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Impact of particulate matter accumulation on the photosynthetic apparatus of roadside woody plants growing in the urban conditions

Robert Popek[a,b,*], Arkadiusz Przybysz[a], Helena Gawrońska[a], Krzysztof Klamkowski[c], Stanisław W. Gawroński[a]

[a] Laboratory of Basic Research in Horticulture, Faculty of Horticulture, Biotechnology and Landscape Architecture, Warsaw University of Life Sciences – SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland

[b] Laboratory of Ecology, Institute of Dendrology Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland

[c] Research Institute of Horticulture, Pomologiczna 18, 96-100 Skierniewice, Poland

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ABSTRACT

Particulate matter (PM) is one of the most harmful inhaled pollutants. When pollutants are emitted into the atmosphere, the only possible method for cleaning the air is through phytoremediation, where plants act as biological filters for pollutants. However, PM also has negative impacts on plants, although knowledge concerning the effects of PM on vegetation remains limited. In this work, an attempt was therefore made to define the amount of PM and waxes on foliage, and to evaluate the efficiency of the photosynthetic apparatus in seven plant species (three trees, three shrubs and one climber) grown in two locations (centre and suburbs of Warsaw) that differed in their level of PM pollution in the air.

More PM and waxes accumulated on the foliage of plants grown in the highly polluted location. These plants also exhibited a lowered efficiency of their photosynthetic apparatus, manifested by a lower photosynthesis rate that corresponded with an increased stomatal resistance. Plants grown in the more polluted environment also showed decreased values of F_v/F_m parameter and no statistically significant trend to increase total chlorophyll content. Among the tested species, *Betula pendula* Roth accumulated the greatest amount of PM and *Physocarpus opulifolius* L. showed no weakening of its parameters of photosynthesis in a more contaminated environment.

1. Introduction

In urban areas, which cover ca. 0.5% of the Earth's land area (United Nations, 2014), air pollution is an increasing threat to both human and ecosystem health (European Environment Agency EEA, 2015). One of the dangerous inhaled pollutants is particulate matter (PM) (Salvi, 2007), which consists of liquid and solid particles composed of different organic and inorganic compounds (Bell et al., 2011) with an aerodynamic diameter in the range of 0.001–100 µm (Farmer, 2002). As an aerosol, PM can be suspended in the air for weeks and can be transported long distances from the source of emission (Farmer, 2002). Inhaled PM can cause hypertension, heart diseases, allergies and asthma (Atkinson et al., 2001) and worldwide causes approximately 2.1 million premature deaths annually (ca. 154 thousand in Europe) (Silva et al., 2013).

If pollutants have been released into the atmosphere, the only possible way to remove them is via phytoremediation. This involves growing plants in urban areas that accumulate PM on their surface, allowing them to act as biological filters (Popek et al., 2013, 2017a; Ram et al., 2014; Sæbø et al., 2012) and to significantly limit the amount of PM suspended in the air (McDonald et al., 2007). Due to their large surface area, deciduous trees and shrubs possess the greatest ability to accumulate PM on foliage (McDonald et al., 2007), but species differ in their potential to remove PM from the air (Dzierżanowski et al., 2011; Popek et al., 2013, 2017a, 2017b; Ram et al., 2014; Sæbø et al., 2012). Morphological structures on the surface of the leaf, such as hairs and waxes, may increase PM accumulation (Jouraeva et al., 2002; Leonard et al., 2016).

Urban vegetation is constantly subjected to anthropopressure, limited sunlight, contamination, restricted space, increased temperature and soil compaction (Ferrini et al., 2014). These factors negatively affect every level of plant biological organisation, including efficiency of photosynthesis, thus they decrease plants' productivity (Hunt, 2003). The negative impact of urban stress on the photosynthetic apparatus is

* Corresponding author at : Laboratory of Ecology, Institute of Dendrology Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland.
E-mail addresses: robert.popek@gmail.com (R. Popek), arkadiusz_przybysz@sggw.pl (A. Przybysz), helena_gawronska@sggw.pl (H. Gawrońska), krzysztof.klamkowski@inhort.pl (K. Klamkowski), stanislaw_gawronski@sggw.pl (S.W. Gawroński).

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well described, but PM is not considered as a key factor reducing its efficiency (Hanslin et al., 2017; Naidoo and Chirkoot, 2004; Przybysz et al., 2014a). PM accumulated on the foliage may absorb and scatter light rays, preventing its free access to the chloroplasts (Hirano et al., 1995). Small-diameter PM can clog the stomata, thereby reducing gas exchange (Cape, 2009), while chemically-active PM e.g., trace elements, organic pollutants and $Cl-$ and $Na+$, that, depending on the type and environmental conditions, can affect the physiological processes of plants (Chauhan, 2010). In an environment with high levels of PM pollution, the amount of chlorophyll may also be reduced (Van Heerden et al., 2007), and the values of fluorescence of chlorophyll *a* parameters may be decreased (Hanslin et al., 2017; Naidoo and Chirkoot, 2004). Moreover PM with pH values of ≥ 9, may cause direct injury to leaf tissues or indirectly through changing of soil pH (Vardaka et al., 1995). PM leaf cover can also increase leaf temperature (Sharifi et al., 1997). On the other hand there are differences between species. Some authors show that for tree species e.g. *Ilex rotunda* Thunb. the opposite effect was observed. This was explained by a possible protective role of PM by firstly, reducing photoinhibition and secondly, by buffering PM-induced oxidative stress (Takagi and Gyokusen, 2004).

Plant selection in cities is related to their decorative and functional role in the urbanized environment as well as their tolerance to various abiotic stresses. With recent discoveries about phytoremediation another criterion for selecting plants is also being taken into account – their ability to clear air of PM. Nevertheless selection of plants for PM phytoremediation should be a compromise between the amount of accumulated PM and the functioning of the plant in an environment with a raised PM level. A number of studies show the short term effect of PM on different species but environmental studies on the real impact of PM on plants grown in urban conditions are still rare and are needed. Therefore, the aim of this study was to determine the long term effect of PM on the efficiency of the photosynthetic apparatus of seven deciduous plant species from different types (trees, shrubs and climbers) recommended for planting in urban areas and expected to be good candidates for PM accumulation in a temperate climate. Plants were grown in the Polish capital city, Warsaw, in two locations that differed in levels of PM in the air. An attempt was made to: (1) determine the accumulation of surface PM, in-wax PM (in three different size fractions) and (2) wax deposition on foliage, (3) assess the efficiency of the photosynthetic apparatus and (4) correlate the efficiency of the photosynthetic apparatus with the amount of accumulated PM.

2. Materials and methods

2.1. Plant material and study area

The plants selected for this study included three tree species – silver birch (*Betula pendula* Roth), Swedish whitebeam (*Sorbus intermedia* Ehrh.) and London plane (*Platanus* × *hispanica* Münchh.); three shrub species – border forsythia (*Forsythia* ×*intermedia* ZAB.), common ninebark (*Physocarpus opulifolius* [L.] Maxim.) and Japanese spiraea (*Spiraea japonica* L.); and one climber, common ivy (*Hedera helix* L.). Plants had already been growing in vivo in the selected locations for several years and were approximately the same age and size. Studies were conducted in 2008, 2009 and 2010 in Warsaw (52°14'N, 21°00'E), the capital of Poland, in two locations with different levels of PM air pollution (Fig. 1). The site with the higher concentration of PM was located in the city centre. In this location, the average concentrations of PM_{10} and $PM_{2.5}$ for three vegetation seasons (2008 – 2010) amounted to 44.0 μg/m^3 and 25.5 μg/m^3, respectively (Chief Inspectorate for Environmental Protection, 2015). The area with lower PM pollution was located on the Warsaw University of Life Sciences campus situated in the suburban of southern part of the city, and possessed PM_{10} and $PM_{2.5}$ concentrations of 25.5 μg/m^3 and 19.6 μg/m^3, respectively (Chief Inspectorate for Environmental Protection, 2015). The main source of PM in city centres is car exhausts because of heavy traffic. The suburban PM is a mixture of car exhausts and particulates from heating in houses from burning wood and coal, which is a still big problem in Poland especially in winter, spring and late autumn.

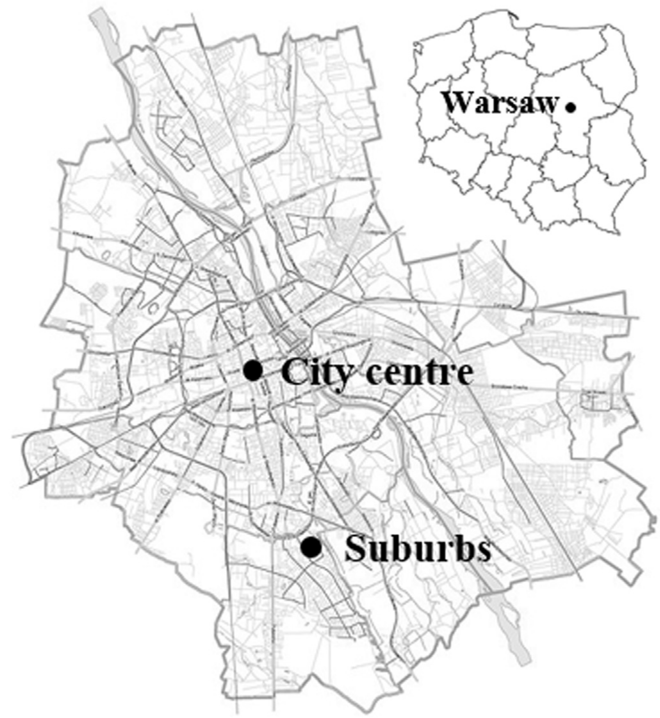

Fig. 1. Study locations differing in level of air pollution.

2.2. Evaluation of efficiency of photosynthetic apparatus

Measurements were carried out four times in every vegetative season, in June, July, September and October. All parameters/processes were always measured on the same plants, which were selected in the first year of the study. For all tested species, leaves selected for measurements were chosen from the middle part of annual twigs located on the side of the plant facing the road, 1.0 – 1.7 m above ground level (the height of a human face). All leaves were undamaged, healthy and free of pests. The following parameters describing the efficiency of the photosynthetic apparatus were measured in vivo.

2.2.1. Plant gas exchange

As part of the gas exchange measurements using an infra-red gas analyser method, (i) rate of photosynthesis and (ii) stomatal resistance were evaluated via the LICOR 6200 Photosynthesis System (Li-6200) in 2008 and via the LICOR 6400 Photosynthesis System (Li-6400) in 2009 and 2010 (Lincoln, Nebraska, USA). The Li-6200 was equipped with the standard leaf chambers, whereas the Li-6400 possessed a 6400-40 Leaf Chamber Fluorometer and a 6400-01 CO_2 mixer. The light intensity for all measurements was 800 – 1000 mmol m^{-2} s^{-1}, provided by natural light (Li-6200) or a red-blue (10% blue) light source (Li-6400). The CO_2 concentration in the chambers was adjusted to a constant 400 μmol mol^{-1}, while relative humidity was approximately 30 – 35%. Measurements were always conducted under the same weather conditions (cloudless, sunny days), between 9 a.m. and 6 p.m. Leaves were placed separately in the chamber of the LICOR photosynthesis system and measured for 2 – 3 min until the photosynthesis rate stabilised, and then results were recorded. Despite the fact that two different Licor systems were used in this experiment, obtained results were very similar between subsequent years of measurements. For each location and term, 12 technical measurements (mean of them were used for