Green spaces as indicator of air quality and mechanism for city’s environment stabilization in the Baltic region

Natalia Terekhina*
St. Petersburg State University, St. Petersburg, Russian Federation

Abstract. Air pollution is one of the main environmental problem. And although average air pollution indicators in the Baltic region countries exceed limit values rarely, nevertheless, high pollution is present in some areas, damages ecosystems and public health. It is possible to use green spaces as one of the tools for cleaning atmospheric air. This article describes the scientific approaches to assess the cleansing function of urban plants. Particulate matters are considered as the main pollutant. Conclusions are drawn about the need to use an integrated approach that takes into account a number of characteristics of both plants and the ecosystems themselves, which allows solving the problems of environmental improvement in the cities of the Baltic region.

1 Introduction

Air quality is one of the most important factors, which related with population health. Environmental policy in Europe aims to reduce different types of pollutants, and the data of European Environmental Agency shows great success in the last years. The European Commission adopted in 2013 a Clean Air Policy Package, including a Clean Air Programme for Europe setting objectives for 2020 and 2030, and accompanying legislative measures. In 2018, The Commission adopted a Communication "A Europe that protects: Clean air for all' that provides national, regional and local actors with practical help to improve air quality in Europe. There is an established list of atmospheric pollutants, among which there are particulate matter (PM) – a broad class of chemically and physically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide range of sizes. PM10 – particles of coarse fraction with a diameter less than or equal to 10 micrometers (µm). PM2.5 – fine particles with a diameter less than or equal to 2.5 µm. Coarse particles are emitted largely as a result of mechanical industrial processes, construction and demolition operations, residential burning, wildfires, and dust resuspended by cars. Fine particles are formed by combustion processes from power plants, gas and diesel engines, many industrial processes, and by atmospheric reactions of gaseous pollutants [1].

Scientific investigations showed for fine particles much stronger harmful human health effects [2, 3, 4]. Though both of particles effects associated with premature mortality,
aggravation of respiratory and cardiovascular disease, changes in sub-clinical indicators of respiratory and cardiac function, and exacerbation of allergic symptoms. Children, older adults, individuals with preexisting heart and lung disease (including asthma), and persons with lower socioeconomic status are considered to be among the groups most at risk for effects associated with PM exposures [1]. The adverse effects of air pollutants on human health are mainly (64%) caused by fine particulate matter (PM2.5), which contains carcinogenic compounds and heavy metals, for example [5].

Limit values for air pollutants established by different organizations are similar, and all countries strive to achieve established standards. For the Baltic sea region Sweden, Finland, Estonia and Norway have already made significant strides. Most concentrations of air pollutants have fallen so much over the period 1990–2016 that air quality limit values are not exceeded or only rarely exceeded. Average annual concentration of PM for St.-Petersburg is in accordance with the standards established by the EU Directives also [6]. However, air pollutants still cause adverse effects on both human health and the environment. In some places, PM is caused by long-range transboundary pollution, in others – small-scale woodburning or heavy traffic, and the serious problem of air pollution still remains for large industrial cities.

In addition to technical emission reduction measures, improving air quality requires that this factor be taken into account systematically in all planning and decision-making activities and when assessing the health and environmental impacts of any measures to be taken in other sectors [5]. Therefore, the use of green spaces for assessment of their role in cleaning of air and in optimization of city environment is very relevant. There are several reviews on the assessment of atmospheric air pollution by particulate matter and the role of plants in its purification [7, 8, 9, 10, 11]. This article discusses a number of approaches to assessing the role of individual plant species and green spaces in general in the regulation of PM and individual chemical elements, especially for the Baltic region.

2 Vegetation and PM

Vegetation can act as an additional tool to reduce the content of PM in the atmosphere, accumulating them on/in foliage. Plants, like all living organisms, have individual and species characteristics in this process; in addition, the structure of green spaces can vary widely. Nevertheless, there are a lot of articles of Polish scientists, and scientists of other countries, who offer different methods for assessing the accumulation of PM by plants.

Kajetan Dzierzaniowski et al. [12, 13] investigated leaves of nine tree species and four shrub species growing on streets of Warsaw in order to assess amount of PM different sizes accumulated on leaves surface and in wax layer. Amounts of particles rinsed with water theoretically can be washed off during heavy rainfalls and those rinsed with chloroform, deposited inside wax layer and therefore retained for longer period of time. The water and chloroform were then filtered using a metal sieve and filters in order to get two fractions of particulate matter: large 10–100 μm, and coarse 2.5–10 μm. Total area of the leaf sample was measured using Image Analysis System (Skye Instruments Ltd, UK), and SkyeLeaf software, which allowed the amount of PM and waxes to be expressed as μg*cm⁻² leaf area. Sorbus intermedia, whose leaves have a dense pubescence, demonstrated the highest accumulation of the large fraction (19.85 μg*cm⁻²), washed away by water. Then followed by Pyrus calleryana and Populus simonii (14.85 and 13.72 μg*cm⁻²). Populus simonii and Betula pendula respectively captured most of the coarse fraction (3.94 and 3.04 μg*cm⁻²). B. pendula is the most effective accumulator of wax-related PM, and can be recommended as the best species for traffic-related sites, where organic substances from vehicle exhausts are present in highest concentrations, as they accumulate better in the wax layer. B. pendula demonstrated three to over eightfold higher accumulation rate of smaller and wax-related PM
than other tested species. The highest rates of PM assayed on leaves of *B. pendula* (18.77 for large fraction, and 8.39 µg·cm⁻² for coarse fraction) are probably a result of thick epicuticular wax layer, characteristic for this species. In this study, oak, regardless of the fraction and rinsing-agent, was the least effective species. Among shrubs Japanese spirea (*Spiraea japonica*) demonstrated the highest ability to capturing of PM. Not for all species there is a correlation between the thickness of the wax layer and the amount of accumulated particles. Probably chemical composition and structures of wax layer, which are a species-specific trait, are also important.

Robert Popek et al. [14] carried out experiment with 13 ornamental trees and shrubs, which were grown in pots in nursery located in Pechcin, central Poland. In the end of vegetative season, the PM was determined in two categories, leaves were washed with water (surface PM) or chloroform (in-wax PM), for three size fractions (10–100, 2.5–10, and 0.2–2.5 µm). The amounts of PM and waxes were recalculated to µg·cm⁻² after measurement of sample leaf area. Results showed higher surface deposition, than deposition in wax of leaves (60 and 40% respectively). Average amount of surface PM for all species is 9.98 µg·cm⁻², wax PM 6.65 µg·cm⁻². Maximal amount of PM accumulated by *Syringa meyeri* ‘Palibin’: 17.11 and 14.99 µg·cm⁻² respectively.

Arne Sæbø et al. [15] conducted an experiment to determine the accumulative capabilities of the leaves of 22 trees and 25 shrubs grown in pots in Poland and Norway. High total PM accumulation (24–55 µg·cm⁻²) in Norway has been identified for *Betula pendula*, *Pinus mugo*, *Pinus sylvestris*, *Salix cinerea*, *Skimmia japonica* and *Stephanandra incisa*. Moreover, *B. pendula*, *P. mugo* and *S. incisa* had the largest accumulation (4.2–8.0 µg·cm⁻²) of the PM0.2 fraction. Considerably lower total accumulation of total PM (6–13 µg·cm⁻²) was found for *Acer platanoides*, *Prunus avium*, *Prunus leurocerasus*, *Prunus padus*, *Symphoricarpus albus* and *Tilia cordata*. The smallest accumulation of the fine PM0.2 fraction (1.0–1.6 µg·cm⁻²) had *Fagus sylvatica*, *A. platanoides*, *T. cordata* and *P. leurocerasus*.

The experiment’s assortment in Poland had only 6 common species with Norway one, therefore the results are different. Polish data showed that *B. pendula* had the highest total PM accumulation (38.4 µg·cm⁻²). The species with the highest accumulations of PM0.2 (1.4–4.5 µg·cm⁻²) were *B. pendula*, *Taxus baccata*, *Alnus saphthii*, *Spiraea×vanhuttei*, *Hydrangea arborescens* ‘Annabelle’ and *Pyrus calleryana*. The species with the lowest accumulations of this fraction (0.6–0.8 µg·cm⁻²) were *A. platanoides*, *Robinia pseudoacacia* and *Fraxinus excelsior*.

It should be noted that in Norwegian and Polish cases the results of two years of research do not coincide much, but both of them confirm the high accumulative ability of *B. pendula* leaves. They are rich in waxes and have the potential for selection of species that can accumulate more pollution in urban green spaces.

The very interesting work was made by A. Przybysz et al. [16]. Four young plants of three species *Taxus baccata*, *Pinus sylvestris* and *Hedera helix* were planted in random positions at three sites: 1. near the busy road (suburban area of Stavanger, Norway); 2. near the same road, but under a viaduct that protected them from precipitation; 3. rural site nearby, where the plants were grown in a clean environment. Plant material was collected in three time periods: at the beginning of the experiment mid-February, early spring at the end of March, and late spring at the beginning of June. Content of PM was examined by two categories: water-washable from leaf surfaces (SPM) and chloroform-washable from leaf wax (WPM). Fractional division for both categories was done sequentially. Also, they organized the simulated rainfall event (20 mm) removed large quantities of PM from pine shoots.

Total PM accumulation differed considerably between species and sites and between terms, but the three test species showed the same trends across sites. *Pinus sylvestris* had the greatest (between 27.7 and 417.6 µg·cm⁻², respectively for Rural site in the first term and
Roadside Dry site in the third term) mass of total accumulated PM, while Hedera helix had the lowest (between 8.0 and 140.6 µg cm⁻², respectively for Roadside Dry site in the first term and Roadside Dry site in the third term). The simulated rainfall event (20 mm) removed 30% and 41% of accumulated PM from Pinus sylvestris shoots collected at the Roadside Wet and Roadside Dry sites, respectively. The proportion of WPM at the Roadside Dry site was relatively low (18%) compared with that at the Roadside Wet site (31%). Probably, on plants protected from precipitation, most of the PM was less strongly bound to the foliage. The largest size fraction made up the greatest proportion of removed PM (75%–87%) and the fine fraction – the smallest (2%–5%). The fine fraction seemed to adhere most strongly to the foliage, with a loss of only 21%–30% when exposed to simulated rainfall. However, significant amounts of all fractions of PM were still present on the shoots after treatment with simulated rainfall.

The results of investigations have implications for bioremediation programmes, allow to calculate pollutant deposition and interpret data on plant bio-indicators, taking into account the local weather conditions.

3 Biogeochemical properties of plants

Sometimes it is very important to get not only quantitative data of contamination, but qualitative one also.

Jenny Klingberg et al. [17] investigated air pollution levels (NO₂, PAHs, O₃) before and after leaf emergence (BLE, ALE), in the urban landscape of Gothenburg, Sweden. At a vegetated site, NO₂ and particulate PAH levels were lower than at a non-vegetated site at a certain distance from a busy traffic route. This effect was significantly larger ALE compared to BLE for NO₂, indicating green leaf area to be highly significant factor for air quality improvement. Results are evidence that urban green spaces are beneficial for urban environmental quality.

Stanislaw Chwil et al. [18] studied three tree species: Sorbus aucuparia, Tilia cordata, and Populus tremula growing in a pollution free environment (near the village Huszlew, Poland) and in an urban agglomeration (Lublin, Poland). The aim of this research was to make comparative observations of the structure of leaves in relation to the content of lead, zinc, copper, nitrogen and sulphur determined in these organs. Among these elements only the Zn content (69 mg*kg⁻¹ for Populus tremula leaves) exceeded the permissible limit, but difference of Pb content between washed and unwashed leaves was about 25% for all species from Lublin, that demonstrates the predominance of this element in urban dust. Compare heavy metal concentrations in plants from two places demonstrated excess of 1.5-2 times for plants in Lublin, but for Tilia cordata the Pb content (0.372 mg*kg⁻¹) is 4 times higher than that in Huszlew.

Monika Czaja et al. [19] investigated accumulation of heavy metals for leaves of Tilia tomentosa growing along the streets with heavy traffic in Cracow (Poland). Content of heavy metals accumulated by leaf blades were estimated as in unwashed as washed leaves also. Results demonstrated: such elements as Cu, Pb, Cr, Fe are more accumulated on the surface of the leaves, whereas Mn, Zn, Ni, Cd, – inside leaves. The content of all elements does not exceed the level of the reference plant [20] and the toxic level [21]. The ratio of the content of elements in linden to their content in the soil showed a high value for Cu (1.54) near the road, which is possibly related not only to its role in the plant, but also to its significant input from the atmospheric air.

Our investigation of chemical content of urban plants [22] was carried out for 9 species of trees and shrubs, growing in Central District of St.-Petersburg. Such species as Tilia cordata and Ulmus laevis had the highest value of ash content between washed and unwashed leaves, that showed their ability to successfully accumulate dust particles. On the second
place can be called *Quercus robur* and *Rosa rugosa*. In compare with background data unwashed leaves of *Tilia cordata* have high excess by Fe (8.83 times), Co (7.47), Cr (5.62), Pb (4.31), Zn (3.04 times), which are the main pollutants in city. Species accumulated high amount of heavy metals are the same, which had high ash content, and also *Populus* sp. This species did not have a big difference in the ash indicators of washed and unwashed leaves, that is explained by the inclusion of pollutants in the composition of the wax covering the leaves with a thick layer. Almost for all species content of chemical elements is above the level of reference plant [20]. The concentration of Cr exceeds the toxic level [21] for unwashed leaves of *Ulmus laevis, Rosa rugosa, Tilia cordata*. Comparing the chemical content of washed and unwashed *Tilia cordata* leaves, it should be noted the high difference between these indicators for almost all analyzed elements, except Sr, that indicates a significant aerogenic supply of these elements as pollutants.

4 Modeling of pollutants distribution

A study of the influence of urban vegetation on air quality through the effects of deposition and dispersion of pollutants is also carried out by creating theoretical models and experiments in wind tunnels. This issue is well covered in the work of Sara Janhäll [8]. So, there are models, which are theoretical framework to describe the behavior of an aerosol in interaction with a vegetation canopy, using the leaf size, shape and area index as well as the height of the plants. Their predictions are compared against available measurements for grass and forest environments, obtained under controlled aerosol size and aerodynamic conditions [23, 24].

A number of researches, using the ENVI-met model, which evaluated the relationship between the height-to-width ratio of streets flanked by buildings and the vertical and horizontal density of vegetation cover. Air quality is reduced in configurations with poor ventilation: at low wind speeds and perpendicular inflow, as well as in deep canyons. Moreover, larger trees with a dense crown significantly reduced dispersion. It is recommended that dense tree cover in deep canyons should be avoided, as they might inhibit the upward flow and mixing of air, helping to reduce pollution concentrations. In addition, crown closure should be avoided or pruning methods should be employed that favour the penetration of air through tree canopies. Authors suggested that hedges might be an alternative to trees in deep canyons as they appear to retain more particles due to their position closer to pollution sources, as well as reducing concentrations at the height of the human respiratory tract [25, 26].

To simulate the processes of pollutant dispersion in the urban environment taking place on the street’s canyons of the city, wind tunnels were used. The conditions close to natural ones allowed to identify patterns of deposition of pollutants depending on the speed and direction of the wind, on the size of the particles of pollutants, as well as on the height, density and location of green spaces. It is concluded that continuous hedgerows can effectively be employed to control concentrations of traffic pollutants in urban street canyons. They can advantageously affect the air quality at street level and can be a significant remedy to the pedestrians’ and residents’ exposure in the most polluted center area of streets [7, 27, 28].

5 Problem in assessment

One of the urgent problems in solving the problem of calculating the total area of leaves in green spaces is that the leaf index does not allow to accurately determine the desired indicator. Urban plants are represented by a variety of species and varieties of trees and shrubs, for which there are no taxation tables indicating the area or mass of leaves per plant...
of a certain age. In addition, climatic and environmental conditions of their location affect plant productivity. Trees and shrubs in green spaces are often pruned or sheared, which also significantly affects these indicators. To date, there is little data in the literature to solve this problem for specific types of urban trees. Suggestions for non-destructive methods for measuring the mass and area of tree leaves are given in the work of V.A. Usoltsev [29], but these are very laborious approaches and they are not applicable for individual urban plants. Today only an approximate calculation of the amount of chemical elements/particulate matter entering on/into the leaves is possible. The information available in the literature on dust and gas resistant wood species helps to select an assortment for green spaces of different functional significance, but they do not allow quantifying the characteristics of their potential cleaning activity. Perhaps modern technologies, for example, the modeling of crowns on the multi-platform LiDAR [30], will solve the problem of calculating the area of the leaf surface of individual trees and shrubs.

6 Conclusion

Thus, for a more efficient use of green spaces for atmospheric air purification, it is necessary to take into account factors such as: qualitative and quantitative features of pollution of the study area, climatic characteristics, features of relief, plant species possessing the necessary gas and dust absorption properties; when building models of urban landscapes territory to considerate structure of green spaces, leaf surface area and mass of plant leaves. When planning landscape design and green plant care program, their environmental services must be taken into account. It is necessary to comprehensively solve the problems of environmental improvement for the cities of the Baltic region.

References

1. Criteria Air Pollutants from URL: https://www.epa.gov/sites/production/files/2015-10/documents/ace3_criteria_air_pollutants.pdf
2. E.A. Shtokman Air cleaning. (Moscow, 2007) (in Rus.)
3. L. Stockfelta, E. M. Andersson, P. Molnára, L. Gidhagenb, D. Segerssonb, A. Rosengrenc, L. Barregardb, G. Sallsten, Environmental Research 158 (2017)
4. D. Segersson, K. Eneroth, L. Gidhagen, Ch. Johansson, G. Omstedt, A. Engström Nylén and B. Forsberg, Int. J. Environ. Res. Public Health 14(7), 742 (2017)
5. National Air Pollution Control Programme, Finland (2019)
6. Report on the environmental situation in St. Petersburg (2010-2019) from URL: https://www.gov.spb.ru/gov/otrasl/ecology/ecorep/ (in Rus.)
7. T. Litschke, W. Kuttler, MeteoroL Z 17 (2008)
8. S. Janhäll, Atmospheric Environment 105 (2015)
9. J. Yang, Y. Chang, P. Yan, Atmospheric Pollution Research 6, 2 (2015)
10. P.K. Rai, Ecotoxicology and Environmental Safety 129 (2016)
11. L. Zhang, J. P. Wilson, B. MacDonald, W. Zhang, T. Yua, Environment International 142, 105862 (2020)
12. K. Dzierzanowski, S.W. Gawroński, Challenges of Modern Technology 1(2), (2011)
13. K. Dzierzanowski, R. Popek, H. Gawrońska, A. Sæbø, S.W. Gawroński, Int. J. Phytoremediation 13 (2011)
14. R. Popek, H. Gawrońska, M. Wrochna et al., Int. J. Phytoremediation, 15 (2013)
15. A. Sæbø, R. Popek, B. Nawrot, H.M. Hanslin, H. Gawronska, S.W. Gawronski, Science of The Total Environment, 427–428 (2012)
16. A. Przybysz, A. Sæbø, H.M. Hanslin, S.W. Gawroński, Science of the Total Environment 481, (2014)
17. J. Klingberg, M. Broberg, B. Strandberg, P. Thorsson, H. Pleijel, Science of the Total Environment, 599–600 (2017)
18. S. Chwil, J. Kozłowska-Strawska, P. Tkaczyk, P. Chwil, R. Matraszek, Journal of Elementology 20(4), (2015)
19. M. Czaja, A. Kolton, Baran A., P. Muras, Logistyka, 4, (2014)
20. A. Kabata-Pendias, H. Pendias Trace Elements in Soil and Plants (CRC Press, 1986)
21. B. Markert, Water Air and Soil Pollution 64, (1992).
22. N. Terekhina, M. Ufimtseva, Geography, Environment, Sustainability 13, 1 (2020)
23. A. Petroff, A. Mailliat, M. Amielh, F. Anselmet, Atmos.Environ 42, (2008)
24. A. Petroff, L. Zhang, Geosci. Model Dev. 3 (2010)
25. A. Wania, M. Bruse, N. Blond, C. Weber, J. Environ. Manag. 94, (2012)
26. P.E. Vos, B. Maiheu, J. Vankaerkom, S. Janssen, Environ. Pollut. 183, (2013)
27. Ch. Gromke, Atmospheric Environment 41(16), (2007)
28. Ch. Gromke, N. Jamarkattel, B., Atmospheric Environment 139, (2016)
29. V.A. Usoltsev Biological productivity of forests of Northern Eurasia: methods, database and its applications. (Ekaterinburg, 2007) (in Rus.)
30. T. Yun, L. Cao, F. An, B. Chen, L. Xue, W. Lid, S. Pincebourde, M.J. Smith, M.P. Eichhorn, Agricultural and Forest Meteorology., 276–277, 107610 (2019)