [mg/m³]	HI
P	1											
I_s	−0.46	1										
Mt	0.09	0.13	1									
L	−0.37	0.46	0.41	1								
Nt	0.52	−0.33	−0.01	−0.62	1							
W	0.54	0.27	0.18	0.05	0.25	1						
H_{str}	0.46	0.13	0.40	0.31	0.21	0.48	1					
Inv	0.38	0.12	0.03	−0.30	0.42	0.75	0.03	1				
D	0.26	−0.21	−0.46	−0.21	0.24	0.12	−0.06	0.20	1			
Number of cars per hour	0.59	−0.21	−0.19	−0.36	0.27	0.45	0.02	0.44	0.75	1		
C [mg/m³]	0.34	0.00	−0.24	−0.58	0.23	0.26	−0.16	0.54	0.49	0.72	1	
HI	0.29	−0.04	−0.26	−0.57	0.19	0.16	–0.21	0.45	0.51	0.72	0.99	1

Note: medium and strong correlations are highlighted.

ber of cars, species saturation of the grass tier decreases ($r = -0.57$).

HI was carried out based on the determination of the number of vehicles, the amount of emissions of air pollutants, the intraterritorial zoning of the urban ecosystem, (Fig. 3–5). Zones were selected as in Table 1.

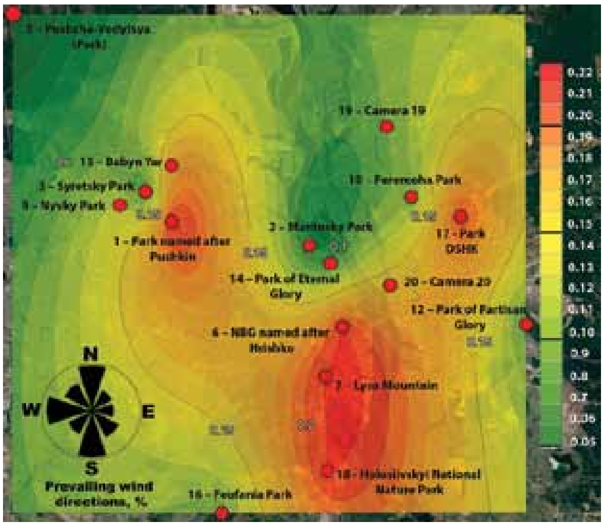

Figure 3. Amount of air pollutants' emissions (mg/m^3) from vehicles and distribution by prevailing wind directions,%

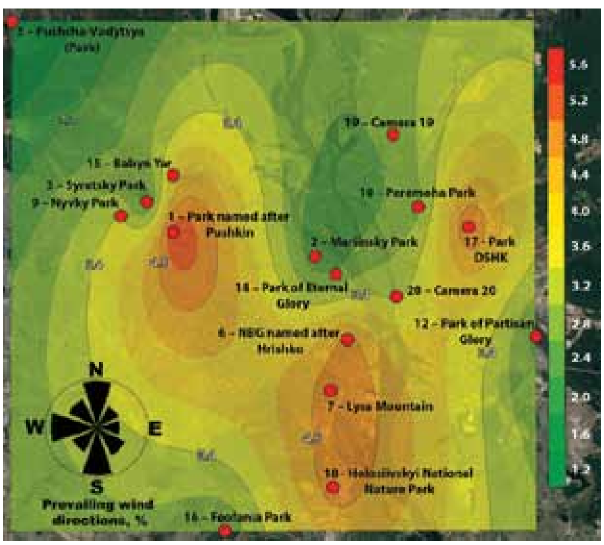

Figure 4. HI of air pollutants from vehicles (HI – hazard index)

Zones by the concentrations sum of aerial emissions and HI (Fig. 3, 4) are concentric and coincide – the largest air pollution was at the points of NBG named after Grishko, Lysa Hora, Holosiivskyi NNP; and in the city centre Pushkin, Nyvky parks. The least air pollution from cars was near Pushcha-Vodytsya (PE 5, although the condition of plantations here is greatly weakened and the mortality of trees is significant [35%]) because here, most of the plantations consisted of *P. sylvestris* L., which is less resistant to phytotoxicants. Also, the lowest level of air pollution was near Mariinsky, Syretsky, Eternal Glory Park and Feofania park. The scattering of air pollutants coincides with the directions of the prevailing winds in north and south directions. In east, there is more scattering of air impurities, although the prevailing winds blow in the opposite direction, due to rising terrain – airborne impurities spread into the Dnipro River valley by lowering the terrain (Fig. 3, 4).

Mapping GIS by the number of cars per hour is slightly different from mapping the concentrations of air pollutants. The worst areas were near the parks Nyvky, Syretsky, Mariinsky, named after Pushkin, NBG named after Grishko, Holosiivskyi NNP and Lysa Hora (Fig. 5). This can be explained by the peculiarity of the roads' locations, their smaller width and capacity, the features of the old city centre, more congestion and reduced speed of cars in traffic jams, when the engine is idling, where the number of cars is less. The concentration of air pollutants depends on shares of prevailing wind directions West, South, too.

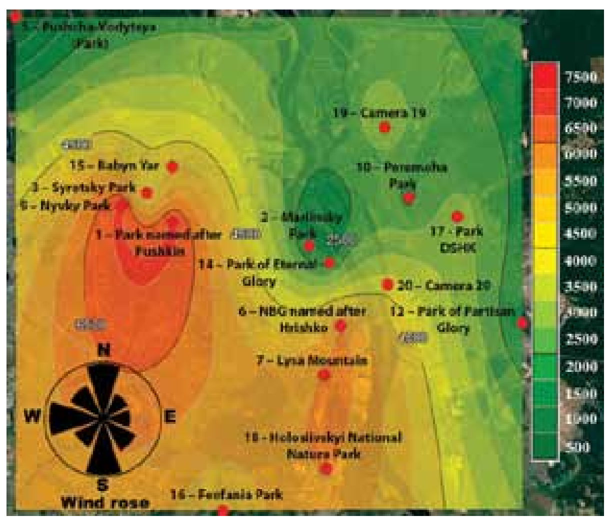

Figure 5. Number of cars per hour

Verification of the division of the HQ and HI indices obtained for PE into groups depending on the level

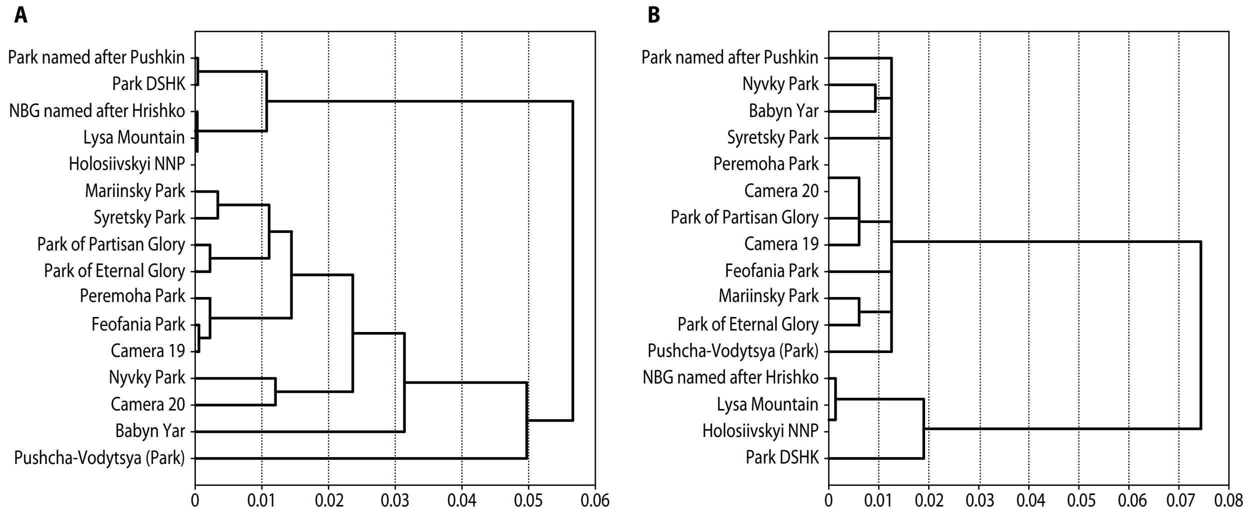

Figure 6. Clustering of PE in Kyiv by concentrations of air pollutants. A – NO_x concentration in the air, mg/m^3; B – concentration of SO_2 in the air, mg/m^3

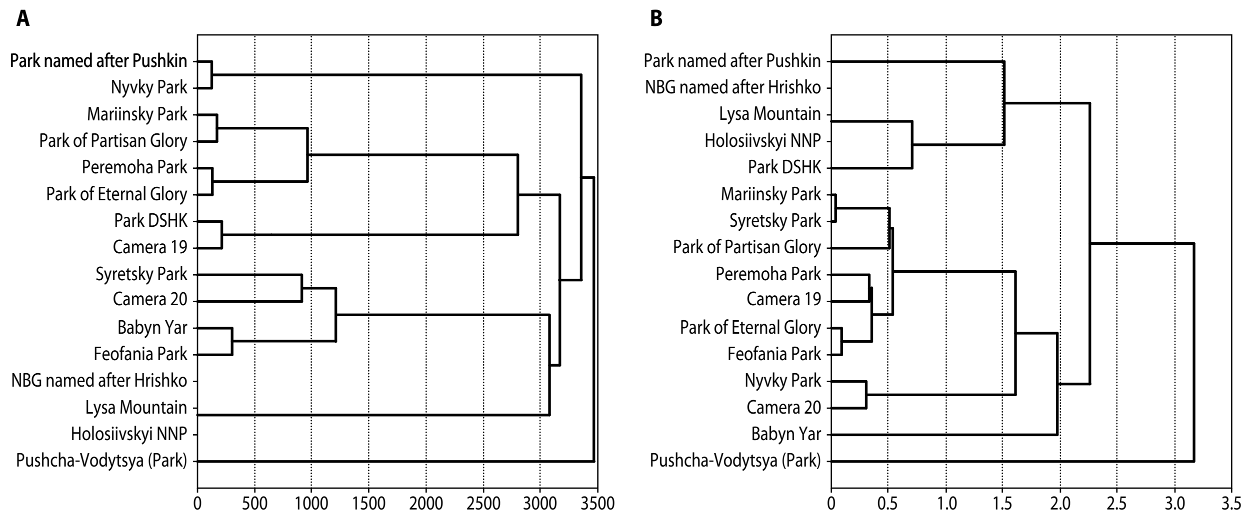

Figure 7. Clustering of PEs according to the parameters of air pollutants: A – cars per hour and B – HI (PE – park ecosystem, HI – hazard index)

of air pollution was performed by cluster analysis using Euclidean distance, and Ward's method was used to combine the clusters (Fig. 6).

It was found that based on the NO_x concentration, the measurement points of PEs can be divided into two groups – the largest pollution was found in the PEs NBG named after Grishko, Lysa Hora tract, Holosiivskyi NNP and DSHK park (Fig. 6A). According to the SO_2 concentration, the measurement points are divided into two groups – the largest air pollution was near four PEs (NBG named after Grishko, Lysa Hora, Holosiivskyi NNP and DSHK park; Fig. 6B). The maximum values of HI are found near five PEs – park named after Pushkin, NBG named after Grishko, Lysa Hora tract, Holosiivskyi NNP and DSHK park (Fig. 7).

The largest number of cars was found in the city centre near the Park of Eternal Glory, NBG named after Grishko, Lysa Hora and Holosiivskyi NNP. On the left bank, air pollution was less and the highest concentration of pollutants was near the DSHK park. The inten-

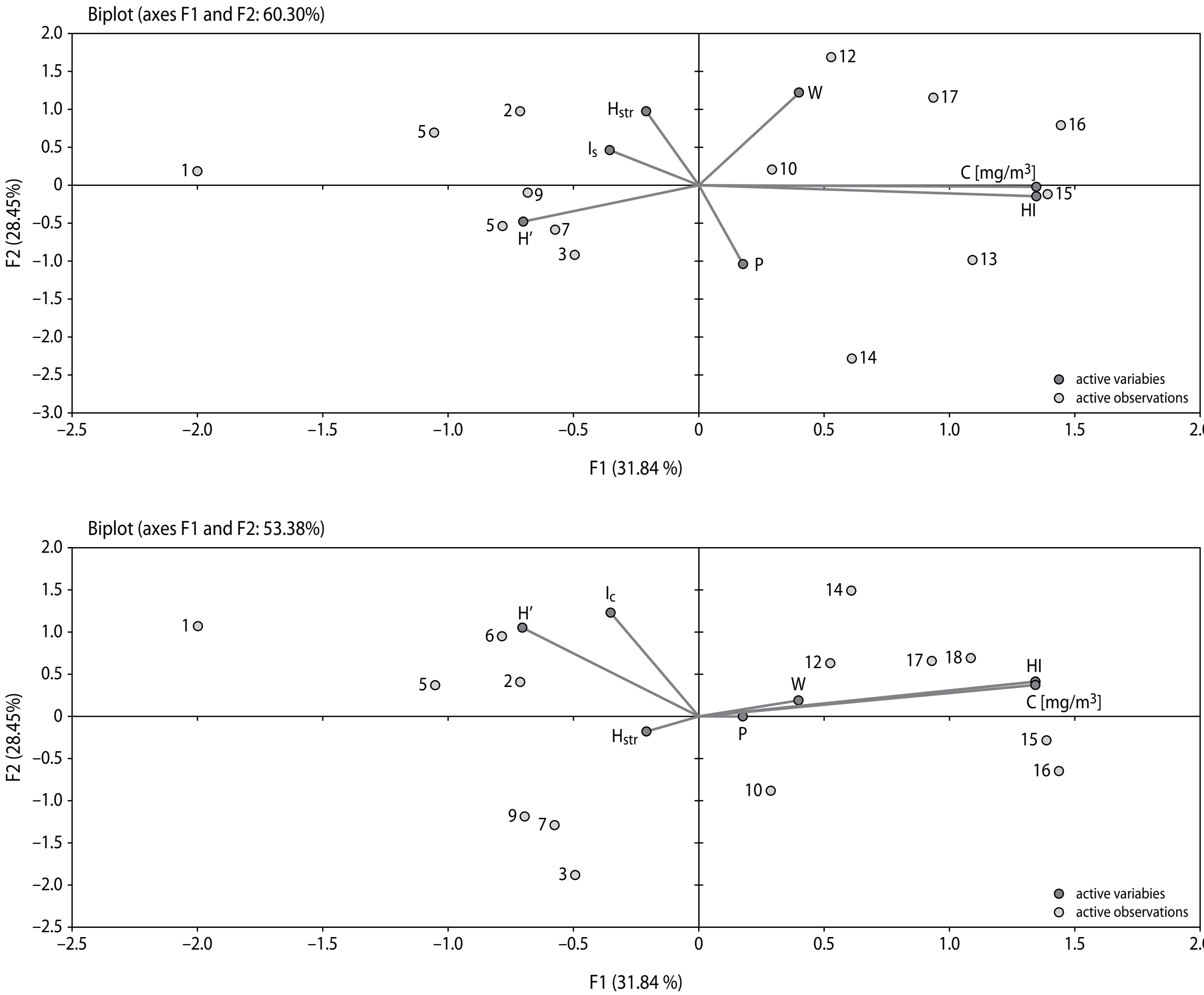

Figure 8. PCA using integrated indices for the PE state(PCA – principal component analysis, PE – park ecosystem)

Table 6. Sterility of *Taraxacum officinale* pollen in the conditions causing pollution in metropolis

No PE	Distance to the road [m]	Number of cars per hour	Pollen grains (pieces) $M \pm m$	V [%]	Number of sterile pollen (pieces) $M \pm m$	V [%]	Share of a sterile pollen (S) [%]	CID
5	238	860.0	1785 ± 8.86	34	236 ± 2.74	21	13.00	0.21
2	226	2010.0	1715 ± 9.26	33	342 ± 2.57	20	19.92	0.58
10	80	2357.0	1589 ± 6.68	28	344 ± 2.71	19	22.00	0.73
15	5	4989.0	1396 ± 11.26	44	361 ± 3.21	25	25.86	0.91
16	1000	5085.0	2035 ± 7.75	34	235 ± 4.53	27	11.55	0.17
7	143	6059.0	1506 ± 9.77	43	361 ± 3.27	24	23.97	0.86

Notes: CID – conditional indicator of damage, PE – park ecosystem, V – coefficient of variation, M – average values of the sign, m is the mean error. Mean values differ significantly in the Student's t-test ($P < 0.05$).

sity of traffic here was 3.2 thousand cars per hour; there were frequent traffic jams (the average speed of traffic was 36 km/h) (Fig. 7).

HI of vehicle emissions and the concentration of air pollutants (component F1) generated 32% of the variability of PE state integrated indices. Also, 28% of the variability of signs was formed by the F2 component (H_{str}, *P, W*). Component F3 (I_s, *H'*) generated 21.5% of the variability of integral indicators (Fig. 8).

We studied the impact of vehicle emissions on the generative sphere of plants – the proportion of sterile and teratomorphic pollen grains of *T. officinale* (Tab. 6).

In addition to the typical pollen grains of *T. officinale* (symmetrical, round shape), teratomorphic pollen with anomalies such as dwarfism (dwarf pollen; pollen grains with a diameter of less than 18 µm), gigantism (diameter of the pollen exceeds 48 µm) and shell deformation (crumpled or torn) were found (Fig. 9).

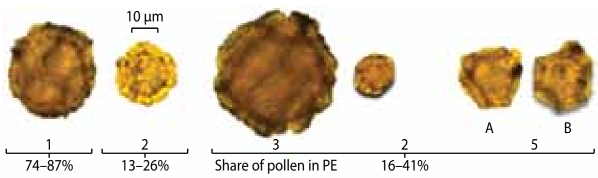

Figure 9. Pollen of *Taraxacum officinale* in the conditions of Kyiv: 1 – fertile pollen grain (38.2 µm); 2 – sterile pollen grain (24.8 µm); 3 – pollen gigantism (51.1 µm); 4 – pollen dwarfism (17.8 µm); 5 – anomalies of the shell (A – torn, B – crumpled)

It was found that the lowest level of *T. officinale* pollen sterility (11.5%) was recorded in PE 16 Feofania park and the amount of pollutants here was 0.1137 mg/m^3, but the distance to the road with active traffic was the largest of all studied PEs (about 1000 m); also, PE was separated from the forest by a fence (Fig. 9). Therefore, the best conditions for plant growth are found here. In this point, there was a high percentage (88.5%) of normally developed pollen (sterility *S* 11.5%), the share of teratomorphosis was the lowest – 16.5%, and the rate of CID was 0.17, that is, the level of the bioindicator damage is characterised as below average. Approximate values of pollen variability (sterility – 13.0%, teratomorphism – 19.7%) were recorded in PE 5 – Pushcha-Vodytsya (Tab. 6). Near this PE, there was the lowest transport load (859 cars per hour) and the lowest sum of pollutant concentrations in the air (0.0513 mg/m^3); CID bioindicator was equal to 0.21 (below average). Near PE 5 and 16, the lowest HIs for humans and plants were 2.62 and 1.24, respectively (Fig. 10). The territory of the Pushcha-Vodytsya and Feofania parks, according to the fuel indication, belongs to the category of ecological safety – 'safe' urban ecosystem. The level of the bioindicator damage in PE 2 (Mariinsky park) was average and the CID indicator was 0.58 – 'moderately safe' category by the toxic–mutagenic background. Indicators of variability of *T. officinale* pollen were found to be average here (sterile pollen – 19.9%, teratomorphic pollen – 30.8%) (Fig. 10).

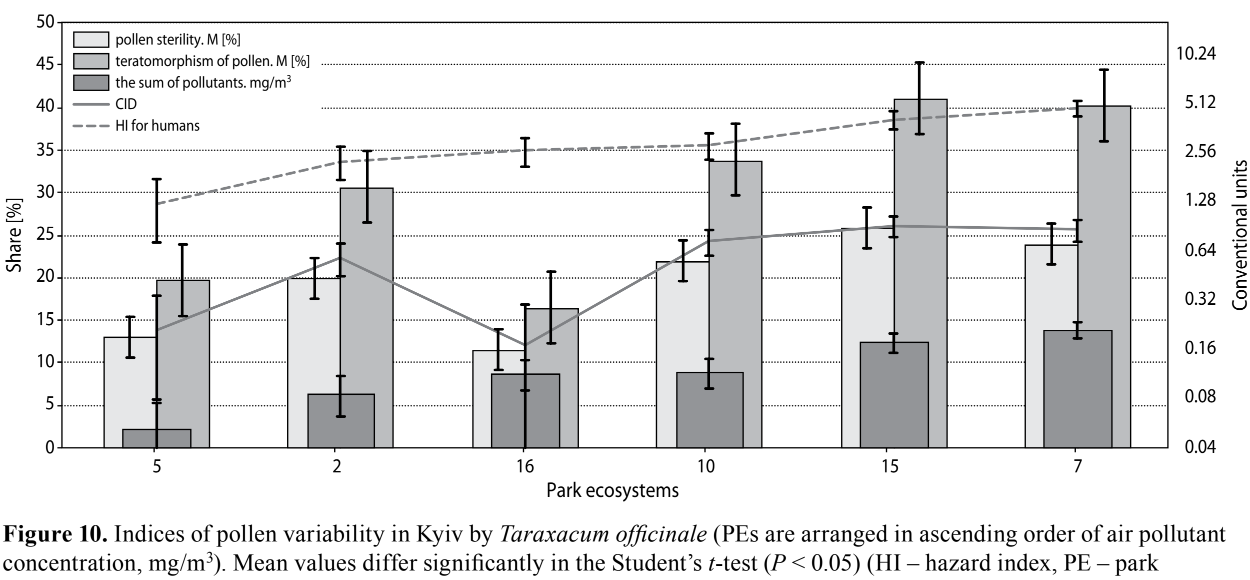

Figure 10. Indices of pollen variability in Kyiv by *Taraxacum officinale* (PEs are arranged in ascending order of air pollutant concentration, mg/m^3). Mean values differ significantly in the Student's *t*-test ($P < 0.05$) (HI – hazard index, PE – park ecosystem)

Table 7. Correlation of air pollution and pollen indication

	Distance to the road [m]	Number of cars per hour	*V* by amount of *S* [%]	*S* [%]	*T* [%]	CID	Inv	*C* [mg/m³]	HI
Distance to the road [m]	1.00								
Number of cars per hour	0.21	1.00							
V by amount of *S* [%]	0.57	0.80	1.00						
S [%]	−0.78	0.36	−0.14	1.00					
T [%]	−0.78	0.40	−0.11	0.99	1.00				
CID	−0.75	0.41	−0.11	1.00	1.00	1.00			
Inv	0.17	0.68	0.84	0.15	0.16	0.16	1.00		
C [mg/m³]	−0.25	0.89	0.48	0.72	0.76	0.76	0.53	1.00	
HI	−0.29	0.86	0.44	0.76	0.80	0.80	0.49	1.00	1.00

Note. A strong correlation is highlighted. CID – conditional indicator of damage, HI – hazard index.

With increasing concentration of air pollutants, the number of teratomorphic pollen grains increases. As in PE 2, sampling was performed at a distance of about 226 m from the roads, so the HI index was 2.26 (satisfactory).

In PE 7, 10 and 15, there was a significant excess of the studied indicators, which shows an additional negative impact of aerotechnogenic factors. PE 7 (Lysa Hora) and PE 15 (Babyn Yar) showed 'extremely dangerous' characteristics of the urban environment, which is confirmed by the highest amount of sterile pollen *T. officinale* (23.97% and 25.86%, respectively). The share of teratomorphic grains was 40.24% and 41.40% (highest), respectively (Table 6, Fig. 10). Here, the CID of pollen was 0.86 and 0.91, respectively. Such critical indices of the phytoindicator directly depend on the amount of pollutants released from transport (for 0.211 and 0.176 mg/m^3, the value of HI was very bad and bad, respectively) and high activity of motor traffic (4989 and 6058 cars per hour, respectively) (Tab. 7).

With increasing distance to roads and the number of cars, the coefficient of variation in the amount of sterile pollen increases (r = 0.57 and 0.80, respectively). As the distance to the road increases, the share of sterile, teratomorphic pollen and CID decreases (r = −0.78 and −0.75, respectively). As the natural value index (Inv) increases, the coefficient of variation of the amount of sterile pollen increases (r = 0.84). If the number of cars increases, Inv increases as well (r = 0.68). With increasing amount of a.d. concentration of pollutants, the number of cars (r = 0.89), the share of sterile (r = 0.72) and teratomorphic (r = 0.76) pollen, CID (r = 0.76) and Inv (r = 0.53) increase. With an increase in HI, the number of cars (r = 0.86), the share of sterile (r = 0.76) and teratomorphic (r = 0.80) pollen and CID (r = 0.80) increase.

Discussion

Climate change within the metropolis compared to its surroundings, terrain, loss of green areas in recent decades, the spread of areas covered with asphalt and concrete, significant construction and loss of heating networks increase the temperature of ground layers, reduce relative humidity and change the wind regime. High density of highways causes intense gassiness and air pollution (Shevchenko and Snizhko 2008; Van Wittenberghe et al. 2012; Wei et al. 2021). Stagnant phenomena contribute to the intensive accumulation of impurities in the city. High air temperature and solar radiation contribute to the photochemical reactions of formaldehyde formation, and stagnant air leads to an increase in its concentration. Thus, within the city, there is a significant differentiation of meteorological indicators. In urban conditions, the wind speed decreases significantly, which is associated with an increase in the roughness of the underlying surface. There is also a relative increase in wind speed on some streets and massifs (Shevchenko and Snizhko 2008; Vieira et al. 2018; Arghavani et al. 2021). These indicators in the complex have different effects on the dispersion of harmful impurities from vehicles and their deposition on the edge of the forest and within the green infrastructure and spread over large areas. Our research has shown that although the prevailing winds in the metropolis are in north, west and south directions, the spread of air pollutants occurs in the direction of east – in the valley of the Dnipro. Therefore, the process of air pollution should be considered as probable and the concentration of impurities at each point as random functions of coordinates and time (Kiptenko and Kozlenko 2016; Bonilla-Bedoya et al. 2021). In our research, the highest level of pollution was associated with the terrain and building features of the city, the specific conditions of location and capacity of roads, and aggregated green infrastructure. Greenery is important for urban systems because it absorbs air and dust pollutants (Pietras-Couffignal and Robakowski 2019; Jaung et al. 2020; Jin et al. 2021); additionally, it cools and humidifies the air, regulates the microclimate and mitigates the urban heat island effect (Vieira et al. 2018; Jaung et al. 2020; Wei et al. 2021). In summer, greenery helps to reduce the air temperature by 4°C–6°C and increase the humidity by 10%–15%. The presence of trees reduces the air temperature in summer (1.1°C), significantly cools the surface (12°C) and reduces wind speed by 45% (Georgi and Tzesouri 2008). Single- and double-row greenery, 5–10 m wide, reduces air pollution by 5%–25%. A strip of tree–shrub plantations 10–14 m wide reduces the concentration of carbon dioxide by 40%–45% and the sound level by 2–8 dB (Polyakova and Gutnikov 2000; Jaung et al. 2020). PE reduces the level of air pollution by 40%–70%, depending on the plant height and completeness. The larger the area of green infrastructure, the better the air quality in urban areas (Van Wittenberghe et al. 2012; Jaung et al. 2020; Bonilla-Bedoya et al. 2021) and the lesser the manifestations of near-surface turbulence or air stagnation (Arghavani et al. 2021).

The zone of negative impact of vehicles on the greenery of cities is 20–60 m and in some cases, up to 100 m in the depth of plantings. This is due to a complex of natural and anthropic factors: vegetation stability, the influence of microclimatic features, geochemical soil conditions, landscape characteristics and planning structure of the territory (Polyakova and Gutnikov 2000; Pietras-Couffignal and Robakowski 2019). In the roadside, about 20% of the particles (size ≥0.005 mm) settle near the road, about 60% (≤0.001 mm) settle in the area of 10–100 m and the rest are carried by the wind over long distances (Jin et al. 2021). Dispersion of pollutant emissions is influenced by the azimuth of the route and the prevailing wind direction. On the leeward side of the road, the accumulation of heavy metals in the soil increases by 2 times (Pietras-Couffignal and Robakowski 2019; Polyakova and Gutnikov 2000; Bonilla-Bedoya et al. 2021). It is proved that the intensity of traffic has a negative impact on growth in height, diameter of trees and their living condition (Miroshnyk 2018; Pietras-Couffignal and Robakowski 2019). The intensity of traffic flow over 300 cars per hour and the distance less than 100 m from the carriageway of streets are considered to be dangerous for biota and humans (Klebanova and Klebanov 2011). According to our data, the average traffic intensity on the highways of Kyiv is 4219 cars per hour and exceeds the optimal by 92.9%. Interestingly, in 2010, the load of roads near PE 6 (NBG named after Grishko) was 3.2 thousand cars per hour (Rud, 2013), that is, 2 times less than now. The average traffic intensity in the city in 2018 was 4.1 thousand cars per hour (Rabosh and Kofanova 2019), and according to our data in 2020, it was 4.2 thousand cars per hour.

Under the influence of aerotechnogenic pollution, there is a deterioration of trees, their drying, defoliation of crowns and deterioration of integrated indicators of ecosystems (Bednova et al. 2015; Miroshnyk 2018; Lavrov et al. 2019; Pietras-Couffignal and Robakowski 2019; Vacek et al. 2020). We also observed similar processes. We studied the correlations between the parameters of pollen indication in Kyiv (Mazura et al. 2020), but now, it is found that compared to studies in 2013 (Kudryavska and Dychko 2013), there has been a deterioration of the environmental situation in the integrated indicator of CID by 19.3% for 7 years. We have shown that there is a process of nitrification in PEs with excess nitrogen from the emissions of vehicles through phytoindication (Miroshnyk 2020). Indicators of crown defoliation, the share of premature yellowing of leaves and dechromation of leaves of *T. cordata* L. were the lowest in parks compared to linear plantings near highways (Miroshnyk 2018). Changes in the floristic composition of the grass cover under the influence of air pollution (Simmons et al. 2016; Lavrov et al. 2019), an increase in the number of nitrophils and alien species in the grass cover are indicated. Our research also confirms this.

We found that in the conditions of the urban ecosystem of Kyiv, the vital state of 14 PEs and the state of the generative sphere of *T. officinale* were significantly different from each other and were worse than the control (Pushcha-Vodytsya park). The highest indicators of hazard and pollution indices were recorded in the city centre, where there is dense construction and high-traffic roads, and were lower in the suburbs, where the area of green infrastructure is larger. Concentrations of air pollutants here exceed the control by 4 times, and the intensity of traffic by 8 times. The average excess MACa.d. of phytotoxicants for humans is 1.5 MACa.d. and depends on the terrain and directions of the prevailing winds. The PE natural value index (Inv) had a strong correlation with the total concentration of phytotoxicants in the air ($r = 0.54$).

Pollutants significantly affect plant pollen, accompanied by changes in the morphological parameters of pollen grains, increasing the abnormal pollen fraction and reducing fertility and viability (Cuinica et al. 2014, 2015; Azzazy 2016; Mazura et al. 2020; Leghari et al. 2018). Cuinica et al. (2015) indicated that even at low levels of pollutants below the standard level of safety for human health, pollen viability decreased to 25%. The total amount of teratomorphic pollen increased with increasing concentration of air pollutants and reached 11.1% (Ivanchenko and Bessonova 2016; Petrushkevych and Korshykov 2020). The percentage of natural polymorphism of pollen grains in plants under favourable conditions usually does not exceed 5%–10% and rarely exceeds 20% (Dzyuba 2006; Ivanchenko and Bessonova 2016). In our studies, the amount of teratomorphic pollen reached 41.4% and increased with increasing concentration of contaminants ($r = 0.76$). The share of fertile pollen grains decreased by 11%–26% with increasing concentration of air pollutants (Ivanchenko and Bessonova 2016; Petrushkevych and Korshykov 2020). The share of fertile pollen near the parks in Kyiv decreased with an increase in aerotechnogenic load on an average by 11% ($r = 0.72$). Thus, the results of pollen indication confirm significant contamination with aerophytotoxicants and the reaction of *T. officinale* Web. plants to it.

PE is divided into two groups according to the level of air pollution. Green infrastructure is highly responsive to air pollution, as it has been experimentally proven that the concentration of air pollutants for plants, which leads to damage, is less than for humans (Nikolaevsky 1998; Polyakova and Gutnikov 2000; Furdychko et al. 2008; Cuinica et al. 2015). Our bioindication results show that the state of PEs depends on the amount of vehicle emissions, but not all indicators have a linear relationship, which requires further research. Under the influence of pollutants on the same organs or systems of the body, the most likely type of their combined effect is summation or additivity. Although this approach may exaggerate the health hazards, it has a greater advantage than a separate assessment of each component. In the case of a combined presence in atmospheric air, the effects of summation of biological action for NO_2, NO, SO_2 and fuel oil ash; NO_2, formaldehyde; and SO_2 and NO_2 were established (Environmental Protection 2005; Order of the Ukraine Ministry 2020). Therefore, the total emission concentrations from vehicles and the HI are indicators that describe the impact on urban ecosystems. It is important to create a system of informative indicators for assessing the state of the environment and for the long-term monitoring of urban systems (Cuinica et al. 2015; Azzazy 2016; Vacek et al. 2020). We have developed the rationing and parameters of indication values of biotic indices and abiotic characteristics of the urban system of Kyiv. Value of NO_x concentration in the air <0.020 mg/m^3 is very good and >0.081 is very bad; value of HI <1.060 is very good and >4.242 is very bad.

The analysis indicates the complex nature of air pollution in Kyiv from vehicles and its distribution, taking into account the influence of prevailing winds and the terrain of the city, and the reaction of PEs to it. The results of our study emphasise the importance of green infrastructure for improving air quality in megacities. There is a need to plan the expansion of green areas to improve the quality of ecosystem services, urban microclimate, air, human life and health.

Conclusions

For the first time, for the urban ecosystem of Kyiv, zoning and analysis of the spread of aerial emissions from vehicles using GIS technologies was conducted. The state of green infrastructure was integrated and its dependence on the level of air emissions from vehicles was proved. Our research indicates the dependence of the response of living systems to air pollution at the level of the cell, organism, group and PEs in time and space. Therefore, it is recommended to use integrated indicators of the state of PEs as a response of ecosystems to aerotechnogenic pollution.

In our research, the primary information about the state of green plantations was systematised into the following blocks: the state of the stand, grass tier and the structural diversity of PE. As parameters of the abiotic environment, the levels of air pollution from vehicles were recorded. The ranges of values of ecological indicators of the state of PEs in the conditions of the metropolis were developed, tested and defined. It was found that a high and above-average level of damage to the generative sphere of plants is characteristic of the areas with the highest level of pollution. Green infrastructure needs to be expanded to improve the urban environment and reduce pollution. For this purpose, it is necessary to optimise the transport infrastructure (expand transport interchanges to reduce congestion, build bypass roads or highways to increase the speed of vehicles, which will reduce the emission of air pollutants when braking at traffic lights and in traffic jams), plant protective plantings of four to six rows along highways, design new microdistricts taking into account the microclimate, terrain and prevailing winds to increase aeration, and improve the air quality for humans to breathe clean air.

References

Ali, M.U, Liu, G., Yousaf, B., Abbas, Q., Ullah, H., Munir, M.A.M., Fu, B. 2017. Pollution characteristics and human health risks of potentially (eco)toxic elements (PTEs) in road dust from metropolitan area of Hefei, China. *Chemosphere*, 181, 111–121. DOI: 10.1016/j.chemosphere.2017.04.061

Aliyar, Z.B., Shafiei, A.B., Seyedi, N., Rezapour, S., Moghanjugi, S.M. 2020. Effect of traffic-induced air pollution on seed germination of Arizona cypress (Cupressus arizonica Green) and Black Pine (Pinus nigra Arnold). *Urban Forestry and Urban Greening*, 55 (126841). DOI: 10.1016/j.ufug.2020.126841

Anuchin, N.P. 1982. Forest inventory (in Russian). Lesnaya Promyshlennost, Moscow.

Arghavani, S., Malakooti, H., Aliakbari Bidokhti, A.A. Evaluation the effects of urban green space scenarios on near-surface turbulence and dispersion related parameters: A numerical case study in Tehran metropolis. *Urban Forestry and Urban Greening*, 59 (127012). DOI: 10.1016/j.ufug.2021.127012

Azzazy, M. 2016. Environmental impacts of industrial pollution on pollen morphology of *Eucalyptus globulus* Labill. (*Myrtaceae*). *Journal of Applied Biology and Biotechnology*, 4, 57–62. DOI: 10.7324 / JABB.2016.40509

Bednova, O., Kuznetsov, V., Andryushin, Yu. 2015. Information and analytical support for monitoring the state of forest ecosystems in urban specially protected natural areas (in Russian). *Forestry Bulletin*, 1, 140–151.

Bessonova, V., Sklyarenko, A. 2020. The accumulation of fluoride by leaves of woody plants growing in the area of sanitary protection zones in the industrial region of Zaporizhzhya. *Folia Forestalia Polonica, Series A – Forestry,* 62 (2), 128–138. DOI: 10.2478-ffp-2020-0013

Bonilla-Bedoya, S., Zalakeviciute, R., Coronel, D.-M., Durango-Cordero, J., Molina, J.-R., Macedo-Pezzopane, J.-E. 2021. Spatiotemporal variation of forest cover and its relation to air quality in urban Andean socio-ecological systems. *Urban Forestry and Urban Greening*, 59 (127008). DOI: 10.1016/j.ufug.2021.127008

Boychenko, S.G., Karamushka, V.I., Tishchenko, O.V., Mokhnach, R.Yu. 2017. Environmental threats to biodiversity in Kyiv from climate change (in Ukrainian). *Reports of the National Academy of Sciences of Ukraine*, 12, 104–111. DOI: 10.15407/dopovidi2017.12.104

Celebi, H., Gok, G. 2018. The examination for pollution of the soils due to highways and traffic. *Pamukkale University Journal of Engineering Sciences*, 24 (6), 1169–1178. DOI: 10.5505/pajes.2016.55632

Cuinica, L.G., Abreu, I., Esteves da Silva, J. 2014. Effect of air pollutant NO_2 on *Betula pendula*, *Ostrya carpinifolia* and *Carpinus betulus* pollen fertility and human allergenicity. *Environmental Pollution*, 186, 50–55. DOI: 10.1080 / 09603123.2014.938031

Cuinica, L.G., Cruz, A., Abreu, I., Joaquim, C.G., Esteves da Silva, J. 2015. Effects of atmospheric pollutants (CO, O_3, SO_2) on the allergenicity of *Betula pendula, Ostrya carpinifolia, and Carpinus betulus* pollen. *International Journal of Environmental Health Research*, 25 (3), 312–321. DOI: 10.1080/09603123.2014.938031

Dzyuba, O.F. 2006. Pollen-indication of environmental quality (in Russian). Nedra, Saint Petersburg. Available at https://www.libex.ru/detail/book316158.html

Ecological passport. City of Kyiv (in Ukrainian). 2020. Available at https://dostup.pravda.com.ua/request/77440/response/191449/attach/4/eco%20passport%202019.pdf?cookie_passthrough=1 (access on 17.04.2021).

Environmental Protection Agency. 2005. Human Health Risk Assessment Protocol for Hazard do us Waste Combustion Facilities. U.S. EPA. Available at https://archive.epa.gov/epawaste/hazard/tsd/td/web/pdf/05hhrapcover.pdf

Ferreira, A.D., Soares, D.B., Serrano, L., Walsh, R.P.D., Dias-Ferreira, C., Ferreira, C. 2016. Roads as sources of heavy metals in urban areas. The Coves catchment experiment, Coimbra. *Portugal Journal of Soils and Sediments*, 16 (11). DOI: 10.1007/s11368-016-1492-4

Fuller, L., Quine, Ch.P. 2016. Resilience and tree health: a basis for implementation in sustainable forest management. *Forestry*, 89 (1), 7–19. DOI: 10.1093/forestry/cpv046

Furdychko, O., Slavov, V., Voytsytsky, A. 2008. Standardization of anthropogenic load on the environment: Textbook (in Ukrainian). Pos. Basis, Kyiv.

Gąsiorek, M., Kowalska, J., Mazurek, R., Pająk, M. 2017. Comprehensive assessment of heavy metal pollution in topsoil of historical urban park on an example of the Planty Park in Krakow (Poland). *Chemosphere*, 179, 148–158. DOI: 10.1016/j.chemosphere.2017.03.106

Georgi, N., Tzesouri, A. 2008. Monitoring Thermal Comfort in Outdoor Urban Spaces for Bioclimatic Conditions Environment. 1st WSEAS International Conference on landscape architecture, Algarve, Portugal, 98–103. Available at http://www.wseas.us/elibrary/conferences/2008/algarve/LA/13-588-398.pdf

Grodzinskaya, A., Nebesnyi, V., Samchuk, A., Honchar H. 2019. Content of trace elements, 137Cs and 40K in bioindicators and soils from Kyiv (Ukraine). *Journal of Medicinal Plants Studies*, 7 (5), 115–125. Available at https://www.researchgate.net/publication/339875773_Content_of_trace_elements_137Cs_and_40

Ivanchenko, O., Bessonova, V. 2016. Pollen quality in woody plants in the city parks of Dnipro, Ukraine. *International Letters of Natural Sciences*, 59, 29–37. DOI: 10.18052/www.scipress.com/ILNS.59.29

Jaung, W., Carrasco, R., Edros, S.-F., Shaikh, A., Yok-Tan, P., Richards, D.R. 2020. Temperature and air pollution reductions by urban green spaces are highly valued in a tropical city-state. *Urban Forestry and Urban Greening*, 55 (126827). DOI: 10.1016/j.ufug.2020.126827

Jin, E.J., Yoon, J.H., Bae, E.J., Jeong, B.R., Yong, S.H., Choi, M.S. 2021. Particulate matter removal ability of ten evergreen trees planted in Korea urban greening. Forests, 12 (4), 438. DOI: 10.3390/f12040438

Khan, S., Munir, S., Sajjad, M., Li, G. 2016. Urban park soil contamination by potentially harmful elements and human health risk in Peshawar City, Khyber Pakhtunkhwa, Pakistan, *Journal of Geochemical Exploration*, 165, 102–110. DOI: 10.1016/j.gexplo.2016.03.007

Kijewska, K., Konicki, W., Freight, I.S. 2016. Transport pollution propagation at urban areas based on Szczecin example. *Transportation Research Procedia*, 14, 1543–1552. DOI: 10.1016/j.trpro.2016.05.119

Kiptenko, E.M., Kozlenko, T.V. 2016. Methods of short-term forecast of air pollution for the city of Kyiv (in Ukrainian). *Scientific Reports of UkrNDGMI*, 269, 138–150.

Klebanova N., Klebanov D. 2011. Influence of mobile and stationary sources of pollutant emissions on air quality in the city of Kyiv for 2009–2010 (in Ukrainian). *Scientific Works of the Ukrainian Research Hydrometeorological Institute,* 260, 235–249.

Kudryavska, T., Dychko, A. 2013. Estimation of pollution of the urban ecosystem of the city of Kyiv according to the indicator of bioindicator damage (in Ukrainian). *Bulletin of Kremenchug National University,* 6 (83), 140–144. Available at http://nbuv.gov.ua/UJRN/Vkdpu_2013_6_27

Lavrov, V., Miroshnyk, N., Grabovska, T., Shupova, T. 2021a. Forest shelter belts in organic agricultural landscape: structure of biodiversity and their ecological role. *Folia Forestalia Polonica, Series A – Forestry*, 63 (1), 48–64. DOI: 10.2478-ffp-2021-0005

Lavrov, V., Miroshnyk, N., Shupova, T., Teslenko, I., Gonchar, G. 2021b. Scientific bases of integrated assessment of park forest ecosystems in the conditions of a big city. Methodical recommendations (in Ukrainian). Kyiv. DOI: 10.13140/RG.2.2.25365.86245

Lavrov, V.V., Miroshnyk, N.V., Grabovska, T.O., Yashchenko, S.A. 2019. The herbaceous tier analysis in protective forest plantations, Ukraine. *Phytologia Balcanica*, 25 (3), 345–361. Available at http://www.bio.bas.bg/~phytolbalcan/PDF/25_3/contents.html

Lee, C.S.L., Li, X.-D., Shi, W., Cheung, S. Ch., Thornton, I. 2006. Metal contamination in urban, suburban, and country park soils of Hong Kong: A study based on GIS and multivariate statistics. *Science of The Total Environment*, 356 (1/3), 45–61. DOI: 10.1016/j.scitotenv.2005.03.024

Leghari, S.K., Saeed, S., Asrar, M., Ahmed, A., Tariq, I., Marri, A.A., Sadiq, N., Baloch, A., Latif, A., Shawani, N.A. 2018. Response of sweet cherry (*Prunus avium* L.) pollen grains to vehicular exhaust pollution at Quetta, Balochistan, Pakistan. *Applied Ecology and Environmental Research,* 16 (4), 4387–4399. DOI: 10.15666/aeer/1604_43874399

Livesley, S.J., McPherson, E.G., Calfapietra, C. 2016. The urban forest and ecosystem services: Impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. *Journal of Environmental Quality*, 45, 119–124. DOI: 10.2134/jeq2015.11.0567

Magurran, A.E. 2004. Measuring biological diversity. Blackwell Publishing, Oxford. DOI: 10.2989/16085910409503825

Mazura, M., Miroshnyk, N., Teslenko, I., Grabovska, T., Rozputnii, O., Mazur, T., Polishchuk, Z., Oleshko, O. 2020. Using of *Taraxacum officinale* (L.) pollens for the urban park bioindication. *Ukrainian Journal of Ecology*, 10 (5), 49–53. DOI: 10.15421/2020_205

Methods for determining vehicle emissions for summary calculations of urban air pollution. Approved. 1999. State Committee for Ecology of Russia, Moscow. Available at http://www.gostrf.com/normadata/1/4293852/4293852298.pdf (in Russian)

Miroshnyk, N. 2018. Estimation of air pollution in Kiev megalopolis using the complex of bioindication methods (in Russian). *Problems of Ecological Monitoring and Ecosystem Modelling*, 29 (3), 107–129. DOI: 10.21513/0207-2564-2018-3-107-129

Miroshnyk, N.V. 2020. Assessment of nitrogen status of park forest ecosystems based on phytoindication data (in Ukrainian). *Factors in Experimental Evolution of Organisms*, 27, 245–251. DOI: 10.7124/FEEO.v27.1288

Monitoring and increasing the resilience of anthropogenically disturbed forests. 2011. Collection of recommendations of UkrNDILGA/Cf.: V.P. Voron and others (in Ukrainian). Nove slovo, Kharkiv.

Monok, D., Kardos, L., Pabar, S.A., Kotroczo, Z. 2020. Comparison of soil properties in urban and non-urban grasslands in Budapest area. *Soil Use and Management*, 37 (4), 790–801. DOI: 10.1111/sum.12632

Nikolaevsky, V.S. 1998. Environmental assessment of environmental pollution and the state of terrestrial ecosystems by phytoindication methods (in Russian). Moscow.

Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E. 2014. Tree and forest effects on air quality and human health in the United States. *Environmental Pollution*, 193, 119–129. DOI: 10.1016/j.envpol.2014.05.028

Order of the Ukraine ministry of health on approval of hygienic regulations of permissible content of chemical and biological substances in the air of populated areas. 14.01.2020. No 52 (in Ukrainian). Available at https://zakon.rada.gov.ua/laws/show/z0156-20#n16

Pausheva, Z.P. 1980. Workshop on plant cytology (in Russian). Kolos, Moscow. Available at http://booksshare.net/index.php?id1=4&category=biol&author=pausheva-zp&book=1988

Petrushkevych, Y. M., Korshykov, I. I. 2020. Ecological and biological characteristics of *Betula pendula* in the conditions of urban environment. *Regulatory Mechanisms in Biosystems*, 11 (1), 29–36. DOI: 10.15421/022004

Pietras-Couffignal, K., Robakowski, P. 2019. The impact of air pollution on growth features and the health of trees in Berlin. Dendrobiology, 82, 52–65. DOI: 10.12657/denbio.082.006

Polyakova, G., Gutnikov, V. 2000. Moscow parks: ecology and floristic characteristics (in Russian). GEOS, Moscow.

Rabosh, I.O., Kofanova, O.V. 2019. Lichen-indicative researches in a gradient of anthropogenic loading (on an example of park zones of Kiev) (in Ukrainian). *Ecological Sciences*, 1 (24), 46–51. DOI: 10.32846/2306-9716-2019-1-24-1-7

Rao, M., George, L.A., Rosenstiel, T.N., Shandas, V., Dinno, A. 2014. Assessing the relationship among urban trees, nitrogen dioxide, and respiratory health. *Environmental Pollution*, 194, 96–104. DOI: 10.1016/j.envpol.2014.07.011

Rud, N.V. 2013. Monitoring of air pollution of the surface layers of the territory of the National Botanical Garden named after M.M. Grishka (in Ukrainian). *Scientific Journal of the National Pedagogical University named after Dragomanova*, 20 (5), 231–239.

Rybakova, N. Glazunov, Y. 2020. The influence of motor transport pollution on the growth of european larch. *Forestry Engineering Journal*, 10 (2), 70–80. DOI: 10.34220/issn.2222-7962/2020.2/7

Sanitary rules in the forests of Ukraine. Ruling of October 26, 2016. No 756 (in Ukrainian). Available at http://sfmu.org.ua/en/laws/

Shevchenko, O., Snizhko, S. 2008. Influence of wind direction and speed on the level of air pollution in the city of Kyiv (in Ukrainian). *Ukrainian Hydrometeorological Journal*, 3, 33–38.

Simmons, B.L., Hallett, R.A., Sonti, N. F., Auyeung, D.S.N. Lu, J.W.T. 2016. Long-term outcomes of forest restoration in an urban park. *Restoration Ecology*, 24 (1), 109–118. DOI: 10.1111/rec.12281

Takhtajan, A. 2009. Flowering plants. 2nd edition. Springer, New York. DOI: 10.1007/978-1-4020-9609-9

Vacek, Z., Vacek, S., Prokůpkova, A., Bulusek, D., Podrazsky, V., Hůnová, I., Putalová, T., Král, J. 2020. Long-term effect of climate and air pollution on health status and growth of Picea abies (L.) Karst. peaty forests in the Black Triangle region. *D*endrobiology, 83, 1–19. DOI: 10.12657/denbio.083.001

Van Wittenberghe, S., Alonso, L., Verrelst, J., Hermans, I., Delegido, J., Veroustraete, F., Valcke, R., Moreno, J., Samson, R. 2012. Upward and downward solar-induced chlorophyll fluorescence yield indices of four tree species as indicators of traffic pollution in Valencia. *Environmental Pollution*, 173, 29–37. DOI: 10.1016/j.envpol.2012.10.003

Vieira, J., Matos, P., Mexia, T. et al. 2018. Green spaces are not all the same for the provision of air purification and climate regulation services: the case of urban parks. *Environmental Research*, 160, 306–313. DOI: 10.1016/j.envres.2017.10.006

Voordeckers, D., Lauriks, T., Denys, S., Billen, P., Tytgat, T. 2021. Guidelines for passive control of traffic-related air pollution in street canyons: An overview for urban planning. *Landscape and Urban Planning*, 207 (103980). DOI: 10.1016/j.landurbplan.2020.103980

Weather archive in Kiev. Electronic resource. Available at https://world-weather.ru/archive/ukraine/kyiv/ (access on 17.04.2021).

Wei, J., Li, H., Wang, Y., Xu, X. 2021. The cooling and humidifying effects and the thresholds of plant community structure parameters in urban aggregated green infrastructure. Forests, 12 (2), 111. DOI: 10.3390/f12020111

Zaitsev, G.N. 1990. Mathematics in Experimental Botany (in Russian). Science, Moscow.

Zajecka, E., Świercz, A. 2021. Biomonitoring of the urban environment of Kielce and Olsztyn (Poland) based on studies of total and bioavailable lead content in soils and common dandelion (*Taraxacum officinale* agg.). *Minerals*, 11 (1), 52. DOI: 10.3390/min11010052

Żak, A.M. 2017. Analysis of transport pollution at the urban areas with GIS application. *Inżynieria Ekologiczna*, 18 (2), 217–224. DOI: 10.12912/23920629/68330